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This is the sixty-ninth progress report of the Laboratory for Nuclear Science at the Massachusetts Institute of Technology. Progress reported covers the period for Physics from October 1, 1965, to October 1, 1966.

TABLE OF CONTENTS

Cosmic Ray Group	1
Accelerator Physics Collaboration	16
Linear Accelerator Group	19
High Energy Accelerator Physics Group.	35
ONR Generator Group	52
Radioactivity Group	66
Cyclotron Group	74
Theoretical Group	83
Personnel Listing	116

Reprints of published papers listed herein are available in limited numbers upon request from the Laboratory for Nuclear Science Document Room.

COSMIC RAY GROUP

I. X-Ray Astronomy

A. Rocket Experiments

The optical identification of ScoX-1, the great x-ray source in Scorpio, was achieved in an investigation carried out in collaboration with scientists at American Science and Engineering, the Palomar Observatory and the Tokyo Observatory. The investigation was based on a rocket experiment which was conducted in March 1966. The experiment employed a multi-grid modulation collimator which is based on the same principle as the two-grid modulation collimator developed earlier at MIT¹ and used by the ASE-MIT group in a rocket experiment that set an upper limit of 7 arc minutes on the angular diameter of ScoX-1.² The multi-grid collimator was composed to two sets of four grids. Each set had narrow transmission bands approximately 75 arc seconds wide separated by approximately 5 arc minutes. The separation between the bands of the two sets was arranged to differ by about 5% so that the transmission directions of the two sets of grids coincided approximately every $(1/.05) \times 5' = 100$ arc minutes. X-rays transmitted by the grids were detected by bands of proportional counters. Analysis of the relative phase of the counting rate peaks from the two collimators in relation to aspect data derived from direct photographs of stars through a portion of the grid structure yielded two probable locations of ScoX-1, each with an uncertainty of about one arc minute.

Astronomers at the Tokyo Observatory and Mt. Palomar were informed of these results and both groups observed a blue stellar object of magnitude $13.0 \pm .5$ within one arc minute of one of the prescribed positions. This object was observed to fluctuate rapidly by as much as one-half magnitude in one day. The visible spectrum shows several identified lines with rapid variations.

The modulation collimator for this experiment was designed and fabricated at MIT. Extensive optical and x-ray tests were carried out to align the grids and study the transmission properties of the collimator for x-rays and visible light.

A complete description of the results on ScoX-1 obtained in this investigation is contained in three publications in the Astrophysical Journal.^{3,4,5} (M. Oda, H. Bradt, G. Garmire, B. V. Sreekantan, G. Spada)

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1. M. Oda, "High resolution x-ray collimator with broad field of view for astronomical use", *Applied Optics* 4, 143 (1965).
 2. M. Oda, G. Clark, G. Garmire, M. Wada, R. Giacconi, H. Gursky, and J. Waters, "Angular sizes of the x-ray sources in Scorpio and Sagittarius", *Nature* 205, 554 (1965).
 3. H. Gursky, R. Giacconi, P. Gorenstein, J.R. Waters, M. Oda, H. Bradt, G. Garmire, and B. V. Sreekantan, "A measurement of the angular size of the x-ray source ScoX-1", *Astrophys. J.* 144, 1249 (1966).
 4. H. Gursky, R. Giacconi, P. Gorenstein, J.R. Waters, M. Oda, H. Bradt, G. Garmire, and B. V. Sreekantan, "A measurement of the location of the x-ray source ScoX-1", *Astrophys. J.*, October 1966.
 5. A.R. Sandage, P. Osmer, R. Giacconi, P. Gorenstein, H. Gursky, J. Watters, H. Bradt, G. Garmire, B. V. Sreekantan, M. Oda, K. Osawa and J. Jugaku, *Astrophys. J.*, October 1966.

B. Balloon Experiments

Activities in the area of balloon x-ray astronomy increased very substantially in this year. New results on the spectra and distribution of cosmic x-ray sources were obtained. In summary the activities and results were:

1. A sky survey between right ascensions 18^h and 6^h and declinations -10° and $+70^\circ$, and measurements of the spectra of Cyg XR-1 and Tau XR-1 between 15 and 70 keV were carried out with a 400 cm^2 NaI(Tl) scintillation detector telescope.

2. Several potential x-ray sources (SN1604, Cas A) were inspected and the spectrum of Tau XR-1 was measured with a 100 cm^2 NaI(Tl) scintillation detector telescope whose orientation is controlled by telemetry from the ground.

3. A 5000 cm^2 survey spectrometer-telescope employing xenon proportional counters was designed and is under construction.

4. A 2000 cm^2 orientation-controlled "broom" telescope for studying the x-ray emission of the Virgo and Coma Clusters was designed and is under construction.

5. A lithium drifted germanium detector telescope for high resolution spectroscopic analysis of x-ray sources was designed and is under construction. (G. Clark, J. Overbeck, W. Lewin, I. Glass, J. Stein, R. Sullivan, H. Tannenbaum, and A. Womack)

II. High Energy Gamma Ray Astronomy

A. OSO Program

The backup version of the S-57 gamma ray experiment for OSO-E1 is being integrated and tested at Ball Bros. Research Company. Preflight data analysis programming has been continued, and the analysis programs have been tested on artificial data. (G. Clark, G. Garmire, M. Greenberg, LNS and W. Kraushaar, University of Wisconsin)

B. OAO Program

The backup gamma ray experiment that used the spare model of the Explorer XI instrument and that was to be carried out in collaboration with the principle investigator, W. Kraushaar, of the University of Wisconsin, was lost aboard the OAO-1. (G. Clark, G. Garmire; LNS. R. Rasche; Center for Space Research. W. Kraushaar; Univ. of Wisconsin)

III. Interplanetary Plasma

A. Plasma Probe Instrumentation for Satellites

In the period December 1965 through September 1966 plasma experiments were launched on the following satellites: Pioneer A, OGO-B. A-IMP, and Pioneer B. All of these experiments

operated successfully and all are operating at the present time. Instruments for the second A-IMP launch and for the Mariner '67 mission are currently in the final stages of calibration and testing. (J. Binsack, J. Davis, T. Dawson, A. Lazarus, and W. Shaw)

B. Detector Design and Development

An extensive study of particle trajectories in the MIT detector has been carried out using a computer. The calculation allows one to predict the response of the detector in the positive ion mode to an arbitrary spectrum and intensity of electrons; similar calculations have been carried out for the response when the detector is operated in the electron mode. Although the response is small in all cases, a sufficiently high flux of electrons will give a signal in the positive ion channels and vice versa. The result of the above calculation is that, in general, the output of the instrument contains sufficient information to allow the determination of the velocity distributions of both the electrons and the positive ions.

It is also possible, using the above calculations as a guide, to design sensors in which the separation of the positive and negative ion fluxes is several orders of magnitude greater than that exhibited by the detectors used so far. This is particularly important for measurements in the transition region. The design and testing of these improved sensors is in progress.

(J. Binsack)

C. Analysis of Data from Satellite-borne Plasma Experiments

During the past year an intensive program of data analysis has been in progress using results from IMP-I, IMP-II, OGO-I, Mariner IV, and Pioneer VI. Work has started on the analysis of results obtained from A-IMP, OGO-III and Pioneer VII. The analysis of the IMP-I data reported in the LNS Progress Report for December 1965 has been repeated taking into account the effects mentioned in Section B of this report. A summary of the results obtained for IMP-I, IMP-II and OGO-I is as follows.

1. Analysis of the IMP-I Plasma Measurements

The MIT plasma experiment carried aboard IMP-1 (Explorer 18) carried out plasma measurements for an extended period of time out to geocentric distances of 31 earth radii. The flux of positive ions was explored in the range of E/q between 45 and 5400 eV, and the electron flux in the range 65 to 210 eV was also recorded.

The initial analysis of these data used the results obtained for the first three months of operation and showed conclusively that in the vicinity of the earth three physical regions can be defined. Region I, beyond the influence of the earth, contains an omnipresent antisolar-directed "supersonic" plasma flow in qualitative agreement with the model of the "Solar Wind" advanced by Parker. Typical plasma properties observed during periods of low K_p were: flux densities from 1 to 4 times $10^8 \text{ em}^{-2}\text{sec}^{-1}$; densities from 4 to 15 cm^{-3} , and bulk velocities from 250 to 450 km sec^{-1} . The spread in thermal velocity is consistent with temperatures in the range of $10^5 \text{ }^\circ\text{K}$. In the vicinity of the earth on the sunlit side, Region II, the "transition region", separates the solar wind from

the region of stable trapping, the van Allen belts. The IMP-I results show that Region II is analogous to the classical region of thermalization which separates a blunt body from a detached bow shock in the case of supersonic flow. In terms of this model, Region III corresponds to the blunt body, in this case the magnetosphere, and is characterized by the absence of detectable low energy plasma.

One of the most interesting problems which should perhaps be soluble using the IMP-I data is whether or not Region I is separated from Region II by a classical detached bow shock. If this is the case, there must be conservation in the flow of mass, momentum and energy across the boundary. In turn, these conservation equations (the Rankine-Hugoniot equations) predict that the number densities before and after the shock are related by:

$$\rho_1/\rho_2 = (\gamma - 1)/(\gamma + 1)$$

Since gamma almost certainly lies between 5/3 and 2, the number density should change by about a factor of 3 going from Region I to Region II.

The calculation outlined above was performed about two years ago and resulted in very high density ratios, about 8 to 10. Since then it has gradually become clear that low energy electrons, ~ 50 eV, are present in the transition region and cause spurious signals when the detector is operated in the positive ion mode. Although the response (relative to positive ions of the same energy and intensity) is small in all cases, a sufficiently high flux of electrons will produce a signal in the positive ion channels. Taking this effect into account, the number densities of the positive ions can be computed correctly in Region II. This has been done for the first 21 orbits of IMP-I and the average change in density is found to be 2.4. The results are not so conclusive as one might hope, but it must be remembered that the conservation equations should be checked by simultaneous measurements in Region I and Region II. In the present case, a measurement requires about one hour and the properties of the plasma often change drastically on this time scale.

The method of calculation outlined above has been used to compute hourly averages of the plasma parameters in Region I for the four months during which IMP-I penetrated this region of space. The results are being prepared for publication. (E. Lyon, G. Moreno, S. Olbert, and G. Pai)

2. Analysis of the IMP-II Plasma Measurements

The IMP-II satellite (Explorer 22) was launched on October 4, 1964, into a highly elliptical orbit with apogee at 15.9 earth radii (R_E) into the subsolar region. The MIT plasma experiment on this satellite (a Faraday cup similar to the experiments flown on previous satellites) made extensive measurements of the solar plasma in the vicinity of the earth. The nearly five months of useful data that have been analyzed included some measurements of the interplanetary solar wind, but a greater portion of the data was obtained while the satellite was in the earth's magnetosphere and the transition region.

During the lifetime of the IMP-II satellite, solar cycle number 19 was waning and the new cycle was just becoming established. The satellite was able to provide information on the spatial and temporal behavior of the boundaries of the transition region during two solar rotations. The average positions of the outer boundary, the bow shock, and the inner boundary, the magnetopause, during this period agree remarkably well with those computed from the IMP-I data a year earlier (Lyon, 1966). However, comparing the deviations about the mean values shows that the spreads are greater for the IMP-II data. This almost certainly reflects the increased activity at the start of solar cycle 20 beginning in October 1966.

Some of the larger excursions from the mean boundary positions exhibit a recurrent pattern and can be related to the recurrent geomagnetic storms and solar M regions. This same pattern is evident in the 3-hour K_p diagrams. Several of these storms resulted in boundary compressions to 80 percent of the average positions, and one event was simultaneously explored by the IMP-II and the OGO-I satellites on opposite sides of the magnetosphere.

In addition to the larger, more prominent motion of the boundaries at the time of solar activity, it has been found that the boundaries are essentially continuously in motion. Usually shock and magnetopause satellite traversals are rich in multiple boundary crossings. One example of long term oscillatory boundary motion has been observed with period of 2.7 hours and 10 percent amplitude.

The structure of the interplanetary medium has been studied from the viewpoint of contact discontinuities associated with recurrent M-region storms on the sun. On one occasion the velocity of the "driver gas" of the enhanced plasma exceeded 750 km/sec, but more normal values were near 500 km/sec. A plasma density pile-up usually preceded the velocity jump by approximately a third of a day.

Measurements in the transition region revealed the presence of disturbed plasma behind the shock boundary. Estimates of the electron thermal energy show it to be below 50 eV. Fluxes of electrons have also been measured in the magnetosphere in the dawn hemisphere where thermal energies near 1 keV are common.

A study of the IMP-II data near perigee was rewarded by an unforeseen bonus. A consistent feature of the data in one of the channels can be shown to be caused by the satellite passing through a high density stationary cloud of positive ions near the earth. The region occupied by these ions has a rather sharp boundary near $5 R_e$ where the density increases by one or two orders within a fraction of an earth radius. This region has been investigated by knee-whistler radio techniques and has been tentatively termed the plasmasphere. The IMP-II data have mapped the boundary of the plasmasphere and its response to solar and geomagnetic activity and agree remarkably well with data obtained from whistler propagation studies. (J. Binsack)

3. Analysis of the OGO-I Plasma Measurements

Data from the OGO-I electron detector covering the period October to December 1964 have now been analyzed; a summary of the principal results follows:

Electrons of energies between 125 eV and about 2000 eV were observed out to distances of 24.4 earth radii near the geomagnetic equator on the dusk side of the earth by means of a Faraday cup detector with four energy windows. In the transition region between the magnetosphere and the solar wind, fluxes of electrons varying from $10^8 \text{ cm}^{-2} \text{ sec}^{-1}$ to $10^{10} \text{ cm}^{-2} \text{ sec}^{-1}$ were found, the higher values occurring during magnetic storms; the differential flux of the electrons varied with energy roughly as E^{-4} to E^{-6} indicating that the electrons were a non-Maxwellian high energy tail of a distribution peaked well below 125 eV. Weak or no fluxes were detected in the solar wind; the termination of transition region electron fluxes occurred at the shock front, except that during one magnetic storm strong fluxes were found out to some distance in front of the shock. In the magnetosphere a band of electrons of mean energy of a few hundred eV, density of order 1 cm^{-3} , and flux of order $10^9 \text{ cm}^{-2} \text{ sec}^{-1}$ was found extending from the magnetosphere boundary inward to a sharp termination at 11 ± 1 earth radii, occasionally closer; crossing this termination inward, the mean energy of the electrons dropped sharply (as much as a factor of 5 in 1 earth radius distance) while the density increased slightly. This band is identified with the soft electron belt previously inferred from Lunik 1 and 2 observations by Gringauz. At distances greater than about 10 earth radii from the dawn-dusk meridian on the night side, a region of electrons of mean energy 40 to 80 eV, density 5 to 10 cm^{-3} , and flux of the order of $10^{10} \text{ cm}^{-2} \text{ sec}^{-1}$ was found, but limited data prevented determining its precise boundary. Throughout the surveyed region of the magnetosphere, including both the high and low energy regimes mentioned, the electron energy density was found to be approximately the same and relatively unvarying; the total energy density of the plasma, if equipartition of energy between electrons and protons is assumed, corresponded to magnetic fields of 20 to 40 γ , comparable to the measured fields.

Work is continuing on data from the proton detector and on later periods. (V. M. Vasyliunas)

IV. BASJE Cerenkov Light Experiment

An experiment to measure at high altitude the pool of Cerenkov light (CL) emitted by Extensive Air Showers (EAS) during their traversal of the atmosphere is presently being conducted by the Laboratory for Nuclear Science (LNS) of the Massachusetts Institute of Technology in collaboration with the Department of Physics and Astronomy at the University of Maryland. This experiment will be operated in conjunction with the present array of EAS detectors of the Bolivian Air Showers Joint Experiment (BASJE) on Mr. Chacaltaya at an altitude of 17,200 feet above sea level.

The objectives of the experiment may be described as follows: The Cerenkov light emitted by the EAS particles in the atmosphere is attenuated only slightly during its passage through the atmosphere to the level of detection. Thus the measured pool of CL is closely related to the total track length of EAS particles above the experimental station and therefore yields information about shower development high in the atmosphere which, in turn, is closely related to the nature of the nuclear cascade in the core of the EAS and also to the nature of the primary particle.

In practice, the magnitude and the fluctuations of the relative amounts of Cerenkov light and electrons at Mt. Chacaltaya will be studied as a function of shower size. Ideally, the showers may be found to fall into several distinct classes according to the character of their CL pools. Optimistically, these classes might then be identified with the various primary particles such as protons, heavy nuclei and gamma rays. More realistically, the CL measurements will provide very significant new data on the character of each detected shower. Added to the wealth of other data provided by the present BASJE, it will open new possibilities for studying the composition of the primary particles and the development of showers.

The average atmospheric depth of the maximum development of EAS initiated by heavy primaries is smaller than those initiated by protons of the same total energy. They should, therefore, exhibit a significantly higher CL photon (γ_c) to electron ratio. Estimates based upon calculations by Zatsepin and Chudakov¹ indicate that this is a 60 percent effect for the case of Fe primaries. The average depth of EAS produced by primary photons is also less than that of proton-initiated showers. However, because of the electromagnetic character of photo-initiated showers, they have a greater average size at a given primary energy at the altitude of Mt. Chacaltaya and thus exhibit a lower γ_c/e ratio than do proton-initiated EAS. Estimates indicate that this is about a 30 percent effect.

The 60 m² BASJE muon detector has already made possible the selection of a group of "no-mu" EAS which may be produced by photon primaries. If these showers are also associated with unusually small amounts of CL, our earlier conclusion that these showers are basically electromagnetic in character would be confirmed. Similarly, if the showers with an unusually large amount of CL also have a large muon content, it would strengthen arguments that these showers are due to heavy primaries. One form of analysis of the data may be to construct a two-dimensional plot of shower frequency with respect to the μ/e ratio (in 60 m²) and the γ_c/N_e ratio where N_e is the shower size, or total number of electrons at the level of observation. Distinct classes of EAS would appear as a clumping of points in this presentation (See Fig. 1.1)

No systematic study of the pool of Cerenkov Light emission by EAS has as yet been carried out at altitudes above 3860 m. It is clear that such a study should be performed while BASJE is still in operation, not only because the CL data can be correlated with the other EAS characteristics, but because at the high altitude of Mt. Chacaltaya (5200 m) the experimentally observed quantities are more closely related to the physically interesting properties of the first

1. V.I. Zatsepin and A. E. Chudskov, Soviet Physics JETP 15, 1126 (1962).

few generations of EAS development. Also, from a phenomenological point of view, this experiment is essential to the complete description of the character of EAS at these high altitudes.

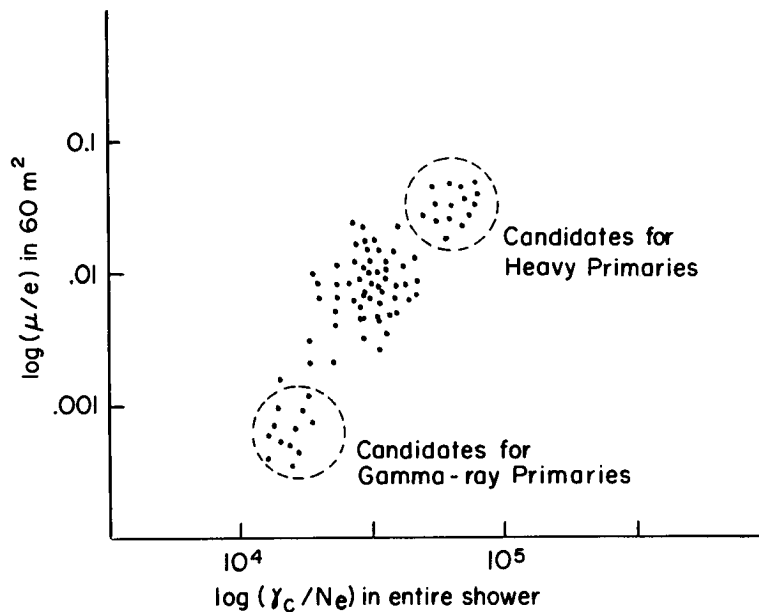


Fig. 1.1

Sample presentation of data. Each point represents one air shower. γ_c is number of Cerenkov photons.

Consideration of fluctuations in the depth of the first interaction of primary particles clearly indicates that this experiment must be carried out at mountain altitudes rather than at sea level. Indeed, at sea level, fluctuations in the γ_c/N_e ratio due to differing primary particles would be completely masked by normal fluctuations in the electron number due to this effect, whereas at the altitude of Mt. Chacaltaya this would not be the case.

Each detector (Fig. 1.2) consists simply of nine five-inch diameter photomultiplier tubes which view the sky directly during moonless nights. In order to optimize the ratio of the Cerenkov Light flash signal to the noise from fluctuations in the background DC starlight flux, it is important to have short integration times (< 100 rsec) at the phototube anodes. Because of the long cable lengths between the detectors (≤ 400 m) and the electronics room, this signal must be analyzed at each detector. Accordingly, rather complex electronics are contained in each detector. An array of 13 such detectors will be installed over an area of radius 300 m.

At present five detectors have been installed and initial data have been accumulated. Preliminary runs under controlled conditions indicate that we are successfully observing the CL emitted by the EAS in the atmosphere rather than CL emitted by electrons in the glass of the photomultipliers.

This experiment continues to be the principal research project of Mr. Allen Krieger, a graduate student in the MIT Physics Department, who is making it the subject of his doctoral thesis. He has successfully carried out the partial installation and initial tests of the array. He

had the assistance of three students from MIT and the University of Maryland during this period. He utilized their talents and abilities with excellent results. He continues to be assisted by one graduate student from Maryland, Mr. Brian Rennex. Overall supervision of this project is provided by Professor H. Bradt. Prof. Martin La Pointe is the senior collaborator at the University of Maryland. (H. Bradt, A. Krieger, G. Minagawa, LNS; M. La Pointe, B. Rennex, University of Maryland)

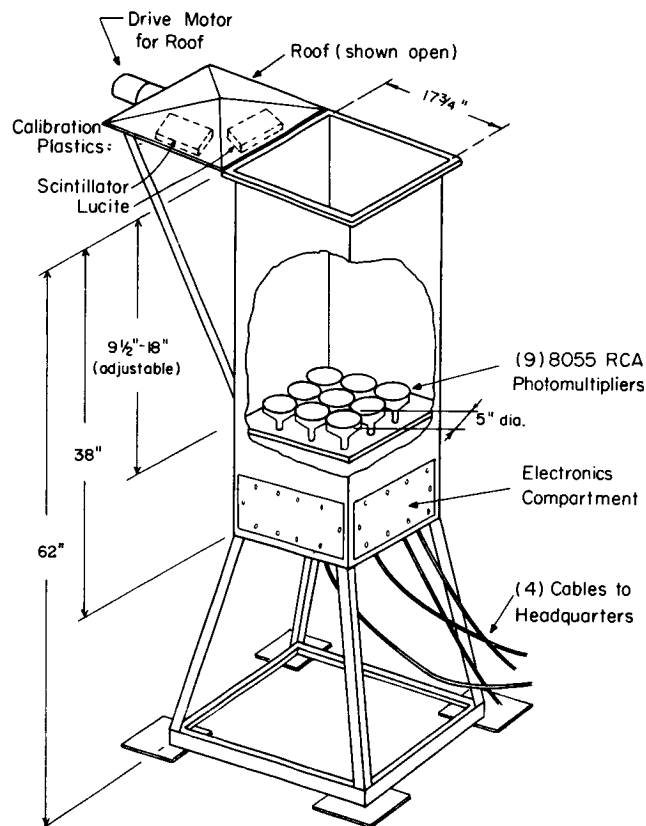


Fig. 4 CERENKOV LIGHT DETECTOR

Figure 1.2

Cerenkov Light Detector

V. Search for Quarks in Cosmic Rays

Recently theoretical concepts based on unitary symmetry (SU 3) have led to speculations about the existence of fractionally charged ($1/3 e$ and $2/3 e$) particles of mass heavier than the nucleon. Experiments carried out both at BNL and CERN have yielded a negative result indicating that if quarks exist their mass must be higher than about 4 BeV which is the maximum mass particle that can be produced at these accelerators.

Several cosmic ray experiments have been carried out both at mountain altitude and sea level and these have set an upper limit of about few times $10^{-9}/\text{cm}^2 \text{ sc. st.}$ for the flux of relativistic quarks. In all these experiments the charge identification is based on the measurement of the

energy loss of ionization which is for relativistic $1/3 e$ particles $1/9 I_{\min}$, and for $2/3 e$ particles $4/9 I_{\min}$, where $I_{\min}$ is the energy loss of a minimum ionizing singly charged particle. Most of these experiments have not yielded unambiguous results because of i.) small area and aperture telescopes and consequently poor statistics; ii.) poor charge resolution, and iii.) heavy background.

A telescope of considerably larger area and aperture and with the possibility of much better charge resolution compared to any that have been operated so far, has been designed and is being set up in a basement laboratory under a total equivalent absorber thickness of about a meter of concrete.

The telescope (Fig. 1.3) consists of three scintillators S_1 , S_2 , and S_3 , and three proportional counters P_1 , P_2 , and P_3 , stacked one above the other as shown in the figure. S_1 and S_3 are plastic scintillators 6" thick and 38" diameter and S_2 is a liquid scintillator 7" thick and 42" diameter. Each scintillator is looked at by four Dumont 6364 photomultipliers. The proportional counters are 4" high and cover an area of 48" x 48". They are filled with Argon-Methane mixture at atmospheric pressure. The scintillators have a uniform response over the entire area and the distribution of pulse heights as determined by the passage of cosmic ray muons through the telescope up to an angle of $\sim 45^\circ$, show a FWHM of 20% for the scintillators and 25% for the proportional counters. The advantage of proportional counters is that they have a negligible efficiency for gamma rays, thus reducing considerably the background anomalous events.

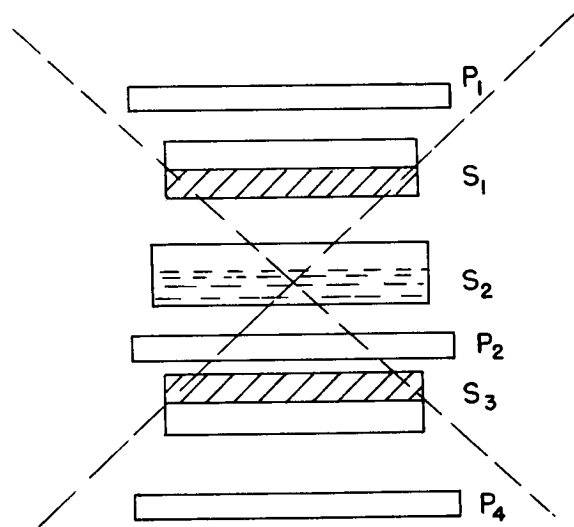


Figure 1.3

A block diagram of the electronics, triggering system, and display of the proportional counter pulses is shown in Fig. 1.4. The window discriminators are adjusted such that the first channel passes pulses which are centered around $1/9 I_{\min}$, the second channel around $1/4 I_{\min}$ and the third channel $4/9 I_{\min}$. The sweep of the oscilloscope is triggered and the proportional counter pulse heights recorded whenever there is a coincidence between the corresponding

channels in the three scintillators. The identity of the channel that triggers is indicated by a corresponding neon lamp which is photographed along with the scope traces.

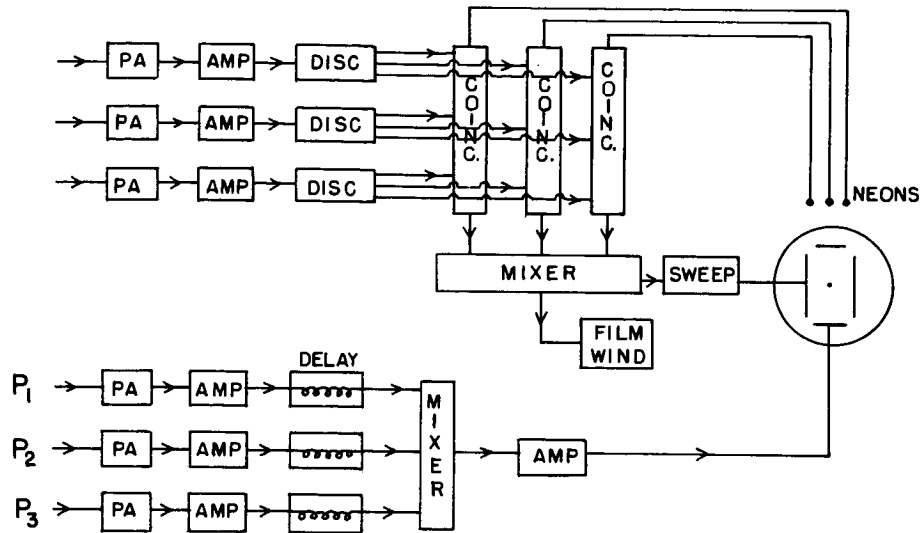


Figure 1.4

A preliminary experiment extending over a period of about 136 hours has been carried out with all the three scintillators in position and with only the middle proportional counter. The results are as follows:

Area X solid angle of the telescope	0.75 m ²
Time of operation	136 hrs
Flux of cosmic ray muons	$1.8 \times 10^5/\text{hr}$
Triggering rate with windows set as above	40/hr
Rate of association of pulses in the middle proportional counter	10/hr
Rate of association with pulses between 0.08 and $0.75 I_{\text{min}}$	1/hr
Upper limit to 1/3 e candidates	0.07/hr
Upper limit to 2/3 e candidates	0.4/hr
(These upper limits are on the assumption that all quarks are relativistic.)	
Upper limit to the flux of 1/3 e	$\sim 5 \times 10^{-9}/\text{cm}^2 \text{ sc. st.}$
Upper limit to the flux of 2/3 e	$\sim 3 \times 10^{-8}/\text{cm}^2 \text{ sc. st.}$
(The over-all efficiency was estimated to be $\sim 50\%$).	

It is seen that even with one proportional counter operating and with only 136 hours of operation, the limits that have been obtained are as good as any of the earlier experiments that have been reported. The insertion of the other two proportional counters should reduce the

background events considerably and enable the determination of a more reliable upper limit even in a month's operation.

After an initial period of operation of about three months at sea level, it is proposed to move the telescope to Mt. Chacaltaya in Bolivia (alt. 17,000 ft) because of the following considerations:

The method adopted for charge identification works only for relativistic quarks, since otherwise the rate of ionization loss becomes comparable to that of singly charged fast particles. Quarks of mass say 10 BeV are relativistic only at energies greater than 40 BeV, which can be produced only in interactions of energy greater than 200 BeV. Because of this most of the quarks are produced only at very high altitudes. If the quarks are even slightly interacting, the chances of catching them as relativistic quarks are much higher at an altitude of 500 gms/cm² than at sea level. Even an interaction mean free path of 200 gms/cm² would increase the flux of relativistic quarks by a factor of 10 at 500 gms/cm², compared to sea level. Also the relativistic quarks will be associated with much smaller size showers at 500 gms/cm² than at sea level. This may help in filtering out the accompanied soft component more easily. (G. Garmire, B. V. Sreekantan)

VI. Infrared Astronomy

Using the 61-inch reflector of Harvard Observatory, we have attempted to measure the spectrum of the Crab Nebula, the Orion Nebulae, and the Andromeda Nebula (M-31) in the range 1 - 2.5 microns. The spectral scans were made using an interferometer loaned to us from Block Associates by Mr. Lawrence Mertz. No reliable signals were obtained from either M-31 or M-42, probably due to their large zenith angle at the time the scans were made. There is evidence of a signal from the Crab Nebula in the continuum between 2.1 and 2.4 microns; however, the quality of the data was rather poor and further scans of this object will be made during the winter of 1966-67. Theoretical estimates yield an estimated intensity some 50 times less than that measured in this experiment.

A lamellar grating spectrometer is under construction, which will be capable of spectral measurements between 10 microns and 2 mm. The first object to be studied will be the sun. Measurements of the solar spectrum will be made as a function of altitude up to perhaps 120,000 feet. The general features of the solar spectrum in this region are well understood, so the emphasis will be on obtaining data on the transmissivity of the upper atmosphere. Should a significant portion of this region of the spectrum be accessible from balloon altitudes, scans will be made of the reststrahlung spectrum of the moon and nearer planets. (G. Garmire, H. Hinteregger, R. Thompson)

VII. Development of a Lithium-drifted Germanium Detector for Gamma Ray Lines

This new type of photon detector has already demonstrated its ability to improve the results of nuclear spectroscopy. Only 3 eV of an incoming photon's energy is required for the production of each electron-hole pair, as contrasted with 30 eV for the production of an ion-electron pair in a gas counter or 300 eV for the production of a photoelectron in a NaI scintillation counter.

The germanium crystals used have just enough lithium drifted into them to provide the electrons to compensate the impurity gallium. The mobile holes produced by the gallium would otherwise greatly outnumber the electron-hole pairs produced by photons. The lithium is introduced by a lengthy process of heating the crystal while an electric field is applied to it. The field causes the lithium to drift until each lithium ion stops near a gallium atom. The lithium near the crystal's surface is in a supersaturated solution at room temperature so in order to preserve this unstable state and also to suppress the thermal generation of electron-hole pairs the detector must be kept at liquid nitrogen temperature.

With the help of Prof. Norman Rasmussen of MIT's Nuclear Engineering Department we are now drifting lithium into two germanium crystals 1 cm thick and 15 and 20 cm² in area. Not only is it inexpensive to do this ourselves, but we have the capability of reprocessing the detector if it should warm up or of replacing it with improved detectors as they are developed.

The cryogenic equipment for it is being built with special consideration given to the necessity of surrounding the detector by an active, high Z anticoincidence shield. Since background reduction is as important as attainment of high resolution we are using a very thick anticoincidence shield made of a 5-inch thick, 7-inch diameter cylinder and a tube one foot long, with 8-inch and 3-inch outside and inside diameters.

This detector system should be as good as the present state of the art permits in both area and background rejection. We hope that it will also have an energy resolution near 3 keV FWHM from 30 keV to well over 1 MeV. This type of detector with its thick anticoincidence shield seems to be the best detector available today for detecting cosmic gamma ray lines above 100 keV. A schematic drawing of the detector is shown in Figure 1.5.

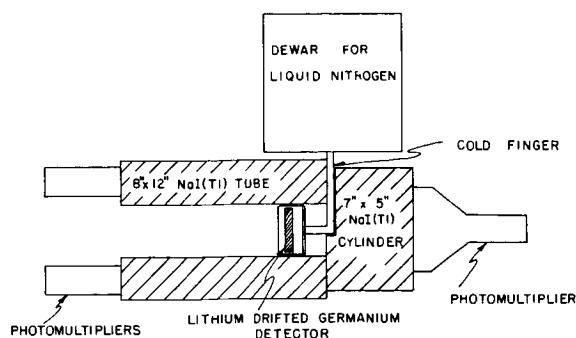


Figure 1.5
Sketch of detector telescope

The detector's sensitive depth will be about 5 gm/cm^2 so that its efficiency will be greater than 60% to about 200 keV and essentially 100% below 100 keV. At higher energies, its somewhat lower efficiency is offset by its excellent resolution.

As an example of the detector's capability, let us take the Clayton and Craddock flux estimate for 390 keV Cr^{251} photons from the Crab Nebula: $9.7 \times 10^{-5} \text{ cm}^{-2}\text{sec}^{-1}$. We estimate the background in the detector at this energy to be about $1.2 \times 10^{-5} \text{ cm}^{-2}\text{sec}^{-1}\text{keV}^{-1}$ and its efficiency to be about 30%. Its area and energy resolution are taken as 20 cm^2 and 3 keV respectively. We can expect from the Crab Nebula, then, about 2.1 counts per hour due to Cr^{251} , and that these counts will be more than four standard deviations above the background after an observing time of four hours.

Because our understanding of the sites for nucleosynthesis is still vague it is not unreasonable to expect fluxes even larger than the above from some sources. X-ray astronomers with instruments of considerably lower resolution have already seen "bumps" of unknown origin in x-ray source spectra. Our detector telescope should be able to clarify the origin of these quite rapidly.

It should also be noted that the detector we are developing has a reasonable size and complexity so that in addition to the high altitude balloon experiments we propose, it would be well suited for use on a satellite which could supply the necessary orientation and cryogenic facilities. With exposure times of days or months one could be sure of getting significant results concerning cosmic radioactivity as well as lunar, terrestrial, and solar radioactivity.

Addresses and Invited Papers

- H. Bradt, "The Bolivian Extensive Air Shower Experiment", MIT Physics Colloquium, Nov. 18, 1965.
- H. Bradt, "Possible Existence of Gamma Ray Primaries above 10^{14} eV ", Paper HF8, Washington, DC, Spring Meeting of the Am. Phys. Soc., April 27, 1966.
- H. Bradt, "The Location and Optical Identification of ScoX-1", Mexico City Summer Meeting of the Am. Phys. Soc., August 1966.
- H. Bradt, "Recent Cosmic Ray Results at Mt. Chacaltaya", Invited Paper, 13th Nuclear Science Symposium of the IEEE, Boston, October 19, 1966.
- H. Bridge, A. Lazarus (with C. Snyder, JPL) "Plasma Probe Observations from Mariner 4", A.G.U. 46th Annual Meeting, Washington, D.C., April 19, 1965.
- H. Bridge, Participation in the Study Group on Space and Laboratory Plasmas at the European Space Research Institute (ESRIN) in Frascati, Rome, Italy, May 9 - June 3, 1966.
- G. Garmire, "X-Ray Astronomy", talk given at the New York Academy of Science, Nov. 1965.
- A. Lazarus, "Initial Results from the Mariner 4 Solar Plasma Experiment", COSPAR Meeting, Vienna, May 1966.
- A. Lazarus, "Preliminary Results from the Pioneer 6 MIT Plasma Experiment", 47th Annual Meeting of the A.G.U., Washington, D.C., April 1966.
- S. Olbert, "Solar Wind and its Interaction with the Magnetosphere"
 - Invited paper, Am. Phys. Soc., Central States meeting, Chicago, Oct. 29, 1965.
 - Invited paper, Physics Colloquium, University of Wisconsin, Nov. 1, 1965.
 - Invited paper, 4th Western National Meeting of A.G.U., Seattle, Washington, Dec. 1965.
 - Two invited talks, Physics Colloquium and Cosmic Ray Group Seminar, University of Minnesota, Jan. 12, 13, 1966.
- S. Olbert, Participation in the Study Group on Space and Laboratory Plasmas at the European Space Research Institute (ESRIN) in Frascati, Rome, Italy, "Measurement in Space", paper presented at ESRIN, May 9 - June 3, 1966.

- B. Rossi, "X-Ray Astronomy"
Haverford Colloquium, Haverford College, Haverford, Pa., Oct. 7, 1965.
Atomic Energy Commission of Mexico, Mexico City, Jan. 25, 1966.
- B. Rossi, NASA Committee on Physics Meeting at MIT, Apr. 22, 23, 1966.
- B. Rossi, Participation in the Study Group on Space and Laboratory Plasmas at the European Space Research Institute (ESRIN) in Frascati, Rome, Italy, May 9 - June 3, 1966.
Opening lecture on "Measurements in Space", May 9, 1966.
- B. Rossi, "Recent Advances in X-ray Astronomy", Symposium on Radio Astronomy and the Galactic System, Noordwijk, Netherlands, Aug. 25-Sept. 1, 1966.
- B. Rossi, Talk for Senior Students at MIT, Oct. 13, 1966.
- B. Rossi, "Galaxies and the Universe", Symposium at Columbia University, Lamont Observatories, New York, Oct. 18, 1966.
- B. Rossi, "Some Recent Results of X-Ray Astronomy", Goddard Scientific Colloquium, G.S.F.C., Greenbelt, Maryland, Oct. 27 and 28, 1966.
- V. Vasyliunas, "Observations of 50 to 2000 eV electrons with OGO-A", paper presented at the 47th Annual Meeting of the A.G.U., Washington, D.C., April 1966.

Publications

- H. Bradt, M. Oda, G. Garmire, B. V. Sreekantan, H. Gursky, R. Giacconi, P. Gorenstein, J. Waters, "A Measurement of the Angular Size of the X-ray Source Sco-1", *Astrophys. J.* 144, 1249 (1966).
- H. Bradt, M. Oda, G. Garmire, B. V. Sreekantan, H. Gursky, R. Giacconi, P. Gorenstein and J. Waters, "A Measurement of the Location of the X-ray Source ScoX-1", submitted to *Astrophys. J.*
- H. Bradt, G. Garmire, B. V. Sreekantan, M. Oda, K. Osawa, J. Jugaku, A. Sandage, P. Osmer, R. Giacconi, P. Gorenstein, H. Gursky, and J. Waters, "On the Optical Identification of ScoX-1", submitted to *Astrophys. J.*
- H. Bridge, A. J. Lazarus, and J. Davis, "Preliminary Results from Pioneer 6 MIT Plasma Experiment", *J. Geophys. Res.* 71, #15, August 1966.
- A. Lazarus, E. A. Womack and S. W. W. Liu, "Linear Relationship for Heavy-Ion Pulse Heights in Alkali Halides", *Phys. Rev.*, April 1966.
- A. Lazarus, H. Bridge, J. Davis, and C. W. Snyder, "Initial Results from the Mariner 4 Solar Plasma Experiment", submitted for publication in the Proceedings of the 1966 COSPAR Meeting, Vienna, June 1966.

Theses

- E. F. Lyon, "A Study of the Interplanetary Plasma", Ph.D., January 1966.
- J. H. Binsack, "Plasma Studies with the IMP-2 Satellite", Ph.D., August 1966.
- A. J. Klimas, "The Transport of Charged Particles in the Galaxy", Ph.D., August 1966.
- V. M. Vasyliunas, "Observations of Low Energy Electrons with the OGO-A Satellite", August, 1966, Ph.D.

ACCELERATOR PHYSICS COLLABORATION

I. Scope

The program of the Accelerator Physics Collaboration consists of four main parts:

1. Neutral decay modes of elementary particles and charge exchange reactions. This work has been mainly carried out with spark chamber and counter arrays at Brookhaven National Laboratory.
2. Photo-induced reactions in a hydrogen bubble chamber: This work has been carried out in a hydrogen bubble chamber at the CEA and is almost complete.
3. PEPR: This is the development of a computer-controlled measuring and scanning machine. This development is now beginning its production mode on the study of $p\bar{p}$ interactions at 3.7 BeV/c.
4. MIT 500-liter Bubble Chamber: It has been decided to reassemble this chamber and install it as a facility at Argonne National Laboratory. It will be used, at first, in a pion study in the multi-BeV range. As part of this study, we have requested 100,000 pictures from the MURA 30-inch bubble chamber.

II. Summary of Past Year's Work and Expected Progress

1. Spark Chamber

The A.G.S. exposure of $\pi^- + p \rightarrow$ neutrals in the energy range 1 BeV - 4 BeV has been under analysis during this past year. We hope to complete the analysis shortly. The results will include angular distributions for charge exchange scattering and η^0 production; also, we will break down the multiple π^0 production into $2\pi^0$, $3\pi^0$, etc., contributions.

We have set up and are currently making an exposure at the B.N.L. Cosmotron on the reaction $\pi^- + p \rightarrow \eta + N$. Our aim is to study the η^0 branching ratios for decay. We are using a neutron time-of-flight system plus visual detection of the neutron as part of our triggering system. We plan to take this equipment with suitable additions and modifications to higher energies and look at the general class of reactions $\pi^- + p \rightarrow O^0 + N$, where O^0 can be any neutral boson resonance such as ρ^0 , ω^0 , f^0 , X^0 , etc. The point would be to study decay branching ratios, with- in one experiment, of both neutral and charged final states.

2. 12-inch Bubble Chamber Studies

During this period, we have completed the analysis of the data taken at the CEA. This is being reported in a series of six papers to the Physical Review. Five of the six papers are complete and submitted. They are:

- a. Analysis of γ -p reactions in a hydrogen bubble chamber to 6.0 BeV, cross sections and laboratory distributions.
- b. Photoproduction of ρ^0 mesons.
- c. Photoproduction of strange particles.
- d. Photoproduction of ω^0 mesons.
- e. Production of the $N^*(1238)$ nucleon isobar by photons of energy up to 6 BeV.
- f. Photoproduction of multi-pion resonances.

These papers will complete our studies on photo-induced reactions in a bubble chamber. These studies are the first of their kind and, although we shall not pursue this field any longer, the work will continue at other electron accelerators, such as SLAC and DESY.

3. PEPR

In this period, the prototype PEPR, coupled to the PDP-1, has measured some 50 events on an experimental basis. Plans are being implemented to schedule PEPR on a one-shift production basis starting in October.

In addition, the bidding cycle for a three-view PEPR has been completed. Our recommendations as to choice of vendor has been forwarded to the A. E. C. This three view system will make available the possibility of track-following in three dimensions for the first time. This extremely powerful aid to pattern recognition should improve the throughput of events in a substantial way.

The PDP-6 has arrived and has been installed. After the usual software and hardware difficulties, the computer is now operational. The changeover from the PDP-1 to the PDP-6 will begin in November. Most of the translation of the programs from the PDP-1 to the PDP-6 has been completed. It is expected that production operation will resume early in 1967. Transferring from the PDP-1 to the PDP-6 should result in a significant improvement of the analysis rate.

As part of the PEPR program, we are analyzing $p\bar{p}$ interactions at 3.7 BeV/c incoming momentum. We have hand-measured 6,000 events. These same events will be measured by PEPR and compared.

On careful examination, the yield of events from the film on hand (5-year-old BNL 20-inch film), will not be as high as the 100,000 events originally estimated. This film contains probably a factor five less than this. Although the film will yield interesting results, it will not be the large-scale experiment originally expected.

4. MIT 500-liter Bubble Chamber

Negotiations have been completed with Argonne National Laboratory to transfer the MIT 500-liter Bubble Chamber there.

An orderly transition from the MIT operation to the Argonne operation has been planned. This transition should be complete in the next two years.

The program with the chamber, combined with PEPR, will be a systematic survey of pion physics in the multi-BeV region. As a start on this program, we have requested 100,000 pictures at 3.9 BeV/c from the MURA 30-inch hydrogen bubble chamber. This film will be analyzed on PEPR.

III. Proposed Work

Although our work in photoproduction with a hydrogen bubble chamber will not be continued, all other areas will be actively pursued. In particular, we are looking forward to analyzing about 300,000 pion interactions in this period.

Besides counter and spark chamber work, we will be doing a systematic study of high-momentum k interactions at Argonne. This will be in the unique rf separated beam that our group is instrumental in developing.

PUBLICATIONS

P. Bastien, B. T. Feld, V. K. Fischer, et al., Photoproduction on Hydrogen of ρ^0 Mesons between Threshold and 6 BeV, Phys. Rev. 146, No. 4, 994-1000, (June 24, 1966).

THESIS

I. M. Asher, H. M. Bozler, Development of an Ultrasonic Helium Bubble Chamber, B.S., (June 1966).

LINEAR ACCELERATOR GROUP

I. Photodisintegration of Be^9

Analysis of the $\text{Be}^9(\gamma, n)$ data, now nearing completion, will yield cross sections for and angular distributions of photoneutron production leaving the Be^8 nucleus in its ground state and the excited states accessible with the gamma-ray energies available at the MIT accelerator (4-15 MeV). Cross sections for the three-body breakup of Be^9 are also being derived.

The data were taken at electron energies from 4.2 to 15 MeV in steps of 1.5 MeV. The photoneutron spectra have been treated with a Monte Carlo method to remove target scattering effects and each run has been reduced to a cross section assuming that all neutron emissions proceeded via the Be^8 ground state. From a comparison of these data it has been possible to derive the actual $\text{Be}^9 + \gamma \rightarrow n + \text{Be}^8$ ground state cross section from $E_\gamma = 2.5 - 15$ MeV. From measurements performed at neutron emission angles of 24° , 76° , and 155° relative to the photon beam, angular distributions have been derived in the form $\frac{d\sigma}{d\Omega} = a_0 + a_1 P_1(\cos \theta) + a_2 P_2(\cos \theta)$.

The cross sections for the runs at the four lowest bremsstrahlung end point energies and the resulting actual ground-state cross sections for the three angles are shown in Figures 3.1, 3.2, and 3.3. The values of a_2/a_0 and a_1/a_0 obtained from these cross sections are shown in Fig. 3.4.

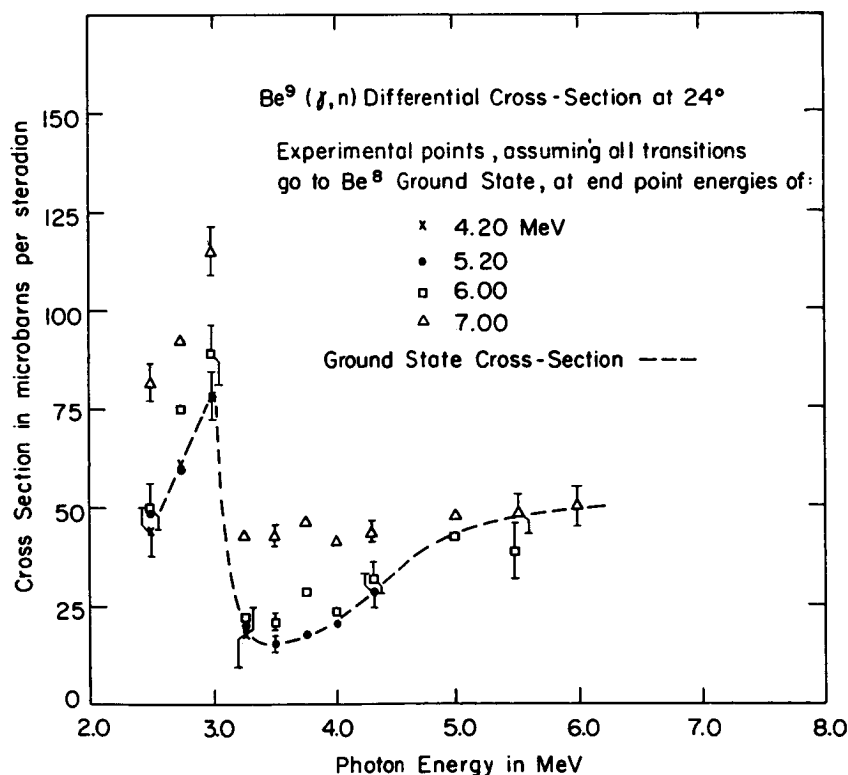


Figure 3.1

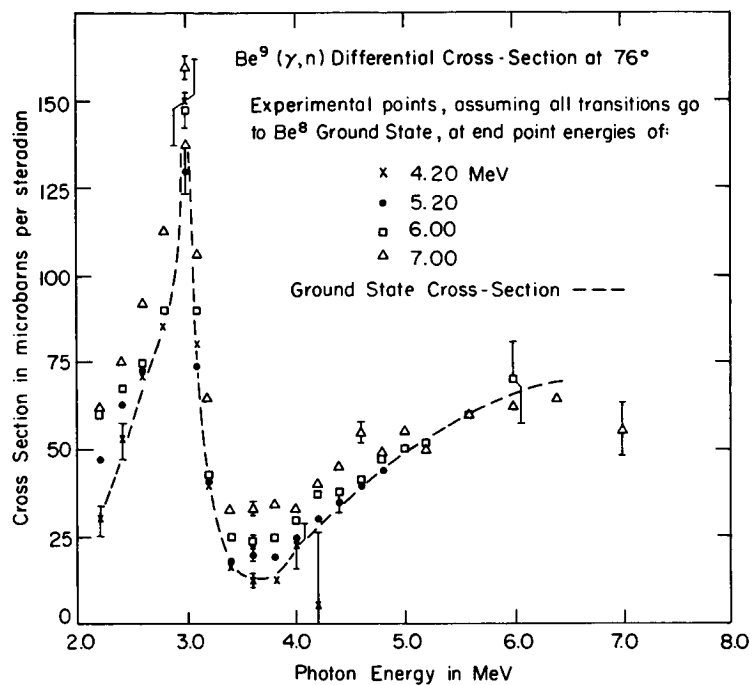


Figure 3.2

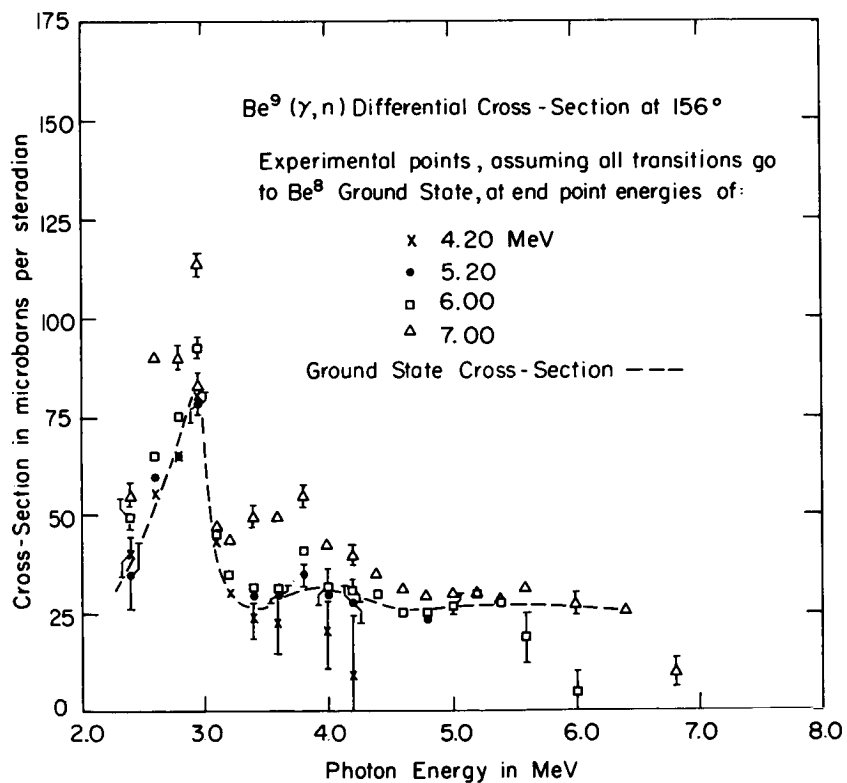


Figure 3.3

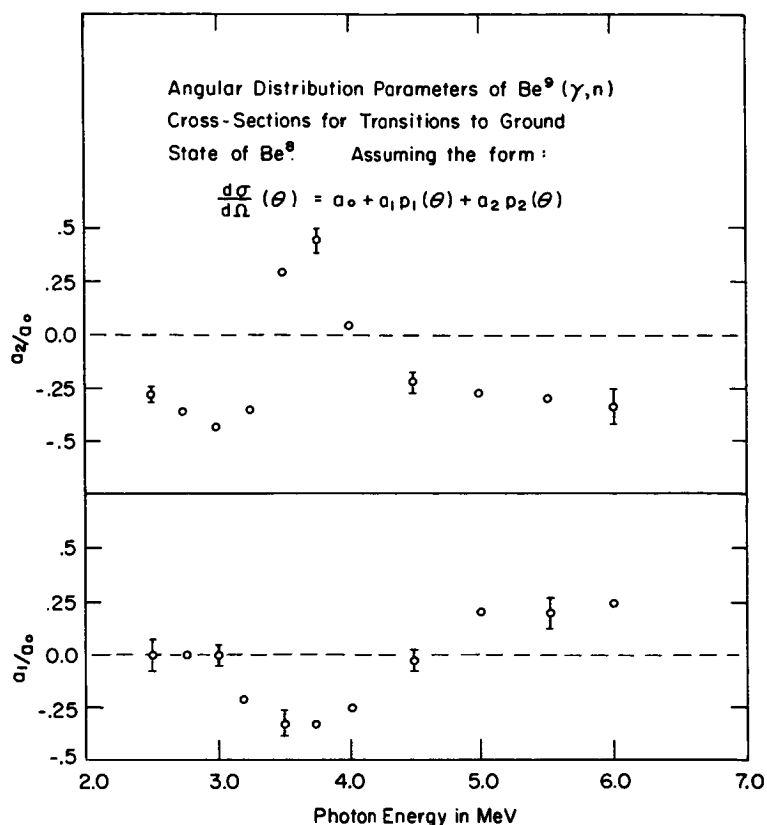


Figure 3.4

The non-zero values a_1/a_0 above 3.2 MeV are indicative of the presence of both even and odd parity amplitudes in this region of excitation of Be^9 . The lack of any other experimental evidence for a state in this region and the lack of evidence for assigning the $1/2^-$ spin and parity to any other detected level leads us to make the tentative assignment of $1/2^-$ to this interfering level. The value, -0.4, of a_2/a_0 at 3.0 MeV is consistent with that obtained for electric dipole excitation of a pure $5/2^+$ level. This is further evidence to confirm the $5/2^+$ spin and parity assignment to this level.

Analysis of the higher energy runs to obtain the ground-state cross sections and angular distributions at higher energies is almost complete, as is the analysis of the excited-state cross sections and their angular distributions.

II. Photoneutron Systematics: The Angular Distributions and Energy Spectra of Photoneutrons from Heavy Elements

The energy spectra of photoneutrons from Bi, Pb^{208} , Pb^{207} , Pb^{206} , Tl, Hg, Au, W, Ta, Er, Ho, Sm, Pr, La, I, Sn, and In were measured at 24° , 76° , and 156° relative to the photon beam from the MIT Linear Accelerator. Bremsstrahlung spectra were used with endpoints of

15, 14, and 13 MeV. The neutron energies were determined using a time-of-flight spectrometer with 10 meter flight paths and 8 ns resolution. Subtracting the 14 MeV (or 13 MeV) data (properly normalized) from the 15 MeV (or 14 MeV) data yields neutron spectra generated by an equivalent photon spectrum peaked at 14 MeV (or 13 MeV) with a FWHM of 2 MeV.

The angular distributions of the photoneutron spectra from these three bremsstrahlung spectra were analyzed in the form $W(\theta) = a_0 + a_1 P_1(\cos \theta) + a_2 P_2(\cos \theta)$. a_1 was found to be approximately constant with energy for each target, and to range from -0.07 to +0.05 with statistical errors of ± 0.02 and estimated systematic errors of ± 0.09 . Therefore a_1 was assumed to be zero for all targets, and the angular distributions are presented in the form $W(\theta) = a_0 + a_2 P_2(\cos \theta)$. The anisotropy (a_2/a_0) was found to increase with neutron energy. The low energy photoneutrons (< 3 MeV) are isotropic ($a_2/a_0 = 0$) and the anisotropy is a maximum at or near the neutron endpoint. This maximum value of the anisotropy shows marked shell effects. It is a maximum ($-a_2/a_0 = 0.6$ to 0.7) near the closed shell nuclei Pb^{208} and Pr , and it has a minimum ($-a_2/a_0 = 0.15$ to 0.3) between these two closed shells, in the region of the deformed nuclei. These results are shown in Figure 3.5.

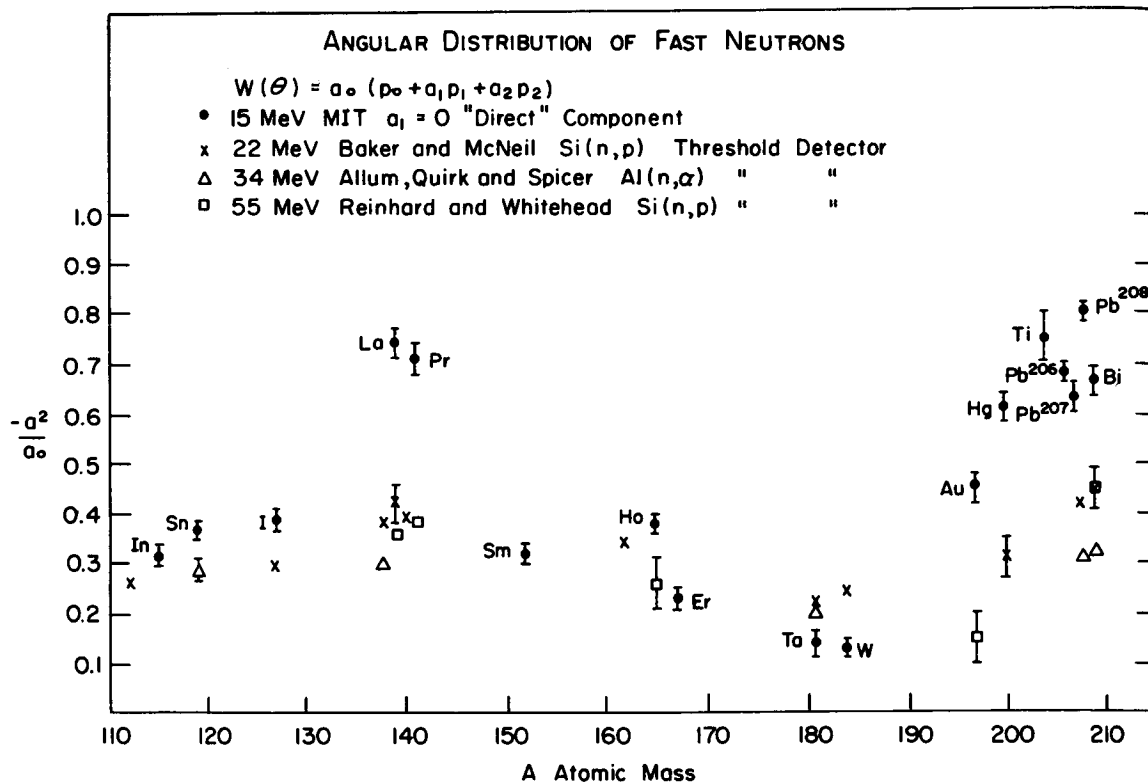


Figure 3.5

The neutron difference spectra are characterized by an isotropic evaporation component which dominates at low neutron energies, and an anisotropic resonance direct component which dominates at high neutron energies. The transition from one component to the other is quite abrupt, typically taking place in an energy interval of about one to two MeV.

It was found to be possible to fit the neutron difference spectra with the theoretical curve $dN/dE_n = \text{const } E_n \sigma_C \omega(U) + kS(E_n)$, where $\omega(U)$ is the level density of the residual nucleus at an excitation energy U , σ_C is the inverse capture cross section, and $S(E_n)$ is the energy spectrum of the direct component. The data was analyzed using three approximations for the level density, $[\exp 2\sqrt{a_3/2}U] / (U+t)^{3/2}$, $[\exp 2\sqrt{a_2}U] / (U+t)^2$, and $\exp (-E_n/T)$, where t is given by the equation $U = a_m t^2 - t$. $S(E_n)$ was calculated using Wilkinson's model of the giant resonance. In the above equations, a_m (or T), and k were the only adjustable parameters. Figure 3.6 shows the data for Pb^{208} along with the difference spectrum and fit according to the above model.

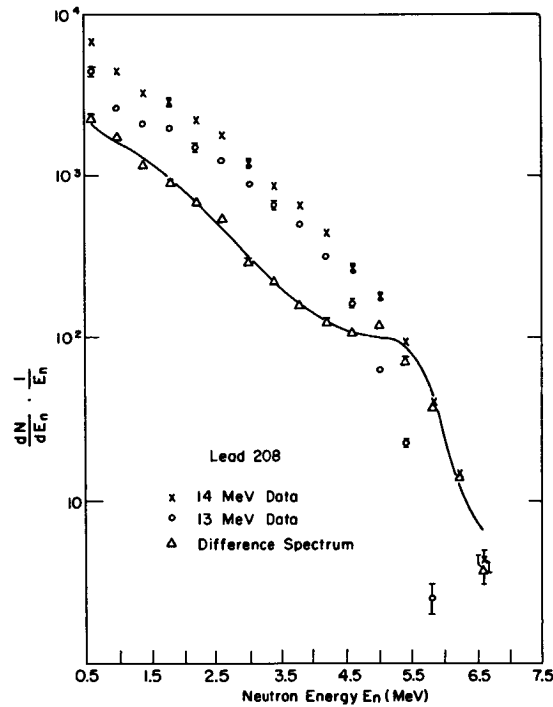


Figure 3.6

The values of a_2 generally follow the predictions of Newton, $a_2 = K(\bar{j}_z + \bar{j}_p + 1)A^{2/3}$. K was found to be 0.067. Fig. 3.7 shows the results for a_2 . The fraction of directly emitted neutrons, f , defined as the integral of the direct spectrum divided by the integral of the total spectrum, was found to be about 14%, and approximately constant with A , the mass number.

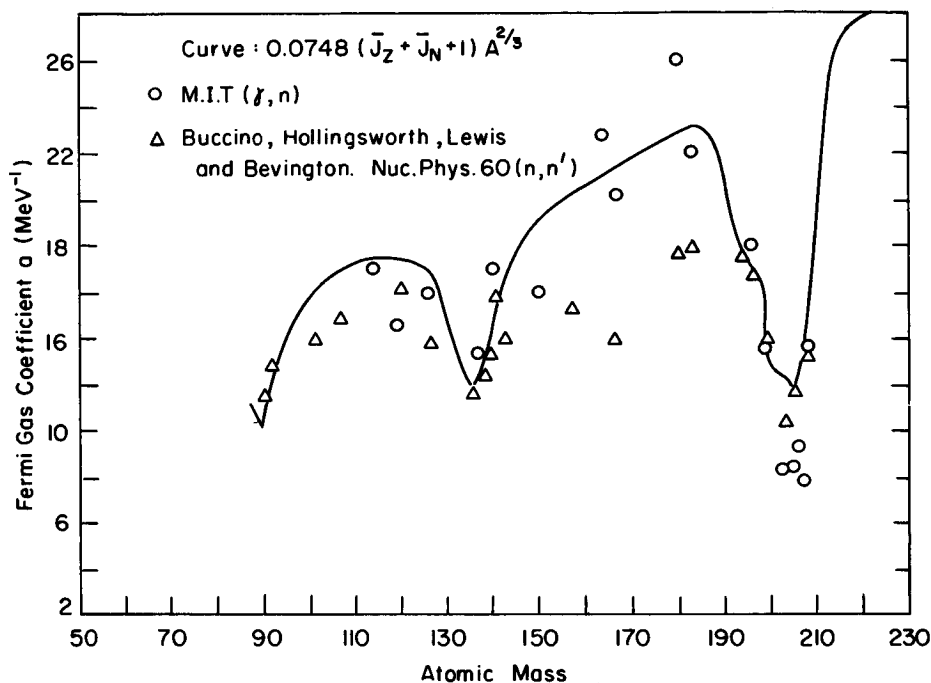


Figure 3.7

These results are being prepared for publication.

III. Photoneutron Polarization Experiments

The final analysis of the photoneutron polarization data has been completed. Table 3.1 lists the elements, laboratory neutron production angles, and the bremsstrahlung end-point energies for which results were obtained. These final results combine all measurements made in 1962, 1963, and 1964. Plots of some of these results are shown in Figs. 3.8 to 3.13. The polarization P_n is defined to be positive in the direction of $\vec{k}_\gamma \times \vec{k}_n$, the directions of the incoming photon and outgoing photoneutrons respectively (Basel convention). The data plotted have been corrected for the polarimeter response function and tunnel scattering, and for internal scattering in the Photoneutron targets. The errors shown include all known sources of statistical and systematic uncertainties.

Measurements of the polarimeter response function for 14.7 and 2.86 MeV neutrons were completed last spring and final theoretical fits to the experimental corrections made. These fits were then used to correct the experimental data. The theoretical calculations for polarimeter response function and tunnel scattering are estimated to be accurate to 30% or better.

Table 3.I

A list of elements for which photoneutron polarization measurements were made.

<u>Element</u>	<u>Neutron emission angle (degrees)</u>	<u>Bremsstrahlung end-point energy (MeV)</u>
O^{16}	45	24, 30, and 38
	90	30
C^{12}	45	30 and 47
	90	30 and 50
Ca^{40}	90	28
Pb^{208}	45	28
	90	21
H^2	45	--
	90	--

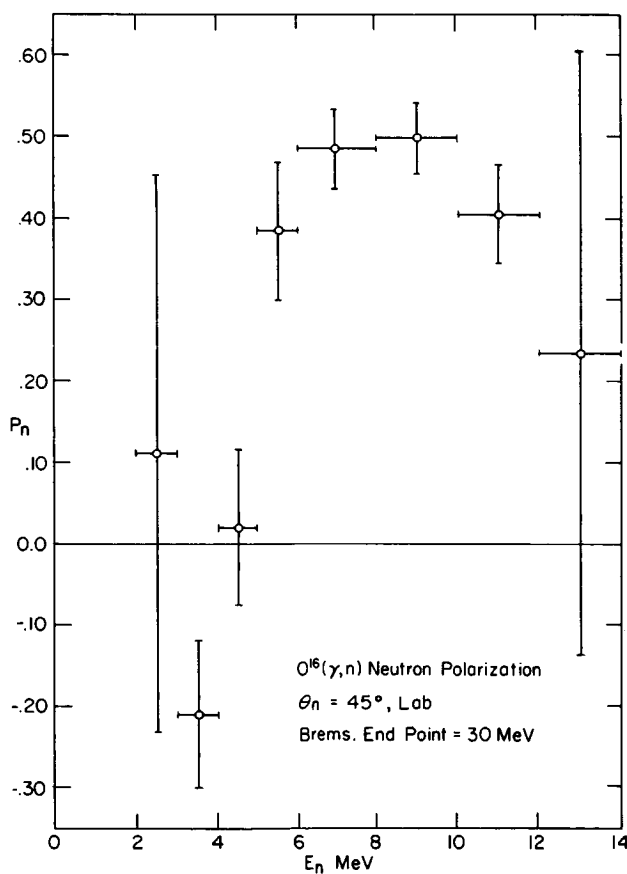


Figure 3.8

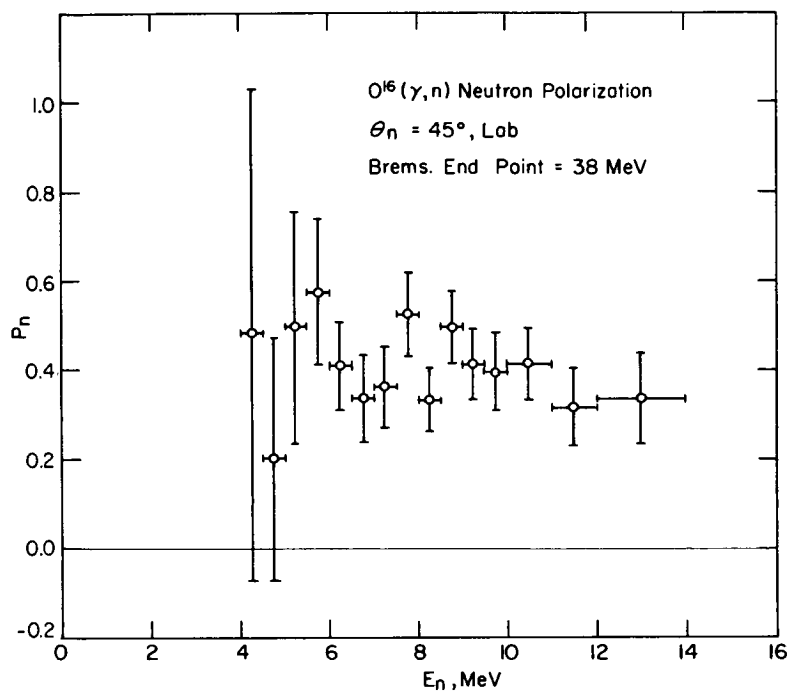


Figure 3.9

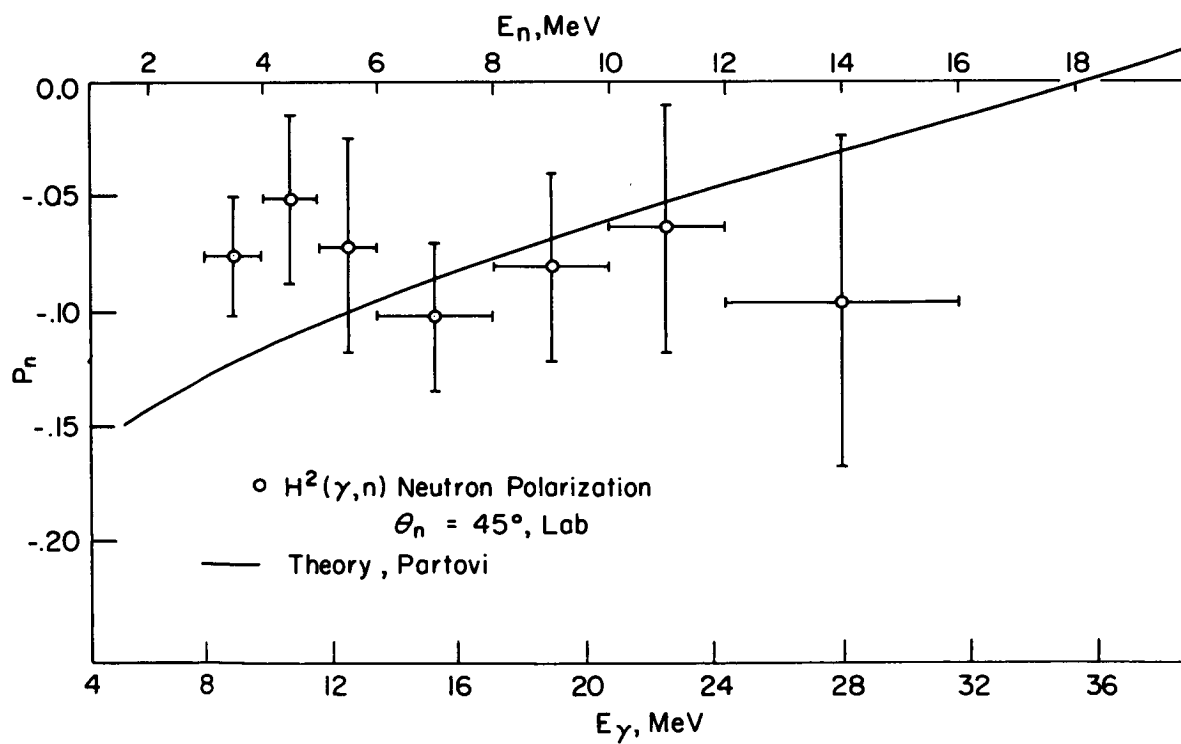


Figure 3.10

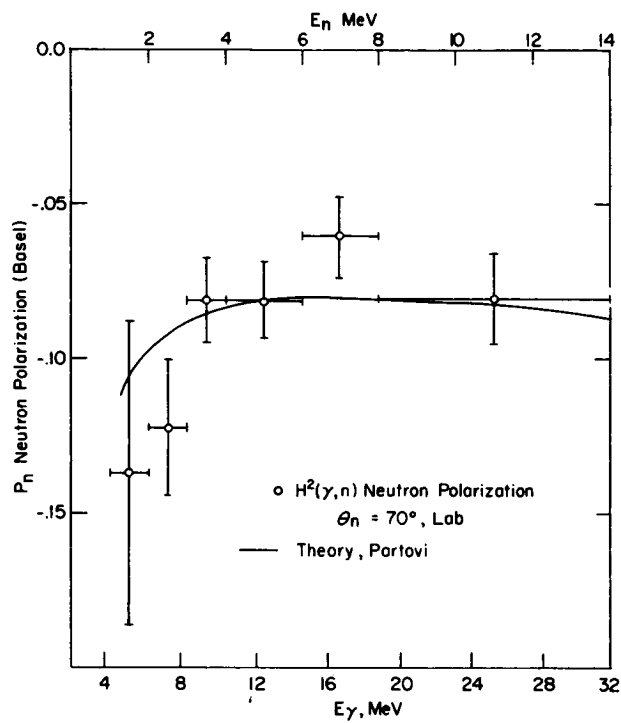


Figure 3.11

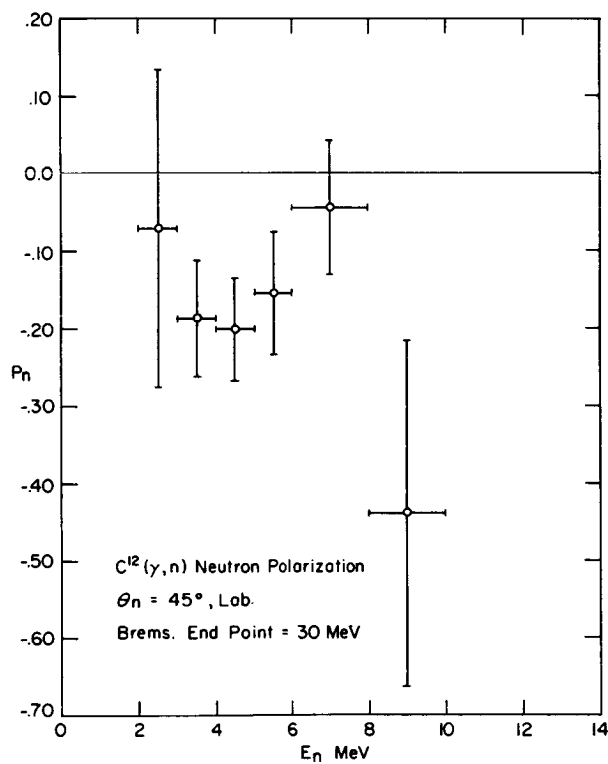


Figure 3.12

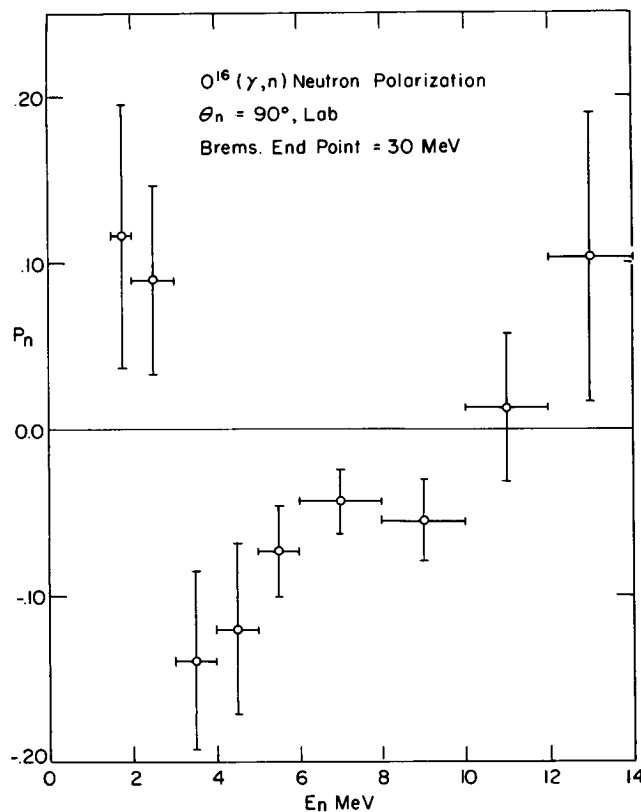


Figure 3.13

A new set of $He^4(n, n)$ scattering phase shifts was obtained from Hoop and Barschall.¹ These revised phase shifts were used to recalculate the polarimeter's polarizing power and detection efficiency, and a complete re-analysis of the data has been made. At present all the data are being prepared for publication.

IV. Polarization of Scattered Neutrons

A new program is underway to measure the angular distribution of the polarization of elastically and inelastically scattered fast neutrons. The 150 keV Cockcroft-Walton Accelerator of the MIT Nuclear Engineering Department is being used to produce unpolarized 14.7 MeV neutrons by means of the $T(d, n)He^4$ reaction. An intensity of 5×10^{10} neutrons in 4 pi steradians has been attained using 3-5 c tritium-titanium targets and a 500 μA deuteron beam.

The polarizations of the various neutron groups scattered by a target are analyzed by means of a Helium-Xenon polarimeter. (MIT Progress Report, Dec. 31, 1965, and earlier.) Basically, it consists of a high pressure (50 atm) He-Xe gas scintillation counter and an array of liquid scintillation detectors. The left-right asymmetry in the scattering of neutrons by the

1. Private communication, to be published.

helium is determined by counting rates in the liquid detectors. The scintillation pulses produced by recoiling helium nuclei in the gas counter are analyzed only when they are in delayed coincidence with neutron-proton recoils in the liquid scintillation detectors. Since the angle of scattering of the neutron is known, the recoil pulse height spectrum represents the energy distribution of the neutrons incident on the gas counter. By suitable addressing of a multi-channel analyzer, events are stored in the memory according to the polar and azimuthal angle of the second neutron scattering.

The experimental arrangement is shown in Figure 3.14.

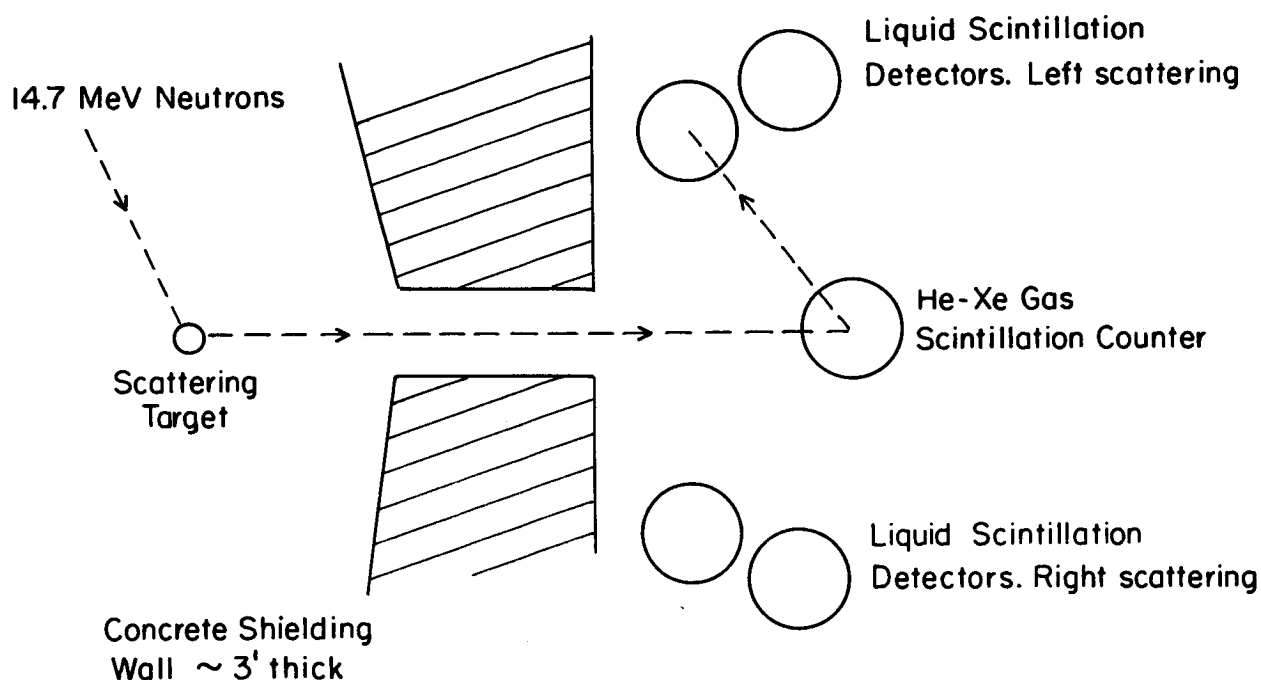


Figure 3.14

Preliminary data using C^{12} as a target have been obtained. The spectrum of He^4 recoils in delayed coincidence with neutron-proton recoils in one side detector is shown in Fig. 3.15.

In order to increase the rate of data acquisition, four more liquid scintillation detectors are being added. In addition to C^{12} , O^{16} and Ca^{40} will be used as targets in the initial experiments.

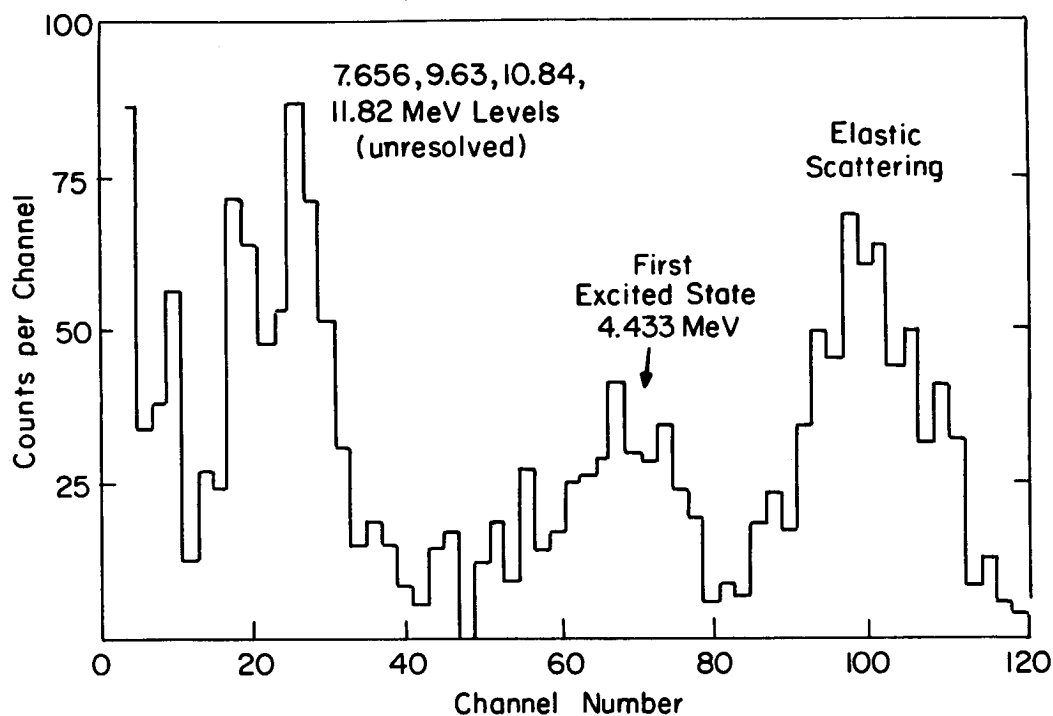


Figure 3.15

14.7 MeV neutrons scattered by C^{12} at 45° c.m.
Coincidence spectrum for 141° scattering from He.

V. Saskatoon Collaboration: Shell Effects in the High Energy Photoproton Spectra from Li^6

A study of the high energy protons emitted in the nuclear photoeffect in the $E_\gamma \sim 100$ MeV region can yield information about the photonuclear reaction mechanism, about the structure of the nucleus, and about the high-momentum components of nuclear wave functions. Experiments with $E_\gamma \gtrsim 200$ MeV are consistent in some detail with the quasi-deuteron model, in which the photon interacts with a neutron-proton pair.¹ At lower energies, the situation is not so clear. The most complete experiment is that of Whitehead, *et al.*², who measured differential cross sections for photoprotons at five energies from carbon, lithium, and beryllium with 40-100 MeV bremsstrahlung. Most of the data could be accounted for with the quasi-deuteron model. However, for the "threshold protons", i. e., those with the maximum energy kinematically allowed for a given photon energy, the size of the cross section and the angular distribution deviated substantially

1. J. Garvey, B. H. Patrick, J. G. Rutherglen, and I. L. Smith, *Nuclear Phys.* **70**, 241 (1965), with references to earlier work.
2. C. Whitehead, W. R. MacMurray, M. J. Aitken, N. Middlemas, and C. H. Collie, *Phys. Rev.* **110**, 941 (1958).

from the predictions of a quasi-deuteron calculation. Moreover, the cross section for the production of 37 MeV photoprotons from lithium as a function of E_γ exhibited two peaks, at $E_\gamma \sim 45$ MeV and $E_\gamma \sim 62$ MeV. A subsequent calculation by Fujii¹, using a direct-interaction mechanism and the shell model, showed that this phenomenon, as well as the observed angular distribution, could be represented as the ejection of protons from the p-shell and the s-shell of Li^7 , and that in this respect the nuclear photoeffect was thus very similar to the (p, 2p) reaction. A significant difference between the two processes lies in the initial particle momentum range investigated -- the majority of the (p, 2p) data sample proton momenta up to ~ 200 MeV/c, whereas for a 100 MeV photon ejecting a proton from the p-shell of Li^6 , the initial proton momentum goes from 310 MeV/c at $\theta_p = 0^\circ$ to 475 MeV/c at $\theta_p = 180^\circ$.

If these single-particle effects are indeed occurring, a measurement of the photoproton energy spectrum with sufficient resolution at a single bremsstrahlung energy should show two features displaced in energy by the difference in proton separation energies for the s- and p-shell.

An experiment to investigate with good resolution the proton spectra and angular distributions in the nuclear photoeffect at 100 MeV has been performed at the Saskatchewan Accelerator Laboratory. Bremsstrahlung produced by the electron beam striking a .004" aluminum radiator was collimated to a 2" spot at the target position. The electron beam was removed by a sweeping magnet. Protons were detected at eight angles -- 45° to 139° -- simultaneously by an array of two-counter telescopes. A $\frac{1}{4}$ " plastic scintillator ΔE counter was backed up by a 5" plastic scintillator E counter, the two parameter pulse-height distribution thus obtained yielding a clean separation of protons from particles of other masses. The energy resolution of the E counter was measured with monoenergetic protons to be about 4%; the angular resolution of each telescope was $\pm 3^\circ$. The reactions $\text{Li}^6(\gamma, p)$, $\text{Li}^7(\gamma, p)$, and $\text{C}^{12}(\gamma, p)$ were examined; the majority of the data were taken on Li^6 at bremsstrahlung endpoint energies of 95 and 102 MeV.

A typical spectrum, for Li^6 photoprotons at $E_{\gamma \text{ max}} = 102$ MeV and $\theta_p = 82^\circ$, is shown in Fig. 3.16. The proton energy scale was calibrated through a series of runs with different thicknesses of copper absorbers placed in front of each telescope. The scale thus derived is consistent with that obtained from observing the position of the 1 MeV Na^{22} Compton edge with the signals passed through a gain-of-10 amplifier, and using the proton vs electron response data for plastic scintillator of Gooding and Pugh.² The arrows indicate "threshold proton" energies computed from the $\text{Li}^6(\gamma, p)\text{He}^5$ reaction kinematics, using $E_\gamma = 102$ MeV, and proton separation energies of $E_s = 4.9$ MeV for the p-shell and $E_s = 22.7$ MeV for the s-shell, values derived from the (p, 2p) measurements.³ What the data suggest is two "bremsstrahlung endpoints"; a group of protons at each of the maximum energies allowed by the kinematics.

1. S. Fujii, Prog. Theor. Phys. 29, 374 (1963).

2. T. J. Gooding and H. G. Pugh, Nucl. Instr. and Meth. 7, 189 (1960).

3. H. Tyren, S. Kullander, O. Sundberg, R. Ramachandran, and P. Isacsson, Nuclear Phys. 79, 321 (1966).

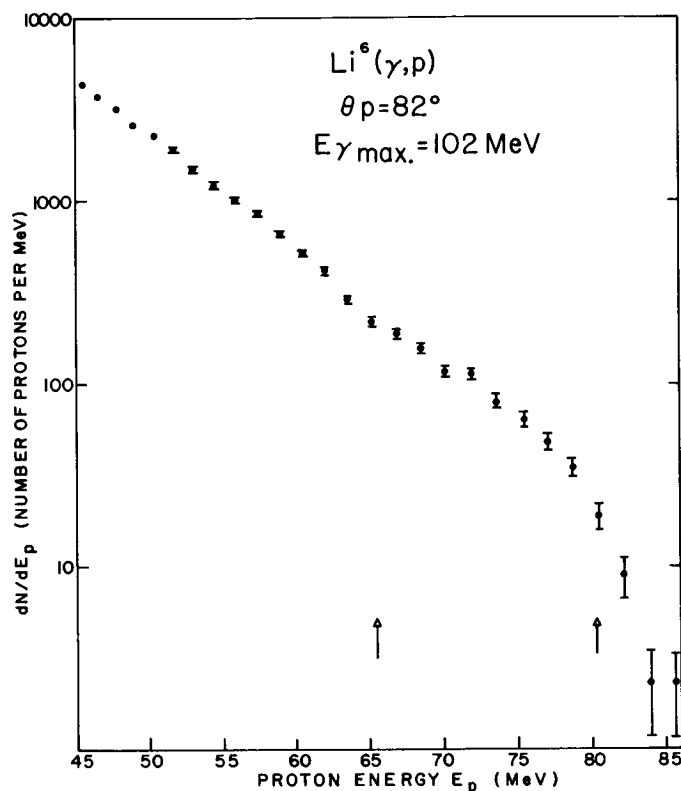


Figure 3.16

Spectrum of photoprotons from Li^6 at $\theta_p = 82^\circ$, with bremsstrahlung of maximum energy 102 MeV. The arrows indicate proton energies calculated from $\text{Li}^6(\gamma p)\text{He}^5$ kinematics for $E_\gamma = 102$ MeV, and $E_s = 4.9$ MeV and 22.7 MeV.

To simulate the proton spectrum that would be observed with monochromatic incident photons, a spectrum measured with 95 MeV bremsstrahlung was subtracted, properly normalized, from the data of Fig. 3.16. This "difference spectrum" is displayed in Fig. 3.17. The threshold proton energies for $E_\gamma = 102$ MeV are again indicated by arrows.

Comparable data, exhibiting similar structure, are available at the other seven angles investigated in this experiment. Analysis of the angular distribution is in progress. The results are in qualitative agreement with predictions based on a single-particle direct-interaction model and are not to be expected from a simple quasi-deuteron model.

Spectra from the $\text{Li}^7(\gamma, p)$ reaction were obtained with 95 MeV bremsstrahlung only. Similar features are also seen in these data, though less distinctly than in Li^6 ; as might be expected in the s- to p-state separation in Li^7 is 4 MeV less and both states are 2 MeV wider than in Li^6 . The $\text{C}^{12}(\gamma, p)$ measurement provides an absolute scale for the differential cross section for Li^6 and Li^7 , normalizing our C^{12} spectra to those measured by Whitehead, *et al.*

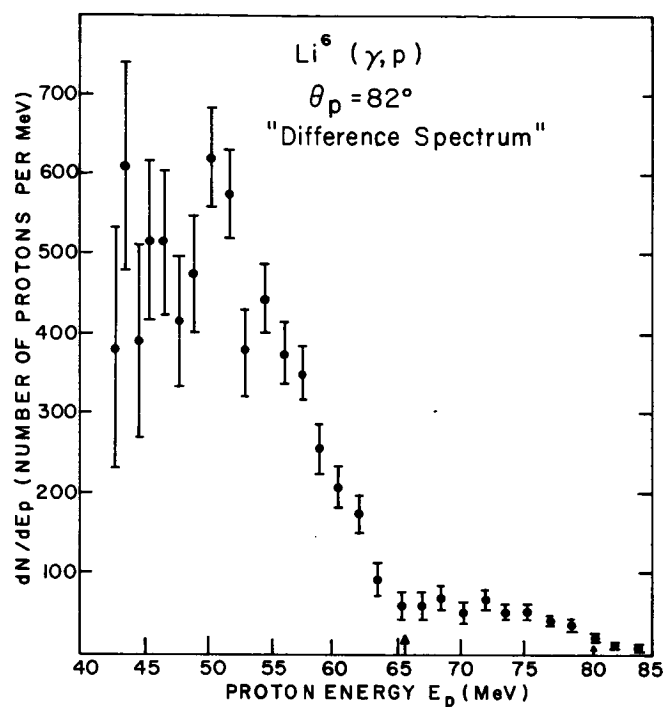


Figure 3.17

"Difference spectrum": the photoproton spectrum measured with 95 MeV bremsstrahlung subtracted from that measured with 102 MeV bremsstrahlung, for Li⁶ at $\theta = 82^\circ$. The arrows indicate proton energies calculated^p from Li⁶(γ, p) He⁵ kinematics for $E_\gamma = 102$ MeV, and $E_s = 4.9$ MeV and 22.7 MeV.

VI. National Bureau of Standards Collaboration

The beam optics have been investigated, and a design study initiated, for a "Koerts" magnet, which is eventually to be used to accommodate 150° - 180° elastic and inelastic electron scattering at the NBS linac facility. The magnet is to have cylindrical symmetry and a field pattern such that $\int r B_z dr = 0$ over the trajectory of the electron. If these conditions are satisfied, a particle starting from $r=0$ will automatically leave the magnet with zero angular momentum relative to the center ($r=0$). This useful feature guarantees that the solid angle subtended at the target, by a detection system outside the magnet, is independent of the scattering angle. Calculations indicate the optical aberrations of the magnet are small and can be minimized by proper choice of geometry.

Initially, the Koerts magnet is to be used to study the breakup of the deuteron in the 180° region, near threshold, by electrons of energy 50-150 MeV ($q = .5 - 1.5 f^{-1}$). The high resolution possible ($<0.1\%$) with the NBS system, together with the large current, will enable the final -

Linear Accelerator Group

state interactions in the $^1S_0$ state to be studied in detail.

HIGH ENERGY ACCELERATOR PHYSICS GROUP

I. Researches of the L. S. Osborne, D. Luckey, D. Garelick, et al., Group

Photoproduction Experiments at the Cambridge Electron Accelerator

A. Apparatus Improvements

1. Computer Link. The main improvement to our spectrometer system, used in studies of meson photoproduction and other photo-induced reactions, was the completion of the on-line connection of our small LINC computer to the LNS-IBM-7044 computer. The computing power now directly available to the experiment allows us to perform complete kinematic reconstructions, complex event identification, and calculation of cross sections while recording data. This information has greatly improved our efficiency in taking data. For example, the results of the π^0 cross section measurements at high t (see section B.2) are essentially the results deduced during the experiment. In this experiment the immediately available knowledge of the number of useful π^0 events, and of the production cross section corresponding to the collected data allowed us to decide during the experiment how much additional data should be recorded. This on-line analysis also led us to make measurements of additional cross section points which clarified the more interesting features of the data. (G. C. Bolon, D. Garelick, S. Homma, D. Luckey, R. Lewis, L. S. Osborne, J. Uglum)

2. Wire Spark Chambers. We have built a prototype chamber, with magnetic core read-out, and have obtained single gap efficiencies of better than 95% and a single gap spatial resolution of about ± 0.6 mm. Design of a wire spark chamber system for our spectrometer which will provide more accurate momentum and angle measurements has been completed. Construction of four $12.8'' \times 12.8''$ chambers and two $20.0'' \times 32.0''$ chambers and the associated electronics is nearly complete, and tests of the final chamber system with cosmic rays will begin within the next few months. (D. Bellenger, J. Davin, D. Field, D. Garelick, T. Krause, R. Martin, R. Patton, J. Revelli)

B. Cross Section Measurements

1. Our measurements of the cross sections for the reactions

- a) $\gamma + p \rightarrow K^+ + \Lambda^0$
- b) $\gamma + p \rightarrow K^+ + \Sigma^0$
- c) $\gamma + p \rightarrow \pi^+ + n$

have been completed and the data analyzed, and a partial description of the experimental results has been published.¹ A complete, detailed description of the experiment has been written and submitted to The Physical Review. The conclusion of these experiments is that the relationships

1. V. B. Elings, et al., Phys. Rev. Letters 16, 474 (1966).

between the cross sections predicted by SU3 are valid for the range of angles and energies measured. (V. Elings, K. Cohen, D. Garelick, S. Homma, R. Lewis, W. Lobar, D. Luckey, and L. S. Osborne)

2. We have made extensive measurements of single π^0 production cross sections for baryon four momentum transfers between 0.5 and 4.0 (GeV/c)² and for incident gamma energies between 2.0 GeV and 5.5 GeV. Some of the cross section results, along with earlier data¹ and data from the Bonn group are shown in Figures 4.1, 4.2, and 4.3. The interesting features of these data are:

a) The π^0 photoproduction cross sections in the region of baryon momentum transfers, $-t$ of 0.2 to 0.8 (GeV/c)², can be expressed in the form $d\sigma/dt = Ae^{Bt}$ where $B \approx 3.0$ (GeV/c)². A similar exponential behavior, but with larger values of B , is observed in meson-nucleon reactions and in single π^+ and K^+ meson photoproduction reactions where B approximately equals 3.0 (GeV/c)².

b) For momentum transfers larger than 0.8 (GeV/c)², the $\pi^0 p$ cross sections show a break or secondary peak which becomes less pronounced at 4.0 and 5.0 GeV photon energies.

c) We observe an increase in the cross section at backward π^0 center-of-mass angles, which apparently is a feature common to two-body scattering cross sections at high energies.

d) The minimum in the angular distributions appears at a π^0 center-of-mass angle of approximately 90°. This minimum in the cross section, unlike the forward of small $|t|$ structure, does not appear at fixed $|t|$ as the incident energy is increased.

Preliminary results of these measurements have been published² and a more complete analysis of all our data is now in progress. (G. C. Bolon, D. Garelick, S. Homma, D. Luckey, R. Lewis, L. S. Osborne, J. Uglum)

1. R. Alvarez, Z. Bar-Yam, D. Garelick, S. Homma, W. Kern, R. Lewis, D. Luckey, L. S. Osborne, J. Uglum, and R. Fessel, Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg (DESY), June 8-12, 1965, Vol. II, p. 207; L. S. Osborne, Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg (DESY), June 8-12, 1965, Vol. I, p. 91.

2. G. C. Bolon, D. Garelick, S. Homma, D. Luckey, R. Lewis, L. S. Osborne, and J. Uglum, "Pi Zero Photoproduction at 3.0, 4.0, and 5.0 GeV for Baryon Four Momentum Transfers between 0.5 and 4.0 (GeV/c)²", paper presented at the XIIIth International Conference on High Energy Physics, 31 August - 7 September 1966, Berkeley, California.

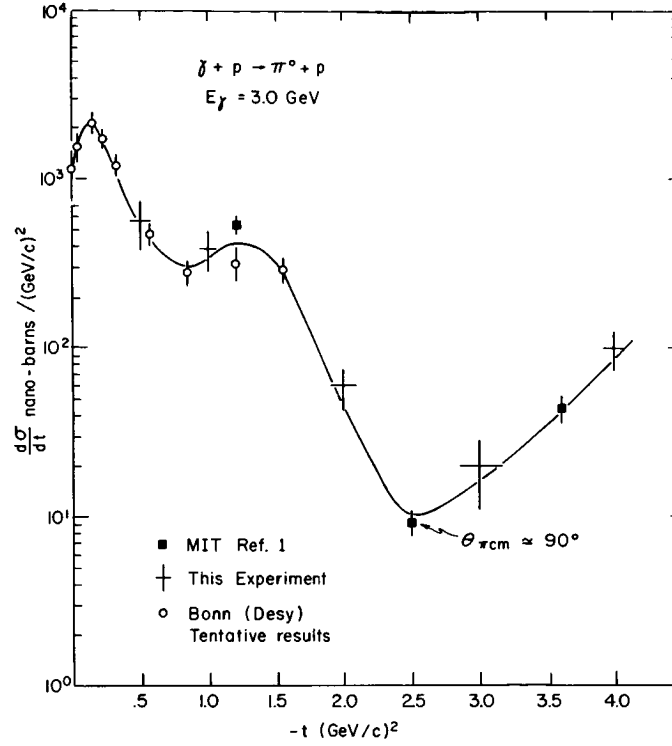


Figure 4.1

$d\sigma/dt$ as a function of t for a bombarding gamma ray energy of 3.0 GeV. The Bonn results are those quoted by U. Meyer-Berkhout on March 24, 1966, at a meeting of the Special Committee on Nuclear Physics at Bad Freienstadt, West Germany.

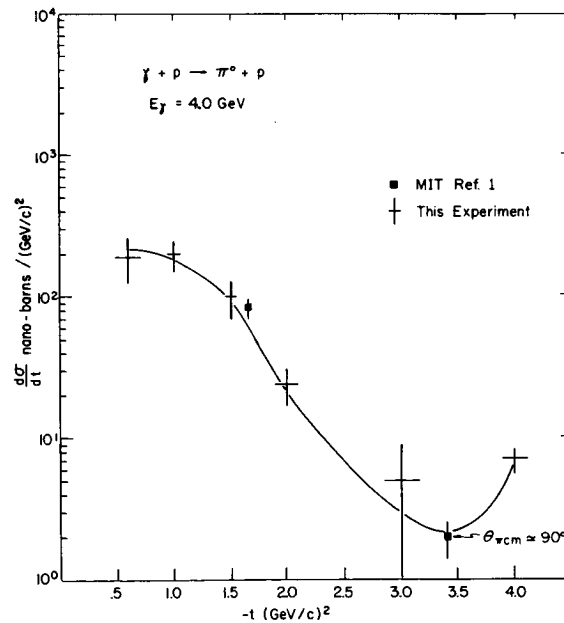


Figure 4.2

$d\sigma/dt$ as a function of t for a bombarding gamma ray energy of 4.0 GeV.

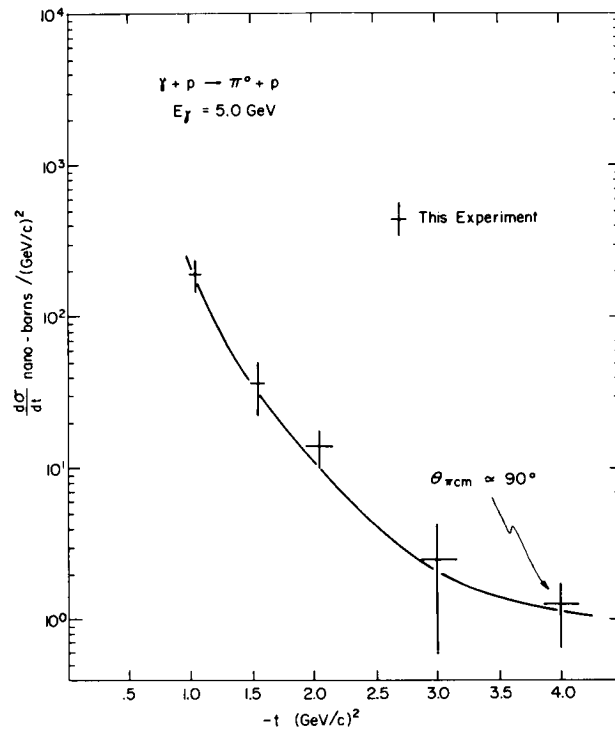


Figure 4.3

$d\sigma/dt$ as a function of t for a bombarding gamma ray energy of 5.0 GeV.

3. A search for photoproduced weakly interacting, fractionally charged particles is in progress. The characteristics of the experiment are as follows:

a) The 5.0 GeV bremsstrahlung beam from the Cambridge Electron Accelerator impinges on a 24"-long carbon target (2 radiation lengths).

b) The detector is made up of eight scintillation counters and is positioned at 0° relative to the photon beam.

c) Between the detector and the carbon target, 24" of lead serve to absorb strongly interacting particles and other low energy particles. The counters making up the detector are each separated by more than 2" of lead in order to reduce room background. A charge-one particle must be produced with a kinetic energy of greater than 1.8 GeV in order to be registered by the detector.

d) Whenever four beam-defining counters register pulses indicating a particle traversed the detector, and if two of these had pulses less than that expected from a charge-one particle, the pulses from six counters are photographed.

We expect that the particles observed by the telescope are mainly μ mesons pair-produced in the carbon target. The present tentative results of our search are given in the following table ($3.4 \text{ GeV} \leq E_\gamma \leq 5.0 \text{ GeV}$).

Charge	(Number of Observed Fractionally Charged Particles)/(Number of Observed Charge-One Particles)
$ q = 2/3$	$< 1 \times 10^{-6}$
$ q = 1/3$	$< 4 \times 10^{-6}$

If we assume that fractionally charged particles are produced by a standard photon pair-production mechanism (Bethe-Heitler-like calculation), then our experiment is sensitive to particles of masses between one to five muon masses. For example, we estimate that a particle of charge $2/3$ with a mass of .500 GeV should be observed with an abundance of greater than 3 per 10^6 detected muons.

Additional data has been taken and is being analyzed. (J. Foss, D. Garelick, S. Homma, W. Lobar, L. S. Osborne and J. Uglum)

4. The cross section for the photoproduction of wide angle e^+e^- pairs from the reaction $\gamma + (\text{carbon}) \rightarrow e^+ + e^- + (\text{carbon})$ was measured as a check of the predictions of quantum electrodynamics. The data was obtained using the existing spectrometer system. At present, analysis of the data is well underway. Tentative results indicate an agreement between our measurements and quantum electrodynamic predictions and a disagreement with the published results of Blumenthal, et al.¹ (K. Cohen, S. Homma, L. S. Osborne)

5. Differential cross sections for the reactions

$$\gamma + D \rightarrow \pi^+ + n + n$$

$$\gamma + D \rightarrow \pi^- + p + p$$

for forward meson production angles (30 to 90 degrees in center of mass system) and for bombarding photon energies between 3.0 and 4.0 GeV have been measured in collaboration with a group from Southeastern Massachusetts Technological Institute. The experiment has just been completed and a final analysis of the data is in progress. (Z. Bar-Yam (SMTI), J. de Pagter (SMTI), D. Luckey, L. S. Osborne, W. Lobar)

6. Large Angle π^+ and K^+ Meson Photoproduction. The momentum analyzing magnet is now in position at CEA and we have begun to move our detection apparatus into the experimental area. We expect to have the spark chambers and optical systems sligned by the beginning of November and begin taking data in late November. (R. A. Alvarez, R. Lanza, G. Cooperstein, J. Onorato, J. Acevedo, R. Doxsey, K. Kalata, J. Schoenwald)

7. Colliding Beams. In collaboration with physicists at CEA, we are investigating the feasibility of several types of detectors for use with the proposed CEA colliding beam facility. Wide gap spark chambers, and digitized narrow gap chambers are being studied from the point

1. Blumenthal, et al., Phys. Rev. 144, 1199 (1966).

of view of their possible use in a magnetic analyzer. In addition, the problem of triggering the detectors on rare events, and the identification of various types of particles is under study.

(R. Lanza, L. S. Osborne, G. Cvijanowitch (CEA), J. Deklava (CEA))

II. Researches of the D. H. Frisch, et al., Group

A. MASCOT Program

The study of reactions producing all-neutral final states containing strange particles has continued, using the MASCOT large solid angle spark chamber array mounted inside the Argo magnet. A 300 hour run with a beam of 8 GeV/c π^- and K^- was completed at the AGS in March, 1966. Scanning, measurement and computer analysis of the events is being concentrated on the reactions $\pi^- + p \rightarrow K_S^0 + K_S^0 + \text{neutrals}$, with approximately 1500 events estimated to be in the full sample of data, and on $K^- + p \rightarrow K_S^0 + \text{neutrals}$, where it is expected that the charge exchange reaction $K^- + p \rightarrow \bar{K}^0 + n$ can be separated and measured, with about 200 events contained in the data. It is expected that the analysis will also be extended to include data taken in an earlier test run at the AGS with 5 GeV/c π^- , with approximately 1000 events expected from the reactions $\pi^- + p \rightarrow \text{two V-particles} + \text{neutrals}$. (A. Buffington, C. Nelson, C. Ward)

B. CEA Tagged Photon Beam

Progress on setting up the facility for tagging photons produced by the internal beam has been slow. The original model of the special vacuum section and the special straight section have been mounted and tested in the CEA magnet prototype setup, with satisfactory operation of the straight section and of the beryllium window on the vacuum section, but we are having vacuum problems with a weak section near the target insertion flange.

The CEA electronics shop has completed the special DEC circuitry required for storage of normalization counts and the system has been satisfactorily bench-tested.

We have completed the tagging hodoscope and its support table. The associated fast electronics has been tested and is ready for installation. (S. Smith, S. Gray)

C. Photoproduction Experiments with the Internally Tagged Gamma Beam

Recent results from other groups have caused us to revise our plans. We have decided not to carry out the experiment on pair-production of electrons and muons at large angles, in spite of the relatively advanced state of preparations. We intend to do another photoproduction experiment using the same electron tagging system and, hopefully, a major portion of the already constructed parts of the old experimental setup. Preliminary calculations on the reaction $\gamma + p \rightarrow \Lambda + K^0 + \pi^+$ look promising. (S. Smith, S. Gray, E. Shibata, H. French, R. Gauthier)

D. Experimental Array for Use with Colliding Beams

A 2π solid-angle is being designed for measurements of QED and a search for heavy boson pairs. A prototype of one of the three cylindrical spark chambers in the array has been built and tested. (J. Martin)

E. $\pi^- + p \rightarrow K_1^0 + K_1^0 + \text{neutrals}$

Groundwork has been laid for an experiment to study the reaction $\pi^- + p \rightarrow K_1^0 + K_1^0 + \text{neutrals}$, with protons bound in nuclei of a dense target. Programs for Monte Carlo generation and analysis of this and related reactions have been written. (G. Smoot, D. Fox)

F. $\Delta S/\Delta Q$

A test of the $K^+ + \text{tungsten}$ interaction of a localized source of K^0 's for use in a $\Delta S/\Delta Q$ experiment has been completed. The design and construction of the necessary equipment for the experiment is continuing. (O. Fackler, L. Sompayrac, A. Hanson, S. Liu, D. Underwood)

G. $\pi^+ + P \rightarrow \pi^+ + \pi^0 + P$

We are now studying the reaction $\pi^+ + P \rightarrow \pi^+ + \pi^0 + P$ at an incident pion beam momentum of 964 ± 14 MeV/c. Some of the results of this experiment have been published in the two previous progress reports. The experimental equipment, schematized in Fig. 4.4, consisted chiefly of a central hydrogen target surrounded by a cylindrical spark chamber. Protons and kaons in the beam were rejected by a liquid Cerenkov counter. The spark chambers were triggered when a beam particle or any of its secondaries did not give a pulse in the anticoincidence counter following the hydrogen target; to minimize bias a no more selective trigger was used. Approximately 5 radiation lengths of lead plates served to detect the gammas from the π^0 and give range information on the charged tracks.

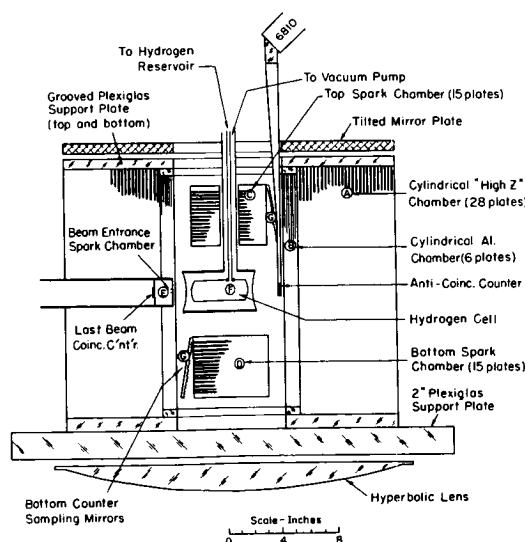


Figure 4.4

About 150,000 pictures have been scanned for those events where, in addition to the incoming beam pion, the outgoing pion, proton and two gammas were detected. About 6000 of the approximate 9000 events found have been measured on Hydel measuring devices and the digitized results recorded on IBM punch cards for analysis by reconstruction and kinematic fitting programs.

Using the four-vector of the incoming pion and the mass and angles for each outgoing particle, coupled with the constraint that the invariant mass of the two gammas be that of a π^0 , a 1C fit to the reaction hypothesis $\pi^+ + P \rightarrow \pi^+ + \pi^0 + P$ was made. For both mass assignments to the outgoing charged particles, two kinematic solutions are possible. The one with the invariant mass of the two gammas closest to the π^0 mass was selected. The range-energy data for the charged particles along with their spark efficiency and density were used as additional checks to reject spurious solutions.

The effective mass of the two gammas has a full width at half maximum of about 30 MeV before applying the constraint (see Fig. 4.5). The yield of events satisfying the consistency checks is about 70 percent. A histogram of the di-pion mass of 3170 fitted events is shown in Fig. 4.6.

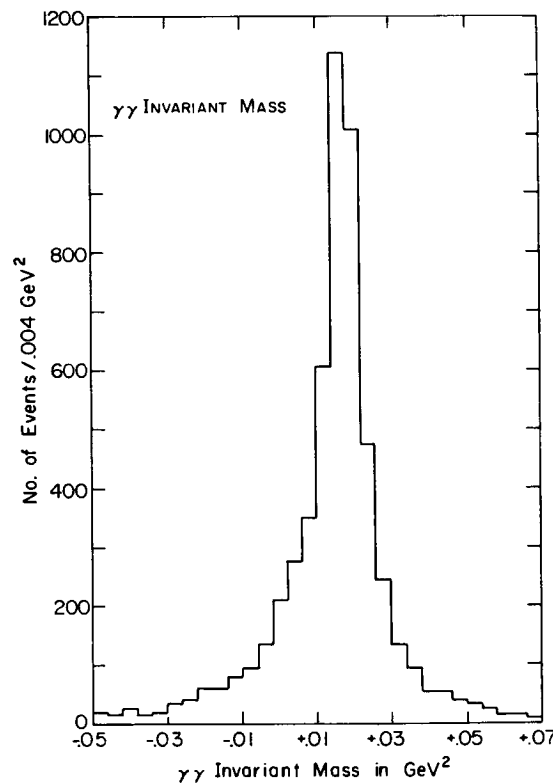


Figure 4.5

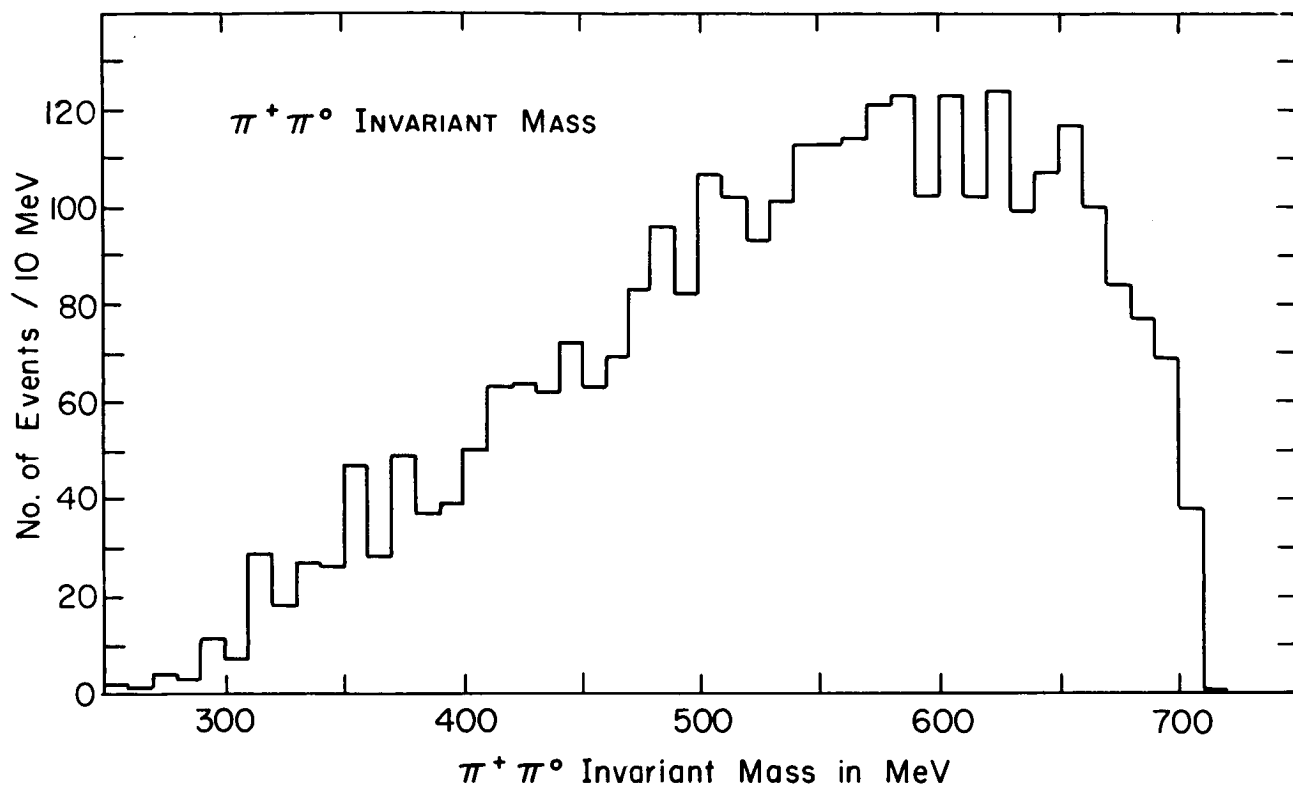


Figure 4.6

Work continues on the measurement of the remaining events and those previously measured but not satisfying the consistency checks. The detection efficiency and mass resolution are being studied. (P. Mockett)

III. Researches of the M. Deutsch, et al., Group

Since this group did not submit a progress report for the preceding period, we summarize progress of the work during the last 12 months.

Our activities fall into two main categories:

- 1) Work at the Cambridge Electron Accelerator. Some of this work is undertaken and technically carried entirely by our group with support from the CEA staff. Some of it is carried out in support of other groups in the Laboratory.
- 2) Cooperative research with groups at other institutions in which our technical contribution centers on the use of the SPASS automatic film measuring system.

A. Work at the CEA

1. Proton Compton Effect

Preparation for resumption of these experiments was completed and we are at present gathering data. Because of uncertainties in the absolute cross sections remaining from our previous experiments, rather elaborate instrumentation has been provided for diagnostic purposes. In particular an analog pulse storage and analysis system PANSY now permits the simultaneous monitoring and digital recording on the photographs of fourteen analog signals through a single analog-to-digital converter. The system is used to record, in digital form, pulse heights and time intervals in all relevant channels. Initial experience has fully justified the effort invested in this system.

2. Pion Photoproduction at Small Angles

This experiment was initiated and largely carried out under the supervision of Prof. David Caldwell. After Prof. Caldwell left the Laboratory, the measurement of the photographs and evaluation of the results was carried out by Dr. John P. Dowd in collaboration with our group. Results have been reported at the 1966 International Conference on High Energy Physics and have been submitted for publication in the Physical Review Letters.

3. Pion Photoproduction at Large Angles

We are collaborating in the evaluation of an experiment by Prof. R. Alvarez and co-workers now in the data-gathering stage at CEA.

4. Strange Particle Photoproduction

Apparatus has been built and preliminary feasibility studies are being made for an experiment to study K^+ photoproduction in the energy range above 1.4 GeV. We hope to determine the lambda particle polarization as well as production cross sections at selected angles and possibly to gather data on sigma zero production.

5. Recoil Proton Polarization in Pion Photoproduction

This is a cooperative project with the Tufts University group. It will employ the proton spectrometer and gamma ray detector presently used in the gamma-ray scattering experiments and a large carbon-plate spark chamber provided by the Tufts group. All apparatus is essentially ready and the experiment will be carried out as soon as the CEA facilities become available for this purpose.

B. Other Research

1. K^+ Decay

This study, in support of the Berkeley group of Stiening, Wiegand and collaborators, is aimed primarily at the measurement of muon polarization in $K\mu_3$ decay to determine the weak-interaction form factors and to search for transverse polarization violating T-conservation.

The spark chamber data have been recorded on film at the Bevatron and we have measured the coordinates and angles of the kaon and of the muon as well as the coordinates and approximate energies (by spark count) of the showers produced by the neutral pion decay in about 120,000 events, including two-body events used to calibrate the gamma-ray measurements ($K\pi_2$) and the

polarization measurement ($K\mu_2$). The muon polarization for those events (several thousand) which satisfy $K\mu_3$ kinematics (several thousand) is determined by a relatively simple visual measurement on the decay electron. This procedure of "premeasurement" in contrast with the more usual "prescanning" is characteristic of the balance of effort when fully automatic measurement is available. The evaluation of this experiment is now in the final stages.

As an incidental, ancillary experiment about 10,000 events were recorded under conditions appropriate to reveal the totally forbidden $K\pi\gamma$ process. Observation of such a process would imply either violation of conservation of angular momentum or the existence of a particle (or component of the pion) of non-zero spin. We find that such a process, involving either a pion or any other particle of definite mass between 137 and 144 MeV occurs in less than 2×10^{-5} of all K^+ decays.

2. K^0 Mass Difference.

Final results of this collaboration with the BNL-Maryland group have been published.¹

C. SPASS Development

The program system of SPASS has been consolidated and improved. The scanning and measuring program for a new experiment can now be assembled almost entirely from existing subroutines. All restrictions on search direction and on the location and form of fiducial marks have been removed. We have had remarkable and unexpected success with the evaluation of gamma ray showers in lead-plate spark chambers. This is true for the identification of several showers in one chamber and for the determination of gamma ray energies by spark counting.

With the increasing complexity of the events analyzed, the limitations on speed and, to a lesser extent, resolution of the system begin to make themselves felt. For example, in the K^+ decay experiment, described above, ten views of tracking chambers (two kaon chambers and three muon chambers) and six views of shower chambers were measured. Because of the large dimensions, almost one cubic meter, of the region analyzed, the data was spread over two film frames per event and the SPASS measuring time was of the order of ten seconds per event. The consolidation of the program system permits several experiments per year to be analyzed and the time spent on production operation now greatly exceeds the time for program development. We are therefore pursuing the development of faster and, incidentally, more precise hardware.

1. Jovanovich, Fuji, Turhot, Zorn and Deutsch, Phys. Rev. Letter 17, 1075 (1966).

IV. Researches of the J. I. Friedman, H. W. Kendall, et al., Group

A. The Photoproduction of Wide Angle Muon Pairs

We have completed and published^{1,2} the second set of measurements of the photoproduction of μ pairs from carbon at a photon energy of 5 BeV, which was carried out in collaboration with physicists from Northeastern University. The second experiment yielded about 400,000 analyzable events as compared to 10,000 from our first experiment in μ pair production. Because of the large amount of data available, we were able to discern a peak in the yield as a function of the invariant mass of the two muons which arises from the decay of the ρ^0 meson into a muon pair. Utilizing the cross sections for the photoproduction of the ρ^0 from carbon previously measured³ by the Harvard group at the CEA we were able to determine the branching ratio for the decay of the ρ^0 meson into a muon pair. The result is

$$R = \frac{\rho^0 \rightarrow 2\mu}{\rho^0 \rightarrow 2\pi} = 0.44 \begin{matrix} +0.21 \\ -0.09 \end{matrix} \times 10^{-4}$$

Our major objective in this experiment was to test quantum electrodynamics (QED). The main conclusion from the experiment is that the behavior of μ pair production is not compatible with the large deviation from the predictions of QED observed in the electron pair experiment⁴ carried out at the CEA. While the muon appears to be reasonably well described by QED in this kinematic range, there is, nevertheless, a suggestion of a small deviation between experiment and theory which indicates the need for further investigation. Because of the sizable systematic errors present in the analysis of this type of experiment, we feel that future investigation of the validity of QED should be carried out at considerably higher energies where possible deviations would probably be greatly enhanced. With this in mind, we (J. I. Friedman, H. W. Kendall, L. Van Speybroeck) have submitted to SLAC, in collaboration with a SLAC group, a proposal to measure asymmetric μ -pair production⁵ at an incident energy of about 20 BeV. (J. I. Friedman)

B. Elastic Electron-Deuteron Scattering

We are nearing the completion of the analysis of measurements of the differential cross sections for the elastic scattering of electrons from deuterons in the range of squared four momentum transfers from 14 to 35 F^{-2} . The objective of this experiment is to measure the electromagnetic form factor of the deuteron and from this information determine some of the characteristics of the n-p interaction, especially its short range characteristics. In Fig. 4.7 are shown

1. J. K. de Pagter, J. I. Friedman, G. Glass, R. C. Chase, M. Gettner, E. Von Goeler, R. Weinstein, and A. M. Boyarski, Phys. Rev. Letters 16, 35 (1966).
2. J. K. de Pagter, J. I. Friedman, G. Glass, R. C. Chase, M. Gettner, E. VonGoeler, R. Weinstein, and A. M. Boyarski, Phys. Rev. Letters 17, 767 (1966).
3. L. J. Lanzerotti, R. Blumenthal, D. C. Ehn, W. L. Faissler, P. Joseph, F. M. Pipkin, J. Randolph, J. J. Russel, D. G. Stairs, and J. Tannenbaum, Phys. Rev. Letters 15, 210 (1965).
4. R. B. Blumenthal, D. C. Ehn, W. L. Faissler, P. M. Joseph, L. J. Lanzerotti, F. M. Pipkin, and D. G. Stairs, Phys. Rev. 144, 1199 (1966).
5. S. D. Drell, Phys. Rev. Letters 13, 257 (1964).

the measurements of the deuteron form factor from this experiment, along with those from previous experiments and, in addition, the predictions of two of the current models of the n-p interaction. The models being tested in our analysis are of the following general types: repulsive core, finite repulsive core, boundary value, and velocity dependent potential models. Also being tested is a limit on the asymptotic behavior of the deuteron form factor proposed by Drell¹ on the basis of general analyticity arguments. A preliminary analysis indicates that the Drell limits are well satisfied. (J. Elias, J. I. Friedman, G. Hartmann, H. W. Kendall, L. Van Speybroeck)

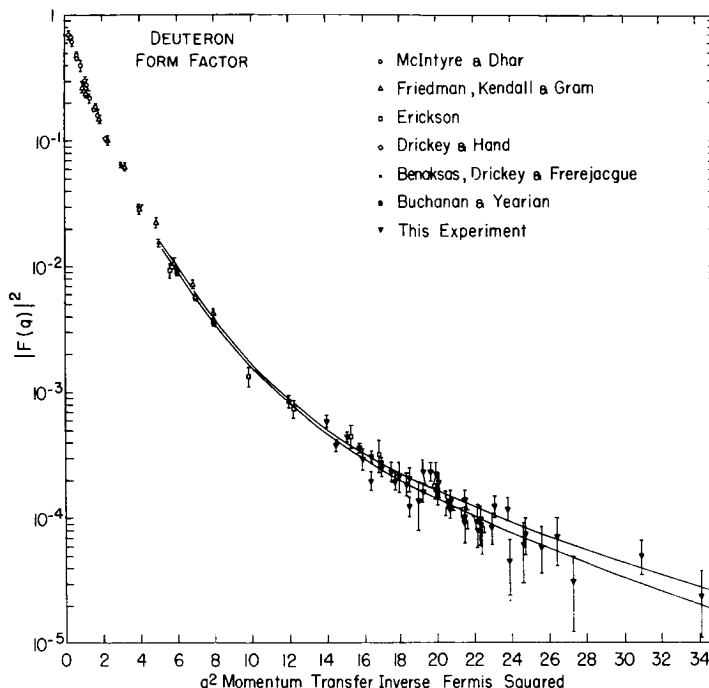


Figure 4.7

The square of the deuteron form factor as a function of the square of the four momentum transfer. The theoretical predictions are based on the wave functions from the Hamada Johnston potential (upper curve) and Bessel potential (lower curve). Both predictions include the relativistic correction of Jones and the meson exchange correction of Adler and Drell.

C. The Two-Nucleon Correlation Function

All of the primary data for this experiment have been analyzed with the use of our radiative correction computer programs. The experiment will soon be written up for publication (in collaboration with Dr. D. Isabelle, Orsay). (H. W. Kendall)

1. S. D. Drell, private communication.

D. Phase-Shift Analysis of Inelastic High Energy Electron Scattering

An initial version of this program has been tested and debugged. Square well and delta function nuclear charge densities were employed. A set of subroutines which will calculate the required potentials for arbitrary point specified densities has been written and debugged. The predictions of the calculation are now being compared with experimental scattering results.

(J. I. Friedman, H. W. Kendall, R. Verdier)

E. The Search for a Heavy Electron

Low¹ has suggested the possibility of the existence of a heavy electron, the e' , which decays into an electron and a photon. This heavy electron could be formed in the reaction $e + p \rightarrow e' + p$. A search for this process was carried out at the CEA by observing the spectrum of recoil protons from a hydrogen target bombarded by a high energy electron beam. The existence of this process would manifest itself as a peak in the recoil proton spectrum at a momentum which depends on the mass of the e' . An analysis of the data indicates that the cross section for this process is less than about 5% of the elastic e - p cross section, for an e' mass up to about 1000 MeV and somewhat larger in the mass region 1000-1300 MeV. The observed limits for this cross section can be related to limits on the strength of a coupling constant for the coupling of the e' to an electron-photon system. The limits on the strength of this coupling constant derived from our measurements for various mass regions of the e' are given in Fig. 4.8. (C. Boley, J. Elias, J. I. Friedman, G. Hartmann, H. W. Kendall, P. Kirk, M. Sogard, L. Van Speybroeck)

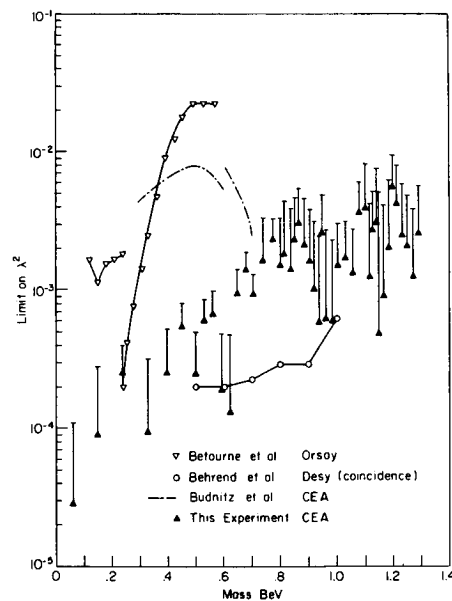


Figure 4.8

Experimental limits on the square of the coupling constant for a heavy electron coupled to an electron-photon system derived from our measurements and from other experiments. The error flags represent the standard deviations of the measurements.

1. F. E. Low, Phys. Rev. Letters 14, 238 (1965).

F. External Beam Facilities at the CEA

The quadrupole spectrometer with which we carried out the elastic electron-deuteron scattering program will soon be placed in an external beam. In addition a second arm which will enable us to make coincidence measurements will be placed on the same pivot. We are constructing apparatus to implement this site and we expect to be ready for preliminary runs by January 1, 1967. We are making preparations for the following experiments to be done with this new facility. The first two will hopefully be started early in 1967.

(1) Elastic electron- α particle scattering up to squared four momentum transfers of about 36 F^{-2} . This experiment will provide information on the electromagnetic structure of the α particle and will be programmed in such a way as to provide a limit on possible anomalous structure of the electron.

(2) Measurements of the final state interaction in the electro-disintegration of the deuteron. By measuring this process at high momentum transfers we hope to learn about the short range characteristics of the unbound n-p system at low relative energies.

(3) Coherent photoproduction of π^0 mesons from the deuteron at photon energies of 1-3 BeV. This measurement can provide information about the interference of the amplitudes for the photoproduction of pions from the proton and the neutron.

(4) Measurements of the photoproduction of the η^0 and ρ^0 mesons at large momentum transfers. The results of these measurements can be used to test various dynamic models and can be used, in addition, in Regge pole analyses. (C. Boley, J. Elias, J. I. Friedman, G. Hartmann, H. W. Kendall, R. Shafer, M. Sogard, L. Van Speybroeck)

G. SLAC Collaboration

Our collaboration with the SLAC spectrometer group is well under way, and now that the 2 mile accelerator is operating and the spectrometers are nearly complete we will soon begin the data taking phase of our SLAC program. Our group has had the responsibility for the design and construction of the particle detector hodoscopes and the associated electronics to be employed in the 8 and 20 BeV spectrometers which have been constructed for the electron scattering program. The following objectives have been completed during the past year:

(1) The construction of the hodoscopes to be placed in the focal planes of the 8 and 20 BeV spectrometers.

(2) The construction of a detector that will be able to distinguish electrons and π^- mesons of the same momentum in the range from 1 BeV/c to about 20 BeV/c. This detector is expected to have a rejection factor for π^- in the range of about 10^{-4} to 10^{-5} .

(3) The construction of the electronic logic associated with the detectors and of the slow electronics used to read the information into an on-line computer.

(4) The radiative correction programs to be used in analyzing the data have been finished and are now being tested.

In collaboration with the SLAC spectrometer group, we have submitted the following proposals, the first three of which have been accepted and allotted running time.

(1) Elastic electron-proton scattering at large momentum transfers. The objective of this experiment is to measure the proton form factors GEP and GMP up to as high a four momentum transfer, q , as is possible, in order to determine the asymptotic behavior of these form factors. This proposal covers a range of q^2 up to about 400 F^{-2} .

(2) Inelastic electron-proton scattering. The first objective of this experiment is to search, at small angles and hence with large yields, for nucleon resonances produced in the electroproduction process. The second aim is to separate the transverse and longitudinal form factors for the production of these resonances and to measure them as a function of four momentum transfer.

(3) A comparison of positron-proton and electron-proton elastic scattering. This experiment will provide a determination of the corrections to the Rosenbluth cross section arising from two photon exchange. This experiment, in addition to being necessary for the proper interpretation of the elastic electron-proton scattering results, gives information about the polarizability of the proton. We expect that this comparison can be made up to a q^2 of about 250 F^{-2} .

(4) Asymmetric μ -pair production. The aim of this experiment is to test quantum electrodynamics at the highest possible energies and momentum transfers. With an incoming photon energy of 20 BeV it is possible for the kinematics of this measurement to give the virtual muon in the process a squared four momentum transfer $q\mu^2$ of about $4 (\text{BeV}/c)^2$, which is about a factor of 16 larger than that achieved in the CEA μ pair experiment. For models in which the deviation from the Bethe-Heitler predictions are proportional to $q\mu^2$ or some higher power of $q\mu^2$, the deviations which could be observed in the SLAC experiment are many times larger than would be observed in measurements at CEA energies. (M. Breidenbach, J. I. Friedman, G. Hartmann, H. W. Kendall, P. Kirk, R. Shafer, L. Van Speybroeck)

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O.N.R. GENERATOR GROUP

I. Introduction

During the period covered by this report, the He^{3++} ion source has been rebuilt, the particle-gamma coincidence spectrometer has been completed and tested, and data have been taken with the multiple-gap spectrograph with He^{3++} , as well as deuteron and proton, beams.

The He^{3++} ion source, after considerable modification and testing, now delivers an analyzed beam on target of close to $0.1 \mu\text{A}$. This is entirely adequate for experiments with the multiple-gap spectrograph.

As part of the program of charged-particle-reaction studies with solid-state detectors, a scattering chamber has been designed and is now being built.

The automatic plate scanner has done some routine scanning and is now being modified slightly to cure a problem of time jitter in the electronics circuitry.

Members of the ONR Group have participated in a program of heavy-ion studies under the direction of Dr. R. J. Van de Graaff utilizing the MP Tandem facility at High Voltage Engineering Corporation.

II. Studies of Nuclear Structure in the $f_{7/2}$ Shell

A. Inelastic Deuteron Scattering

Work has continued on the inelastic deuteron scattering by target nuclei in the $1f_{7/2}$ shell. The data analysis has been completed, and the results are now being analyzed in terms of the DWBA code. Work on the systematics of these nuclei is being carried out. (T. A. Belote, W. E. Dorenbusch, and Ole Hansen (Copenhagen))

B. The $\text{V}^{50}(\text{d}, \text{p})\text{V}^{51}$ Reaction

The $\text{V}^{50}(\text{d}, \text{p})\text{V}^{51}$ reaction was investigated at 7.50-MeV bombarding energy. A total of 71 transitions were recorded below 6.65-MeV excitation in V^{51} . The proton spectrum is shown in Fig. 5.1. Angular distributions for levels were extracted and are shown in comparison with DWBA curves in Fig. 5.2. Spectroscopic strengths and ℓ_n values were extracted. These results were further analyzed in terms of the multipole sum rules of French¹ for multipole orders 0, 1, and 2. It is concluded that the V^{50} ground state does not have good seniority.² (W. E. Dorenbusch, T. A. Belote, Ole Hansen, Maria E. Ortiz, and M. Mazari, U. of Mexico)

1. J. B. French, Phys. Letters 13, 249 (1964).

2. W. E. Dorenbusch, T. A. Belote, and Ole Hansen (Copenhagen), to be published in Nucl. Phys.; and Maria E. Ortiz, M. Mazari (Univ. of Mexico) with T. A. Belote, W. E. Dorenbusch, MIT, and Ole Hansen (Copenhagen), Bull. Am. Phys. Soc. 11, 751 (1966).

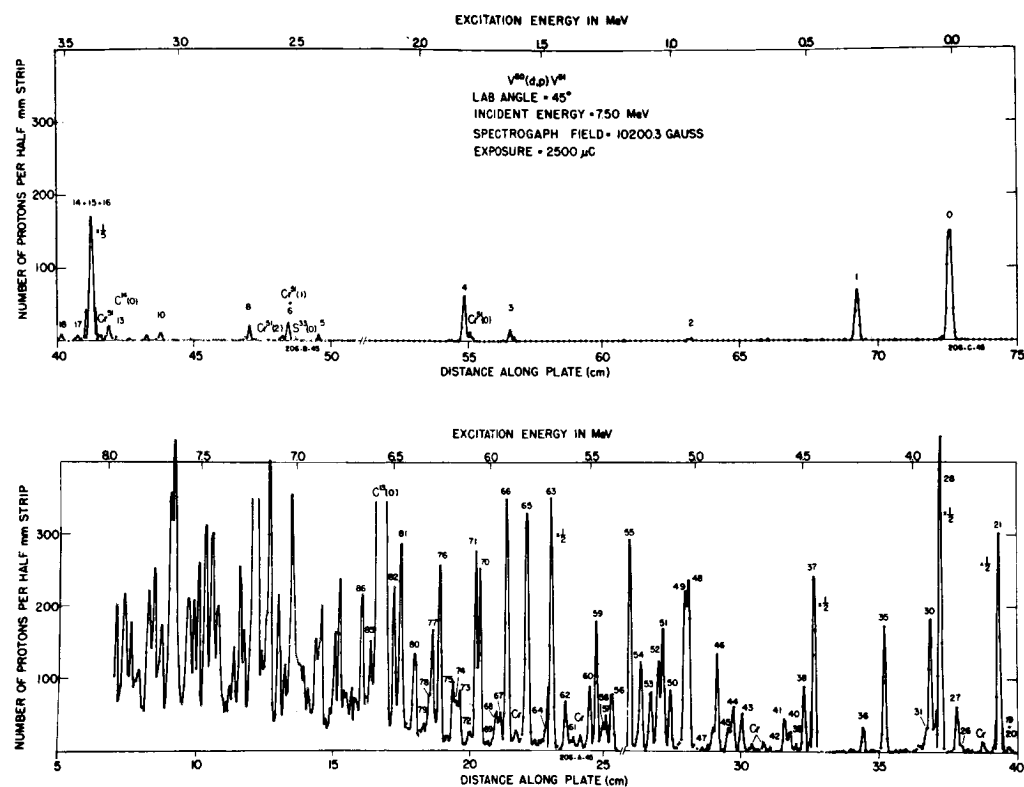


Figure 5.1

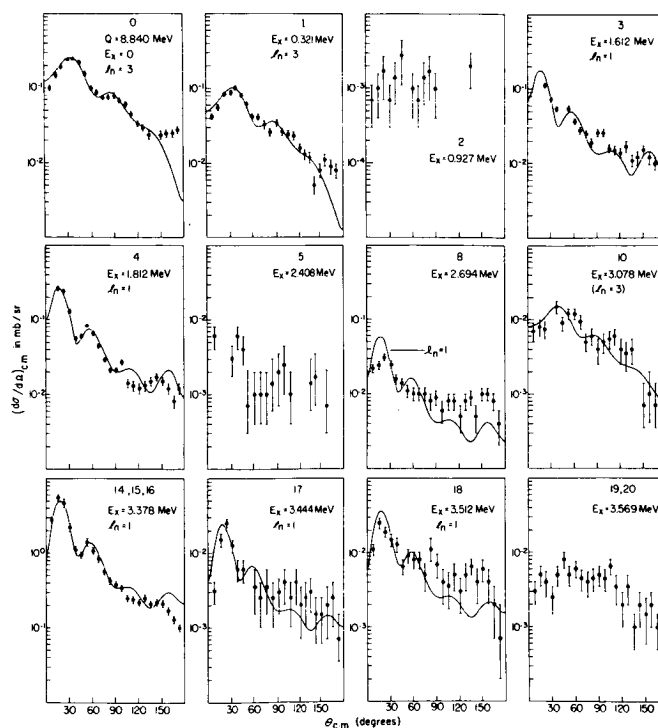


Figure 5.2

C. The Enriched Calcium Target Experiment

The special calcium target data are being analyzed, and preliminary DW calculations are being carried out. The proton spectrum at $\theta_{\text{lab}} = 37.5^\circ$ is shown in Fig. 5.3. In order to extend this experiment to higher bombarding energies, a sum at A.W.R.E. has been carried out by Ole Hansen at 10.0 MeV. (W. E. Dorenbusch, Ole Hansen, J. Rapaport, and T. A. Belote)

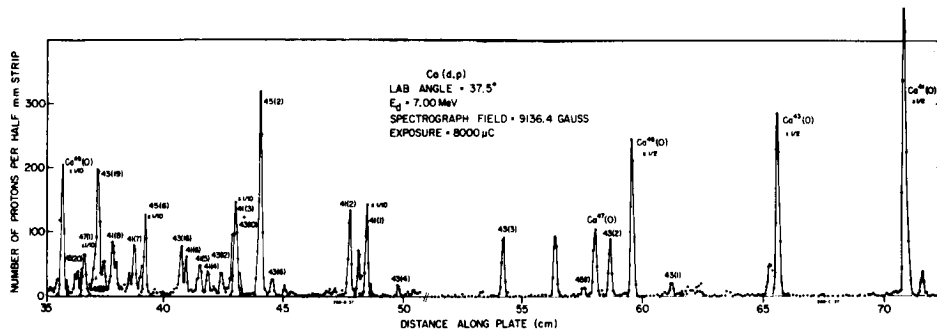


Figure 5.3

D. The $\text{Ca}^{44}(\text{d}, \text{p})\text{Ca}^{45}$ Reaction

The level structure of Ca^{45} below 6.3-MeV excitation has been studied by the $\text{Ca}^{44}(\text{d}, \text{p})\text{Ca}^{45}$ reaction. Twenty-eight of the observed 88 transitions showed stripping angular distributions and were analyzed in terms of the distorted-wave Born approximation to obtain ℓ_n values and spectroscopic factors. The proton spectrum at $\theta_{\text{lab}} = 67.5^\circ$ is shown in Figure 5.4. A level at 1.886 MeV (see Fig. 5.5) was excited by an $\ell_n = 2$ transition and is interpreted as a $1d_{3/2}^{-1}$ state in Ca^{45} . The observed level scheme has been compared with recent calculated level schemes. A manuscript has been submitted to Physical Review. (J. Rapaport, W. E. Dorenbusch, and T. A. Belote)

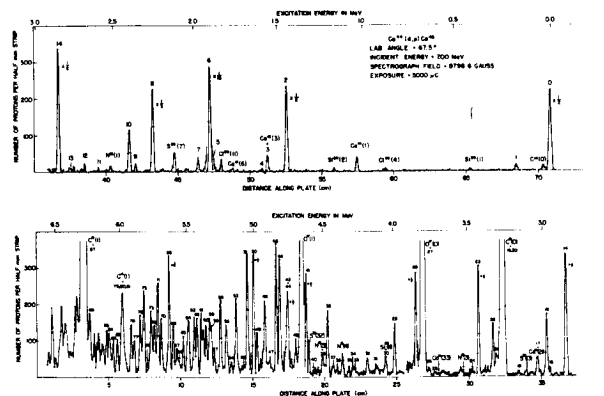


Figure 5.4

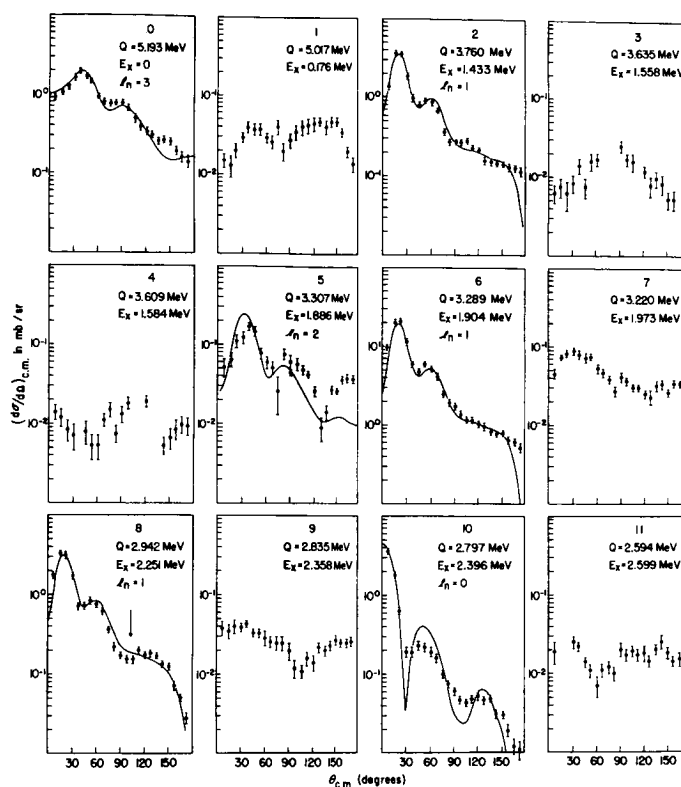


Figure 5.5

E. The $K^{39}(\text{He}^3, p)\text{Ca}^{41}$ Reaction

The deuteron-transfer reaction $K^{39}(\text{He}^3, p)\text{Ca}^{41}$ has been used to investigate the two-particle, one-hole ($2p - 1h$) states of Ca^{41} . A beam of 13.0-MeV He^{3++} particles was used to bombard a $63 \mu\text{g}/\text{cm}^2$ KI target enriched to 99.9 percent in K^{39} , and the emitted protons were detected in the multiple-gap spectrograph with an overall proton energy resolution of 55 keV. The energy spectra for the protons at $\theta_{\text{lab}} = 7.5^\circ$ and 22.5° are shown in Fig. 5.6. A comparison of the yields at these two angles shows that most of the states excited in this reaction display an angular distribution that is strongly peaked forward with an angle of maximum cross section $\sim 7.5^\circ$, which is typical for an $L=0$ transition. The angular distributions for some of these transitions, as well as for the transitions to the ground state ($1f_{7/2}$ single-particle state) in Ca^{41} , are shown in Fig. 5.7. Preliminary DWBA calculated curves are shown for $L=0, 1$, and 2 transfers in the transition to the 2.017-MeV level, thus indicating the $L=0$ character of this state. (T. A. Belote, F. T. Dao, W. E. Dorenbusch, J. Kuperus, and J. Rapaport)

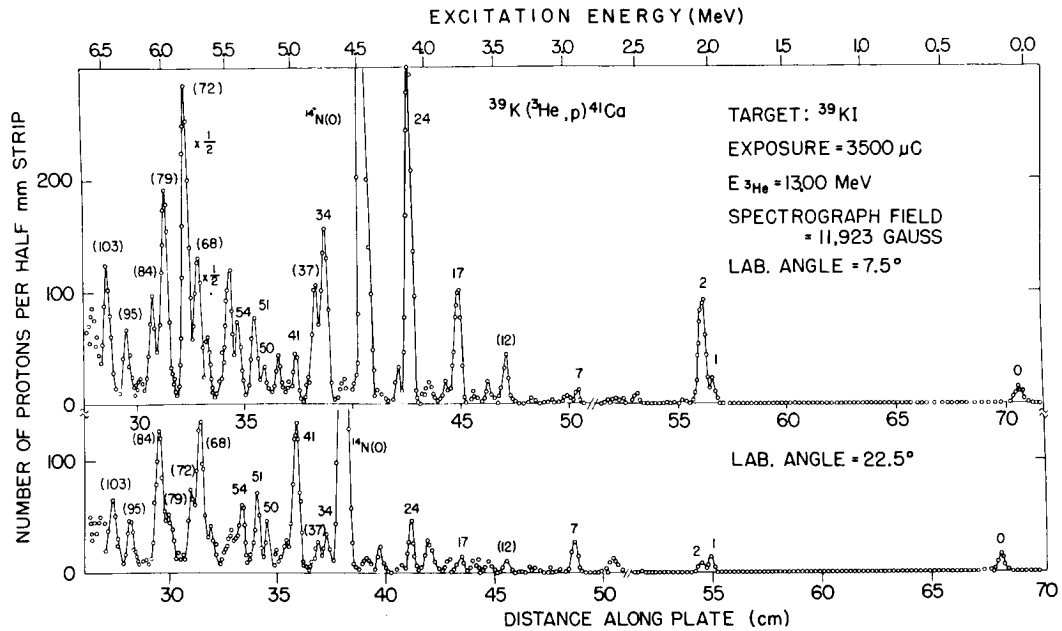


Figure 5.6

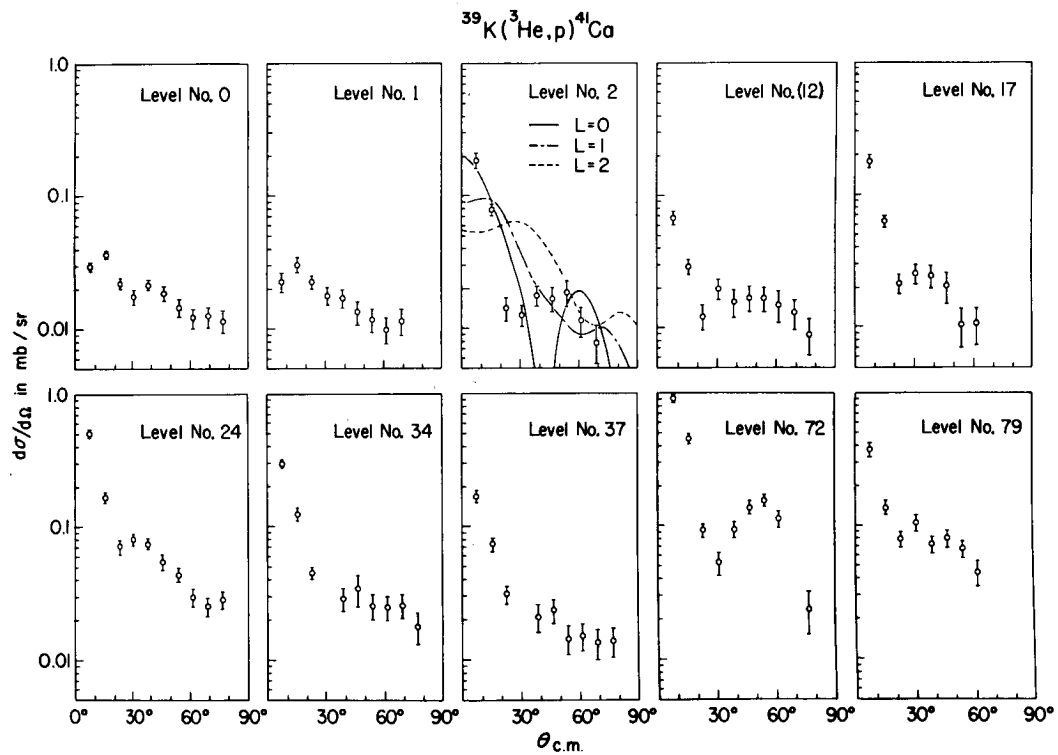


Figure 5.7

F. (He^3, d) Reactions on $N=28$ Nuclei

1. The $\text{Fe}^{54}(\text{He}^3, d)\text{Co}^{55}$ Reaction.

An exposure was made for this reaction at an incident energy of 12 MeV. The reaction deuterons were detected on 50-micron nuclear-emulsion plates in the multiple-gap spectrograph. Scanning has been completed for the B and C plates, and absolute differential cross sections have been determined for five levels of Co^{55} up to an excitation energy of 3.32 MeV. Theoretical cross sections for comparison are being calculated using the DWBA code.

2. The $\text{Cr}^{52}(\text{He}^3, d)\text{Mn}^{53}$ Reaction.

An exposure was made at an incident energy of 11 MeV, and the reaction deuterons were detected at 24 angles on 50-micron emulsion plates inside the multiple-gap spectrograph. Only the plates at 22 deg have been scanned at this time.

3. The $\text{Ti}^{50}(\text{He}^3, d)\text{V}^{51}$ Reaction.

An exposure was made with He^{3++} ions of 10 MeV. The reaction deuterons were detected at 24 angles on 50-micron emulsion plates inside the multiple-gap spectrograph. Scanning of these plates is now in progress.

(B. J. O'Brien, W. E. Dorenbusch, J. Rapaport, and T. A. Belote)

G. Angular Distributions from Shell-Model Forbidden (He^3, d) Transitions to Spin $5/2^-$ States

The neutron configurations $(1f_7/2)^{+3}$ leading to states with spins $7/2^-$ (shell model allowed) and $5/2^-$ (shell model forbidden) have been reported¹ in (d, p) transitions to final states in Ca^{43} , Ca^{45} , and Ti^{47} . The proton configurations leading to shell-model forbidden $5/2^-$ states can be excited by the (He^3, d) reactions in several cases. The following reactions have been performed using the He^{3++} beam:

		Exposure (μC)
$\text{Cr}^{52}(\text{He}^3, d)\text{Mn}^{53}$	$E_{\text{He}^3} = 11 \text{ MeV}$	3000
$\text{Ti}^{50}(\text{He}^3, d)\text{V}^{51}$	$E_{\text{He}^3} = 10 \text{ MeV}$	3000
$\text{Ti}^{46}(\text{He}^3, d)\text{V}^{47}$	$E_{\text{He}^3} = 12 \text{ MeV}$	3700
$\text{Cr}^{50}(\text{He}^3, d)\text{Mn}^{51}$	$E_{\text{He}^3} = 12 \text{ MeV}$	4000

The data analysis for the angular distributions to the $5/2^-$ and $7/2^-$ transitions is now in progress.

(J. Rapaport, W. E. Dorenbusch, and B. J. O'Brien)

H. Energy Levels in V^{47} and Mn^{51}

States in V^{47} and Mn^{51} can be reached by means of (He^3, d) reactions in Ti^{46} and Cr^{50} targets, respectively. Data have been taken at 12.0-MeV He^{3++} bombarding energy, and the scanning of the nuclear plates is now in progress. (W. E. Dorenbusch, J. Rapaport, and T. A. Belote)

1. T. A. Belote, W. E. Dorenbusch, Ole Hansen, and J. Rapaport, Nucl. Phys. 73, 321 (1965).

I. The $\text{Fe}^{54}(\text{He}^3, \alpha)\text{Fe}^{53}$ Reaction

The data for this neutron pickup reaction have been taken at 13.0-MeV He^{3++} bombarding energy with a 3000 μC exposure. The scanning of the plates, as well as the analysis of this reaction, will be made in conjunction with Dr. Alex Trier at the Universidad de Chile, Santiago, Chile. (J. Rapaport, W. E. Dorenbusch, T. A. Belote, and University of Chile)

III. Stripping Analysis of the $\text{Cr}^{50}(\text{d}, \text{p})\text{Cr}^{51}$ Reactions

A Cr^{50} target, enriched to 95.9 percent in Cr^{50} , was bombarded with 7.5-MeV deuterons. Proton groups from the $\text{Cr}^{50}(\text{d}, \text{p})\text{Cr}^{51}$ reactions were analyzed in the multiple-gap spectrograph and recorded in nuclear emulsions. The nuclear-track plates were scanned, and the data were analyzed at Providence College in Rhode Island. A DWBA analysis, using the code JULIE, was carried out at the MIT Computation center. A preliminary report of the results was presented at the April meeting of the Physical Society in Washington, and a final manuscript for publication is currently being prepared. The results are partially summarized in Table 5.I.

Table 5.I
DWBA Analysis of the $\text{Cr}^{50}(\text{d}, \text{p})\text{Cr}^{51}$ Reactions

Level	E_x (MeV)	Q (MeV)	Q_{max} in deg	$(d\sigma/dr)_{\text{max}}$ mb/sr	ℓ_n	$(2J_f+1)S$
0	0	7.041	40	0.86	3	3.04
1	0.748	6.293	15	5.77	1	1.75
2	0.775	6.266	15	2.28	1	0.67
4	1.346	5.695	38	0.37	3	1.17
6	1.552	5.489	35	0.26	3	0.80
7	1.895	5.146	15	3.09	1	0.74
12	2.761	4.280	28	0.76	0	0.02
14	2.887	4.154	15	2.06	1	0.41
15	2.907	4.134	40	0.14	3	0.38
16	2.946	4.095	46	0.11	3	0.31
17	2.999	4.042	46	0.12	3	0.32
19	3.054	3.987	15	0.64	1	0.12
21	3.124	3.917	15	4.08	1	0.77
22	3.204	3.837	38	0.09	3	0.22
24	3.352	3.689	46	0.32	3	0.81
26	3.767	3.274	15	2.16	1	0.36
34	4.036	2.305	15	3.32	1	0.53
35	4.070	2.971	23	0.89	2	0.28
36	4.099	2.942	50	0.21	4	1.36
38	4.158	2.883	50	0.62	4	3.90

(J. Robertshaw (Providence College), A. Sperduto, and W. W. Buechner)

IV. Stripping Analysis of the $\text{Ni}^{61}(\text{d}, \text{p})\text{Ni}^{62}$ Reactions

A Ni^{61} target enriched to 74.4 percent was bombarded with 7.0-MeV deuterons, and proton groups from the $\text{Ni}^{61}(\text{d}, \text{p})\text{Ni}^{62}$ reactions were analyzed in the multiple-gap spectrograph and recorded in nuclear emulsions. The nuclear-track plates were scanned, and the data were analyzed at the University of Mexico. During the past year, we have collaborated in carrying out a DWBA analysis, using the code JULIE at the MIT Computation Center. A preliminary report of the results was presented at the August meeting of the Physical Society in Mexico City. A final manuscript for publication is now being prepared. The results are partially summarized in Table 5.II.

Table 5.II
DWBA Analysis of the $\text{Ni}^{61}(\text{d}, \text{p})\text{Ni}^{62}$ Reactions

Level	E_x (MeV)	Q (MeV)	θ_{max} in deg	$(d\sigma/dr)_{\text{max}}$ mb sr	ℓ_n	$\left(\frac{2J_f+1}{2J_i+1} \right) S$
0	0	8.379	15	0.770	1	0.65
1	1.171	7.208	17	0.620	1	0.368
2	2.050	6.329	17	0.910	1	0.105
3	2.301	6.078	17	0.115	1 + 3	0.061
4	2.336	6.043	37	0.110	3	0.568
5	2.892	5.487	20	0.250	1	0.112
7	3.160	5.219	20	0.320	1	0.133
9	3.254	5.125	37	0.290	3	1.43
10	3.266	5.113	19	0.370	1	0.145
11	3.368	5.011	22	0.530	1	0.207
12	3.467	4.912	37	0.024	3	0.116
13	3.520	4.859	20	0.820	1	0.321
14	3.755	4.624	22	0.090	1 + 3	0.034
15	3.858	4.521	22	1.120	1	0.408
16	3.973	4.406	20	0.320	1	0.112
17	4.011	4.368	37	0.040	(3)	0.180
18	4.042	4.337	17	0.070	1	0.023
19	4.067	4.312	17	0.200	1	0.067
20	4.164	4.215	37	0.155	3	0.687
21	4.207	4.172	18	0.400	1	0.138

(F. Alba (University of Mexico), A. Sperduto, and H. A. Enge)

V. The $\text{Cu}^{63}(\text{d}, \text{d}')\text{Cu}^{63}$ Reaction

An isotopically enriched target of Cu^{63} on Formvar was bombarded with the 7.0-MeV deuteron beam. A full load of Kodak NTA plates was exposed. The longest exposure was 6000 μC . The target thickness, as determined from the elastic scattering of 3.0-MeV deuterons, is 24.7 $\mu\text{g}/\text{cm}^2$.

All of the elastic-scattering data have been scanned as well as a small portion of the inelastic spectrum at several angles. Analysis of these data will commence when further scanning has been completed. (D. L. Smith)

VI. The $\text{Ni}^{62}(\text{He}^3, d)\text{Cu}^{63}$ Reaction

An isotopically enriched target of Ni^{62} on Formvar was bombarded with 11.0-MeV He^{3++} particles. The target measured $41 \mu\text{g}/\text{cm}^2$ in thickness, as determined by the elastic scattering of 5.5-MeV He^3 particles. A full load of Kodak NTA plates was exposed. The longest exposure was $2500 \mu\text{C}$.

A major portion of the scanning of these plates has been completed, and analysis of the data is in progress. The angular distribution of elastically scattered 11.0-MeV He^3 particles has been obtained, and several sets of optical-model parameters that fit these data have been obtained. A number of low-lying levels in Cu^{63} have been observed that compare well with the $\text{Cu}^{63}(p, p')\text{Cu}^{63}$ experiment of Mazari, *et al.*¹ More levels are seen by Mazari, *et al.*, because they obtained better resolution with proton scattering than could be expected with a He^3 experiment. The information obtained for the higher excitation states ($E_x > 2.5 \text{ MeV}$) in the present experiment is somewhat limited because the yield was lower than required for good statistics, and the resolving power was insufficient to separate many of the levels. Better yield could have been obtained without a loss in resolving power if it had been feasible to use a higher energy incident beam.

The optical-model parameters obtained are being used to calculate angular distributions for two $\ell = 1$ levels and one $\ell = 3$ level in the distorted-wave Born approximation (DWBA). Other levels will be studied when the necessary scanning is completed. (D. L. Smith and H. Y. Chen)

VII. The $\text{Zn}^{66}(d, p)\text{Zn}^{67}$ Reaction

Data from the $\text{Zn}^{66}(d, p)\text{Zn}^{67}$ reaction have been analyzed for neutron structure to about 3-MeV excitation using conventional DWBA techniques. The $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ strengths seem well accounted for if we assign J values to the p states on the basis of the Lee-Schiffer effect and indicate that the ground-state neutron wave function of Zn^{66} is $0.98 (f_{5/2})^{-2} + 0.19 (p_{3/2})^{-2}$.

A comparison of two long-exposure, low-background runs on the above reaction and on $\text{Zn}^{66}(d, d')\text{Zn}^{66}$ shows ten or twelve levels that can be seen in both reactions. In the (d, d') reaction, only one state at 1.52-MeV excitation is strongly excited, corresponding to a weakly excited level in the $\text{Zn}^{66}(d, p)\text{Zn}^{67}$ data. An angular distribution for the (d, d') transition has been extracted but has not as yet been analyzed.

Further work on Zn^{67} planned for this year includes (p, p') and $(p, p'\gamma)$ experiments to establish the level structure more nearly completely and to pin down spin assignments, particularly for the neutron p states. (W. H. Moore, H. Ismail, D. J. Pullen (Univ. of Penna.), and Ole Hansen (Copenhagen))

1. M. Mazari, W. W. Buechner, and R. P. deFigueiredo, *Phys. Rev.* **108**, 373 (1957).

VIII. Nuclear-reaction Studies in the Strontium Isotopes

The $\text{Sr}^{88}(\text{d}, \text{p})\text{Sr}^{89}$ reaction has been studied at a bombarding energy of 7.0 MeV. Eighty-four levels have been observed in Sr^{89} up to an excitation of 5.85 MeV. The angular distributions of proton groups showing stripping patterns were analyzed with the DWBA code JULIE, and spectroscopic strengths $(2J+1)S_{\ell}^{n,j}$ were extracted. A sum-rule analysis has been made using these (d, p) strengths, as well as strengths normalized to results of a coupled-channel fit to $\text{Sr}^{88}(\text{p}, \text{p})$ analogue-state data taken previously. (See the December 1965 Progress Report.) The latter method seems to give better agreement to the expected shell-model limits. (E. R. Cosman, H. A. Enge, and A. Sperduto)

IX. Work on Tellurium

Work on the reaction $\text{Te}^{128}(\text{d}, \text{p})\text{Te}^{129}$ has been reported earlier. This work is now being completed as part of a B.S. thesis. The data for the reaction $\text{Te}^{130}(\text{d}, \text{p})\text{Te}^{131}$ have been analyzed at the University of Bergen, Norway, by A. Graue and co-workers. This work is now being prepared for publication. An exposure has also been made on Te^{126} , and the plates from twelve of the twenty-four angles have been counted in Bergen. (S. L. O'Dell, W. H. Moore, and H. A. Enge)

X. The $\text{Ba}^{138}(\text{d}, \text{p})\text{Ba}^{139}$ Reaction for Deuteron Energies
Between 5.0 and 7.5 MeV

A natural barium target was bombarded with incident deuteron energies between 5.0 and 7.5 MeV in steps of 0.5 MeV. The proton angular distributions were measured between 7.5 and 172.5 deg using the multiple-gap spectrograph. The elastic scattering of 7.5-MeV deuterons was measured in order to obtain the optical-model deuteron optical parameters. Figure 5.8 gives the observed angular distributions for the ground-state transition. The data have been analyzed using the DWBA code JULIE and a 25 percent difference is found for the transition strength $(2J + 1)S$ calculated at 5.0 and 7.5 MeV. A further analysis is being conducted by using the zero-range Tobocman DWBA code, which has been modified by Gibson and Kerman to incorporate finite-range and polarization effects, assuming a Coulomb stripping process. (J. Rapaport and H. Y. Chen)

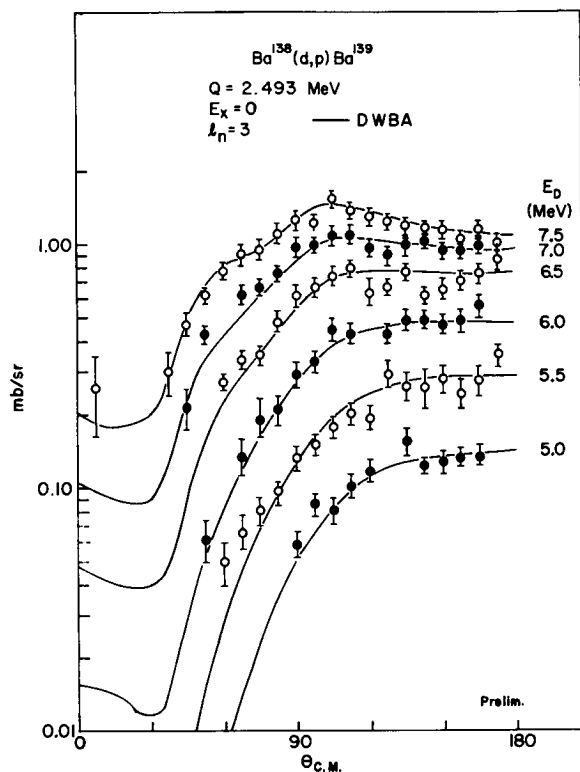


Figure 5.8

XI. Optical-model Analysis and DWBA Calculations

In the past year, DWBA calculations using code JULIE were made for a number of (d, p) reactions at bombarding energies of 7 and 7.5 MeV. The optical-model parameters for the outgoing protons were taken from Perey.¹ For the incoming channel, the deuteron parameters were obtained from analyses of the d + target elastic-scattering data at the same incident energies by use of the ABACUS program. The DW curves based on these parameters seem to fit the reaction data reasonably well, giving the correct ℓ_n values as well as good spectroscopic factors. The results of these analyses are either given in this Progress Report or are published elsewhere by various members of our Group. The deuteron parameters for various nuclei will be tested further in the analysis of (d, d') reactions.

In addition to the (d, p) work, two (He^3 , d) reactions at 12 MeV are now being analyzed along the same lines as were the (d, p) reactions. Aside from the known Vr^n ambiguities, it was found that several sets of optical potentials would fit the elastic data equally well, but one of them is slightly better than the other in fitting the reaction data. Furthermore, when the nuclides, such as He^3 , are strongly absorbed in the nucleus, additional uncertainties arise in such a manner

1. F. G. Perey, Phys. Rev. 131, 745 (1963).

that several groups of potentials can be found giving essentially the same elastics but differing from each other in the characteristic that one additional half wavelength of each pertinent partial wave is pulled into the potential for successively deeper potentials. Accordingly, we have tried to derive three groups of potentials, characterized by the real depth V approximately equal to 80, 140, and 180 MeV, respectively; these have all been applied to our (He^3, d) reaction data. Preliminary analysis of the ground states of $\text{Fe}^{54}(\text{He}^3, d)\text{Co}^{55}$ and $\text{Ni}^{62}(\text{He}^3, d)\text{Cu}^{63}$ seem to indicate that the third group with the deepest potential is slightly favored. In our calculations, we have used the usual separation-energy procedure to calculate the bound-state wave functions; no cutoff is employed. The normalization factor N is chosen to be 4.4, as given by Bassel.¹ (H. Y. Chen)

XII. Quadrupole Lens Magnetic Spectrometer and the $(p, p\gamma)$ Project

The equipment for this project, including a magnetic quadrupole lens, beam slit system, target holder, scintillation-counter apparatus for gamma-ray spectrometry, and a charged-particle detector, has been built and installed inside the multiple-gap spectrograph. This apparatus has been tested mechanically and electrically. The optics of the spectrometer is now being studied with the aid of 5.5-MeV protons elastically scattered from a thin gold target. The solid angle of the spectrometer and the resolving power are being measured in this manner. A thin target of a lighter isotope (Cu^{63}) will be used to study the Doppler corrective properties of this instrument. (D. L. Smith and N. M. Rao)

XIII. The He^{3++} Ion Source

A He^{3++} ion source, purchased from Oak Ridge Technical Enterprises, has been installed in the ONR Generator. The source consists of a regular rf type followed by an electrostatic einzel lens and a magnet for separating the He^{3+} ions from He^{3++} . After installation, the source was able to produce a maximum on the target of about 0.015 microamperes. Also, the separation of the He^+ and He^{++} beams was insufficient to reduce the large He^+ component to a reasonable intensity.

The source was modified by increasing the range of deflection in the field of the bending magnet from 3.5 to 7 deg. The source then gave adequate separation between the He^{++} and He^+ ions, reducing the intensity of the latter about 100 times. The power supply for the einzel lens was also reversed to make the central electrode negative rather than positive. These modifications resulted in a 3 to 5 times increase in the He^{3++} current striking the target. Beams of He^{3++} ions with currents in the 0.05 to 0.08 microampere range can now be produced at energies of

1. R. H. Bassel, Phys. Rev. 149, 791 (1966).

10 to 14 MeV. (M. K. Salomaa and B. J. O'Brien)

XIV. The Split-pole Spectrograph

A new single-gap spectrograph with ultra-high resolving power is being designed to operate in conjunction with the multiple-gap instrument; that is, facing the same target. Preliminary drawings have been made, but the final optimization of the design parameters by computer calculations has taken longer than anticipated. However, a good solution has presently been found. We expect that a resolving power of $E/\Delta E \approx 10^4$ can be obtained with this instrument. (H. Iuzzolino, J. E. Spencer, and H. A. Enge)

XV. The Scattering Chamber

The design of a multiple-purpose scattering chamber for charged-particle reactions has been completed, and the first stages of construction have been initiated. (T. A. Belote, D. W. Baker, and E. R. Cosman)

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- J. Rapaport, W. W. Buechner, and H. Y. Chen, "Stripping Analysis of the $\text{Ba}^{138}(\text{d}, \text{p})\text{Ba}^{139}$ Reaction for Deuteron Energies between 5.0 and 7.5 MeV", *Bull. Am. Phys. Soc.* **11**, 752 (1966).
- P. Morales, F. Alba (Univ. of Mexico) with H. A. Enge, "Cylindric-Lens Focusing Properties in Mass Spectrograph", *Bull. Am. Phys. Soc.* **11**, 747 (1966).

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- H. A. Enge and J. E. Spencer, "Test Results for Split-Pole Magnetic Spectrograph", with B. L. Cohen and J. B. Moorhead (Univ. of Pittsburgh). Paper presented by H. A. Enge at Conference on Recent Progress in Nuclear Physics with Tandems, July 18-21, 1966 at Heidelberg, Germany.
- H. A. Enge, "Past, Present, and Future Work in Nuclear-Reaction Spectroscopy", University of Mexico, August 31, 1966.

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- F. T. Dao, "Study of $\text{V}^{50}(\text{d}, \text{d}')\text{V}^{50}$ Reaction," B.S., Jan. 1966.
- G. K. Schlegel, "Stripping Analysis of the Reaction $\text{Te}^{128}(\text{d}, \text{p})\text{Te}^{129}$ ", M.S., Jan. 1966.
- E. R. Chalbaud, "Energy Levels of the Stable Chromium Isotopes", M.S., Jan. 1966.
- R. L. Kusper, "Design Optimization of a Magnetic Spectrograph", B.S., June 1966.
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RADIOACTIVITY GROUP

I. Introduction

The study of magnetic moments of short-lived excited states has continued, concentrating on the measurement of 2^+ states using a Coulomb excitation ion implantation technique. The same technique has been used to study hyperfine magnetic fields on dilute impurities in ferromagnetic materials. Some results using radioactive sources for the measurement of magnetic moments and internal fields have also been obtained. Isomer shift studies of the stretching of rotational states have continued with emphasis on Sm^{152} . In a collaborative effort with High Voltage Engineering Corp. scientists, quantitative investigations of the stripping of electrons from energetic heavy ions passing through foils and gases have been carried out.

Considerable progress has also been made in two areas which are not yet completed sufficiently for detailed description, but which are expected to be of some importance during the coming year. First is the investigation of the distribution of small internal magnetic fields, particularly in type II superconductors, using time dependent perturbed angular correlation methods. The experimental equipment has been completed and checked out for the measurement of internal fields down to 100 gauss, at temperatures down to the lambda point of helium. The second important study in progress concerns the investigation of the decay of a nuclear state as a function of the mode of excitation of that state. States of nominal lifetime τ , are resonantly excited by gamma rays having $\Delta E \geq \hbar/\tau$, and the line widths and time dependence of the excited state decay modes are being investigated.

II. Coulomb Excitation Ion Implantation

In a collaborative effort with the University of Wisconsin we have been measuring the magnetic moments of short-lived 2^+ states in even-even nuclei and internal fields on dilute impurities in ferromagnetic materials using perturbed angular correlations measured after the nucleus in question has been Coulomb-excited and implanted into the desired material. This work is a continuation of work begun in Copenhagen by L. Grodzins¹. The magnetic moments of the first 2^+ states in the even Te nuclei have been systematically investigated.² The results are presented in Table 6.I. The g_R values increase from 0.44 for Te^{120} to 0.93 for Te^{128} . These values are in strong disagreement with the theoretical predictions;³ the latter are included in Table 6.I. The values for the heavier tellurium are not only substantially greater than the Z/A hydrodynamical model prediction, but are considerably higher than any hitherto obtained experi-

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1. L. Grodzins, R. Borchers and G. Hagemann, Phys. Letters 21, 214 (1966).
 2. R. Borchers, J. Bronson, D. Murnick, and L. Grodzins, Phys. Rev. Letters 17, 1099 (1966).
 3. L. Kisslinger and R. Sorensen, Rev. Mod. Phys. 35, 853 (1963).

mentally for collective states. These results may be indicative of strong pairing effects between neutrons and protons in the same shell.

Table 6.I

Summary of experimental data on magnetic moments of 2^+ states in even Te isotopes. An internal field of 620 ± 20 Kgauss is assumed.⁴

Isotope	E	τ ($\times 10^{-12}$ sec)	$-\omega_H \tau$	$g_R(\text{exp})$	$g'_R(\text{theory})$
Te ¹²⁰	560	13.4	$.0175 \pm .0036$	$.438 \pm .092$	.20
Te ¹²²	564	11.0	$.0177 \pm .0012$	$.541 \pm .036$	.17
			$.0154 \pm .0015^5$	$.44 \pm .06$	
			$.0132 \pm .0013^6$	$.368 \pm .06$	
Te ¹²⁴	603	8.5	$.0148 \pm .0009$	$.585 \pm .035$	.16
Te ¹²⁶	667	5.82	$.0151 \pm .0025$	$.872 \pm .144$	.18
Te ¹²⁸	743	4.36	$.0121 \pm .0020$	$.932 \pm .146$	.21

The internal magnetic fields on rare earths in ferromagnetic environments are under study; the investigation of samarium in iron, nickel, and cobalt has been completed.⁷ We find that the internal fields on samarium decrease from iron to cobalt to nickel in direct proportion to the atomic magnetic moment of the ferromagnetic host. These results appear surprising since they indicate that crystal field effects are small at room temperature, at which these data were obtained. (D. Murnick, L. Grodzins)

III. The Temperature Dependence of the Internal Field of Osmium in an Iron Lattice

Measurements of the magnetic moments of excited states by the use of perturbed angular correlations using internal fields generally make use of those internal fields determined by other techniques (NMR, Mössbauer effect) at liquid helium temperature. It is generally assumed that for very dilute alloys the internal field on the solute will have a temperature dependence the same as that of the ferromagnetic host. We have examined this in the case of Osmium in iron using the measured anisotropy of the angular correlation vs temperature in the randomly oriented internal magnetic field, for the temperature range 4.2°K to 1250°K. We find that the magnetization curve falls below that of pure iron, although the Curie temperature is the same as that of iron within our

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4. R. Frankel, J. Huntzecker, E. Matthias, S. Rosenblum, D. Shirley, and N. Stone, Phys. Letters 15, 163 (1965).
 5. K. Auerbach, B. Harms, K. Siepe, G. Wittkemper and H. Körner, Phys. Letters 22, 299 (1966).
 6. K. Johansson, E. Karlsson and R. Sommerfeldt, Phys. Letters 22, 297 (1966).
 7. D. Murnick, Proceedings of NATO Advanced Study Institute on Hyperfine Interactions, to be published.

experimental errors. This data is the first evidence that there may be a local moment from the osmium nucleus in a ferromagnetic environment, so that the net field at the osmium nucleus derives partially from induced effects arising from conduction electron polarization and partly from a net moment on the solute. Evidence for a similar effect has recently been obtained by other groups in the rhodium-palladium region.⁸ (G. C. Pramila, L. Grodzins)

IV. The Magnetic Moment of the 2^+ State of Os^{192}

The above temperature dependence study was part of an investigation to determine g_R of the 2^+ state of Os^{192} . An earlier measurement gave a value for $g_R = 0.10 \pm 0.03$, which is a factor of three less than that obtained by the group of Goldring, *et al.*, using Coulomb excitation.⁹ We have very carefully examined possible systematic errors in the original work. Triple coincidence measurements, field flip measurements as a function of angle, and the above temperature-dependent measurements were carried out. The best value we now quote is $g_R = 0.19 \pm 0.02$, the error arising from uncertainties in the subtraction of a substantial background. To extract g_R from the measured $\omega_H \tau$, $\tau = .393$ ns, and $H_{\text{INT}} = 1.11$ kOe (from recent NMR measurements) is assumed. (G. C. Pramila, L. Grodzins)

V. The Internal Magnetic Field on Lead Nuclei in an Iron Lattice

The magnitude and sign of the internal magnetic field acting at the lead nucleus in an iron lattice has been measured to be $+262 \pm 20$ kG at room temperature. This value was determined from a measurement of the Larmor precession angle in the $13/2^+$ (1064 keV) $5/2^-$ gamma-gamma angular correlation in ^{207}Pb using a source of Bi^{207} in iron metal. This measurement is of interest for two reasons; first, the magnitude of the internal field on lead in iron is large enough to make practical the measurement of the g value of several short-lived states in the isotopes of lead; second, the sign of the internal field is opposite to that observed in the iron alloys formed at the neighboring lower Z elements, W, Re, Os, Pt, and Au, thus suggesting the onset of another region of positive internal fields. (G. C. Pramila, L. Grodzins)

VI. Evidence for Centrifugal Stretching in Sm^{152}

The isomer shift of the 122 keV state in Sm^{152} has been determined via Mössbauer effect experiments between the 2^+ and 3^+ valence states. Various combinations of sources and absorbers

8. E. Matthias, private communication.

9. G. Goldring, R. Kalish, and H. Spehl, Nucl. Phys. 80, 33 (1966).

were used. Because of the high energy of the gamma transition, it was necessary to find an environment with a reasonably large Debye-Waller factor. Such an environment is the CaF_2 lattice. Using the source of 2^+ Eu in CaF_2 , which decays to Sm, we have investigated the Mössbauer spectrum for an absorber of Sm_2O_3 . In this case the samarium is expected to be mainly 3^+ . A clear isomer shift is obtained and is strong evidence that the samarium in the source is indeed in the 2^+ valence state. An absorber of samarium in CaF_2 was investigated. This is a complex source, since samarium in CaF_2 tends to go in as both 2^+ and 3^+ ; the latter is para-magnetic, and recent NMR measurements indicate that relaxation times could be rather long at the 4.2°K temperature used in our experiments. The Mössbauer velocity spectrum shown in Figure 6.2 shows two independent spectra, a single line which we take to be the 2^+ portion of samarium, and a five-line, magnetically split spectrum, which we believe to be the 3^+ portion of the absorber. The latter has been analyzed assuming no quadrupole interaction, and we find that the isomer shift between the 2^+ source and the 3^+ absorber is approximately the same as that for Sm_2O_3 . The magnitude of the splitting gives us a value for the free ion magnetic field, and that value is $4.1 \pm .2$ mOe. The difference in $(\Psi(0))^2$ between the 2^+ and 3^+ valence states of samarium has been estimated from optical experiments to be $2.2 \times 10^{26} \text{ cm}^{-3}$.¹⁰ Using this value, we can obtain the fractional change in radius between the 122 keV level and the ground state. We find $\Delta R/R = 3.3 \times 10^{-4}$ and this value can be compared with various predictions. In general, all predictions, such as those of Udagawa,¹¹ those based on β band mixing, and those which are based on very simple ideas of centrifugal stretching all give predicted values of $\Delta R/R$ that are greater than that obtained. (D. Yeboah-Amankwah, R. Frankel (NML), and L. Grodzins)

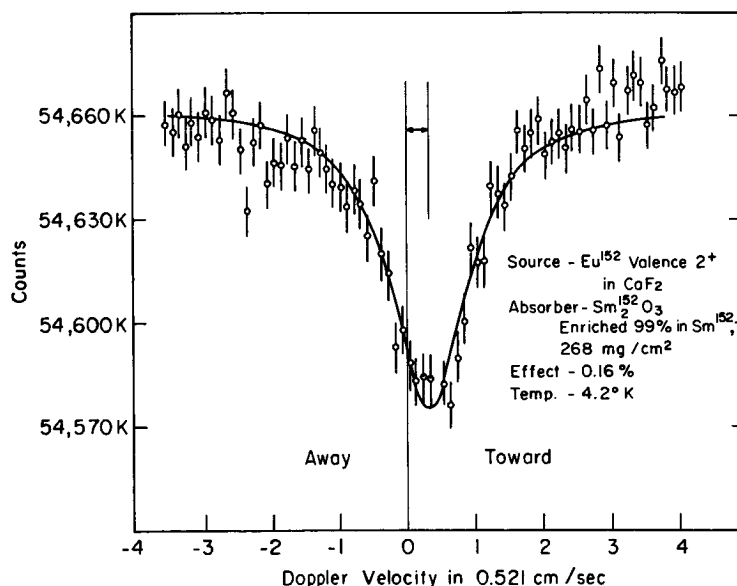


Figure 6.1

Mössbauer absorption spectrum for 122 keV gamma of Sm^{152} , with Sm_2O_3 absorber.

10. P. Brix, S. Hüffner, P. Kienle and D. Quitmann, Phys. Letters 13, 140 (1964).
11. T. Udagawa and R.K. Sheline, to be published.

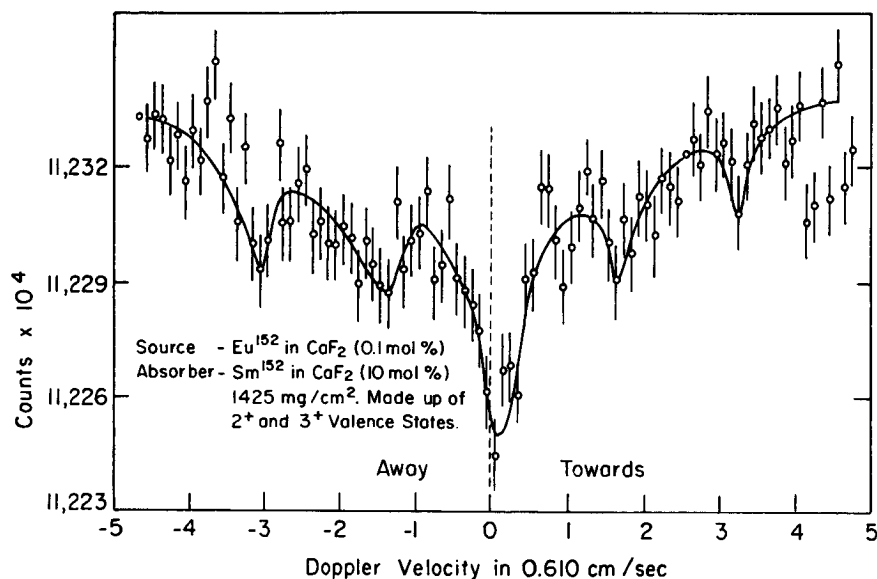


Figure 6.2

Mössbauer absorption spectrum for 122 keV gamma of Sm^{152} , with Sm^{152} in CaF_2 absorber. The unsplit 2^+ line is superimposed on the hyperfine split 3^+ portion of the absorber.

VII. The Stripping of Electrons from Energetic Heavy Ions Passing through Foils and Gases

In a collaborative effort between members of the Laboratory for Nuclear Science and scientists from High Voltage Engineering Corp., under Dr. P. Rose and Dr. R. Van de Graaff, a series of experiments were conducted in which the MP tandem accelerator was used to accelerate beams of Br, I, Ta, and U ions for the investigation of charge stripping. The beams from the tandem were sorted by combinations of magnetic, electrostatic, and pulse height analyses. Homogeneous beams were passed through foils or gases and the subsequent charge spectrum was analyzed with a magnet and a surface barrier heavy ion detector.

Figure 6.3 shows typical spectra for 154 MeV iodine traversing gas (dashed line) and foil (solid line). The increase in stripping on passing through a foil is clear and is expected. In Figure 6.4 the mean charge at equilibrium, $\bar{q}$, for Br, I, Ta and U is presented as a function of the square root of energy. The maximum of the probability distribution is $\sim 20\%$ in all cases. The present data are shown as solid symbols, that of previous workers by open symbols.^{12,13} Figure 6.5 shows a typical energy spectrum of a uranium beam of constant rigidity, ME/q^2 , passed through a $20 \mu\text{g}/\text{cm}^2$ carbon foil. (L. Grodzins, D. Murnick, R. Kalish)

12. H. Betz, G. Hortig, E. Leischner, Ch. Schmelzer, B. Stradler, and J. Weihtough, Phys. Letters 22, 643 (1966).
13. A. Litherland, E. Almquist, B. Andrews, C. Bronde, and J. Kuehner, Bull. Am. Phys. Soc. 8, 75 (1963).

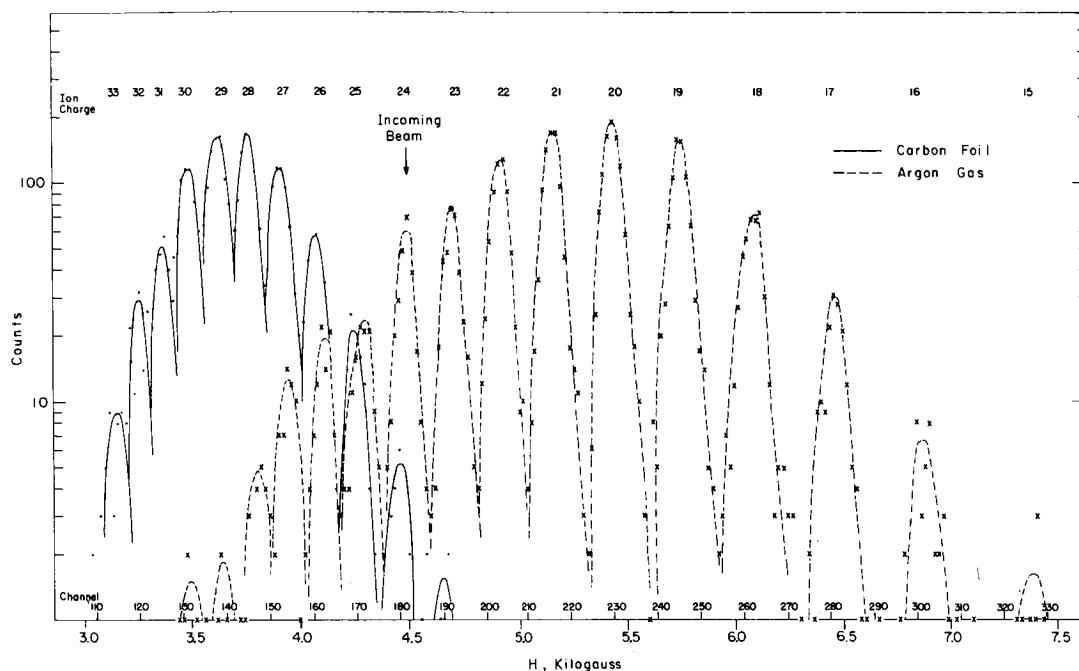


Figure 6.3

The charge spectrum obtained after passage of a primary iodine beam of charge state 2+ and energy 154 MeV through a 20 $\mu\text{g}/\text{cm}^2$ carbon foil (solid line), and through 1700 μcm of oxygen (dashed line). The slight displacement of peaks of the same charge in the different targets is due to the different energy loss in the foil and the gas.

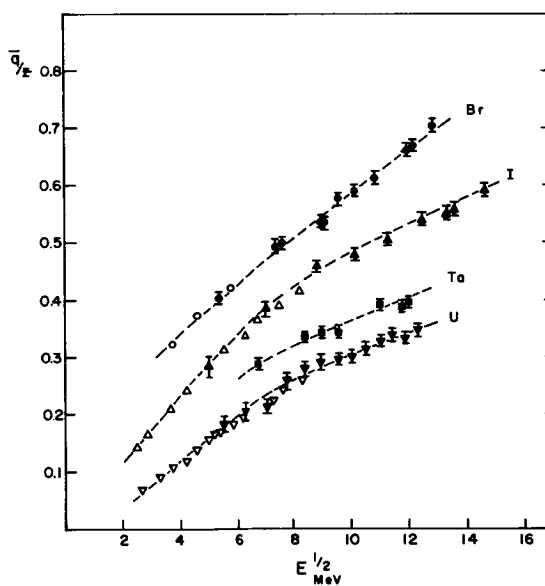


Figure 6.4

The most probable ionized fraction, $\bar{q}/Z$, for passage through an equilibrium thickness of carbon foil as a function of $E^{1/2}$ of the incoming ions. Open symbols are taken from references 12 and 13.

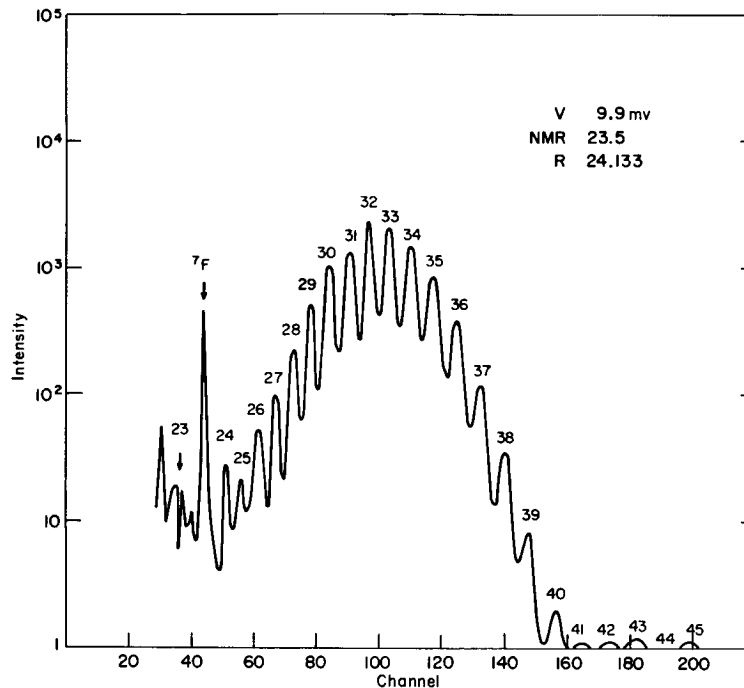


Figure 6.5

Energy spectrum of portion of uranium beams passed through a $20 \mu\text{g}/\text{cm}^2$ carbon foil, having $ME/q^2=24.133$. The peak labeled 7F is due to some fluorine contamination in the beam. The uranium peaks are labeled by charge state.

VIII. Studies in the Ac^{227} Decay Series

Using a silicon surface barrier α -particle detector, the α branching ratio of Ac^{227} decaying to Fr^{223} was measured to be $(1.48 \pm 0.19)\%$. Alpha-gamma angular correlation measurements of Ra^{223} decay indicate that the spins of the first four excited states of Em^{219} are:

4.6 (5/2), 14.4 (1/2 or 5/2), 127 (5/2), 158.6 (3/2)

or 4.6 (7/2), 14.4 (3/2 or 7/2), 127 (7/2), 158.6 (5/2)

with the first sequence being more probable. Similar angular correlation measurements in the decay of Th^{227} to Ra^{223} lead to the following spin assignments for excited levels in Ra^{223} :

329.7 (3/2 or 5/2), 334.3 (5/2), 342.6 (7/2) .

(A. Lewis)

IX. Nuclear Physics

A measurement of internal conversion coefficients of $2+$ to $0+$ transitions in several trans-lead nuclei is being made. The nuclei under investigation are $\text{Em}^{220, 222}$, $\text{Ra}^{224, 226}$, Th^{228} and

$U^{234, 236}$. The measurements are being made using standard α - γ coincidence techniques. A preliminary measurement of the total conversion coefficient of the first excited level in Ra^{224} gives $\alpha_{TOT} = 28.1 \pm 7$. The theoretical value is 21.4. (R. Schlenker)

X. Instrumentation

Lithium-drifted germanium γ -ray detectors are being fabricated and used with uncooled field effect transistor pre-amplifiers made in our laboratory. The best resolution measured to date using such a system is 2.3 keV fwhm, using a Co^{57} source. (R. Schlenker)

ADDRESSES

- L. Grodzins, "Nuclear Magnetic Moments of Coulomb-Excited Vibrational States", A.P.S. Summer Meeting at Mexico City, August, 1966.
- D. Murnick, "Acceleration of Heavy Ions", University of Wisconsin, May, 1966.
- D. Murnick, "Ion Implantation Perturbed Angular Correlation Method", NATO Advanced Study Institute on Hyperfine Interactions at Aix-en-Provence, August, 1966.

PUBLICATIONS

- R. Borchers, J. Bronson, D. Murnick, and L. Grodzins, Phys. Rev. Letters 17, 1099 (1966).
- L. Grodzins, R. Borchers and G. Hagemann, Phys. Letters 21, 214 (1966).
- L. Grodzins, S. G. Cohen, N. A. Blum, Y. W. Chow, and R. B. Frankel, "Isomer Shift Measurement in W^{182} ", Phys. Rev. Letters 16, 322 (1966).
- L. Grodzins and A. Buyrn, "Mössbauer Effect of the 99 and 129 keV Transitions in Pt^{195} ", Phys. Letters 21, 389 (1966).
- L. Grodzins, P. Rose and R. Van de Graaff, "Proposed Methods for Producing Intense Pulsed Beams of Mono-Energetic Neutrons", Nucl. Instr. and Meth. 36, 202-212 (1965).

CYCLOTRON GROUP

I. Cyclotron Operation and Equipment

During the past year the Cyclotron Group has been engaged in several experiments with our own cyclotron and has continued to work at other accelerators.

The main improvement in cyclotron operation has been in the quality of the alpha particle beam, by reducing the slit scattering from the energy defining slits. This was accomplished by polishing the previously used Ta slits and resulted in a factor of 10 reduction in the "beam tail". This has been of considerable help in extending measurements to smaller angles and to higher Z targets.

The electronics associated with the gamma ray experiments have been considerably improved. These experiments were started with a 3" x 3" NaI gamma detector. Recently a 15 cc Ge detector has been obtained. To take advantage of the inherent resolution of solid state detectors a magnetic tape system has been added to our 4096 channel analyzer which enables us to make 512 x 512 channel, two-dimensional analysis. The data is then read off the magnetic tape by the 7044 computer and analyzed. This system is proving to be quite valuable.

II. (α, α') Reactions.

A. Zr^{90}

The experiment was performed with considerable improvement after the beam was cleaned up. In Fig. 7.1 we show an old spectrum near 30° , while in Fig. 7.2 we show a new spectrum. The large differences, particularly in the number of states seen in the new spectrum, is quite striking. These differences show up strongly in the quality of the angular distributions. Fig. 7.2 gives our results for the spin and parity assignments that were made on the basis of this experiment, and compares them with the results of a (p, p') experiment. The most striking feature of our results is the three new 3^- states between 5 and 6 MeV excitation energy, indicating that the fractionization of the octupole strength is present in this region as well as in the $f_{7/2}$ shell, as was demonstrated by our results in the Ca isotopes.¹ It appears that the reason that the octupole state has not been previously observed is that sufficiently sensitive experiments have not been performed.

1. A. M. Bernstein and E. P. Lippincott, Phys. Rev. Letters 17, 321 (1966).

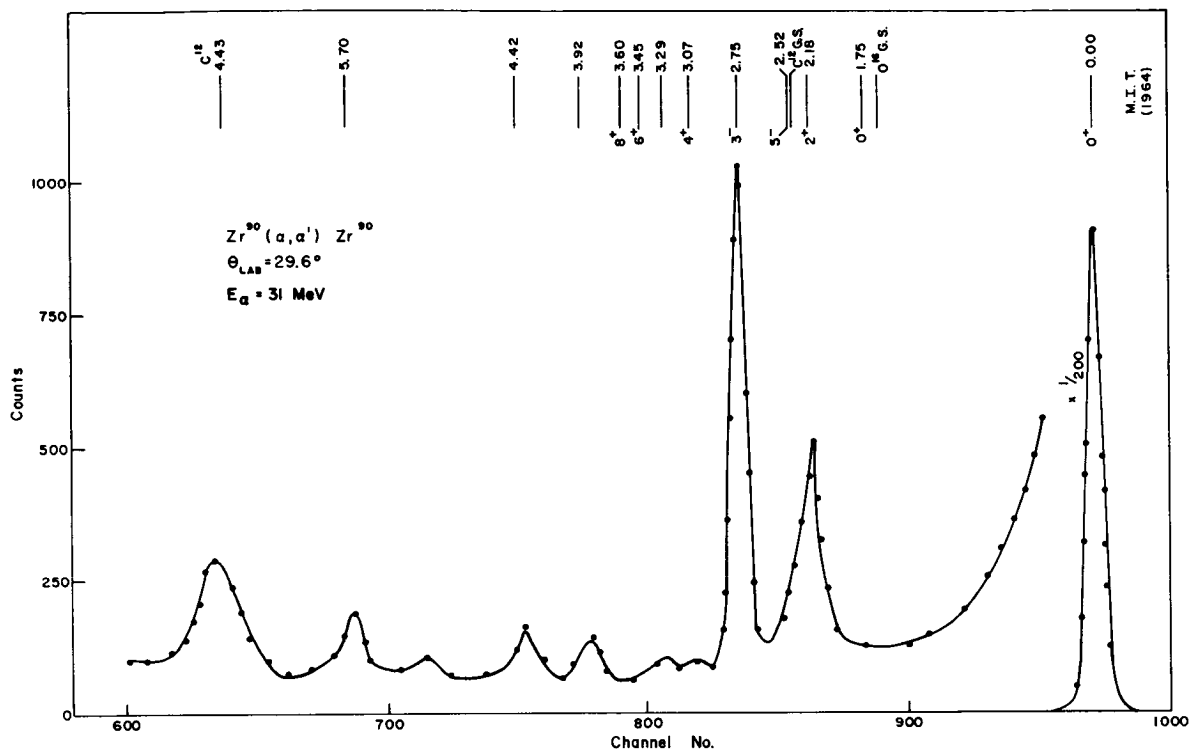


Figure 7.1
"Old" Zr^{90} Spectrum

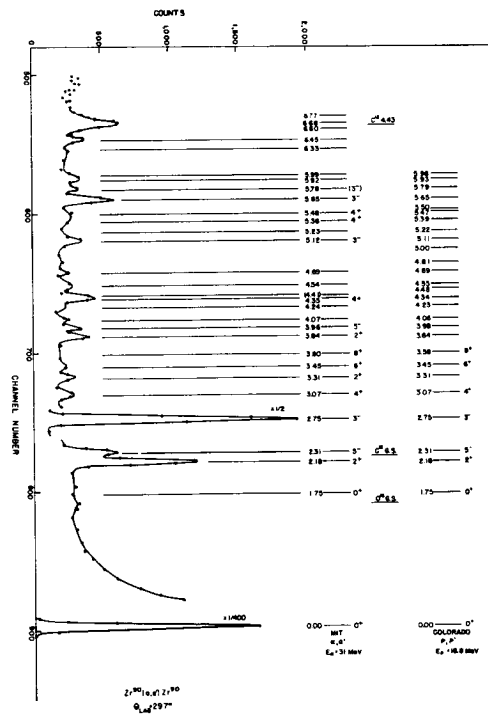


Figure 7.2
New Zr^{90} spectrum showing the results of cleaning up the beam.

In Fig. 7.3 we present the 3^- states that have been recently measured in this laboratory. The length of each line is proportional to the strength of each state relative to the lowest 3^- state in each nucleus.

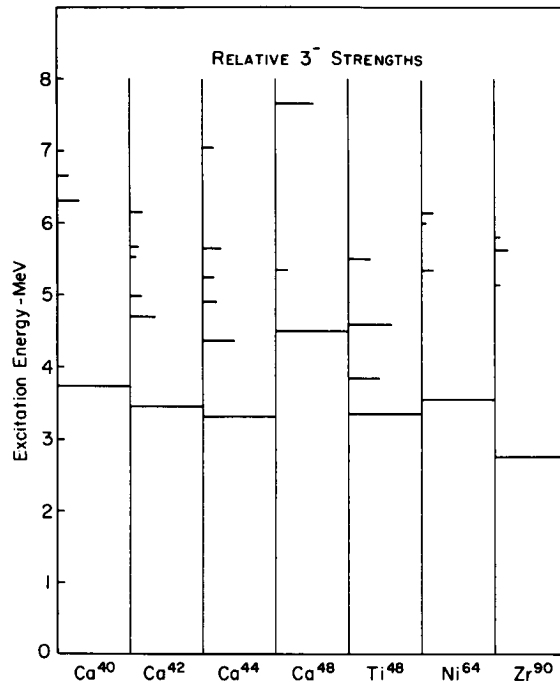


Figure 7.3

Systematics of 3^- states. The length of the lines represents the strength of each state relative to the lowest octupole state in each nucleus.

B. Ca Isotopes.

The data analysis on the inelastic scattering from these nuclei has been finished and a Ph.D. thesis (E. P. Lippincott) has been written. A short account of the results has been published.¹ A paper presenting the detailed data is in preparation. We are presently analyzing the data on the relative sizes of the Ca isotopes and on the large angle elastic scattering.

C. Gas Targets

A gas target handling system has been constructed which can handle enriched isotopes. Data has been obtained for Ar^{40} and O^{18} . For the sake of brevity these shall not be presented here.

1. A. M. Bernstein and E. P. Lippincott, Phys. Rev. Letters 17, 321 (1966).

D. Ti Isotopes

The data analysis on Ti^{50} has been completed with results which were not too different from a previous experiment on this target.¹ Data analysis on Ti^{48} is almost completed. Several 3^- states have been found and they are presented in Fig. 7.3. We note that the lowest state at 3.36 MeV does not give a clean angular distribution, from which we infer that it is a doublet. This is the only case, as far as we know, in which this has occurred for the lowest octupole state. We are fairly sure that this state is indeed an octupole state because it is the strongest inelastic state in the spectrum.

E. Ni⁶⁴

An (α, α') on Ni^{64} has been performed, but with worse statistics than most of our other experiments. Although Ni targets seem to be popular, this isotope seems to have been relatively neglected in the past. The most interesting results are the discovery of four 3^- states which are shown in Fig. 7.3.

The particularly interesting results on the fractionization of the octupole state are being further studied at the present time. We hope to expand these measurements to nuclei between Zr^{90} and the Sm isotopes, in which the transformation from spherical to rotational nuclei takes place. (E. J. Martens, E. P. Lippincott, M. Shork, C. Thorne, J. Siegel, B. Cos, T. Ho, K. Nagatani, J. Alster, C. Moazed, and A. M. Bernstein)

III. The (α, p) Reaction on $\text{Ca}^{40, 42, 44, 48}$ and Ti^{48}

Data analysis on this reaction has been completed and a Ph.D. thesis has been written (R. Ginaven). A paper is being prepared for publication. (R. Ginaven and A. Bernstein)

IV. The $\text{Ca}^{48}(\alpha, d)\text{Sc}^{50}$ Reaction

Data on this reaction have been obtained and are presently being analyzed. (K. Nagatani, T. Ho, and A. M. Bernstein)

V. (p, d) and (p, t) Reactions

A. $\text{Ca}^{42, 44}$

The data taken for these reactions with a proton energy of 26 MeV at the University of Colorado Cyclotron in collaboration with M. Rickey have been analyzed. The (p, d) data have

1. E. P. Lippincott and A. M. Bernstein, Bull. Am. Phys. Soc. 10, 122 (1965).

been compared with DWBA theory. Theoretical fits to the data using finite-range and non-local corrections in the local energy approximation have been compared with fits obtained with the usual zero-range approximation. Figs. 7.4 through 7.6 give some of the data for the $\text{Ca}^{42}(\text{p}, \text{d})\text{Ca}^{41}$ reaction. The improvement of the fits by using the finite-range and non-local corrections is quite noticeable. However even with these corrections the extracted spectroscopic factors do not agree with sum rule expectations. We are presently engaged in analyzing the data in terms of the shell model.

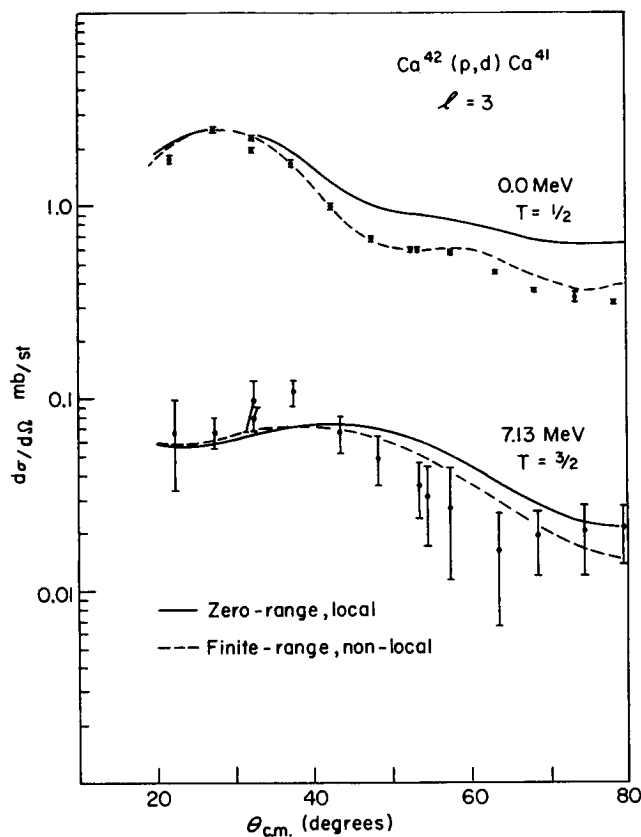


Figure 7.4
Cross sections for $L=3$ states in the $\text{Ca}^{42}(\text{p}, \text{d})\text{Ca}^{41}$ reaction.

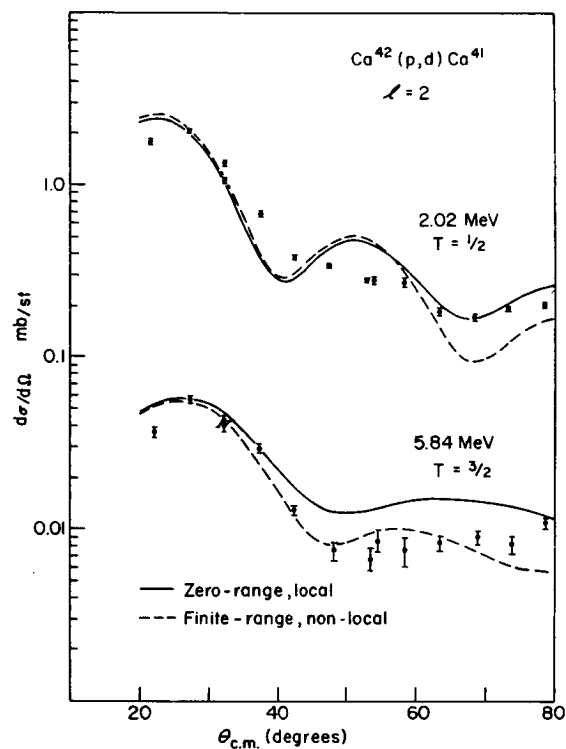


Figure 7.5

Cross sections for $L=2$ states in the $\text{Ca}^{42}(\text{p}, \text{d})\text{Ca}^{41}$ reaction.

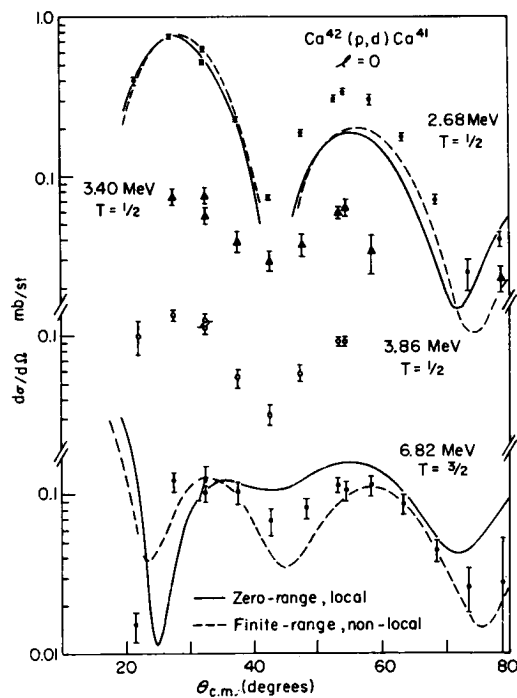


Figure 7.6

Cross sections for $L=0$ states in the $\text{Ca}^{42}(\text{p}, \text{d})\text{Ca}^{41}$ reaction.

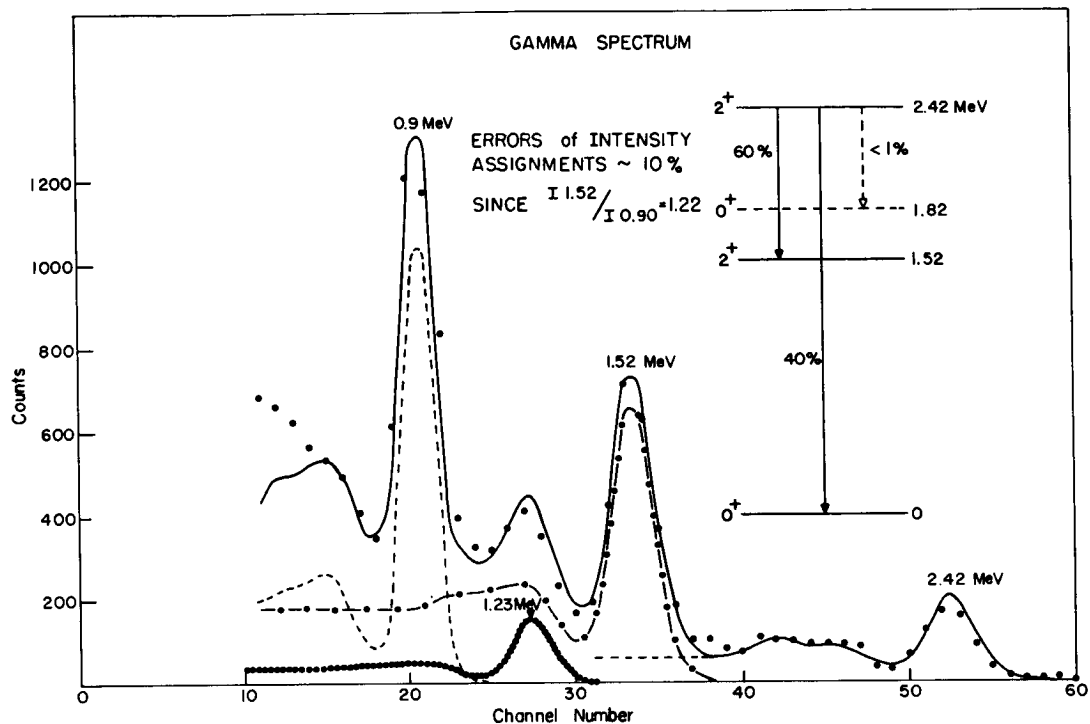


Figure 7.7

Gamma ray spectra from the decay of the 2.42 MeV
2⁺ State in Ca⁴².

VII. Computer Programs for the Analysis of Gamma Ray Data

A program has been written to read the data from the magnetic tapes and reduce it to yield gamma spectra corresponding to various particle groups. This includes gamma spectra in coincidence (chance) with the elastic scattering. This gives us the chance gamma spectra to subtract from the total gamma spectra associated with an inelastic particle group.

Programs called PEEL and FIT have been written. Both decompose spectra into constituent parts, PEEL by fitting the highest peak and stripping it from the spectra then proceeding to the next highest, etc., FIT by a linear least-squares fit to all the gamma rays simultaneously. The standard line shapes are empirical, taken with the actual experimental apparatus. A linear-interpolation scheme is used to obtain line shapes for energies other than those of the standard sources. A sample of the fits obtained is shown for the data in Fig. 7.7. (T. Ophel and W. Kossler)

B. Pb^{208}

Preliminary data on this nucleus and others have been obtained at the Oak Ridge cyclotron at a proton energy near 40 MeV, in collaboration with P. Roos. These data were obtained in a run last spring. We are presently improving our electronic system and hope to finish this experiment and others. (S. Smith, C. Moazed, and A. Bernstein).

VI. Gamma Ray Decay of Low Lying States in $\text{Ca}^{42, 48}$

We have undertaken the gamma-ray study of nuclei near the $f_{7/2}$ shell. As part of this study we have taken data using $\text{Ca}^{42}(\text{p}, \text{p}' \gamma)$ and $\text{Ca}^{48}(\text{p}, \text{p}' \gamma)$ reactions. The particle detector was either an annular detector placed so as to detect back-scattering from the target, or a "nuclear triode" placed at about 90° from the beam direction. With the annular detector a solid angle approaching one steradian was achieved, while with the triode a somewhat smaller solid angle was the case. A novel feature concerning the "triode" was that kinematic broadening could be partially cancelled by using the position signal. The gamma detectors for most of the experiment were 3" x 3" sodium iodide crystals, though a Ge(Li) detector was also used for part. In Ca^{42} we observed the decay of the 1.52 MeV 2^+ , 1.84 MeV 0^+ , 2.42 MeV 2^+ , 2.75 MeV 4^+ , and some further excited states. Perhaps the most interesting data is that for the decay of the 2.42 MeV 2^+ state. This is shown in Fig. 7.7. The curves are fits to the data using PEEL and FIT mentioned under the section of this report called Computer Programs for the Analysis of Gamma Ray Data. Note that the 1.23 MeV peak is due to leakage from the 4^+ group. The gamma ray detector subtended a large solid angle but there may still be some angular correlation effects. An estimate for these is given by the ratio of the observed 1.52 MeV and 0.90 MeV intensities. This ratio should be equal to one. The decay of the lower Ca^{48} states has also been examined. The Ca^{42} results are now being prepared for publication. (W. Kossler, T. Ophel, and M. Slade)

VIII. Germanium Detectors

Apparatus to diffuse lithium into germanium, drift the lithium, and associated processes in Ge(Li) detector production have been established. Inexpensive dewars have been designed and constructed. A test stand with facilities for raising and lowering the pressure in the dewars and for generally testing leakage current with bias applied has been designed and constructed. Several small (5 cc) planar detectors with satisfactory resolution (≈ 5 keV) have been constructed. At present larger detectors are in process. (W. Bucelewicz and W. Kossler)

ADDRESSES

A. Bernstein, "Systematics of Vibrational States in Medium Weight Nuclei from Inelastic Scattering Experiments"

McMaster University, February 1966; Princeton University, April 1966; invited paper at Mexico City meeting, August 1966.

PUBLICATIONS

A. M. Bernstein and E. P. Lippincott, "Systematics of 3^- and 5^- States in $\text{Ca}^{40,42,44,48}$ and Ti^{50} from Inelastic Alpha Scattering", Phys. Rev. Letters 17, 321 (1966).

W. J. Kossler and K. Nagatani, " $\text{Ca}^{40}(\alpha, \alpha' \gamma)$ Angular Correlations for a State at 6.94 MeV", Bull. Am. Phys. Soc. 11, 81 (1966).

THESES

R. O. Ginaven, "The (α, P) Reaction on Nuclei in the $f_{7/2}$ Shell", Ph.D., May 1966.

E. P. Lippincott, Jr., "An Investigation of Nuclear Structure in the $f_{7/2}$ Shell by Inelastic Alpha Scattering," Ph.D., June 1966.

M. B. Shork, "Alpha Particle Scattering by Ti^{50} ", B.S., May 1966.

J. A. Siegel, "Alpha Scattering by Ni^{64} ", B.S., August 1966.

THEORETICAL GROUP

Introduction

Particle theory has in the last years been very much concerned with current algebras and with quark models of the elementary particles. From the current algebras sum rules relating experimental quantities and coupling constants may be determined. Quark models provide for example non-obvious relations between meson and hadron behavior. This is illustrated in the first abstract in which the decays of these particles resulting from a mechanical or isotopic spin flip is calculated. In addition, quark models may be used to test the assumptions of current algebra. As is outlined in the third abstract matrix elements of various commutators of quark currents can be evaluated in perturbation theory. One can ask under what circumstances will the results be those "naively" expected, i.e., follow just from the free field commutator rules and when will there be extra terms which are model dependent?

It has become increasingly apparent that before much more progress on the dynamics of strongly interacting particles can be achieved, a more complete way of taking multi-particle intermediate and final states into account is essential. An important beginning has been made in the discovery of exact solutions (see abstracts 5 and 6) to models which, although they do not conform precisely to the physical world, are rich enough so that their behavior is qualitatively suggestive of the behavior of more realistic systems.

The most thoroughly explored field theory, that of quantum electrodynamics, has been attacked by non-perturbative methods (see abstracts 15-17; 25). This procedure is of interest not only because of the possibility that it may provide the logical completion of quantum electrodynamics, but also because it may provide a clue for the treatment of strongly interacting systems for which perturbation techniques are not satisfactory. Other field theory abstracts include the development of methods for the proof of the Regge hypothesis for field theories (abstracts 23, 24). A book on the important topic of the analyticity of Feynman and unitary integrals has been published (abstract 22; see also abstracts 26, 27).

The Regge hypothesis is used for phenomenological analysis (abstract 12). Other phenomenological analyses include abstract 29 in which the effect of final state interactions on a production amplitude is considered. In particular, the appearance of spurious resonances is predicted. Studies were made of the pion-nucleon interaction, the kaon-nucleon (abstracts 30, 31) the one-pion exchange model for inelastic processes (abstracts 32, 33), as well as the nucleon-nucleon interaction (abstracts 44, 45). With regard to the latter an interaction employing the boson-exchange theory of nuclear forces using experimental masses and coupling constants is found to give as good an agreement with the experimental data (nucleon-nucleon scattering from 0 to 350 MeV lab, deuteron photoeffect, electron-deuteron interaction) as the best phenomenological potential.

Considerable study has gone into the possibility of modifying the nucleon-nucleon potential so that it can be used for Hartree-Fock calculations in nuclei -- in particular it is hoped that suitable separable potentials can be found to represent the core (see abstracts 46, 47).

Developments in the theory of nuclear reaction have included attacks on fundamental problems, the description of a new phenomenon and various applications. At the fundamental level one might mention the discussion of deuteron scattering (abstract 48) which builds the amplitude for this process up from the individual neutron and proton scattering from the target nucleus. A second study is that of the effect of exchange and the Pauli principle on nucleon-nucleus scattering (abstract 50).

The description of intermediate structure, its inclusion in reaction theory and its explanation in terms of doorway states is the subject of the study in abstracts 54, 56. Abstracts 52 and 53 involve applications. The most thoroughgoing discussion of this new phenomenon has been made for the case of the isobar-analogue resonance. A reaction theory has been developed (abstract 57), the width of these resonances has been estimated (abstract 58), and an optical model involving coupled equations (abstract 59) has been used with great effectiveness.

Another large group of studies has been connected with the direct calculation of the ground and excited states of $4n$ nuclei from potentials which fit the nucleon-nucleon scattering. The Hartree-Fock method has been applied using the separable potential of Tabakin (abstracts 64-67). The question of whether or not mixed parity orbitals should be used in the Hartree-Fock method was the subject of much study. It was concluded that with the present strength of the tensor force, no such parity mixing is to be expected (abstracts 67, 69).

Generalizations of the Hartree-Fock for the case of singular potentials have been applied to the calculation of the properties of He^4 , O^{16} , Ca^{40} , Zr^{90} , Ti^{50} with considerable success (abstracts 71, 72, 73, 74). Another method based on the Eden-Emery version of the Brueckner method has also been applied (abstracts 77, 78) with comparable results. As a final example, the rigorous development of a theory of the rotational motion of nuclei (abstract 81) is in progress.

For the period of this report, Professors Huang and Lomon were on leave. It is a pleasure to record that Prof. Weisskopf returned to the fold. Visiting professors included M. Ross from the University of Michigan and C. Zemach from the University of California. (H. Feshbach)

I. Hadron Decay Processes and Quark Model

The quark model is used for the calculation of the decay rates of baryons and mesons. According to this model the 56 states of baryons contained in the fundamental octet and decuplet are S-states of a three-quark system and the 36 states of mesons in the scalar and vector octets are S-states of a quark-antiquark system. The states differ from each other in the relative orientation of spin and unitary spin of the quarks and not much in the spatial wave functions.

The rates are calculated for transitions between these states which are: (A) by weak interaction-emission of lepton pairs, (B) by electromagnetic interaction-emission of γ -rays or electron pairs, and (C) by strong interaction-emission of pions.

These rates are calculated with the same method for all transitions. In all cases the interaction is transmitted by a spin flip only (mechanical and/or isotopic).

In addition, the same methods lend themselves for a calculation of the annihilation of the quark and the antiquark in mesons, accompanied by either a lepton pair emission (weak or electromagnetic interaction) or a pair of γ -rays.

These methods allow the calculation of the rates of the processes in group I without any assumptions regarding the quark interactions. All that enters are the known weak, electro-magnetic, and strong coupling constants.

These methods allow the calculations of the rates of all decay processes where the number of hadrons remain unchanged, without any assumptions regarding the quark interactions. All that enters are the known weak, electromagnetic, and strong coupling constants and the proton magnetic moment.

The processes where a meson disappears depend also upon the value $|\psi(0)|^2$, which is the square of the wave function of the quark-antiquark system at zero distance. From comparison with the observed rates that magnitude turns out to be of the order (Fermi) $^{-3}$ and proportional to the meson mass.

The following predictions can be made on the basis of our model for the partial width of decays not yet measured:

$\Sigma_0 \rightarrow \Lambda + \gamma$	8.3 keV	$\omega \rightarrow e^+ e^-$	0.63 keV
$\rho \rightarrow \eta + \gamma$	.50 keV	$\phi \rightarrow e^+ e^-$	1.0 keV
$\omega \rightarrow \eta + \gamma$	.6.3 keV	$\eta \rightarrow 2\gamma$	1.3 keV
$\phi \rightarrow \eta + \gamma$	0.34 MeV	$\eta \rightarrow \pi^0 2\gamma$	0.53 keV
		$\eta \rightarrow 2\pi\gamma$	.0.16 keV

(V. F. Weisskopf) (The work on these problems was performed by B. T. Feld, A. Dar, and R. Van Royen (CERN).)

II. Adler-Weissberger Relation

A simple derivation of the Adler-Weissberger expression for the axial-vector-coupling constant is given on the basis of a non-relativistic quark model. This derivation is, of course, not as general as the ordinary one, but it illuminates the essential assumptions and connections, because of its simplicity. (A. Dar and V. F. Weisskopf)

III. Current Algebras in a Simple Model

We use third order Feynman diagrams in an interacting quark model to compare local equal-time commutators of quark currents with their conventionally expected values. We find no extra terms for the $(V_0 A_0)$ algebra, nor the (SP) algebra, nor for the commutator $[V_j, A_k]$. All other commutators have model dependent extra terms which we discuss. The behavior of these algebras at $p_z = \infty$ can also be studied in the same model. We find again that the (V_0, A_0) algebra is model independent. (K. Johnson and F. E. Low)

IV. Current Algebra and Non-Regge Behavior of Weak Amplitudes

Certain weak amplitudes exhibit non-Reggeistic behavior. These amplitudes have fixed poles in the complex angular momentum plane which have the dual property of (1) allowing a sum rule of the Dashen-Gell-Mann¹, Fubini² type to hold, although one might naively expect a super-convergence relation³ for this amplitude, and (2) insuring that spin one particle poles are reproduced in the left hand side of the sum rule correctly. (J. B. Bronzan, I. S. Gerstein, B. W. Lee, F. E. Low)

V. A Two-Meson Solution of the Charged Scalar Static Model

A solution of the charged scalar static model was constructed in which the scattering amplitude is crossing symmetric and has two- and three-particle intermediate states (two-meson approximation). The production and six-point amplitudes are also obtained and are shown to lead to a two- and three-particle unitary scattering matrix. For strong couplings there are bound states in both the two and three particle channels.⁴

An interesting consequence of this work for particle dynamics is the demonstration that a bound state can occur in a channel due to three-particle effects, even when the Born approximation force is repulsive. This can happen for strong coupling in the π -p channel of the charged scalar model.⁵ (J. B. Bronzan, M. Feinroth)

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1. R. Dashen and M. Gell-Mann, in 1966 Coral Gables Conference on Symmetry Principles at High Energy (Freeman and Son, San Francisco, 1966).
 2. S. Fubini, *Nuovo Cim.* 43, 1 (1966).
 3. V. deAlfaro, S. Fubini, G. Rossetti and G. Furlan, *Phys. Letters* 21, 567 (1966).
 4. J. B. Bronzan, "A Two-Meson Solution of the Charged Scalar Static Model with Bound States", *J. Math. Phys.* (to be published).
 5. J. B. Bronzan, "Example of an 'Inelastic' Bound State", *Phys. Rev.* (to be published).

VI. Crossed Elastic Cut Versus Three Particle Unitary Cut as Determinants of Low Energy Scattering

We examine the relative importance of the crossed elastic cut and the three particle unitarity cut for π^+ -p scattering in the charged scalar static model. This is done by comparing four approximate solutions for the scattering amplitude in which different singularities of the amplitude are retained: (1) The Born pole and the elastic unitarity cut are present. (2) The Born pole, the crossed elastic cut and the elastic unitarity cut are present. (3) The Born pole and both the elastic and three particle unitarity cuts are present. (4) The Born pole, a second pole representing the crossed elastic cut, and both the elastic and three particle unitarity cuts are present. In the channel we study all three dynamical singularities -- Born pole, crossed elastic cut, and three particle unitarity cut -- are attractive at low energy. We find that for strong coupling, and particularly at higher energies, production has a decidedly greater effect on scattering than does crossing. We also find that the coupling strength required to produce π^+ -p bound state at threshold is reduced when either the crossed elastic cut or three particle unitarity cut is present. The reductions effected by the two singularities are comparable, and about twice as much reduction occurs when both singularities are retained. (J. B. Bronzan and R. W. Brown)

VII. Existence of Spurious Solutions to Many-Body Bethe-Salpeter Equations

The many-body equations studied by Weinberg are applied to a particular system of three particles interacting with separable potentials. For certain values of the energy, it is found that the homogeneous equation has extraneous nonzero solutions. (P. G. Federbush)

VIII. Bound on the Coupling Constant from Unitarity and Analyticity

Unitarity of the S matrix is used to bound the sum of the pole term and the left-hand contribution appearing in a dispersion relation for a partial-wave scattering amplitude. An upper bound for the coupling constant is then constructed for the case of an arbitrary distribution of any finite number of sign changes in the left-hand cut discontinuity. (H. D. Dahmen and A. S. Reiner)

IX. Levinson's Theorem in the Lee Model

The spectrum of the S-matrix in the $V-\theta$ sector of the Lee model is analyzed. It consists, at fixed total energy, of a continuous spectrum identical with that of the disconnected S-matrix,

together with a possible discrete spectrum consisting of the roots of a certain transcendental equation. This equation may have zero, one, or two roots, depending on circumstances. If at least one root exists, at all physical energies, the eigenphase shift which joins continuously to the $V-\theta$ elastic scattering phase shift below production threshold satisfies a Levinson theorem. The phase of the determinant of the connected S-matrix, as defined by Wright, is shown to satisfy a Levinson theorem. The situation when no stable V-particle exists is also analyzed. Here the phase of the determinant of the connected S-matrix does not satisfy a Levinson theorem, but a more general result is not obtained. (J. B. Bronzan, M. Cassandro and M. T. Vaughn)

X. Diagonalization of the Lee Model S-Matrix

The scattering matrix of the Lee Model was diagonalized in the second sector where both two and three particle states participate.¹ Both the complete S-matrix and "connected" S-matrix were examined, and discrete eigenphases were found which satisfy Levinson's theorem. (J. B. Bronzon and M. Cassandro)

XI. Regge Trajectories in Unphysical Energy Sheets

It is shown that an essential singularity of the scattering amplitude exists on the second energy sheet reached through the unitarity cut. It has the same location as the nearest left-hand branch point, and it is an accumulation point of poles in all higher, even partial waves. The connection of these poles with bound states and resonances is investigated by following (inverse) Regge trajectories in the energy plane. The determinantal approximation is used and a method is developed, which allows the discussion of trajectories without having their explicit equations. (C. H. Schmid and F. E. Low)

XII. Regge Poles in the Production of Meson and Baryon Resonances

The theory of Regge trajectory exchange is applied to the high energy production of meson and baryon resonances. The helicity representation is used for the production amplitudes. The partial wave summation for the crossed channel reaction is transformed into a contour integral in the complex angular momentum plane using the Sommerfeld-Watson transform. The partial wave amplitudes are continued to complex angular momentum using a single dispersion relation in momentum transfer, and are found to be holomorphic in a region of the complex J plane. Their

1. J. B. Bronzan, M. Cassandro and M. T. Vaughn, "V- θ Sector of the Lee Model II. Eigenphaseshifts and Levinson's Theorem", Nuovo Cimento (to be published).

continuation outside this region is assumed to contain only Regge poles -- simple poles which move with energy. Crossing relations are used to express the high energy differential cross section for resonance production and the spin density matrix elements for resonance decay in terms of the crossed channel helicity amplitudes. The Regge pole terms dominate the amplitudes for trajectories in the right half J plane, and an extension of this region to the left is made by assuming a symmetry property of the partial wave amplitudes which is true for potential scattering. The predictions are compared with experimental data, on production of the $N^*(1238)$ nucleon resonance by pions and kaons, and also the production of the f^0 and ρ mesons by pions. The energy dependence of the differential cross sections is found to be consistent with the Regge pole exchange model. Values for the ρ , A_2 , and π trajectories are determined. The ρ and A_2 values are in agreement with those determined by analysis of elastic and charge exchange scattering data. The π trajectory values have not been determined in other reactions, but they are consistent with the known general properties of Regge trajectories. The spin density matrix elements are not strongly restricted by the theory, but the predictions that can be made are also consistent with experiment. The extrapolation of the residue functions outside the physical scattering region to compare them with field theoretic expressions is found to be inaccurate due to their rapid variation. (R. L. Thews and K. Huang)

XIII. Reggeization of Elementary Particles in Field Theory

The Mandelstam counting procedure for determining under what circumstances elementary particles in field theory must lie on Regge trajectories was examined. It was found that certain conditions on the scattering amplitude at zero total energy must be included in the counting. The conditions are generalizations to arbitrary spin of conditions found by Goldberger, Grisaru, MacDowell, and Wong in 1960 for nucleon-nucleon scattering. (V. L. Teplitz and E. Abers)

XIV. On the Bethe-Salpeter Equation

The Bethe-Salpeter equation for relativistic two body interactions is analyzed in momentum space. Only spinless particles are considered. Principal attention is paid to the elastic scattering case with the "ladder diagram" approximation. Analyticity properties as a function of the relative energy variable are investigated in detail and an extension of the Wick rotation method to scattering energies is presented. A formulation of scattering amplitudes is given and formal analogies to non-relativistic scattering theory are discussed. A method for obtaining approximate solutions to the Bethe-Salpeter equation, using a cut-off and a superposition of separable potentials is proposed and worked out in detail. Computed results are presented. These results and methods are compared with those given by other authors. (R. M. Saenger and H. Feshbach)

XV. Quantum Electrodynamics - Vacuum Polarization

We have studied the vacuum polarization function $\pi_{\mu\nu}$ expressed as a functional power series in the exact photon propagator $D_{\mu\nu}$ where $1/D_{\mu\nu} = (g_{\mu\nu}q^2 + \pi_{\mu\nu})$. We find that $q^2 \rightarrow \infty$, $D_{\mu\nu} \rightarrow g_{\mu\nu}/q^2$ (i.e., $\pi/q^2 \rightarrow 0$) then the series for $\pi_{\mu\nu}$ diverges with the same power of $\log(\Lambda^2)$ in each order where Λ^2 is cut off. Consequently, the assumption that $\pi/q^2 \rightarrow 0$ is consistent only if the coefficients of $\log(\Lambda^2)$ add up to zero. The coefficient of $\log \Lambda^2$ is equal to $f(\alpha_0)$ where $f(\alpha_0)$ is defined as a power series in the true bare structure constant α_0 . The finiteness of the theory then requires that $f(\alpha_0) = 0$, that is, α_0 obeys an eigenvalue equation. We have then shown that the physical fine structure constant α is still a free parameter, and that the equation $\alpha_0 = \alpha/Z_3(\alpha)$ holds as an identity in α for $0 < \alpha < \alpha_0$. Methods for calculating $f(\alpha_0)$ have been established. A paper is in preparation. (K. Johnson and M. Baker)

XVI. Quantum Electrodynamics - Renormalization in Quantum Electrodynamics

By using the scale invariance of the theory (the fact that e^2 is dimensionless), we have obtained equations for the Greens function for both electron and photon. These equations can be used to a) generate renormalized perturbation theory or b) investigate the unrenormalized theory. We have shown with this approach that it is possible to use the renormalized theory with finite physical mass m for the particle to calculate the bare mass, m_0 . The result is $m_0 = 0$ in agreement with a previous analysis of the self-consistency of the unrenormalized theory which forced us to take $m_0 = 0$. We have also used this approach to investigate the photon propagator and reproduce the results. Finally, we have found it possible to prove the assumptions about perturbation theory made by Gell-Mann and Low in Phys. Rev. 95, 1300 (1954). (K. Johnson and M. Baker)

XVII. Quantum Electrodynamics - Sum Rule in Quantum Electrodynamics

The sum rule of Kallen which relates the renormalized vertex function $\Gamma_\mu(p+q, p)$ to Z_2 , the wave function renormalization constant is being studied. (K. Johnson)

XVIII. Strong Coupling Vector Theory

The idea that for sufficiently strong coupling, a vector field coupled to a conserved current in a manner precisely analogous to electrodynamics will yield a vector particle with finite physical mass starting from zero mass, is being investigated. (See previous reports.) A calculation of this sort in a model is being made. (K. Johnson and M. Fry)

XIX. Quantum Field Theory - Canonical Commutators

The fact that in unrenormalizable field theories, the equal time commutators of the fields, $\{\psi, \psi^*\}$, become operators is being investigated. (K. Johnson and E. Poggio)

XX. Ratio of e^-p and e^+p Scattering Cross Sections

We are investigating the influence of virtual nucleon polarization on the ratio of e^-p to e^+p scattering at low momentum transfer. Our aim is to obtain the ratio in terms of known external radiative corrections plus terms coming from virtual Compton scattering contributions to the second Born approximation. We will then use models of the off-mass-shell forward Compton amplitude to estimate the virtual polarization terms. (J. B. Bronzan, R. W. Brown)

XXI. C Violating Electromagnetic Currents

The process $\gamma + p \rightarrow \left| \begin{smallmatrix} \eta \\ \pi_0 \end{smallmatrix} \right|_{2\pi_0} + p$ via a vacuum exchange at high energy would show the existence of C violating electromagnetic currents with $|\Delta I| = 0, 1, 2, \dots$ etc., and furthermore, would dominate at high enough energy. (F. E. Low, C. Froyland)

XXII. Homology and Feynman Integrals

A book has been written in association with R. Hwa. It is concerned with the application of homology theory to the analytical structures of Feynman and unitarity integrals. The principal achievements of the study of the analyticity of Feynman integrals by classical methods are summarized. A chapter describing homology theory is self-contained and easy to follow. By using the homological approach, the geometric problem of determining the structure of the Riemann surface associated with a Feynman integral is converted into an algebraic problem. This new approach (due to Fotiadi, Froissart, Lascoux and Pham) provides a systematic language for understanding the analytic properties of the general scattering amplitude. The text also contains a brief survey of some modern mathematical techniques which by itself may be of use to the theoretical physicist. (V. L. Teplitz, R. C. Hwa)

XXIII. High Energy Behavior of Feynman Integrals with Spin I

We outline a method of determining the leading behavior of planar graphs for two body processes in a spin 1/2-spin 1 conserved vector theory. The leading behavior can be found by inspection. Coefficients of lower order terms can be found explicitly. In a later paper, we hope to use our methods together with analysis of non-planar graphs to justify the Reggeisation hypothesis to nth order. (J. V. Greenman)

XXIV. High Energy Behavior of Feynman Integrals with Spin II

We apply the analysis of a previous paper to determine the leading behavior and coefficients of specific lower order terms of planar graphs in the nucleon-meson scattering process. We essentially rederive the results of Cheng and Wu in verifying the Reggeisation hypothesis in sixth order and indicate how the analysis can be extended to nth order. (J. V. Greenman)

XXV. A Derivation of K. Wilson's Equations and Applications to Current Operators in Relativistic Quantum Field Theory

It is shown that, in any renormalizable quantized field theory, the renormalized field operators satisfy local partial differential field equations. The proof is based on rigorously proved properties of renormalized perturbation theory and is valid to all orders. The field equations have their usual form except that products of field operators at the same space-time point are replaced by current operators proposed by K. Wilson. In neutral pseudoscalar meson theory, Wilson's proposal implies that the current operator $h(x)$ associated with the product $\psi\phi$ is given by the limit

$$\lim_{\xi \rightarrow 0} h(\xi, x) = \lim_{\xi \rightarrow 0} \frac{1}{E_3(\xi)} [\psi(x+\xi)\phi(x) - E_1(\xi)\psi(x) - E_2\mu(\xi)\partial^\mu\psi(x)]$$

for suitable functions $E_i(\xi)$ with singularities at $\xi=0$. It is shown that E_i exist such that, in each order of perturbation theory, for any product χ of field operators, $\langle 0 | Th(\xi, x)\chi | 0 \rangle$ converges to $\langle 0 | Th(x)\chi | 0 \rangle$ in the Schwartz topology on distributions on the space $\mathcal{D}$ of C^∞ functions of fast decrease, and that different such E_i correspond to finite renormalizations of the relevant parameters. These results are applied to present a finite formulation of quantum electrodynamics. The gauge invariance of this theory is established and is shown to be equivalent to the gauge invariance of the field equations. (R. A. Brandt, P. G. Federbush)

XXVI. The Non-Landau Singularities of Feynman Graphs

The Feynman integral is studied as an integral over a compact manifold. The denominator surfaces are "prepared" by a process of stratification wherein singular parts are removed to become "strata" of lower dimension. These strata are shown to obey regularity properties which allows the application of a theorem of Rene Thom. This theorem gives necessary criteria for the Feynman integral to experience a singularity.

This work is concerned with a subset of the singularities the integral may possess -- the so-called "non-Landau" singularities. These are shown to be due to behavior of the integral at the point at infinity in each integration variable. Two examples, the sixth-order scattering graph, and the tetrahedral graph, are worked out. (P. B. Ulrich and P. G. Federbush)

XXVII. Triangle Singularities

It is shown that triangle singularities and the generalized Peierls mechanism cannot produce peaks in the total transition rate nor in any two-body spectrum of the final state, although the singularities considered can be on the physical boundary. The reason is a cancellation of the peak, which occurs when the diagram without rescattering is added coherently to the triangle diagram. The triangle amplitude is integrated explicitly apart from a smooth and monotonic background.

It is also shown that interference effect never produce peaks in the total transition rate nor in any two-body spectrum of the final state. (C. H. Schmid and F. E. Low)

XXVIII. Strange Particles and Parastatistics

A field theory of paraparticles interacting with ordinary particles can be established. As an example, we show that, by treating strange particles as paraparticles and attributing their strangeness to their being paraparticles, a parafield theory of strange particles can be formulated; the consequences of such theory are investigated. The Greenberg-Messiah selection rules are shown not to be generally valid but depend upon their assumptions as to the commutation rules among the interacting fields. (N. Tomljanovich)

XXIX. Caldwell-Weinstein Effect

The aim of this paper is to compare the predictions of a model with the recent conjecture of Caldwell and Weinstein stating that in particular circumstances the mass and the width of a resonance could be altered by the final state interactions following the production process. This

effect, which they call pre-decay resonance mixing, should be observed in a reaction in which there is the possibility of producing either one of two resonances of comparable mass as, for example, ρ and ω . Our model refers explicitly to the ρ ; ω case but the conclusions we draw are entirely general and can be applied to any other similar case. Our results can be formulated as follows. No finite range final state interaction can displace a resonance or change its width. However, the production amplitude acquires a modulating factor which can in principle modify considerably the production cross-section. Additional peaks may appear simulating spurious resonances. These could be discriminated from true resonances by studying their energy dependence. (G. Jona-Lasinio and F. E. Low)

XXX. The (3/2, 3/2) Resonance

The $T=3/2$, $P=3/2$ pion nucleon interaction was approximated by a Yukawa potential outside a boundary condition with a pole in energy.¹ (E. L. Lomon) (This work was completed while on leave at CERN, Geneva)

XXXI. Kaon-Nucleon Scattering and Threshold K^* Production

Using the boundary-condition model, it is shown that the rise of the $I=0$ S-state $K\bar{N}$ phase shift near P_L (kaon laboratory momentum) = 800 MeV/c can be attributed to the effect of the $K^*\bar{N}$ threshold. Approximately 2.8 mb of K^* production at 1140 MeV/c is predicted for that channel. If the interchannel coupling is reduced for the $I=1$ channel in the ratio given by isovector exchange, the experimental production cross section is obtained and the earlier fit to the $I=1$ S-state phase shift altered negligibly. Elastic-boundary-condition fits are given for the P and D waves. The boundary radius, consistent with theory, is $0.45 \mu^{-1}$ except for one D-state. The $0.7 \mu^{-1}$ radius required in the latter case indicates a significant repulsive potential tail. (W. J. De Bonte and E. L. Lomon)

XXXII. Distorted-Wave One-Pion-Exchange Model for Inelastic Proton-Proton Scattering

The one-pion-exchange model, modified to allow for initial- and final-state interactions, is applied to those inelastic two-body proton-proton scattering processes involving the excitation of the two lightest nucleon isobars. The model apparently overestimates the $N^{*+}(1238)$

1. A. H. Huffman and E. L. Lomon, Nuovo Cim. 43, 817 (1966).

production cross section, but gives a satisfactory account of $N^{*+}(1430)$ production.
(P. C. M. Yock)

XXXIII. Form Factors and the Absorptive One Pion Exchange Model

The one pion exchange model, corrected for absorption in the initial and final states, is examined for those two body reactions involving the production of high spin particles. It is found that the inclusion of vertex functions brings the theory into agreement with experiment. By consideration of a number of reactions explicit forms for the $N\pi N^*(1238)$ and $\pi\pi f$ vertex functions are obtained. It is shown that these vertex functions do not require the existence of any as yet undiscovered mesons. Implications of these vertex functions in two pion exchange calculations are also discussed. (P. C. M. Yock and D. Gordon)

XXXIV. Analysis of Photoproduction of Vector Mesons

The photoproduction of neutral vector mesons, in the reactions $\gamma + p \rightarrow V + p$ and $\gamma + p \rightarrow V + N^{*+}(1238)$ at photon momenta of a few BeV/c, is discussed in terms of the one-particle-exchange and absorption models. Initial- and final-state interaction effects are included. The absorptive amplitudes are calculated by recourse to the unitarity equation. Difficulties arising in this calculation associated with Born amplitudes involving particles of high spin are discussed in detail. The analysis indicates that both the one-particle-exchange and absorptive mechanisms fail to account for the observed ρ photoproduction data. On the other hand, the presently available ω photoproduction data are found to be consistent with the one-pion-exchange model, corrected for absorption in the final state. (P. C. M. Yock, with U. Maor - Harvard)

XXXV. A Theoretical Investigation of the Production of Weakly Interacting Intermediate Vector Bosons

The production of intermediate vector bosons is considered in two reactions: (1) $\pi + p \rightarrow w + p$ and (2) $\gamma + p \rightarrow w + n$. Reaction (1) is computed by single particle exchange with corrections for (1) empirical form factors, (2) absorption in the initial state, and (3) Regge pole exchange. Omega meson exchange is found to dominate and to give a cross section of about 10^{-33} cm^2 .

Reaction (2) is considered by W exchange, Compton Graphs, and pion exchange. W exchange is found to dominate and, when corrections for CVC and PCAC form factors are taken into account, to give a cross section of $5 \times 10^{-36} \text{ cm}^2$. An anomalous magnetic moment for the W of 1 boson magneton multiplies this result by 3. (J. D. Cornwell, III, and K. Huang)

XXXVI. Unconventional $U(3) \times U(3)$ Assignment

An (8, 8) and (6, 3) assignment for the $J \leq 3/2$ baryons is being worked out. However, breaking is compulsory in this model, and leaves considerable ambiguity. (F. E. Low, T. Yao)

XXXVII. Shadow Effect in High-Energy Scattering from Deuterons

The extraction of neutron cross sections from deuteron data is nontrivial; the most widely used model is the semi-classical ray formula of Glauber, which gives, in addition to the impulse approximation terms, a shadow correction due to the mutual eclipsing of the nucleons in the deuteron. In this work we showed that, if the nucleon-nucleon scattering amplitudes near the forward direction can be represented as a sum of Regge poles, the shadow term that Glauber includes vanishes rapidly at high energies but that other terms remain which provide a somewhat smaller shadow effect. We gave a diagrammatic derivation of the Glauber formula and showed that his shadow term, which comes from the diagram where both nucleons interact with the incident fast particle, does not in fact have the Regge cut necessary for its persistence at high energies. We then showed that certain diagrams with inelastic virtual states between the two interactions do have such cuts and we expressed their contribution in terms of a partial inelastic cross section and a statistical factor. An experimental clarification can only be achieved by accurate experiments with high-energy neutron beams. (V. L. Teplitz)

XXXVIII. Pion Production from Nuclei

Estimations of various photo and electro pion production processes are being made. In particular, the coherent charged pion production to isobaric analog states is being studied. (A. K. Kerman and L. Saunders)

XXXIX. Nuclear Correlations from Deuteron-Nucleus Scattering

To describe deuteron nucleus scattering accurately at high energies one has to correct the approximation that the potential which acts on the deuteron is the sum of the neutron and proton optical potentials. This correction is largely due to nuclear correlations and presents a method of determining the correction to the nucleon optical potential due to correlations.

The method is applied to 650 MeV deuteron-carbon scattering. Good agreement is found between theory and experiment. (J. F. Reading)

XL. The High Energy Approximation and Slightly Non-Local Potentials

The high energy approximation is extended to non-local potentials. Applied to the high energy optical potential a rough estimate indicates the removal of a large discrepancy between theory and experiment in the imaginary part of the potential. (J. F. Reading)

XLI. High Energy Approximation

The semi-classical high energy approximation is examined and generalized to apply to coupled channels and vibrating nuclei. (W. Bassichis, H. Feshbach, J. F. Reading)

XLII. High Energy Deuteron Cross Sections

A theoretical analysis of the collisions of particles with deuterons is carried out in the high-energy approximation. This approximation, which corresponds to a generalized form of diffraction theory, takes explicit account of double collision processes as well as single ones. It is used to express the amplitudes for elastic and inelastic scattering by deuterons in terms of the elastic scattering amplitudes of the neutron and proton and the deuteron wave functions. The resulting expressions are used to evaluate the differential cross section for elastic scattering, and the angular distribution of inelastic scattering (i.e., the differential cross section for deuteron breakup integrated over final energies of the incident particle). The contributions to these cross sections of the various single and double scattering processes and the terms which represent their interference are exhibited individually. Expressions are derived for the total cross section of the deuteron and for its elastic and inelastic total scattering and absorption cross sections. The difference between the various types of deuteron cross sections and the sum of the corresponding cross sections for the free neutron and proton is explained in some detail. Spin-dependent interactions are treated, and for incident particles of spin $\frac{1}{2}$ an expression is given for the deuteron total cross section in terms of the general spin-dependent scattering amplitudes of the neutron and proton. The theory is applied to antiproton-deuteron collisions in the energy range from 0.13 to 17.1 BeV. The results for the total and absorption cross sections which are calculated for a variety of models of the deuteron wave function are found to be in good agreement with the measurements. The magnitudes of such effects as double scattering and the interference of single and double scattering amplitudes are seen to be appreciable. (V. Franco, with R. J. Glauber, Harvard)

XLIII. The Mandelstam Representation for the Boundary Condition Model of Strong Interactions

Double dispersion relations are derived for two cases: The first is scattering by an energy dependent boundary condition on the wave function at a fixed boundary radius, without an external potential; the second is that of scattering by an energy dependent boundary condition with a superposition of Yukawa potentials outside of the boundary.

In the former case, sufficient conditions for the uniform convergence of the partial wave sum, analytically continued to complex values of energy and momentum transfer have been derived and verified for the model. The behavior of the total scattering amplitude, for complex values of energy and momentum transfer approaching infinity, has been investigated by use of saddle point techniques, with the result that the amplitude has an energy dependent essential singularity at infinity in momentum transfer. The behavior in the energy plane gives rise to one subtraction in the corresponding dispersion relation.

The latter case of a superposition of Yukawa potentials outside of the boundary cannot be treated by the same methods since the uniform convergence of the partial wave sum is restricted to the small Lehmann ellipse. The Regge techniques of employing the Watson transform on the total scattering amplitude in order to analytically continue to complex energy and momentum transfer have been employed, with the result that the analytic properties of the model have been obtained in the finite complex energy and momentum transfer planes. Our inability to complete the Watson transform parallel to the imaginary ℓ axis results in our inability to extract the standard Regge behavior in momentum transfer. Instead, an essential singularity again results at infinity. The double dispersion relation is similar to that of the pure BCM case, except for an additional branch cut in the momentum transfer variable. (F. Newman and H. Feshbach)

XLIV. A Nucleon-Nucleon Interaction Consistent with Experiment and the Boson Exchange Theory of Nuclear Forces

The nucleon-nucleon data are fitted by a boundary condition model interaction determined largely by field theoretic forms. One and two pions, ρ , ω , and η meson exchange adiabatic local potentials determine the interaction for $r \geq \frac{1}{2\mu}$ where $(1/\mu)$ is the pion Compton wavelength. The two pion exchange contribution contains a degree of ambiguity measured by the parameters ξ and λ for the pion ladder and nucleon pair diagrams respectively. The interaction at r_0 ($\equiv 1/2\mu$) is given by an energy independent boundary condition for each partial wave sensitive to the short range interaction. A very good fit to the pp data and a good fit to the np data below 350 MeV nucleon laboratory energy comparable to the better phenomenological are obtained. The optimum or fixed values of exchange particle mesons and coupling constants correspond to their known measured values, and the λ and ξ parameters optimize in their theoretical range. The value

obtained for r_0 corresponds to that predicted by the theory of the boundary condition model. There remain 19 boundary condition parameters freely fitted to which the data is sensitive. Rescattering and ϕ meson exchange contributions remain to be investigated as does the effect of coupling to inelastic channels. (E. Lomon and H. Feshbach)

XLV. Two Body Force - Finite Soft Cores

A paper is in preparation on the subject of soft cores in the nucleon-nucleon potential. We find that the Hamada Johnston potential can actually be improved by using "soft" cores (height 656 MeV) of larger radius (0.67 F). (A. K. Kerman and C. Bressel)

XLVI. Nucleon-Nucleon Cores

Work is under way to determine whether the potential cores of nucleon-nucleon forces can be replaced by non-local "smooth" cores such that the nuclear problem can be attacked with ordinary perturbation theory. We are using a local potential outside of the core radius and a separable non-local potential inside the core radius. (B. Levy, A. K. Kerman, and B. Rouben)

XLVII. Two-Body Forces

An attempt is made to construct explicitly the unitary transformation connecting the Hamiltonians $H_1 = p^2/2m + V_1$ and $H_2 = p^2/2m + V_2$ in cases where V_1 and V_2 have the same Jost function and hence the same S-matrix. We are particularly interested in the case where V_1 is local and static and V_2 is a separable (that is, velocity dependent) potential. It is hoped that this way we may be able to construct families of phase-equivalent potentials and, subsequently, compare their effects in many-body situations. (F. Villars and M. Rinehart)

XLVIII. Deuteron Scattering

This work was undertaken in order to find out to what extent diagram analysis could be used in describing collisions with complex projectiles and rearrangement collisions. In this study, the no recoil approximation is used throughout. Deuteron elastic scattering is the simplest case. Its T-matrix can be obtained from a Greens-function (no recoil!)

$$(k' | g(\omega) | k) = \langle \psi_0 | D_{k'}(-) \frac{1}{\omega - H + i\eta} D_k^+ (+) | \psi_0 \rangle$$

D_k^+ and D_k^- being certain deuteron creation and annihilation operators defined in terms of Hartree-Fock continuum states. One has then:

$$(k' | T | k) = (k' | T_{HF} | k) + \lim_{\omega \rightarrow E_{k'} = E_k} (\omega - E_{k'}) (\omega - E_k) (k' | g(\omega) | k).$$

A linked diagram perturbation series expansion for g gives the "compound" elastic scattering matrix T_N due to g . T_N is given by the series:

$$(k' | T_N | k) = \langle \phi_{HF} | D_{k'}^- V_N D_{k'}^+ | \phi_{HF} \rangle_{\text{Linked}} + \sum_{n=0}^{\infty} \langle \phi_{HF} | D_{k'}^- V_N \frac{1}{E_0 + E_k - H_0 + i\eta} (V \frac{1}{E_0 + E_k - H_0 + i\eta})^n V_N D_{k'}^+ | \phi_{HF} \rangle_{\text{Linked}}$$

and V_N is a submatrix of V , excluding transitions from continuum to continuum states. The term T_{HF} is a kind of "shape-elastic" scattering amplitude.

Formulae for stripping, inelastic scattering and deuteron break-up have also been derived. This work is essentially terminated and will be presented in the near future as a technical report. (W. Junkin and F. Villars)

XLIX. The Problem of Target Recoil

In a Hartree-Fock theory of reactions, a no-recoil approximation is always used. If this is tolerated, then Feshbach's "generalized optical potential" $u(\omega)$, describing ground state elastic nucleon scattering, can be derived by many-body perturbation theory from the approximate (no recoil) one particle Greens-function. A comparison of the matrix-elements of $u(\omega)$ between Hartree-Fock states, $|\phi_{HF}\rangle$, and momentum projected Hartree-Fock states $e^{iK \cdot \mathbf{X}_{op}} \delta(\mathbf{P}_{op}) |\phi_{HF}\rangle$ shows a correction factor due to recoil of the type $\exp[-\frac{1}{2}(k_f - k_i)^2 \langle \mathbf{X}^2 \rangle]$. In order to find a more systematic approach to this question, we use the fact that the T-matrix for elastic scattering may be written as $(K' k' | T | K k) = T_{fi} \delta(K' + k' - k - K) = \langle \psi_{K'} | 0 | \psi_K \rangle$, ψ_K and $\psi_{K'}$ being the target ground state. One now has the identity

$$T_{fi} = \lim_{\beta \rightarrow \infty} \langle \phi_{HF} | e^{-\beta H} e^{-iK_f \cdot \mathbf{X}_{op}} \delta(k_f, k_i) e^{iK_i \cdot \mathbf{X}_{op}} e^{-\beta H} | \phi_{HF} \rangle \langle \phi_{HF} | e^{-2\beta H} | \phi_{HF} \rangle \quad (2)$$

which we use as a basis for expressing T_{fi} in terms of a perturbation series of linked diagrams. The previously mentioned correction factor can be recovered from (2); the elaboration of further details is in progress. (F. Villars and E. Redish)

L. The Effect of Exchange and the Pauli Principle on Nucleon-Nucleus Scattering

The Pauli principle and exchange effects in nucleon-nucleus scattering are treated by introducing "exchange operators" into the coupled-channel formalism of the Unified Theory of Nuclear Reactions. The influence of the Pauli, and exchange, features on the choice of a convenient representation for the total wave function is discussed in wave mechanic and field theoretic notations. Also discussed is the truncation of the wave function and the coupled equations to include only the channels of interest, while properly handling the exchange problem. It is in connection with this truncation that the exchange operators are introduced. The construction of these operators is discussed. This discussion involves an analysis of the K-matrix (generalized density matrix) eigen-problem. The role of the exchange operator is interpreted, and some specific examples for shell model target states are exhibited. For reference, a general discussion of dependent bases is included, with special emphasis on the related ambiguities and spurious effects. An effective Hamiltonian for the open-channel amplitudes is constructed along the lines of the Unified Theory, modified by the inclusion of exchange operators. For this purpose, there is a discussion of projection operators which separate the open channels from the other channels which are retained after the initial truncation; the operator Q_{0I} , which projects on to the closed channels of interest, is introduced. The components of the effective Hamiltonian are discussed, and sample forms are given for the case of particle-hole excited target states.

A model calculation has been carried out to demonstrate the use of the formalism, and to illustrate the importance of correctly treating the Pauli principle and exchange effects. A "control" calculation has also been done in which the exchange operators are omitted. The location and widths of the predicted scattering resonances are compared, and a great variation between the calculations is noted. It is found that, for the sample problem, the major differences are contained in the lower energy region. Tests are discussed for locating the resonances which are spurious because of the Pauli principle. It was learned, from the application of these tests, that, when the exchange was correctly treated, spurious resonances could be found and eliminated. This was not the case for the control calculation. (W. A. Friedman and H. Feshbach)

LI. A Study of the Many-Channel Scattering Matrix in the Intermediate Energy Region

The scattering matrix for a nuclear interaction with many closely-coupling channels is considered in a model which replaces all contributions due to closed channels by a complex potential. Some of the analytical properties of the scattering matrix are studied, the relation between the magnitude of the absorption potential and the magnitude of the violation of unitarity is

derived. The resonance behavior of the scattering matrix is studied, and it is shown that the scattering matrix can readily be written in a multiple-interaction expansion, and that a Breit-Wigner form appears for the highly fluctuating part which predicts poles approximately at the zeros of the intermediate state wave functions (in contrast to the predictions of the R-matrix expansion with a zero value of the typical R-matrix boundary parameter.)

The statistical model of nuclear structure is studied, in which the distribution function for the Hamiltonian matrix elements is generated from an ensemble of systems which are consistent with certain invariance properties of the Hamiltonian. It is shown that meaningful correlations can be introduced among the Hamiltonian matrix elements, and the distribution function for the reduced width matrix elements is derived from this ensemble, where it is shown that the reduced width matrix elements have a mean square value inversely proportional to the number of channels open to the interaction, and that the magnitude of the total resonance width is approximately independent of this number.

A computation is made of the widths and the positions of the poles of the exact scattering matrix in the case of the s-wave scattering of a spinless particle from a square-well potential, the matrix elements of the Hamiltonian being generated according to the statistical distribution function, and it is found that the poles are positioned according to the predictions of the resonance formula. The widths are found to be on the order of a few keV at an energy of around 25 MeV, and it is shown that the resulting reduced width matrix elements follow the distribution predicted in the statistical model. The inelastic cross section is computed, and, for zero imaginary potential, is found to be approximately one-half of the experimental value. Considering that a square-well potential is expected to give too small an inelastic cross-section, this agreement shows that a good proportion of the inelastic scattering is due to contributions from the closely-coupled open channels. (V. J. Newton, S.J., and H. Feshbach)

LII. Resonance Scattering of Neutrons in the Extended Shell Model

A systematic study of the role of target vibrational states in the resonance elastic scattering of s-wave neutrons by medium-weight even-even nuclei is presented. The theory of average cross sections of Feshbach, Kerman, and Lemmer is employed in conjunction with a phenomenological model recently used by Lande and Brown. This model describes the low-lying target states as phonon excitations, after Bohr and Mottelson, and treats the residual neutron-nucleus interaction as an operator linear in the phonon creation and annihilation operators. A model closed-channel subspace is constructed by diagonalizing the model Hamiltonian on a basis consisting of as many as three 2+ phonons and one 3- phonon coupled to unoccupied bound single-neutron orbitals. All model parameters are taken from experiment. Escape widths are computed

for model closed-channel states in the compound nuclei Ni^{61} , Ge^{71} , and Se^{77} . It is found that the 3 - vibration is of negligible importance for s-wave neutron scattering by even-even targets in the mass region $A=60$ to $A=80$. A critical discussion of ambiguities in the numerical results is given. Using the calculated escape widths, s-wave neutron strength functions for large averaging intervals (2 MeV) are evaluated. The maximum local deviations from these large-interval values are estimated for the Ge^{70} and Se^{76} targets on the basis of the doorway strength function expression of Feshbach, Kerman, and Lemmer. It appears that the calculated strength functions are in qualitative agreement with experimental values, and it seems likely that the 2+ vibration is important in determining average s-wave neutron cross sections for the targets studies. (H. S. Picker and R. H. Lemmer)

LIII. Shell Model Theory of Nuclear Reactions in Deformed Nuclei

An attempt has been made to explain the intermediate structure resonances observed in neutron scattering on light nuclei in terms of simple excitation of the compound system. Feshbach's theory for nuclear and photonuclear reactions was used to evaluate neutron total cross section on $\text{F}^{19}(\rho, \gamma_0)\text{Ne}^{20}$, $\text{F}^{19}(\rho, \gamma_1)\text{Ne}^{20*}$ differential cross section. The compound system in both reactions was taken as linear combinations of particle-hole states in a deformed scheme. The neutron total cross section was evaluated between 0.5 and 2.5 MeV taking into consideration all possible open channels, and we took s, p, and d partial waves. Similarly in the proton capture cross section most of the open channels were taken into consideration. It is found that the calculated neutron total cross section is in rather good agreement with the experiment especially as far as the width and number of resonances is concerned. A better agreement with the experiment is obtained when the average calculated cross section was compared with the experiment. The agreement between the calculated proton capture cross section and the experiment is not very good. This can be due to the fact that the model does not describe the giant dipole resonance properly. However, the calculated widths for the resonances in proton capture are of the same order of magnitude as the observed widths. (I. R. Afnan and R. H. Lemmer)

LIV. Theory of Nuclear Reactions

An extension of Feshbach's unified reaction theory to the case of deformed nuclei with rotational bands is under investigation. (A. K. Kerman and R. Kujawsky)

LV. Intermediate Structure and Doorway States in Nuclear Reactions

Intermediate structure in the energy dependence of cross sections is interpreted in terms of an intermediate model, which describes the transition amplitude averaged over an energy interval which is much larger than the width and spacing of the compound nuclear levels but which is much smaller than the widths of the structure in the optical model cross sections. The intermediate structure is ascribed to resonances in the intermediate amplitude which in turn are assumed to be the consequence of the existence of doorway states which are described and defined. A formalism is developed which takes the existence of these states explicitly into account. The resultant amplitude is then averaged and the intermediate model obtained. For an isolated doorway state this amplitude can be divided into a slowly varying part and a rapidly varying resonant part. The energy width of the resonant term equals the width of the doorway state which is composed of an escape width into open channels and a decay width into more complex excitations. Strength functions are shown to exhibit intermediate structure. These results are generalized to the case of overlapping doorways. Reactions as well as elastic scattering are discussed. The results are put in a form which permit the analysis of experimental data in terms of intermediate model resonances, and the quantum numbers of the doorway states extracted. Experimental situations which would tend to exhibit intermediate structure, and the identification of such structure as an intermediate model resonance is outlined. Some examples of intermediate structure are discussed. (H. Feshbach, A. K. Kerman, and R. H. Lemmer)

LVI. Intermediate-Structure Strength Function

Measurement of the two-particle one-hole or doorway-state strength function by suitable averaging of (d, p) and (p, p') cross section is proposed. (M. Bolsterli, W. R. Gibbs, A. K. Kerman, and J. E. Young)

LVII. A Reaction Theory for Isobaric Analogue Resonances

The study of isobaric analogue resonances in reactions initiated by low energy protons on nuclei having a neutron excess is approached from the point of view of the unified theory of nuclear reactions: the analogue resonances are described in terms of special states related to the low lying states of the neutron rich isobar by the total charge raising operator. These states are shown to act as doorway states in producing localized anomalies in the cross sections. The properties of these anomalies are examined both from a low-resolution and from a high resolution point of view. The various experimental features found in the analogue state anomalies are then related to the various interference effects which arise between the special analogue state and the other nuclear degrees of freedom. An attempt is made to derive a coupled channel inter-

mediate model from the general formulation, but it is shown that the present approach leads rather more naturally to an intermediate model of a different sort. A simple discussion is also given of the effects to be expected in the inelastic scattering cross sections. Some numerical estimates of both escape and damping widths are given in order to illustrate the orders of magnitude predicted by the formalism. (A. F. R. de Toledo Piza and A. K. Kerman)

LVIII. Damping of Isobaric Analogue States

The spreading width of analogue states due to the Coulomb interactions in a nucleus is calculated. The coupling to single-particle, two-particle-one-hole and three-particle-two-hole configurations is considered. The effect of nuclear interactions is taken into account in the large energy separation between the analogue and the configuration states (symmetry energy displacement) and in the natural distribution of the latter representing their fragmentation. The spreading widths are found to be small, less than 3 keV in ^{89}Y and ^{91}Nb . (A. F. R. de Toledo Piza and A. K. Kerman - MIT; S. Fallieros and R. H. Venter, Bartol Research Foundation)

LIX. Isobaric Analog States - Coupled Equations

A study has been made of the coupled equations proposed by Lane as a means of understanding the "single-particle" analog resonances. It has been found that these resonances can be substantially explained in terms of the coupled equations where the strength of the coupling potential is determined by the splitting between the analog state and the configuration state with isospin one unit less. The parameters used are consistent with normal optical model parameters. The role of the spectroscopic factor is also under investigation. This work has been carried out in collaboration with Ervin Schwarcz of LRL Livermore. (E. Auerbach, C. Dover, A. K. Kerman, and R. H. Lemmer)

LX. Isobaric Analog States - dn and dp Stripping

Recent experiments of Moore have indicated that the coupled equations used in studies of analog resonances may be relevant as a final state interaction in (dp) reactions below the Coulomb barrier and the related (d,n) reaction to isobaric analog final states. We are investigating the possibility of a simple modification in the DWBA stripping theory to take account of this interaction. This work is being carried out in collaboration with Ervin Schwarcz of LRL, Livermore, and William Gibbs of LASL. (A. K. Kerman)

LXI. Investigation of the Effects of a Spin Spin Interaction on
the Elastic Scattering of Neutrons by Nuclei

The effects of an interaction between the spin of the incident neutron and the spin of the target nucleus are considered in the framework of the optical model. It is found that the differential elastic scattering is insensitive to the interaction. However the interaction splits the single particle states and the elastic scattering shows structure as a function of energy when the absorption is small. The spin-spin interaction has negligible effect on the polarization. The rotation parameter, $R(\theta)$ and the asymmetry parameter, $A(\theta)$ are sensitive to the spin-spin interaction for $\theta = 180^\circ$ and 90° respectively. For angles near the minima in the differential elastic scattering the depolarization is approximately zero. (A. P. Stamp)

LXII. Experimental Evidence for a New Theory of (t, p) and (p, t) Reactions

A theory of two-nucleon transfer reactions is constructed in which the proton is scattered from the proton-target interaction as if the other particles were not present. (Y. Waghmare and E. H. Auerbach; C. A. Pearson - Atomic Energy Commission, Lucas Heights, Australia and Neils Bohr Institute, Copenhagen, Denmark)

LXIII. Analytic Structure of the Two- and Four-Point Function in a Soluble Many Fermion Model

The analytic properties in the energy variables of the one- and two-particle propagator are investigated on the basis of an exact solution of an N particle model with a simplified and separable two body potential. (H. D. Dahmen)

LXIV. Nucleon-Nucleon Boundary Condition Methods for Nuclear Matter

It is shown that, as a consequence of the energy independence of the boundary condition f on the radial Schroedinger wave function u at r_0 , $u = 0$ for $r < r_0$, and that the boundary condition is equivalent to replacing Vu , in the equation for u in $r < r_0$, by an expression linear in $u(r_0 + \epsilon)$ and $u'(r_0 + \epsilon)$. The Bethe-Goldstone wave function u^N is determined by the same replacement in its integral equation. But $u^N \neq 0$ in $r < r_0$, so that u^N depends on an extra parameter b , the boundary condition at $r_0 - \epsilon$. Pseudo-potentials at r_0 which give the boundary condition exactly are presented. The self-consistent single particle potential energy in nuclear matter is investigated with a simple S state boundary condition, without a potential tail. The effective mass approximation is found inadequate. For the same interaction, the effect of summing the hole-hole contributions is found to be important for the two-body correlations, and small but significant for the

saturation and binding energy. A calculation is made with a more realistic model with a potential tail. A modified Moszkowski-Scott type expansion, separated at r_0 , is used. Convergence is poor and binding is not obtained. More recent nucleon-nucleon boundary condition models may give convergence and binding. (M. M. Hoenig and E. L. Lomon)

LXV. Hartree-Fock Calculation for Finite Nuclei with a Nonlocal Two-Body Potential

An application of the Hartree-Fock (HF) method to calculation of the structure of finite nuclei is presented. The nonlocal, separable potential of Tabakin is used as the two-body interaction. The calculation is carried out by writing the HF equations in an oscillator basis and applying the Moshinsky transformation to relative coordinates. The closed-shell nuclei O^{16} and Ca^{40} are considered. Under the assumption that they are spherical, their binding energy per particle is found to be -2.41 and -3.74 MeV for O^{16} and Ca^{40} , respectively. Possible reasons for the large discrepancy with the experimental binding are discussed. The single-particle energies show better agreement with data, but have too much spin-orbit splitting, namely, 10.2 MeV for 1p states in O^{16} , and 11.13 and 14.59 MeV, respectively, for the 1p and 1d states in Ca^{40} . The rms radii for O^{16} and Ca^{40} were found to be 2.38 and 2.96 F, compared with experimental values of 2.64 F and 3.52 F, respectively. Corrections for Coulomb force and center-of-mass motion have also been calculated. (A. K. Kerman, J. P. Svenne, and F. M. H. Villars)

LXVI. Hartree-Fock - Second Order

Hartree-Fock calculations have been performed previously on the binding energy of finite nuclei using the separable potential of Tabakin. We report here on an evaluation of the second order correction to the binding energy of O^{16} . Including the second order terms, we obtain a binding of 6.7 MeV per particle. (M. K. Pal, A. K. Kerman and J. P. Svenne)

LXVII. Nuclear Hartree-Fock Calculations

Hartree-Fock calculations have been carried out for the ground state binding energy of the even-even nuclei from $A=4$ to $A=40$. The calculations are unrestricted in the sense that angular as well as radial variations are allowed in the single particle trial wave functions. The Tabakin and Yale-Shakin forces were used. Reasonable agreement with observed binding energies and quadrupole moments was obtained. Parity mixing was also investigated. It was concluded that parity mixing does not occur in Hartree-Fock calculations with realistic forces. (W. Bassichis, A. K. Kerman, and J. P. Svenne)

LXVIII. Isobaric Analog States - Extension of Hartree-Fock Theory

The role of isospin invariance in Hartree-Fock theory is under investigation. The relationship of the random phase approximation to the generalized Hartree-Fock theory in this connection may be of some relevance. (J. Ginnochio, A. K. Kerman and J. Weneser)

LXIX. Nuclear Hartree-Fock Theory - The Problem of Parity-Mixed Orbitals

It has recently been suggested (J. P. Amiet and D. P. Huguenin, Nuclear Phys. 46, 171 (1963)) that the Hartree-Fock variational problem leads to single particle wave functions of mixed parity if the effects of the tensor force are included.

In order to obtain some orientation in this question, an assumed even parity HF solution $\phi_0(1, 2, \dots, A)$ was modified by operating on it with operators of type $e^{i\lambda F}$, where F was chosen to be one of the operators:

$$F = \sum \vec{\sigma}^{(i)} \cdot \vec{r}_i \quad F = \sum \tau_3^{(i)} \vec{\sigma}^{(i)} \cdot \vec{r}_i \quad (1a)$$

$$F = \sum \vec{\sigma}^{(i)} \cdot \vec{r}_i / r_i \quad F = \sum \tau_3^{(i)} \vec{\sigma}^{(i)} \cdot \vec{r}_i / r_i \quad (1b)$$

The HF energy of the system is then:

$$\langle \phi_0 | e^{-i\lambda F} H e^{i\lambda F} | \phi_0 \rangle = E(\lambda)$$

It is found that $E(\lambda)$ can be written, for F of type (1b) as:

$$E(\lambda) = E(0) + A_2 \sin^2 \lambda + A_4 \sin^4 \lambda$$

The coefficients A_2 and A_4 , however, turn out to be very difficult to evaluate exactly. Contributions to them from kinetic energy, central spin-exchange potential energy, spin-orbit potential, and tensor force enter with various signs (depending on exchange mixture of potential), and many near cancellations make their approximate evaluation unreliable.

It is concluded that the question of parity mixing is of potential interest but that the best approach to the question of whether the minimum of the variational problem is obtained for good parity solutions is through extended numerical HF calculations. (F. Villars and G. Cooper)

LXX. Examination of the Hartree-Fock Wave Functions of Ne^{20}

The purpose of this paper is to examine how close the projected Hartree-Fock wave functions of Ne^{20} are in comparison with its actual eigenfunctions. By calculating $\langle H \rangle^2$ and $\langle H^2 \rangle$, it is found that the upper limit of the inaccuracy of the projected wave functions of Ne^{20}

for $J=0, 2, 4, 6$ is 17 percent, while the energies for the same angular momentum states are determined within the accuracy of 4 percent. (S. N. Tewari)

LXXI. Unitary Model Operator Approach to Nuclear Structure Physics

Tables of the matrix elements of an effective interaction derived from the Yale potential have been prepared. This effective interaction has been used in Hartree-Fock calculations of the binding energy of several spherical nuclei and in the calculation of nuclear spectra. A detailed paper describing the numerical methods used and the results obtained will be submitted for publication. Good results are obtained for the properties of O^{16} while for Ca^{40} the effective interaction appears somewhat too strong indicating the need for a more careful treatment of the spectral corrections to the second-order terms in the effective interaction. (C. Shakin, Y. R. Waghmare, M. H. Hull)

LXXII. Generalized Hartree-Fock Calculation with an Effective Interaction for Finite Nuclei

Results are reported for generalized Hartree-Fock calculations on ^{16}O using the Yale potential. Positions of single particle orbits, binding energy and rms radii are given. The results are compared with those of other authors and the experimental data. (C. M. Shakin, J. Svenne, and Y. R. Waghmare)

LXXIII. Realistic Potentials and Shell Model

Using the recent theory developed by Shakin, et al., for nuclear-structure calculations, energy-level calculations are made for realistic potentials such as the Yale potential and the nonlocal Tabakin potential. As examples, Zr^{90} and Ti^{50} are considered. The results for the spectra of these nuclei are compared with those of other authors and the experimental data. The agreement with the Ti^{50} spectrum is good. In the case of Zr^{90} the agreement is improved if we admit a configuration dependence for the effective interaction arising from the possibility of having different size parameters for the $g_{3/2}$ and $p_{1/2}$ orbits. The Yale potential yields better agreement with the experimental data than does the Tabakin potential. It is shown that the matrix elements of the Coulomb force between two protons in these nuclei do not affect the relative splittings of the energy levels by an appreciable amount. These matrix elements have a tendency to vary systematically with the total angular momentum for a given configuration. (C. M. Shakin, J. P. Svenne, and Y. R. Waghmare)

LXXIV. Hartree-Fock Calculations with an Effective Interaction

Calculations of the ground state properties of spherical nuclei are continuing. The nuclei He^4 , O^{16} , and Ca^{40} are being considered. The interaction used is derived from the Yale potential. Various improvements in the construction of the effective interaction will be considered. (M. Tomaselli, C. Shakin)

LXXV. Corrections to RPA Transition Rates

Electromagnetic transition strengths above the giant-dipole region are being calculated. Coupling of high lying two-particle, two-hole states to the dipole state is being taken into account as well as the direct excitation of these states via ground-state correlations. Pauli corrections to the transition rate for the dipole state are also being considered. (C. Shakin, J. daProvidencia)

LXXVI. On the Tensor Correlations in Nuclei

The accuracy of a particular perturbative approach to tensor correlations in nuclei is investigated.

The matrix elements of the effective interaction in the $^3S_1$ state of relative motion are compared to those of MacKellar, who has solved the Bethe-Goldstone equation for finite nuclei in the Eden-Emery approximation.

Reasonable agreement with MacKellar's results for the matrix elements and wave functions is obtained for the larger oscillator size parameters considered. (M. Tomaselli)

LXXVII. Effective Interaction for 1P Shell Nuclei Calculated from the Hamada-Johnston Potential

Reaction matrix elements with respect to harmonic oscillator orbitals for use in shell model calculations of the spectra of the 1P shell nuclei have been calculated in the extended Eden-Emery approximation, employing the Hamada-Johnston potential. (A. D. MacKellar and R. L. Becker)

LXXVIII. Dependence of Brueckner-Hartree-Fock Calculations for Light Nuclei on Details of the Nucleon-Nucleon Interaction: Comparison of the Yale, HJ, and Reid Potentials

Calculations of matrix elements of Brueckner's reaction matrix and the Bethe-Goldstone wave functions for pairs of nucleons in light nuclei were carried out for the three currently most

prominent phenomenological nucleon-nucleon interactions. Significant differences in binding energies, single-particle energies, spin-orbit splittings, and effective interactions were found. The proton-proton correlation function was derived and evaluated. (A. D. MacKellar, R. L. Becker, B. M. Morris)

LXXX. Hartree-Fock Theory of Projected Wave Function

In a recent publication (Nucl. Phys. 78, 353, 1966) Yoccoz and Rouhanjejad propose to determine rotational energies by a modified variational principle:

$$\delta \langle \phi | \mathbf{H} P_J | \phi \rangle / \langle \phi | P_J | \phi \rangle = 0$$

ϕ being a Hartree-Fock type trial function, and P_J a projection operator on angular momentum J . The authors restrict ϕ to being an eigenfunction of J_3 , which we think is a serious error. We investigate the effect of relaxing this restriction. (N. Rogerson and F. Villars)

LXXXI. Rotational States in Nuclei

In a recent paper (Elementary Quantum Theory of Nuclear Collective Rotation, F. Villars, Nucl. Phys. 74, 353 (1965)), a two dimensional model of a system of identical particles was investigated. Conjugate operators $\mathbb{J}$ and φ were introduced ($[\mathbb{J}, e^{i\varphi}] = e^{i\varphi}$) and a method was devised to write the Hamiltonian as

$$H = H^{(0)} + H^{(1)} \mathbb{J} + \frac{1}{2} H^{(2)} \mathbb{J}^2 + \dots$$

where the $H^{(i)}$ all commute with both $\mathbb{J}$ and φ . Assuming $\mathbb{J}$ diagonal, $\mathbb{J} \rightarrow M$, the eigenvalue problem for $\mathcal{H}(M) = H^{(0)} + MH^{(1)} + \frac{1}{2} M^2 H^{(2)}$ was solved in a Hartree-Fock approximation and gave a rotational energy with a moment of inertia similar to the Thouless-Valatin expression.

The corresponding, more realistic, three dimensional case is now under study. In place of $\mathbb{J}$, φ one has 3 body fixed unit vectors $\vec{e}_A$ ($A=1,2,3$) and 3 components $\mathbb{J}_A$, representing the collective variables. H can then be written as

$$H = H^{(0)} + \sum_A H_A^{(1)} \mathbb{J}_A + \frac{1}{2} \sum_{AB} H_{AB}^{(2)} \mathbb{J}_A \mathbb{J}_B + \dots$$

where the $H^{(i)}$ commute with the collective operators. Assuming $\mathbb{J}_3$ and $\vec{\mathbb{J}}^2$ diagonal, one has the eigenvalue problem of a matrix:

$$\langle JK | \mathcal{H} | JK' \rangle = H^{(0)} \delta_{KK'} + \sum_A H_A^{(1)} \langle JK | \mathbb{J}_A | JK' \rangle + \frac{1}{2} \sum_{AB} H_{AB}^{(2)} \langle JK | \mathbb{J}_A \mathbb{J}_B | JK' \rangle$$

Again, we attempt to solve the eigenvalue problem of $\mathcal{H}$ by a perturbation method, based on a Hartree-Fock zero order approximation.

No satisfactory way to handle the case of small deformations has yet been found.

(F. Villars and G. Cooper)

LXXXII. Time and Time Delay in Classical and Quantum Mechanics

There are two ways of considering the correspondence between classical mechanics and quantum mechanics. First, we have the correspondence of Poisson bracket and operator commutator and, secondly, the equality of the classical function and the first terms in the JWKB expansion of the corresponding quantum mechanical quantity. It has been shown before that the quantum mechanical notion of the coarse grained structure of space and time delay corresponds in the lowest order of the JWKB approximation to the impact parameter and time delay in the classical theory. In this paper, we introduce additional formalism to show that the time delays in classical and quantum mechanics are identical limits on the corresponding Poisson brackets and operator commutators. (J. V. Greenman)

LXXXIII. On the Validity of the Semiclassical Method for the Coupled Channel Atomic Scattering Problem

We examine the question of whether it is valid to interpret the elastic and inelastic differential cross sections of a typical atomic scattering system such as $\text{He}^+ \text{He}^-$ in terms of the "interference of classical trajectories". We examine the S-matrix elements and consider whether it is possible to express these elements as a sum of complex vectors with slowly varying moduli and univalent phases. We show that for typical molecular potentials, it is impossible to get such an expansion that leads to any intuitive physical picture. (J. V. Greenman)

LXXXIV. Spectrum of Alkali Atoms

The spectrum of alkali atoms was studied with every simple method. It was assumed that the valence electron moves in a simple potential, which is the Coulomb-field for $r > r_c$ and an infinite repulsive potential for $r < r_c$. This is an approximate description of the fact that the electron enters the core only with a very high momentum, because of the Pauli principle.

It turned out that this potential reproduces the S and P levels of all alkalis with an accuracy of a few percent. The core radii r_c were found (best fit) to be (in Bohr radii):

	Li	Na	k	Rb	Cs
r_c	1.031	1.116	1.443	1.523	1.678

The repulsive potential description of the core will be used to calculate the cohesive energy of the alkali metals. (R. Parsons (SLAC) and V. F. Weisskopf)

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- N. M. Tomljanovich, Strange Particles and Parastatistics, Ph.D. (June 1966).
- P. B. Ulrich, The Non-Landau Singularities of Feynman Graphs, Ph.D. (September 1966).

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University of Rochester
Rochester, New York

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Laboratory of Nuclear Studies
Cornell University
Ithaca, New York

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California Institute of Technology
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Copenhagen, Denmark
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