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COSMIC RAY PROTON AND HELIUM MEASUREMENTS
OVER HALF A SOLAR CYCLE 1965-1969

by

Thomas A. Rygg

Technical Report No. 70-111

June 1970



UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
COLLEGE PARK, MARYLAND

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Thomas A. Rygg

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Thesis submitted to the Faculty of the Graduate School
of the University of Maryland in partial fulfillment
of the requirements for the degree of
Master of Science
1970

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ABSTRACT

Title of thesis: Cosmic Ray Proton and Helium Measurements Over Half
a Solar Cycle 1965-1969

Thomas A. Rygg, Master of Science, 1970

Thesis directed by James A. Earl, Associate Professor of Physics

Cosmic ray proton and helium differential energy spectra covering the energy range 100 MeV/nucleon - 260 MeV/nucleon were obtained in balloon flights made each summer 1965-1969 from Ft. Churchill, Manitoba, using a Geiger-tube hodoscope detector. The flights cover nearly the full extent of the solar cycle from solar minimum to solar maximum.

The detector is basically a sandwich of Geiger tubes, plastic scintillator, and lead plates totalling 75 gms./cm.² in thickness. Particle energy is determined by ionization range for particles stopping in the detector.

Supplementary data obtained with the detector, including balloon flights made from Minneapolis, Minnesota and Sioux Falls, South Dakota, and calibration runs made at the Brookhaven AGS and the Cornell Electron Synchrotron, are used to verify predicted detector response. Techniques that were devised to maintain consistency of data reduction are discussed. These include tests and corrections for Geiger tube inefficiency, δ -rays, nuclear interactions, and detector resolution. The spectral contribution of atmospheric secondary protons is calculated, including the effect of solar modulation, and agrees with observations made with this and other detectors. The calculated secondary proton intensity varies 47% over the solar cycle.

Integral proton and helium fluxes above 260 MeV/nucleon obtained at Churchill and Minneapolis confirm the general rigidity dependence of solar modulation as predicted by most diffusion-convection models. However, the spectral results, including the proton flux from 260 MeV to 720 MeV obtained by ionization measurements, show that simple diffusion-convection theory does not explain the results below a few hundred MeV/nucleon. The yearly proton differential spectra show a total factor of 5 in modulation, but the spectral shape does not appear to change. The yearly helium spectra do appear to steepen as the solar cycle progresses and show a total modulation factor of 3.5 to 4.

A model that assumes that adiabatic deceleration due to the expansion of the solar wind provides the major source of low energy cosmic rays predicts spectra of the form $K(t)E^{1.0}$. $K(t)$ contains all the time variation and actually represents the modulation acting at a few hundred MeV, where the transition from diffusion-convection to adiabatic deceleration takes place. The model also predicts that low energy spectra can be no steeper than $E^{1.0}$. The 1965 and 1967 proton spectra obtained by combining data from this experiment with satellite results fully agree with the predicted form from 20 MeV to 200 MeV. Spectra obtained in other years also agree with this form, but the absence of satellite data at the present time restricts the measurement to this detector. The significantly smaller helium modulation is also explained by this model. If this model is valid, strong objections occur in relation to present interpretations of the spectra of low energy heavy nuclei.

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CHAPTER I

INTRODUCTION

The predominant interest in cosmic ray studies in recent years has been concentrated on the low energy portion of the cosmic ray spectrum (1 GeV). The reasons for this interest are the recent availability of that portion of the spectrum from satellites, rockets, and high-altitude balloons and the relative ease of identifying particle energies and fluxes with the fairly small detectors that can be employed. Probably the foremost reason is the presumed high information content of the spectra, due to the susceptibility of these particles to matter and fields in the interplanetary and interstellar media.

Low energy cosmic rays are, therefore, the convenient tool used in studying propagation phenomena. The most obvious of these is the modulation of cosmic ray intensity, which is correlated with the eleven year cycle of solar activity (Forbush 1954). Unfortunately propagation studies that extend beyond the solar neighborhood require a complete understanding of solar modulation effects in terms of both energy and intensity changes. It is also necessary to demodulate the spectrum in order to understand the roles of cosmic ray heating of the interstellar medium and cosmic ray pressure in galactic dynamics. The demodulated spectral shape is also of interest in sorting out cosmic ray source and acceleration mechanisms. Finally, a complete understanding of the modulation process itself can give insight into mechanisms of interstellar propagation through analogy with the interplanetary case.

A widely accepted modulation mechanism is the diffusion-convection model proposed by Parker (1958). In this model magnetic scattering centers carried by the solar wind tend to sweep the cosmic rays

out of the solar cavity. The resulting density gradient promotes inward diffusion, which eventually balances the outward convection. Jokipii (1966, 1967) has developed the concept of scattering centers into a picture in which small scale irregularities in a generally uniform magnetic field are treated as transverse waves. This picture is quite consistent with interplanetary magnetic field observations (Ness 1964). Particles whose gyro-radii are of the same scale as the wave length of the irregularities are most effectively scattered by those waves. Measurements of the interplanetary field irregularities then yield an effective diffusion coefficient to be applied in the diffusion convection model. Since this same model is proposed for interstellar propagation, simultaneous measurements of the interplanetary magnetic field, solar wind velocity, and cosmic ray intensity over a reasonable extent of interplanetary space and time in the solar cycle should yield not only the unmodulated spectra but should also serve as a test of Jokipii's propagation model.

Solution of the diffusion — convection problem properly includes the effects of energy changes due to the expansion of the solar wind (Parker 1965, Axford 1965). If the energy changes due to adiabatic deceleration are large then one needs to re-examine those current interpretations placed on the relative abundances of low energy cosmic rays which assume that particle energies do not change during the penetration of interplanetary fields.

The experiment described in this thesis is an attempt to clarify some of the modulation effects through yearly measurements of the proton and helium low energy spectra (100 - 250 MeV) from 1965 (a period of minimum solar activity) through 1969 (a period of maximum solar activity). Combined with surveys of the other important parameters, one could hope to obtain the unmodulated spectra of these components. Alone, they can

be used to test the specific predictions of models giving the charge and velocity dependence of the average diffusion coefficient in the solar cavity

The detector used in this experiment is quite well suited to the task, in that consistency in energy and intensity determinations is easily attained with reasonable care in data reduction. Since the same detector was used throughout, systematic errors in flux levels will cancel when fractional changes are considered. The energy discrimination of the detector is perhaps its most important feature. The employment of the particle's range as the determination of energy gives sharp non-drifting energy resolution and the capability of measuring the rapidly changing spectral intensities, that are predicted by most diffusion - convection models of modulation. The digital nature of the data allows computer analysis for detector faults and provides consistency in the analysis procedures.

Chapter II presents the detector, its operation, and preliminary data processing. Chapters III and IV contain a discussion of the observed and predicted detector response to flight data and calibration data obtained at the Brookhaven AGS and the Cornell Electron Synchrotron. The data processing techniques used to obtain the particle flux measurements are introduced in Chapter V. Chapters VI and VII present the particle spectra that are obtained and discusses their conflict with simple diffusion - convection theory. By selecting appropriate elements in a set of conflicting data, a plausibility argument is presented in Chapter VII which explains a number of important features that are observed with this and other detectors. For example, low energy spectra have the form $K(t)E^{1.0}$, and a significantly deeper proton modulation compared with the helium modulation cannot be explained

by a rigidity-dependent modulation. The model developed in Chapter VII assumes that adiabatic deceleration predominates over diffusion as the phenomenon which determines the intensity of low energy particles. Chapter VII is a discussion of the implications of this model on the interpretation of the spectra of cosmic ray heavy nuclei at low energies.

CHAPTER II

THE DETECTOR

The detector, as shown in Figure 1, consists of a Geiger tube hodoscope, a dE/dx scintillator, and a sandwich of lead and plastic scintillator plates, which comprise a total energy calorimeter. The hodoscope defines the range and geometry of a particle and detects nuclear interactions occurring in the lead. The dE/dx scintillator measures the rate of ionization loss of the incident particle. The combined light output of the five calorimeter plates is a sample of the total energy deposited in the lead absorber. The trays of Geiger tubes measure $15\text{ cm} \times 15\text{ cm}$, and the apparatus is 32 cm high. The total absorber thickness of the detector is equivalent to 75 gms/cm^2 of lead.

The organically quenched Geiger tubes are 1.59 cm outside diameter stainless steel with a wall thickness of 0.26 mm. Their sensitive length is 14.96 cm. The tubes are arranged in five pairs of crossed trays to give a 90° stereo picture of each event. The scintillator plastic is Semi-elements Polyfluor and measures $15.2\text{ cm} \times 15.2\text{ cm} \times 0.635\text{ cm}$.

The light output of the dE/dx scintillator and the combined output of the five calorimeter scintillators are each directed by edge mounted light pipes to a $1\frac{1}{2}$ " RCA 6199 Photomultiplier tube. The amplitude of the photomultiplier signal is determined by a logarithmic pulse height analyzer, which has a channel width of 33% (8 channels cover a factor of 10). Two such analyzers are cascaded to cover a factor of 100 in pulse height.

Upon receipt of a trigger command, the state of each of the Geiger tubes and the two scintillator pulse heights are read out and recorded as an event. Figure 2 is a logical diagram of the detector. Each Geiger tube and each pulse height discriminator is connected to an associated binary circuit. These binary circuits are connected as a circular 144 bit shift register. The output of each binary is also available for triggering purposes.

When the apparatus is waiting for a cosmic ray event, the binaries are all monostable. Each Geiger tube and each discriminator transition causes its associated binary to turn on for 5 microseconds. When a trigger requirement (to be discussed later) is satisfied, the control electronics generates hold and shift commands which perform the following functions: 1). all further inputs are gated off; 2). the binaries are clamped in whatever state they were in at that time; 3). the shift register is activated to shift all information in a circular path through the control electronics.

A modulator circuit in the control electronics converts the binary information contained in the shift register to a Pulse Code Modulation (PCM) signal suitable for telemetry. The shift clock which serves as the basic clock for the entire system was operated at 1 KC in 1965 and 1966 and at 4 KC in 1967-1969. Both the 1 KC tuning fork and the 4 KC crystal proved to be accurate to better than 0.1%. An Olland cycle altimeter was used to amplitude modulate the PCM wave form. In 1965 and 1966 a modified GMD meteorological transmitter operating at 1680 MC F.M. was used for telemetry. Incorporation of a Sonex telemetry transmitter operating at 237.8 MC F.M. in 1967 allowed the factor of 4 increase in bit rate plus

a substantial decrease in bit error probability and telemetry coverage to the horizon.

The directional filter coincidence is the designation of the detector's trigger requirement. As indicated in Figure 3, eleven two-fold coincidences between tubes in trays 1 and 3 select particle trajectories which pass through tray 10 of the apparatus. An identical set of coincidences exists between trays 2 and 4. To satisfy the directional filter requirement such a coincidence must occur in both pairs of trays. This use of multiple telescopes defines a well collimated beam of reasonable geometric factor with economy of space before it enters the main body of the detector. The tray spacing of 8.3 cm gives a geometric factor of 10.3 cm^2 steradian.

Figure 4 outlines the data processing scheme. In operation during a balloon flight a 12 bit sync word, 6 bits of housekeeping information, 36 bits of pulse height information and 90 bits of Geiger tube information are read out three times. The triple read-out aids in detection of bit errors due to transmission noise and assures that no bits are lost by the shift register. The 237.8 Mc telemetry signal is a 4 Kc PCM waveform that is amplitude modulated by the altimeter signal.

At the ground station the PCM signal is recorded on one-half inch magnetic tape with NASA 36 Bit Time Code on a parallel track. In addition a "real time" event monitor provides a pictorial display on a CRT of each event as it is received to assure that the apparatus is functioning properly and that data is being received correctly. The demodulated altimeter signal and event rate are recorded with a time signal on a strip chart also for "real time" analysis.

The computer processing of the PCM data begins with a digitization of the information on the analog flight tapes. The PCM telemetry and time formats were selected to be compatible with facilities made available by Goddard Space Flight Center in Greenbelt, Maryland. The analog signal is fed at eight times "real time" to a bit synchronizer and analog-to-digital converter which is connected to one data channel of a CDC 3200 computer. The time signal is fed to a time decoder which in turn feeds the time to another data channel. A short control program converts the PCM data to the original binary bit stream which is segmented and written on a digital tape with the appropriate time.

The second stage of computer processing is performed by an IBM 7094 computer under the control of a program named FINDUM. This program locates the events in the bit stream by recognition of the sync word in all three read-outs. Noise is rejected by comparing the three event read-outs bit by bit and defining the truth as the two bit read-outs that agree. A set of loose criteria based on bit error and directional filter information is applied to determine whether an event is worthy of further consideration. The digital tape which is generated by FINDUM contains the binary representation of accepted events plus a set of descriptive parameters which characterize each event such as waiting time, pulse heights, bit errors, etc. The printed output generated by FINDUM is a rather extensive set of housekeeping information corresponding to each 15 minute interval of balloon flight time. These include pulse height and waiting time histograms, Geiger tube discharge tallies, and various bit error tables.

The final stage of computer processing proceeds in the IBM 7094 under control of a program named ULTIMATE. The primary output from ULTIMATE is a three dimensional matrix whose axes are various properties of an event as assigned by FINDUM. The matrix is a tally of only those events which satisfy a set of stringent acceptability criteria. These criteria are tailored to the particular type of analysis that is being performed. ULTIMATE also compiles more housekeeping information concerning sensitive times, Geiger tube tray efficiencies and directional filter telescope firing probabilities.

CHAPTER III

DETECTOR RESPONSE

The objective of the present experiment is to determine the energy spectra of cosmic ray protons and helium nuclei from 66 - 250 MeV/nucleus as determined by the range, dE/dx , and calorimeter responses to the various particles. The energy and species of a particle are uniquely determined by measuring any two of these parameters as long as ionization losses dominate. However, the large amount of absorber in the detector produces a considerable background of nuclear interactions which tends to mask non-interacting particles in any two dimensional analysis. We reduce the background interactions in two ways. 1). By selecting for analysis events which fire ≤ 1 Geiger tube per tray, we eliminate obvious interactions. 2). By analyzing the events in a three dimensional matrix, plotting dE/dx pulse height vs. calorimeter pulse height vs. the number of the last tray in which a Geiger tube was fired (LASTRA), the overall density of the residual interactions is reduced.

Figure 5 shows the predicted dE/dx vs. calorimeter response as a function of particle species and energy. The curves were calculated by first converting all materials in the detector to their lead equivalent absorber thickness and the depths to the various counter elements was determined as shown in Table I. A computer program was then used to determine the dE/dx and calorimeter response and the range of particles of various energies by integrating an ionization-energy power law fit to the range-energy graphs published by the UCRL (Trower 1966). The non-

linear response of the scintillation plastic was included using an equation of the following form:

$$\frac{L}{L_m} = \left[\frac{E}{E_m} \right]^{[1-\gamma \log(E/E_m)]} \quad (3.1)$$

In Eq. 3.1 L is the observed light output due to a loss of energy E in the scintillator. L_m and E_m are the corresponding values for a minimally ionizing particle. The non-linearity parameter γ was found to be 0.10 for protons and 0.07 for helium nuclei by fitting the data of Badhwar et al. (1967) over an appropriate range of energies.

In Figure 5, the + symbols indicate the points of accumulation of relativistic particles. Slower particles which still pass through the detector lie on the positively sloped branch rising out of this point. Particles which stop in the detector lie on the multibranched locus at larger dE/dx . The multiple branches are due to the discrete nature of the calorimeter wherein the cusps correspond to particles actually stopping in the scintillator plastic. The numbers on the curves are the values of LASTRA for each branch and correspond to events lying on separate pages of the matrix. Since the range-energy relation is quite exact, LASTRA defines distinct energy intervals which are a function of absorber thickness rather than electronic calibration.

Also shown in Figure 5 is the size of the detector resolution for minimally ionizing particles. To assure that non-interacting events and the background events were well separated considerable care was applied in constructing synthetic response curves for the non-interacting events.

For the most favorable separation of protons and alpha particles all analyses have been made using diagonalized distributions wherein the elements of the pulse height matrix are summed along lines of $dE/dx + \text{calorimeter} = \text{constant}$. These are lines of slope -1 on the matrices. We define this as the "negative diagonal" distribution. Figure 6 shows normalized distributions for sea level cosmic ray muons and 4 Gv protons plus pions from the Brookhaven A.G.S. The curve that is drawn in is a Gaussian with a variance of 4.35 channels. The third set of data verifies that the distribution in the matrix is a two dimensional Gaussian with equal standard deviations in all directions. It is the distribution of 4 GV protons and pions obtained by summing matrix elements along lines of slope $+1$. The advantage of the "positive diagonal" distribution is that it gives the detector resolution even when there are small positive correlations in the matrix.

In Figure 7, we make use of the positive diagonal to demonstrate that the detector resolution is a function of scintillator output. The curves are "positive diagonal" distributions of the LASTRA 10 protons and helium nuclei obtained in a balloon flight. In the lower part of the figure the standard deviations of the proton, helium and slow proton distributions are plotted as a function of the sum of dE/dx plus calorimeter pulse height. The dashed line which has been normalized to the proton point is the expected behavior of σ when the only cause of fluctuations is photoelectron statistics. Obviously this is the major cause of counter fluctuations for this detector. An empirical fit to the fluctuation data is:

$$\sigma = 3.54 \exp(-0.0575 \times \text{pulse height}) \quad (3.2)$$

The final step in constructing the synthetic distributions involves folding the resolution function into the detector response curves to obtain the expected peak shapes for protons and helium nuclei. In this procedure, we assume that the amplitude of the fluctuations varies exactly as in Figure 7 for all pulse heights and that the distribution in energy of the particles along the response locus is independent of energy. Each LASTRA branch of the response locus is divided into five or six intervals. At the dE/dx plus calorimeter position of each of these intervals a Gaussian is constructed whose width is determined by Eq. 3.2. The normalized weighted sum of these Gaussians is the synthetic detector response.

In calculating the synthetic distributions for LASTRA 10 events, the distributions along the response loci were obtained using the 1965 proton and helium spectra given by Meyer (1969). However these peak shapes do not depend critically upon the exact form of the energy spectra.

Figures 8a and 8b, which demonstrate the validity of the synthetic distributions for both fast and stopping particles, exhibit the shapes and positions relative to minimum ionization of the synthetic curves and show that they closely match the observed points. The broad peak in Figure 8b near minimum ionization is the shape of the electron and fast proton background events as determined from accelerator calibrations.

CHAPTER IV

THE VOLUME OF DATA

The set of data obtained with this detector is summarized in Tables II and III. It includes 15 balloon flights and calibration exposures to protons and pions at the Brookhaven Alternating Gradient Synchrotron and to electrons at the Cornell Synchrotron. The 8 balloon flights launched from Ft. Churchill, Manitoba cover nearly the entire period from cosmic ray maximum in May 1965 to cosmic ray minimum in June 1969 with one or two flights each summer. The balloons are launched at Ft. Churchill, and once they reach ceiling they drift nearly due west and are cut down near Uranium City, Saskatchewan after about 12 hours at ceiling. Although the geomagnetic cutoff rigidity at the latitude of Churchill varies from day to night, it remains below 100 MV. The atmospheric cutoff at 2 gms/cm^2 for protons is, however, 300 MV; therefore the protons and helium nuclei seen at Churchill are galactic cosmic rays plus atmospheric secondaries. The data from the Churchill flights will be used to study the shape of the solar modulation function throughout the solar cycle. All of the flights at Churchill were made during relatively quiet times as determined by neutron monitors.

The seven balloon flights launched at intermediate latitudes (Minneapolis and Sioux Falls) cover the period 1965-1968. These flights were made in the late summer when the upper winds are generally slow and random in direction so that flights of up to 32 hours at ceiling have been made while the balloon remains within 300 miles of the launch site.

The geomagnetic cutoff in the area covered by these flights runs from 1.0 to 2.0 GV so that the protons stopping in the detector are all below cutoff and consist of secondaries plus re-entrant albedo. The rigidities of stopping helium nuclei however span the cutoff region and provide quite accurate determinations of cutoff rigidities since there are very few secondary or albedo helium nuclei. All of these flights except 1057 were made during relatively undisturbed times. Flight 1057 occurred during an active geomagnetic period associated with a solar flare two days before and will not be considered in the present analysis.

The calibration exposure at the Brookhaven A.G.S. consists mainly of 2 and 4 GV particles in the momentum-selected test beam. Figure 9a depicts the Brookhaven calibration set-up. During a portion of the beam pulse the G-10 target is flipped into the main beam. The G-10 secondary particles emitted at 10° are then momentum analyzed by magnets M1 and M2 giving a momentum width of about 1%. Restrictions on magnet current limited the highest available momentum to 4 GV. The 400 microsecond dead time of the Geiger tubes requires that counting rates be kept at a minimum. Since the intensity of the beam was not adjustable, the detector was gated so that only the first particle in any beam pulse passing through the detector was allowed as a trigger. The pulse rate of 1800 events per hour made it rather difficult to obtain the desired volume of data. Some exposures were made at momenta ranging from 450 MV to 700 MV in hopes of defining the response to stopping protons. However, the high pion population at these lower momenta overwhelmed any contribution from protons. Separate runs at 2 and 4 GV were made with a slab of lead 3.0 radiation lengths thick above

the detector to avoid the possible positron contamination of the beam from (π , μ , e) decays. It was later confirmed at Cornell that the lead slab was 100% efficient for electrons in initiating large enough showers to cause multiple discharges in trays 1 through 4. The 2 and 4 GV exposures were made primarily to study proton interactions and their visibility in the detector so that suitable interaction corrections could be made to flight data.

A calibration exposure to electrons from 105 MeV to 1200 MeV was made at the Cornell Synchrotron. As shown in Figure 9b, γ -rays from the synchrotron convert in a thin lead plate and the resulting electron - positron beam is momentum analyzed. The beam pulses 60 times per second so that the inherent dead time during read out of an event assures that only the first electron of each beam pulse is accepted. The Cornell electrons-especially the 300 MeV data-were used to demonstrate that electrons at these energies can give a single particle signature in the Geiger tubes and therefore account for most of the background at low ionization as in Figure 8b.

Sea-level muon data also has been analyzed to better define the detector response to non-interacting particles.

CHAPTER V

COMPUTATION OF FLUXES

Since the goal of this analysis is to compare fairly small flux variations over the solar cycle, a number of techniques have been developed to assure that the analysis is consistent and reproducible even when the quality of the data varies. These techniques also identify detector problems when they occur. A detailed discussion of each of the techniques is provided in the appendices. The following summary of the step-by-step computation of fluxes makes numerous references to these appendices.

The analysis begins with the generation of a three dimensional matrix which contains essentially all the clean trigger (one and only one discharge in trays 1 - 4) events for the ceiling portion of the balloon flight. Each page of the matrix is a two dimensional dE/dx vs. calorimeter pulse height histogram for a certain class of events. The classes are based on the Geiger tube information and are listed in Table IV. Pages 0 through 5 contain mostly stopping particles where the page numbers define the range interval of the particles. Pages 6 and 12 contain mostly penetrating or so-called "through" particles. Pages 7 through 11 and 13 through 19 contain various categories of interacting particles. To qualify for pages 0 through 5 an additional requirement is that no edge tube (Tube #1 or #9) be fired in either LASTRA or the tray preceding it. This requirement rejects events which appear to be stopping particles but are actually faster particles being scattered out the side of the detector (see Appendix H). Upward moving products of interactions generated by particles incident through the sides of the detector may also be a source of these events.

The present analysis concentrates on pages 0 through 5 which determine the energy spectra of protons and helium stopping in the detector. Pages 6 and 12 determine the "through" proton and helium fluxes. For each of these pages the negative diagonal distribution is constructed and compared with the predicted peak shapes discussed earlier. The

negative diagonal is then divided into and summed over three pulse height intervals—background, protons, and helium nuclei—named for the major component in each interval. Assuming that the peak shapes for each of these components is completely known, one can determine fairly easily the contributions of each of the components. This is the process referred to as "mixing" in Appendix E. Just prior to the mixing correction, the raw numbers in each of the three intervals are corrected for "leakage" from one value of LASTRA to the tray above due to Geiger tube inefficiencies and an occasional dead Geiger tube. Geiger tube efficiency is discussed in Appendix B.

The mix-corrected numbers are next corrected for the various mechanisms which remove particles from the matrix that they should lie in. The major correction here is the nuclear interaction correction which is discussed in considerable detail in Appendix F. Other corrections include those for 1) "real" and "geometric" δ -rays, 2) allowed trajectories which fire edge tubes, 3) events in which two trays are missed due to Geiger tube inefficiency, and 4) an atmospheric absorption correction for the helium nuclei. The absorption mean free path for helium (54 gms./cm^2) determined by Ormes (1967) was verified using ascent helium data. The proton atmospheric correction was not applied at this point because it is not a simple absorption process.

At this point calculation of proton and helium fluxes is a simple matter of dividing the corrected numbers of particles by the detector exposure. Differential fluxes at the top of the atmosphere are then obtained by subtracting the atmospheric secondary protons, applying an absorption correction ($\lambda_{\text{proton}} = 150 \text{ gms./cm}^2$ Chen et. al. 1955) to the remaining protons, and dividing by the energy intervals appropriate

to particles at the top of the atmosphere. The results so obtained are presented in Tables V - VII and plotted in Figures 12 - 20.

The errors that are quoted with the results are a quadratic combination of particle statistics and the 3% error in the determination of the geometric factor. In determining the statistical errors considerable care was exercised in including the effect of the mixing correction wherein small numbers of particles may result from the difference of two large numbers. The 3% error in the geometric factor results from the inability to exactly reproduce the structure of the directional filter telescope from one flight to the next. The tray separation was measurable within ± 0.5 mm (0.6%). The variation in tube diameter due to variations in roundness was estimated at ± 0.06 mm (0.4%). Since the geometric factor varies as the square of the tray separation and as the fourth power of the tube width, the combination of the two uncertainties amounts to the previously quoted 3%.

The exposure is defined as the product of the geometric factor and the total sensitive time. Since the directional filter consists of 121 separate four-fold coincidences, its geometric factor can be computed as the sum of the geometric factors of 121 elementary square telescopes whose edge is one tube diameter. The fact that pairs of trays are displaced relative to each other (one tube diameter) does not affect the geometric factor because each pair of trays defines the beam only in one dimension while the other dimension is completely free. It is shown in Appendix A that these 121 elementary telescopes can be grouped in such a manner that the formulae for computing geometric factors of rectangular solids given by Critchfield, Ney, and Oleksa (1952) can be applied. Two additional corrections also discussed in Appendix A are applied to the

geometric factor to correct for tray inefficiencies and an edge effect in the telescopes defined by trays 2 and 4. The resulting geometric factor is then independent of particle species or energy. All particle dependent corrections are applied to the particle types individually.

A great deal of care was exercised in computing the total sensitive time since data taken in the early years was seriously complicated by transmission noise. This effect plus other causes of data being absent for short periods such as tape drop-outs, antenna adjustments, etc. result in the computer missing events that did trigger the apparatus. An alternate way of describing the effect is that there will be an excess of events with large waiting times. The waiting time is the time between the end of the readout of the previous event and the beginning of the readout of the present event. To verify this effect we plot in Figure 10 a histogram of number of events vs. waiting time for data taken during periods of noisy and clean transmission. A less conventional log-log plot is used to demonstrate the wide range of agreement with the expected exponential form:

$$N(t) = N_0 e^{-t/\tau} \quad (5.1)$$

where τ is the average waiting time per event. The clean data follows this form over four decades of time and intensity. In the noisy data we note a departure only for times longer than one readout period. This reflects the fact that when the computer misses an event, the entire readout period (432 milliseconds) is included in the waiting time of the next event that is found. As is shown in Appendix D, these events with waiting times less than one readout period can be used to determine the true average waiting

time under the assumption that their distribution strictly matches an exponential.

Another effect of transmission noise on the data is to reduce confidence in the correctness of an event when the bit error count (number of miscorrelations) determined by comparisons of the three readouts is large. Although a bit error rate of 3% would result in an average of one wrong bit per event, we somewhat arbitrarily choose a bit error count of three or more as cause for rejection of an event. This maximum allowable count corresponds to one event in one hundred having one wrong bit. As long as this rejection criterion is independent of the nature of the event it is completely valid to ignore the sample of events thrown out in both the matrix analysis and in the computation of sensitive times. This assumption was verified by comparing sets of events having zero miscorrelations with those having one and two miscorrelations and noting that the fractions of clean, stopping, and penetrating events did not vary significantly. The total sensitive time of the flight is then equal to the product of the number of so-called correlated events and the average "true" sensitive time per event.

In addition to the spectral determination using stopping particles an attempt was made to resolve the LASTRA 10 negative diagonal proton distribution into a minimally ionizing peak plus a more heavily ionizing component. Figure 11 shows the results of subtracting the 1968 LASTRA 10 Minneapolis distribution from the 1968 Churchill distribution. Any difference in the peaks can be due only to particles below the 720 MeV proton cutoff energy even if there is a significant contribution from re-entrant albedo. The difference peak then should correspond to the predicted distribution of 260 - 720 MeV particles. The theoretical distribution for

this energy interval which is also shown in Figure 11 appears to fit the data quite satisfactorially except at low pulse heights where there appears to be a small contamination of minimally ionizing particles. The theoretical peaks constructed for a number of possible energy spectra were found to differ very little in shape. The particular curve shown assumes a constant distribution in energy.

The analysis of the flight data using this technique is similar to that used for other values of LASTRA. The pulse height distribution was divided into intervals consisting of three major constituents: fast protons, slow protons, and helium nuclei. The standard mixing techniques discussed in Appendix E were then applied to correct for particles spilling over into adjacent bins. Since the mixing correction is so critically dependent on the detector resolution function for this particular measurement, the size of the resolution function was verified for each balloon flight by using the positive diagonal distributions as discussed in a preceeding section.

CHAPTER VI

RESULTS

The results obtained are summarized in Tables V through VII and Figures 12 through 20. The regression plot presented in Figure 12 demonstrates the gross effects of solar modulation on the integral flux of all cosmic rays above approximately 100 MeV/nucleon. The so called "clean flux" presented in that figure is the flux obtained by using all clean directional filter events with the exception of LASTRA 4 electrons. Minor corrections were also made to correct for atmospheric effects and geometric differences from year to year. Also included in Figure 12 are the clean fluxes obtained with a similar detector (Neely 1968) flown as a part of this same experimental series. The reduction in intensity of more than a factor of two over the solar cycle indicates the strong effect that the sun's presence has on cosmic rays that are observed at earth.

The data obtained from the Minneapolis flights where the geomagnetic cutoff is 1.36 GV (720 MeV) (Shea et al. 1965) show considerably less modulation and reflect the fact that the solar modulation has some type of energy dependence.

The regression curves for LASTRA 10 ($E \geq 260$ MeV/nucleon) protons and helium presented in Figures 13 and 14 serve to define this dependence more specifically. It is quite important to emphasize here that the energy cutoff (actually a range cutoff) for these fluxes is very well defined and is extremely insensitive to the spectral distribution of particles. The Churchill-Minneapolis difference in the protons again reflects the energy dependence of the modulation. Note, however, that there is no

significant difference in the helium fluxes at Minneapolis and Churchill. This is not surprising, since the 260 MeV/nucleon energy cutoff corresponds to a 1490 MV rigidity - clearly above the geomagnetic cutoff. The important comparison, however, is that between the LASTRA 10 Minneapolis proton and the LASTRA 10 helium regression curves, which have essentially the same rigidity cutoff. If one ignores the possible complicating effects of re-entrant proton albedo, the close agreement in fractional modulation indicates that the modulation is basically rigidity dependent at these energies. This is further indicated in Figure 15 where the separation of the LASTRA 10 protons based on ionization shows a fractional modulation of protons above 720 MeV (1.36 GV) similar to that for helium and Minneapolis protons. Here, however, there is an implicit though not unreasonable assumption that the primary proton and helium spectra have the same shape above 1.36 GV.

Comparison of the regression curves in Figure 15 for 260 to 720 and > 720 MeV protons again demonstrates the well known property of solar modulation that cosmic rays experience stronger modulation at low energies than at high energies.

Let us now consider the yearly energy spectra of protons and helium, which are presented in Figures 16 and 17, respectively. In the helium spectra one sees the expected progressive steepening to more positive slopes in addition to the overall modulation factor of 3.5 to 4 as the cycle proceeds. However, upon examination, the proton spectra exhibit a healthy modulation factor of 4 but only a slight steepening, if any.

As is often the case, results from a larger range of energies than that obtainable with a single type of detector must be combined to verify results and get the "big picture." The recent analysis by Hsieh (1970) of proton and helium spectra obtained by the University of Chicago IMP

satellite series for 1965 and 1967 has proved most valuable in this connection, since the periods covered correspond closely to the times at which the present results were obtained. Figures 18 and 19 present the proton and helium spectra, respectively, for 1965 and 1967. The proton points spanning 260 - 720 MeV have been plotted as inclined lines to give the spectrum continuity and an indication of the probable spectral shape. Along the same lines, the integral flux above 720 MeV has been plotted as a differential line, using the 1965 spectral shape given by Meyer (1969) above 720 MeV. Since the present analysis is unable to distinguish between He^3 and He^4 , the Chicago spectra for these isotopes were combined on the basis that all would be identified as He^4 . The curve representing the 1965 helium spectrum is a smooth curve fit to Meyer's (1969) summary of the 1965 helium spectrum. In all four cases the spectra appear to join smoothly, although it is somewhat unfortunate that there is no overlapping region in which to compare intensities.

The major point of this comparison is the existence for both protons and helium of a wide energy range over which the spectrum is a simple power law in energy that does not apparently steepen as the solar cycle proceeds. The earlier observation of a steepening for helium may alternatively be interpreted, in light of the results over the large energy interval, as the movement of this straight line region up into the energy interval covered by the present detector. In the case of the protons this straight line region always extends into the hodoscope's energy interval.

As a final example of the data that have been obtained with this detector, in Figure 20 we show the helium rigidity spectrum obtained from a balloon flight over Minneapolis in 1965. That figure also shows

the shape of the 1965 helium spectrum seen at Churchill. Since the Minneapolis results are not particularly relevant to the present discussion, we wish only to point out the existence of a sharp geomagnetic cutoff, which fully agrees with the value of 1.36 GV obtained in the detailed orbit calculations of Shea, et al. (1965). The second relevant point is to demonstrate that since the spectra are based on a range measurement no difficulty is encountered in defining spectra which vary rapidly with energy nor in assigning the correct energy to a particular particle.

CHAPTER VII

DISCUSSION

Prior to more extensive analysis, a brief review of the theoretical description of solar modulation of cosmic rays seems appropriate. Within a sphere of a few A.U. radius, the extended solar corona is in a constant state of radial expansion at a velocity in the range of 200 - 600 km/sec. Since this so-called solar wind is a fully ionized plasma, is therefore a very good conductor, and has a kinetic energy density greater than that of the solar magnetic field, the surface field is "frozen" in the plasma and is convected outward with it. This effect combined with the effect of the sun's rotation results in an Archimedian spiral field configuration within the solar cavity. At the orbit of Earth the interplanetary magnetic field has been observed to have an average direction 45° west of the Earth-Sun line with a magnitude of about 5γ ($1\gamma = 10^{-5}$ gauss) (Ness et. al. 1965). The fluctuations in this magnetic field have been measured at $\langle \Delta B \rangle^2 = 5\gamma^2$ compared with the total field $\langle B^2 \rangle = 25\gamma^2$ (Coleman 1966).

It is generally accepted that it is this fluctuating component that couples the solar wind and the cosmic rays. The picture of cosmic ray modulation, then, is one in which the convection of cosmic rays out of the solar system is balanced by their inward diffusion (Parker 1958).

Eq. 7.1, below, which results from Gleeson and Axford's (1967) treatment of modulation, serves to introduce two simple theoretical models. One is the usual simple diffusion-convection model. The other assumes that convection is balanced mainly by the deceleration produced by the expansion of the solar wind.

$$S(r,T) = V(r) U(r,T) - \kappa(r,T) \frac{\partial}{\partial r} U(r,T) - \frac{V(r)}{3} \frac{\partial}{\partial T} [\alpha(T) T U(r,T)] \quad (7.1)$$

$S(r,T)$ is the cosmic ray radial current density or "streaming" at a radial distance r measured from the sun at a kinetic energy T . $U(r,T)$ is the number density. $V(r)$ is the solar wind velocity and $\kappa(r,T)$ (assumed isotropic here) is the diffusion coefficient of cosmic rays through the interplanetary medium. $\alpha(T) = (T + 2T_0)/(T + T_0)$ where T_0 is the rest energy of the particle. $\alpha(T)$ ranges from a value of 2 for non-relativistic particles to 1 for extremely relativistic particles.

The simplified treatment of the modulation problem results from Eq. 7.1 . The first two terms on the right hand side of that equation represent the streaming due to radial convection and diffusion of cosmic rays, respectively. The third term is the so called adiabatic deceleration term, which represents the streaming in energy space due to energy losses caused by the expansion of the solar wind. The simplified treatment ignores this term and thereby removes the energy coupling of the effects. Since this results in no energy losses by particles, the streaming $S(r,T)$ must be zero, assuming that there are no cosmic ray sources inside the solar system. One can now equate the diffusion and convection terms and obtain the following solution (Parker, 1963).

$$U(r,T) = U_0(T) \exp \left[- \int_r^L \frac{V(r)dr}{\kappa(r,T)} \right] \quad (7.2)$$

L is the radius of the outer boundary of the modulating region. A further simplifying assumption is that the diffusion coefficient is separable into a radial and an energy dependent term $\kappa(r,T) = k(r) \kappa(T)$, thus allowing one to write the solution in the following form.

$$U(T,t) = U_0(T) \exp[-\eta(t)/\kappa(T)] \quad (7.3)$$

$$\eta(t) = \int_r^{L(t)} \frac{V(r,T)dr}{k(r,T)} \quad (7.4)$$

We have introduced long-term time dependence in the modulation parameter $\eta(t)$. This form has been used by a number of authors (Fan et al. 1965, Silberberg 1966, Gloeckler and Jokipii 1966, Nagashima et al. 1966, Badhwar et al. 1967a, Balasubrahmanyam et al. 1967, Hoffman 1967, Lockwood and Webber 1967, Ormes 1967, Teegarden 1967, Webber 1967a, 1967b, Ormes and Webber 1968, O'Gallagher 1969, Hsieh 1970) to deduce the energy dependence of the diffusion coefficient by plotting ratios of fluxes obtained at two different times in the solar cycle, using Eq. 7.5.

$$\kappa(T) = \frac{\eta(t_1) - \eta(t_2)}{\ln[U(T, t_2)/U(T, t_1)]} \quad (7.5)$$

The validity of this method is based on the assumption that the diffusion coefficient is a separable function of energy, heliocentric radius, and time, and that the effects of adiabatic deceleration are ignored.

The energy dependence of the diffusion coefficient has been related to the power spectrum of the fluctuations in the interplanetary magnetic field by Jokipii (1966, 1967) who predicts $\kappa \propto \beta R^{2-\alpha}$, where α is the spectral index of the magnetic power spectrum, β is v/c

and R is particle rigidity. Early application of this method by Gloeckler and Jokipii (1966) predicted a diffusion coefficient of the form $\kappa \propto R\beta$, which they verified using satellite observations of protons and helium from 10 to 100 MeV/nucleon, the IMP Geiger tube monitor, and the Climax neutron monitor. Badhwar et al. (1967a), Webber (1967a, 1967b), and Lockwood and Webber (1967) also observe that such a form is consistent with their determinations of $\kappa(T)$.

In a more recent analysis involving magnetic power spectra measured at 1 A.U. and 1.5 A.U., however, Jokipii and Coleman (1968) predict a

diffusion coefficient at 1 A.U. parallel to the local magnetic field $\kappa_{\parallel} \approx 5 \times 10^{21} R^{1/2} \beta \text{ cm}^2/\text{sec.}$, where R is measured in GV. The value of $\kappa_{\parallel}$ is found to be slightly smaller at 1.5 A.U. and appears to retain the $R^{1/2} \beta$ dependence.

In a more recent analysis of their proton and helium data, Ormes (1967) and Ormes and Webber (1968) obtain a diffusion coefficient $\kappa \propto R^{0.6 - 0.55} \beta$, which appears to flatten to a simple $\kappa \propto \beta$ dependence in the neighborhood of 0.6 GV. This mysterious tendency to flatten to a simple β dependence had been observed earlier by Webber (1967b) in a review of results extending to lower rigidities.

At this point let us consider the analysis of $\kappa(R, \beta)$ as determined by Hsieh (1970), using the IMP results discussed earlier. He plots $\beta[\ln(\mu_1/\mu_2)]$ vs. rigidity. This amounts to plotting $1/\kappa(T)$ in the simplified analysis and assuming the β dependence given by Jokipii's model. Figure 21 is a duplication of his Figure 8 to which has been added the similar determination of κ obtained in the present analysis. The data presented for this detector was obtained by drawing regression curves as semi-log plots for the entire data set and taking the best fit line to each curve. The modulation ratios appropriate to the neutron monitor variation corresponding to Hsieh's analysis were then plotted in Figure 21.

As is evident from Hsieh's data alone, the apparent diffusion coefficient has an inverse dependence on rigidity and has a different value for protons and helium at the same rigidity. Both observations strongly contradict the predictions of diffusion-convection theory. In fact, the line through the proton data represents the form one expects when κ has neither an R nor β dependence. At higher rigidities

the data obtained with this detector shows a transition to a form more consistent with $\kappa \propto R^{1/2} \beta$ and which is apparently the same for protons and helium.

Hsieh attempted to explain his observations as a temporal change in the rigidity dependence of κ , in which case the simple analysis based on the ratios of fluxes becomes invalid. However, the extension of his data provided by the present analysis confirms the fact that the protons and helium of the same rigidity undergo different fractional modulations. This effect is in no way explainable by a change in rigidity dependence.

It is Hsieh's alternative explanation (i.e., evidence of adiabatic deceleration) that seems more plausible in the light of the present analysis. In our discussion of "simplified" diffusion-convection as presented in Eq. 7.2, we assumed that adiabatic deceleration was a negligible factor. This is probably quite a safe assumption as long as the slope of the energy spectrum remains a small positive ($\ll 1$) or a negative quantity. However, if one calculates the sizes of the terms in Eq. 7.1 for a 100 MeV proton in 1965 at the orbit of Earth, using a solar wind speed of 400 km/sec, a radial cosmic ray density gradient of 60% per A.U. (O'Gallagher 1967), and Jokipii and Coleman's (1968) diffusion coefficient, one finds the following values:

$$\begin{aligned}
 VU &= 4 \times 10^{-6} \text{ part./cm}^2 \text{ sec MeV} \\
 -\kappa \frac{\partial U}{\partial r} &= -5 \times 10^{-6} \text{ part./cm}^2 \text{ sec MeV} \\
 -\frac{V}{3} \frac{\partial}{\partial T} (\alpha TU) &= -4 \times 10^{-6} \text{ part./cm}^2 \text{ sec MeV}
 \end{aligned} \tag{7.6}$$

The adiabatic deceleration term is of the same magnitude as both the diffusion and convection terms. We have neglected the possibly important fact that the diffusion most probably is not radial but rather along the "garden hose" field (Parker 1965, Axford 1965). Nevertheless the streaming is inward at low energies as long as a positive gradient exists and the slope of the energy spectrum remains ≥ 1 .

The magnitude of this streaming would result in an anisotropy of 1.5%, which is much larger than the largest anisotropy observed by Rao et.al. (1967). Those authors observed an anisotropy of $0.34 \pm .30\%$ for 45 - 90 MeV particles. This conflict of large gradient and low streaming has been discussed in more detail by Jokipii and Parker (1968) and Forman (1968). Further complications to the gradient picture are the observations of Anderson (1968) and Krimigis (1968), which indicate rather small gradients.

The whole point of the two previous paragraphs was to justify in some sense the approximations that are about to be made. Let us again consider Eq. 7.1, which describes the streaming of cosmic rays, and assume 1.) that the streaming is zero and 2.) that the gradient term is also small. One is then left with the following equation, which equates diffusion with adiabatic deceleration.

$$VU = \frac{V}{3} \frac{\partial}{\partial T} (\alpha TU) \quad (7.7)$$

We note that the solar wind velocity cancels and that the exact solution including the energy dependence of α is the following

$$U(t) = U_0 [t(t+2)]^{1/2} (t+1) \quad (7.8)$$

Where: $t = T/T_0 = \gamma - 1$. Since we are interested in particle fluxes

$$J = \frac{vU}{4\pi} :$$

$$J(t) = J_0 t(t+2) \quad (7.9)$$

The result, then, is that the slope of the cosmic ray spectrum is very nearly +1 for energies below 1 BeV.

Consider again the proton and helium spectra presented earlier (Figures 16 through 19). We note that the spectral slopes for protons in 1965 and 1967 are 1.09 and 1.14 respectively from 30 MeV to 250 MeV and that the proton spectra for the years for which low energy data is not yet available are certainly consistent with a slope of 1. The slopes of the helium spectra in 1965 and 1967, on the other hand, are about 0.75. We note, however, that the 1969 helium spectrum has a slope of 1, possibly indicating a trend to that slope as the solar cycle progresses.

The interpretation is that once the spectrum bends over at low energies one no longer needs diffusion and a large gradient to balance the convection. This same effect also keeps the spectrum from becoming much steeper than $E^{1.0}$. The cosmic ray spectrum in this model has a sort of "angle of repose." The obvious question now is "If there is no diffusion, how do the low energy cosmic rays ever enter the solar system?" The answer in part is that the low energy cosmic rays seen at the orbit of Earth entered the solar system through the normal diffusion process at

higher energies $\gtrsim 260$ MeV, where we have seen that normal diffusion convection theory is well supported by observations. They are then decelerated to lower energies by the expansion of the solar wind. The high energy particles should have no problem supplying this drain, since 85% of the cosmic rays observed at solar minimum have energies above 260 MeV.

If we again consider Figure 21 and attempt to explain the low energy effects in terms of the present picture, we are reminded of two important properties of modulation that it revealed: 1.) Hsieh's observations that the fractional modulation for low energy protons and helium appear to be the same at the same energy per nucleon rather than at the same rigidity; 2.) the fractional modulations below 250 MeV/nucleon are independent of energy for a given particle species. Using the "angle of repose" concept, one expects the modulation of a given particle species at low energies to be independent of energy and the fractional modulation of that species to equal the fractional modulation that is effective at the energy at which the slope of the spectrum becomes positive.

Since the proton and helium spectra appear to have the same general shape on a energy-per-nucleon basis (Webber 1967), the turn over of the helium spectrum should occur at twice the rigidity of the turn over in the proton spectrum. If we define the turn over rigidity in Figure 21 as the point at which the $R^{1/2}_\beta$ line intersects the fit to the low energy data, we obtain proton and helium turn over rigidities of 0.82 and 1.55 GV, respectively. Now we examine the effect of comparing fractional modulations at the same energy per nucleon by sliding all helium points to the left by a factor of 2 and observe the agreement noted by Hsieh.

This agreement is somewhat fortuitous in this interpretation, in the sense that if the helium data had the same form as the protons, the helium points would still lie somewhat below the corresponding proton points, but the agreement would certainly improve over the rigidity comparison.

In the "explanation" above we have used the observed similarity of the proton and helium spectra compared on an energy/nucleon basis. Since models based on rigidity-dependent modulations operating on power laws in kinetic energy or rigidity predict effects at the same rigidity, one might speculate that the interstellar spectrum exhibits a turn over, or at least a flattening, at some characteristic energy. A power law in total energy is a prime example.

Since the spectral shape predicted by this model is independent of the level of modulation, one would expect that the low energy radial gradient would be equal to the presumably smaller gradient at the turn-over energy. The model is thus somewhat self-consistent, in that we assumed that we could ignore the gradient term in Eq. 7.1. However, the radial gradient observed by O'Gallagher (1967) even at higher energies is such that the diffusion cannot be ignored in that equation as long as the diffusion coefficient remains of the order $2 \times 10^{21} \text{ cm}^2/\text{sec}$.

Due to its complexity, the general solution to the modulation problem including adiabatic deceleration has not yet been obtained. Jokipii (1967) and Fisk and Axford (1969) however, have solved the problem by assuming a diffusion coefficient of the form $\kappa = K T^a r^b$. $a \approx 0.5$ to 1, according to most accepted forms of κ . Jokipii's solution for $b < 1$ results in a complicated integral equation involving the confluent hypergeometric

function and an arbitrary adjustable function for which no solutions have yet been published. He does obtain, however, an approximate solution for comparison of low energy fluxes measured at two different times assuming $b \sim 0.6 - 1.0$ and $r V/\kappa$ large. This solution predicts that the fractional modulation will retain the T^a energy dependence of the diffusion coefficient. The quarrel with this solution would be the assumption of large $r V/\kappa$, which Jokipii himself estimates to be of order 1.

Fisk and Axford (1969) have published sample spectra, but their solution applies to a power law in kinetic energy and $b > 1$. The solutions obtained with this strong radial dependence produce very steep low-energy spectra and large radial gradients. The implementation of such a strong radial dependence in κ conflicts with Jokipii and Coleman's (1968) observations of magnetic power spectra at the orbits of Earth and Mars (1.0 and 1.5 A.U.), which indicate a negligible change in diffusion coefficient with radius. It's quite apparent that further theoretical work is required in this area.

Before concluding this discussion, it is of some interest to apply the concepts presented here to a somewhat unrelated cosmic ray problem - that of the abundance of low energy heavy cosmic ray nuclei. The spectra of 20 - 200 MeV/nucleon nuclei ranging from $Z = 2$ to $Z \approx 26$ observed by Comstock et al. (1966, 1969) show a remarkable but puzzling similarity in shape. One expects that the spectra of the higher Z nuclei would be depleted at low energies due to their expected ionization losses in passing through the standard 3 gm/cm^2 slab of interstellar matter. The observed similarity forced Comstock (1969) to propose the following two

alternatives: 1.) a two-component model, one component of which had not passed through any significant amount of matter, 2.) an efficient accelerating mechanism for low energy particles in interstellar space.

Our previous discussion would add a third alternative explanation - that of an efficient decelerating mechanism in interplanetary space. The model presented here would attempt to explain the observed spectra as primarily a property of the interplanetary propagation. The particles seen at Earth actually come from significantly higher energies where ionization losses would be considerably less. The sought after ionization effects could actually exist in interstellar spectra, producing steeply falling spectra at low energies. But the fact that the adiabatic deceleration term in Eq. 7.1 varies strongly with spectral slope quickly forces the spectrum toward the more gentle $E^{1.0}$ form. In actuality the C. N. O spectra presented by the authors are best fit by a power law $\propto E^{0.43}$ certainly not as steep as the protons or helium. However, we noted that the effects of adiabatic deceleration as shown in Figure 21 for helium (which has the same Z/A) were significant long before the spectrum had reached the full slope $E^{1.0}$. Certainly it suffices to say that adiabatic deceleration is a complicating factor in the analysis of these spectra.

CHAPTER VIII

CONCLUDING REMARKS

In conclusion we note that in order to explain the low energy proton and helium results satisfactorily, we came up with a rather pessimistic picture of the origin of the low energy cosmic rays seen at Earth. They were merely decelerated high energy cosmic rays. The spectra contain only one element of information — that adiabatic deceleration is the dominant factor. One must always be very cautious of pessimistic conclusions, especially when their development is based on selection of elements of a conflicting data set. Obviously one solution is to test the hypothesis by remeasuring and trying to reconcile the radial gradients and anisotropies. Other tests involve further satellite measurements of the proton and helium spectra in 1968 and 1969 to confirm the persistence of the invariant spectral shape throughout the solar cycle. Yet another confirmation would lie in the observation of radio-isotope ratios of high and low energy particles. For cosmic ray ages in the appropriate interval, one expects the high-energy isotopes to prevail due to the effect of time dilation. Adiabatic deceleration would predict energy independence. However, the usual lesson in this case is that energy dependence of production mechanisms predominates. In the absence of further measurements there is certainly room for more extensive numerical calculations which include the effects of long term time variations and the depletion of the region around the spectral maximum.

Lacking any of these more conclusive tests, we are obliged at this point to stress the importance of adiabatic deceleration in low energy cosmic ray propagation and urge that interpretations of low energy results at least consider the effects of local propagation phenomena.

APPENDIX A

GEOMETRIC FACTOR

For purposes of calculating the geometric factor, the 121 four-fold coincidences in the directional filter can be considered as 121 elementary telescopes consisting of squares whose edge is one tube diameter and whose separation is the center-to-center spacing of the directional filter trays. The standard correction for the fact that the tubes were cylindrical (Greisen 1942) was not applied, because it would amount to counting overlapping areas twice (a highly inclined particle may actually pass through two real telescopes but will pass through only one of the elementary telescopes). It would be valid to apply this correction to the 20% of the telescopes that were edge telescopes, but it was deemed too small to worry about.

The 121 elementary telescopes consist of 36 telescopes whose centers are offset one tube diameter in both directions (double diagonals), 60 telescopes with an offset in only one direction (single diagonals), and 25 telescopes with no offset (verticals). If we think of the telescopes as a three component vector $\begin{pmatrix} v \\ s \\ d \end{pmatrix}$ whose basis vectors are the three types of elementary telescopes, we can imagine defining a set of new basis vectors whose geometric factor can be calculated using the formulae of Critchfield, Ney and Oleksa (1952). The requirement of the new basis is that all telescopes describe rectangular solids. A basis that satisfies this requirement consists of:

A = The old vertical telescope 1 × 1 tube: $\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$

B = A vertical telescope 1 × 2 tubes: $\begin{pmatrix} 2 \\ 2 \\ 0 \end{pmatrix}$

C = A vertical telescope 2 × 2 tubes: $\begin{pmatrix} 4 \\ 8 \\ 4 \end{pmatrix}$

The detector's telescope vector is: $\begin{pmatrix} v \\ s \\ d \end{pmatrix} = \begin{pmatrix} 25 \\ 60 \\ 36 \end{pmatrix} = A - 6B + 9C$. It is

now a simple matter of combining the geometric factors to find:

$$G_n = 121 \frac{w^4}{h^2} \left\{ 1 - 0.7121 (n+3) \left(\frac{w}{h} \right)^2 + 0.4162 (n+3) (n+5) \left(\frac{w}{h} \right)^4 + 0 \left(\frac{w}{h} \right)^6 \right\} \quad (A.1)$$

w and h are the width and height of the telescope, respectively, and n is the exponent plus one of the cosine in the zenith angle distribution of the cosmic ray intensity. (n = 1 for isotropic fluxes and 3 for a $\cos^2 \theta$ distribution such as sea level mesons.)

The geometric factor used in calculating particle fluxes also includes corrections for Geiger tube efficiency and the fact that edge telescopes in trays 2 and 4 look beyond the ends of the tubes in tray 1. The efficiency correction assumes that the tray efficiency for trays 1 - 4 is the same as the measured efficiency for trays 5 - 9, excluding any dead tubes. (See Appendix B for a discussion of Geiger tube efficiency.) For a tray inefficiency ϵ the geometric factor is then reduced by an amount $(1 - \epsilon)^4$.

The edge telescope correction makes use of one of the housekeeping tables provided by program ULTIMATE. It is a tally of the number of clean events that fire each directional filter telescope. The numbers in the

edge telescopes of trays 2 and 4 fall about a factor of 2 below the average for the non-edge telescopes. An average "filling" factor can be defined as:

$$f = \frac{\text{average rate of all telescopes (1 - 11)}}{\text{average rate of filled telescopes (2 - 10)}} = \frac{\sum_{i=1}^{11} n_i}{\sum_{i=2}^{11} n_i} \quad (\text{A.2})$$

where n_i are the number of clean events in each telescope. This equation ignores the slight difference between geometric factors for inclined and vertical telescopes. The final geometric factor is then computed by multiplying G_n in Eq. A.1 by $(1 - \epsilon)^4 \times f$.

APPENDIX B

GEIGER TUBE INEFFICIENCY AND THE "LEAKAGE" CORRECTION

The fact that the trays of Geiger tubes are not 100% efficient introduces significant corrections into the geometric factor and into the number of events that fall into a certain value of LASTRA. By defining the inefficiency as tray inefficiency we combine the effects of 1) particles passing between tubes, 2) possible dead or partially dead tubes, and 3) dead time inefficiency. This treatment is valid because all these phenomena have the same effect on the data. The tray inefficiency is evaluated by consideration of all cosmic ray events in a particular sample that must discharge a tube in tray 10, discharge one and only one tube in each tray 1 - 9. The absence of a discharge in one tray (5 - 9) is also allowed. The tray inefficiency is then defined for trays 5 - 9 as the ratio of events not firing a tray to the total number of events with a small correction for events that fail to discharge more than one tray. Since the inefficiencies of each of trays 5 - 9 do not vary significantly, the inefficiencies of trays 1 - 4 and tray 10 are then assumed to be equal to the average efficiency of trays 5 - 9 with appropriate corrections for dead tubes when they occur.

The inefficiency observed for sea level mesons is 1.5% and is attributed to the wall thickness of the Geiger tubes. The observed inefficiency for ceiling cosmic rays, however, is about 3%, where the difference can be accounted for in terms of inefficiency due to the 400 μ sec dead time of Geiger tubes. Using the omnidirectional flux of $1.2 \text{ particles/cm}^2 \text{ sec}$

given by Winckler, Bhavsar, and Peterson (1961) for a Geiger tube at ceiling altitudes, one predicts an additional efficiency of 1% due to dead time, which is certainly an order of magnitude explanation of the effect.

Since there is such a high relative population of LASTRA 10 particles compared with LASTRA 9 particles, a "leakage" of only 3% of the LASTRA 10 particles produces an appreciable contamination of the LASTRA 9 matrices plus a 3% reduction in the LASTRA 10 intensity. Similar effects that occur between other pages of the matrix are usually minor, except when there is a dead Geiger tube. As a standard procedure, the first step in any flux calculation is to correct the number of particles in any matrix having a particular value of $L = \text{LASTRA}$ for "leakage" and efficiency according to the following equation.

$$N_{\text{TRUE}}(L) = \frac{\text{Nobs}(L)}{1 - \epsilon(L) - \epsilon(L-1) + \epsilon(L) \epsilon(L-1)} - \frac{\text{Nobs}(L+1) \epsilon(L+1)}{1 - \epsilon(L+1)} \quad (\text{B.1})$$

where: N is the number of particles in any subsection of the matrix, and $\epsilon(L)$ is the inefficiency of tray L . The rather complicated form of the denominator of the first term is due to the fact that events not firing a tube in LASTRA - 1 are treated as events firing an edge tube and therefore are excluded from the matrix. The inefficiencies used are, of course, those obtained by the "in-flight" efficiency evaluation.

It was mentioned earlier that the inefficiency of trays 1 - 4 and tray 10 were assumed to be the same as those for trays 5 - 9 when effects for dead Geiger tubes were included. This introduces the problem of recognizing dead or weak tubes in trays 1 - 4 and 10. A dead or weak tube in the directional filter trays could seriously affect the measured flux if it wasn't detected. The procedure used to verify that all tubes

are working is to intercompare the trigger rates of each of the 11 directional filter telescopes for odd and even numbered trays measured during the flight. Figure 22a is an example of such a distribution and shows that the counting rates of the individual telescopes vary by at most 2% when all are working. Using this method, weak telescopes readily show up, and an appropriate correction can be applied.

Weak tubes in tray 10 show up when one plots a distribution of discharges across the tray for single "through" particles as in Figure 22b. This plot can then be compared with the distribution predicted by a model that assumes straight particle trajectories projected from the directional filter telescopes. An additional inefficiency due to the weak tube can then be computed, to be added to the average tray efficiency.

In closing this section it should be mentioned that the dead tube corrections for trays 1 - 4 and tray 10 were necessary for only one flight out of the whole series included in this analysis.

APPENDIX C

DELTA-RAYS

Penetrating particle events that have a single pair of adjacent discharges in an otherwise normal event comprise about 9% of the LASTRA 10 events. Application of the term delta-ray to all such events suggests the interpretation of "knock-on" electrons firing an adjacent tube that has been applied to these events. Since these events comprise a significant fraction of the non-interacting events, clean directional filter events having a single pair of adjacent discharges in trays 5 - 10 and one discharge in all other trays were placed on pages 7 through 12 of the analysis matrix according to their value of LASTRA. (See Table IV.) By comparing the number of LASTRA 10 events with zero and one delta-ray (pages 6 through 12 respectively) and treating the problem as an exercise in binomial statistics with 6 trials, one obtains the delta-ray probability per tray given in Eq. C.1.

$$p_{\delta} = \frac{n_{12}}{6 n_6 + n_{12}} \quad (C.1)$$

By evaluating p_{δ} for protons and helium separately, we show in Figure 23 that the delta-ray probability can be decomposed into a component proportional to Z^2 and a charge independent-component. The Z^2 component is interpreted as being due to knock-on electrons firing a tube adjacent to the particle trajectory, while the charge-independent component is attributed to the finite probability that an inclined particle can pass through two adjacent tubes (so-called geometric delta rays). The nature of the geometric delta-ray effect is further demonstrated in

Figure 23 by the fact that p_δ increases by an appropriate amount when singly and doubly inclined telescopes are specified, thus allowing more highly inclined trajectories which have correspondingly larger probabilities of discharging adjacent tubes.

The correction of flight events for the effect of delta-rays consists of dividing the observed number of events with no delta-rays by the probability P_0 that an event will not have a delta-ray in any tray.

$$P_0 = (1-p_\delta)^{LASTRA} \quad (C.2)$$

The value of p_δ used here, however, does depend on particle energy, fortunately in a rather simple way. Using Rossi's (1952) discussion of delta-rays and assuming the "knock-on" electrons are more energetic than 500 keV, one can show that such delta-rays can originate only from protons or helium nuclei of energies greater than 250 MeV/nucleon. Clearly this fact restricts the correction for "real" delta-rays to LASTRA 10 where there is a measurement of p_δ , while the geometric delta-ray correction applies to all energies.

APPENDIX D

SENSITIVE TIME DETERMINATION

It was noted in the main text that the distribution of waiting times always follows an exponential of the form

$$N(t) dt = \frac{N_0}{\tau} e^{-t/\tau} dt \quad (D.1)$$

for times less than the readout period, but that during noisy periods there is a significant departure from this distribution for times larger than one readout period. Under the assumption that the distribution is exactly of the form Eq. D.1 for times $t \leq T$ (the readout time), one can define an average truncated sensitive time τ^* which is given by Eq. D.2.

$$\tau^* = \frac{\tau N_0 \int_0^T \frac{t}{\tau} \exp(-t/\tau) dt / \tau}{N_0 \int_0^T \exp(-t/\tau) dt / \tau} = \tau \left(1 - \frac{T}{\exp(T/\tau) - 1} \right) \quad (D.2)$$

The observed value of τ^* is then easily related to the mean sensitive time by multiple iteration of Eq. D.3.

$$\tau = \frac{\tau^*}{1 - \left(\frac{T}{\tau} \right) \left(\frac{1}{\exp(T/\tau) - 1} \right)} \quad (D.3)$$

Typical values of τ and T are 0.20 and 0.432 sec, respectively, so that the iteration converges fairly rapidly. When the new transmission system was employed in 1967 the bit rate was increased to 4Kc, with a corresponding four-fold decrease in readout time. Since the truncation method works well only when $T/\tau < 1$, the value of T was maintained at 0.432 sec, or four readout periods. While the advantage of eliminating the effects of all missed events is lost, these effects were greatly reduced because the readout time was shorter and because the bit error rate was greatly reduced.

The rejection of the longer dead periods due to tuning and tape dropouts is still maintained, however.

APPENDIX E

MIXING CORRECTIONS

The method of resolving the negative diagonal pulse height distributions into their source components is referred to as the mixing correction. The distribution for each value of LASTRA is divided into three pulse height intervals (labelled A, B, C) each containing background, protons, or helium as its major constituent. The total number of observed events in each interval N_A , N_B , N_C can be expressed in terms of the "true" numbers of protons, helium, or background, M_p , M_α , M_b respectively, if the pulse height distribution of each component is known.

$$\begin{aligned} N_A &= C_{Ab} M_b + C_{Ap} M_p + C_{A\alpha} M_\alpha \\ N_B &= C_{Bb} M_b + C_{Bp} M_p + C_{B\alpha} M_\alpha \\ N_C &= C_{Cb} M_b + C_{Cp} M_p + C_{C\alpha} M_\alpha \end{aligned} \tag{E.1}$$

The mixing constants C are obtained using the synthetic pulse height distributions discussed in the main text. It is a simple matter of inverting a 3×3 matrix to obtain the result in the following form:

$$M_i = D_{iA} N_A + D_{iB} N_B + D_{iC} N_C \quad i = b, p, \alpha \tag{E.2}$$

In practice the constants D depend only on the choice of the pulse height intervals and the shape of the resolution curves, so that the matrix need be inverted only once for each value of LASTRA.

The unmixing correction for a particular flight then simply consists of determining the appropriate pulse height intervals based on the position normalization of the LASTRA helium peak and inserting the appropriate totals into Eq. E.2. As before, the philosophy behind this approach is

the application of standardized procedures so that consistency is maintained throughout the analysis of all flights.

APPENDIX F

NUCLEAR INTERACTION CORRECTION

Since the absorber thickness of the detector, 75 gms/cm^2 , is a fair fraction of an interaction mean free path ($\sigma_{\text{geom.}} = 160 \text{ gms/cm}^2$ for protons and 143 gms/cm^2 for helium), the correction for nuclear interactions could amount to as much as 70% for LASTRA 10 helium. Preliminary investigations of the proton calibration data indicated that a significant fraction of the interactions were not so identified by the detector; therefore, it was decided that the calibration data be used to derive an effective mean free path for protons, and that the balloon data be used to obtain the helium interaction mean free path by comparison of proton and helium interactions.

After it was assured that nearly all clean directional filter events observed in the 4 GV Brookhaven test beam were actually single 4 GV particles, it was easy to obtain the mean free path by observing the number of clean events that were identified by the detector as LASTRA 10, zero delta ray events. When the known efficiency and delta-ray corrections were applied to these events, the effective mean free path $\lambda_p \text{ eff.}$ was obtained from Eq. F.1 .

$$\frac{N_{\text{obs. (LASTRA 10)}}}{N_{\text{clean}}} = \exp[-x(10)/\lambda_p \text{ eff.}] \quad (\text{F.1})$$

$x(10)$ is the depth to the center of tray 10. The proton mean free path obtained from this analysis is $\lambda_p \text{ eff.} = 268 \text{ gms/cm}^2$. If this mean free path is interpreted in terms of a visibility of interactions occurring at a rate given by the geometric mean free path, one obtains a visibility of 60% for proton interactions.

The analysis of the balloon flight data to obtain the helium interaction mean free path concentrates on the numbers of events that appear to interact at or slightly above Trays 7 through 10. The depth of the interaction is defined as the Geiger tube tray in which the first multiple discharge occurs, and the charge of the interacting particle is determined by the dE/dx pulse height. If one considers fluxes of protons and helium, N_{op} and N_{oh} respectively, incident on a slab of material of thickness x , and asks the relative number of each N_{ip} and N_{ih} that will interact in a small absorber thickness Δx just below the larger slab, one obtains the following equation:

$$\frac{N_{ih}(x)}{N_{ip}} = \left(\frac{\Delta x}{\lambda_h} \right) \left(\frac{\lambda_p}{\Delta x} \right) \exp \left(-x \left(\frac{1}{\lambda_h} - \frac{1}{\lambda_p} \right) \right) \quad (F.2)$$

Similarly, the relative numbers not interacting $N_{non p}$ and $N_{non h}$ up to a depth x have the following ratio:

$$\frac{N_{non h}(x)}{N_{non p}(x)} = \exp \left(-x \left(\frac{1}{\lambda_h} - \frac{1}{\lambda_p} \right) \right) \quad (F.3)$$

In the present analysis the ratio defined by Eq. F.2 was obtained at the depths of Trays 7 - 10, and the ratio defined by Eq. F.3 was obtained at the depth of tray 10. Obviously the ratios of these two sets of numbers uniquely define the effective helium mean free path, assuming that the proton mean free path is known. In determining the ratios defined by both Eqs. F.2 and F.3 small, well defined corrections were applied for the selective effects of delta-rays and a small electron contamination to the protons interacting in tray 7. The electron contamination in trays 5 and 6 is so large that the data are not useful in this analysis. The helium mean free path obtained in this analysis is $\lambda_{eff} = 154 \text{ gms/cm}^2$

and gives a visibility of helium interactions of 91%.

The mean free paths obtained in this analysis result in correction factors of 1.32 and 1.62 for LASTRA 10 protons and helium, respectively. Table VIII summarizes the nuclear interaction correction applied to the various values of LASTRA.

APPENDIX G

ATMOSPHERIC SECONDARIES

The largest correction to the low energy portion of the proton spectra is, of course, that for atmospheric secondaries. The method used here consists of a combination of calculation of the spectral shape, altitude dependence, and solar cycle effects with verification of the amplitude of the secondary flux obtained by using a variety of observational data. The generation and propagation of atmospheric secondaries is governed by Eq. G.1 .

$$\frac{\partial n(E,x)}{\partial x} + \frac{\partial}{\partial E} \left(n(E,x) \frac{dE}{dx} \right) = q(E) - \frac{n(E,x)}{\lambda_{abs}} \quad (G.1)$$

$n(E,x)$ is the secondary intensity at an energy E and atmospheric depth x . The first term on the left is the spatial propagation term, and the second term is the energy propagation term due to ionization losses. The source term on the right has been assumed to be independent of atmospheric depth. This is valid to first order, since the nuclear interactions producing the secondaries are caused by high energy cosmic rays whose intensity is observed to be constant over small depths. We have also included a sink term for nuclear absorption of the secondaries. The solution to Eq. G.1 by a method similar to that presented by Ray (1960) is complicated only by the selection of the appropriate ionization and source functions. The dE/dx function was represented (Eq. G.2) as a simple power law which is valid over the interval of interest (10 MeV to 300 MeV).

$$\frac{dE}{dx} = -243.6 E^{-0.78} \text{ MeV/gm/cm}^2 \quad (E \text{ in MeV}) \quad (G.2)$$

With this simplification the solution to Eq. G.1 becomes:

$$n(E, x) = \frac{\exp[R(E)/\lambda]}{|dE/dx|} \int_E^{E''} \exp[-R(E')/\lambda] q(E') dE'$$

$$= \frac{E^{.78}}{243.6} \exp\left\{\frac{E^{1.78}}{(1.78)(243.6)\lambda}\right\} \int_E^{E''} q(E') \exp\left\{\frac{-E'^{1.78}}{(1.78)(243.6)\lambda}\right\} dE' \quad (G.3)$$

$$E'' = [E^{1.78} + (1.78)(243.6)x]^{1/1.78} \quad (G.4)$$

E' is the energy that a particle of energy E at a depth x would have at the top of the atmosphere. $R(E)$ is the range of a particle of energy E .

The source function $q(E)$ which has been used in Eq. G.3 is based on the secondary protons, deuterons and tritons emitted from nuclear interactions induced by cosmic rays in nuclear emulsions [$N(E)$ in Eq. G.5] studied by the Bristol group (Powell et al. 1959).

$$q(E) = 0.85 \Theta(E) N(E) dE \int_z^J \frac{J_{\text{prim}}}{\lambda_z} \quad (G.5)$$

The factor 0.85 is that deduced by Fichtel et al. (1964) for converting secondary intensities observed in emulsions to air. To obtain the fraction of secondaries emitted in the forward direction $\Theta(E)$, the angular distributions of secondary particles given for Al^{27} by Metropolis et al. (1958) have been integrated to obtain:

$$\begin{aligned} \Theta(E) &= 0.77 && \text{protons } 30-90 \text{ MeV} \\ \Theta(E) &= 0.92 && \text{protons } >90 \text{ MeV} \end{aligned}$$

Figure 24 shows that when the angular distribution is folded into the Bristol star spectrum, a two-component power law in energy fits the data fairly well above 50 MeV.

$$N(E) \Theta(E) dE = \left[\left(\frac{E^{1.1}}{1.38} \right)^2 + \left(\frac{E^{2.8}}{17000} \right)^2 \right]^{-1/2} dE \quad (G.7)$$

In the summation in Eq. G.5, $J_{\text{prim}}(Z)$ is the integral primary flux above 250 MeV/nucleon of charge Z , and λ_Z is the corresponding mean free path in emulsion. Particles of higher charge are assumed to be no more effective than protons in the numbers of secondaries that are produced. In principle, each of these terms should involve an integral of nucleon multiplicity times the primary spectrum. However, since the data is available already integrated we need to define a cutoff energy.

The cutoff of 250 MeV/nucleon was selected on the basis of the information presented in Figure 25. It is a plot of the relative importance in secondary production as a function of the energy of the primary. The importance is defined as the multiplicity of the nuclear interaction given by Metropolis (1958), multiplied by the solar minimum proton spectrum presented by Meyer (1969). Multiplication of the curve by the energy E to compensate for the logarithmic scale allows the interpretation of the area under the curve as a number of particles. The cutoff at 250 MeV was somewhat arbitrarily selected because for this detector it is the energy above which integral fluxes are most readily obtained. Note, however, that the cutoff position is not critical. A change of ± 100 MeV would alter the intensity by only $\pm 5\%$. For the lack of any better information, the cutoff for the heavier cosmic rays was also selected as 250 MeV/nucleon.

An absorption mean free path for the secondaries of 150 gms/cm^2 (Chen et al. 1955) was assumed.

Now that all the quantities in Eq. G.5 are defined, the integral in Eq. G.3 can be computed numerically with the resulting spectra shown in Figure 26. These spectra are based on a flux of $2000 \text{ particles/m}^2 \text{ sec}$ of protons and $220 \text{ particles/m}^2 \text{ sec}$ of helium nuclei and 40

particles/m² sec ster of heavier nuclei, with interaction mean free paths of 100, 45 and 25 gms/cm², respectively, and correspond to the calculation and observations of secondary protons made by Freier and Waddington (1968). In Figure 27 the derived secondary spectra are compared with the observed spectra presented by Freier and Waddington, which were obtained from emulsion studies and Teegarden (1967), which were obtained from simultaneous balloon satellite observations. Note that the shapes are all quite similar, and that the Freier and Waddington spectrum has the same intensity as this model predicts above 40 MeV, while the Teegarden spectrum is 20% more intense. We will withhold any interpretation of this difference until the effect of solar modulation has been discussed.

Referring to Figure 25 we are reminded that the flux of secondary cosmic rays is sensitive to the primary intensity in a broad neighborhood around 1.5 GeV. Since the primary intensity at 1.5 GeV is expected to change by 60% over the solar cycle, we should expect a similar change in the secondary flux. The actual change as represented by the areas under the curves in Figure 25 is 55%.

The top section of Figure 25 presents the relative intensity variation of atmospheric secondaries over the solar cycle, as deduced from the bottom of that figure, normalized to the point where the spectral calculation was made. The variation was assumed to be linear over the solar cycle. The points plotted on that line are those determined by fitting the observed secondary spectra mentioned previously with the 3 gm/cm² theoretical curve from Figure 26. It appears that the slight excess of secondaries observed by Teegarden can be explained by solar modulation of the source of the secondaries. In application of the secondary correction to flight data,

the shapes of the secondary spectra were assumed to remain the same with the amplitude being scaled by the use of Figure 25.

As a final verification of the intensity of the secondary flux, we consider the atmospheric "growth curve" presented in Figure 28. The data points in that figure were obtained by combining the LASTRA 4 proton fluxes from the ascent portions of four balloon flights made in 1968 and 1969. The secondaries are most intense and primaries least intense at these low energies (66 - 106 MeV). The curve labelled "secondaries" is the growth curve obtained from the model at the appropriate energy and solar cycle normalization. The curve labelled "primaries" was obtained by propagating a combination of the 1968 and 1969 primary proton spectra through the atmosphere, taking account of ionization and nuclear absorption losses. The curve representing the total proton intensity vs. depth is observed to pass through most of the points up to depths of 50 gms/cm^2 and is only in slight excess from $50 - 100 \text{ gms/cm}^2$. The excess that the model predicts at large depths may be an indication that the source function of the secondaries is diminishing somewhat at these large depths.

This method is somewhat different from the usual procedure of using the growth curves to derive the secondary intensity in that it assumes that the primary spectrum is already known. However, these methods usually assume that the growth processes are linear at small depths. Figure 28, on the contrary, shows that the growth processes are quite complex and are by no means linear. The agreement demonstrated in Figure 28 is interpreted as a further verification of the intensity and solar cycle variation of the secondary correction.

APPENDIX H

EDGE TUBE EFFECTS

A fair fraction of the apparent stopping particles are observed to fire edge tubes in either of the last two trays discharged. This effect is demonstrated in Figure 29, which is a plot of the ratio of stopping events to "through" events as a function of Geiger tube fired. The edge tubes have a much higher ratio of "stopping" events. For this reason, all "stopping" events that fired an edge tube in either of the last two trays discharged were rejected.

Since a small fraction of the real stopping events is rejected by this criterion, an appropriate correction was determined by using the predicted discharge distributions, assuming straight particle trajectories projected from the directional filter telescopes. The validity of these distributions was previously demonstrated in Figure 22b for LASTRA 10 protons.

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Table I

IONIZATION DEPTHS IN THE DETECTOR

Location	DEPTH ~ (gms/cm ² Pb equivalent)	Proton or He Energy/Nucleon*		Proton Rigidity (MV) (1966-1969)	He Rigidity (MV) (1966-1969)
		1965	(MeV/Nucleon) 1966-1969		
Tray 4 (Center)	8.27	67.2	66.4	359	718
Calorimeter Plate 1	18.05	107.6	106.3	459	916
Tray 5 (Center)	20.42	115.9	114.5	477	953
Tray 6 "	29.62	145.1	143.2	538	1073
Tray 7 "	41.96	178.9	176.7	602	1201
Tray 8 "	51.16	201.6	199.1	643	1282
Tray 9 "	63.50	229.7	226.8	691	1376
Tray 10 "	76.52	257.0	253.8	735	1465

* Includes correction for inclined trajectories.

TABLE II SUMMARY OF FLIGHT DATA

Flight	Location	Launch Date	Time *	Ceiling	End of Data	Altitude (millibars)	CEILING DATA			Exposure (m ² sec-ster)	Deep River Neutron Monitor
							Total No.† of Triggering Events	Clean	Total No.†† of Triggers		
1036	Churchill	8/2/65	1234	1430	1730	6.3	7,765	3,260	1.02	6999	
1037	Churchill	8/7/65	1130	1320	1730	6.5	16,477	8,005	2.53	7014	
1038	Minneapolis	9/8/65	1210	1350	2251	8.0	38,612	17,037	6.66	7042	
1178	Churchill	8/6/66	0928	1200	2200	6.3	17,942	7,412	2.56	6860	
1056	Minneapolis	8/27/66	1200	1540	2140	8.2	32,962	13,358	5.32	6880	
1057	Minneapolis	8/30/66	0022	0215	2340	9.0	116,386	48,767	19.74	6840-6600	
1208	Churchill	7/31/67	1007	1300	0046 8/1/67	3.4	128,501	50,569	21.72	6572	
974	Sioux Falls	9/14/67	1334	1620	1905 9/15/67	3.3	215,727	73,325	34.69	6614	
975	Sioux Falls	9/21/67	2356	0215 9/22/67	2332 9/22/67	4.0	168,429	55,247	27.56	6536	
1236	Churchill	7/18/68	0120	0530	1818	2.5	128,415	41,852	22.92	6414	
1244	Churchill	7/23/68	2007	0030 7/24/68	1321	2.0	135,876	43,641	23.31	6462	
1078	Minneapolis	9/5/68	1204	1440	1805	5.0	34,731	11,773	6.79	6324	
1079	Minneapolis	9/10/68	1137	1430	2251	4.6	307,443	94,903	59.17	6416	
1273	Churchill	7/11/69	2048	2246	1604 7/12/69	4.7	165,002	52,358	34.41	6174	
1274	Churchill	7/18/69	0500	0730	0141 7/19/69	4.7	147,265	46,941	30.25	6225	

* All times are Universal Time.

† This includes only the events received without bit errors.

†† Clean triggers are defined as events in which one and only one tube was fired in trays 1-4. The analysis was limited to this class of events.

TABLE III SUMMARY OF CALIBRATION DATA

Particles	Total No. [†] of Triggering Events	Total No. ^{††} of Clean Triggers	Apparent Stopping Particles	Apparent Non-Interacting Thru Particles	Apparent Interacting Particles
4GV P+ π No Pb	2209	1442	85(5.9%)	949(65.8%)	494(34.2%)
2GV P+ π No Pb	3580	2655	132(5.0%)	1863(70.2%)	792(29.8%)
4GV P+ π With Pb	4700	3343	98(2.9%)	2332(69.8%)	913(27.3%)
2GV P+ π With Pb	4910	3487	163(4.7%)	2466(70.7%)	858(24.6%)
105MeV electrons	3024	2436	920(37.8%)	1(.04%)	1515(62.2%)
150MeV electrons	3726	3060	810(26.5%)	6(0.2%)	2244(73.3%)
300MeV electrons	3899	3135	202(6.4%)	92(2.9%)	2841(90.6%)
600MeV electrons	3971	3136	17(0.5%)	60(1.9%)	3059(97.5%)
1200MeV electrons	5570	4468	1(.02%)	10(0.2%)	4457(99.8%)
Sea level muons plus electrons	2295	1819	214(11.8%)	1418(77.9%)	187(10.3%)

[†] This includes only the events received without bit errors.

^{††} Clean triggers are defined as events in which one and only one tube was fired in trays 1 - 4.

TABLE IV
IDENTIFICATION OF MATRIX PAGES

Page Number	Event Classification
0	LASTRA ¹ = 4 No δ -rays ²
1	LASTRA = 5 No δ -rays
2	LASTRA = 6 No δ -rays
3	LASTRA = 7 No δ -rays
4	LASTRA = 8 No δ -rays
5	LASTRA = 9 No δ -rays
6	LASTRA =10 No δ -rays
7	LASTRA = 5 One δ -ray
8	LASTRA = 6 One δ -ray
9	LASTRA = 7 One δ -ray
10	LASTRA = 8 One δ -ray
11	LASTRA = 9 One δ -ray
12	LASTRA =10 One δ -ray
13	ISHOWR ³ = 5 Interacting Event ⁴
14	ISHOWR = 6 Interacting Event
15	ISHOWR = 7 Interacting Event
16	ISHOWR = 8 Interacting Event
17	ISHOWR = 9 Interacting Event
18	ISHOWR =10 Interacting Event
19	LASTRA =10 Single Lateral Gap ⁵

¹LASTRA is the number of the last tray containing a Geiger tube discharge.

²A δ -ray is defined as a pair of adjacent Geiger tube discharges in a tray.

³ISHOWR is the number of the first tray in which a multiple discharge occurs.

⁴Interacting events are defined as events with two or more discharges over one per tray.

⁵A single lateral gap is defined as a single pair of non-adjacent discharges.

TABLE V

INTEGRAL FLUX MEASUREMENTS (Particles / M ² Sec. Ster.)						
Flight	Deep River Neutron Monitor	Clean Flux	Protons E > 260 MeV.	Protons 260 < E < 720 MeV.	Protons E > 720 MeV.	Helium E > 260 MeV/Nuc.
Churchill:						
1036	6999	2974 ± 96	2506 ± 114	822 ± 114	1684 ± 114	213 ± 26
1037	7014	2912 ± 88	2369 ± 87	756 ± 64	1613 ± 87	247 ± 18
1171	6872	2729 ± 79	---	---	---	---
1174*	6839	2664 ± 78	---	---	---	---
1178	6860	2737 ± 80	2141 ± 79	583 ± 47	1558 ± 79	246 ± 17
1195*	6679	2263 ± 60	---	---	---	---
1208	6572	2139 ± 60	1675 ± 52	446 ± 17	1229 ± 52	195 ± 7
1236	6414	1723 ± 51	1349 ± 43	335 ± 16	1014 ± 43	188 ± 7
1244	6462	1784 ± 53	1422 ± 45	327 ± 16	1095 ± 45	188 ± 7
1273	6174	1368 ± 39	1101 ± 35	246 ± 11	854 ± 35	159 ± 6
1274	6225	1387 ± 39	1123 ± 35	196 ± 11	927 ± 35	149 ± 6
Minneapolis/Sioux Falls:						
1038	7042	2278 ± 69	1989 ± 66	403 ± 66	1586 ± 66	243 ± 12
1056	6880	2206 ± 66	1789 ± 61	337 ± 29	1452 ± 61	236 ± 12
1057	6840-6600	2155 ± 63	---	---	---	---
1058*	6546	2154 ± 65	---	---	---	---
974	6614	1944 ± 58	---	---	---	---
975	6536	1818 ± 54	---	---	---	---
1078	6324	1525 ± 46	1218 ± 42	269 ± 12	949 ± 42	176 ± 10
1079	6416	1540 ± 46	1223 ± 42	170 ± 10	1053 ± 42	181 ± 5

*Flights made with a similar detector (Neely 1968).

TABLE VI

DIFFERENTIAL PROTON SPECTRA FOR THE YEARS 1965-69

Lastra	1965		1966		1967		1968		1969	
	Flux [†]	Energy ^{††}	Flux	Energy	Flux	Energy	Flux	Energy	Flux	Energy
4	1.05 $\pm$.19	113-144	.88 $\pm$.16	93-127	.52 $\pm$.06	90-125	.51 $\pm$.04	85-120	.23 $\pm$.04	101-134
5	1.66 $\pm$.22	151-176	1.31 $\pm$.20	134-160	.80 $\pm$.06	132-159	.55 $\pm$.04	128-155	.37 $\pm$.04	141-167
6	1.78 $\pm$.26	176-206	1.64 $\pm$.26	160-192	.83 $\pm$.07	159-190	.82 $\pm$.06	155-187	.40 $\pm$.04	167-197
7	2.11 $\pm$.27	206-227	2.14 $\pm$.31	192-213	1.07 $\pm$.08	190-212	.89 $\pm$.06	187-209	.57 $\pm$.04	197-218
8	2.48 $\pm$.28	227-253	1.84 $\pm$.30	213-240	1.10 $\pm$.08	212-238	.91 $\pm$.06	209-236	.65 $\pm$.05	218-245
9	2.37 $\pm$.26	253-279	2.20 $\pm$.27	240-266	1.31 $\pm$.08	238-265	.96 $\pm$.06	236-262	.57 $\pm$.04	245-270
10 (slow)	1.60 $\pm$.20	279-732	1.28 $\pm$.12	266-726	.92 $\pm$.07	265-726	.72 $\pm$.07	262-724	.48 $\pm$.05	270-729

[†] Differential fluxes are quoted in units of Particles / M² Sec. Ster. MeV.^{††} Energies are quoted in units of MeV.

TABLE VII

DIFFERENTIAL HELIUM SPECTRA FOR THE YEARS 1965-69

Year	1965		1966		1967		1968		1969	
	Lastra	Flux [†]	Energy ^{††}	Flux	Energy	Flux	Energy	Flux	Energy	Flux
4		.28 $\pm$.05	113-176	.19 $\pm$.04	93-161	.139 $\pm$.018	91-125	.120 $\pm$.009	85-121	.065 $\pm$.006
5						.175 $\pm$.021	133-159	.124 $\pm$.013	128-155	.086 $\pm$.010
6		.26 $\pm$.05	176-227	.36 $\pm$.07	161-213	.167 $\pm$.020	159-191	.137 $\pm$.014	155-187	.110 $\pm$.011
7						.189 $\pm$.027	191-212	.173 $\pm$.019	187-209	.124 $\pm$.014
8		.41 $\pm$.08	227-279	.36 $\pm$.08	213-266	.191 $\pm$.025	212-238	.183 $\pm$.019	209-236	.125 $\pm$.013
9						.222 $\pm$.030	238-264	.172 $\pm$.021	236-262	.118 $\pm$.015

[†] Differential fluxes are quoted in units of Particles / M² Sec. Ster. MeV./Nuc.^{††} Energies are quoted in units of MeV./Nuc.

TABLE VIII

NUCLEAR INTERACTION CORRECTIONS
FOR PROTONS AND HELIUM

LA STRA	Average Depth (gm/cm ²)	Nuclear Interaction Correction	
		Protons	Helium
4	6.9	1.026	1.046
5	19.0	1.073	1.131
6	28.0	1.110	1.199
7	40.1	1.161	1.297
8	49.0	1.200	1.376
9	61.2	1.256	1.488
10	74.1	1.319	1.618

$$\lambda_{\text{proton}} = 268 \text{ gms/cm}^2$$

$$\lambda_{\text{helium}} = 154 \text{ gms/cm}^2$$

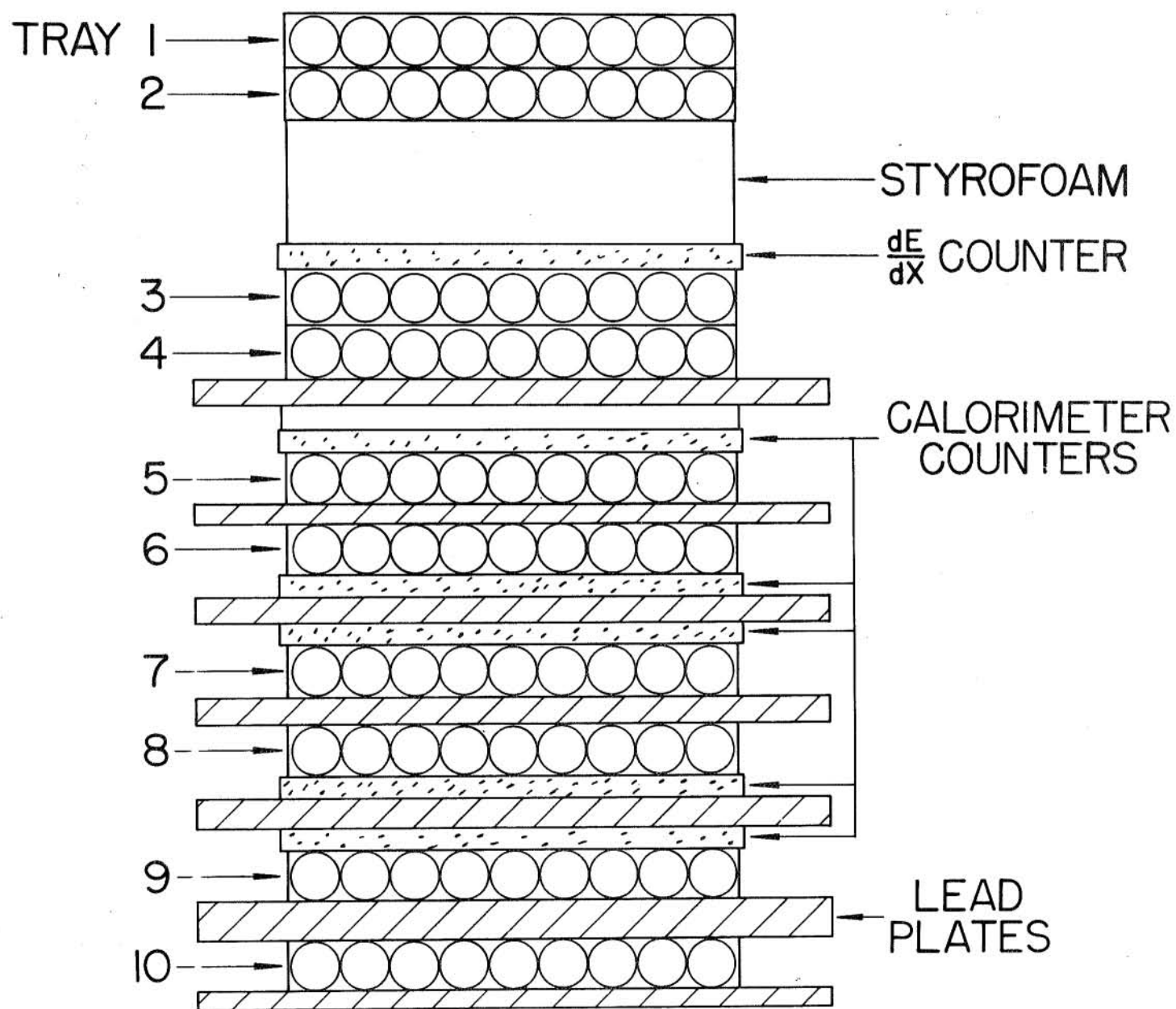


Figure 1.

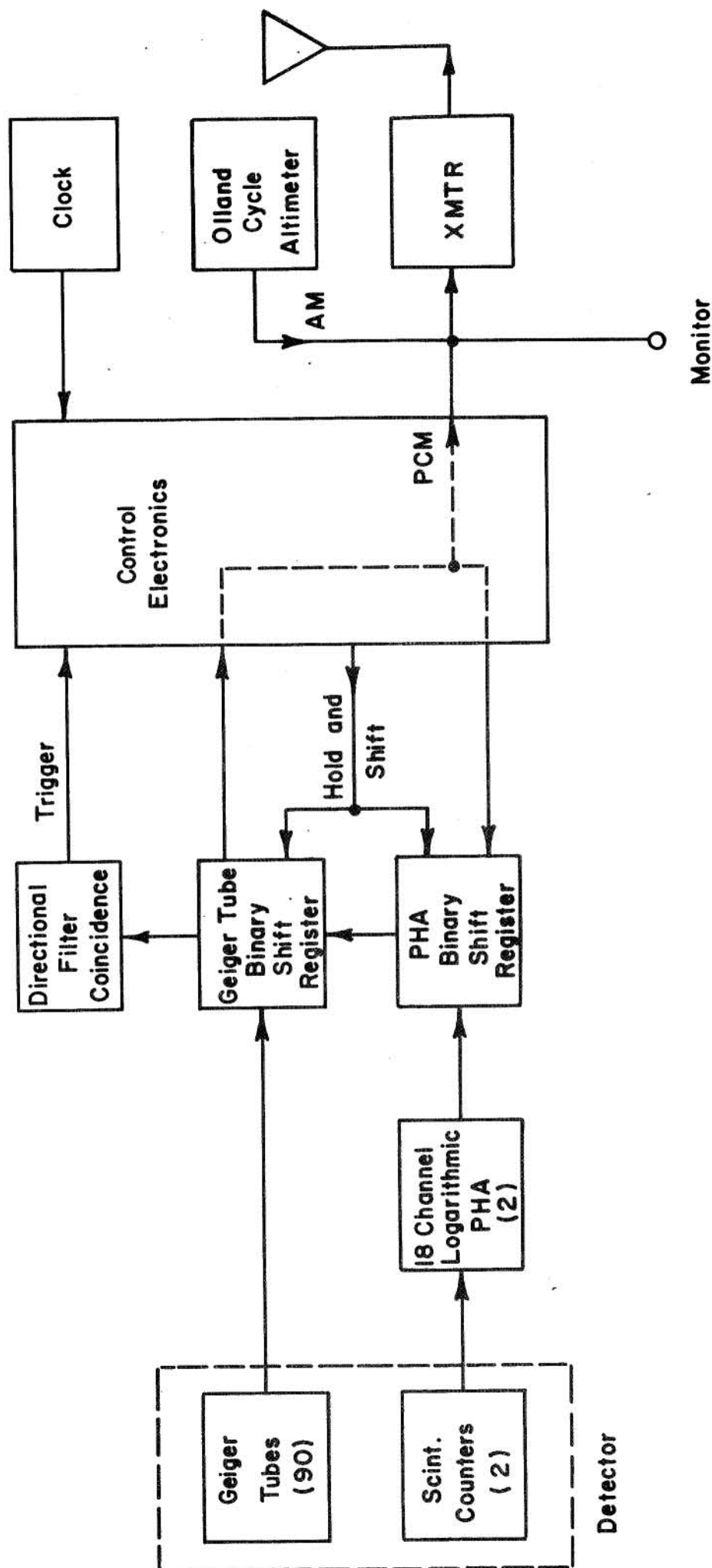


Figure 2.

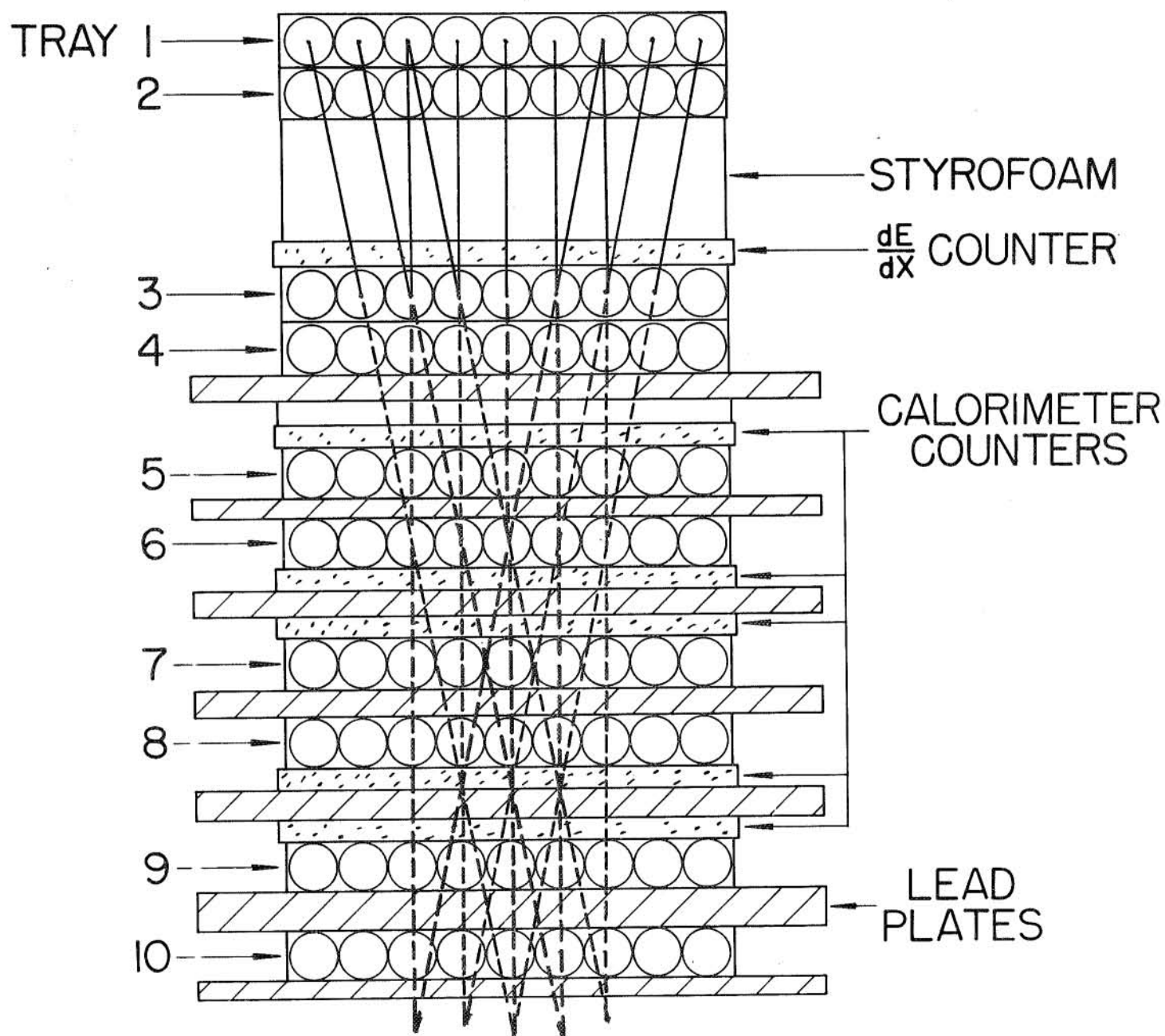


Figure 3.

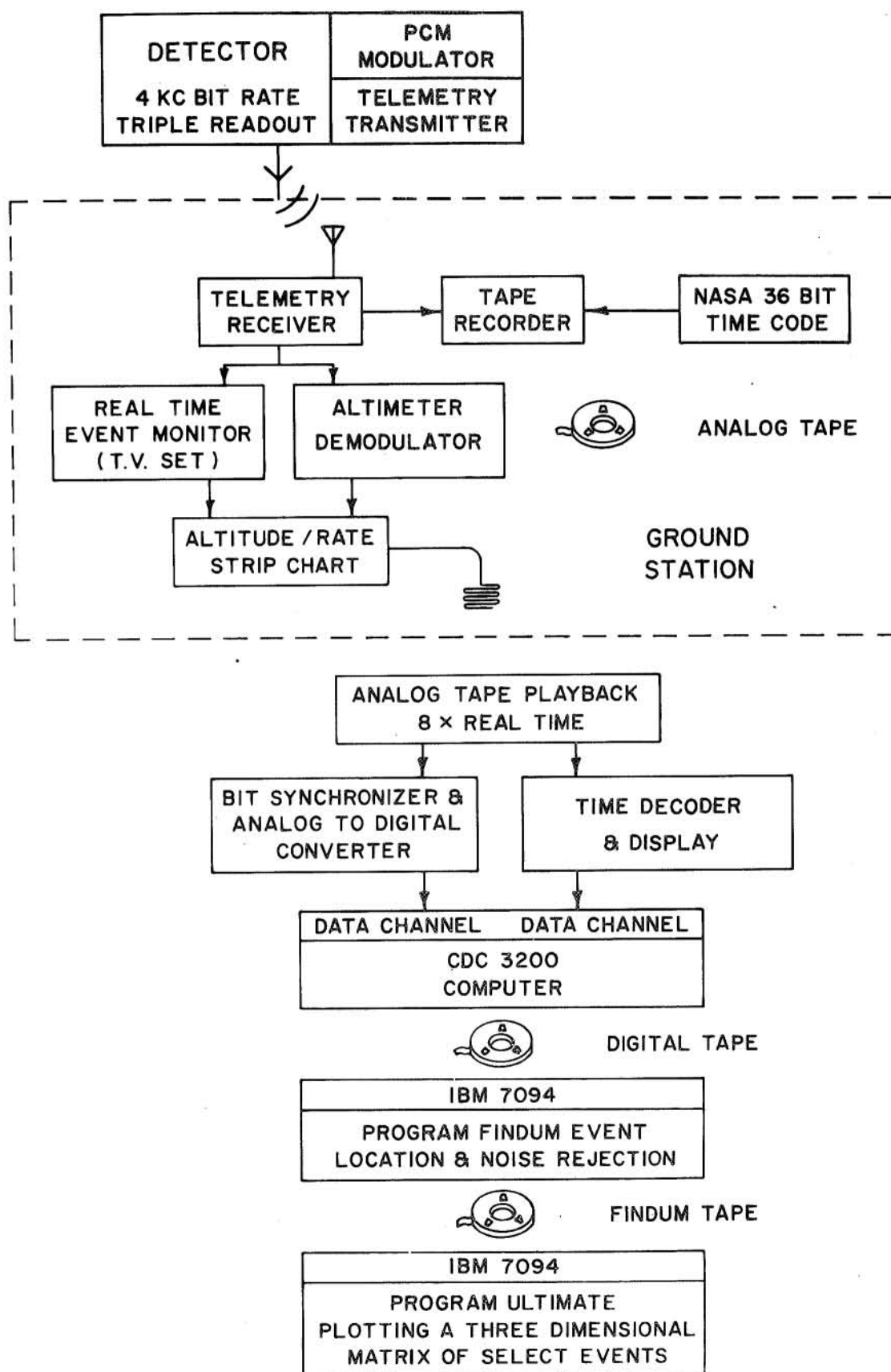


Figure 4.

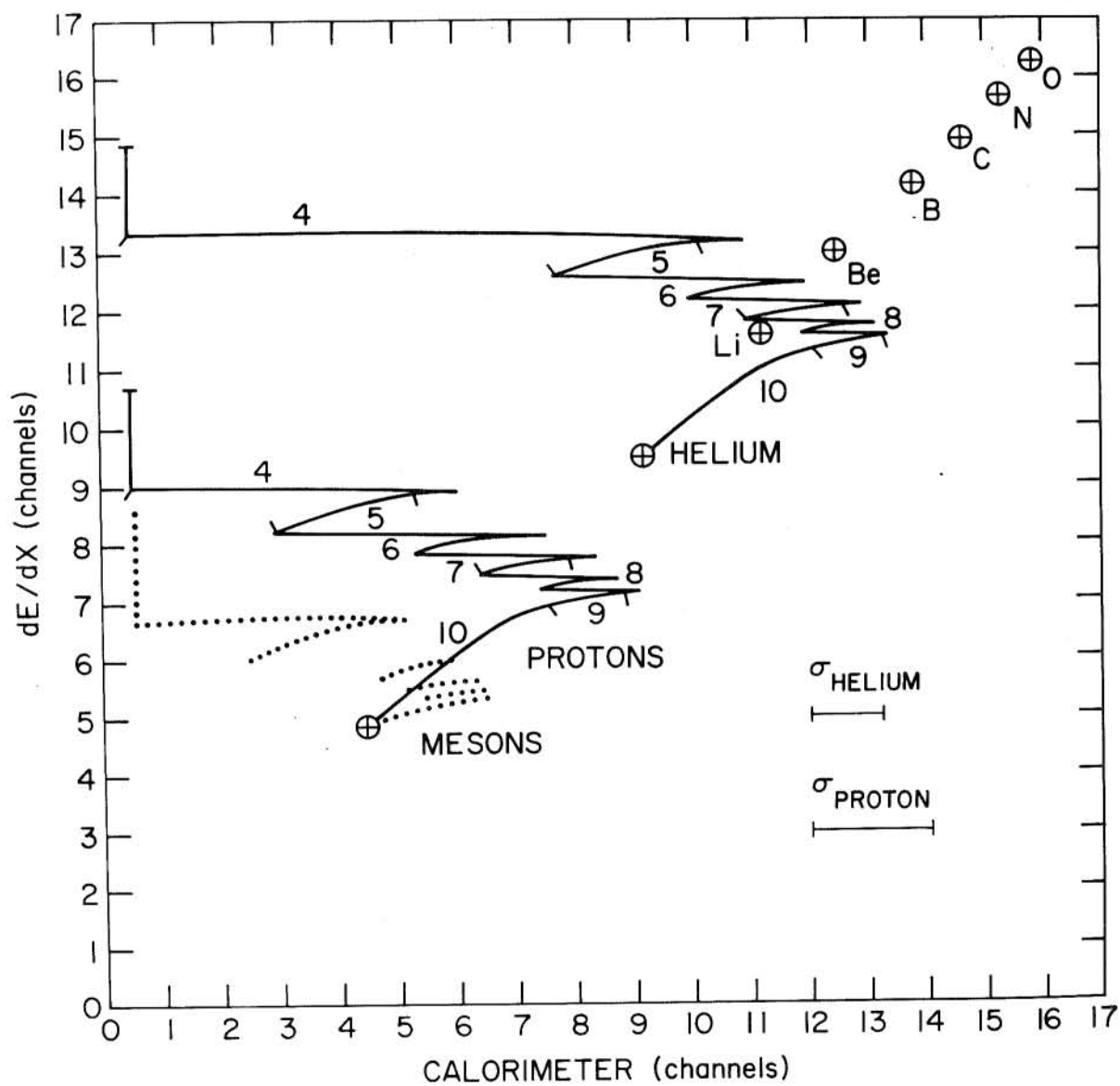


Figure 5.

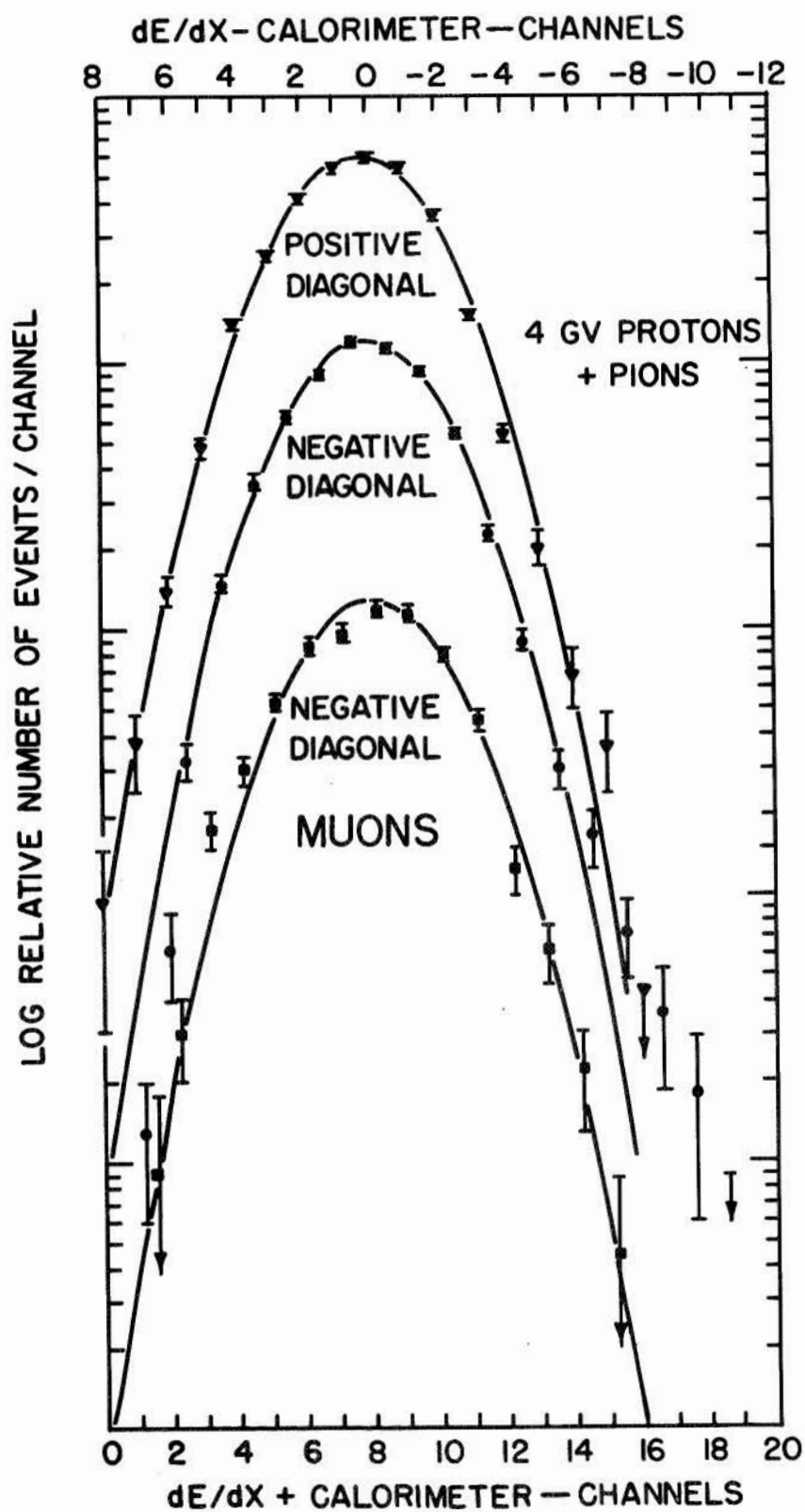


Figure 6.

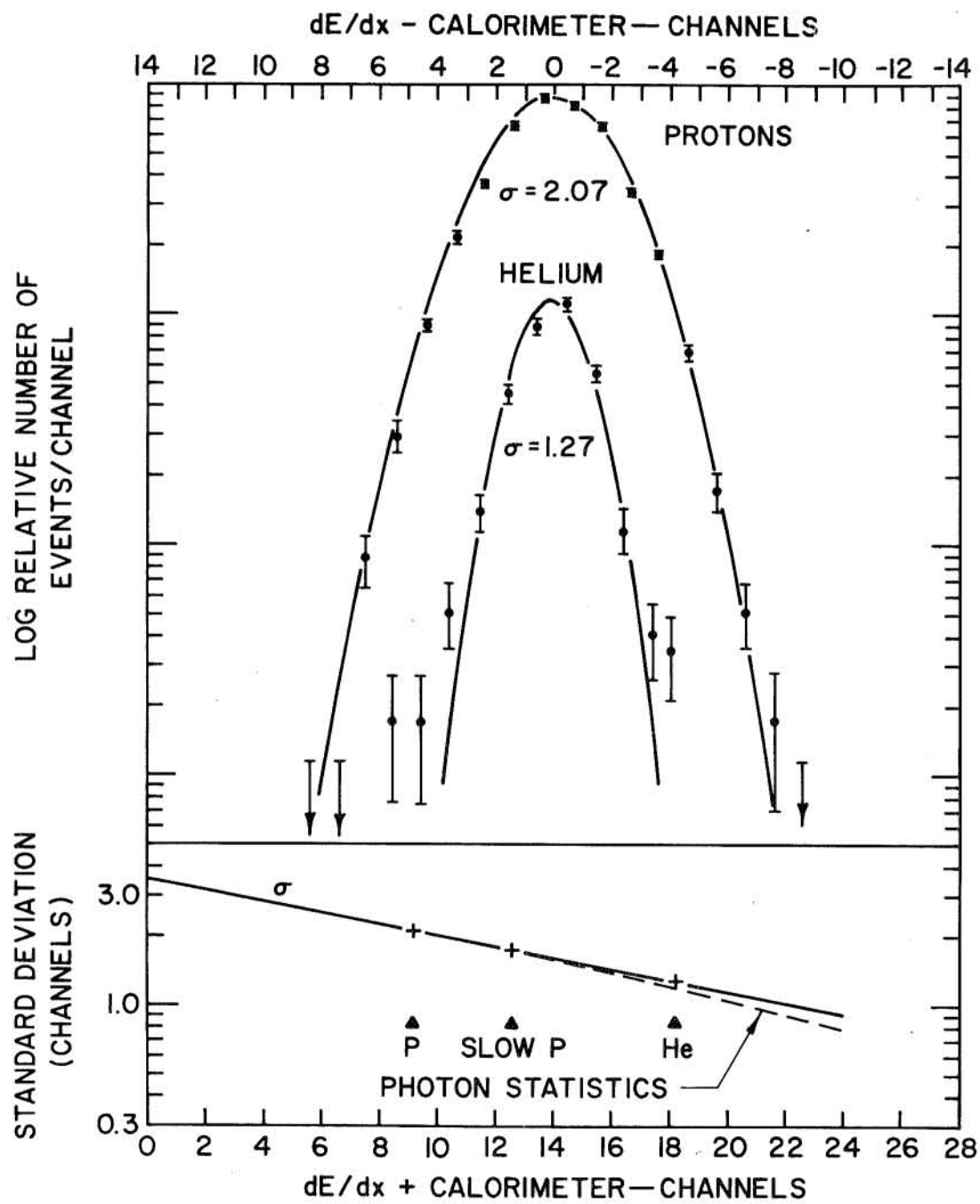


Figure 7.

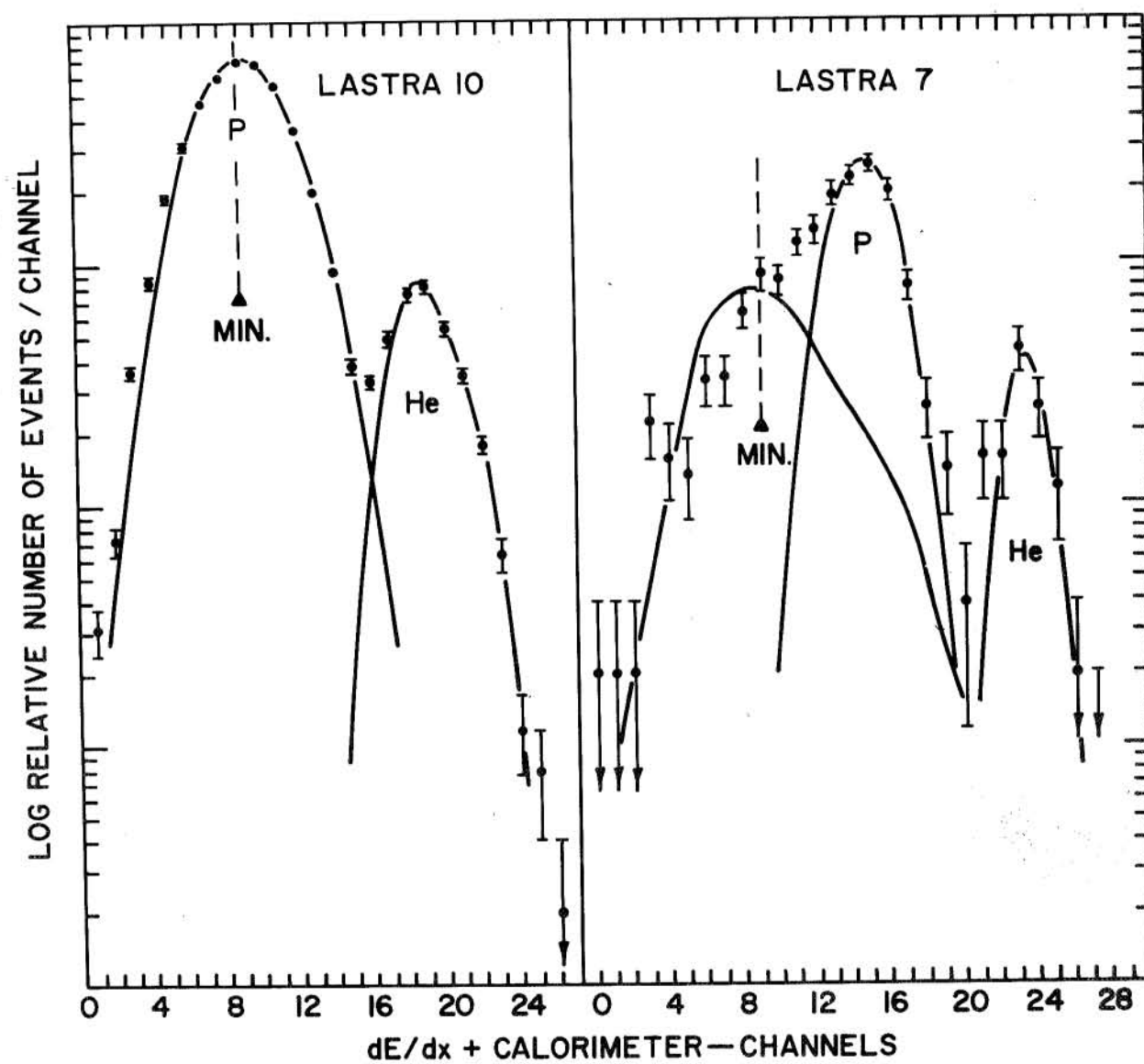


Figure 8.

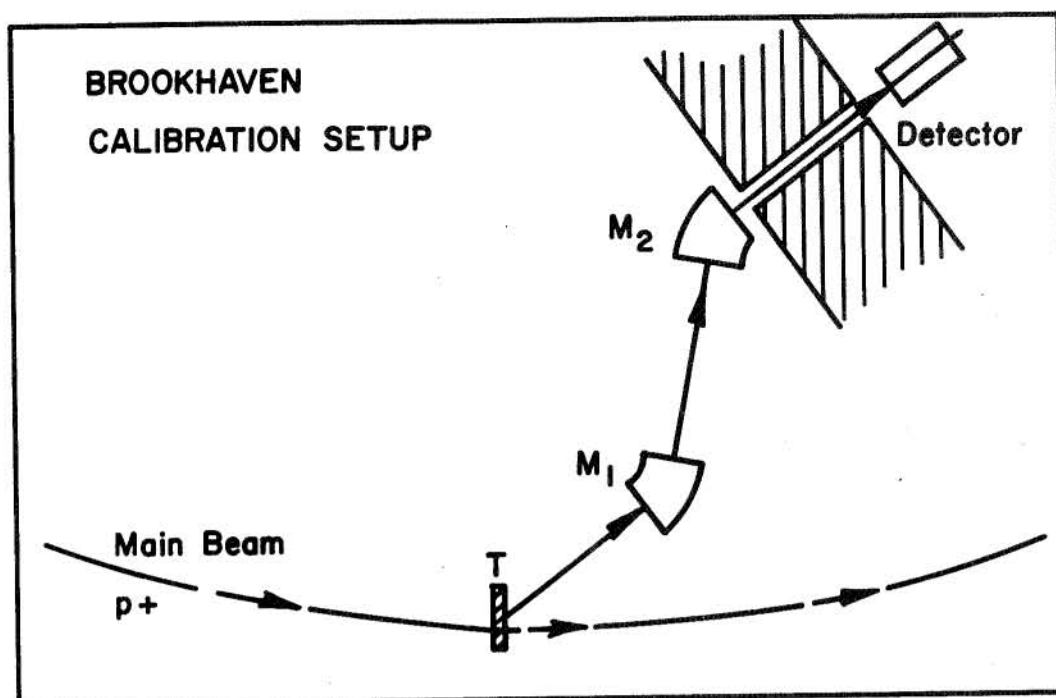


Figure 9a.

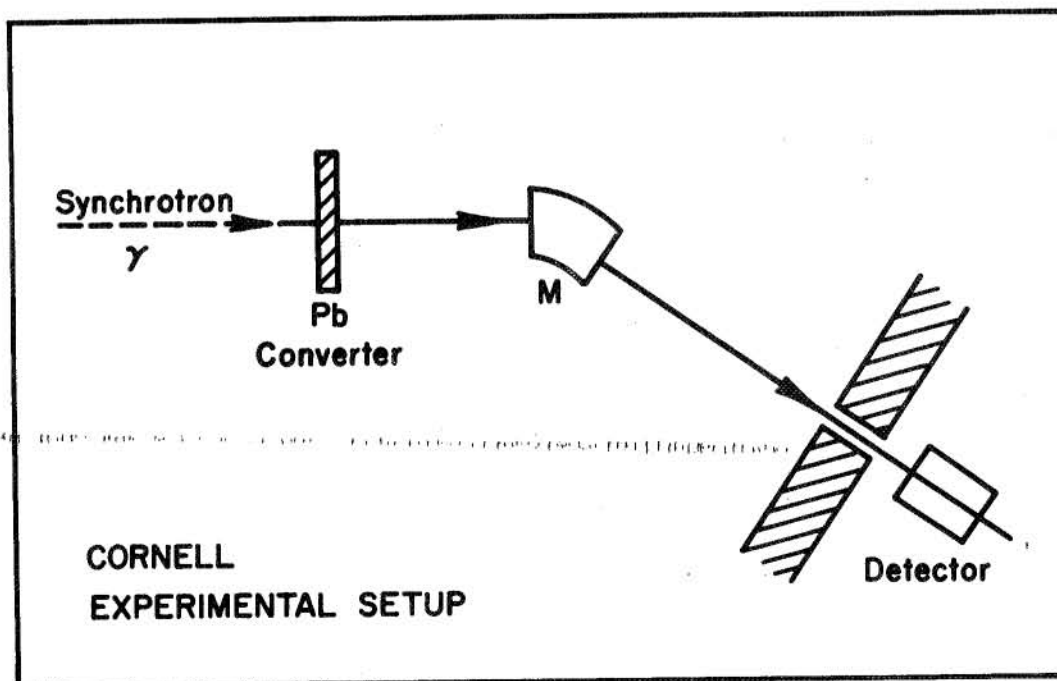


Figure 9b.

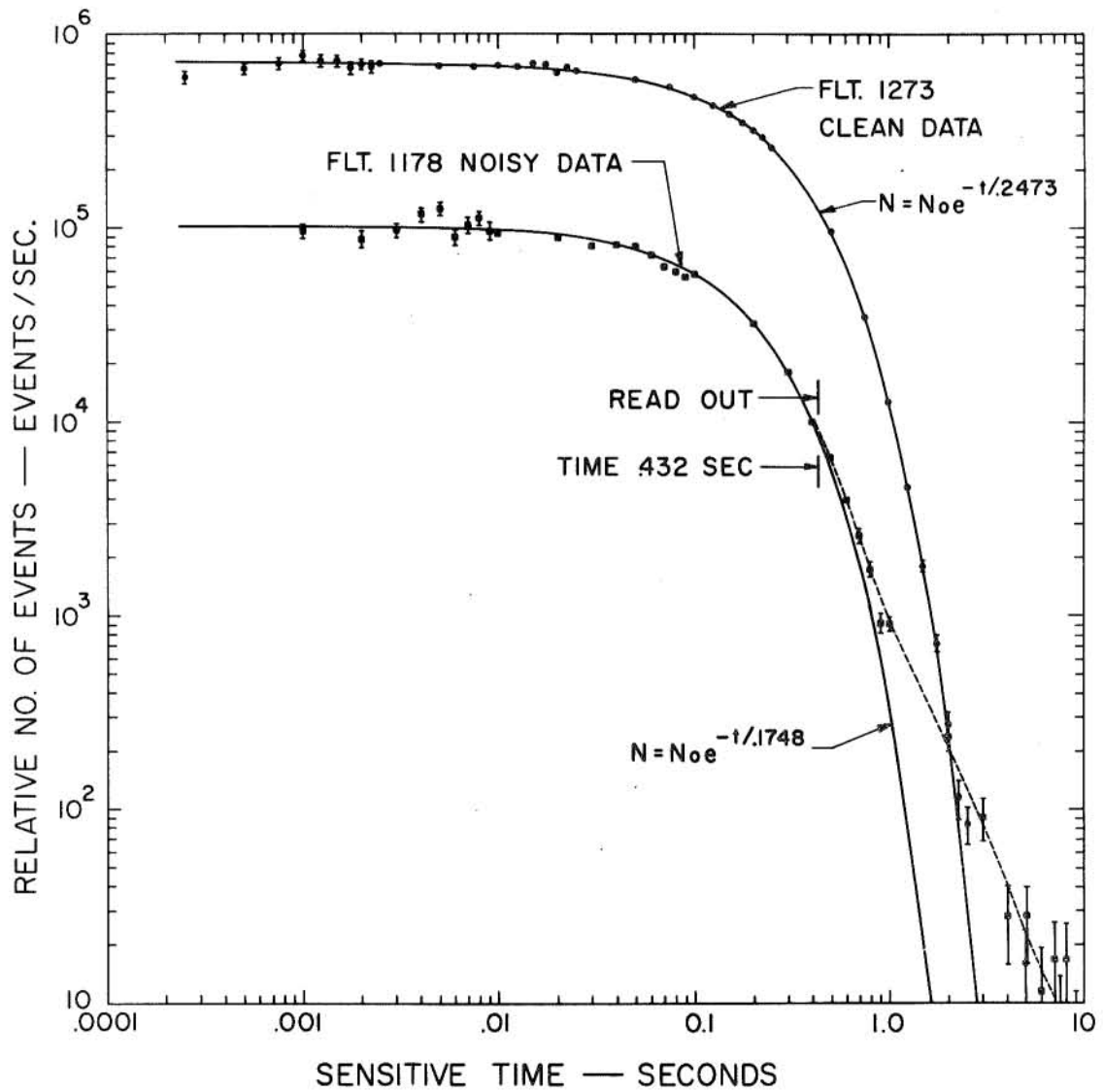


Figure 10.

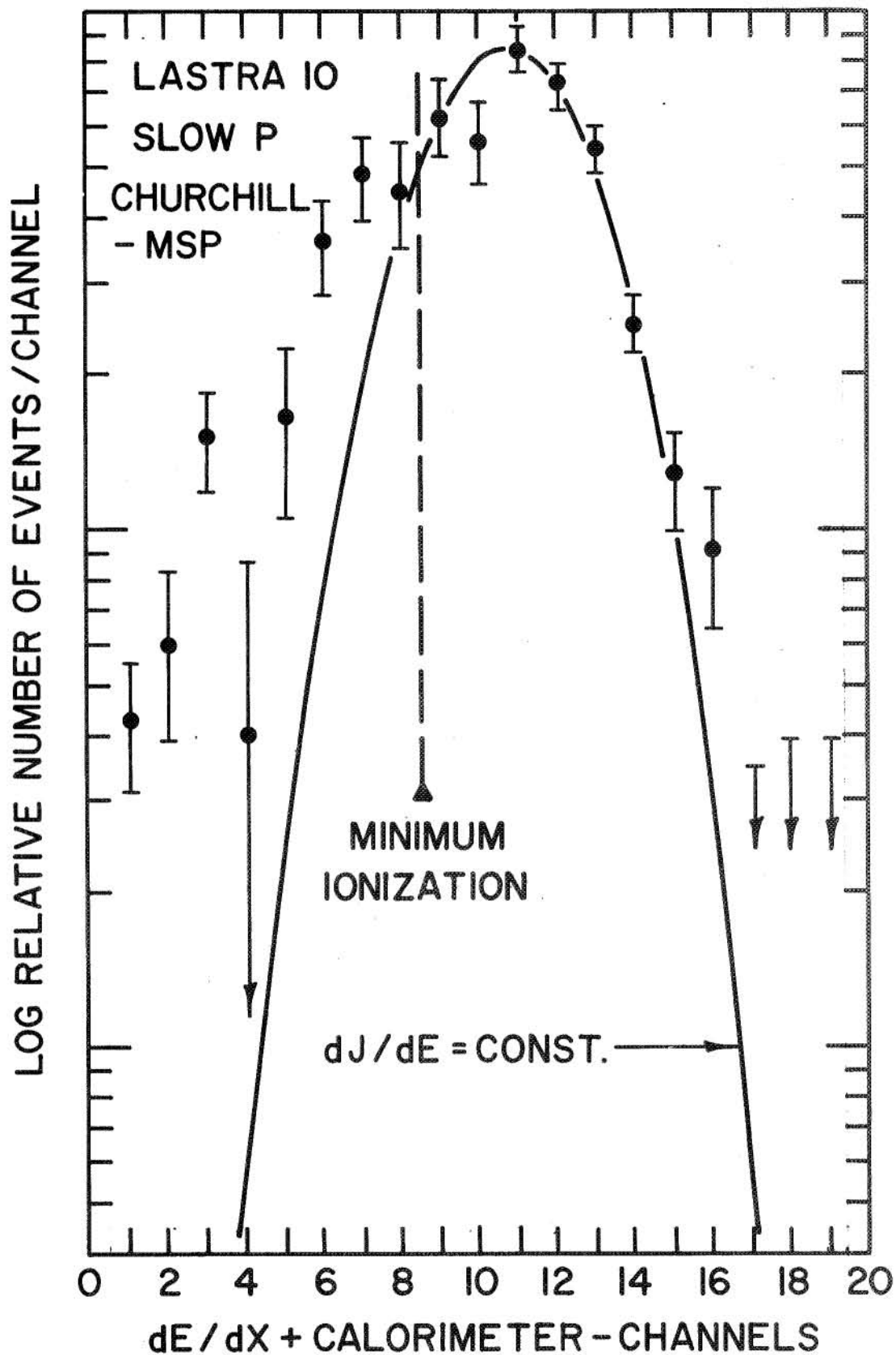


Figure 11.

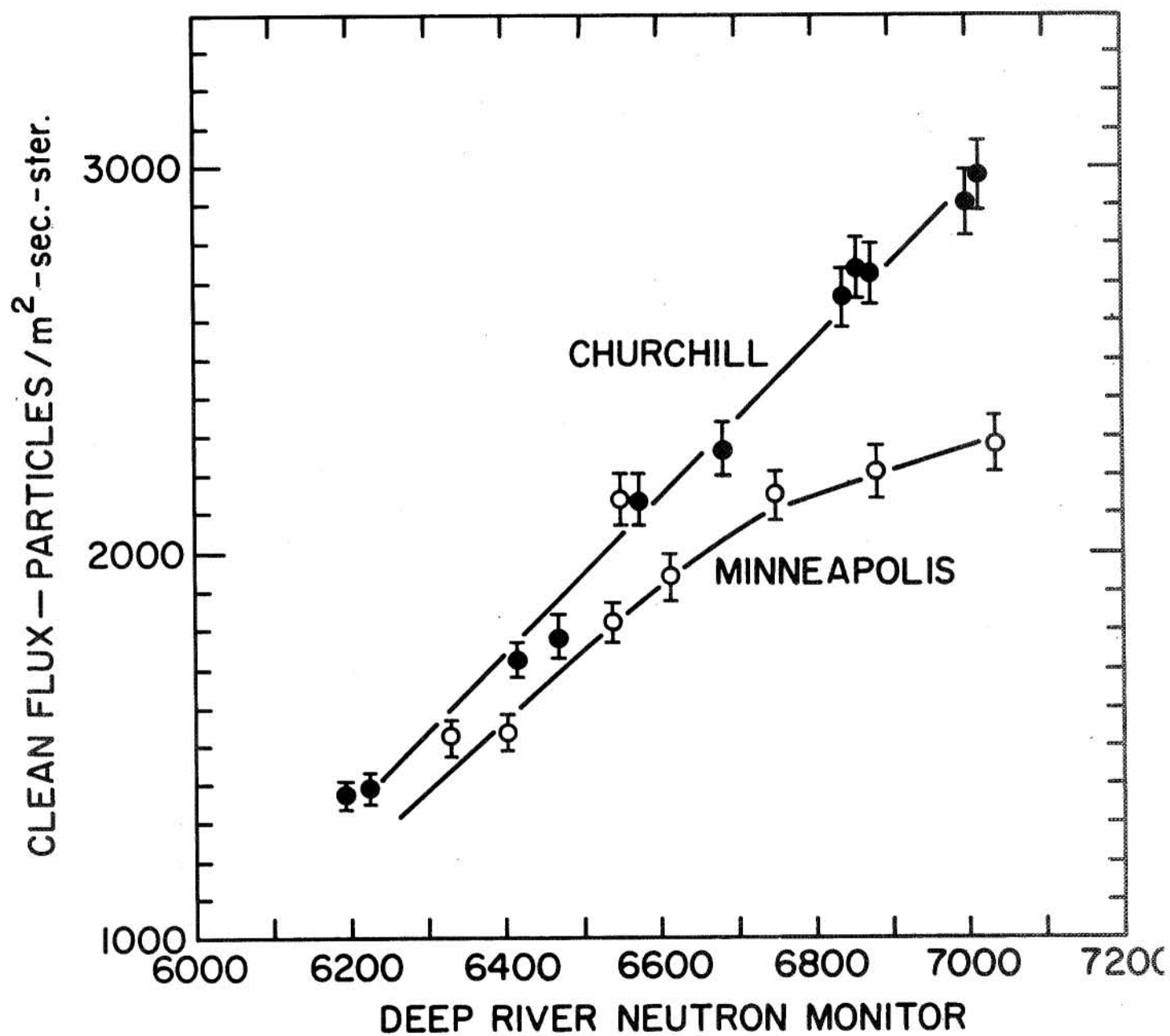


Figure 12.

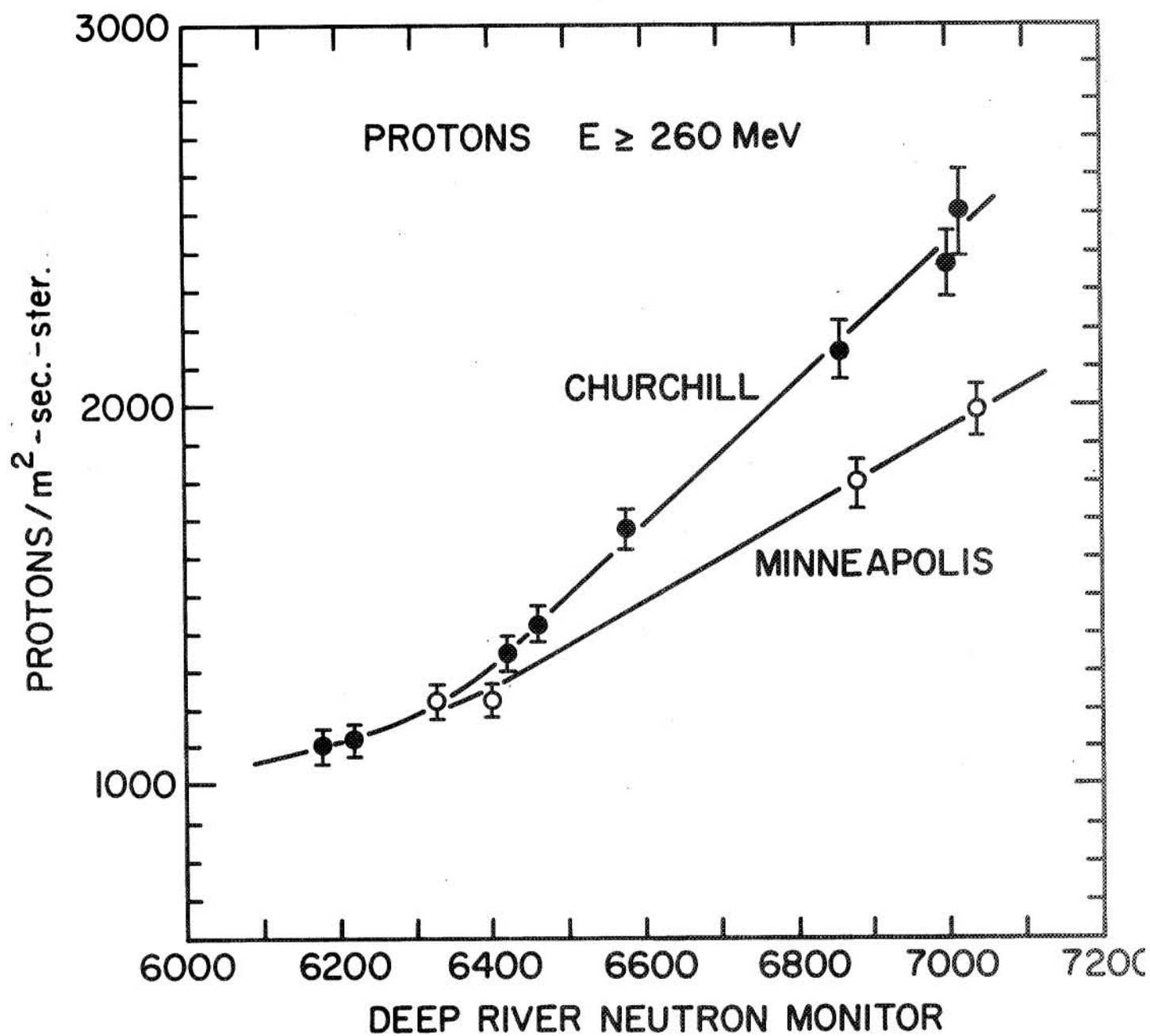


Figure 13.

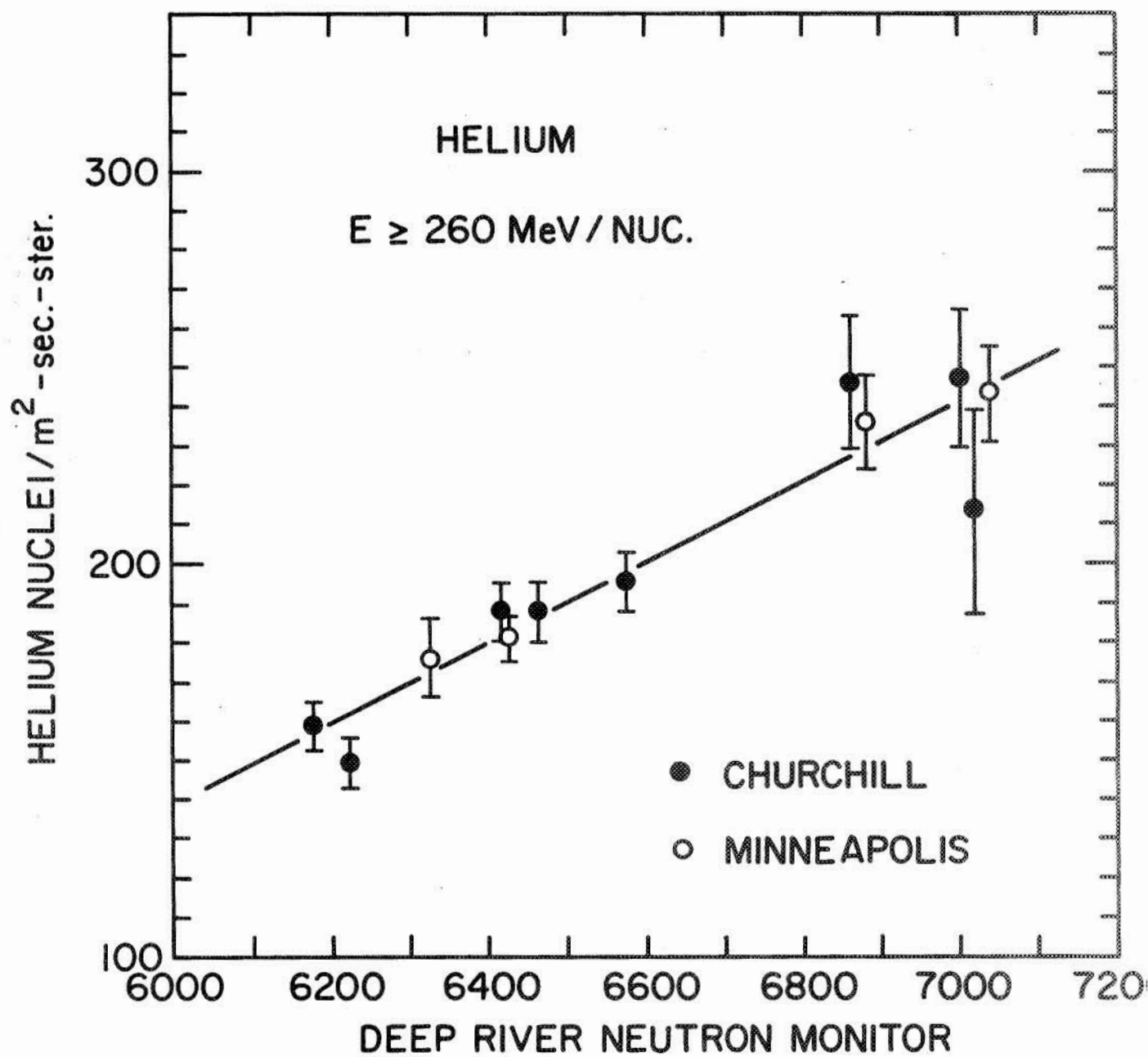


Figure 14.

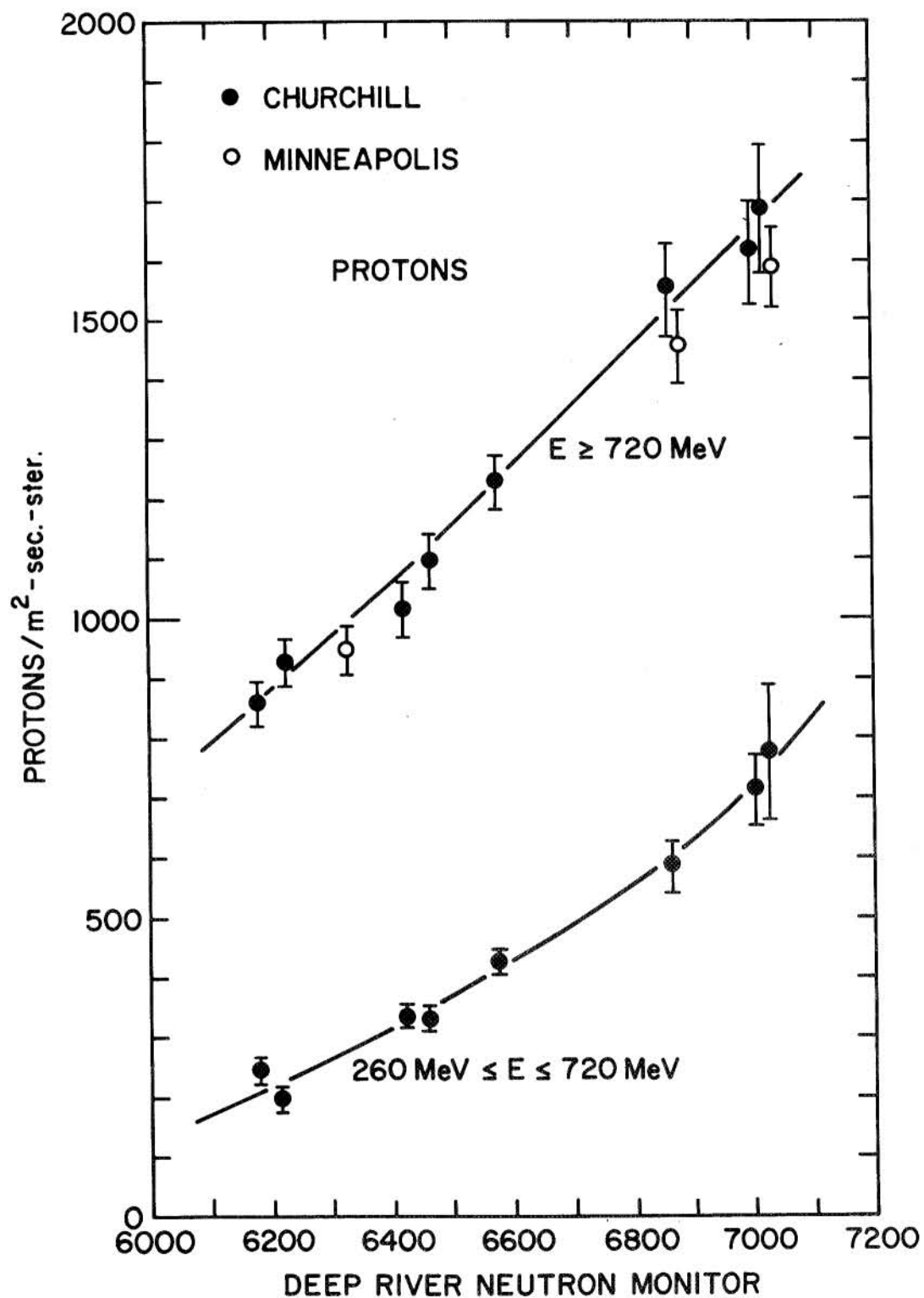


Figure 15.

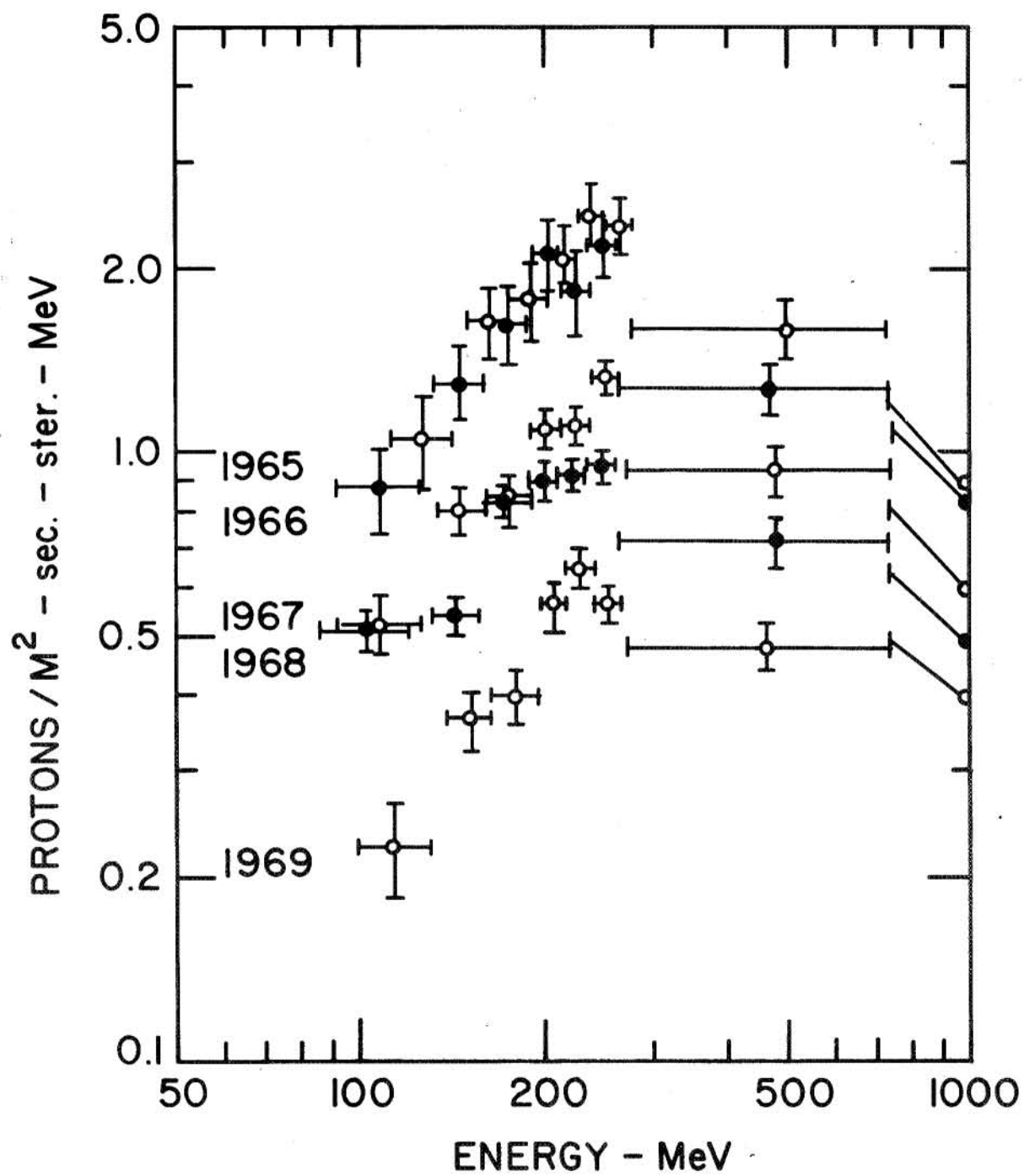


Figure 16.

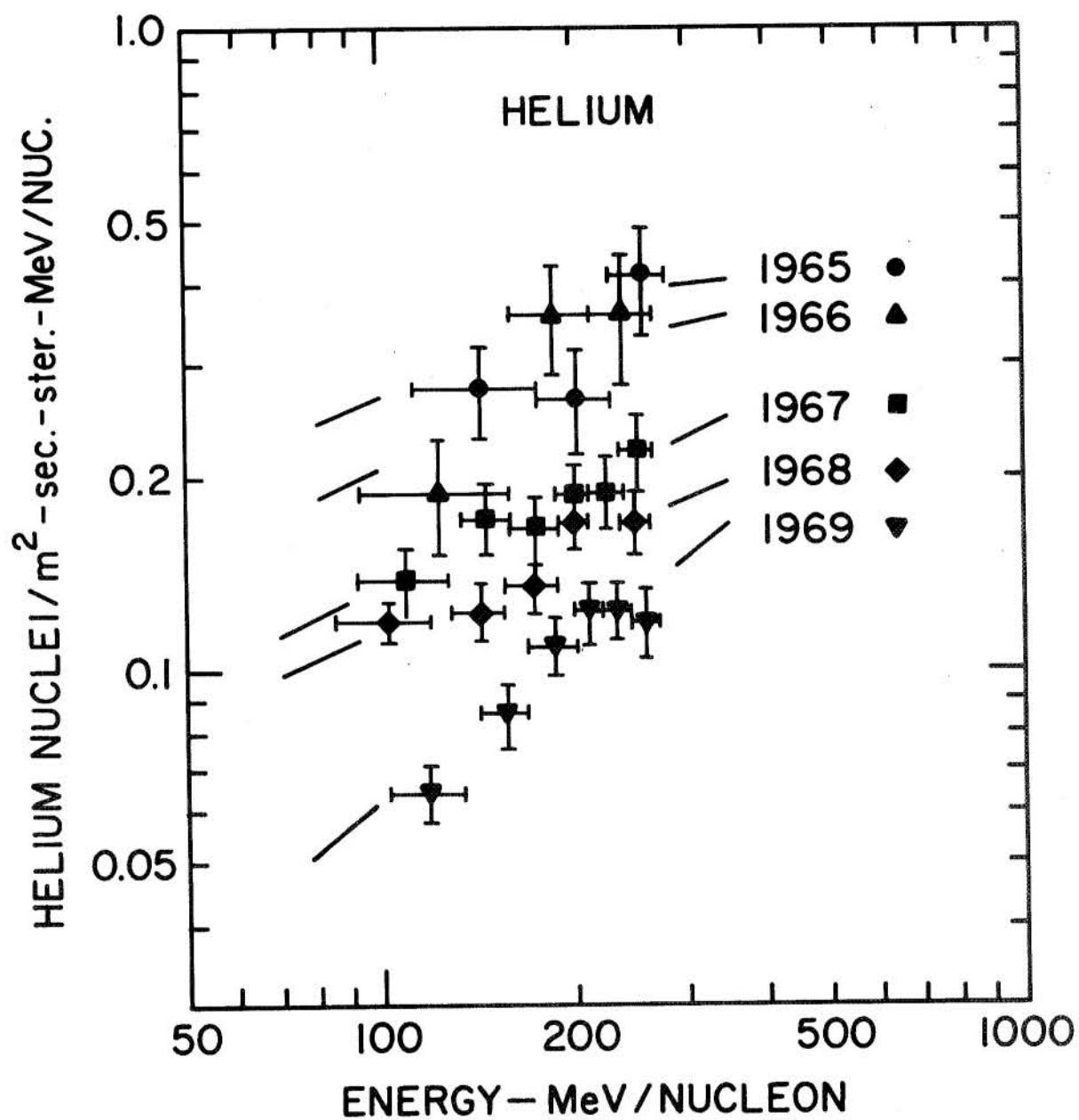


Figure 17.

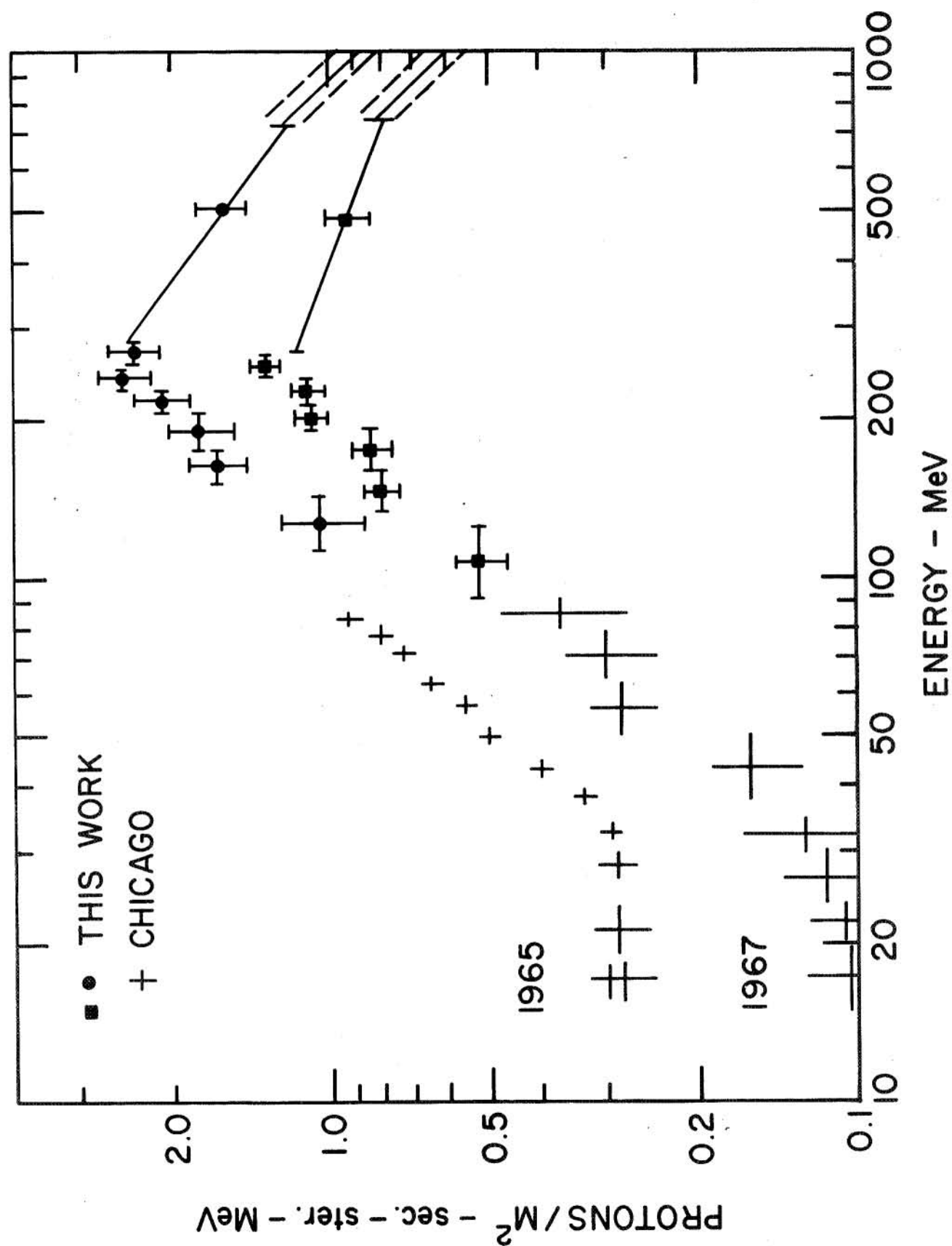


Figure 18.

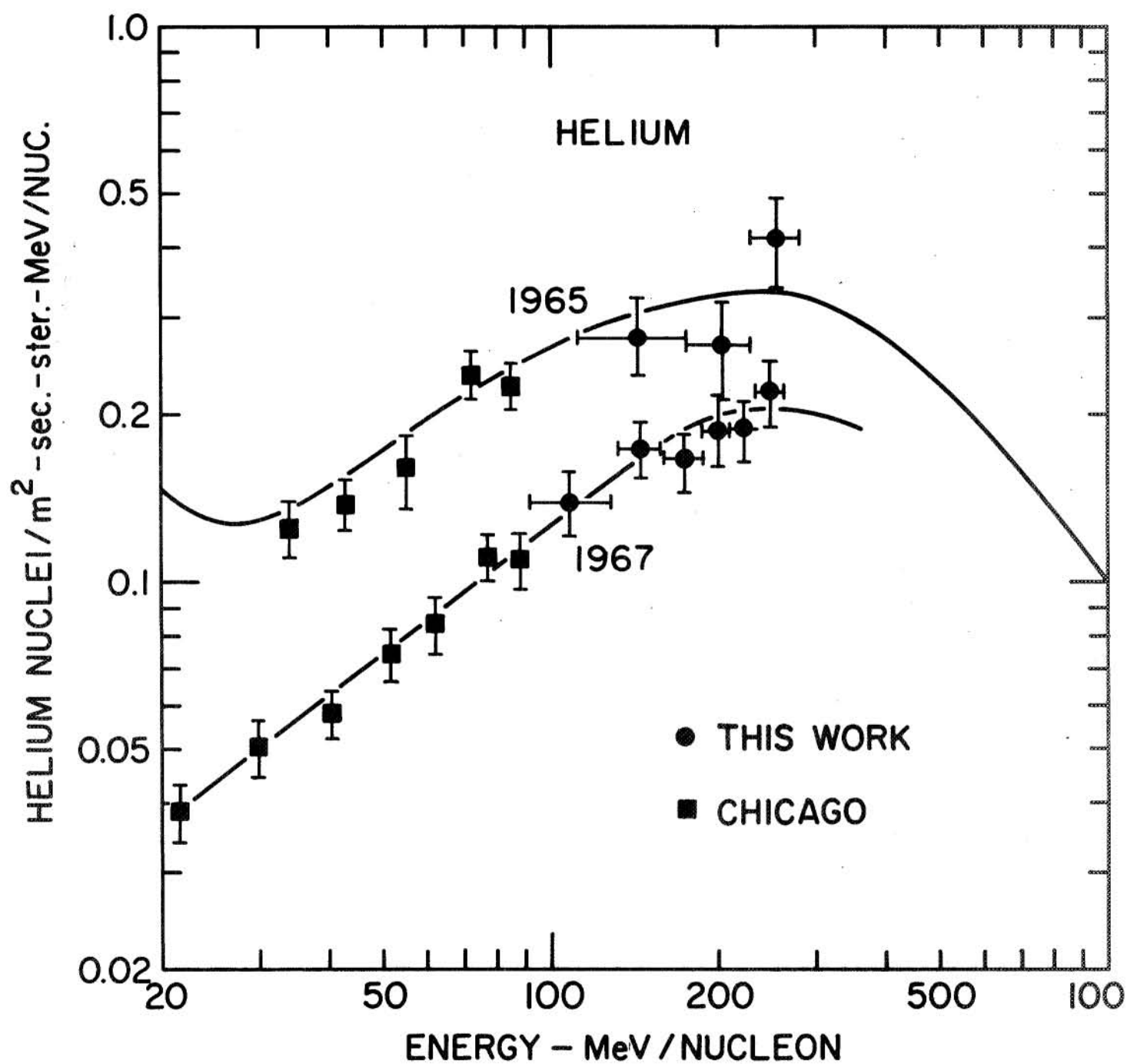


Figure 19.

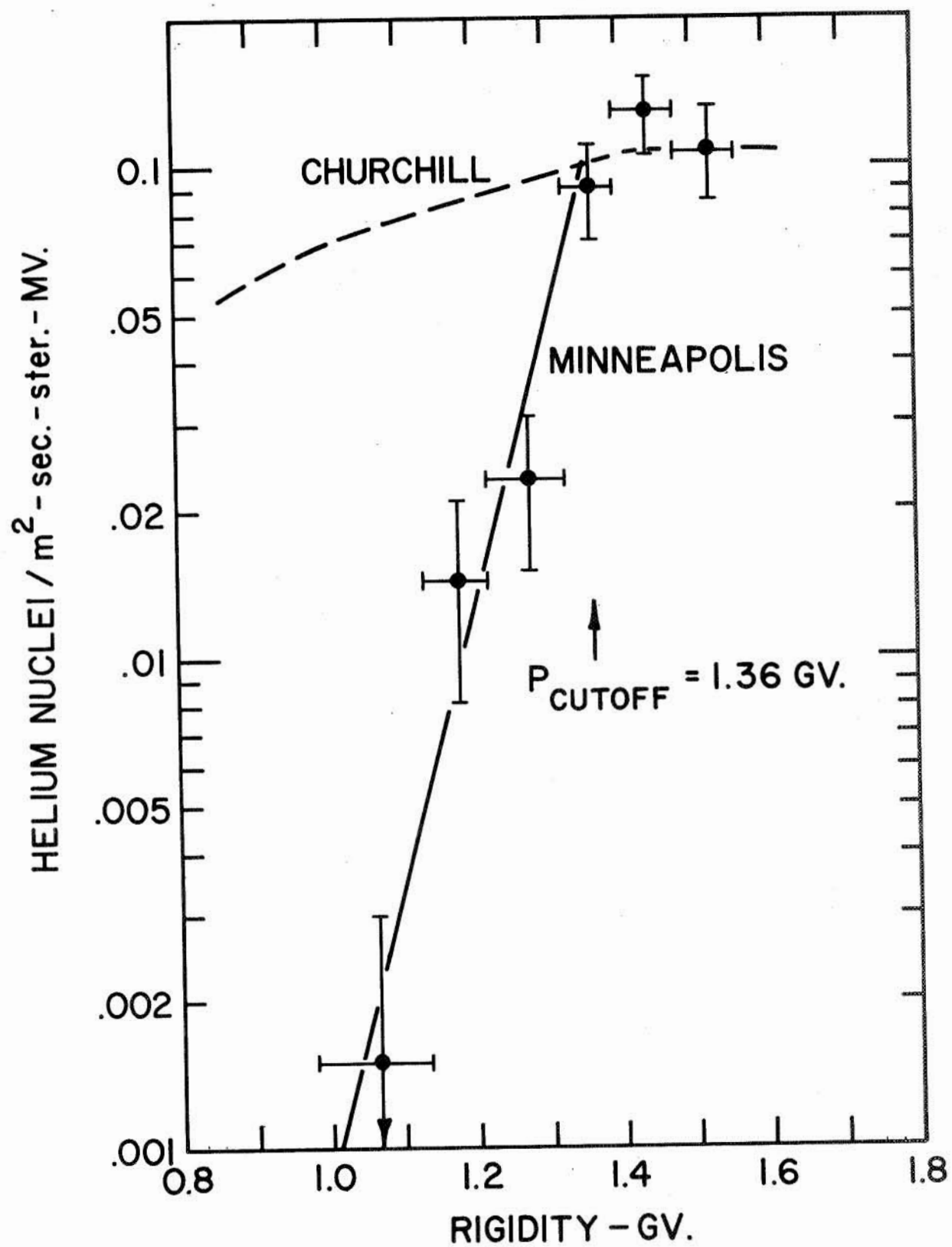


Figure 20.

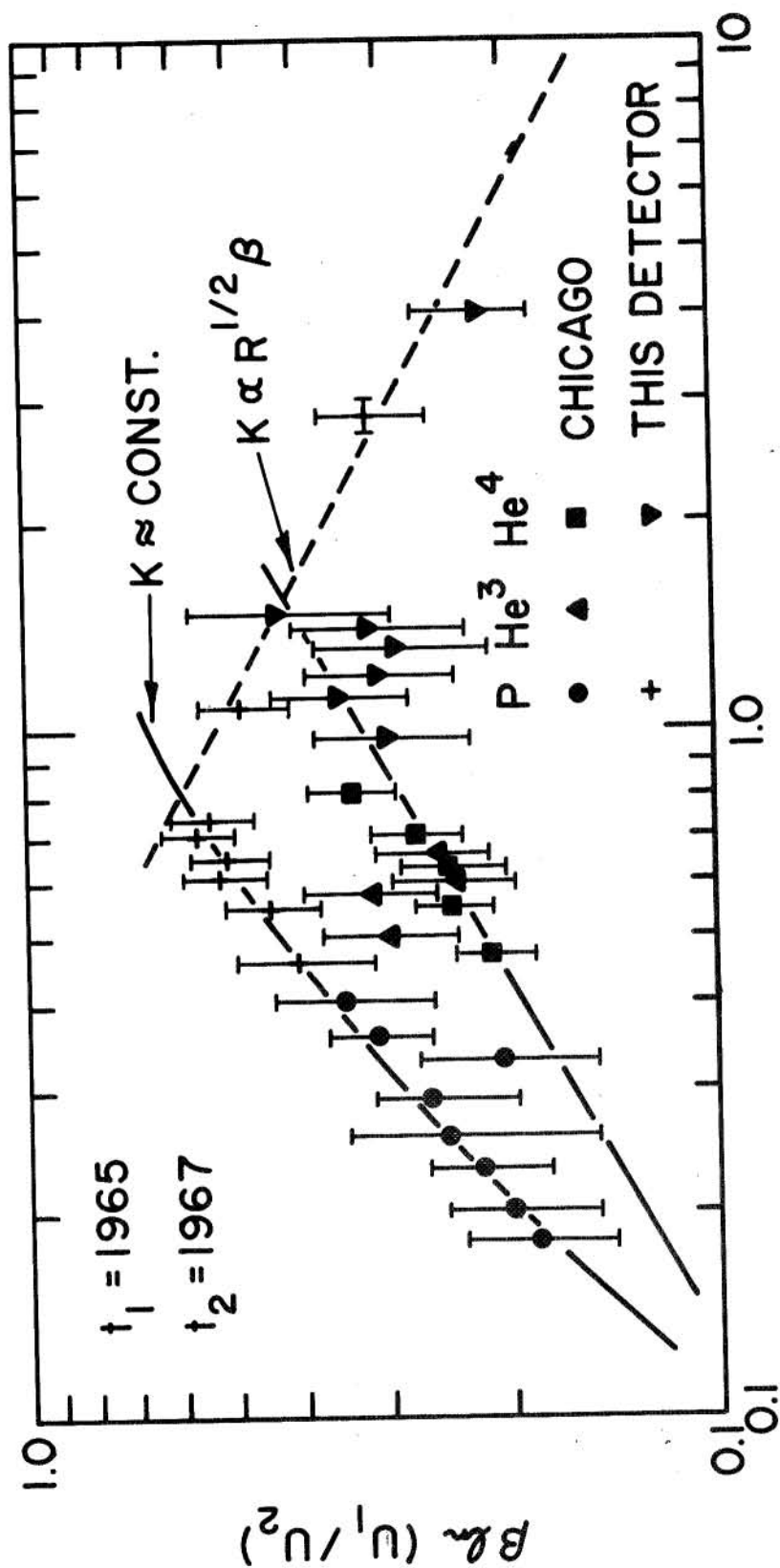


Figure 21.

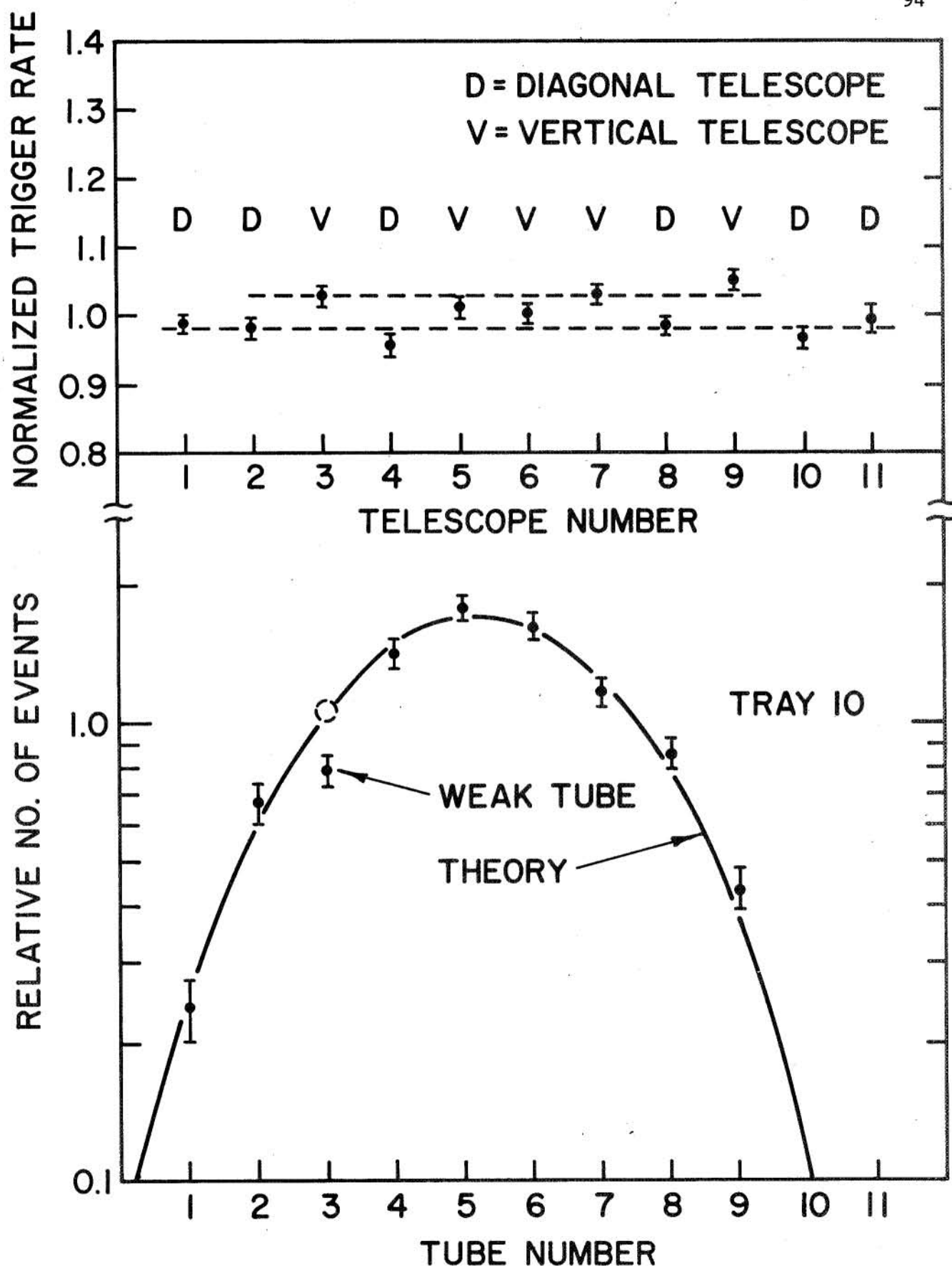


Figure 22.

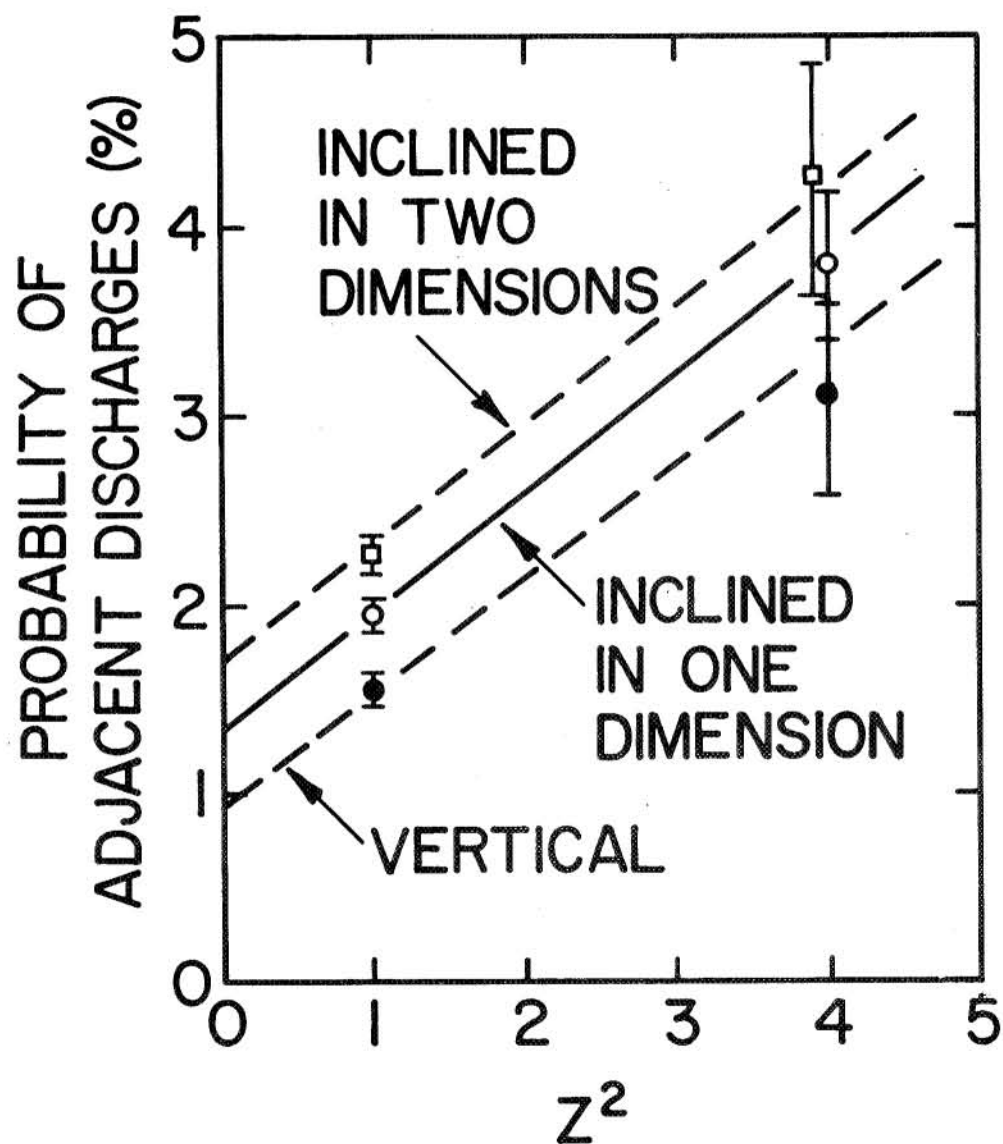


Figure 23.

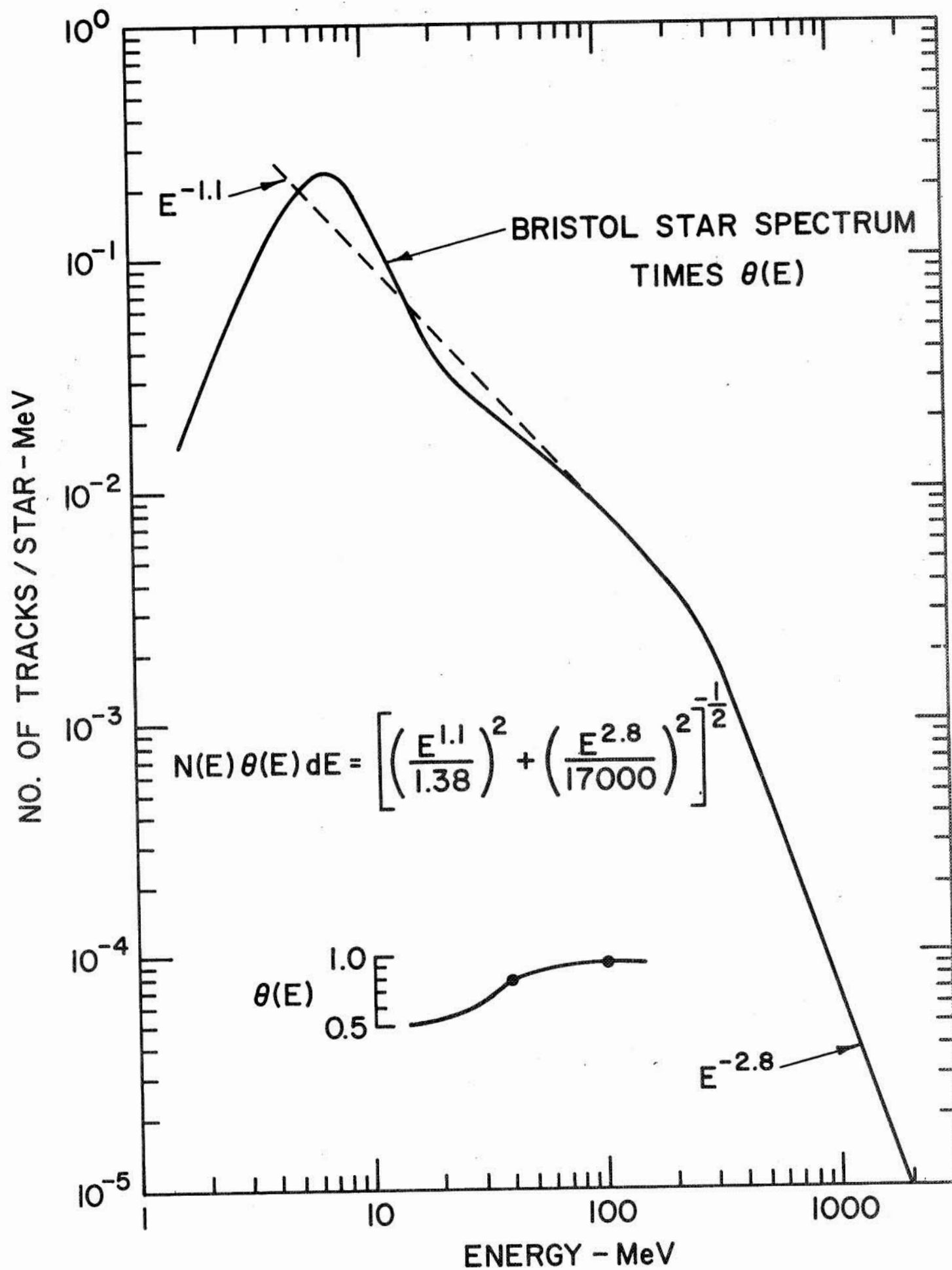


Figure 24.

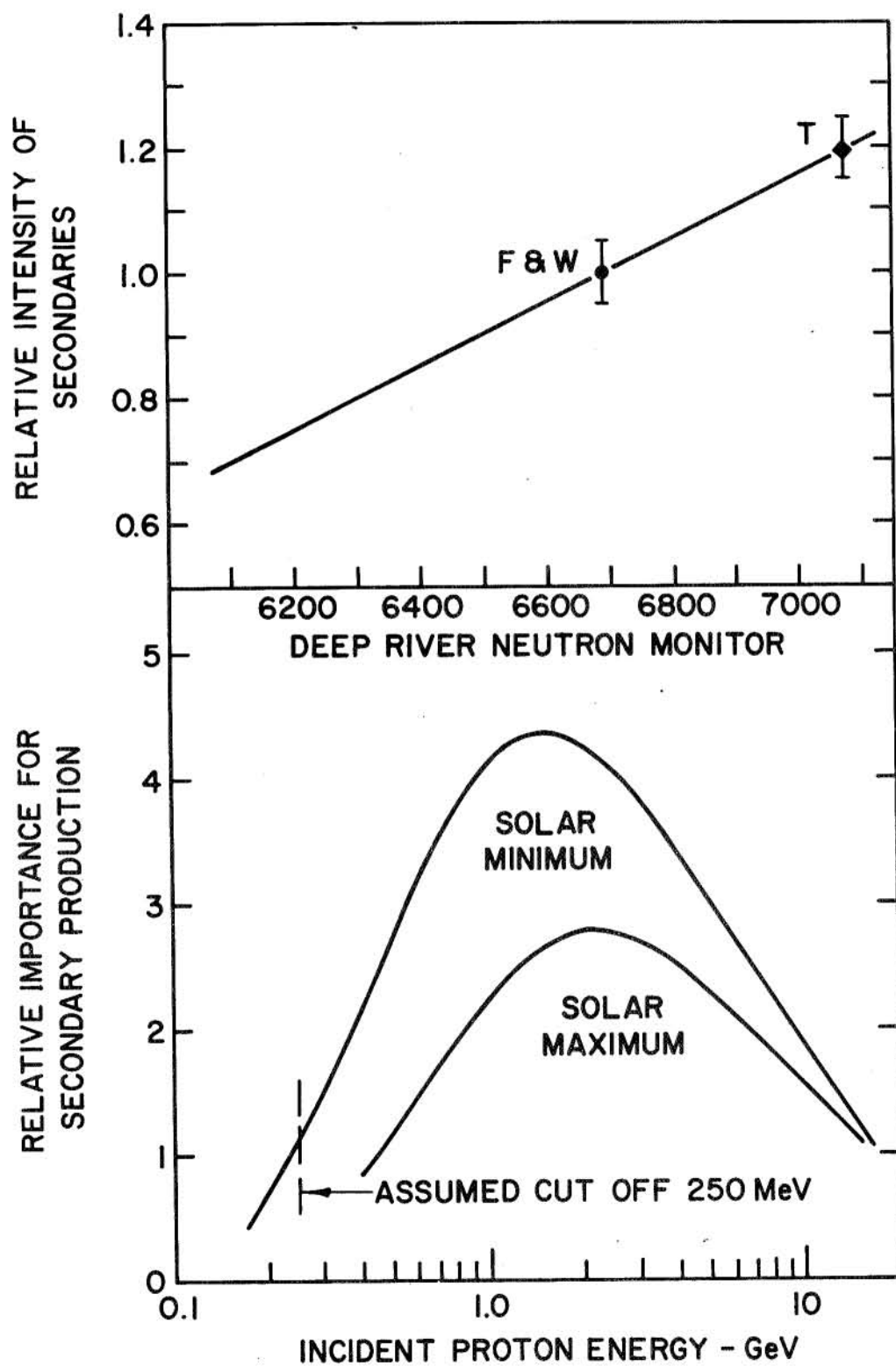


Figure 25.

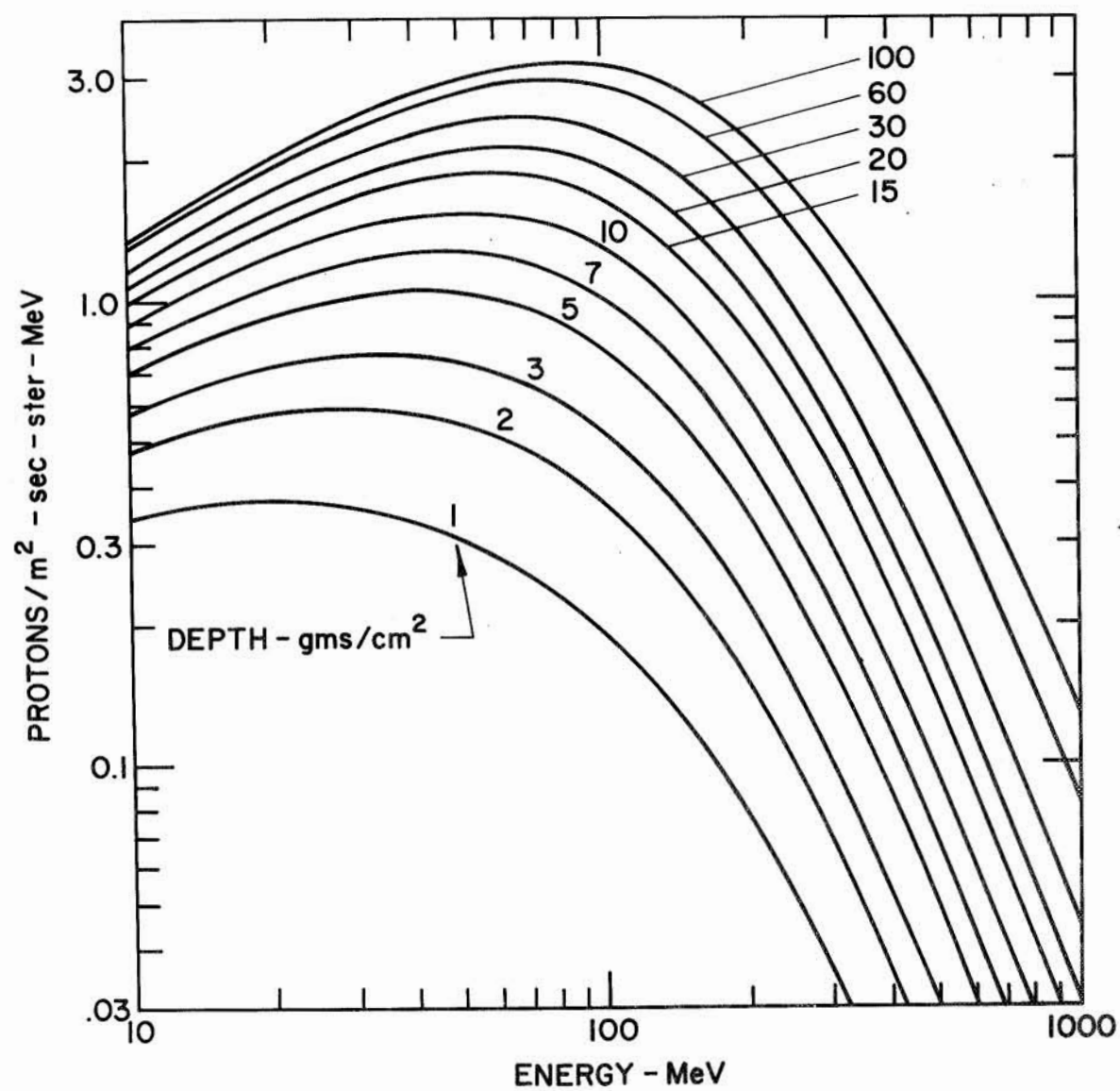


Figure 26.

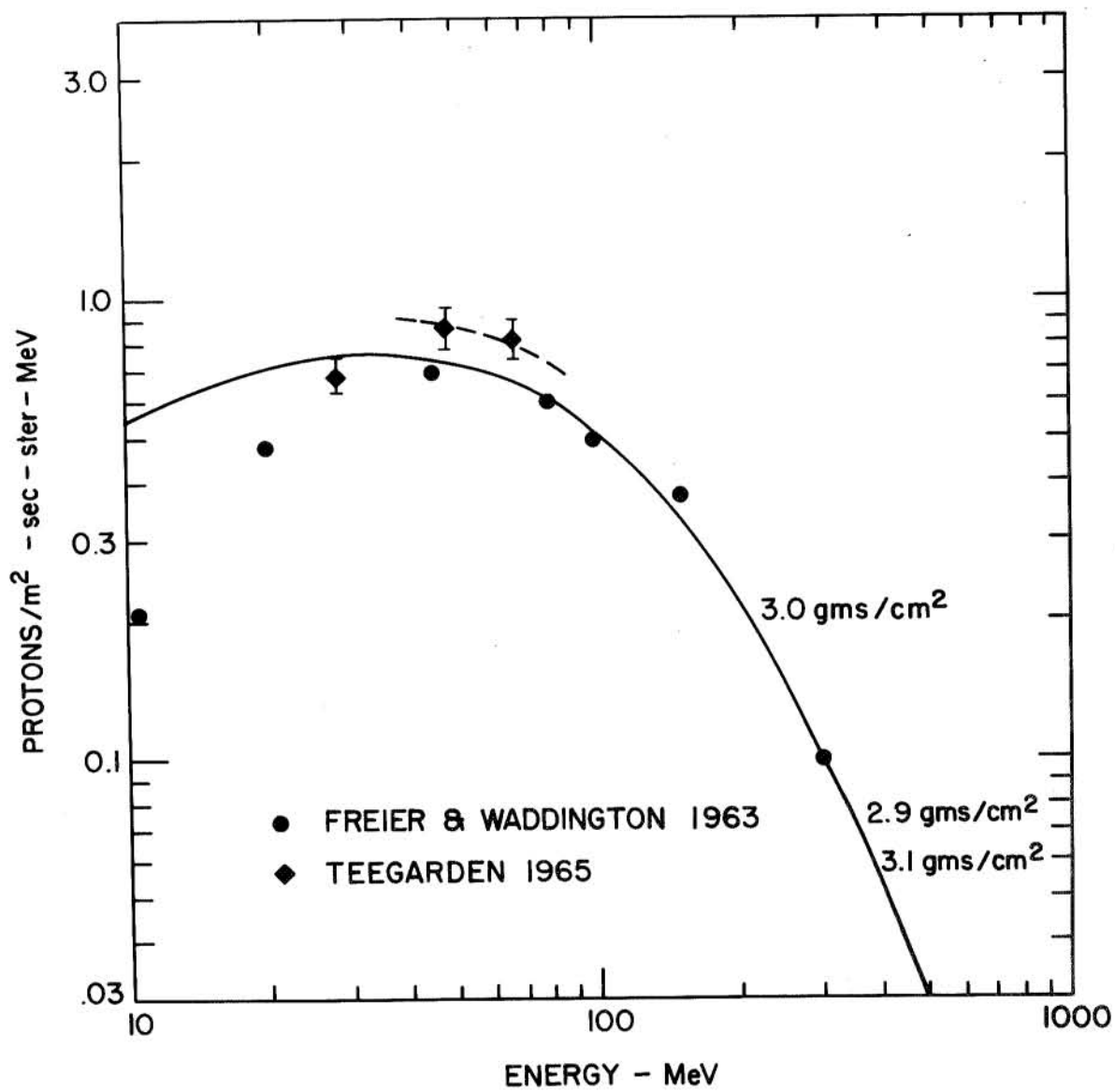


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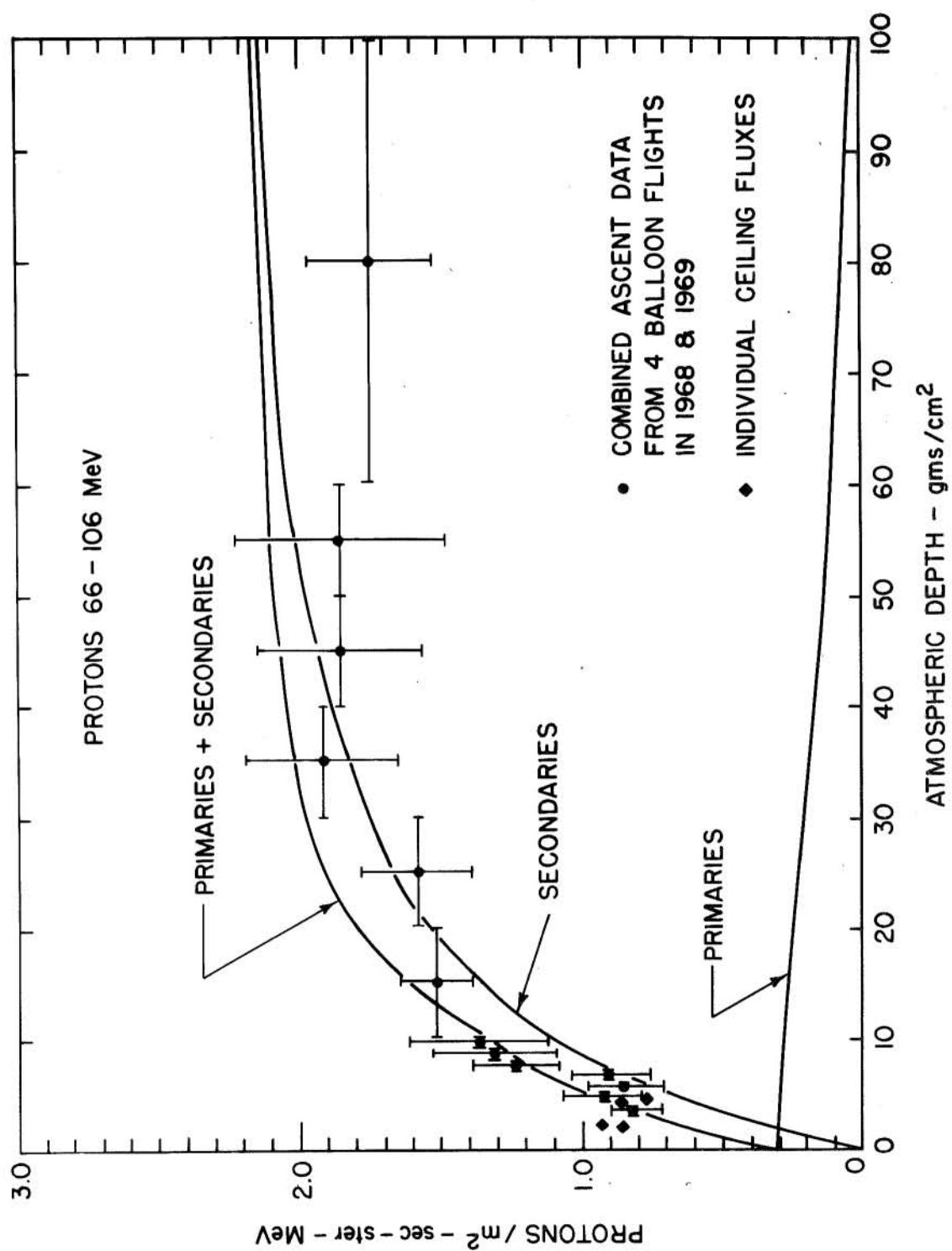


Figure 28.

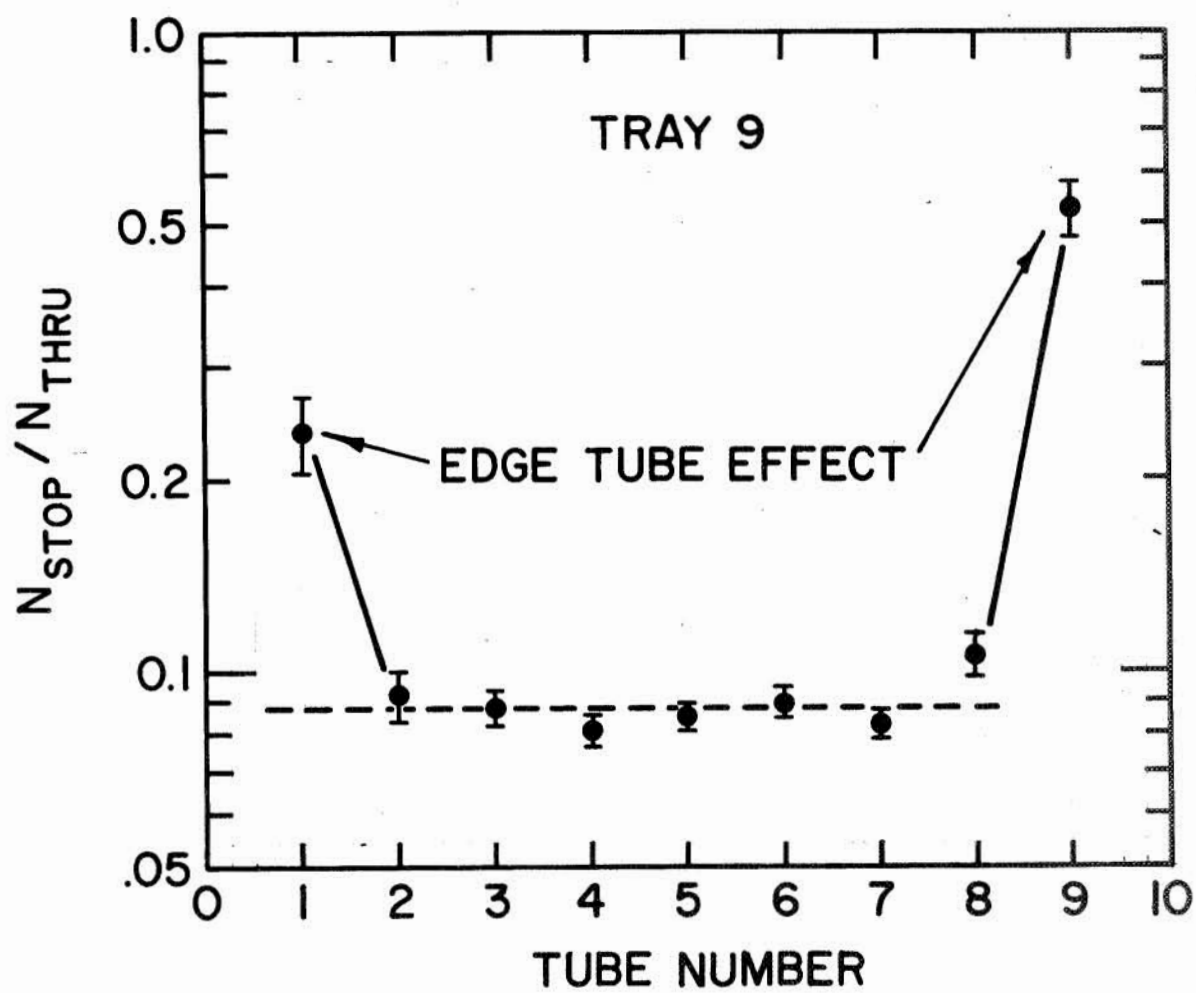


Figure 29.