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FINAL REPORT

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Entitled

MONTE CARLO SIMULATION OF THE
NUCLEAR-ELECTROMAGNETIC CASCADE DEVELOPMENT AND
THE ENERGY RESPONSE OF IONIZATION SPECTROMETERS

For the Three-Year Period From
1 July 1970 through 30 June 1973

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Prepared By:

W. V. Jones

Department of Physics and Astronomy
Louisiana State University
Baton Rouge, Louisiana 70803

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Final Report for Contract NAS9-10986

Monte Carlo Simulation of the Nuclear-Electromagnetic
Cascade Development and the Energy Response
of Ionization Spectrometers

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MONTE CARLO SIMULATION OF THE NUCLEAR-ELECTROMAGNETIC
CASCADE DEVELOPMENT AND THE ENERGY RESPONSE
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Contract NAS9-10986

Final Report

by

W.V. Jones
Department of Physics and Astronomy
Louisiana State University
Baton Rouge, Louisiana 70803

I. GENERAL SUMMARY OF WORK

Monte carlo program for cascade studies. During the contract period (1 July 1970 - 30 June 1973) work has been carried out on developing a Monte Carlo simulation technique for studying nuclear-electromagnetic cascades in ionization spectrometers. The basic computer program for performing the simulations existed prior to this contract. However, the program was lacking in some areas which were considered important for a sufficiently detailed understanding of the cascade process. The contract has supported much of the effort which has been necessary to modify the original program so that the program could be applied more reliably to the understanding of energy measurements made over a wide range of energies with ionization spectrometers.

Calculations for CRISP. The primary objective of the contract effort was to develop a program which could reliably simulate the cascade process in the spectrometer designed and built as part of the Cosmic Ray Ionization

Spectrograph Program (CRISP) being carried out by the Cosmic Ray Physics Branch, Space Physics Division, of the NASA Manned Spacecraft Center under the leadership of Dr. Richard J. Kurz. To this end, a version of the program specifically coded for the CRISP spectrometer was given to Kurz early in the contract period. Kurz was given additional versions of the program as major modifications were made in the program logic.

Comparison of calculations and measurements. As the simulation technique was refined, the results of the calculations were compared with measurements made on protons and pions by the CRISP group at the Alternating Gradient Synchrotron (AGS) at the Brookhaven National Laboratory. Attempts were made to optimize the program modifications so that the best possible agreement between the calculations and the measurements could be achieved. The calculations were also compared with measurements performed by the Cosmic Ray Physics Group of the Goddard Space Flight Center (GSFC). The GSFC group exposed apparatus similar to the CRISP spectrometer to protons and pions from the AGS and to electrons from the Stanford Linear Accelerator Center (SLAC). The measurements made by the MSC and GSFC groups were with particles of energies ≤ 20 GeV. Although there was good agreement between the calculations and the measurements at these energies, it was desirable to check the calculations with measurements at much higher energies (up to 500 GeV) obtainable at the National Acceleratory Laboratory (NAL).

NAL Experiment. The Cosmic Ray Physics group at Louisiana State University (LSU) and the Max Planck Institute for Extraterrestrial Physics (MPI) have had an approved experiment (Expt. No. 34) at NAL for more than two years. This experiment involves essentially a subcollaboration between LSU and MPI as part of a larger collaboration involving these two groups and the Goddard Space Flight Center, the Marshall Space Flight Center and the University of Arizona for the High Energy Cosmic Ray experiment ACR-6 which was scheduled for Mission A of the High Energy Astronomy Observatory (HEAO-A). The LSU-MPI experiment at NAL will obtain data on the development of nuclear-electromagnetic cascades which are initiated by protons and pions with energies up to 500 GeV. It was planned, as part of this contract effort, to compare the results of the calculations with the NAL measurements at these significantly higher energies. However, because of problems at NAL in developing the accelerator, and subsequently in scheduling experiments, this work has not yet been carried out. Presently, it appears that the LSU-MPI experiment will not be scheduled until late 1973 or perhaps even in 1974. Therefore, it has not yet been possible to make the comparisons of the calculations with measurements at the higher energies.

SLAC and Berkeley experiments. Although the NAL experiment has not been carried out, LSU and the other ACR-6 collaborators with R.J. Kurz (TRW Systems) and C.D. Orth (University of California, Berkeley) exposed (in April - June

1972) a tungsten spectrometer to 5 - 15 GeV/c electrons and pions at SLAC and to 2.1 GeV/nucleon ^{12}C and ^{16}O ions at the Bevatron. (This tungsten spectrometer is the one which will be used in the NAL experiment.) These SLAC measurements provided the first opportunity to compare the calculations with measurements for a tungsten spectrometer. The comparisons indicated that the Monte Carlo program gives reliable results of the overall cascade development in tungsten. The Berkeley data provided a unique opportunity to check the reliability of the calculations for cascades initiated by heavy nuclei. Some minor modifications of the program are currently underway as a result of comparing the calculations with the heavy ion data. One of these modifications involves taking into account the nonlinearity of the scintillation light output when heavy ions penetrate plastic scintillators.

II. PROGRAM MODIFICATIONS

Major program changes. Several major changes have been made in the original computer program. The most significant of these include:

1. Monte Carlo simulation of electromagnetic cascades. Prior to the contract, the average cascade development within Approximation B of cascade theory was used for the electromagnetic cascade calculations.
2. Extension of the calculations to include the development of cascades initiated by heavy nuclei. Previously, the calculations were done only for protons and pions.

3. Improved treatment of the nuclear disintegrations which occur during the interactions of hadrons in heavy absorbers. This part of the program is still believed to be somewhat questionable. There is very little experimental information available from which a reliable model of the disintegration process can be constructed.
4. Incorporation of accurate multi-pion final-state cross sections for p-p, n-p, π^{\pm} -p and π^{\pm} -n interactions at accelerator energies (< 20 GeV). This change was made in order to take advantage of the better known pion multiplicities in interactions occurring at energies where more detailed studies had been carried out. Previously the multiplicities at these lower energies were determined from the total pion multiplicities under the assumption that 2/3 of the produced pions were charged and 1/3 were neutral.
5. Restructuring of the program logic so that calculations can be made for sandwich-type detectors. Originally the program logic was such that the calculations were done for cascades developing in single, pure absorbers. This change permits a more realistic simulation of the cascade development in ionization spectrometers, which frequently employ several different materials.
6. Logic changes related to execution of the program. These changes include, for example, options to write out intermediate data on a disk or a tape so the

program could be interrupted and later restarted at the place of interruption. This capability is necessary for accumulating a statistically significant number of events if blocks of computer time are not large enough to complete the required number of events for a particular set of data.

Minor program changes. In addition to the major program modifications mentioned above, several relatively minor, but nevertheless significant, changes have been made to perform a more realistic simulation of the cascade process. Such changes include:

1. Using energy dependent interaction lengths for hadrons.
2. Using energy dependent ionization energy loss rates (dE/dX) for hadrons.
3. The propagation of recoil nucleons resulting from nucleon disintegrations. Previously the energies of these recoil nucleons were taken to be deposited at the point of the interaction from which they originated.

III. SCIENTIFIC PAPERS

Publications in print. Several scientific papers making use of the calculations supported by the contract have appeared in print.

1. "Measurement of the Nuclear-Electromagnetic Cascade Development in Glass at Energies above 200 GeV,"

C.R. Gillespie, R.W. Huggett, D.R. Humphreys, W.V. Jones, and L.B. Levit, Conference Papers (University of Tasmania) Vol. 4, p. 1282. Presented at the Twelfth International Conference on Cosmic Rays, Hobart, 1971, Paper HE-58.

2. "Nuclear-Electromagnetic Cascades from Alpha Particles Incident on an Iron Absorber," W.V. Jones, Conference Papers (University of Tasmania) Vol. 1, p. 184. Presented at the Twelfth International Conference on Cosmic Rays, Hobart, 1971, Paper OG-56.
3. "Nuclear-Electromagnetic Cascades from Nuclei with $Z \geq 3$," W.V. Jones, Conference Papers (University of Tasmania) Vol. 1, p. 190. Presented at the Twelfth International Conference on Cosmic Rays, Hobart, 1971, Paper OG-57.
4. "Cascades Initiated by Heavy Nuclei," W.V. Jones, Trans. Am. Nucl. Soc. 15, 168 (1972). Invited paper presented at the International Conference on Nuclear Solutions to World Energy Problems, November, 1972, Washington, D.C.
5. "Stopping Pions in High Energy Nuclear Cascades," W.V. Jones, D.P. Johnson, and J.A. Thompson, Phys. Rev. D 7, 2013 (1973).
6. "Electron Calibration of a High-Energy Cosmic Ray Detector," C.J. Crannell, R.A. Gearhart, F.A. Hagen, W.V. Jones, R.J. Kurz, J.F. Ormes, R.D. Price, R.F. Silverberg, and G.M. Simnet, Nucl. Instr. Methods 108, 445 (1973).

Publications in press. Some additional papers regarding work supported by this contract are currently in press.

Abstracts of these papers, which are listed below, are appended to this report.

1. "Energy Calibration of a Cosmic Ray Ionization Spectrometer," H. Whiteside, C.J. Crannell, H. Crannell, J.F. Ormes, M.J. Ryan, and W.V. Jones, Nucl. Instr. Methods (in press).
2. "Hadron Energy Measurement in a Stopping Pion Calorimeter," J.A. Thompson and W.V. Jones, in Proceedings of the 1973 International Conference on Instrumentation for High Energy Physics, Frascati, Italy, 8-12 May 1973 (in press).

3. "Measurement of the Fragmentation Cross Section of 2.1 GeV/nucleon ^{12}C and ^{16}O Ions," D.L. Cheshire, R.W. Huggett, W.V. Jones, S.P. Rountree, S.D. Verma, W.K.H. Schmidt, R.J. Kurz, T. Bowen, and E.P. Krider, in Proceedings of the Thirteenth International Conference on Cosmic Rays, Denver, 1973 (in press).
4. "Instrumental and Analytic Techniques for Separating Protons from Electrons in the Cosmic Ray Flux," C.J. Crannell, W.V. Jones, R.J. Kurz, R.F. Silverberg and W. Viehmann, in Proceedings of the Thirteenth International Conference on Cosmic Rays, Denver, 1973 (in press).

Papers presented at national meetings of the American Physical Society. In addition to the above cited publications, several papers on work supported by this contract have been presented at national meetings of the American Physical Society. The published abstracts of these papers, which are listed below are also appended to this report.

1. "Separating Interacting Protons from Electrons in the Cosmic Ray Flux," C.J. Crannell, W.V. Jones, R.J. Kurz, and R.F. Silverberg, Bull. Am. Phys. Soc. 18, 541 (1973). Abstract.
2. "Exposure of a Tungsten-Scintillator Ionization Spectrometer to 2.1 GeV/c ^{12}C and ^{16}O Ions," W.V. Jones, D.L. Cheshire, R.W. Huggett, D.P. Johnson, S.P. Rountree, S.D. Verma, W.K.H. Schmidt, R.J. Kurz, T.A. Bowen, and E.P. Krider, Bull. Am. Phys. Soc. 18, 541 (1973). Abstract.
3. "Calibration of a Tungsten-Scintillator Ionization Spectrometer with 5, 10, and 15 GeV/c Electrons," W.V. Jones, D.L. Cheshire, R.W. Huggett, D.P. Johnson, S.P. Rountree, W.K.H. Schmidt, R.J. Kurz, T.A. Bowen, D.A. DeLise, E.P. Krider, and C.D. Orth, Bull. Am. Phys. Soc. 18, 541 (1973). Abstract.
4. "Response of a Tungsten-Scintillator Ionization Spectrometer to 5, 10, and 15 GeV/c Pions," R.W. Huggett, D.L. Cheshire, D.P. Johnson, W.V. Jones, S.P. Rountree, W.K.H. Schmidt, R.J. Kurz, T.A. Bowen, D.A. DeLise, E.P. Krider, and C.D. Orth, Bull. Am. Phys. Soc. 18, 541 (1973). Abstract.

ENERGY CALIBRATION OF A COSMIC RAY IONIZATION SPECTROMETER

Haven Whiteside and Carol Jo Crannell

Department of Physics
Federal City College
Washington, D.C. 20005

Hall Crannell

Department of Physics
The Catholic University of America
Washington, D.C. 20017

Jonathan F. Ormes and Michael J. Ryan
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

W. Vernon Jones

Department of Physics and Astronomy
Louisiana State University
Baton Rouge, Louisiana 70803

Nuclear Instruments and Methods (in press).

Abstract

The NASA/GSFC High Energy Cosmic Ray Experiment was calibrated at the AGS at Brookhaven National Laboratory during the summer of 1970 using protons and pions with energies from 9.3 GeV to 17.6 GeV.

The best measure found for the energy E of an incoming primary particle is ΣI , the total number of ionizing particles observed in the instrument, summed over the various iron modules. The resolution in the calibration energy range is about $\pm 30\%$ (s.d.) over a wide range of incident angles and positions.

The calibration function may be parameterized as $E = \Sigma I/K$, where K is predominantly a function of the location of the first interaction and the trajectory of the incoming particle. To a fair approximation the geometrical dependence of K can be encompassed by writing K as a function of d , the distance from the first interaction along the primary ray to the edge of the instrument. Empirically, $K = 5.83 (1 - \exp(-d/\lambda)) \cos\theta$, where λ is a characteristic length which is a slowly varying function of energy. The value of K , and thus the average energy values calculated from the experimental data are accurate to about $\pm 10\%$ under calibration conditions.

HADRON ENERGY MEASUREMENT IN A STOPPING PION CALORIMETER

J.A. Thompson

Department of Physics
University of Utah
Salt Lake City, Utah 84112

W.V. Jones

Department of Physics and Astronomy
Louisiana State University
Baton Rouge, Louisiana (USA) 70803

in

Proceedings of the 1973 International Conference
on Instrumentation for High Energy Physics,
Frascati, Italy, 8-12 May 1973 (in press).

Abstract

The energy of a hadron can be estimated from a knowledge of the stopping charged pions produced in a nuclear-electromagnetic cascade. Monte Carlo results for the slow pions are presented and discussed for primary hadron energies from 3 to 3000 GeV. The number of charged pions which stop in an absorber increases logarithmically with the primary energy of the hadron initiating the cascade. The delayed electrons from the $\pi \rightarrow \mu \rightarrow e$ decay chain distinguish between a cascade with a nuclear component and a purely electromagnetic shower. Since the largest fraction of the cascade energy is fed into the electromagnetic component via the production and immediate decay of π^0 's, the number of stopping pion decays gives only a rough estimate of the primary hadron energy; normal standard deviations range from 66% at 3 GeV to 30% at 3000 GeV. Therefore ionization spectrometer measurements are necessary if a cascade energy measurement of high statistical precision is required. This technique has been successfully used in a cosmic ray experiment studying inelastic muon interactions.

MEASUREMENT OF THE FRAGMENTATION CROSS SECTION
OF 2.1 GeV/NUCLEON ^{12}C AND ^{16}O IONS
IN CsI AND TUNGSTEN

D.L. Cheshire, R.W. Huggett, W.V. Jones,
S.P. Rountree and S.D. Verma
Department of Physics and Astronomy
Louisiana State University
Baton Rouge, Louisiana (USA) 70803

W.K.H. Schmidt
Max Planck Institut fuer Extraterrestrische Physik
8046 Garching bei Muenchen, West Germany

R.J. Kurz
TRW Systems, Redondo Beach, California (USA) 90278

T. Bowen and E.P. Krider
Department of Physics, University of Arizona
Tucson, Arizona (USA) 85721

in

Proceedings of the Thirteenth International Conference
on Cosmic Rays, Denver, 1973 (in press).

Abstract

A tungsten-scintillator ionization spectrometer (1000 g/cm^2 total depth) has been exposed to 2.1 GeV/nucleon ^{12}C and ^{16}O ions at the Bevatron. The apparatus included a five-layer CsI target (each layer 9 g/cm^2 thick). Fragmentations of the incident ions could be observed in the five layers of the CsI target and in five "high resolution" layers (each 13 g/cm^2 thick) of tungsten and scintillator. The number of fragmentations occurring in each of these layers has been used to determine the total fragmentation cross sections and the Bradt-Peters overlap parameters for the incident beam particles in CsI and tungsten.

INSTRUMENTAL AND ANALYTIC TECHNIQUES FOR SEPARATING
PROTONS FROM ELECTRONS IN THE COSMIC RAY FLUX

Carol Jo Crannell

Federal City College, Washington, D.C. (USA) 20001

W.V. Jones

Louisiana State University, Baton Rouge, LA (USA) 70803

Richard J. Kurz

TRW Systems Group, Redondo Beach, CA (USA) 90278

Robert F. Silverberg and Walter Viehmann

NASA/Goddard Space Flight Center, Greenbelt, MD (USA) 20771

in

Proceedings of the Thirteenth International Conference
on Cosmic Rays, Denver, 1973 (in press).

Abstract

Techniques are being investigated to aid in distinguishing between electrons and the large background of interacting protons which simulate electron-induced electromagnetic cascades. For cosmic ray primaries, incident on the HECRE ionization spectrometer, statistical criteria are employed to test the cascade curves with the incident energy and starting point as free parameters. The physical significance of the distribution of apparent cascade starting points is being studied using Monte Carlo 100-GeV protons. The proposed use of a CsI detector module (totally-active and high Z) to further discriminate against protons is described.

BULL. AM. PHYS. SOC. 18, 541 (1973)

AP 12 Separating Interacting Protons from Electrons in the Cosmic Ray Flux.* CAROL JO CHANNELL, Federal City College; W. V. JONES, Louisiana State University; RICHARD J. KURZ, TRW Systems Group; and ROBERT F. SILVERBERG, NASA/Coddard Space Flight Center.--Instrumental and analytic techniques are being investigated to aid in distinguishing between electrons and the large background of interacting protons which simulate electron-induced electromagnetic cascades. The dependence of the apparent cascade starting point on the nuclear disintegration energy will be presented. Discrimination, based on this dependence, will also be described.

*Work supported in part by NASA Grants NGR-09-050-001 and NGR-19-001-012, NASA Contract NAS-9-10986, and NSF Grant GP-27927.

AF 13 Exposure of a Tungsten-Scintillator Ionization Spectrometer to 2.1 GeV/c ^{12}C and ^{16}O Ions* W. V. JONES, D. L. CHESHIRE, R. W. HUGGETT, D. P. JOHNSON, S. P. ROUNTREE, and S. D. VERMA, LSU, Baton Rouge; W. K. H. SCHMIDT, MPE, Garching; R. J. KURZ, TRW Systems; T. A. BOWEN and E. P. KRIDER, Univ. of Arizona -- Results from the exposure of a tungsten-scintillator ionization spectrometer (1000 g/cm² total depth) to 2.1 GeV/c ^{12}C and ^{16}O ions at the Bevatron will be presented. The apparatus included a five-layer CsI target (50 g/cm² total thickness) which was used in conjunction with the spectrometer to study the cascade development as a function of the initial break-up of the incident nucleus. Although the interaction mean free path decreases for heavier nuclei, the attenuation coefficient for cascades initiated by heavy nuclei is smaller than that for cascades initiated by nucleons and pions.

* Supported in part by NASA Contracts Nos. NAS5-11426, NAS5-11425, NAS8-27408, NAS9-10986, NASA Grant No. NGR 19-001-012, and by the National Science Foundation.

AF 14 Calibration of a Tungsten-Scintillator Ionization Spectrometer with 5, 10, and 15 GeV/c Electrons* W. V. JONES, D. L. CHESHIRE, R. W. HUGGETT, D. P. JOHNSON, and S. P. ROUNTREE, LSU, Baton Rouge; W. K. H. SCHMIDT, MPE Garching; R. J. KURZ, TRW Systems; T. A. BOWEN, D. A. DeLISE, and E. P. KRIDER, Univ. of Arizona; C.D. ORTH, Univ. of Cal., Berkeley -- A tungsten-scintillator ionization spectrometer has been exposed to 5, 10, and 15 GeV/c electrons at SLAC. The apparatus, which had a total depth of 1,000 g/cm² and included a five-layer CsI target, was a prototype for an experiment designed to study the composition and energy spectra of primary cosmic rays. Studies have been made of the cascade development curves for electrons in CsI and W and of the transition effect when cascades cross the boundary between these two materials.

* Supported in part by NASA Contracts Nos. NAS5-11426, NAS5-11425, NAS8-27408, NAS9-10986, NASA Grant No. NGR 19-001-012 and by the National Science Foundation.

BULL. AM. PHYS. SOC. 18, 541 (1973)

AF 15 Response of a Tungsten-Scintillator Ionization Spectrometer to 5, 10, and 15 GeV/c Pions* R. W. HUGGETT, D. L. CHESHIRE, D. P. JOHNSON, W. V. JONES, and S. P. ROUNTREE, LSU, Baton Rouge, W. K. H. SCHMIDT, MPE, Garching; R. J. KURZ, TRW Systems; T. A. BOWEN, D. A. DeLISE, and E. P. KRIDER, Univ. of Arizona; C. D. ORTH, Univ. of California, Berkeley -- A study has been made of the response of a tungsten-scintillator ionization spectrometer (1000 g/cm² total depth) to 5, 10, and 15 GeV/c pions from SLAC. The distribution of starting points of cascades has been used to determine the interaction mean free path of pions in tungsten. The cascade development is such that the energy resolution (standard deviation) is about 40% at 5 GeV/c and 20% at 15 GeV/c. Wedge-shaped scintillators were used at two depths in the tungsten in order to study their effectiveness as a means of trajectory determination.

* Supported in part by NASA Contracts Nos. NAS5-11426, NAS5-11425, NAS8-27408, NAS9-10986, NASA Grant No. NGR 19-001-012, and by the National Science Foundation.