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NEUTRON PHYSICS DIVISION
ANNUAL PROGRESS REPORT
FOR PERIOD ENDING AUGUST 1, 1963

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

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NEUTRON PHYSICS DIVISION
ANNUAL PROGRESS REPORT
For Period Ending August 1, 1963

E. P. Blizard, Director
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OAK RIDGE NATIONAL LABORATORY
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PREFACE

This volume of the Neutron Physics Division annual progress report consists of papers describing the Division's high-energy radiation shielding research program. The work reported in Chapter 8, "High-Energy Radiation Shielding Calculations," was performed both to provide information for the design of shields for high-energy particle accelerators and to investigate the interactions of high-energy radiations in materials proposed for space vehicle shields. Chapter 9, "Measurements of Secondary Radiations from High-Energy Proton Interactions," reports the experimental studies of materials proposed for space vehicle shields, and Chapter 10, "Radiation Detector Studies (II)," describes new instruments and methods that have been developed for the experimental research. The accelerator shielding work is supported by the Research Division of the Atomic Energy Commission, and the space radiation shielding studies are supported by the National Aeronautics and Space Administration under NASA Order Nos. T-7632 and R-104.

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TABLE OF CONTENTS AND SUMMARY

8. HIGH-ENERGY RADIATION SHIELDING CALCULATIONS

8.1. CALCULATIONS OF THE THREE-DIMENSIONAL DEVELOPMENT OF HIGH-ENERGY ELECTRON-PHOTON CASCADE SHOWERS 3

C. D. Zerby and H. S. Moran

Results from the IBM-7090 Monte Carlo calculations of electron-photon cascades for particle energies up to 50 Gev are now being compared with experiments. Fair agreement is shown with preliminary results from a Stanford experiment in which the energy deposited in copper by a shower initiated by 950-Mev electrons was determined. Reasonably good agreement is also shown with results of an experiment in which electron beams of 100, 200, and 380 Mev were directed into a bubble chamber and the number of charged particles ($E > 1$ Mev) that passed through a lead slab in the chamber was determined.

8.2. STUDIES OF THE CREATION OF POSITRONS IN TARGETS BY A 1-GeV ELECTRON BEAM 7

C. D. Zerby and H. S. Moran

The electron-photon cascade calculation discussed in Sec. 8.1 was used to calculate the generation of positrons in 3-radiation-length-thick targets bombarded by a narrow 1-GeV electron beam. The materials considered were lead, tin, copper, and aluminum, with lead yielding the largest conversion of incident electrons into positrons. For the lead target the ratio of electrons to positrons is always greater than unity, and their energy distributions appear to be similar in shape. Radial distributions of the positrons and electrons in the lead were also calculated.

8.3. CALCULATION OF ENERGY DEPOSITED IN WATER, ALUMINUM, AND COPPER BY A 20-GeV ELECTRON BEAM 9

C. D. Zerby and H. S. Moran

Calculations of the energy deposited by a narrow 20-GeV electron beam in water, aluminum, and copper (materials being considered for the beam stopper of the Stanford linear accelerator) have been performed. In the case of water a rough calculation using the energy deposition data indicates that it would take approximately 11 sec to completely vaporize the water if it were not circulated. The dissociation of hydrogen and oxygen would also be significant.

8.4. CALCULATION OF ENERGY DEPOSITED IN SHIELDED SOLAR CELLS BY HIGH-ENERGY ELECTRONS 12

C. D. Zerby and H. S. Moran

Calculations of the energy deposited by 3.0- and 6.0-Mev electrons incident on a 0.04064-cm-thick solar cell having an aluminum shield of various thicknesses have been made. Discrepancies between the calculated results for the 3.0-Mev case and experimental results obtained for a 3.51-Mev incident energy are probably due to inaccuracies in the calculation at low energies and to the slight difference in the incident energies. The discrepancies are small enough, however, for the calculations to be useful in extending the experimental data.

8.5. A COLLIMATOR STUDY FOR A 20-GeV ELECTRON BEAM 13

C. D. Zerby and H. S. Moran

This paper is a summary of a report previously published as ORNL TM-524.

- 8.6. PRELIMINARY RESULTS FROM NUCLEAR EMULSIONS EMBEDDED IN A STEEL SHIELD EXPOSED TO A NARROW 9-Gev/c PROTON BEAM** 14
 R. L. Childers
 Preliminary measurements have been made on a set of nuclear emulsions exposed at various positions in a steel shield on which a narrow 9-Gev/c proton beam impinged. The emulsions were placed both along the axis of the nuclear cascade and at various distances off the axis. The results of the measurements of the track intensity indicate an attenuation length of 133 ± 8 g/cm² along the shower axis. The lateral distributions of shower-track intensity and the star density along the beam axis are presented.
- 8.7. A PERTURBATION METHOD FOR SOLVING THE ANGLE-DEPENDENT NUCLEON-MESON CASCADE EQUATIONS**..... 23
 R. G. Alsmiller, Jr., and F. S. Alsmiller
 This paper consists of a summary of information that has been published as ORNL-3467.
- 8.8. AN IMPROVED CODE FOR THE NUMERICAL ANALYSIS OF A NUCLEON-MESON CASCADE**..... 23
 R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy
 Work on an IBM-7090 code to solve the nucleon-meson cascade equations in the straightahead approximation is continuing. The portion of the code which deals with incident beams having a continuous energy spectrum has been completed, but the portion which deals with monoenergetic beams is still incomplete.
- 8.9. NUCLEON-MESON CASCADE CALCULATIONS: TRANSVERSE SHIELDING FOR A 45-Gev ELECTRON ACCELERATOR** 24
 R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy
 This paper discusses the third of a series of reports describing nucleon-meson cascade calculations carried out for several cases of interest in the design of the transverse shield for the proposed 45-Gev linear electron accelerator at Stanford University.
- 8.10. SPACE VEHICLE SHIELDING STUDIES: THE ATTENUATION OF SOLAR FLARES BY ALUMINUM SHIELDS**..... 25
 R. G. Alsmiller, Jr., and J. E. Murphy
 Nucleon-meson cascade calculations have been carried out, with the straightahead approximation, for several solar-flare proton spectra incident on a shield. The shielding material has approximately the properties of aluminum. Both spherical-shell and slab geometries are considered.
- 8.11. INTRANUCLEAR CASCADE CALCULATIONS FOR INCIDENT PARTICLE ENERGIES FROM 25 TO 350 Mev AND FROM 25 Mev TO 2 Gev** 27
 H. W. Bertini
 The code to calculate the reactions of 25- to 350-Mev particles with complex nuclei has been put into production, and data will soon be available for distribution through the Radiation Shielding Information Center (RSIC), along with the cascade code itself and the three codes used to analyze the results of the calculation. The code to calculate the reactions of particles with energies up to 2 Gev with complex nuclei is now in the debugging stage and should be available for calculating preliminary data within the next few months; considerable modification will be required, however, before the final version of the code is completed.
- 8.12. PARAMETRIC STUDY OF CALCULATED CASCADE AND EVAPORATION REACTIONS FOR 25- TO 400-Mev NUCLEONS INCIDENT ON COMPLEX NUCLEI** 31
 H. W. Bertini
 A parametric study has been made of typical cases from the cascade calculations discussed in Sec. 8.11. The study covers 50-, 200-, and 400-Mev protons incident on C¹², Al²⁷, Cu⁶⁵, and Pb²⁰⁷ and neutrons incident on Al²⁷ at the same energies. The type of information covered includes excitation energy distributions of the residual nucleus resulting from cascade reactions, the average number of emitted cascade nucleons per inelastic collision, normalized cascade and evaporation particle spectra, and angular distributions of emitted cascade nucleons. In addition, comparisons of calculated and experimental radiochemical cross sections are made.

8.13. LITERATURE SURVEY OF NONELASTIC NUCLEON AND PION REACTIONS WITH COMPLEX NUCLEI 54

H. W. Bertini

In order to locate experimental data with which the results from the intranuclear cascade calculations discussed in Sec. 8.11 can be compared and also to provide the particle-particle cross-section data required by the calculations, a continuing survey of the literature is being made by examining the abstracts published in *Physics Abstracts*. Some of the results of the search for the nonelastic reactions have been collected in a single publication, and a sample page from that report is presented.

8.14. CALCULATION OF DOSE IN TISSUE DUE TO NUCLEONS BELOW 400 Mev 56

W. E. Kinney and C. D. Zerby

Calculations of the average whole-body dose in an infinite slab of tissue 30 cm thick due to 100-, 200-, 300-, and 400-Mev nucleons both normally incident and isotropically incident on the slab have been performed. For all cases of incident protons the primary proton beam is the main contributor to the dose, although for an incident energy of 400 Mev the rem dose due to heavy secondary particles amounts to as much as 69% of the normally incident primary dose and the secondary proton dose amounts to 43% of the primary dose. At 100 Mev the rem dose due to secondaries is only one-sixth the normally incident primary rem dose. At 400 Mev the dose from secondary radiation at a 400-Mev incident energy is about the same for both incident neutrons and incident protons. Flux-to-dose conversion factors are presented for all cases considered.

9. MEASUREMENTS OF SECONDARY RADIATIONS FROM HIGH-ENERGY PROTON INTERACTIONS

9.0. A PROPOSED NOMENCLATURE SCHEME FOR EXPERIMENTAL HIGH-ENERGY NUCLEAR CROSS SECTIONS 63

C. D. Zerby and H. Goldstein

A set of rules previously formulated for low-energy nuclear cross-section terminology and associated notation has been modified and extended to include high-energy radiations. The new set of rules is included here as an aid in interpreting the current set of experiments (see other sections in Chap. 9) with beams of 160-Mev protons.

9.1. SPECTRA OF GAMMA RAYS PRODUCED BY THE INTERACTION OF ~160-Mev PROTONS WITH Be, C, O, Al, Co, AND Bi 66

W. Zobel, F. C. Maienschein, and R. J. Scroggs

Photon spectra due to interactions of 160-Mev protons from the Harvard University synchrocyclotron with Be, C, O, Al, Co, and Bi were measured with two multiple-crystal scintillation spectrometers. Time-of-flight requirements aided in the rejection of neutron-induced backgrounds. Thin-target pulse-height spectra are presented, together with one unscrambled spectrum. A limited amount of thick-target data was also obtained. Cross sections are given for the production of gamma rays at specified energies.

9.2. DIFFERENTIAL SECONDARY-NUCLEON CROSS SECTIONS BY FLIGHT-TIME SPECTROSCOPY FOR REACTIONS OF 160-Mev PROTONS WITH NUCLEI 73

R. W. Peelle, T. A. Love, N. W. Hill, R. L. Cowperthwaite, and R. T. Santoro

Flight-time spectral data have been obtained at several angles for secondary neutrons and protons resulting from reactions of 160-Mev protons on targets of Bi, Pb, Co, Cu, Al, C, Be, D₂O, and H₂O. The status of the data analysis is described, and representative low-resolution proton spectra are shown. Details are given of the method of handling the low-intensity proton beam so that events are recorded only when incident protons are separated sufficiently in time to avoid ambiguity. Observed cross sections for the production of secondary protons from cobalt are shown for five angles, illustrating the softening of the spectrum at large scattering angles.

**9.3. DEPTH-DOSE DISTRIBUTION PRODUCED IN A SPHERICAL WATER-FILLED PHANTOM
BY INTERACTIONS OF A 160-Mev PROTON BEAM 84**

F. C. Maienschein and T. V. Blosser

This paper consists of an abstract of information that has been published as ORNL-3457.

**9.4. ABSORBED DOSE IN A WATER-FILLED SPHERICAL PHANTOM DUE TO 14-Mev AND Po-Be
NEUTRONS 85**

T. V. Blosser and R. M. Freestone, Jr.

A small ethylene-filled ionization chamber was used to measure the depth-dose distribution within a water-filled 42-cm-diam spherical Lucite phantom resulting from a beam of 14.1-Mev neutrons and from the neutron spectrum of a Po-Be source. The results are compared with earlier depth-dose curves resulting from exposure of the phantom to the nuclear secondaries from aluminum targets in a 160-Mev proton beam.

9.5. NEUTRON AND PROTON SPECTRA FROM TARGETS BOMBARDED BY 160-Mev PROTONS 89

J. W. Wachter, W. A. Gibson, W. R. Burrus, and C. F. Johnson

The spectra of neutrons and protons resulting from interactions of 160-Mev protons from the Harvard University synchrocyclotron with targets of H_2O , D_2O , Be, C, Al, Co, Cu, and Bi have been measured with proton-recoil spectrometers. The method used to calculate energy spectra from the pulse-height distributions obtained from the spectrometers is described, and typical spectra obtained for beryllium, aluminum, and bismuth are presented. The results for the energy range 50 to 160 Mev include neutron spectra at 10 and 45° to the incident beam for targets thicker than the incident proton range, proton spectra at 10° for the same targets, and proton spectra at 60° for thin targets that absorbed about 2.5 Mev from the primary beam. Proton spectra at 135° for the energy range 10 to 50 Mev are also shown.

9.6. SCINTILLATION EFFICIENCY OF NaI(Tl) FOR CHARGED PARTICLES 93

W. A. Gibson, W. R. Burrus, J. W. Wachter, and C. F. Johnson

A method is described for calculating the efficiency (dl/dE) of a scintillator from a knowledge of the pulse-height distributions produced by charged particles as they penetrate the scintillator. A curve of dl/dE vs dE/dx is presented for 50- to 160-Mev protons incident on a 1.464-g/cm² NaI(Tl) crystal.

**9.7. SPACE, TIME, AND ENERGY DISTRIBUTIONS OF THE PROTON BEAM FROM THE HARVARD
UNIVERSITY SYNCHROCYCLOTRON 95**

R. T. Santoro

The distributions in space, time, and energy of the proton beam of the Harvard University synchrocyclotron were measured. Measurements of the spatial distribution by x-ray film techniques and by profile telescope methods indicate that there was a normal distribution of protons across the beam, with 86% of the protons included in two standard deviations and a full-width at half-maximum at 6.6 mm. The beam cross section was circular. The cyclotron duty factor was found to be about 4%. From range-energy measurements, for which copper absorbers were used, the proton energy was found to be 160.9 Mev, while independent time-of-flight measurements resulted in a value for the energy of 154.4 Mev.

**9.8. MEASUREMENTS OF THE INTENSITY OF THE PROTON BEAM OF THE HARVARD UNIVERSITY
SYNCHROCYCLOTRON FOR ENERGY-SPECTRAL MEASUREMENTS OF NUCLEAR
SECONDARIES 100**

R. T. Santoro and R. W. Peelle

Two thin helium-filled parallel-plate ionization chambers were used to monitor the intensity of the 160-Mev beam of the Harvard University synchrocyclotron during the various spectral measurements described elsewhere in this report. The chambers were calibrated by two independent methods: by comparison with measurements of the absolute beam intensity made with a Faraday cup and by comparison with the results of direct counting of the protons in the beam by fast counting techniques. The two determinations were in agreement within <5%. A drift in the calibration of the chambers during the spectral runs was confirmed by measurements with an Sr^{90} source and is ascribed to a gradual contamination of the helium filling gas by air leakage.

9.9. PREPARATIONS AT ORIC FOR CONTINUED MEASUREMENTS OF ENERGY SPECTRA OF NUCLEAR SECONDARIES 104

R. T. Santoro

The experimental space shielding program will be continued at the Oak Ridge isochronous cyclotron (ORIC), where an ~ 75 -Mev proton beam will be available. Existing experimental apparatus is being modified for use with this accelerator, and the gamma-ray spectrometer to be used in the first measurements of secondary spectra has already been installed at ORIC. A spectrometer positioning device and a special evacuated target holder are being designed.

10. RADIATION DETECTOR STUDIES (II)

10.1. PROTON-RECOIL SPECTROMETERS FOR MEASURING NEUTRON AND PROTON ENERGY SPECTRA FROM 10 TO 450 Mev 109

W. A. Gibson, W. R. Burrus, J. W. Wachter, and C. F. Johnson

Two proton-recoil spectrometers for use in the neutron and proton energy range 10 to 450 Mev have been tested. The difficulties encountered with the 10- to 50-Mev spectrometer are discussed, and it is concluded that the background due to interaction of high-energy neutrons with the sensitive portions of the counters and with the carbon of the radiator places severe restrictions on the usefulness of this spectrometer. The 50- to 450-Mev spectrometer performed satisfactorily when exposed to secondary neutrons and protons from a target bombarded by 160-Mev protons; however, a large background was encountered in measuring the spectra of secondaries from targets bombarded by 450-Mev protons. A device to eliminate this background is being constructed.

10.2. DETERMINATION OF COINCIDENCE-CIRCUIT EFFICIENCY BY VARYING THE INPUT SIGNAL DELAY 112

R. W. Peelle

The efficiency of a twofold coincidence circuit for counting simultaneous events is considered in terms of the jitter in the timing of the pulses at its input relative to the detected event. Two methods are suggested for analysis of empirical delayed coincidence curves for inferring coincidence efficiency. Graphs are given to relate the breadth of the jitter distribution and the coincidence efficiency to the derivative of the observed delayed coincidence curve near efficiency one-half.

10.3. CALCULATION OF THE EFFICIENCY AND RESOLUTION OF A PROTON RECOIL SPECTROMETER BY MONTE CARLO METHODS 115

W. E. Kinney and J. W. Wachter

A computer code employing Monte Carlo methods has been constructed to calculate the absolute efficiency and energy resolution of a proton-recoil neutron spectrometer from a knowledge of the n,p scattering cross section, the dimensions of the proton radiator, and the experimental geometry. The computation allows radiators of arbitrary thickness and a variety of source distributions and takes account of energy losses in materials intervening between the radiator and the dE/dx counter. The results given by the code have been checked against infinitely thin radiator calculations made by conventional numerical integration techniques, and excellent agreement exists.

10.4. SOME RECENT APPLICATIONS OF THE SLOP CODE FOR UNFOLDING INSTRUMENT RESPONSE 120

W. R. Burrus

The SLOP code has been applied to the analysis of pulse-height distributions resulting from the exposure of a liquid scintillator, NE-213, to Po-Be neutrons, the exposure of a plastic scintillator (Pilot B) to $\text{Li}^6(p,n)\text{Be}^6$ neutrons ($E_p = 2.8$ and 3.1 Mev), and the exposure of a multicrystal NaI(Tl) spectrometer to Y^{88} gamma rays. The response functions required by the code for the scintillators were generated by interpolation between experimental values obtained at several energies. In the case of the NaI(Tl) spectrometer, the response function was generated analytically.

10.5. A CALCULATION OF THE PULSE-HEIGHT RESPONSE OF SCINTILLATORS TO HIGH-ENERGY ELECTRONS, POSITRONS, OR PHOTONS 124

C. D. Zerby and H. S. Moran

The electron-photon cascade calculation discussed in Sec. 8.1 was modified for use in calculating the pulse-height response of scintillation counters to high-energy radiations. The computer program considers a cylindrical detector of almost arbitrary composition and a source of positrons, electrons, or photons having energies up to 50 Gev. The source can be an isotropic point on the axis of the detector or a monodirectional source uniformly distributed over a circle which is concentric with the cylinder. Although the accuracy of the calculation has not yet been confirmed, the shapes of calculated and experimental curves for a plastic scintillator exposed to 129.4-Mev photons have a striking similarity.

10.6. PERFORMANCE CHARACTERISTICS OF MODULAR NANOSECOND CIRCUITRY EMPLOYING TUNNEL DIODES 127

N. W. Hill, R. J. Scroggs, and J. M. Madison

Modular circuits employing tunnel diodes have been used in the instrumentation for many of the high-energy particle experiments described in Chapter 9. These circuits include discriminator modules, coincidence and anti-coincidence modules, positive and negative output scaler-driver modules used to drive commercially built scalars, and a 100-Mc scaler-driver module. Their response to various conditions of temperature and input pulse magnitude was measured.

8. High-Energy Radiation Shielding Calculations

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8.1. CALCULATIONS OF THE THREE-DIMENSIONAL DEVELOPMENT OF HIGH-ENERGY ELECTRON-PHOTON CASCADE SHOWERS

C. D. Zerby and H. S. Moran

Introduction

The electron-photon cascade Monte Carlo calculations^{1,2} programmed for the IBM-7090 computer for the purpose of studying the development of soft showers in various simplified configurations have continued. The maximum particle energy allowed in the calculation is 50 Gev, and the lowest photon energy is 0.05 Mev. The minimum charged-particle energy is restricted to 0.5 Mev; however, for all energies below 5 Mev the treatment of the transport of the charged particles becomes inaccurate because of the approximations used in the calculation.

The calculation has undergone various stages, beginning with formulating the problem, choosing the approximations that were appropriate, proceeding through the coding and debugging stages, verifying internal consistency, and verifying by comparison with other calculations. The final stage of checking the accuracy of the calculation by comparing the results with experimental data is still in process.

The formulation of the problem has been described previously in some detail^{1,2} and is briefly reviewed below. The comparisons that were made¹ with previous calculations and theories have yielded reasonably good agreements and tend to verify that the internal workings of the computer program are correct. In this report the comparisons with existing experimental results are discussed.

Review of the Calculation

Only electrons, positrons, and photons are considered in the calculation. The positrons are distinguished from the electrons because the difference in the cross sections that apply makes the behavior of the two particles slightly different and because the distinction is of current interest in connection with the generation of positrons in targets. All cross sections are included in the calculation in tabular form as a function of energy.

The only physical photon processes included in the calculation are pair production, Compton scattering, and photoelectric events. For the charged particles, bremsstrahlung and Coulomb scattering from the nuclei and the atomic electrons are included. Since Coulomb scattering occurs frequently as a charged particle moves through a material, the process had to be treated in a special way. The method used was to consider the large-angle scattering from the nuclei and from atomic electrons as separate processes from small-angle scattering. In this way the infrequent large-angle scattering could be treated with standard Monte Carlo techniques, and multiple small-angle scattering could be included by using the analytic formula derived by Eyges.³ The scattering formula of Eyges is essentially Fermi's multiple small-angle scattering solution⁴ modified to include constant ionization energy loss.

Since the large-angle Coulomb scatterings from atomic electrons were treated as individual events in which the kinematics of the collisions were

¹C. D. Zerby, *Neutron Phys. Div. Ann. Progr. Rept.* Sept. 1, 1962, ORNL-3360, p 248.

²C. D. Zerby and H. S. Moran, *A Monte Carlo Calculation of the Three-Dimensional Development of High-Energy Electron-Photon Cascade Showers*, ORNL TM-422 (1963).

³L. Eyges, *Phys. Rev.* **74**, 1534 (1948).

⁴B. Rossi, *High-Energy Particles*, Prentice-Hall, Englewood Cliffs, N. J., 1952.

accurately taken into account, the energy loss attributed to the large-angle Coulomb scattering from the atomic electrons had to be subtracted from the standard stopping-power formula for energy loss by ionization collisions.⁵ This modified formula was used to determine the energy loss of the charged particles as they moved from one point of interaction to another.

The present version of the computer program will develop cascades in a homogeneous material with mixtures of up to 20 elements. The geometrical configuration of the medium can be a slab, a cylinder, or a cylindrical shell. The cascades can be initiated by any of the three particles allowed in the calculation. The results of the calculation include data on the flux of charged particles and photons in various energy, radial, and depth intervals and on energy deposited in the depth and radial intervals. Also included is the joint energy and angular distribution of the radiation penetrating a scattering medium having a finite thickness.

Other details of the program and the sequence of carrying out the Monte Carlo calculation can be obtained from previous reports.^{1,2}

Comparison with Experiment

In a previous electron-photon calculation⁶ the shape of the curve for the energy deposited as a function of depth differed from the shape of an experimental curve obtained by Kantz and Hofstadter⁷ at small depths. Since the lateral spreading of the beam had not been included in the calculation, it was thought that some of the difference could be attributed to this effect. A similar comparison of the present calculation, which includes the lateral spreading of the beam, with experimental data is shown in Fig. 8.1.1 for 187-Mev electrons incident on copper. The Kantz-Hofstadter data were normalized to the calculated values at 3.5 rl (radiation lengths) because the shapes of the calculated and experimental curves at greater depths are essentially the same.

⁵E. A. Uehling, *Ann. Rev. Nucl. Sci.* 4, 315 (1956).

⁶C. D. Zerby and H. S. Moran, *J. Appl. Phys.* 34(8), 2445 (1963); see also C. D. Zerby and H. S. Moran, *Studies of the Longitudinal Development of High-Energy Electron-Photon Cascade Showers in Copper*, ORNL-3329 (Sept. 1962).

⁷A. Kantz and R. Hofstadter, *Nucleonics* 12(3), 36 (1954).

Fig. 8.1.1. Energy Deposited in Copper by a Shower Initiated by 187-Mev Electrons (Normalized to 1 Incident Electron). The results of Kantz and Hofstadter and the latest Stanford experiment were arbitrarily normalized to the calculated data at 3.5 rl.

The results from the present calculation also disagree with the Kantz-Hofstadter results at small depths and in a manner similar to the previous calculation. This stimulated a check of the experiment⁸ at Stanford at 187 Mev, the preliminary results of which are included in Fig. 8.1.1. Again the experimental data were normalized to the calculated data at 3.5 rl. Although the present calculation and the new experiment are still in disagreement, the discrepancy is not so great as it is for the Kantz-Hofstadter experiment. It should be stressed that the new experimental results are preliminary, and it is hoped that the final experimental results will agree more closely with the calculated data.

The preliminary results of a 950-Mev experiment at Stanford⁸ are compared with the results of the present calculation in Fig. 8.1.2, the experimental data being normalized to the calculated values at 6 rl. The agreement is much better in this case but is not as good as would be expected.

The calculations have also been compared with a recent series of shower experiments performed in Germany with lead and copper in a propane bubble chamber.^{9,10} Electron beams of 100, 200, and

⁸R. F. Mozley, private communication.

⁹H. Lengler, *Messungen von Elektronenkaskaden in Blei mit Hilfe einer Blasen-kammer*, dissertation, Technischen Hochschule, Aachen, Germany, 1962.

¹⁰H. Lengler, private communication.

380 Mev were directed into the chamber through a 2.5-cm-thick beryllium shell and passed through 5.5 cm of propane before encountering the first slab of material. Slabs of various thicknesses were placed in the chamber along the beam axis, with a 2.35-cm thickness of propane separating the slabs in all cases. From pictures of the showers in the chamber, the average number of charged particles with energies above 1 Mev (kinetic energy) that passed through the back face of each slab was determined. The original experimental data, which have not been corrected for the presence of the propane, are given in Tables 8.1.1 and 8.1.2. The quantity tabulated is $\Pi(E_0, E, t)$, the number of charged particles above energy E passing through a plane at t radiation lengths in a shower initiated by electrons of energy E_0 .

Curves through the tabulated experimental data are compared with the Monte Carlo results in Fig. 8.1.3 for lead and in Fig. 8.1.4 for copper. The Monte Carlo calculations included the effects of stratification by considering each layer of material

Fig. 8.1.2. Energy Deposited in Copper by a Shower Initiated by 950-Mev Electrons (Normalized to 1 Incident Electron). The Stanford results are normalized to the calculated data at 6 rl.

Table 8.1.1. Experimental Values of $\Pi(E_0, E, t)^a$ for Lead

rl = 0.514 cm; $E = 1$ Mev (kinetic energy)

Slab	Lead Thickness (cm)	Total Lead Thickness (rl)	$\Pi(E_0, E, t)^a$		
			$E_0 = 380$ Mev	$E_0 = 200$ Mev	$E_0 = 100$ Mev
1	0.1	0.195	1.134 ($\pm 2\%$)	1.086 ($\pm 4\%$)	1.013 ($\pm 3\%$)
2	0.1	0.390	1.395 ($\pm 2\%$)	1.104 ($\pm 4\%$)	1.075 ($\pm 3\%$)
3	0.5	1.363	2.418 ($\pm 1.5\%$)	1.564 ($\pm 4\%$)	1.163 ($\pm 3\%$)
4	0.5	2.336	2.958 ($\pm 1.5\%$)	1.737 ($\pm 5\%$)	0.776 ($\pm 5\%$)
5	0.5	3.309	2.701 ($\pm 2\%$)	1.316 ($\pm 4.5\%$)	0.449 ($\pm 10\%$)
6	0.5	4.282	2.129 ($\pm 2\%$)	0.937 ($\pm 6.3\%$)	0.267 ($\pm 12\%$)
7	1.0	6.229	1.195 ($\pm 2.5\%$)	0.358 ($\pm 7\%$)	0.078 ($\pm 29\%$)
8	1.0	8.176	0.554 ($\pm 5\%$)	0.140 ($\pm 12.5\%$)	0.031 ($\pm 66\%$)
9	1.0	10.123	0.214 ($\pm 14\%$)	0.067 ($\pm 42\%$)	0.020 ($\pm 200\%$)
10	1.0	12.070	0.086 ($\pm 50\%$)	0.023 ($\pm 93\%$)	0.006 ($\pm 200\%$)
11	1.5	14.990	0.019 ($\pm 150\%$)	0.003 ($\pm 300\%$)	

^aNumber of charged particles above energy E passing through a plane at t radiation lengths in a shower initiated by electrons of energy E_0 .

Table 8.1.2. Experimental Values of $\Pi(E_0, E, t)^a$ for Copper $rl = 1.432$; $E = 1$ Mev (kinetic energy)

Slab	Copper Thickness (cm)	Total Copper Thickness (rl)	$\Pi(E_0, E, t)^a$	
			$E_0 = 380$ Mev	$E_0 = 200$ Mev
1	1.0	0.698	1.75 ($\pm 2.2\%$)	1.45 ($\pm 1.9\%$)
2	1.0	1.396	2.25 ($\pm 2.0\%$)	1.56 ($\pm 1.7\%$)
3	1.0	2.094	2.32 ($\pm 2.0\%$)	1.23 ($\pm 1.8\%$)
4	1.0	2.792	1.94 ($\pm 2.2\%$)	0.87 ($\pm 5\%$)
5	2.0	4.188	1.24 ($\pm 5.2\%$)	0.51 ($\pm 9\%$)
6	2.0	5.584	0.69 ($\pm 11\%$)	0.298 ($\pm 14\%$)
7	2.0	6.980	0.40 ($\pm 16\%$)	0.183 ($\pm 23\%$)
8	2.0	8.376	0.23 ($\pm 23\%$)	0.123 ($\pm 34\%$)
9	2.0	9.772		0.088 ($\pm 48\%$)
10	2.0	11.168		0.055 ($\pm 77\%$)

^aNumber of charged particles above energy E passing through a plane at t radiation lengths in a shower initiated by electrons of energy E_0 .

Fig. 8.1.3. Charged-Particle Shower Curves in Lead. Curves are fits to the experimental data; the lead thickness is given as the depth and neglects the propane thickness between lead slabs.

Fig. 8.1.4. Charged-Particle Shower Curves in Copper. Curves are fits to the experimental data; the copper thickness is given as the depth and neglects the propane thickness between copper slabs.

separately. A group of source particles was allowed to enter the first slab, and all particles passing through the back face of the slab were recorded (including angle, position, and energy) and used as source particles for the second slab. Since reflected radiation from any slab was lost from the shower, some inaccuracies occurred because of the neglect of multiple reflections.

The agreement between the calculated and experimental results for lead (Fig. 8.1.3) is reasonably good considering the inaccuracy in the calculation due to neglecting multiple reflections at boundaries and due to certain mathematical

approximations in the calculation when treating the charged particles with energies below 5 Mev. One striking difference occurs at the larger depths in that the calculated results tend toward the exponential attenuation calculated with the minimum photon cross section whereas the experimental data continue to decrease more rapidly with depth.

The comparison between experiment and calculation for the case of copper, shown in Fig. 8.1.4, is not quite so favorable as it was for lead, especially at 200 Mev. In any case, however, the comparison is made on an absolute basis and clearly indicates that the calculation is reasonably accurate.

8.2. STUDIES OF THE CREATION OF POSITRONS IN TARGETS BY A 1-GeV ELECTRON BEAM

C. D. Zerby and H. S. Moran

Studies of the generation of positrons in targets bombarded with high-energy electron beams have continued as part of an investigation of the performance of the 20-GeV Stanford linear accelerator as a positron machine.¹ The electron accelerator is converted into a positron accelerator by accelerating electrons to 1 Gev in the first part of the tube and having them strike an internal target. The incident electrons produce cascade showers in the target in which positrons are created in pair production events by the bremsstrahlung radiation. The positrons that penetrate the target are then accelerated in the remaining length of the accelerator by a field whose polarity is reversed from the field polarity of the first part of the machine.

The information required to determine the positron beam strength in such an accelerator is the intensity of the positrons penetrating the internal target and their radial, angular, and energy distributions. These distributions are needed to determine the number and energy distribution of

positrons that will reach the end of the accelerator without striking the sides of the accelerator tube.

For purposes of this study, the three-dimensional electron-photon cascade calculation (Sec. 8.1) was used to calculate the positrons generated in 3-radiation-length-thick targets bombarded by a narrow 1-GeV electron beam. The positrons above 3 Mev created in lead, tin, copper, and aluminum targets are shown in Fig. 8.2.1. Of the various materials considered, lead yields the largest conversion of incident electrons into positrons.

The buildup of positrons in the lead target is shown in comparison with the electron population in Fig. 8.2.2. As can be seen, the ratio of electrons to positrons is always greater than unity, as would be expected. The energy distributions of the penetrating positrons and electrons (Fig. 8.2.3) appear to be very similar in shape, differing only in magnitude.

The radial distribution of the penetrating positrons and electrons is given in Fig. 8.2.4 as a function of the radial distance from the beam axis. The angular distribution of the penetrating positrons is given in Fig. 8.2.5 as a function of the polar angle with respect to the beam axis.

¹C. D. Zerby and H. S. Moran, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 261.

Fig. 8.2.1. Positrons Above 3 Mev Generated in 3-Radiation-Length-Thick Slabs by a 1-Gev Electron Beam.

Fig. 8.2.2. Particles Above 3 Mev Generated in a 3-Radiation-Length-Thick Lead Slab by a 1-Gev Electron Beam.

Fig. 8.2.3. Energy Distribution of Particles Penetrating a 3-Radiation-Length-Thick Lead Slab for the Case of Normally Incident 1-Gev Electrons.

Fig. 8.2.4. Lateral Distribution of Particles Penetrating a 3-Radiation-Length-Thick Lead Slab for the Case of Normally Incident 1-Gev Electrons.

Additional studies of the positrons penetrating targets are being prepared, for the purpose of extracting data as a function of parameters more

suitable for determining the number of positrons that reach the end of the accelerator in the accelerating field of the Stanford machine.

Fig. 8.2.5. Angular Distribution of Positrons Penetrating a 3-Radiation-Length-Thick Lead Slab for the Case of Normally Incident 1-Gev Electrons.

8.3. CALCULATION OF ENERGY DEPOSITED IN WATER, ALUMINUM, AND COPPER BY A 20-GeV ELECTRON BEAM

C. D. Zerby and H. S. Moran

One of the problems involved in designing the beam stopper for the Stanford linear accelerator is how to provide adequate cooling to prevent the electron beam from burning its way through the stopper. With the present machine design for a 20-GeV electron beam, the average beam current will be 30 μ a and the beam power will be 0.6 Mw. This will be increased eventually to

a 60- μ a beam current of 40-GeV electrons, resulting in a factor of 4 increase in the beam power.

The beam-stopping problem has been studied by calculations with the three-dimensional electron-photon cascade code (Sec. 8.1) to determine the energy deposited by a narrow 20-GeV electron beam in water, aluminum, and copper (stopper materials being considered). The results are

Fig. 8.3.1. Average Energy Deposited in Water by 20-GeV Incident Electrons.

Fig. 8.3.2. Average Energy Deposited in Aluminum by 20-GeV Incident Electrons.

shown in Figs. 8.3.1 through 8.3.3, the three sets of curves being made comparable by taking the unit of length as the radiation length.

In order to obtain an estimate of the heating problem in the beam stopper, assume that the diameter of the beam is restricted to the inside diameter of the accelerator tube (2.206 cm) and that the beam is uniformly distributed over that

area. In the case of water a rough calculation using the data presented in Fig. 8.1.1 shows that the energy deposition by a 20-GeV beam at the peak of the energy deposition curve will be approximately 207 watts/cm³ or 49.5 cal/g-sec. In other words, it would take approximately 11 sec to completely vaporize the water if it were not circulated. In the case of water, the dissociation of hydrogen and oxygen would also be significant.

Fig. 8.3.3. Average Energy Deposited in Copper by 20-GeV Incident Electrons.

8.4. CALCULATION OF ENERGY DEPOSITED IN SHIELDED SOLAR CELLS BY HIGH-ENERGY ELECTRONS

C. D. Zerby and H. S. Moran

The current interest in the damage to solar cells by electrons in the earth's artificial radiation belt, which consists principally in electrons with energies below 7 Mev, has prompted a series of experimental studies by Bell Telephone Laboratories to determine the energy deposited by electrons in cells shielded with various thicknesses of materials. In an effort to verify these experiments and also to provide a means of extending the available data, an attempt was made to calculate the energy deposited in solar cells with the high-energy three-dimensional electron-photon cascade code (see Sec. 8.1) even though the code is not particularly suitable for treating electrons below approximately 5 Mev. The reason for the reservation concerning the low-energy electrons is that certain mathematical approximations for the behavior of the electrons were introduced into the calculations which are accurate at high energies but only approximate at low energies.

Trial calculations for the solar-cell problem were set up for normally incident electrons on a 0.04064-cm-thick solar cell with an aluminum shield. The solar-cell material was approximated by aluminum in each case. Calculations were performed for 3.0- and 6.0-Mev (total energy) incident electrons and various shield thicknesses. The results are presented in Table 8.4.1.

In Fig. 8.4.1 the 3.0-Mev case is compared with Bell Telephone Laboratories experimental results¹ at 3.51-Mev incident energy. The discrepancy between the two sets of data is probably due to the inaccuracies in the calculation at low energies and to the slight difference in incident energy. The discrepancies are small enough, however, for the calculations to be very useful in extending the experimental data.

¹Mary Donnelly, Bell Telephone Laboratories, Whippany, New Jersey (private communication).

Table 8.4.1. Energy Deposited in Solar Cells by Electrons Normally Incident on the Outside of a Thin Aluminum Shield

E_0 = total electron energy (kinetic plus rest mass)
Solar cell material: aluminum
Solar cell thickness: 0.04064 cm

Shield Thickness (cm)	Shield Thickness (g/cm ²)	Energy Deposited (Mev/incident particle)					
		In Shield			In Cell		
		By Photons	By Charged Particles	Total	By Photons	By Charged Particles	Total
$E_0 = 3.0$ Mev							
0.03705	0.1	0.00100	0.1603	0.1613	0.00166	0.2083	0.2099
0.07410	0.2	0.00267	0.3481	0.3508	0.00169	0.2384	0.2401
0.18525	0.5	0.00660	1.019	1.026	0.00152	0.2608	0.2623
0.37051	1.0	0.01175	1.648	1.660	0.00078	0.1329	0.1337
0.55576	1.5	0.01403	2.368	2.382	0.00008	0.02355	0.02363
1.37088	3.7	0.01547	2.391	2.407	0	9.55×10^{-6}	9.55×10^{-6}
$E_0 = 6.0$ Mev							
0.03705	0.1	0.00077	0.1664	0.1672	0.00071	0.1869	0.1876
0.07410	0.2	0.00207	0.3369	0.3389	0.00114	0.1943	0.1955
0.18525	0.5	0.00636	0.885	0.8949	0.00174	0.2314	0.2331
0.37051	1.0	0.01206	1.978	1.990	0.00164	0.2967	0.2983
0.55576	1.5	0.01990	3.083	3.103	0.00191	0.2818	0.2837
1.37088	3.7	0.03083	5.231	5.262	0	0.00747	0.00747

Fig. 8.4.1. Average Energy Deposited in a 0.04064-cm-Thick Solar Cell with an Aluminum Shield by Normally Incident Electrons.

8.5. A COLLIMATOR STUDY FOR A 20-GeV ELECTRON BEAM

C. D. Zerby and H. S. Moran

The study reported previously¹ to investigate the behavior of incident electrons and the resulting secondary radiations in collimators, or constrictions, proposed for installation along the tube of the Stanford linear electron accelerator was continued with a calculation for a 20-GeV beam.² The purpose of the collimators is to strip off electrons in the outer part of the beam that might otherwise be deposited in the tube walls, where they not only would produce secondary radiations, and thus create a shielding problem, but could also deposit sufficient heat to necessitate that the entire tube be cooled. By using collimators, it is hoped to restrict the shielding

and cooling problems to the rather localized regions containing the collimators. However, a collimator cannot be constructed to totally absorb the primary radiations that strike it or the secondary radiations that are produced in it. Therefore, in order to study the behavior of radiation resulting from electron beams incident on such collimators, calculations with the three-dimensional cascade code described in Sec. 8.1 were initiated.

The 20-GeV beam calculation was for a cylindrical aluminum collimator which was assumed to be 162.5 cm thick (18 radiation lengths) and to have a 0.625-cm-diam hole. Numerical results of the energy absorbed in and penetrating the collimator were obtained for the case of narrow beams incident at various distances from the lip of the collimator hole. In addition, the energy penetration and the spatial distribution of the energy deposited in the collimator by a uniform beam having an outside radius of 1.1303 cm were calculated. The results are presented elsewhere.²

¹C. D. Zerby and H. Moran, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 256; see also C. D. Zerby and H. S. Moran, *A Collimator Study for a 5-GeV Electron Beam*, ORNL TM-423 (Dec. 1962).

²C. D. Zerby and H. S. Moran, *A Collimator Study for a 20-GeV Electron Beam*, ORNL TM-524 (March 1963).

8.6. PRELIMINARY RESULTS FROM NUCLEAR EMULSIONS EMBEDDED IN A STEEL SHIELD EXPOSED TO A NARROW 9-GeV/c PROTON BEAM

R. L. Childers¹

The work reported here is a continuation of the studies² by a number of laboratories of nuclear showers induced in various shielding materials by highly energetic protons of energies ranging from 9 to 30 Gev. In this experiment, which was performed in cooperation with Rutherford High-Energy Laboratory, nuclear emulsions were placed at various positions in a steel shield exposed to a narrow 9-GeV proton beam. The exposed emulsions are being scanned for shower-track intensity, defined as the number of charged particles above a certain energy crossing the unit area per incident beam particle, and for star density, defined as the number of nuclear interactions per unit volume. The measurements at ORNL on the shower-track intensity are essentially complete, but the investigation of the lateral distribution of the stars and angular distributions of fast secondary particles from stars is still in progress.

Exposure

The exposures were made in October 1962 to the 9-GeV/c proton beam of the CERN proton synchrotron. Four 7.5×2 cm Ilford G5 emulsions mounted on glass plates were placed between blocks of steel (density, 7.83 g/cm^3) as shown in Fig. 8.6.1. The plates were stacked one above the other, with the plane of the emulsion parallel to the horizontal plane and with the long edge of the plates perpendicular to the direction of the beam. The thickness of each stack was less than the width of the incident proton beam. Each stack consisted of two thin and two thick plates whose nominal respective thicknesses were 50 and 200μ , or 100 and 600μ , or 200 and 600μ . The top and bottom plates (one thin and the other thick) from each stack were sent to ORNL, and the middle two were sent to the Rutherford Laboratory.

Since the shower intensity, as measured either by star density or by shower-track intensity, falls

off quite rapidly after the initial buildup, it is desirable to give different exposure times to different plates. Properly done, this ensures that each plate will have enough tracks or stars for reasonable statistics to be obtained in a moderate

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Fig. 8.6.1. Plan View of Placement of Emulsions and Steel Blocks.

¹Consultant, University of Tennessee.

²R. L. Childers, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, pp 241-48.

length of time, but not so many that they will be difficult to count. In this experiment the exposure times varied by a factor of about 10^4 from the shortest to the longest exposure. The shower-track intensity varied by a factor of about 2×10^5 from the most intense to the least intense position. This resulted in a satisfactory number of shower tracks and stars in most plates. The exposures, as measured by a counter telescope of two scintillation counters at the point at which the beam entered the steel, are given in Table 8.6.1.

Scanning

The emulsions were scanned for shower tracks with a Bausch & Lomb Dyna Zoom microscope by essentially the same procedure described previously.² However, both the stars and shower tracks were classified in somewhat greater detail than in the previous experiments. The thinnest plate from each position was scanned for tracks every 3 mm over a total width of 75 mm. At each point the number of tracks crossing an area perpendicular to the shower axis, 100 μ long and as thick as the emulsion, was counted and the angle of the tracks was recorded. The tracks were grouped according to angular intervals: 5°-intervals from 0 to 45°, one interval from 45 to 60°, and one interval from 60 to 90°. The angles were measured with respect to the shower axis with an eyepiece protractor capable of reading to within 0.25°. For each plate the shower axis was taken as a line perpendicular to the leading edge. By looking at the angular distributions in the plates along the shower axis (which should be symmetric about 0°), we estimate that, if the off-axis plates were aligned with the same accuracy as the on-axis plates, our defined shower axis differs by no more than ~ 2 to 3° from the true shower axis in any case.

The stars are classified under two broad headings: those induced by neutral particles and those induced by charged particles. A star is classified as "neutral" if it has no minimum ionizing track in the backward direction within 5° of the beam direction, a condition which must be satisfied only for on-axis stars, or if it has no minimum ionizing track in the backward hemisphere. Stars not meeting these requirements are classified as "charged primary."

For all stars the number of shower tracks (n_s) and heavy tracks (n_h) was counted. The projected angles of the shower tracks (projected in the plane of the emulsion) were measured with respect to the shower axis to within $\pm 1^\circ$. A camera attached to the microscope was used to photograph each star.

The scanning for both stars and shower tracks was done over the full width of each plate. When there was no appreciable variation in intensity over the length, the whole plate was used to give the intensity at a point. If there was appreciable variation, a smaller portion of the plate, as small as 100 μ long in the plate in the incident beam, was used to establish the intensity. For the first few plates (20 to 30 cm) this aided in obtaining information about the lateral shape of the shower, but beyond that point the intensity was found to be essentially constant over the dimensions of the plate.

Thickness Measurements

In order to have an absolute, rather than a relative, measure of the shower intensity (either star density or shower-track intensity), it was necessary to know the thickness of the emulsion before the plates had been processed, since during processing a nuclear emulsion shrinks by a factor of about 2. Emulsions as small as those used in this experiment are supplied already mounted on the glass backing; therefore the combined thickness of the emulsion and glass had been measured before the plates were processed. For each plate the measurement was made at two points along a line through the middle of the plate and equidistant from each end.

To determine the original thickness of the emulsion it was necessary merely to subtract the thickness of the glass. In order not to damage the plates, we accomplished this by mechanically measuring the combined thickness of the processed emulsion and glass and subtracting the thickness of the emulsion, which was measured optically. It was easy to obtain the thickness of the emulsion since the effective index of refraction of the emulsion plus the immersion oil used on the microscopes is unity.³ This was verified to be true to within a

³C. F. Powell, P. H. Fowler, and D. H. Perkins, *The Study of Elementary Particles by the Photographic Method*, p 89, Pergamon, New York, 1959.

Table 8.6.1. Exposure Data for Various Nuclear Emulsions

Plate		Exposure (particles/cm ²)	Average Original Thickness (μ)
Nominal Thickness (μ)	Position		
50	A-0 ^a	5.126×10^5	60
	B-0	5.126×10^5	50
	C-0	5.126×10^5	49
	D-0	3.574×10^6	42
	E-0	3.574×10^6	56
100	F-0	3.574×10^6	102
	G-0	3.574×10^6	88
	H-0	1.886×10^7	87
	I-0	5.380×10^7	101
	K-0	1.650×10^8	93
	L-0	5.677×10^8	78
	M-0	4.075×10^9	100
	N-0	4.075×10^9	96
	O-0	3.574×10^6	101
	P-0	4.075×10^9	102
	A-8	5.380×10^7	93
	B-8	1.886×10^7	106
	C-8	3.574×10^6	108
	C-16	1.886×10^7	72
	D-8	3.574×10^6	79
	D-16	1.886×10^7	86
	D-24	4.075×10^9	84
	E-16	1.886×10^7	96
	F-8	3.574×10^6	78
	F-20	1.886×10^7	93
	F-30	5.380×10^7	81
	H-8	1.886×10^7	88
	H-20	5.380×10^7	99
	H-32	5.677×10^8	92
	I-8	5.380×10^7	95
	I-20	1.650×10^8	106
	I-32	5.677×10^8	101
	I-44	4.075×10^9	104
	K-8	1.650×10^8	104
	K-20	5.677×10^8	95
	K-32	4.075×10^9	112
	K-44	4.075×10^9	111
	L-8	5.677×10^8	104
	L-20	4.075×10^9	96
	L-32	4.075×10^9	108
	L-44	4.075×10^9	79
	M-8	4.075×10^9	110
	M-20	4.075×10^9	102
	M-32	4.075×10^9	98

Table 8.6.1 (continued)

Plate		Exposure (particles/cm ²)	Average Original Thickness (μ)
Nominal Thickness (μ)	Position		
100	M-44	4.075×10^9	113
	M-58	4.075×10^9	79
	N-8	4.075×10^9	115
	N-20	4.075×10^9	102
	N-32	4.075×10^9	101
	N-44	4.075×10^9	90
	N-58	4.075×10^9	79
	N-72	4.075×10^9	76
	O-8	4.075×10^9	89
	O-20	4.075×10^9	108
	O-32	4.075×10^9	93
	O-44	4.075×10^9	82
	O-58	4.075×10^9	114
	A-0	5.126×10^5	210
	B-0	5.126×10^5	222
	C-0	5.126×10^5	210
	D-0	3.574×10^6	211
	F-0	3.574×10^6	223
	F-0	3.574×10^6	565
	G-0	3.574×10^6	577
	H-0	1.886×10^7	553
	I-0	5.380×10^7	559
	K-0	1.650×10^8	563
	L-0	5.677×10^8	559
	M-0	4.075×10^9	581
	N-0	4.075×10^9	562
	O-0	4.075×10^9	579
	P-0	4.075×10^9	539
	A-8	5.380×10^7	555
	B-8	1.886×10^7	582
	C-8	3.574×10^6	540
	C-16	1.886×10^7	541
	D-8	3.574×10^6	548
	D-16	1.886×10^7	570
	D-24	4.075×10^9	581
	E-16	1.886×10^7	572
	F-8	3.574×10^6	570
	F-20	1.886×10^7	560
	F-30	5.380×10^7	552
	H-8	1.886×10^7	571
	H-20	5.380×10^7	560
	H-32	5.677×10^8	561
	I-8	5.380×10^7	574
	I-20	1.650×10^8	582

Table 8.6.1 (continued)

Plate		Exposure (particles/cm ²)	Average Original Thickness (μ)
Nominal Thickness (μ)	Position		
600	I-32	5.677×10^8	579
	I-44	4.075×10^9	526
	K-8	1.650×10^8	567
	K-20	5.677×10^8	568
	K-32	4.075×10^9	574
	K-44	4.075×10^9	565
	L-8	5.677×10^8	569
	L-20	4.075×10^9	585
	L-32	4.075×10^9	569
	L-44	4.075×10^9	575
	M-8	4.075×10^9	582
	M-20	4.075×10^9	577
	M-32	4.075×10^9	536
	M-44	4.075×10^9	542
	M-58	4.075×10^9	559
	N-8	4.075×10^9	530
	N-20	4.075×10^9	557
	N-32	4.075×10^9	565
	N-44	4.075×10^9	560
	N-58	4.075×10^9	572
	N-72	4.075×10^9	571
	O-8	4.075×10^9	557
	O-20	4.075×10^9	561
	O-32	4.075×10^9	547
	O-44	4.075×10^9	557
	O-58	4.075×10^9	570

^aSee Fig. 8.6.1 for plan view of plates; number following letter indicates the distance, in cm, of the plate from the beam axis.

few percent by stripping the emulsion from a few plates and measuring the thicknesses directly.

The values obtained for the thicknesses of the various plates are listed along with the exposure times in Table 8.6.1.

Results

Shower-Track Intensity. — The shower-track intensity along the beam axis is shown in Fig. 8.6.2 as a function of depth into the steel. No initial buildup region (the distance over which the shower

builds up before it drops to its original intensity) is observed along the beam axis. There is an exponential decay region followed by a non-exponential region. This nonexponential region is evidence for mu mesons, which have an extremely small interaction cross section.

A least-squares fit in the attenuation region (i.e., that region between 20 and 180 cm) gives a value of 17.0 ± 1.0 cm for the attenuation length. If the attenuation region were taken to be that region between 10 and 220 cm, the value would be 18.2 ± 1.0 cm.

Fig. 8.6.2. Shower Track Intensity Along the Beam Axis as a Function of Depth into the Steel.

If the density of the steel is taken to be 7.83 g/cm^3 , the attenuation length can be expressed as $133 \pm 8 \text{ g/cm}^2$. When the attenuation length is expressed in these units, the values for different energies and different materials group rather closely together. Table 8.6.2 gives the results from several different experiments which were performed under slightly different conditions (i.e., width or beam, scanning details, etc.) and therefore are not strictly comparable. The value of $133 \pm 8 \text{ g/cm}^2$ observed by ORNL is in good agreement with the value of about 130 g/cm^2 observed by the group at the Rutherford Laboratory.⁴

Figures 8.6.3–8.6.5 depict the lateral development of the shower. Each curve represents the lateral development at a given depth in the concrete. As might be expected, the curves become flatter as the depth is increased.

In order to obtain an estimate of the total number of tracks per incident proton at a given depth (i.e., the shower-track intensity integrated over a plane perpendicular to the beam direction), it was decided to approximate the lateral spread in the shower by a Gaussian fit. Although the lateral distribution is not truly Gaussian, the fit does provide some means of approximating the total shower-track intensity, as the above-mentioned quantity is

⁴Kindly furnished by R. H. Thomas: *Preliminary Results from Steel Shielding Experiment at 10 GeV/c*, Rutherford High-Energy Laboratory, Harwell, England (1963).

Table 8.6.2. Attenuation Length Measured Along the Beam Axis for Several Energies and Materials

Material	Incident Proton Momentum (Gev/c)	Attenuation Length (g/cm^2)	Type of Data
Barytes concrete	20 to 24	115 ± 15^a	Star density
Barytes concrete and earth	20 to 24	145 ± 10^a	Star intensity
Barytes concrete	22	128 ± 14^b	Track intensity
Barytes concrete	9	164 ± 18^c	Star density
Steel	9	133 ± 8^d	Track intensity

^aA. Citron *et al.*, *Nucl. Inst. Methods* 14, 97 (1961).

^bUnpublished Stanford Linear Accelerator data.

^cR. L. Childers, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, pp 241–48.

^dThis experiment.

Fig. 8.6.4. Shower Track Intensity vs Distance from Shower Axis for Depths of 40, 50, 80, and 100 cm.

Fig. 8.6.3. Shower Track Intensity vs Distance from Shower Axis for Depths of 0, 10, 20, and 30 cm.

Fig. 8.6.5. Shower Track Intensity vs Distance from Shower Axis for Depths of 120, 140, 180, 220, and 260 cm.

sometimes called. Once a least-squares fit to a Gaussian curve had been made at each depth (with depths greater than 180 cm excluded because of relatively poor statistics and obvious deviation from the Gaussian shape), it was simple to obtain the total shower track intensity by integrating over a plane. The results are plotted in Fig. 8.6.6, along with the beam-axis shower-track intensity. For comparison, both sets of points were normalized to unity at the front face of the steel shield. No statistical error bars were drawn, because the lateral distribution is not strictly Gaussian at any depth.

It is now possible to see the buildup region of the shower. This representation of the shower is the one which should be used in comparison with most calculations, not the beam-axis results alone. The buildup region is of the order of 65 cm, which is about 500 g/cm^2 .

The angular distributions of shower tracks are not presented here because of the great number of separate distributions, 57 in all, but they can be summarized as follows: the distributions at the front of the stack are highly peaked in the forward direction, growing flatter as the depth increases and becoming almost isotropic in the forward hemisphere at depths in excess of 200 cm. Several methods of condensing the angular distribution data are being considered and tried.

Star Density. — The star density has been measured along the center line of the shower only. For these points the measurements of angular distribution of fast secondaries and the track counts have not been completed. Figure 8.6.7 shows the star density along the beam axis as a function of depth into the steel. The attenuation length is $130 \pm 10 \text{ g/cm}^2$, about the same as for the track intensity measurements. A slight buildup is noted.

The buildup along the center line for star density and its absence along the center line for shower track intensity were also noted in a previous experiment.²

Fig. 8.6.6. Shower Track Intensity as a Function of Depth into the Steel. (a) Intensity integrated over a plane perpendicular to beam axis and (b) intensity on shower axis.

Discussion

Although this report is only preliminary, it is worthwhile to point out the importance of placing plates in a lateral direction, as well as along the beam line, in an experiment of this type. The final results of this experiment will include an estimation of the average energy as a function of depth. The energy will be determined from the angular distribution of fast secondaries and the number distribution of heavy and light tracks from stars. An attempt to obtain the attenuation length for inelastic interactions for fast shower particles has not been particularly successful because of poor statistics.

Fig. 8.6.7. Star Density Along the Beam Axis as a Function of Depth into the Steel.

8.7. A PERTURBATION METHOD FOR SOLVING THE ANGLE-DEPENDENT NUCLEON-MESON CASCADE EQUATIONS

R. G. Alsmiller, Jr., and F. S. Alsmiller

A method for obtaining an approximate solution to the equations describing a nucleon-meson cascade by using the angular dependence of the secondary particle production kernels as a perturbation has been described elsewhere.¹ The method is, of course, essentially one of successive approximations and its usefulness lies in the fact that in a slab geometry (the only geometry considered) the equations which must be solved numerically are essentially the same as those which are

used in the straight-ahead approximation and have been solved previously.

In the case of an infinite beam incident either normally or isotropically on a slab it is shown that the equations for the n th-order fluxes are of the same form as the equations for the first-order fluxes. Thus, if a code exists which will solve the first-order equations, one can in principle by repeated use of this code obtain an exact solution for these cases provided, of course, that the iteration converges.

In the case of a narrow beam incident normally on a slab the discussion is carried through only in first order.

¹R. G. Alsmiller, Jr., and F. S. Alsmiller, *A Perturbation Method for Solving the Angle-Dependent Nucleon-Meson Cascade Equations*, ORNL-3467 (July 1963).

8.8. AN IMPROVED CODE FOR THE NUMERICAL ANALYSIS OF A NUCLEON-MESON CASCADE

R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy¹

Work on the IBM-7090 code which is being written to eliminate several approximations that were necessary for earlier nucleon-meson cascade calculations²⁻⁵ is continuing.⁶ As was reported previously,⁷ several new features are being included so that the new code will be not only more accurate but also more efficient and more versatile.

The major improvements in the code are listed below:

1. Each of the secondary energy distributions, $F_{jk}(E', E)$, that is, the number of particles per unit energy of type j produced with energy E when a particle of type k and energy E' induces a nuclear reaction, may be an arbitrary function of E and E' . (The subscripts j and k take values N , P , and π , corresponding to neutrons, protons, and pions.)
2. Monoenergetic sources, in addition to sources with a continuous energy distribution, may be considered.
3. The density of the medium in which the cascade takes place may be an arbitrary function

¹Central Data Processing Facility of the Oak Ridge Gaseous Diffusion Plant.

²R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy, *Nucleon-Meson Cascade Calculations: Transverse Shielding for a 45-Gev Electron Accelerator* (Part I), ORNL-3289 (1962); Part II, ORNL-3365 (1963); and Part III, ORNL-3412 (1963).

³R. G. Alsmiller, Jr., and J. E. Murphy, *Nucleon-Meson Cascade Calculations: Shielding Against an 800-Mev Proton Beam*, ORNL-3406 (1963).

⁴R. G. Alsmiller, Jr., and J. E. Murphy, *Nucleon-Meson Cascade Calculations: The Star Density Produced by a 24-Gev Proton Beam in Heavy Concrete*, ORNL-3367 (1963).

⁵R. G. Alsmiller, Jr., and J. E. Murphy, *Space Vehicle Shielding Studies: Calculations of the Attenuation of a Model Solar Flare and Monoenergetic Proton Beams by Aluminum Shields*, ORNL-3317 (1962).

⁶The coding is being done by R. G. Mashburn of the Central Data Processing Facility of the Oak Ridge Gaseous Diffusion Plant.

⁷R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p. 215.

of depth. (This allowance for density variation was introduced so that the propagation of cosmic rays in the atmosphere could be considered.)

4. The production of muons from the decay of pions is treated more rigorously.

5. A provision has been made for including neutron-proton elastic scattering in hydrogenous media. The slowing-down effect of this elastic scattering on the cascade neutrons is included, as is the introduction of the recoil protons into the cascade, but the method used is very approximate.

The basic approximation, the one-dimensional cascade treatment, is retained in the new code. The cascade components considered are neutrons,

protons, charged pions, and charged muons; no distinction is made between positive and negative pions or positive and negative muons.⁸

The portion of the code which deals with incident beams having a continuous energy spectrum has been completed and is being checked for programming accuracy. The portion which deals with monoenergetic beams is not as yet complete but is expected to cause no difficulty.

⁸The equations which are being solved have been given by R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy, p 698 in *Proceedings of the Symposium on the Protection Against Radiation Hazards in Space*, TID-7652 (1962).

8.9. NUCLEON-MESON CASCADE CALCULATIONS: TRANSVERSE SHIELDING FOR A 45-GeV ELECTRON ACCELERATOR

R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy¹

In the Stanford University 45-GeV electron accelerator it is expected that some electrons will strike the walls of the accelerator tube and give rise to penetrating photonucleons and photopions. The accelerator tube will be surrounded by an earth shield; estimates of the shielding thickness required have been obtained by the Stanford group.^{2,3} To check these estimates a series of nucleon-meson cascade calculations have been carried out for several cases of interest.⁴

Using the straight-ahead approximation (that is, the assumption that a particle and all of the secondaries, tertiaries, etc., produced by the particle

travel in the same straight line), a set of coupled integrodifferential transport equations which give the neutron, proton, charged pion, and muon fluxes as a function of energy and distance have been obtained and solved numerically. Because there is very little experimental information about high-energy interactions, these equations include many quantities (cross sections, multiplicities, etc.) that are known only very approximately. In obtaining the necessary information we have relied insofar as possible on cosmic-ray data,⁵ but even so many *ad hoc* assumptions were required.

Because of the approximations involved, the equations are valid only at reasonably high energies and the particle fluxes are calculated only above 32 Mev. The results are converted to dose (in rads) by a method similar to that introduced by Gibson.⁶ Since only the flux above 32 Mev is calculated, the dose can be calculated only from these

¹Central Data Processing Facility of the Oak Ridge Gaseous Diffusion Plant.

²*Proposal for a Two-Mile Linear Electron Accelerator*, Stanford University, Stanford, California (April 1957).

³H. C. DeStaebler, Jr., *A Review of Transverse Shielding Requirements for the Stanford Two-Mile Accelerator*, W. W. Hansen Laboratories of Physics, M-262 (1961).

⁴R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy, *Nucleon-Meson Cascade Calculations: Transverse Shielding for a 45-GeV Electron Accelerator*, Part I, ORNL-3289 (1962); Part II, ORNL-3365 (1963); Part III, ORNL-3412 (1963).

⁵U. Camerini, N. O. Lock, and D. H. Perkins, chap 1 in *Progress in Cosmic Ray Physics*, vol 1, North Holland Publishing Co., Amsterdam, 1952.

⁶W. A. Gibson, *Energy Removal from Primary Proton and Neutron Beams by Tissue*, ORNL-3260 (1962).

high-energy particles. However, since the low-energy neutron dose is important, an estimate of this dose is obtained by normalizing the measured cosmic-ray neutron spectrum⁷ to our computed neutron flux.

⁷W. N. Hess *et al.*, *Phys. Rev.* 116, 2 (1959).

⁸K. G. Dedrick, *Deuteron Model Calculations of Photonucleon Yields*, W. W. Hansen Laboratories of Physics, M-227 (1960).

⁹K. G. Dedrick, *Calculation of Pion Photoproduction from Electron Accelerators According to the Statistical Model*, W. W. Hansen Laboratories of Physics, M-228 (1960).

¹⁰K. G. Dedrick, *More Calculations of Photopion Yields*, W. W. Hansen Laboratories of Physics, M-229 (1960).

For the calculations reported in Part I of ref 4 the photonucleon and photopion yields that result when a high-energy electron strikes a copper target were taken from the calculation of Dedrick,⁸⁻¹⁰ while for the calculations described in Part II of ref 4 the more recent results of DeStaebler¹¹ were used. In the most recent paper, Part III of ref 4, the results of DeStaebler¹¹ were used and calculations were carried out for two additional cases of interest.

¹¹H. DeStaebler, W. W. Hansen Laboratories of Physics, Stanford, California, private communication.

8.10. SPACE VEHICLE SHIELDING STUDIES: THE ATTENUATION OF SOLAR FLARES BY ALUMINUM SHIELDS

R. G. Alsmiller, Jr., and J. E. Murphy¹

In a previous report² nucleon-meson cascade calculations were presented for a variety of cases of interest in the shielding of manned space vehicles. Additional calculations have now been carried out which show the attenuation of several solar flares by shields having approximately the properties of aluminum.³ The method of calculation and the data used to describe the shielding medium are, except for trivial changes, the same as those used in ref 2.

Proton spectra corresponding to three very different solar events were considered. The

time-integrated integral energy spectra for these events were taken from the work of Gill.⁴ The time-integrated differential energy spectra were obtained by using an analytic fit to the curves of Gill and are shown in Fig. 8.10.1. In the calculations to obtain the data of Fig. 8.10.1 and in all succeeding calculations it was arbitrarily assumed that the flare spectra contain no protons with energy less than 32 Mev or greater than 2 Gev.

It should be emphasized that these calculations are approximate and are meant to give only preliminary answers until the more rigorous results of Bertini⁵ and Kinney⁶ become available. A comparison between the results in ref 2 and the

¹Central Data Processing Facility, Oak Ridge Gaseous Diffusion Plant.

²R. G. Alsmiller, Jr., and J. E. Murphy, *Space Vehicle Shielding Studies: Calculations of the Attenuation of a Model Solar Flare and Monoenergetic Proton Beams by Aluminum Shields*, ORNL-3317 (1963); see also R. G. Alsmiller, Jr., and J. E. Murphy, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 224.

³R. G. Alsmiller, Jr., and J. E. Murphy, *Space Vehicle Shielding Studies (Part II): The Attenuation of Solar Flares by Aluminum Shields*, ORNL-3520 (to be published).

⁴Private communication, Manned Space Flight Center, Houston.

⁵H. W. Bertini, *Monte Carlo Calculations on Intranuclear Cascades*, ORNL-3383 (1963).

⁶W. E. Kinney, R. R. Coveyou, and C. D. Zerby, p 608 in *Proceedings of the Symposium on the Protection Against Radiation Hazards in Space*, TID-7652, Book 2 (1962).

calculations of Kinney for one specific case has been published.⁷

In Fig. 8.10.2 the total dose at the center of a spherical-shell shield and at the back of a slab

shield, when each flare is incident isotropically on the shield, is plotted as a function of shield thickness (r = spherical-shell thickness, x = slab thickness). As was to be expected, the dose attenuates much more rapidly in a slab geometry than it does in a spherical-shell geometry.

In all the cases discussed here, as in ref 2, the dose from secondary particles becomes comparable with the dose from primary protons only for thick shields ($\gtrsim 50 \text{ g/cm}^2$).

⁷R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy, p 698 in *Proceedings of the Symposium on the Protection Against Radiation Hazards in Space*, TID-7652, Book 2 (1962).

Fig. 8.10.1. Time-Integrated Differential Energy Spectra for Solar Proton Events.

Fig. 8.10.2. Total Dose at Center of Spherical-Shell Aluminum Shield and at Back of Slab Shield Due to Incident Solar Protons.

8.11. INTRANUCLEAR CASCADE CALCULATIONS FOR INCIDENT PARTICLE ENERGIES FROM 25 TO 350 Mev AND FROM 25 Mev TO 2 Gev

H. W. Bertini

The code to calculate the reactions of 25- to 350-Mev particles with complex nuclei^{1,2} has been put into production and data will soon be available for distribution through the Radiation Shielding Information Center (RSIC),³ along with the cascade code itself and the three codes used to analyze the results of the calculation. The code to calculate the reactions of particles with energies up to 2 Gev with complex nuclei⁴ is now in the debugging stage and should be available for calculating preliminary data within the next few months; however, considerable modification will be required before the final version of the code is completed. In the paragraphs below the type of information available from the calculations up to 350 Mev is described briefly, and some of the modifications which will be required for the higher-energy calculations are discussed.

Calculation from 25 to 350 Mev

Since full details of the intranuclear cascade calculations for incident-particle energies below about 350 Mev are given elsewhere,^{1,2} only a brief description is included here. Incident nucleons or charged π -mesons are allowed to impinge on any nucleus for which the number of neutrons and the number of protons are two or greater. It is assumed that the nuclear reaction is initially a cascade reaction; therefore its calculation is accomplished by permitting the incident particles and subsequent collision products to make individual particle-particle collisions within the nucleus. The life history of each particle involved in a collision is traced through

subsequent collisions and is terminated only when the particle escapes, in which case its energy and direction cosines are recorded, or when its energy becomes so small (large De Broglie wavelength) that it ceases to behave as a cascade particle, in which case its remaining energy is assumed to contribute to the excitation energy of the residual nucleus. The escaping-particle data are used to obtain a wealth of information about the nuclear reaction such as particle multiplicities, various energy spectra, angular distributions, etc.

The cascade code has been run for a large number of cases in which neutrons, protons, π^+ mesons, and π^- mesons are incident on the elements C¹², O¹⁶, Al²⁷, Cr⁵², Cu⁶⁵, Ru¹⁰⁰, Ce¹⁴⁰, W¹⁸⁴, Pb²⁰⁷, and U²³⁸, the nucleons having energies of 25, 50, 100, 150, ... 400 Mev, and the mesons having energies of 25, 50, 100, 150, ... 300 Mev. The IBM output sheets for the nucleon cases have been photographed on 16-mm microfilm and are available to those interested.³ The sheets for the pion cases will soon be photographed and will also be available. Because the output is so extensive, a report⁵ that describes each sheet will be included with the film.

The cascade code and three codes written to analyze the results will also be available for distribution, all of them being operable on the IBM-7090 by using the standard IBM monitor system. Briefly, the analysis with the three codes is performed as follows. The data pertaining to the escaping-cascade particle are recorded and eventually written on an auxiliary machine tape which is analyzed by means of Analysis Codes I and II. Analysis Code I yields information pertaining both to the residual nucleus, such as its angular and momenta distributions and the excitation energy spectra, and to the escaping particles, such as their multiplicities, energy spectra, and angular distributions. In general, the distributions obtained from this code are normalized to 1. Analysis Code II gives data pertaining to the

¹H. W. Bertini, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, pp 137, 182.

²H. W. Bertini, *Monte Carlo Calculations on Intranuclear Cascades*, ORNL-3383 (April 23, 1963); see also *Phys. Rev.* 131, 1801 (1963).

³These data may be obtained upon request to the Radiation Shielding Information Center, Oak Ridge National Laboratory, P. O. Box X, Oak Ridge, Tennessee (37831); Phone 615-483-8611, Extension 6944. If the number of requests becomes large, a small charge may become necessary.

⁴H. W. Bertini, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 199.

⁵H. W. Bertini, *Description of Printed Output from Intranuclear Cascade Calculation*, ORNL-3433 (May 14, 1963).

escaping particles only, such as cross sections for the emission of particles within certain energy ranges, energy spectra within specified angular intervals, and angular distributions within specified energy limits. To some degree the data from Code II overlap those from analysis Code I but they are reported in terms of absolute cross sections, such as mb/(steradian-Mev), mb/steradian, etc. Also, Code II is more flexible in its application than Code I because the energy and angular ranges of interest can be specified as input to the code.

The third code uses an existing evaporation code⁶ as a subroutine whereby evaporation events are calculated following the cascade process. It provides the evaporation particle multiplicities, the energy spectra, and the cross sections for producing various final nuclei, that is, radiochemical cross sections.

Calculation from 25 Mev to 2 Gev

As was reported previously,⁴ the calculation for incident particles up to 2 Gev is identical to that used for particles with energies up to 350 Mev except that at the point of collision within the nucleus it must treat single- or double-pion production events as well as simple scattering in the individual particle-particle collisions. In general for nucleon-nucleon collisions it is assumed that single- or double-pion production events occur through the formation of one or two $T = \frac{3}{2}$ isobars,⁷ respectively, and for pion-nucleon collisions it is assumed that only single-pion production occurs. The calculation therefore applies for incident nucleons with energies up to about 2.5 Gev and incident pions with energies up to about 1.5 Gev.

The code for the calculation is complete and is now being debugged. As soon as the debugging has been completed the code will be available for preliminary calculations. Before it will be ready in its final form, however, several modifications will be required. For example, comparisons of the calculations with experiments will no

doubt lead to adjustments in the techniques or in the data for which assumptions were required. Also, it has already become apparent that several changes must be made to include data which have become available since the original input tape was prepared and to resolve problems associated with particle production in potential fields.

At the time that the tape containing all the basic cross-section data was prepared, there was very little information on differential scattering cross sections over the required energy range for pion-nucleon reactions other than the $\pi^- + p$ reaction.⁸ Therefore, it was arbitrarily assumed that the differential scattering cross sections for all other combinations of the pions and nucleons were the same as the $\pi^- + p$ cross section. An alternative approach of allowing the nearest resonance at any energy to dominate the scattering was considered, but investigations⁹ revealed that even at the resonance energies (other than the $\frac{3}{2}, \frac{3}{2}$ resonance) there are interference effects due to states of different angular momenta, and hence single resonance states do not dominate.

Since the time that the input tape was prepared, considerable data on the $\pi^+ + p$ differential scattering cross sections have appeared for the energy range under consideration.¹⁰ These data will be incorporated in the code, and other assumptions will be made to describe the $\pi^0 + \text{nucleon}$ reactions.

Another change that probably will be made in the code deals with the treatment of pion production in a potential field. This problem can be illustrated by first considering the reaction in which a π^- incident on a nucleus collides with a proton inside the nucleus and both the π^- and the proton escape from the nucleus without undergoing further collisions. For illustrative purposes, let the nucleus be a one-region nucleus with a potential V that applies equally to both pions and nucleons. Let the nucleons inside the nucleus have a zero-temperature Fermi distribution where the maximum kinetic energy of the nucleons is I_f .

⁸P. Falk-Variant and G. Vallados, *Rev. Mod. Phys.* **33**, 362 (1961).

⁹B. J. Moyer, *Rev. Mod. Phys.* **33**, 367 (1961).

¹⁰One example is J. A. Helland *et al.*, p 3 in 1962 *International Conference on High Energy Physics* (J. Prentki, editor), CERN, Scientific Information Service, Geneva, 1962. Many sources of unpublished data have been kindly supplied by Professor V. P. Kenney, University of Kentucky, private communication.

⁶L. Dresner, *EVAP - A FORTRAN Program for Calculating the Evaporation of Various Particles from Excited Compound Nuclei*, ORNL CF-61-12-30 (December 1961).

⁷R. M. Sternheimer and S. J. Lindenbaum, *Phys. Rev.* **123**, 333 (1961); *Phys. Rev.* **109**, 1723 (1958); *Phys. Rev.* **105**, 1874 (1957).

Kinetic energies inside the well will be designated by I , and those measured outside the range of the nuclear forces (i.e., outside the nucleus) will be designated by T . Unprimed symbols will refer to quantities before the scattering, and primed symbols will refer to quantities after the scattering. The proton suffering the collision has energy I_p prior to the event. Schematically, the event is illustrated in Fig. 8.11.1.

Fig. 8.11.1. Schematic Energy Diagram of the Reaction of a π^- -Meson with a Nucleus in Which the π^- Has an Elastic Collision with a Proton in the Nucleus and Both Particles Escape Without Further Collisions.

At the point of collision inside the nucleus, both the pion and the nucleon have well-defined kinetic energies, and the energy balance equation that governs the relativistic kinematics of the reaction is simply

$$(I_\pi + m_\pi) + (I_p + m) = (I'_\pi + m_\pi) + (I'_p + m) \quad (1)$$

or

$$I_\pi = (T_\pi + V) = (T'_\pi + V) + (T'_p + V) - I_p, \quad (2)$$

where m_π and m are the pion and nucleon rest masses, respectively. The excitation energy, E^* , of the nucleus (where a difficulty will appear later) is given by the difference between the total energy of the incident particle and the initial ground-state nucleus and the total energy

of the escaping cascade particles and the ground state of the nucleus at the end of the cascade:

$$E^* = (T_\pi + m_\pi + E_g) - (T'_\pi + T'_p + m_\pi + m + E'_g), \quad (3)$$

where E_g and E'_g are the ground-state energies of the nucleus before and after the collision, respectively. Then, according to our simple model,

$$E_g - (m + E'_g) = -\text{B.E.}, \quad (4)$$

where all quantities indicated by symbols are positive quantities and B.E. is the binding energy of the last added or most loosely bound nucleon. Using Eq. (2),

$$E^* = -\text{B.E.} - I_p + V. \quad (5)$$

The interpretation is that E^* is zero when the struck proton is most loosely bound, that is, when $I_p = I_f$, and that E^* has its maximum value when the struck proton is most tightly bound, or when $I_p = 0$. This example was used to illustrate the technique and to define the terms.

The problem of pion production in a potential field can also be illustrated by a reaction in which a pion is produced inside the nucleus at the point of collision, that is,

where N^* is the isobar. For calculational expediency the same approach is applied and the energy conservation equation resulting from the relativistic kinematics for the final products at the point of collision is then

$$(I_\pi + m_\pi) + (I_p + m) = (I'_{\pi^-} + m_\pi) + (I'_p + m) + (I'_{\pi^0} + m_\pi) \quad (6)$$

or

$$(T_\pi + V) = (T'_{\pi^-} + V) + (T'_p + V) + (T'_{\pi^0} + V) + m_\pi - I_p, \quad (7)$$

and the excitation energy is

$$E^* = (T_\pi + m_\pi + E_g) - (T'_{\pi^-} + m_\pi + T'_p + m + T'_{\pi^0} + m_\pi + E'_g) = -\text{B.E.} - I_p + 2V. \quad (8)$$

Therefore under these conditions it appears that even when the struck proton is most loosely bound, there is always a positive excitation energy V remaining in the nucleus.

In order to circumvent this problem in the present form of the calculation, it was decided to arbitrarily increase the kinetic energy of the produced pion and the nucleon by $V/2$, which will remove the excess excitation energy from the nucleus. This implies that the isobar, being a nucleon in an excited state, experiences the same potential as a nucleon, and hence the excess energy V , which is assumed to be distributed uniformly among the decay products, does not become manifest until the isobar decays. A more reasonable approach might be to allow the excess energy to become available to all particles at the point of collision. This problem will be examined further before the method used in the final form of the code is selected.

The appearance of the excess energy V is interpreted as follows. In the absence of a potential, a certain amount of energy is required to create a pion at rest, namely, m_π . In the presence of a potential V , with which the created pion interacts, less energy is required to create a pion at rest, namely, $m_\pi - V$; therefore more energy is available for kinetic energy than in the case without the potential.

If the mass of every pion and nucleon were to be reduced when it entered the nucleus by the amount

$$V = m_\pi - {}_r m_\pi = m - {}_r m, \quad (9)$$

where ${}_r m_\pi$ and ${}_r m$ are the reduced masses of the pion and nucleon, respectively, and the kinetic

energy were to be increased by a corresponding amount, then the anomaly would disappear. For the single-pion production case this is illustrated as follows. An energy balance within the nucleus at the point of collision requires that

$$I_\pi + {}_r m_\pi + I_p + {}_r m = I'_{\pi-} + {}_r m_\pi + I'_p + {}_r m + I'_{\pi 0} + {}_r m_\pi \quad (10)$$

or

$$I_\pi = T_\pi + V = (T'_{\pi-} + V) + (T'_p + V) + (T'_{\pi 0} + V) + {}_r m_\pi - I_p \quad (11)$$

The excitation energy is given by

$$\begin{aligned} E^* &= (T_\pi + m_\pi + E_g) - (T'_{\pi-} + m_\pi + T'_p + m + T'_{\pi 0} + m_\pi + E_g) \\ &= -\text{B.E.} + 2V + {}_r m_\pi - m_\pi - I_p \\ &= -\text{B.E.} + V - I_p; \end{aligned} \quad (12)$$

and if the proton which suffers the collisions is most loosely bound, the excitation energy will be zero. To be consistent, all reactions, elastic scattering included, would have to be treated in this manner; that is, the masses of the particles within the nucleus would have to be reduced. This would make the masses of all particles within the nucleus a function of their position since they are assumed to be composed of three regions, each with different potentials.

At this time it is not clear that this approach is any more realistic.

8.12. PARAMETRIC STUDY OF CALCULATED CASCADE AND EVAPORATION REACTIONS FOR 25- TO 400-Mev NUCLEONS INCIDENT ON COMPLEX NUCLEI

H. W. Bertini

A parametric study has been made of typical cases from the cascade calculations for incident energies up to 400 Mev (see Sec. 8.11). The study covers the angular and energy distributions to determine the dependence of the distributions on energy and mass number. It also covers the particle yield, average particle energy, etc., for all mass numbers and a few incident-particle energies. In addition, it includes comparisons with the radiochemical cross sections tabulated by Bruninx.¹

Some of the plots from the study are presented here to illustrate the graphic data that were compiled. Figures 8.12.1 through 8.12.12 give the excitation energy distribution of the residual

nucleus for 50-, 200-, and 400-Mev protons incident on C^{12} , Al^{27} , Cu^{65} , and Pb^{207} and for neutrons incident on Al^{27} at the same energies. For carbon and aluminum the distributions are generally peaked at the low energies, becoming more peaked with increasing energies. These nuclei are apparently diffuse in the sense that they do not retain much of the high energy available from the incident particles. Figures 8.12.4 through 8.12.6 illustrate the fact that distributions obtained for protons and neutrons incident on aluminum are about the same. This is probably true of all the elements. For the medium- and heavy-weight elements, Figs. 8.12.7 through 8.12.12, the nuclei exhibit a greater capacity to retain the energy of the incident particle. This is due to a decreased escape probability enhancing the number of collisions within the nucleus and thus increasing the number of low-energy cascade particles that can be trapped, their

¹E. Bruninx, *High Energy Nuclear Reaction Cross Sections*, CERN 61-1 (Jan. 16, 1961); and *High Energy Nuclear Reaction Cross Sections II*, CERN 62-9 (Feb. 15, 1962).

Fig. 8.12.1. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 50-Mev Protons on ${}^{12}_6C$.

Fig. 8.12.2. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 200-Mev Protons on ${}^{12}_6\text{C}$.

Fig. 8.12.3. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 400-Mev Protons on ${}^{12}_6\text{C}$.

Fig. 8.12.4. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 50-Mev Protons on $^{27}_{13}\text{Al}$ (Solid Lines) and 50-Mev Neutrons on $^{27}_{13}\text{Al}$ (Dashed Lines).

Fig. 8.12.5. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 200-Mev Protons on $^{27}_{13}\text{Al}$ (Solid Lines) and 200-Mev Neutrons on $^{27}_{13}\text{Al}$ (Dashed Lines).

Fig. 8.12.6. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 400-Mev Protons on $^{27}_{13}\text{Al}$ (Solid Lines) and 400-Mev Neutrons on $^{27}_{13}\text{Al}$ (Dashed Lines).

Fig. 8.12.7. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 50-Mev Protons on $^{65}_{29}\text{Cu}$.

Fig. 8.12.8. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 200-MeV Protons on $^{65}_{29}\text{Cu}$.

Fig. 8.12.9. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 400-MeV Protons on $^{65}_{29}\text{Cu}$.

Fig. 8.12.10. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 50-MeV Protons on $_{82}\text{Pb}^{207}$.

Fig. 8.12.11. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 200-MeV Protons on $_{82}\text{Pb}^{207}$.

Fig. 8.12.12. Excitation Energy Distribution of the Residual Nucleus Resulting from Cascade Reaction for 400-Mev Protons on $^{207}_{82}\text{Pb}$.

energy then becoming available as excitation energy.

The discontinuities in the distributions illustrated in Figs. 8.12.7 and 8.12.10 are due to the following: The high-energy spike results from the capture of the incident particles with no cascade particles escaping. (Note that this occurs with appreciable probability for the low-energy incident particles only.) This large peak should really be a delta function at an energy which is the sum of the kinetic energy and the binding energy (assumed to be 7 Mev) of the incident particle. The next highest possible excitation energy that the nucleus can have is determined by the reaction in which only one cascade particle escapes with the minimum possible kinetic energy. In the cascade calculation this energy is the cutoff energy of the calculation: 3.1 Mev for copper and 6.7 Mev for lead. Therefore the difference in excitation energies between the capture reaction and the next highest excitation energy possible is 10.1 Mev for copper and 13.7 Mev for lead. These values bracket the range over which the excitation energy is zero.

Figures 8.12.13 through 8.12.27 illustrate the differential cross sections for neutron and proton emission in the forward direction as a function of the emitted-particle energies for the same cases used above. For the light elements there are both low- and high-energy peaks in the cross sections. For incident protons the cross section for high-energy proton emission is greater than for high-energy neutron emission, while for incident neutrons the cross section for high-energy neutron emission is greater. This results from the fact that the events leading to high-energy particles escaping in the forward direction are single-collision events. When an incident proton collides with a proton it gives two cascade protons, while when colliding with a neutron it gives one cascade proton and one cascade neutron. A p - p collision plus a p - n collision yields three cascade protons and one cascade neutron, whereas an n - n collision plus an n - p collision yields three neutrons and one proton. If the cross sections and the neutron and proton densities within the nucleus were the same, then single-collision processes would result in the emission of three times more particles of

Fig. 8.12.13. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 50-MeV Protons on ${}_6\text{C}^{12}$.

Fig. 8.12.15. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 400-MeV Protons on ${}_6\text{C}^{12}$.

Fig. 8.12.14. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 200-MeV Protons on ${}_6\text{C}^{12}$.

Fig. 8.12.16. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 50-MeV Protons on ${}_{13}\text{Al}^{27}$.

Fig. 8.12.17. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 200-MeV Protons on $^{13}\text{Al}^{27}$.

Fig. 8.12.19. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 50-MeV Neutrons on $^{13}\text{Al}^{27}$.

Fig. 8.12.18. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 400-MeV Protons on $^{13}\text{Al}^{27}$.

Fig. 8.12.20. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 200-MeV Neutrons on $^{13}\text{Al}^{27}$.

Fig. 8.12.21. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 400-Mev Neutrons on $^{13}\text{Al}^{27}$.

Fig. 8.12.23. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 200-Mev Protons on $^{29}\text{Cu}^{65}$.

Fig. 8.12.22. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 50-Mev Protons on $^{29}\text{Cu}^{65}$.

Fig. 8.12.24. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 400-Mev Protons on $^{29}\text{Cu}^{65}$.

Fig. 8.12.25. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 50-Mev Protons on $^{82}\text{Pb}^{207}$.

Fig. 8.12.27. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 400-Mev Protons on $^{82}\text{Pb}^{207}$.

Fig. 8.12.26. Energy Spectra of Emitted Cascade Protons and Neutrons in the Laboratory Angular Interval 0 to 30° for 200-Mev Protons on $^{82}\text{Pb}^{207}$.

the same type as the incident particle. The $n-p$ cross section is greater than the $p-p$ cross section in the energy region being considered and so the effect is reduced, but it is still observable in the light elements. For the copper and lead targets the increased neutron density finally compensates for this effect.

As the target mass increases, the number of single-collision events decreases because the number of mean free paths through the nucleus increases and the high-energy peak becomes relatively smaller.

Figures 8.12.28 through 8.12.42 illustrate the combined cascade and evaporation particle spectra for neutron and proton emission for the same cases given above. These spectra are all normalized to unity and are somewhat deceiving

Fig. 8.12.28. Normalized Cascade and Evaporation Particle Spectra for 50-MeV Protons on ${}_6\text{C}^{12}$.

since they do not reflect the much larger number of neutrons evaporated from the heavier elements. The curves are normalized so that the combined spectrum is given by

$$N(E) = \frac{\langle n \rangle_{cc} N_{cc}(E) + \langle n \rangle_{ev} N_{ev}(E)}{\langle n \rangle_{cc} + \langle n \rangle_{ev}},$$

where $N_{cc}(E)$ and $N_{ev}(E)$ are the normalized cascade and evaporation particle spectra, respectively, and $\langle n \rangle_{cc}$ and $\langle n \rangle_{ev}$ are the average number of emitted cascade and evaporation particles. Note that for a given energy the peaks in the proton spectra, due almost entirely to evaporation protons, tend to increase with mass number up to copper. This is a reflection of both the decrease in the

Fig. 8.12.29. Normalized Cascade and Evaporation Particle Spectra for 200-MeV Protons on ${}_6\text{C}^{12}$.

Fig. 8.12.30. Normalized Cascade and Evaporation Particle Spectra for 400-MeV Protons on ${}_6\text{C}^{12}$.

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2-01-059-909A Fig. 8.12.31. Normalized Cascade and Evaporation Particle Spectra for 50-Mev Protons on $^{27}_{13}\text{Al}$. Fig. 8.12.32. Normalized Cascade and Evaporation Particle Spectra for 200-Mev Protons on $^{27}_{13}\text{Al}$.

Fig. 8.12.33. Normalized Cascade and Evaporation Particle Spectra for 400-Mev Protons on $^{13}\text{Al}^{27}$.

Fig. 8.12.34. Normalized Cascade and Evaporation Particle Spectra for 50-Mev Neutrons on $^{13}\text{Al}^{27}$.

Fig. 8.12.35. Normalized Cascade and Evaporation Particle Spectra for 200-Mev Neutrons on $^{13}\text{Al}^{27}$.

Fig. 8.12.36. Normalized Cascade and Evaporation Particle Spectra for 400-Mev Neutrons on $^{13}\text{Al}^{27}$.

Fig. 8.12.37. Normalized Cascade and Evaporation Particle Spectra for 50-Mev Protons on $^{29}\text{Cu}^{65}$.

Fig. 8.12.38. Normalized Cascade and Evaporation Particle Spectra for 200-Mev Protons on $^{29}\text{Cu}^{65}$.

Fig. 8.12.39. Normalized Cascade and Evaporation Particle Spectra for 400-Mev Protons on $_{29}\text{Cu}^{65}$.

Fig. 8.12.40. Normalized Cascade and Evaporation Particle Spectra for 50-Mev Protons on $_{82}\text{Pb}^{207}$.

Fig. 8.12.41. Normalized Cascade and Evaporation Particle Spectra for 200-Mev Protons on $_{82}\text{Pb}^{207}$.

Fig. 8.12.42. Normalized Cascade and Evaporation Particle Spectra for 400-Mev Protons on $_{82}\text{Pb}^{207}$.

nuclear temperature with mass number² and the increase with mass number of the fraction of total emitted particles which are evaporation particles. The decrease in the height of the peaks with energy for a given mass number reflects the opposite trend of both effects.

The spectra are nearly the same for incident neutrons on aluminum as for incident protons, and this will probably be true for all elements.

Because of the large potential barrier, the peaks in the proton spectra for lead are due almost exclusively to the cascade protons at the lower

incident-particle energies. The evaporation protons have an effect only at the higher incident-particle energies, where the excitation energy remaining in the nucleus prior to evaporation becomes large.

Figures 8.12.43 through 8.12.50 present the yields of cascade and evaporation protons and neutrons for incident protons and neutrons as a function of the mass number A . Here again the enhancement of the yield of particle types which are the same as the incident particle is evident in the cascade particle data, and, as mentioned above, this effect is reduced for the heavier nuclei by the increased ratio of neutrons to protons. The sharp decrease with mass number in the yield of evaporation protons is due to the increase in the potential barrier.

²J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics*, Wiley, New York, 1952, p 372.

Fig. 8.12.43. Average Number of Emitted Cascade Protons per Inelastic Collision vs Mass Number A for Incident Protons.

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Fig. 8.12.44. Average Number of Emitted Cascade Protons per Inelastic Collision vs Mass Number A for Incident Neutrons.

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Fig. 8.12.45. Average Number of Emitted Cascade Neutrons per Inelastic Collision vs Mass Number A for Incident Protons.

Fig. 8.12.46. Average Number of Emitted Cascade Neutrons per Inelastic Collision vs Mass Number A for Incident Neutrons.

Fig. 8.12.47. Average Yield of Evaporation Protons per Inelastic Collision vs Mass Number A for Incident Protons.

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Fig. 8.12.48. Average Yield of Evaporation Protons per Inelastic Collision vs Mass Number A for Incident Neutrons.

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Fig. 8.12.49. Average Yield of Evaporation Neutrons per Inelastic Collision vs Mass Number A for Incident Protons.

Fig. 8.12.50. Average Yield of Evaporation Neutrons per Inelastic Collision vs Mass Number A for Incident Neutrons.

Tables 8.12.1 through 8.12.3 are examples of comparisons of the results of the calculation with the radiochemical data tabulated by Bruninx.¹ In some cases the agreement is reasonable and in others it is not, and the investigation of the discrepancies is the concern of many people in the field. At this time it appears that the accurate prediction of these cross sections is beyond the capability of the present combined cascade and evaporation calculation.

Table 8.12.1. Comparison of Calculated Radiochemical Cross Sections with Experimental Data^a for the $C^{12}(p,pn)C^{11}$ Reaction

Proton Energy (Mev)	Cross Section (mb)	
	Calculated	Experimental
50	67.83	
93		70.5 ± 3.6
100	48.32	
144		56.5 ± 1.5
150	39.03	46.2 ± 1.4
170		39.7 ± 0.9
194		52.0 ± 1.5
200	42.43	

Table 8.12.1 (continued)

Proton Energy (Mev)	Cross Section (mb)	
	Calculated	Experimental
204		37.0 ± 2.0
238		35.8 ± 2.4
240		37.2 ± 1.8
245		49.8 ± 1.2
250	40.57	
260		38.2 ± 0.5
263		50.5 ± 2.6
270		35.9 ± 1.0
290		36.9 ± 0.9
293		47.7 ± 1.0
295		35.5 ± 1.0
300	37.79	
310		31.9 ± 2.4
313		47.6 ± 2.1
320		35.5 ± 0.7
325		35.9 ± 0.8
340		41.2 ± 0.6
350	40.57	36.0 ± 0.7
365		37.4 ± 3.1
390		
400	31.90	

^aSee ref 1.

Table 8.12.2. Comparison of Calculated Radiochemical Cross Sections with Experimental Data^a for the $\text{Al}^{27}(p,3pn)\text{Na}^{24}$ and $\text{Al}^{27}(p,3p3n)\text{Na}^{22}$ Reactions

Proton Energy (Mev)	Cross Section (mb)	
	Calculated	Experimental
$\text{Al}^{27}(p,3pn)\text{Na}^{24}$		
50	11.10	1.52
60		
70		
80		
90		10.7
100	6.58	
110		10.6
112		
125		
135		
150	5.76	9.2
175		
190		
200	2.47	9.2
225		
250	3.70	9.9
275		
300	4.94	11.2
325		
335		
340		
350	5.35	11.2
400	0.82	
$\text{Al}^{27}(p,3p3n)\text{Na}^{22}$		
150	30.02	1.20 ± 0.15
200	21.80	
250	24.27	
260		1.00 ± 0.10
300	23.03	
335		13.6
350	22.62	0.96 ± 0.12
400	17.69	

^aSee ref 1.

Table 8.12.3. Comparison of Calculated Radiochemical Cross Sections with Experimental Data^a for the $\text{U}^{238}(p,pn)\text{U}^{237}$ Reaction

Proton Energy (Mev)	Cross Section (mb)	
	Calculated	Experimental
50	45.52	
100	45.17	93
150	34.14	73
200	52.53	67.65
250	31.52	
300	52.53	81.0
340		85.0
350	49.90	

^aSee ref 1.

8.13. LITERATURE SURVEY OF NONELASTIC NUCLEON AND PION REACTIONS WITH COMPLEX NUCLEI

H. W. Bertini

In order to locate experimental data with which the results from the intranuclear cascade calculations (see Sec. 8.11) can be compared and also to provide the particle-particle cross-section data required by the calculations, a continuing survey of the literature is being made by examining the abstracts published each month in *Physics Abstracts*. The cross sections sought include both those for the particle-particle reactions and those for the secondary nucleons and π -mesons produced when nucleons and π -mesons with energies of about 20 Mev to 30 Gev strike complex nuclei. Some of the results of the search for the non-elastic reactions have already been collected in a single publication¹ so as to make available information that might be of value to other workers in the field. For incident pions the report covers the period from January 1955 to November 1962 and for incident nucleons it covers the period from January 1957 to November 1962.

A typical page from the report is illustrated by Table 8.13.1. The report contains 674 such entries and a bibliography that lists entry numbers applying to each reference.

The notation adopted was intended to correspond to that suggested by the National Cross Section Advisory Group.² With incident protons used as an example, and with all variables measured in the laboratory system, the notation used for differential cross sections as a function of the incident proton energy E and other variables is as follows:

$\sigma_{p, xpy}(E; E_p, \psi_p) \equiv$ cross section for producing protons with energy E_p at angle ψ_p by any nonelastic process (mb/Mev · sr),

$\sigma_{p, xp}(E; E_p, \psi_p) \equiv$ cross section for producing protons with energy E_p at angle ψ_p by those nonelastic processes in which protons only are emitted (mb/Mev · sr),

$$\sigma_{p, xpy}(E; E_p) = \int \sigma_{p, xpy}(E; E_p, \psi_p) d\Omega \text{ (mb/Mev),}^*$$

$$\sigma_{p, xpy}(E; \psi_p) = \int \sigma_{p, xpy}(E; E_p, \psi_p) dE_p \text{ (mb/sr),}^*$$

$\sigma_{p, 2p}(E; E_{p_1}, \psi_{p_1}, E_{p_2}, \psi_{p_2}) \equiv$ cross section for producing two protons only, one with energy E_{p_1} at an angle ψ_{p_1} and the other with energy E_{p_2} at an angle ψ_{p_2} [mb/(Mev)²(sr)²].

*Note:

$$\begin{aligned} \int \sigma_{p, xpy}(E; \psi_p) d\Omega &= \int \sigma_{p, xpy}(E; E_p) dE_p \\ &= \nu_p \sigma_{p, xpy}(E), \end{aligned}$$

where ν_p is the average number of protons emitted per inelastic collision.

The notation used for total reaction cross sections as a function of incident proton energy is as follows:

$\sigma_{pT}(E) \equiv$ total cross section;

$\sigma_{p,p}(E) \equiv$ elastic cross section;

$\sigma_{pX}(E) \equiv$ cross section for all nonelastic processes;

$\sigma_{p,p'}(E) \equiv$ cross section for inelastic scattering of the incident proton;

$\sigma_{pD}(E) \equiv$ cross section for the disappearance of the proton;**

$\sigma_{p, xpy}(E) \equiv$ cross section for proton production, that is, the cross section for producing at least one proton; the reactions may be such that other particles (neutrons, pions, etc.) may be emitted as well;

$\sigma_{p, xp}(E) \equiv$ cross section for proton production only (that is, any number of protons but no other type of particle);

¹H. W. Bertini, *A Literature Survey of Nonelastic Reactions for Nucleons and Pions Incident on Complex Nuclei at Energies Between 20 Mev and 33 Gev*, ORNL-3455 (Aug. 9, 1963).

²J. R. Stehn, *Compilation of Requests for Nuclear Cross Section Measurements*, WASH-1040 EANDC (September 1962).

Table 8.13.1. Typical Page from Report on Literature Survey of Nonelastic Reactions for Nucleons and Pions Incident on Complex Nuclei

No.	Incident Particle	Incident Particle Energy (Gev)	Target	Measured Quantity	Estimate of Experimental Error (%)	Detector	Installation and Accelerator	References	Comments
563	N	3.6	Pb	σ_{nX}	~ 15	Star density in nuclear emulsions	University of California, Santa Barbara, Bevatron	P. H. Barrett, <i>Phys. Rev.</i> 114, 1374 (1959)	Poor geometry
564	N	4.5	Pb	σ_{nT}, σ_{nX}	~ 5	Counter telescope	Berkeley, Bevatron	J. H. Atkinson <i>et al.</i> , <i>Phys. Rev. Letters</i> 2, 168 (1959)	Good and poor geometry
565	N	1.4	Bi	σ_{nT}, σ_{nX}	3-5	Al radiator and scintillation counter telescope	Brookhaven, Cosmotron	T. Coor <i>et al.</i> , <i>Phys. Rev.</i> 98, 1369 (1955)	Good and poor geometry
566	N	0.090	Th	Neutron yield	10	MnSO ₄ solution	Berkeley, Chicago Cyclotron	W. E. Crandall and G. P. Millburn, <i>J. Appl. Phys.</i> 29, 698 (1958)	
567	N	0.090	U	Neutron yield	10	MnSO ₄ solution	Berkeley, Chicago Cyclotron	W. E. Crandall and G. P. Millburn, <i>J. Appl. Phys.</i> 29, 698 (1958)	
568	N	0.095	U	σ_{nT}	$\sim < 5$	Bi fission chamber	Berkeley, Cyciotron	J. DeJuren and N. Knable, <i>Phys. Rev.</i> 77, 606 (1950)	Good and poor geometry
569	N	0.160	U	Neutron yield	10	MnSO ₄ solution	Berkeley, Chicago Cyclotron	W. E. Crandall and G. P. Millburn, <i>J. Appl. Phys.</i> 29, 698 (1958)	
570	N	0.650	U	σ_{nT}, σ_{nX}	5	Telescope liquid scintillator	Institute for Nuclear Problems Synchrocyclotron	V. L. Moskalev and B. V. Gavrilovskii, <i>Soviet Phys. Doklady</i> 1, 607 (1956)	Good and poor geometry

$\sigma_{p,1p}(E) \equiv$ cross section for producing one proton only by nonelastic processes (includes $\sigma_{p,p}$);

$\sigma_{p,1p2n}(E) \equiv$ cross section for producing one proton and two neutrons only;***

$\sigma_{p,fr}(E) \equiv$ cross section for fragment production;

$\sigma_{p,fr}(E; Z > 4) \equiv$ cross section for fragment production with fragment charge greater than or equal to 4;

$\sigma_{p,2Pr}(E) \equiv$ cross section for producing two prongs.

**This example is poor; the notation is more meaningful when the incident particle is a pion, for then $\sigma_{\pi D}$ represents the pion absorption cross section.

*** $\sigma_{\pi^+, 1\pi^0}$ is used at low energies to signify the π^+ charge exchange cross section.

8.14. CALCULATION OF DOSE IN TISSUE DUE TO NUCLEONS BELOW 400 Mev

W. E. Kinney and C. D. Zerby

Introduction

To assess the hazard to astronauts who will encounter radiation in space and to personnel in the vicinity of high-energy particle accelerators, it is necessary to have a means of estimating the biological effects of high-energy radiation. A useful way of obtaining such an estimate is to multiply the flux of a given type of particle incident on the body by the appropriate flux-to-dose conversion factor to obtain a measure of the dose received. Although the physiological effects of radiation can be determined only by experiment, in the past these effects have been correlated with the dose received. Hence by estimating the dose for high-energy radiation and referring to biological experiments which are correlated with the dose, the biological effect of the radiation can be estimated. An extensive series of calculations were therefore undertaken to estimate tissue dose from high-energy radiation in an effort to provide the necessary flux-to-dose conversion factors for the various types of radiation of interest.

The method of performing the tissue-dose calculations has been described previously¹ but will be reviewed briefly here. Basically, it consists of representing a man as a tissue slab 30 cm thick and assuming that a source of monoenergetic

radiation of a particular type is uniformly distributed over one face of the slab. The calculation then determines the energy deposited as a function of depth in the slab by both the primary radiations and all the secondary radiations of importance. For purposes of applying a relative biological effectiveness (RBE) factor to the energy deposited and of assessing the relative importance of the various kinds of contributions to the dose, the energy deposited by the primary radiation and the energy deposited by various components of the secondary radiations are reported separately. In addition, for each component of radiation contributing to the dose, the energy deposited as the radiation passes through certain energy ranges is reported separately. The energy ranges were selected to correspond to appropriate ranges of linear energy transfer (LET) for easy application of the RBE factors. From these data it is then possible to calculate the physical dose in units of rads, which is essentially a measure of the energy deposited (1 rad = 100 ergs/g), or the biological dose in units of rems (roentgen equivalent man), which is the sum of the contribution of the rad dose from all components of

¹W. E. Kinney, C. D. Zerby, and R. P. Leinius, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 213.

radiation multiplied by the RBE factor for a given biological effect that applies in each energy range.

In practical problems one would prefer flux-to-dose conversion factors for radiation incident on the slab of tissue (the man) which has an angular distribution corresponding to the problem of interest. Since it is virtually impossible to provide such a bulk of data, two extremes were calculated which are expected to bound all cases of interest — normal incidence and isotropic incidence.

From the calculated data, flux-to-dose conversion factors can be obtained as a function of incident energy for any depth in tissue. But, because of current interest, factors for the surface dose, for the 5-cm depth dose, and for the average whole-body dose will be extracted to provide three basic sets of conversion factors for each type of incident particle and each incident angular distribution. In this paper, the conversion factors for the average whole-body dose are presented for normally incident and isotropically incident protons and neutrons with energies up to 400 Mev.

Methods

The calculations were performed by Monte Carlo methods using the codes discussed previously.¹ Protons and neutrons of energies 400, 300, 200, and 100 Mev were assumed to be both normally incident and isotropically incident on a 30-cm-thick slab of tissue of infinite extent. The composition of tissue² was taken as $C_{21}H_{140}O_{57}N_3$ with a density of 1 g/cm³. The atomic density of the elements in tissue is given in Table 8.14.1, along with the mean excitation potentials which are required in stopping-power formulas for energy loss by ionization collisions.

The energy deposition in 1-cm-thick subslabs through the medium was separated into contributions from primary protons, when protons were the incident particles; secondary cascade protons, including recoils and evaporation protons; and heavy particles, including evaporation particles with $A > 1$ and recoiling nuclei. Range-energy relationships based on the Bethe-Block formula gave the proton energy deposition above 50 Mev. Pro-

Table 8.14.1. Composition and Mean Excitation Potentials for Tissue

Element	Nucleon Density [(nuclei/cm ³) × 10 ⁻²⁴]	Mean Excitation Potential (ev)
H	6.265 × 10 ⁻²	17.5
O	2.55075 × 10 ⁻²	99.0
C	9.3975 × 10 ⁻³	74.44
N	1.3425 × 10 ⁻³	86.0

tons that were added to the cascade with energies below 50 Mev or degraded below 50 Mev were allowed to proceed straight ahead with no nuclear interaction to the end of their paths. Heavy evaporation and recoil nuclei were assumed to deposit all their energy at the site of their birth. The neutrons below 50 Mev were put into the O5R neutron transport Monte Carlo code³ and were permitted to go to 1 ev if they could. Their contribution to the dose through recoiling nuclei was also separated out and included in the results. The amount of energy transformed into electromagnetic radiation was also recorded, along with the location of where it was created; however, this radiation was not included in the dose calculations reported here.

The energy deposition due to protons was further divided into the energy ranges 0–1, 1–5, 5–10, 10–50, and >50 Mev for each subslab so that a choice of RBE factors would be available for determining a rem dose. The RBE factors for this study were taken to be 8, 3, 1.25, 1, and 1, respectively, for the above energy ranges. The RBE for the heavy particles was taken as 20. The RBE values below 20 are based on values recommended by the National Committee on Radiation Protection and Measurements (NCRP).⁴ The RBE of 20 is arbitrary but is characteristic of

²Recommendations of the International Commission on Radiological Protection and of the International Commission on Radiological Units 1950, *Natl. Bur. Std. (U.S.) Handbook 47*, 16 (1950).

³R. R. Coveyou, J. G. Sullivan, and H. P. Carter, *The O5R Code: A General Purpose Monte Carlo Reactor Code for the IBM-704 Computer*, paper presented at the Symposium on Codes for Reactor Computations, Vienna, Austria (1961); see also R. R. Coveyou, J. G. Sullivan, and H. P. Carter, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1958*, ORNL-2609, p 87.

⁴"Permissible Dose for External Sources of Ionizing Radiation," *Natl. Bur. Std. (U.S.) Handbook vol 59* (1954).

the high RBE recommended for the high LET values associated with low-energy heavy charged particles.

Results

The average whole-body rad and rem doses due to primary protons, all secondary protons, and all heavy particles as a function of the source energy are given in Figs. 8.14.1 through 8.14.4. Figure 8.14.1, which presents results for normally incident protons, shows that the average dose from primary protons increases from 100 to 200 Mev as the source energy increases, as would be expected since essentially all the incident energy is deposited in the slab. At 215 Mev, however, there is a break in the primary dose curve since the range of protons at this energy is 30 cm and thus for higher source energies part of the primary beam energy penetrates the slab, which results in a decrease in the average dose. The dose due to secondary radiation increases steadily with source energy, as would be expected. It is inter-

esting to note that at a 400-Mev incident energy the rem dose due to heavy secondary particles is 69% of the primary dose and the secondary proton rem dose is 43% of the primary dose.

Fig. 8.14.2. Average Whole-Body Dose vs Source Energy for Isotropically Incident Protons.

Fig. 8.14.1. Average Whole-Body Dose vs Source Energy for Normally Incident Protons.

Fig. 8.14.3. Average Whole-Body Dose vs Source Energy for Normally Incident Neutrons.

Fig. 8.14.4. Average Whole-Body Dose vs Source Energy for Isotropically Incident Neutrons.

The dose for isotropically incident protons, given in Fig. 8.14.2, does not show the sharp break in the primary dose contribution at 215 MeV; however, it is evident that the energy loss due to radiation penetrating the slab of tissue is causing the average dose to drop at energies above approximately 215 MeV.

The results for normally incident neutrons and isotropically incident neutrons are presented in Figs. 8.14.3 and 8.14.4, respectively. The striking feature of these data is that the curves are rather flat.

Figures 8.14.5 and 8.14.6 present average whole-body flux-to-dose conversion factors for all cases presented in the preceding figures. It is interesting to note in Fig. 8.14.5 that for normally incident protons the rad dose up to 215 MeV is almost equivalent to the average dose calculated by assuming that all the incident energy is absorbed. This simply implies that very little secondary radiation is leaking from the slab for source energies below 215 MeV. It is also interesting to note from both Fig. 8.14.5 and 8.14.6 that the average RBE, calculated as the ratio of total rem dose to total rad dose; is much higher for incident neutrons than for incident protons. The maximum average RBE factors for neutrons are 4.6 and 4.8 for normal and isotropic incidence, respectively, while for protons they are 1.55 and 1.5, respectively.

Fig. 8.14.5. Flux-To-Dose Conversion Factors for Average Whole-Body Dose for Normally Incident Radiation.

Fig. 8.14.6. Flux-To-Dose Conversion Factors for the Average Whole-Body Dose for Isotropically Incident Radiation.

Conclusions

For the case of incident protons the primary proton beam is the main contributor to the average whole-body dose in tissue at energies below 400 Mev, although the rem dose due to heavy secondary particles amounts to as much as 69% of the normally incident primary dose at 400 Mev

and the secondary proton dose amounts to 43% of the primary dose at this energy. At 100 Mev the rem dose due to secondaries is only one-sixth the normally incident primary rem dose.

It is interesting to note that the average whole-body dose from secondary radiation at a 400-Mev incident energy is about the same for both incident neutrons and incident protons.

9. Measurements of Secondary Radiations from High-Energy Proton Interactions

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9.0. A PROPOSED NOMENCLATURE SCHEME FOR EXPERIMENTAL HIGH-ENERGY NUCLEAR CROSS SECTIONS

C. D. Zerby and H. Goldstein¹

Introduction

In the following a proposed set of rules is formulated for cross-section terminology and associated notation that might serve as a basis for consistency over a wide range of bombarding energies. The scheme for the terminology is a modified and extended version of the terminology for low-energy nuclear cross sections suggested by Goldstein.^{2,3}

The basic reason for extending the terminology is to allow within its framework a notation which will describe higher incident energies than have been considered previously. In the process of extending the notation, certain inconsistencies arose between the notation for low- and high-energy reactions which could be resolved logically only by modifying the previous notation. For this reason a consistent summary of the new notation is given below which includes some of, but not all, the previously established terminology. The major restrictions imposed on the notation are that only monoenergetic microscopic cross sections are considered and that the terminology is particularly formulated for reporting experimental results.

The general rules, which are given immediately below, are followed by a section with a list of examples.

General Principles of Notation

The following general rules have been applied to the notation except where wide usage has dictated

that an exception be made. In some cases the rules have been constructed to avoid conflict with the entrenched usage, leading to a notation a little more complicated than would appear necessary at first glance. Some exceptions are given in the general rules.

In general, the type of reaction is indicated by subscripts. The variables of the reaction (energy, angle, etc.) are indicated in parentheses following the cross-section symbol, following the usual mathematical functional notation. Whether a cross section is total or differential for the reaction is indicated by the variables shown.

Type of Reaction. — Three classes of *type* subscripts are provided:

1. When both the bombarding particle and the outgoing particle are specified for a reaction, they are indicated with a comma following the bombarding particle:

$$\sigma_{n,p3\pi^+}$$

for a reaction with a neutron in and exactly 1 proton and $3\pi^+$ mesons coming out.

Each product particle that is produced in an event must have a coefficient to indicate the number of product particles involved if there is more than one. If only the type of product particle is recorded without regard to number, then the coefficient should be an *x*:

$$\sigma_{n,xp}$$

for a reaction with a neutron in and at least one proton out.

Elastic scattering and inelastic scattering are treated as special cases in the above scheme and are discussed below ("Exceptions to the Rules and Precautionary Notes").

¹Division of Nuclear Science and Engineering, Columbia University, New York City.

²Herbert Goldstein, *A Proposed Nomenclature Scheme for Experimental Nuclear Cross Sections*, letter to AEC Nuclear Cross Section Advisory Group, May 28, 1956.

³Appendix I, p 2227 in *Fast-Neutron Physics*, Vol. IV, Part II, ed. by J. B. Marion and J. L. Fowler, Interscience, New York, 1963.

Photons are not indicated as part of the product unless they are the only product, in which case the symbol for photons, γ , need not have a coefficient. This is the only product treated in this manner.

If there are other products (other than photons) which accompany the detected products but are not recorded, then the product subscripts should be followed with a y :

$$\sigma_{n,2py}$$

for a reaction with 1 neutron in and 2 protons out accompanied by other products (other than photons) which are not recorded.

Standard symbols are to be used for the particles designated such as

$$\gamma, \beta, n, p, d, t, \alpha, \pi, \Sigma, \text{ etc.}$$

The subscript f will be used for all the outgoing particles in fission.

2. When the cross section represents a sum over a number of possible reactions, the subscript consists of a lower-case letter designating the incident particle followed by an upper-case letter chosen more or less arbitrarily. Examples are

$$\sigma_{nT}$$

for the total neutron cross section and

$$\sigma_{nD}$$

for the disappearance of a neutron.

The remaining class consists of a few symbols of such time-honored usage that they cannot lightly be excluded, for example, σ_{tr} for the transport cross section (suitably defined). The number of symbols in this class will be kept as small as possible.

Total Cross Sections. — In total cross sections the only variable present is the bombarding energy, indicated by E , without a subscript:

$$\sigma_{p,n}(E)$$

for the (p,n) reaction at a bombarding energy E .

Differential Cross Sections. — General Scheme. — With differential cross sections there will be more variables indicating the energies or angles of emerging particles. Variables for a given particle are separated by commas, and groups of variables

for the various particles are separated by semicolons. It will be assumed that all energies are in the laboratory system, as this is customary for most cross-section measurements. It is suggested that θ be used for center-of-mass scattering angles and ψ used for the laboratory systems. The variables are associated with the particles by attaching the particle symbol as a subscript. An exception to this is that no subscripts are placed on variables for emergent particles when the emergent particle and incident particle are the same; primes will be used when there is need for distinction. The number of variables that appear for the emergent particles indicates the order of the differential cross section. When the angle of scattering is indicated, the differential is per unit solid angle. Examples of the differential cross sections are

$\sigma_{n,p}(E;E_p,\theta_p) \equiv$ cross section for production of protons with energy E_p at angle θ_p in the (n,p) process,

$\sigma_{p,pn}(E;E',\theta;E_n,\theta_n) \equiv$ cross section for production of protons with energy E' at angle θ and neutrons with energy E_n at angle θ_n in the (p,pn) process.

More Than One of a Given Type of Product Particle. — For cases of more than one of a given type of product particle, it is experimentally difficult, if not impossible, to distinguish the sequence of particle emission; therefore only one set of variables applies; for example, $\sigma_{n,2n}(E;E',\theta)$ for the $(n,2n)$ process.

Spectra and the Differential Cross Section. — Spectral data can be represented by the symbol N , with subscripts and variables as in the case of the differential cross section. The difference between the two quantities is that the cross section is always the number of events or particles of a given nature per incident flux, while spectra give the number of events or particles of a given nature per reaction event. Thus the integral of a spectrum over its differential variable gives the multiplicity, while the integral of the corresponding differential cross section is equal to the total cross section for that event times the multiplicity:

$$\int_E N_{n,kn}(E;E') dE' = k, \quad k = 1, 2, 3, \dots$$

$$\int_E \sigma_{n,kn}(E;E') dE' = k \sigma_{n,kn}(E),$$

$$k = 1, 2, 3, \dots$$

To illustrate the general relation between the differential cross section and the spectrum, for the above case we have

$$\sigma_{n,kn}(E;E') = \sigma_{n,kn}(E) N_{n,kn}(E;E'),$$

$$k = 1, 2, 3, \dots$$

In the event that the coefficient of the product particle is x , then

$$\sigma_{n,xn}(E;E') = \sigma_{n,xn}(E) N_{n,xn}(E;E')$$

and

$$\int_E \sigma_{n,xn}(E;E') dE' = \nu_{xn} \sigma_{n,xn}(E),$$

where ν_{xn} is the average multiplicity.

Exceptions to the Rules and Precautionary Notes. — The most notable exception to the foregoing rules is the nuclear elastic-scattering cross section, which has been established by past usage. For neutrons it is designated as

$$\sigma_{n,n}(E),$$

and is defined to mean nuclear scattering in which the bombarding energy is conserved in the center-of-mass system. The reason for its exception to the rule is that it could be interpreted as inelastic scattering since product photons are not indicated by a subscript in the present scheme. Hence to distinguish elastic from inelastic scattering we must introduce inelastic scattering as another exception, which for neutrons is designated

$$\sigma_{n,n'}(E).$$

It is defined as a process in which the bombarding particle transfers energy to the nucleus in the center-of-mass system, all of which appears eventually as de-excitation gamma rays emitted by the target nucleus. The second subscript, which is primed and has no coefficient, distinguishes the inelastic scattering process.

As a precaution it should be noted that, although the photons are not indicated as a product when other products are present, variables for the photon may appear in the cross section. The prime example of this is in inelastic scattering, where the cross section may be differential with respect to

the gamma-ray variables and we have

$$\sigma_{n,n'}(E;E_\gamma) = \int \sigma_{n,n'}(E;E_\gamma, \theta_\gamma) d\Omega_\gamma$$

$$= \sigma_{n,n'}(E) N_{n,n'}(E;E_\gamma),$$

with

$$\int_{E_\gamma} \sigma_{n,n'}(E;E_\gamma) dE_\gamma = \nu_{n'} \sigma_{n,n'}(E).$$

Special Notation. — The use of biased or threshold detectors introduces the need for indicating a kind of differential cross section for those cases in which all outgoing particles above or below a certain energy are included. This will be indicated by $>$ or $<$, respectively, after the semicolon:

$$\sigma_{n,n'}(E; < E')$$

is the cross section for inelastic scattering of neutrons to below energy E' . In inelastic scattering we often deal with cross sections for excitation of a given level. If, say, we are considering excitation of a level E_1 in neutron inelastic scattering, this might be handled within the above framework as

$$\sigma_{n,n'}(E; E - E_1).$$

A simpler convention would seem to be to drop the E and write merely

$$\sigma_{n,n'}(E; E_1).$$

This procedure can cause no confusion if the subscript denoting the energy level in question is either a number or one of the customary summation indices i, j , or k .

Examples of Notation

The following examples are for incident neutrons. For other bombarding particles the symbol n should be replaced with the proper symbol.

Cross Sections for Incident Neutrons at Energy E

$\sigma_{nT}(E)$: total

$\sigma_{nD}(E)$: disappearance of the neutron

$\sigma_{n,f}(E)$: fission

$\sigma_{n,\gamma}(E)$: photon emission, all processes

$\sigma_{n,n}(E)$: elastic scattering
 $\sigma_{nX}(E) = \sigma_{nT}(E) - \sigma_{n,n}(E)$: nonelastic cross section
 $\sigma_{n,n'}(E)$: inelastic scattering
 $\sigma_{n,2p\pi^+}(E)$: emission of two protons and one π^+
 $\sigma_{n,2py}(E)$: emission of two protons, all processes
 $\sigma_{tr} = \sigma_{n,n}(E) \langle 1 - \cos \theta \rangle$: transport cross sections

Note that

$$\sigma_{n,xpy}(E) = \sum_{k=1}^z \sigma_{n,kpy}(E).$$

Differential Cross Section for Incident Neutrons of Energy E

$\sigma_{n,n}(E;\psi)$: elastic scattering at angle ψ
 $\sigma_{n,n'}(E;E',\psi)$: inelastic scattering, neutron of energy E' emitted at angle ψ
 $\sigma_{n,n'}(E;E') = \int \sigma_{n,n'}(E;E',\psi) d\Omega$
 $\sigma_{n,p}(E;E_p,\psi_p)$: emission of a proton with energy E_p at angle ψ_p

$\sigma_{n,p}(E;E_p) = \int \sigma_{n,p}(E;E_p,\psi_p) d\Omega_p$
 $\sigma_{n,pn}(E;E_p,\psi_p;E_n,\psi_n)$: emission of one proton with energy E_p at angle ψ_p and one neutron at energy E_n at angle ψ_n
 $\sigma_{n,ny}(E;E',\psi)$: emission of a neutron with energy E' at angle ψ by any process
 $\sigma_{n,x\pi^+y}(E;E_{\pi^+},\psi_{\pi^+})$: emission of a π^+ with energy E_{π^+} at angle ψ_{π^+} by any process

$$\sigma_{n,x\pi^+y}(E;\psi_{\pi^+}) = \int \sigma_{n,x\pi^+y}(E;E_{\pi^+},\psi_{\pi^+}) dE_{\pi^+}$$

$$\sigma_{n,x\pi^+y}(E;E_{\pi^+}) = \int \sigma_{n,x\pi^+y}(E;E_{\pi^+},\psi_{\pi^+}) d\Omega_{\pi^+}$$

[Note that $\int_{E_{\pi^+}} \sigma_{n,x\pi^+y}(E;E_{\pi^+}) dE_{\pi^+}$
 $= \nu_{\pi^+} \sigma_{n,x\pi^+y}(E)$]

$\sigma_{n,n'}(E;E_\gamma,\psi_\gamma)$: inelastic scattering, photon emitted with energy E_γ at angle ψ_γ
 $\sigma_{n,n'}(E;E_\gamma) = \int \sigma_{n,n'}(E;E_\gamma,\psi_\gamma) d\Omega_\gamma$
 $\sigma_{n,\gamma}(E;E_\gamma,\psi_\gamma)$: emission of photons with energy E_γ at angle ψ_γ , all processes
 $\sigma_{n,\gamma}(E;E_\gamma) = \int \sigma_{n,\gamma}(E;E_\gamma,\psi_\gamma) d\Omega_\gamma$

9.1. SPECTRA OF GAMMA RAYS PRODUCED BY THE INTERACTION OF ~ 160 -Mev PROTONS WITH Be, C, O, Al, Co, AND Bi¹

W. Zobel, F. C. Maienschein, and R. J. Scroggs²

The nuclear secondaries produced by the interaction of high-energy protons with nuclei are of interest because protons are the most abundant of the charged particles in space that will present a hazard for manned space travel. The

spacecraft shields presently envisaged as necessary for protection in interplanetary flights or in high-altitude orbiting stations are of such thickness that nuclear interactions in the shield become important in comparison to ionization produced by the primary protons. The secondaries may be uncharged, and thus more penetrating than the primaries, and they may produce greater biological damage. Thus their production and

¹Summary of a report to be issued as ORNL-3506.

²Instrumentation and Controls Division.

transport in the spacecraft shield or structure must be carefully assessed.

The application of a simple nuclear model, which assumes interaction of the incoming proton with a single nucleon, appears to give predictions of secondary nucleon spectra that are in reasonable agreement with experimental results for $Z > 12$ and proton energies from 50 Mev to 2 Gev;³ however, no predictions of gamma-ray emission are made. At present, no method is available for predicting proton-induced level excitations and resulting gamma-ray emissions, particularly for light nuclei where levels are well separated. Thus, in order to calculate the effect of secondary gamma-ray emission, measurements of the cross sections for the production of gamma-ray transitions of specified energies are needed.

As part of a larger effort to study secondaries,⁴ measurements were made of the gamma rays produced by 160-Mev protons from the Harvard University synchrocyclotron in thin targets of Be, C, H₂O, Al, Co, and Bi. In addition, measurements were made with an aluminum target which was thick compared with the range of the protons. These latter data were obtained to test a calculation by Monte Carlo techniques of the transport of the gamma rays through a thick target.

Previous measurements of this type include an extensive set by a group at Oxford⁵⁻⁸ using the Harwell synchrocyclotron. In their measurements a single NaI(Tl) crystal spectrometer was used to study the gamma-ray spectra obtained with targets ranging from Li⁶ to Ca. Unresolved backgrounds were ascribed to neutron effects, and cross sections were determined for specified gamma-ray energies. Other measurements have been made of the production of bremsstrahlung by 40- to 185-Mev protons incident on Be, C, Al, and Cu (ref 9). The spectra from these measure-

ments show that the bremsstrahlung contribution extends to higher gamma-ray energies than that from nuclear de-excitation, as was expected; however, the cross sections are relatively quite small. Photons from π_0 decay are also shown by this research⁹ to be present in small abundance compared with those from nuclear de-excitation.

For the measurements described here, the gamma-ray spectrometer requirements were considered to include ascertainable absolute efficiency, high neutron rejection, and an adequate response function (peak-to-total ratio). Multiple-crystal spectrometers were chosen in spite of their inherent complexities and requirements for experimental efficiency calibrations. A three-crystal pair spectrometer was used for gamma-ray energies above 1.5 Mev, and an anticoincidence spectrometer was used for energies below 2.5 Mev in order to meet the last two requirements. In addition, a time-of-flight requirement was established in order to discriminate against neutron-induced effects. This was possible since the output of the synchrocyclotron is not a continuous proton current but, rather, consists of a series of proton current pulses (called "microbursts"). An additional detector (identified as the *D* scintillator) was used to determine the time of arrival of protons at the target. To be accepted as counts in the spectrometer, events had to be in time coincidence with a microburst as detected in the *D* scintillator. The duration of a microburst was 11.8 ± 0.3 nsec, as observed with our equipment,¹⁰ and the separation of consecutive microbursts was 42.0 ± 0.5 nsec. Thus, if the neutrons were uniformly distributed in time, this coincidence requirement would eliminate $(73 \pm 2)\%$ of the neutron-induced counts. Since the arrival of the neutrons at the spectrometer depends upon the neutron spectrum, which in turn depends on the target material, the above rejection fraction can be expected to be only a crude approximation. More refined measurements indicate neutron rejection fractions varying from $(59 \pm 2)\%$ for C to $(77 \pm 2)\%$ for H₂O.

Pulse-height spectra obtained for the different targets are shown in Figs. 9.1.1 and 9.1.2. Backgrounds have been subtracted from the data to produce these curves, but no other corrections

³H. W. Bertini, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 199.

⁴F. C. Maienschein and C. D. Zerby, *Neutron Phys. Div. Space Radiation Shielding Research Ann. Progr. Rept. Aug. 31, 1962*, ORNL CF-62-10-29 Rev.

⁵A. B. Clegg et al., *Proc. Phys. Soc.* **78**, 681 (1961).

⁶K. J. Foley et al., *Nucl. Phys.* **31**, 43 (1962).

⁷K. J. Foley et al., *Nucl. Phys.* **37**, 23 (1962).

⁸G. L. Salmon et al., *Nucl. Phys.* **41**, 364 (1963).

⁹D. Cohen et al., *Phys. Rev.* **130**, 1505 (1963).

¹⁰The resolving time of our coincidence circuit was limited by the rise time of the NaI scintillator. Measurements with faster time equipment (Sec. 9.7) indicate a microburst width of 4.5 to 6.3 nsec.

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Fig. 9.1.1. Pulse-Height Spectra of Gamma Rays Produced by 160-Mev Proton Bombardment of Be, C, H₂O, Al, Co, and Bi Targets. (Measured with the anticoincidence spectrometer; background subtracted.)

Fig. 9.1.2. Pulse-Height Spectra of Gamma Rays Produced from 160-Mev Proton Bombardment of Be, C, H₂O, Al, and Co Targets. (Measured with the pair spectrometer; background subtracted.)

have been made. Figure 9.1.3 shows a comparison of the pulse-height spectrum from a Be target with the result of a first attempt to correct for the nonunique response of the anticoincidence spectrometer.¹¹ The contribution to pulses in the analyzer range for this spectrum from higher-energy gamma rays has not been taken into account. The analysis of the data, which is in progress, will include this contribution.

The pulse-height spectra, plotted on linear scales to improve visible detail, were examined for the presence of peaks, which were apparent in all spectra obtained with both spectrometers except in those for the heavier targets, Co and Bi. The areas of the peaks were determined by subtraction of the background due to the "tails" from other peaks, whether resolved or not. Division of these areas by the efficiency of the spectrometer at the energy corresponding to the peak position and by the effective solid angle gave the number of photons emerging from the target. Corrections ranging from 4 to 16% for attenuation in the targets then gave the number of photons produced in the targets.

Division by the number of protons incident on the target (see Sec. 9.7) and the target thickness (atoms/cm²) yielded cross sections for the specified gamma-ray energy. Corrections were made for the changes in the efficiency of the pair spectrometer with time ($<1.19 \pm 0.09$), count losses (from 1.27 ± 0.15 to 2.14 ± 0.34), and the

fast coincidence circuit efficiency (0.94 ± 0.02). The count losses were clearly larger than desirable. The effective proton energy had been reduced from the initial energy by degradation in the target, which resulted in average effective proton energies of 146 Mev for the Be, C, H₂O, and Al targets and 154 Mev for the Co and Bi targets.

The cross sections for Be, C, O, and Al are shown in Table 9.1.1. For all gamma rays seen by both spectrometers, the two cross-section determinations are consistent within the quoted errors. Comparisons with the published results of the Oxford group show that we determined all the gamma rays that they describe (with one exception at 1.4 Mev from O) plus several more at higher energies. For the lighter nuclei, the results can be correlated with known levels in spite of the variety of reactions possible with incident protons as energetic as 160 Mev. An indication of the most probable assignment of transitions is given in Table 9.1.1. For nuclei of higher *Z*, such as Al, level identification tends to become ambiguous.

Clearly, the hazard posed to manned space flight due to secondary gamma radiation cannot be assessed on the basis of these data alone. Additional measurements are needed, especially at lower proton energies, and plans for such measurements are at an advanced stage. When experimental information on the dependence of gamma-ray production upon proton energy is available, it will be possible to use these "source data" in gamma-ray-attenuation calculations in order to determine the biological effect behind a shield.

¹¹The analysis follows the work of W. R. Burrus (see Sec. 10.4), who also contributed in an indispensable manner to the application of his general method to this problem.

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Fig. 9.1.3. Comparison of Pulse-Height Spectrum (Background Subtracted) for Be with Gamma-Ray Spectrum Resulting from Preliminary Analysis. The indication of a peak at 2600 kev is spurious and results from approximations in the analysis.

Table 9.1.1. Cross Sections for the Production of Specified Gamma Rays by 160-Mev Protons
Incident on Be, C, O, and Al

(Average effective proton energy = 146 Mev)

Target	Spectrometer ^a	E_γ , Measured Gamma-Ray Energy (kev)	σ , Measured Cross Section (mb)		Possible Transition Assignment	
			This Work	Oxford Group ^b	Reaction	Energy of Transition (kev)
Be	A	988 $\pm$ 15	1.05 $\pm$ 0.09	2.4 $\pm$ 0.4	(p,2p)Li ⁸	980
Be	P	3527 $\pm$ 80	0.95 $\pm$ 0.30		(p,pt)Li ⁶	3560
C	A	739 $\pm$ 9	7.0 $\pm$ 0.4	4.5 $\pm$ 0.5	(p,2pn)B ¹⁰	717
C	A	1026 $\pm$ 12	2.5 $\pm$ 0.2	1.8 $\pm$ 0.2	(p,2pn)B ¹⁰	1023 ^c
C	A	1457 $\pm$ 20	0.5 $\pm$ 0.1	0.6 $\pm$ 0.2	(p,2pn)B ¹⁰	1433
C	A	2008 $\pm$ 20	4.4 $\pm$ 0.5	3.9 $\pm$ 0.4	(p,pn)C ¹¹	1990
C	P	2026 $\pm$ 50	6.9 $\pm$ 1.1			
C	P	2890 $\pm$ 40	1.7 $\pm$ 0.4	0.9 $\pm$ 0.4	(p,2pn)B ¹⁰	2860 ^c
C	P	3405 $\pm$ 40	1.3 $\pm$ 0.3		(p,p')C ¹² (?)	3223 ^c
C	P	4451 $\pm$ 50	10.5 $\pm$ 1.6	6.6 $\pm$ 1.0	(p,p')C ¹²	4433
					(p,2p)B ¹¹	4460
C	P	4936 $\pm$ 60	2.2 $\pm$ 0.8	2.3 $\pm$ 1.0	(p,2p)B ¹¹	5030
C	P	6592 $\pm$ 60	1.8 $\pm$ 0.3	2.1 $\pm$ 0.7	(p,pn)C ¹¹	6500
C	P	8798 $\pm$ 112	0.15 $\pm$ 0.06		(p,2p)B ¹¹	8930
O	A	725 $\pm$ 9	2.31 $\pm$ 0.14	3.9 $\pm$ 1.0	(p, α 2pn)B ¹⁰	717
O	A	1032 $\pm$ 12	0.53 $\pm$ 0.14	4.4 $\pm$ 1.1	(p, α 2pn)B ¹⁰	1023 ^c
O	A	1667 $\pm$ 20	3.0 $\pm$ 0.3	1.7 $\pm$ 0.5	(p,2pn)N ¹⁴	1633 ^c
O	A	2369 $\pm$ 30	2.5 $\pm$ 0.3	2.9 $\pm$ 0.8	(p,2pn)N ¹⁴	2312
O	P	2327 $\pm$ 30	3.9 $\pm$ 1.3			
O	P	3808 $\pm$ 60	2.3(?) $\pm$ 1.0(?)		(p,2pn)N ¹⁴	3945
O	P	4488 $\pm$ 50	12.8 $\pm$ 2.0	8.3 $\pm$ 1.7	(p, α p)C ¹²	4430
O	P	5352 $\pm$ 60	12.6 $\pm$ 2.2	2.6 $\pm$ 0.7	(p,pn)O ¹⁵	5250
					(p,2p)N ¹⁵	5310
O	P	6313 $\pm$ 70	39.5 $\pm$ 6.5	22.7 $\pm$ 3.0	(p,2p)N ¹⁵	6330
O	P	7197 $\pm$ 80	2.5 $\pm$ 1.1	2.8 $\pm$ 0.7	(p,p')O ¹⁶	7120
					(p,2p)N ¹⁵	7310
Al	A	844 $\pm$ 12	8.2 $\pm$ 1.4	11 $\pm$ 2	(p,p')Al ²⁷	834
					(p,pn)Al ²⁶	831 ^c
Al	A	1019 $\pm$ 20	6.9 $\pm$ 2.5	14 $\pm$ 3	(p,p')Al ²⁷	1013
					(p,pn)Al ²⁶	1060
Al	A	1386 $\pm$ 23	24.4 $\pm$ 1.8	31 $\pm$ 4	(p, α)Mg ²⁴	1368
Al	A	1661 $\pm$ 23	11.3 $\pm$ 2.3	18 $\pm$ 3.5		
Al	P	1705 $\pm$ 40	13.2 $\pm$ 9.0			
Al	A	1876 $\pm$ 35	5.6 $\pm$ 2.6	14 $\pm$ 3	(p,2p)Mg ²⁶	1830
Al	P	1870 $\pm$ 35	21.0 $\pm$ 9.7			
Al	A	2327 $\pm$ 50	3.0 $\pm$ 3.0	7.1 $\pm$ 1.7	(p,p')Al ²⁷	2210
Al	P	2281 $\pm$ 40	13.4 $\pm$ 5.4			
Al	P	2598 $\pm$ 45	10.2 $\pm$ 4.6	8.8 $\pm$ 2.2		
Al	P	2813 $\pm$ 50	9.5 $\pm$ 4.3			
Al	P	3076 $\pm$ 50	1.8 $\pm$ 1.5			
Al	P	3982 $\pm$ 90	4.5 $\pm$ 2.0			
Al	P	6297 $\pm$ 80	3.4 $\pm$ 1.5			

^aA = anticoincidence spectrometer; P = pair spectrometer.

^bSee refs 5-8 in text.

^cTransition to an excited state.

9.2. DIFFERENTIAL SECONDARY-NUCLEON CROSS SECTIONS BY FLIGHT-TIME SPECTROSCOPY FOR REACTIONS OF 160-MeV PROTONS WITH NUCLEI

R. W. Peelle, T. A. Love, N. W. Hill,¹ R. L. Cowperthwaite, R. T. Santoro

Introduction

The previously proposed² flight-time spectral measurements of secondary neutrons and protons from nuclear reactions have been performed using the 160-MeV protons from the Harvard University synchrocyclotron. The measurements were unique in that the proton arrival time at the target was established by timing individual protons in a very weak beam. Identification of the secondary particle as being charged or neutral was accomplished by coincidence or anticoincidence measurements. The measurements suffered from time resolution perhaps twice as broad as the desired 1 nsec (ref 3), but nevertheless should provide useful surveys of cross-section regions which have not been investigated. Table 9.2.1 indicates the coverage of the experimental measurements. The neutron measurements are only partially analyzed because the detector efficiency is yet undetermined, but some proton differential cross sections for cobalt are given below.

Both the neutron and proton measurements depend upon the methods by which incident protons are detected and the resulting pulses handled. Not only must the integral beam strength be known to allow absolute yield measurements, but also detected secondaries must be ignored whenever incident protons are spaced in time by less than the maximum interval required for time analysis of an individual event. Otherwise, it would not be known which proton led to the observed secondary particle. The discussion below includes a

description of the beam counters and the package of supervisory circuits employed to inspect and count the resulting pulses. The calibration of the beam-monitoring equipment allowed by the counting of individual beam particles is described in Section 9.8.

Handling the Low-Intensity Proton Beam

The time structure of the synchrocyclotron beam is described in Sec. 9.7. A fine structure at the 22-Mc acceleration frequency was superimposed on the approximately 280-cps gross structure induced by the frequency modulation. The fine structure proton bursts had a width of perhaps 4 nsec out of the 42-nsec rf period, while the gross structure (quadratic) duty factor for these measurements was about 2%. As previously reported,² the beam strength for this experiment was limited to about 5×10^4 protons/sec so that no more than 30% of the beam counts would have to be rejected. The above figures imply that, on the average, about 10% of all rf acceleration periods within gross structure peaks contained a proton. As used, the flight-time equipment required that acceptable protons be separated by 110 nsec or more. Since the fine structure was sharp, this implies that two rf burst positions on either side of a period containing an acceptable proton had to be empty. "Pulse pileup" events, wherein two or more protons occupied the same fine structure burst, also had to be rejected because they would tend to degrade the time resolution of the system.

Figure 9.2.1 shows the beam counter geometry and Fig. 9.2.2 the block diagram of the beam-handling apparatus. Two thin scintillation counters⁴

¹Instrumentation and Controls Division.

²R. W. Peelle *et al.*, *Neutron Physics Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, pp 286-295.

³Most of the large timing jitter results from "walk," or pulse-height-dependent timing; therefore only the results for secondary neutrons are greatly affected.

⁴All scintillator detectors were designed by V. McKay and H. Brashear of the Instrumentation and Controls Division.

Table 9.2.1. Number of Detector Angles^a at Which Flight-Time Spectra Were Obtained for Various Targets

Targets	Number of Differential Energy Spectra Measured ^a		
	Differential Cross Sections		Thick-Target Neutron Yields
	Protons	Neutrons	
H ₂ O	2	1	2
D ₂ O	1	2	
Be	1	5	
C	2	5	2
Al	5	6	4
Co	6	5	5
Cu			4
Pb		1	1
Bi	2	6	5
Target thickness ^b	2.5 Mev (~0.5 g/cm ²)	12 Mev (~2.8 g/cm ²)	1.2 × proton range (~27 g/cm ²)

^aDetector angles used, in order of decreasing frequency, were 30, 10, 60, 45, 135, 90, and 120°; however, data obtained for some of the runs may not be usable.

^bFor normal incidence, measured in energy loss for 160-Mev protons.

were placed in the beam before it struck the target. The outputs of the counters were coupled by a pair of independent coincidence and logic systems (see Sec. 10.6). The faster system⁵ used current pulses from the photomultipliers and was capable of responding to closely spaced coincidences (10 nsec), later rejecting any events in which two protons were spaced by less than the preset "isolation" interval. The second system⁶ used charge pulses and employed discriminators and a second coincidence circuit to recognize "pileup" events in which two or more protons reached the detectors within a fine-structure burst. Provisions were made to record the number of pulses reaching each logical level of the circuit.

The A and A' detectors indicated in Fig. 9.2.2 were formed from 1-mm-thick sections of plastic phosphor to the shape indicated in Fig. 9.2.1. Since the beam spot at the counter position had a spatial distribution with a standard deviation of

about 0.14 in., these detectors intercepted the entire beam. A thin edge of each scintillator was viewed by a 56AVP multiplier phototube, from which the following signals were derived:

1. A fast current pulse from the anode (or last dynode) to drive the fast coincidence circuit.
2. A fast current pulse, from the A detector only, to the flight-time measuring system.
3. A charge pulse from the next-to-last dynode, fed into an emitter follower in the socket, for use in the pulse-pileup detection system.
4. A charge pulse for pulse-height analysis from dynode 10 into a standard preamplifier, used only for alignment purposes.

Figure 9.2.3 shows a comparison of the charge spectrum of pulses from the A detector, for a beam strength of a few hundred protons per second, with the energy-loss distribution estimated by using the formulation of Symons.⁷ The points show the observed pulse-height spectrum with the pulse-height scale normalized to give the predicted mean energy loss, neglecting data above 0.9 Mev.

⁵System designed largely by N. W. Hill, Instrumentation and Controls Division.

⁶System designed largely by R. J. Scroggs, Instrumentation and Controls Division.

⁷K. R. Symons, *Fluctuations in Energy Lost by High Energy Charged Particles in Passing Through Matter*, Harvard, Thesis, 1948.

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Fig. 9.2.1. Experimental Geometry for Flight-Time Experiments, Including Cross Section of the 1-mm-thick A and A' Beam Scintillators.

Curve A is the normalized predicted energy-loss distribution folded with a normal distribution to represent the detector resolution. The standard deviation of the normal distribution was chosen by comparing the second moments of the energy-loss spectrum and the portion of the data below 0.9 Mev. Above 0.9 Mev the experimental distribution has greater intensity than the predicted one.

In the actual experiment the detector system was operated with phototube output pulses having a 20-ma peak. With intermittent operation up to a

beam strength of 5×10^4 protons/sec, the observed drift was less than 10%/day, which was sufficiently stable for this application.

Fast current pulses from the A and A' detectors were fed to tunnel-diode univibrator discriminators biased at about half the minimum pulse height produced by the incident protons. A tunnel-diode coincidence circuit with a 2-nsec resolving time (see Sec. 10.6) determined that a given proton passed through both counters. Delayed coincidence curves suggest that this circuit operated with a coincidence efficiency in excess of 99%. The dead time of the univibrators was about 10 nsec, so two protons in the same rf microstructure burst were not resolved, while those accelerated in successive rf periods always generated coincidence outputs. The (AA') coincidence output was shaped for input to duplicate scalers capable of responding to pulse pairs spaced more closely than the required 35 nsec.

It was necessary for the pulses from the fast (AA') coincidence to survive the isolated signal system and the pulse pileup anticoincidence to enable the storage of any detected secondary particle. The isolated signal system shown in Fig. 9.2.4 was constructed using tunnel-diode circuit elements and adjusted to eliminate from a train of pulses any pairs or multiples falling within 110-nsec of each other. In the limit of no dead times or circuit delays, the synchronizing delays D_1 , D_2 , and D_3 were ignored and the pulse storage delays set at the desired isolation interval (115 nsec in this case). An isolated input pulse fired both binaries and reset them at the end of the isolation time, giving an output via the "trailing edge coincidence." If two pulses were too closely spaced, the second pulse was eliminated because binary I could not be reset by the second pulse when the first had already reset it, and the first pulse was eliminated by the second through the early reset of binary II, via the "reset coincidence." Practical circuit delays were important, binary dead times were about 5 nsec, and the reset and output coincidence circuits had about 3 nsec of resolving time. Circuit behavior with more complex pulse trains is more difficult to describe.

While the logic illustrated in Fig. 9.2.4 is believed to be adequate for this purpose, the resolving times of the included coincidence circuits limit the proper function of the equipment

Fig. 9.2.2. Block Diagram of Beam-Handling Apparatus. Variable delays to assure synchronization are not shown. The "tunnel univibrators" act as fast integral pulse-height discriminators. The symbol SC stands for a 10-mc scaler, and the mnemonic name of the resulting count is in quotes.

Fig. 9.2.3. Comparison of Pulse-Height Spectrum from a 1-mm Plastic Phosphor Scintillator Penetrated by 160-Mev Protons with Predicted Energy-Loss Distribution.

in the case of relatively unlikely pulse trains having pulses in four or more successive fine structure bursts.

The pulse pileup detector (Fig. 9.2.2) was used to identify those rf periods in which two or more protons occurred. The input charge pulses were double-delay-line clipped using 25-nsec lines so that protons too close together to be resolved by the fast scaling system would appear as one large pulse. Assuming that the beam detector introduced

a variance proportional to the energy loss in the phosphor, it is possible to estimate the distribution of pulse heights which should result from "double" events involving two protons in the same fine structure interval. Figure 9.2.3 shows the predicted "doubles" pulse distribution in the A counter (Curve B) based on the observed resolution for single events and the predicted energy-loss distribution for two protons simultaneously penetrating 1 mm of plastic phosphor.

Fig. 9.2.4. Block Diagram of Isolated Signal Detector.

Experimental pulse distributions for comparison were available only at beam strengths for which the pulse analysis system is inoperative. Figure 9.2.3 also shows that no single discriminator setting can effect a complete separation of single and pileup events, but one can integrate the distributions shown to obtain a relation between singles and pileup efficiencies like that shown in Figure 9.2.5. To overcome the inadequate

Fig. 9.2.5. Estimated Relation Between Efficiencies for Counting a Pulse from One (ω) or Two (ρ) Protons in a Given Beam Microburst. The points along the curve would be obtained as the A or A' pileup discriminator is adjusted.

resolution of individual detectors, the discriminators on both A and A' channels were set for "singles" counting efficiencies of about 0.03, and the discriminator output signals were placed in coincidence. The efficiencies at the output of the pileup coincidence circuit are roughly the squares of the individual values, so an overall reasonable pileup detection efficiency could be maintained while counting very few single events. The entire pileup discriminator and coincidence system was built with longer dead times than the fast coincidence system because the discriminators were set to count less than one-tenth of the proton pulses. The input circuitry had to be capable of handling the full rates without appreciable baseline and gain shifts.

So far as the spectroscopy of secondary radiations is concerned, the only important pulses are those which appear as isolated signals and which are not recognized as pulse pileups. Others cannot lead to a recorded time interval and are not recorded in the "ISONPP" scaler as being part of the beam. However, in order to establish the proper operation of the system or to determine the total number of beam protons for calibration of beam-monitoring equipment (see Sec. 9.8), it is necessary to determine whether the various scalers monitoring the outputs in the above figures yield internally consistent counts. Under the assumption of a fairly sharp microstructure burst and constant chance for a proton per rf period over intervals short compared to a gross structure burst, equations were written relating the expected count in each scaler to the integrated beam strength, the quadratic and cubic duty factors,⁸ and the efficiencies of the pileup discriminators for counting single and pileup events. This was possible by integrating the expected counting rate over the entire running time, using steps long compared to the rf period but short compared to the gross beam structure bursts. The integration required a series expansion of the exponential of the Poisson distribution,⁹ which is valid for duty factors and count rates employed in this experiment. Unfortunately, unless information is supplied concerning the relative efficiencies of the pileup discriminators, the equations are underdetermined. Under the assumption of equal efficiencies for counting pileups, solutions were obtained for all cases using Newton's method for solving up to six nonlinear coupled equations. The apparent pileup efficiencies often exceeded unity, presumably because of flaws in the mathematical description of the operation of the circuitry or the time dependence of the beam. Using the relation between singles and doubles efficiency given by

⁸If i^n is the n th moment of the proton current distribution averaged over periods of a few hundred nanoseconds, the quadratic duty factor is defined as $f = \langle i \rangle^2 / \langle i^2 \rangle$. If the beam were either off or on with a fixed mean strength, f would be the fraction of the time on. In this simple case the similarly defined cubic duty factor would be the square of f .

⁹If i is the lightly averaged mean current defined above, the probability for finding K protons in a time interval Δ would be $(i\Delta)^K \exp(-i\Delta)/K!$, based on the Poisson statistical distribution.

Fig. 9.2.5, only three cases yielded solutions. The derived total number of incident protons did not vary much with the model, and the quadratic duty factors remained in the neighborhood of 2%. This value is somewhat smaller than was expected for the Harvard machine,¹⁰ but may have been influenced by the low beam strength or the positioning of the slits in the deflected beam.

Flight-Time Spectroscopy of Secondary Protons

Figure 9.2.6 is the block diagram of the electronics employed to record proton flight-time spectra. The pulse-height spectra in the B' counter from protons energetic enough to penetrate that counter were also recorded but have not been analyzed. Figure 9.2.6 shows that protons are recorded only if there is a coincident pulse in the C' detector, a 0.5-mm plastic counter 4 in. in diameter placed 30 to 40 cm from the B' detector. This coincidence requirement eliminates neutrons and gamma rays from detection, but does not prevent detection of some protons which are scattered through both detectors from air or from some part of the apparatus and find themselves in accidental coincidence with a proton detected by the beam counters. These counts should also appear in the target-out background.

Figure 9.2.7 illustrates the delayed coincidence curve between the secondary proton counters. Since the effect of using a lower proton energy would be to delay the signal from B' relative to that from C' , the runs were made with the delay set at 24 nsec. This offset was excessive, since the slowest proton detectable by B' requires only 10 nsec to traverse the 1-ft spacing. The product of coincidence and detection efficiencies throughout the portion of the curve used appear to be in excess of 98%, assuming unit efficiency for the fast system (AA') coincidence detection of the incident protons. Lower energy secondary protons are counted with yet higher efficiency.

A typical pulse-height spectrum from the time-to-pulse-height converter is shown in Fig. 9.2.8. For these measurements a 0.7-g/cm² Co target was used, and the detector angle was 45°. The background was obtained with the target removed. During the run, 9.1×10^7 usable protons were incident on the target. Since nearly all protons of

a given energy deposit the same amount of energy in the B' detector, the effective time resolution is nearly as good as that observed at 0° with the target removed. Approximate secondary energies are labeled on the curve. In Fig. 9.2.8 short flight times appear to the right, so the cutoff at about channel 140 is caused by absorption of energy from the secondary protons along the air paths, in the fairly heavy detector system, and in the target. This energy loss dominates the energy resolution at the lower energies and prevents observations in the energy region below about 20 Mev, while time resolution alone leads to an energy resolution broader than 50% above 50 Mev. Because of this limited range of usefulness, only a few days of cyclotron time were devoted to proton spectra.

Figure 9.2.9 shows differential cross sections obtained for the cobalt target, which was about 3 Mev thick for the incident beam. Symbols represent the cross-section uncertainties, the energy width of a given time channel, the anticipated uncertainty in the energy assigned to the channel, and the approximate energy resolution as a function of energy. Vertical flags on the histogram steps represent estimated statistical counting standard deviations, while horizontal flags indicate energy assignment uncertainties originating largely in estimation of timing-circuit performance as a function of energy loss in the detector. Timing uncertainties also lead to cross-section errors through the energy bin width estimation; these uncertainties range from 1.5% at 50 Mev to 2% at 20 and 110 Mev. Additional uncertainties in the normalization of the cross sections are tentatively estimated at 3%. At energies above 35 Mev most histogram step widths correspond to one time channel, while at lower energies time channels have been combined. The energy quoted on the abscissa is the energy at the center of the 0.7-g/cm² target of a proton which falls at the corresponding point in the time analyzer. The distributions at the lower left show the shape of computed "birth-energy" distributions for the mean energies shown. The two histograms peaked near the top of the graph indicate the apparent energy distribution which would have resulted if the secondary protons were monoenergetic with the measured time falling in the center of the time channel which appears at the peak. The apparent skewness of the distribution originates in the variable energy interval corresponding to one 0.47-nsec time channel.

¹⁰J. Lefrancois, *Rev. Sci. Instr.* 32, 986 (1961).

Fig. 9.2.6. Electronics for Charged-Particle Flight-Time Spectra. Some of the units shown have capabilities not illustrated here, and details of the beam processing package are given in Figs. 9.2.2 and 9.2.4. All scalers were actually located in the instrument area. Only the results from "Route 1" of analyzer No. 10 are reported here.

Fig. 9.2.7. ($B'C'$) Coincidence Delay Curve at 0° Using the 160-Mev Beam with the C' Detector About 30 cm from the B' Detector.

Fig. 9.2.8. Raw Pulse-Height Spectrum from the Time-to-Pulse-Height Converter for Secondary Charged Particles from a 0.7-g/cm^2 Co Target.

To obtain the energy corresponding to a given time channel, energy loss calculations were performed stepwise over the various materials between the point of nuclear interaction in the target and the B' detector, the flight time being summed over all the intervals. Interactions at various depths in the target were considered equally probable,

allowing a time-to-energy conversion to be based on the average birth energy in the target for a given recorded time. The results were found to be equivalent to a calibration based on the proton energy at the center of the target, so the latter system was used in practice.

Fig. 9.2.9. Differential Cross Sections $\sigma_{p, xpy}(160; E, \theta)$ for Cobalt Bombarded with 160-Mev Protons.

The data from Fig. 9.2.9 include heavier charged secondaries and may be subject to small corrections. The data illustrate the gradual softening of the differential energy spectra as the detector angle is increased. The laboratory differential cross-sections $\sigma_{p,xpy}$ (160 Mev; E, θ) are plotted (see Sec. 9.0), so the corresponding integrated cross section is the cross section for emission of at least one proton times the average proton multiplicity. Table 9.2.2 gives the cross section integrated over the measured energy range.

An effort is being made to compare the data against calculations based on the nuclear cascade model (Secs. 8.11 and 8.12), as well as against the experimental results of Gibson *et al.* (Sec. 9.5). Preliminary comparisons for cobalt at 45° in the neighborhood of 60 Mev indicate agreement among all three at this point within about 20%.

Table 9.2.2. Integrated Laboratory Cross Sections for Production at Various Laboratory Angles of >20-Mev Protons by Reactions of 160-Mev Protons with Cobalt^a

Detector Angle (deg)	$\sigma_{p,xpy}$ (160; θ) (mb/ster)	$\delta\sigma$ (mb/ster)
30	166	5
45	116	2
60	63	2
90	49	3
120	8.3	0.6

^aMinor interpolation was performed so that each integral would correspond to the same energy limit. The estimated standard deviations are from counting statistics alone and should be combined with a normalization uncertainty presently estimated at 3%. Some deuterons are doubtlessly included.

9.3. DEPTH-DOSE DISTRIBUTION PRODUCED IN A SPHERICAL WATER-FILLED PHANTOM BY INTERACTIONS OF A 160-Mev PROTON BEAM¹

F. C. Maienschein and T. V. Blosser

Measurements have been made of the total energy deposited at various points within a 42-cm-diam spherical water-filled Lucite phantom by the secondary particles resulting from 160-Mev proton reactions with various targets (see Fig. 9.4.1 in Sec. 9.4 for photograph of phantom). The proton source was the Harvard University synchrocyclotron, and the target materials were water, aluminum, carbon, copper, and bismuth. The detectors were small Lucite-walled ionization chambers filled with 97% A-3% CO₂ or ethylene gas.

Data were taken both with the water-filled phantom on the beam axis and with the phantom offset approximately 54° from the beam axis. The

proton beam energy determined from a part of these results, 160 to 162 Mev, is in good agreement with published values. The energy deposited by secondary particles was found to increase with Z , as was expected. The curves of depth dose due to secondary particles have a steeply negative slope over the region near the surface of the phantom and a more gentle slope at greater depths. The magnitude of the dose in the region of the initial slope, which is presumably due to secondary protons, decreases with increasing target thickness. The magnitude of the dose at greater depths increases with increasing target thickness. At the greater depths the slope of the depth-dose curves, presumably controlled by secondary neutron interactions, is similar to that observed when the depth dose due to a Co⁶⁰ gamma-ray source was measured.

¹Abstracted from ORNL-3457 (June 7, 1963), in which a portion of the data is presented graphically and a complete tabulation of all results is included as an appendix.

9.4. ABSORBED DOSE IN A WATER-FILLED SPHERICAL PHANTOM DUE TO 14-Mev AND Po-Be NEUTRONS

T. V. Blosser and R. M. Freestone, Jr.

Introduction

Measurements of the total energy deposited at various points within a 42-cm-diam spherical water-filled phantom by the secondary neutrons, protons, and gamma rays resulting from 160-Mev proton reactions with various targets have been reported (see Sec. 9.3). The measurements were made with small (16–17 cm³) argon- or ethylene-filled ionization chambers which could be remotely positioned within the Lucite sphere. In the analysis of these measurements it was observed that the depth-dose curve at large depths (at which the dose would be expected to be due predominantly to neutrons) approximately paralleled a curve resulting from an exposure to Co⁶⁰ gamma rays having an average energy of 1.25 Mev. Both as a further comparison for the earlier work and because the information is independently of interest, the spherical phantom has now been used to measure the dose distributions resulting from a beam of 14.1-Mev neutrons and from a Po-Be source.

Preliminary Experiments

Before beginning the proposed depth-dose measurements in the phantom, it was necessary to perform several auxiliary experiments to obtain accurate source calibrations and to verify the performance of the ionization chambers under the conditions of the principal experiment. In both the $H^3(d,n)He^4$ reaction proposed as a source of 14.1-Mev neutrons and in the $Be^9(\alpha,n)C^{12*}$ reaction of the Po-Be source, gamma rays are associated with the neutron emission. In order to calibrate the sources in terms of dose deposited in the phantom, it was required that the magnitude of the gamma-ray and neutron components be separately known.

The 14.1-Mev source consisted of a freshly prepared target containing 377 $\mu\text{g}/\text{cm}^2$ of tritium, or a total of 0.718 curie, contained in titanium upon a platinum backing. It was mounted in the deuteron beam of the Bulk Shielding Facility 300-kv particle

accelerator described by Kington.¹ The gamma-ray dose rate from this target was measured by a traverse in air along the beam axis, with the gamma-ray detector described by Wagner and Hurst.² The response of this detector to neutrons is low in comparison with its gamma-ray response, being <0.5% over the energy range 0.68 to 4.2 Mev. The experimental data from the traverse were satisfactorily fitted by least squares to a $1/R^2$ curve, from which fit the dose rate at a distance of 1 m from the target and with a beam current of 60 μa was determined as 1.84 ($\pm 2\%$) mrad/hr.

The calculation of the dose rate due to neutrons from the tritium target (described later in this paper) was based upon a measurement of the neutron flux by a threshold-foil technique. The threshold reaction was the $Al^{27}(n,\alpha)Na^{24}$ reaction, with a thin aluminum foil in the beam. The cross section used for this reaction at 14.1 Mev was 117.5 ± 5 mb,³ and the assumption was made that the foil activity resulting from 14.1-Mev neutrons degraded to lower energies by scattering in the foil was negligible, since the cross section for interactions at lower energies rapidly becomes small. The neutron emission from the tritium target was determined as 2.5×10^7 ($\pm 7\%$) neutrons/sec at a beam current of 60 μa . The error represents the accumulated error in cross sections, foil counting, and beam monitor corrections.

The Po-Be source used for the second part of the calibration measurements had been intercalibrated with a source calibrated by the National Bureau of Standards, and contained 10.3 curies of polonium. The measured gamma-ray dose rate from this source, at a distance of 1 m, was 0.1 ($\pm 4\%$) $\text{mr}\cdot\text{hr}^{-1}\cdot\text{curie}^{-1}$, where the error consists of the error in source-strength determination and the counting error. This value is in agreement

¹J. D. Kington, *Neutron Phys. Div. Ann. Progr. Rept.* Sept. 1, 1958, ORNL-2609, p 61.

²E. B. Wagner and G. S. Hurst, *Health Phys.* 5, 20 (1961).

³G. S. Mani et al., *Nuclear Phys.* 19, 535 (1960).

with published⁴ values for the gamma-ray dose rate from a Po-Be source, $\sim 0.1 \text{ mr} \cdot \text{hr}^{-1} \cdot \text{curie}^{-1}$.

Ion Chamber Calibrations

The ionization chambers used in the present measurements were the ethylene-filled chambers used in the 160-Mev-proton work, as described by Maienschein and Blosser (Sec. 9.3). In the previous work the chambers were calibrated against known-energy Co^{60} and Cs^{137} gamma-ray sources, and it was observed in every case that the dose rate reported by the dosimeter was lower than that predicted by calculations. This was reflected by the disparity between the nominal volumes of the ionization chambers and their volumes as computed on the basis of their response to the gamma-ray sources.

In order to determine whether the discrepancy also existed with mixed, but predominantly neutron, sources, a comparison was made between calculated and measured dose rates for the 14.1-Mev and Po-Be neutron sources. The comparison was made at 21 cm in air, and the measurements were made with the ethylene-filled ion chamber calibrated against a known-intensity gamma-ray source, exactly as in the previous work.

The dose rate due to the gamma-ray emission from the neutron sources was known from the measurements described above. The kerma⁵ deposited in various absorbers of interest by neutrons was computed from

$$D_f(E) = \frac{\int_0^\infty D_f(E) N(E) dE}{\int_0^\infty N(E) dE},$$

where $D_f(E)$ = kerma at energy E in $\text{ergs} \cdot \text{g}^{-1} \cdot \text{neutron}^{-1} \cdot \text{cm}^2$, and $N(E)$ = neutron spectrum in neutrons $\cdot \text{cm}^{-2}$ unit energy interval.⁻¹.

⁴A. O. Hanson, p 24 in *Fast-Neutron Physics*, part 1 (ed. by J. B. Marion and J. L. Fowler), Interscience, New York, 1960.

⁵The quantity "kerma," defined as the quotient of the sum of the initial kinetic energies of all the charged particles liberated by indirectly ionizing particles in a volume element of a specified material divided by the mass of the material in the volume element, was recommended by the International Commission on Radiological Units and Measurements as a more rigorous replacement for the more familiar term "first-collision dose." See: *Natl. Bur. Std. (U.S.) Handbook 84*, (1962).

For the tritium source E was taken to be 14 Mev and for the Po-Be source the spectrum given by Whitmore⁶ was used. The results are shown in Table 9.4.1.

Table 9.4.1. Kerma at $\bar{E}$ for Po-Be and 14-Mev Sources and Various Absorbers

Absorber	Kerma ($\bar{E}_n$) ($\text{erg} \cdot \text{g}^{-1} \cdot \text{neutron}^{-1} \cdot \text{cm}^2$)
$\times 10^{-7}$	
Po-Be Source	
Ethylene	5.57 ^a
97% Ar, 3% CO ₂	1.50
Lucite	3.31
Tissue	4.78 ^a
14-Mev Source	
Ethylene	8.73 ^a
97% Ar, 3% CO ₂	0.38
Lucite	5.49
Tissue	6.67 ^a

^aValues determined from *Natl. Bur. Std. (U.S.) Handbook 75* (1961).

For the 14.1-Mev source the total dose rate computed on the basis of the data above was 0.97 ($\pm 9\%$) rad/hr. The measured dose rate was 0.93 ($\pm 4.5\%$) rad/hr. The major error in the computed value lies in the source strength determination. The two values are in agreement within the errors quoted.⁷

With the Po-Be source, the computed dose rate was 0.072 ($\pm 9.5\%$) rad/hr, while the measured dose rate was nearly 16% lower, or 0.060 ($\pm 4\%$) rad/hr. The error in the computed value is largely the error assigned to the Po-Be neutron spectrum. The ratios of calculation to experiment are consistent with the existence of a systematic error stemming from chamber fabrication or filling that was suggested in the previous work.

⁶B. G. Whitmore and W. B. Baker, *Phys. Rev.* **78**, 799 (1950).

⁷Comparison of data from Co^{60} , Cs^{137} , and Po-Be measurements indicates that the measured value at 14.1 Mev is probably high..

Dose Measurements in Phantom

The spherical water-filled phantom used in the present work has been described in detail elsewhere (see Sec. 9.3), but for convenience is shown here in Fig. 9.4.1. In the present work the phantom

was positioned 5.5 ft from the floor of the Bulk Shielding Facility accelerator room, centered on the beam axis, 10 cm from the previously described tritium target. The beam current was monitored by a conventional long counter, 200 cm and 90° from the beam axis. When the Po-Be

Fig. 9.4.1. The 42-cm-diam Spherical Lucite Phantom.

source was used, it was set 17.9 cm from the phantom and 5.5 ft from the floor. The ethylene-filled ionization chamber, calibrated against known-intensity gamma-ray sources as in the previous work, was used for these measurements. Neutron scattering from the floor and supports was estimated by positioning the ion chamber 2.35 cm from the front of the phantom and making a vertical dose traverse from $+60^\circ$ to -60° relative to the horizontal. The dose at the negative angles was of the order of 2 to 8% greater than the dose at positive angles. Thus, if it is assumed that the dose at positive angles consists primarily of air-scattered neutrons, the contribution of the floor-scattered neutrons is relatively small, an intentional consequence of the use of low-mass materials in the construction of the accelerator room.

The results of the depth-dose measurements are shown in Table 9.4.2. The phantom was always at 0° relative to the beam axis and the traverses were along a diameter parallel to the beam.

The present results are compared with some data from the 160-Mev proton work in Fig. 9.4.2. In plotting these curves the data have been multiplied by the square of the source-ion-detector distance. All data were obtained with the ethylene-filled chamber except for the 160-Mev proton secondary values at 45° , for which only argon-filled chamber data were available.

An important feature of the curves in Fig. 9.4.2 is the differences in the slopes of the several curves. These differences in slope reflect the differences in the energies retained by the particles in traversing the phantom. As expected, the slope of the curve representing the dose due to 14.1-Mev neutrons was less than that for the Po-Be neutrons, and the even flatter slope of the curves representing the 160-Mev secondaries illustrates the higher energies retained by these particles.

Table 9.4.2. Physical Dose Due to 14.1-Mev and Po-Be Spectrum Neutrons Absorbed in a 42-cm-diam Water Phantom, as a Function of Depth in the Phantom^a

Depth in Phantom (cm)	Absorbed Energy (ergs/g _{H₂O})
14.1-Mev $H^3(d,n)He^4$ Neutrons	
2.35	33.83
5.55	20.10
8.45	12.61
8.75	11.69
8.75 ^b	12.22
11.65	8.177
14.85	5.369
14.85 ^b	5.360
17.75	4.383
17.75 ^b	4.020
20.85	2.887
20.85 ^b	2.940
23.95	2.143
26.85	1.694
27.35	1.612
30.35	1.035
33.05	0.624
Po-Be Source Neutrons	
2.35	11.58
5.75	8.19
8.75	4.98
11.75	3.29
14.75	2.20
17.75	1.68
20.75	1.26
23.75	1.109
26.75	0.790
29.75	0.514
32.75	0.349

^aData are normalized to an incident flux of 10^{10} neutrons and to a source-phantom separation of 10 cm for the 14-Mev source and 17.9 cm for the Po-Be source.

^bRepeated determination.

Fig. 9.4.2. Absorbed Dose Rate as a Function of Depth in Water for Co^{60} Gamma Rays, 14.1-Mev and Po-Be Spectrum Neutrons, and the Nuclear Primary and Secondary Particles Resulting from the Interaction of a 160-Mev Proton Beam with Aluminum Targets.

9.5. NEUTRON AND PROTON SPECTRA FROM TARGETS BOMBARDED BY 160-Mev PROTONS

J. W. Wachter, W. A. Gibson, W. R. Burrus,
and C. F. Johnson¹

The proton-recoil spectrometers described by Gibson *et al.*² have been used to measure the spectra of neutrons and protons resulting from the interactions of the 160-Mev proton beam of the Harvard University synchrocyclotron with targets of light water, heavy water, beryllium, carbon, aluminum, cobalt, copper, and bismuth.

¹General Dynamics Corporation, Fort Worth, Texas.

²W. A. Gibson, W. R. Burrus, and C. F. Johnson, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 281, also, Sec. 10.1, this report.

In order to convert the pulse-height spectra of these spectrometers to energy spectra, it was necessary to determine the transformation between the pulse height, which is proportional to the light output of the energy-measuring scintillators, and the incident-particle energy. In the present work this relation was determined by experiment. The essentially monoenergetic proton beam from the cyclotron was degraded to various energies by copper absorbers placed in the beam, and the pulse-height spectra of each absorber thickness were recorded.

Because of the Landau effect³ within the absorbers, the degraded proton beam will exhibit a spread of energies. The energy of the degraded proton beam was obtained from range tables⁴ calculated by integrating the path length per unit energy absorbed. Thus, in the case of the total absorption scintillator employed in the 10- to 50-Mev spectrometer, the average degraded energy should correspond very nearly to the centroid of the pulse-height distribution. (It was assumed that the quantity of light emitted by the scintillator is proportional to the energy deposited. This is not quite true, since the scintillator efficiency, dl/dE , is not constant over the energy region concerned. However, neglecting the variation in dl/dE will introduce little error in the calibration of the total absorption scintillator.) The transformation obtained by plotting the centroids of the pulse-height distributions as a function of the degraded energy is shown in Fig. 9.5.1. Some of the spread in the points may reflect inaccuracies in the range tables used in calculating the degraded energies.

In the case of the dE/dx energy detector used in the 50- to 450-Mev spectrometer, which absorbs only a small part of the proton energy, the problem of finding the transformation between pulse height and energy is more complicated, since large Landau fluctuations occur in the dE/dx scintillator, as well as in the beam degraders, and a considerable variation in scintillation efficiency exists over the energy range 50 to 450 Mev. In this case the pulse-height spectra produced by the degraded proton beam must be transformed into an energy spectrum in order to find the average energy of the distribution. Since this step itself requires a knowledge of the transformation sought, an iterative process was adopted. First an approximate transformation was found by assigning the calculated degraded energies to the average channel of the pulse-height distribution, and these paired values were fitted by a curve obtained by a least-squares method. This curve was then used to transform each pulse-height spectrum to an energy spectrum. The channels corresponding to the average energy

of these spectra then defined a new transformation, which was applied to convert the pulse-height spectra into energy spectra again. From these spectra new average energies were calculated, and the process was repeated until no change occurred in the average energies between successive transformations. A typical transformation is shown in Fig. 9.5.2.

With the aid of these transformations, the neutron energy spectrum was calculated from

$$\phi(E_i) \Delta E_i = N_i / \epsilon(E_i),$$

where

N_i = number of counts in the i th channel, after background correction,

E_i = energy corresponding to the center of i th channel,

ΔE_i = energy width of i th channel,

$\epsilon(E_i)$ = efficiency for detection of a neutron of energy E_i .

Fig. 9.5.1. Pulse-Height Response as a Function of Proton Energy for a 4.801-g/cm² NaI(Tl) Crystal.

³L. Landau, *J. Phys. USSR* 8, 201 (1944); also, Sec. 10.1, this report.

⁴M. Rich and R. Madey, *Range-Energy Tables*, UCRL-2301 (March 1954).

Fig. 9.5.2. Pulse-Height Response as a Function of Proton Energy for a 1.464-g/cm² NaI(Tl) Crystal.

The proton spectra are calculated in the same manner, except that the efficiency is constant for all energies and is determined by the solid angle subtended by the energy counter. A computer program, which includes such computational details as corrections for amplifier gain shifts, was written to perform the calculation and to produce a machine plot of the energy spectrum.

The spectra reported here are broadened by the energy resolution of the spectrometers. Because of geometrical effects and the nonlinear variation of dE/dx with energy, the curve representing the response of the spectrometers to monoenergetic neutron sources is not Gaussian but, rather, is skewed. It is desirable that this skewed-line shape be replaced by a narrow, symmetrical Gaussian line shape, which can be done by numerically correcting for the instrument broadening. For the neutron data it will not be possible to reduce the width of the peak appreciably because of the statistical error amplification which would result, but the line shape may be modified somewhat to give a more symmetrical curve. The SLOP code⁵ (see Sec. 10.4), recently developed specifically for this type of problem, will be used.

⁵V. D. Bogart and W. R. Burrus, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 22.

The spectrometers also exhibit an angular resolution that depends upon the geometry as well as the spatial distribution of the secondaries over the back side of the target. In the present work the spatial distribution was measured by scanning the back side of the targets with small counters. For targets thicker than the range of 160-Mev protons, the full-width at half maximum of the resulting peak was found to be ~ 6 cm. Thus the angular resolution is approximately $\pm 8^\circ$ for protons and neutrons from thick targets in the geometry of the present work. The resolution for protons from thin targets is somewhat better, because the primary proton beam is broadened only slightly.

Figure 9.5.3 shows proton spectra at 10° from the primary beam axis, obtained by bombarding a 44.3-g/cm² bismuth target and a 26.9-g/cm² aluminum target with 160-Mev protons. These targets are thick enough to stop the primary protons. Figures 9.5.4 and 9.5.5 show proton spectra at 60° and 135° , respectively, resulting from the bombardment of a 0.581-g/cm² aluminum target and a 0.929-g/cm² bismuth target, both of which absorbed only about 2.5 Mev from the primary beam.

Fig. 9.5.3. Energy Spectra, at 10° from Beam Axis, of Protons Resulting from the Interaction of a 160-Mev Proton Beam with Thick Aluminum and Bismuth Targets.

Figures 9.5.6 and 9.5.7 show neutron spectra from a 26.9-g/cm² aluminum target and a 44.3-g/cm² bismuth target, respectively, at 10 and 45°. Data points are given on Fig. 9.5.6 to show the typical spread. The curves were made by passing a freehand line through the points; consequently, the results obtained from different spectrometer radiators have not been combined

properly, nor have the statistical fluctuations been properly accounted for. Thus the curves are only approximate. The points are shown on one proton graph and one neutron graph to indicate typical statistical errors encountered. The neutron curves are estimated to be accurate to within 30% at 50 Mev and to within a factor of 2 at 150 Mev. The accuracy of the proton curves is

Fig. 9.5.4. Energy Spectra, at 60° from Beam Axis, of Protons Resulting from the Interaction of a 160-Mev Proton Beam with Thin Aluminum and Bismuth Targets.

Fig. 9.5.5. Energy Spectra, at 135° from Beam Axis, of Protons Resulting from the Interaction of a 160-Mev Proton Beam with Thin Aluminum and Bismuth Targets.

Fig. 9.5.6. Energy Spectra, at 10 and 45° from Beam Axis, of Neutrons Resulting from the Interaction of a 160-Mev Proton Beam with a Thick Aluminum Target.

Fig. 9.5.7. Energy Spectra, at 10 and 45° from Beam Axis, of Neutrons Resulting from the Interaction of a 160-Mev Proton Beam with a Thick Bismuth Target.

better because of better statistics and because no radiators were involved. The data are to be reanalyzed to properly combine results and estimate the errors.

The spectra illustrated above were obtained with the 50- to 450-Mev spectrometer (as described

for the 50- to 160-Mev range in Sec. 10.1). Figures 9.5.8 and 9.5.9 show proton spectra obtained at 135° from various targets with the 10- to 50-Mev spectrometer.

A compilation of these results and those obtained from other targets is being prepared for publication.

Fig. 9.5.8. Energy Spectra, at 135° from Beam Axis, of Protons Resulting from the Interaction of a 160-Mev Proton Beam with Thin Beryllium, Aluminum, and Bismuth Targets.

Fig. 9.5.9. Energy Spectrum, at 135° from Beam Axis, of Protons Resulting from the Interaction of a 160-Mev Proton Beam with a Thick Bismuth Target.

9.6. SCINTILLATION EFFICIENCY OF NaI(Tl) FOR CHARGED PARTICLES

W. A. Gibson, W. R. Burrus, J. W. Wachter,
and C. F. Johnson¹

The scintillation efficiency dl/dE , the ratio of the incremental light emitted by a scintillator to the incremental energy deposited, of organic and inorganic scintillators is of considerable interest for studies of the scintillation process.²

¹General Dynamics Corporation, Fort Worth, Texas.

²R. B. Murray and A. Meyer, *Phys. Rev.* **122**, 815 (1961).

The light output of a scintillator penetrated by a charged particle is

$$L = \int_{E_{in}}^{E_{out}} (dl/dE) dE, \quad (1)$$

where E_{in} is the energy of the particle as it enters the scintillator and E_{out} is the energy as it emerges. Differentiating this expression with respect to the input energy and rearranging terms gives

$$dl/dE_{out} = (dL/dE_{in} + dl/dE_{in}) / (dE_{out}/dE_{in}),$$

where the subscripts "in" and "out" identify the derivatives at the entrance and exit of the scintillator, respectively. Since

$$E_{out} = E_{in} - \int_0^{x_0} (-dE/dx) dx, \quad (2)$$

where x_0 is the thickness of the scintillator,

$$dl/dE_{out} = (dL/dE_{in} + dl/dE_{in}) / [1 + (d/dE_{in}) \int_0^{x_0} (dE/dx) dx]. \quad (3)$$

The quantity dL/dE_{in} can be obtained experimentally from the slope of a pulse height vs energy calibration curve. A typical curve is shown in Fig. 9.5.2 of Sec. 9.5. The data are for a 1.464-g/cm² NaI(Tl) crystal³ exposed to a 160-Mev proton beam degraded to various energies by passing through copper absorbers. The value of dL/dE_{in} , the slope of the curve, was obtained as a function of E by first fitting the data points with a simple expression by a least-squares method, and then differentiating the result. The derivative obtained in this way is very sensitive to small experimental errors and to the details of the least-squares procedure. This sensitivity may produce large errors in the calculation of dl/dE , and the results of the present work should be considered as tentative until more study has been given this problem.

The value of dl/dE_{in} is calculated by assuming that for high-energy protons dl/dE is essentially constant, since the proton loses little energy in traversing the scintillator. Thus

$$dl/dE_{in} \cong L/\Delta E, \quad \Delta E \ll E,$$

³Obtained from Harshaw Chemical Co., Cleveland, Ohio.

where ΔE is the energy loss of the proton. Once an initial value of dl/dE_{in} is found, values of dl/dE , at energy intervals defined by Eq. (2), are obtained by solving Eq. (3). A computer program was written for this purpose.

A typical result obtained by the technique described here is shown in Fig. 9.6.1, which shows the relative scintillation efficiency as a function of dE/dx for protons on NaI(Tl). The data were for the 1.464-g/cm² crystal and the degraded proton beam discussed above. Data have also been obtained with proton energies up to 450 Mev for both an NaI(Tl) crystal and an organic scintillator,⁴ but the values of dl/dE have not yet been calculated. A detailed report on this measurement is being prepared for publication.

⁴NE-102, manufactured by Nuclear Enterprises, Ltd., Winnipeg, Canada.

Fig. 9.6.1. Scintillation Efficiency, dl/dE , vs dE/dx for Protons on NaI(Tl).

9.7. SPACE, TIME, AND ENERGY DISTRIBUTIONS OF THE PROTON BEAM FROM THE HARVARD UNIVERSITY SYNCHROCYCLOTRON¹

R. T. Santoro

Introduction

Since a detailed knowledge of the beam of the Harvard University synchrocyclotron was required for the analysis of the experiments described in Sections 9 and 10, measurements of the distributions in space, time, and energy of the protons composing the beam were made and are reported here. Some preliminary data were previously presented,² and reference should be made to that report for some details of the experimental arrangement, instrumentation, apparatus, and circuitry.

Proton Distribution in Space

The beam of the Harvard machine is focused by a quadrupole magnet system. Optimum focus was accomplished by successively varying the magnet current until the smallest possible circular image was produced on Type 55 PN Polaroid film exposed in the target plane. A focused beam with an apparent image diameter of 0.5 in., which was six times smaller than the diameter of the smallest target used, was achieved with an incident beam of about 10^7 protons/cm².

Two independent methods were used to determine the cross-sectional distribution of protons in the beam so that the region of the target where proton interactions occurred could be defined. In the first, Kodak Type M Industrial x-ray films were exposed in the target plane to a beam of nominally 4×10^6 protons/sec. The exposures were determined by the collection of accumulated charges in the beam monitor ionization chamber (described in Sec. 9.8) of 1, 5, 10, 50, and 100 ncoul, which was equivalent to a total accumulation of from 1.6×10^7 to 1.3×10^9 protons. The developed x-ray films were analyzed by measuring the fraction of light transmitted through the image as a function of distance along the image

horizontal axis with a Jarrol-Ash photodensitometer. Figure 9.7.1 shows the percent transmission vs image width curves for the five exposures. Figure 9.7.2 is a composite curve which was constructed from the five curves in Fig. 9.7.1 and shows the relative proton beam intensity as a function of beam diameter. The protons are normally distributed, with two standard deviations being defined by a 0.56-cm radius of the beam, which was circular in cross section. The fraction of protons, f_p , contained within a circle of given radius, R , is given by

$$f_p = \int_0^{K\sigma} (R/\sigma^2) e^{-(R^2/2\sigma^2)} dR = 1 - e^{-K^2/2},$$

Fig. 9.7.1. Light Transmission of X-Ray Film Exposed in Harvard Proton Beam as a Function of Image Width.

¹These measurements were made with the advice and assistance of W. R. Burrus, W. A. Gibson, T. A. Love, F. C. Maienschein, and R. W. Peelle.

²R. T. Santoro et al., *Neutron Phys. Div. Space Radiation Shielding Research Ann. Progr. Rept. Aug. 31, 1962, ORNL CF-62-10-29 Rev., p 182.*

Fig. 9.7.2. Relative Beam Intensity as a Function of Beam Diameter as Measured with X-Ray Films.

where K is the number of standard deviations at which f_p is to be measured. The equation defines the fraction of protons within a given radius for a bivariate normal distribution of equal standard deviations.

The fraction of protons striking the target for $R = 2\sigma$ is 0.86. The tails of the curve extend smoothly to a diameter of 2.54 cm, with 98% of the protons falling within this diameter. The full-width at half-maximum of the distribution is 0.66 cm, and the deviation from a true normal distribution is less than 2% of full value.

The second method of determining the proton distribution in the beam consisted of scanning the beam with a profile telescope shown in Fig. 9.7.3 and counting the protons as a function of a fixed charge accumulated in the ion chamber. These data are shown in Fig. 9.7.4. Along the horizontal beam axis two standard deviations of

the normal distribution are within a beam radius of 0.56 cm, with a full-width at half-maximum of 0.66 cm. For the bivariate distribution, the profile telescope and x-ray film results are in agreement.

Proton Distribution in Time

In a synchrocyclotron the proton beam is extracted only when the frequency of the accelerating voltage is within narrow limits, that is, at the extraction frequency. In the Harvard synchrocyclotron, frequency modulation is accomplished by a 16-tooth rotating capacitor operated at about 18 revolutions per second. There are nominally 288 bursts of protons per second, defined as the macrostructure. Because of variations in the shape of capacitor teeth, wobble in its shaft, and variations in the rotation speed, the shape and frequency of the individual proton bursts vary in intensity and duration. In order to assess the effect of variation of machine parameters on the duty cycle, i.e., the fraction of the synchrocyclotron time cycle during which protons are ejected, and burst macrostructure, the macroburst was studied as a function of proton injection and extraction parameters.

The method of analyzing the macrostructure was previously described.²

Seven observations were made of the macrostructure resulting from variations of the ion source. The duration of the individual bursts remained essentially constant with variations in source intensity up to a factor of 5. Two observations were made for variations in the extraction frequency. Raising or lowering the lower frequency limit for extraction by as little as 1% effected a decrease in beam intensity by a factor of 6, with a decrease in burst width by a factor of 2.5. The number of bursts per revolution decreased from 16 to 6. Variations in the phasing, the timing between injection and extraction, showed no significant change in burst duration, but a change only in intensity.

The shape of the burst was different for each tooth. If the duty cycle was determined from the expression $\Delta t/T$, where Δt is the burst width at half-maximum and $1/T$ is the repetition rate, values for the duty cycle of 4 to 6%, depending on the specific tooth, were noted. The average duty cycle computed from composite tooth bursts

Fig. 9.7.3. Schematic Diagram of the Profile Telescope.

was measured to be as high as 6%, a value which seems somewhat high. The value determined by Lefrancois³ by measuring the current from a phototube viewing a plastic scintillator in the beam was $(3 \pm 0.2)\%$, while Zobel *et al.* (Sec. 9.1) obtained values ranging from 2.4 to 4.9% by measuring random coincidence events during several different runs. The duty factor measured by Peelle *et al.* by individual-proton counting techniques (Sec. 9.2) was typically 2% for very low counting rates and narrow slit openings.

The shape of the composite burst may be approximated by either a rectangle or a triangle or both. The duty cycle can be measured by determining the ratio of the square of the average value of the height of the burst to the average value of the square of the height. For the case of a triangle and a rectangle of equal areas and the same full-width at half-maximum, it can be shown that the duty cycle can vary by as much as

³J. Lefrancois, *Rev. Sci. Instr.* 32, 986 (1961).

Fig. 9.7.4. Relative Beam Intensity as a Function of Beam Diameter as Measured with the Profile Telescope.

a factor of 1.5 if the root-mean-square values for each case are compared. Thus a more realistic value of the duty cycle is 4%.

Further study of the burst structure reveals a finer distribution of protons with time, called the microstructure. The microbursts occur at the rf accelerating frequency. In the experiments of Sec. 9.1 a gate circuit was used to operate the detectors as a function of time with respect to the microbursts to minimize the accumulation of background counts due to secondary neutrons. Knowledge of the microburst was required in the design of timing circuits for the measurements of Sec. 9.2.

The microburst duration and frequency were measured with the profile telescope shown in Fig. 9.7.3, as well as by observing, with an oscilloscope; the pulses produced in an organic scintillator in the beam. In the telescope measurements, the microburst frequency was determined by varying the delay in one leg of the circuit until coincidence was established between successive bursts. The required delay, corresponding to the time between microbursts, varied from

41.2 to 44 nsec, with the breadth of the peak in delayed coincidence varying from 4.5 to 6.3 nsec for resolving times from 3.5 to 6.2 nsec. The results of the oscilloscope observations were previously reported.²

Proton Distribution in Energy

The beam energy was measured in two ways, one by determining the range of the protons in copper absorbers and another by measurement of proton flight time over a path of 355 cm.

Figure 9.7.5 is a block diagram of the circuit used to measure the range of protons in copper. The detectors are those described in Sec. 9.2. The range-energy relationship was determined by measuring the $A-B'$ coincidence counts per ten thousand A counts as a function of the thickness of copper between the A and B' detectors. As the thickness increased, the counts decreased, as shown in Fig. 9.7.6. The thickness of copper required to stop the incident protons is defined as the point of maximum slope, the peak of the

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Fig. 9.7.5. Block Diagram of Circuit Used in Range-Energy Measurements.

differential curve, which corresponds to a count rate approximately one-half that for a zero thickness of copper. In two runs the thickness of copper required to stop the beam was measured to be $(26.34 \pm 0.14) \text{ g/cm}^2$, corresponding to a

Fig. 9.7.6. Coincidence (A-B') Counts as a Function of Copper Absorber Thickness.

beam energy of 160.9 Mev. C. F. Johnson,⁴ using a similar technique, obtained a value of 160.5 Mev during the experiments of Sec. 9.5. The error associated with the measurement arises from the uncertainties in the measurements of copper thickness ($\pm 0.1\%$), the areal density ($\pm 0.5\%$) based on the theoretical density of copper, and the conversion from areal density to energy. The conversion was made from the range-energy tables of Rich and Madey,⁵ who quote errors of a few percent, depending on the energy range.

The determination of beam energy by proton flight-time measurement used the circuit shown in Fig. 9.7.7. The energy is given by

$$E = M_0 c^2 [1 - (v/c)^2]^{-1/2},$$

⁴Private communication.

⁵M. Rich and R. Madey, *Range-Energy Tables*, UCRL-2301 (Mar. 1954).

Fig. 9.7.7. Block Diagram of Arrangement for Proton Time-of-Flight Measurements.

where v , the velocity, was measured as 15.26 cm/nsec. Taking into account the loss in beam energy in travelling between the detectors, the beam energy was measured to be $154.4 \text{ Mev} \pm 2\%$. This value is 4.1% lower than that obtained by the range-energy technique. The error includes

uncertainties in the measurement of delay times and errors in the range-energy values used to account for the degraded fraction of the beam. A more detailed examination of these results is in progress.

9.8. MEASUREMENTS OF THE INTENSITY OF THE PROTON BEAM OF THE HARVARD UNIVERSITY SYNCHROCYCLOTRON FOR ENERGY-SPECTRAL MEASUREMENTS OF NUCLEAR SECONDARIES¹

R. T. Santoro and R. W. Peelle

For the various experimental measurements of the spectra of secondaries resulting from the interactions of high-energy protons with nuclei described in other sections of this report, it was necessary to measure the intensity of the 160-Mev proton beam from the Harvard University synchrocyclotron over a range of from 10^5 to 10^{10} protons/sec. It was further required that the beam be monitored continuously during thick-target experiments with a minimum of attenuation in energy and intensity. These requirements made an ionization chamber the most obvious choice for the monitor.

After comparing the relative performances of ionization chambers filled with air, nitrogen, and helium,² it was decided to construct two helium-filled parallel-plate ionization chambers³ by the design shown in Fig. 9.8.1. Each chamber consists of five 1-mg/cm²-thick aluminum-on-Mylar electrodes equally spaced over 2.54 cm, which, together with the 2-mil-thick aluminum windows shown in the figure, reduce the beam energy by 135 kev. The chambers are filled with helium to a pressure of 73 cm Hg at 23°C. With a 300-v

Fig. 9.8.1. Cross Section of Parallel-Plate Ionization Chamber.

¹A detailed version of this paper is to be published as an ORNL report.

²R. T. Santoro et al., *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p. 277.

³The chambers, built by R. K. Abele and Taylor Clay, both of the Instrumentation and Controls Division, are detailed on ORNL-Dwg. Q 2540.

potential between the electrodes, 98% saturation was achieved in a beam of (nominally) 10^{10} protons/sec.

Since ionization chambers measure only relative beam intensity, it was necessary to calibrate them against an absolute beam monitor. Two independent calibrations were made, the first against a measurement of the beam intensity with a Faraday cup and the second against the results of direct counting of protons in the beam by fast counting techniques.

The Faraday cup is shown in Fig. 9.8.2. It consists of a 6-in.-diam, 8-in.-long copper cylinder having a 4-in.-diam, 6-in.-long re-entrant opening into which the proton beam is directed. The base of the cup is 45.21 g/cm^2 in thickness, which is sufficient to stop completely a 160-Mev proton beam. The cup is insulated from its brass housing by Teflon mounting rings. A grid mounted behind the 5-mil aluminum window and a guard cylinder in front of the cup serve as secondary electron suppressors.

A Faraday cup determines the beam intensity by collecting the charge deposited on it by the incident protons, and its accuracy depends on the

fraction of charged particles which scatter into or out of the cup. The errors due to various events occurring within the cup have been computed¹ and are summarized as follows:

Delta-ray formation in the cup:	-0.7%
Electrons scattered out of the aluminum window:	+1.8%
Compton electrons produced in the cup:	-0.06%
Other effects, such as loss of current by ionization in housing (estimated):	+0.5%
Net error in the current measurement	+1.54%

The polarity sign attached to the values above indicates the direction in which the measured current is in error, i.e., the positive net error indicates that the measured current is too high.

It was observed (Fig. 9.8.3) that the apparent calibration of the ion chambers was changed by 8% by a change of 200 v in the potential of the guard cylinder. Calculations showed, however, that only 16% of the protons incident on the cup

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Fig. 9.8.2. Cross Section of Faraday Cup Assembly.

Fig. 9.8.3. The Effects of Variations of Guard Ring and Grid Voltage on the Apparent Calibration of the Ionization Chamber.

could react to form "escapable" electrons provided that the typical proton reaction occurred in the initial 150 mg/cm^2 of copper. The product of this fraction multiplied by the solid angle subtended by the mouth of the cup gave an error of only 0.7% that was possible from such "delta-ray" escapes. The 8% variation is therefore assumed to be related to electron showers arising from the initial electrons produced in the copper.⁴

The Faraday cup was operated in a vacuum of 10^{-4} mm Hg (nominal). At this pressure the error in the measured current due to ionization in the residual gas is only 0.05% and thus is negligible.

The charge collected by the Faraday cup was measured with a vibrating-reed electrometer of the type described by Fairstein.⁵ A block diagram of the calibration circuit is shown in Fig. 9.8.4. The electrometer output was fed to a system which electrically integrated the fluctuating signal from the electrometer and transformed it to a count rate proportional to the time-averaged current measured.

The vibrating-reed electrometer was calibrated against a standard current source by measuring the values of its input resistors, nominally 10^{10} , 10^{11} , and 10^{12} ohms. The measured values, obtained by comparing the measured current to the standard current input, were:

$$R_{10} = (1.00 \pm 1\%) \times 10^{10} \text{ ohms}$$

$$R_{11} = (7.50 \pm 1\%) \times 10^{10} \text{ ohms}$$

$$R_{12} = (8.60 \pm 3\%) \times 10^{11} \text{ ohms}$$

For the first two measurements, a standard source delivering $(1.34 \pm 1\%) \times 10^{-10}$ amp was used; for the third a 3% accurate source had to be used because the output of the 1% accurate source was too high. In practice, measurements with R_{12} were limited to the lowest decade of beam intensity, and constituted less than 20% of all measurements.

The current from the ionization chambers was measured with low-range direct-current integrators.⁶ These instruments, which integrate the input current by producing a pulse rate output proportional to the input current, were calibrated against the 1%-accurate standard current source mentioned above to give an integration rate of $(0.20 \pm 1\%) \times 10^{-9}$ coulomb per-integrator count.

The calibration of the ion chambers in terms of ion pairs per proton, IP , was determined from

$$IP = Q_{IC}/Q_{FC},$$

where Q_{IC} is the ion chamber current and Q_{FC} is the current collected by the Faraday cup, provided that Q_{IC} and Q_{FC} were measured at the same beam intensity and for the same collection time. A typical response curve is shown in Fig. 9.8.5. With IP determined, the beam intensity, in protons/sec, could be calculated directly from the integrator counting rate.

A calibration of the ionization chambers by the Faraday cup method described above was made prior to each of the four spectral measurement runs. The results, summarized in Table 9.8.1,

⁴A. A. Schultz and M. A. Pomerantz, *Phys. Rev.* 130, 2135 (1963).

⁵E. Fairstein, *Nuclear Instruments and Their Uses*, vol I (ed. by A. H. Snell), Wiley, New York, 1962.

⁶Designed by F. M. Glass, Instrumentation and Controls Division; identified by ORNL Dwg. No. Q 2525-2.

Fig. 9.8.4. Block Diagram of Calibration Circuit.

Fig. 9.8.5. Typical Ionization Chamber Calibration Curves.

show that from runs 1 to 4 the values for ion pairs per proton changed by +6.8% for ion chamber No. 1 and +5.7% for ion chamber No. 2. Measurements made prior to runs 1 and 4 using a Sr^{90} source in fixed geometry relative to the chambers showed a like variation. The cause is believed

to be contamination of the helium by inward leakage of air. As the helium becomes diluted, the value of W , the average energy required for production of an ion pair in the gas, decreases. For pure helium W is given as 42.7 ev per ion pair, while for air it is only 35.5 ev per ion pair.⁷

A description of the second calibration method, in which the protons responsible for the collection of a measured charge in the ionization chambers were counted directly, is given in Sec. 9.2 and in ref. 1. The measurements were performed following the completion of run No. 4, and resulted in ion pair per proton values of $87.5 \pm 2.1\%$ for chamber No. 1 (5.3% higher than for run No. 4) and $81.4 \pm 4.3\%$ for chamber No. 2 (4.6% higher than in run No. 4). The consistently higher results suggest that systematic differences exist between the Faraday cup and proton-counting data.

⁷R. D. Evans, *The Atomic Nucleus*, McGraw-Hill, New York, 1955.

Marshall *et al.*⁸ have reported beam measurements accurate to $\pm 7\%$ using counting techniques. Koehler⁹ has measured the intensity of the Harvard University synchrocyclotron beam to within $\pm 9\%$ using a Faraday cup. Confirmation of the ion chamber calibrations to $\pm 5\%$ is more than adequate

for the experiments performed, all of which contain other uncertainties at the 5% level.

⁸J. Marshall *et al.*, *Phys. Rev.* **92**, 834 (1955).

⁹A. M. Koehler, Harvard University, private communication.

Table 9.8.1. Results of Ionization Chamber Calibrations Prior to Spectral Measurements

Run No.	Ion Pairs/Proton		Range of Beam Intensity (protons/sec)	Spectrometer Experiment
	Ion Chamber No. 1	Ion Chamber No. 2		
1	$77.8 \pm 0.4\%$	$73.61 \pm 1.4\%$	$9 \times 10^6 - 9 \times 10^9$	Dosimetry (Sec. 9.3), neutron spectra with Bonner spheres and threshold detectors
2	$77.2 \pm 0.6\%$	$73.0 \pm 1.5\%$	$2 \times 10^6 - 2 \times 10^9$	Gamma-ray spectra (Sec. 9.1)
3	$84.7 \pm 1.4\%$	$75.7 \pm 1.75\%$	$5 \times 10^5 - 5 \times 10^8$	Neutron and proton spectra with proton-recoil telescopes (Sec. 9.5)
4	$83.1 \pm 1.6\%$	$77.8 \pm 2.1\%$	$2 \times 10^5 - 2 \times 10^8$	Neutron and proton spectra by flight-time spectroscopy (Sec. 9.2)

9.9. PREPARATIONS AT ORIC FOR CONTINUED MEASUREMENTS OF ENERGY SPECTRA OF NUCLEAR SECONDARIES

R. T. Santoro

The experimental space shielding program will be continued at the Oak Ridge Isochronous Cyclotron (ORIC) where an ~ 75 -Mev proton beam will be available. Construction of the cyclotron¹ and the associated physical plant has been completed, but the full-energy external proton beam has not yet been successfully obtained. Installation of the ion optics system is also incomplete. It is anticipated that the accelerator will be in operation in January 1964.

The shielding studies are scheduled to be performed at ORIC experimental position No. 3 (Fig. 9.9.1), and work to modify the existing experi-

mental equipment for use with this accelerator is under way. The target-detector holder² has been modified for use with the 48-in.-high beam exit tubes. Semipermanent instrument racks have been installed in the counting room, as shown in Fig. 9.9.1, and underground cables have been laid to the target-detector holder located at position No. 3. The beam exit tube in the experiment

¹R. S. Livingston and F. T. Howard, *Nucl. Instr. Methods* **6**, (1) (1960).

²R. T. Santoro *et al.*, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p. 273.

room has been designed for use with the beam monitor ionization chambers described in Sec. 9.8. Measurements similar to those described in Sec. 9.7 will be made of the time, space, and energy distributions of the beam.

The first space shielding experiment to be performed at ORIC will be for the measurement of secondary gamma rays produced by the interaction of high-energy protons with nuclei. The

gamma-ray spectrometer (Sec. 9.1) has already been installed in order to permit calibration and alignment of the spectrometer components. A positioning device for the 2-ton instrument is being designed, along with a special evacuated target holder to be used with low-energy proton beams. The positioning device will permit rotation of the spectrometer about the target at a fixed distance from the target.

Fig. 9.9.1. Partial Floor Plan of the Oak Ridge Isochronous Cyclotron.

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10. Radiation Detector Studies (II)

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10.1. PROTON-RECOIL SPECTROMETERS FOR MEASURING NEUTRON AND PROTON ENERGY SPECTRA FROM 10 TO 450 Mev

W. A. Gibson, W. R. Burrus, J. W. Wachter, and
C. F. Johnson¹

Introduction

The design and construction of two proton-recoil spectrometers, covering the energy ranges from 10 to 50 Mev and 50 to 450 Mev, respectively, have been reported previously.² Work on these instruments has continued. Problems have been encountered during tests of both spectrometers when exposed to the flux of secondary particles from a target bombarded by 450-Mev protons, but the 50- to 450-Mev spectrometer appeared to perform as intended when exposed to secondaries from a target bombarded by 160-Mev protons.

The results of measurements with the 160-Mev proton beam of the Harvard University synchrocyclotron with a variety of targets are presented elsewhere in this report (see Sec. 9.5). The present paper discusses the difficulties encountered in the development of each spectrometer.

10- to 50-Mev Spectrometer

The 10- to 50-Mev spectrometer consists essentially of a proton radiator, followed by two coincidence detectors and a total-absorption NaI(Tl) scintillation crystal.³ A thin CsI crystal preceding the radiator and operated in anticoincidence with the other three detectors serves to reject pulses due to protons in the incident flux.

The response of the energy detector, the NaI(Tl) crystal, shows an ambiguity stemming from the fact that a high-energy proton which completely passes through the crystal may lose the same amount of energy as a lower-energy proton which is stopped within the detector. It had been planned to remove this ambiguity by making background measurements with a 55-Mev-thick "NaI-equivalent" absorber preceding the detector and performing a suitable subtraction. It was found, however, that either with or without the absorber the background amounted to 60 to 80% of the total counts when the spectrometer was exposed to secondaries from a target bombarded by 160- or 450-Mev protons. Several methods of reducing the background were tried. Since the radiator is necessarily thin, the efficiency of the spectrometer is low, and counts from protons originating in regions other than the radiator create seriously high backgrounds. Thus the first attempt at reducing background was to minimize the mass of the walls of the proportional counters, in order to decrease the background from n, p reactions in the counter walls. Tests showed, however, that a factor-of-3 decrease in the mass of the proportional counter walls had no significant effect on the background.

A second attempt to reduce background was the replacement of the proportional counters by 10-mil-thick glass scintillators, so that possible large random counts resulting from the long resolving times ($\sim 1 \mu\text{sec}$) required by the proportional counters could be reduced. Again tests showed that no significant reduction in the count rate occurred, even though the resolving time of the counters was reduced by a factor of 10.

Finally, in order to further reduce the ambiguity between penetrating and nonpenetrating protons, an organic scintillator was added to the back of the

¹On assignment from General Dynamics, Fort Worth.

²W. A. Gibson, W. R. Burrus, and C. F. Johnson, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 281.

³The authors wish to acknowledge the contribution of N. W. Hill, Instrumentation and Controls Division, to the design and construction of the coincidence circuit.

NaI(Tl) crystal, making a so-called "phoswich."⁴ Protons which stopped in the NaI(Tl) crystal produced a different pulse shape than those which passed through the NaI(Tl) crystal into the organic scintillator. Thus, by electronically sampling the pulse shape, high-energy protons could be rejected. Again, however, no significant decrease of the background was observed.

The tests led to the conclusion that the large background is due to protons resulting from neutron interactions in the sensitive portions of the counters and in the carbon of the radiator. Apparently the background can be reduced only by reducing the masses of the sensitive portions of the counters and by using a radiator with a higher hydrogen-to-carbon ratio. Since other techniques are available for obtaining neutron spectra between 10 and 50 Mev (for example, time-of-flight methods), no further attempts to overcome the background problems are planned.

Although the neutron interaction problems noted have prevented the successful use of this instrument for neutron spectroscopy, it was operated successfully (without radiator and anticoincidence crystal) at Harvard in the measurement of proton spectra between 10 and 50 Mev. The results are shown in Sec. 9.5.

50- to 450-Mev Proton-Recoil Spectrometer Used for 50- to 160-Mev Range

The proton-recoil spectrometer intended for measurements of neutron and proton spectra in the energy range 50 to 160 Mev consists of a hydrogenous radiator followed by two thin organic scintillators, which define the recoil protons and reduce random counts, and a thin NaI(Tl) crystal, which operates as a dE/dx detector to determine the energy. An organic scintillator placed before the radiator and operated in anticoincidence with the other three crystals discriminates against protons in the incident flux. The ambiguity between protons which stop in the detector and those which pass through it (see above) was eliminated by discrimination made possible by the fact that the particles which are low enough in energy to be stopped have the larger dE/dx and thus deposit a larger amount

of energy in the organic scintillator just preceding the dE/dx detector. A signal from this scintillator is placed in anticoincidence with the other signals, and the bias is adjusted so as to reject protons which produce large pulses in the last organic scintillator.

Results obtained with this spectrometer are given in Sec. 9.5, and calculations of its efficiency and resolution are presented in Sec. 10.3.

50- to 450-Mev Proton-Recoil Spectrometer Used in 50- to 450-Mev Range

In addition to the 160-Mev measurements at Harvard, the 50- to 450-Mev spectrometer was tested at the cyclotron of the University of Chicago with secondaries resulting from targets bombarded with 450-Mev protons. Additional tests were made with the thickness of the organic scintillators doubled so that the pulse heights for 450-Mev protons would be the same as those obtained with the original scintillators for 160-Mev protons. Since the resolution of the counters is governed almost entirely by the Landau effect,⁵ the thickness of the NaI(Tl) dE/dx counter was also increased, from 1.473 to 4.670 g/cm², which improved the resolution for 450-Mev protons from 27 to 20%, a value similar to that obtained with the thinner crystal for 160-Mev protons. The improved resolution from the thicker organic scintillators also resulted in improved operation of the discriminator in rejecting low-energy protons.

A high flux of gamma rays (probably resulting from the decay of neutral pions) with energies above 10 Mev was present in the region of the spectrometer. The gamma rays interacted in the radiator and detectors to produce high-energy electrons which passed through the detectors and produced pulses indistinguishable from proton pulses. This gamma-ray background could not be subtracted out by substitution of a carbon radiator, both because of its magnitude and because the overall background increased when the hydrogenous radiator was in place. A Cerenkov detector which will have a proton threshold of 450 Mev (and an electron threshold of 0.24 Mev) is being constructed. This detector will be placed

⁴D. H. Wilkinson, *Rev. Sci. Instr.* 23, 414 (1952).

⁵L. Landau, *J. Phys. USSR* 8, 201 (1944).

in anticoincidence with the three detectors comprising the spectrometer to afford rejection of gamma-ray-induced pulses.

The resolution of the dE/dx detector has been calculated from the theory of Landau and Symon.^{5,6} Figure 10.1.1 is a comparison of the results of this calculation with the experimental pulse-height spectra obtained by exposing NaI(Tl) detectors to direct beams of protons with energies

of 445 and 157 Mev. Since the energy spread of the beam is small, the difference between the calculated and experimental resolutions is attributable to photon and photoelectron statistics in the crystal and photomultiplier. The displacement between the calculated and experimental curves is not experimentally relevant, but reflects differences in the results obtained from the Landau and Bethe-Block theories of energy loss.

Further tests and spectral measurements are planned at the University of Chicago, and a detailed description of the spectrometer is in preparation.

⁶K. R. Symon, *Fluctuations in Energy Lost by High-Energy Charged Particles in Passing Through Matter*, Ph.D. Thesis, Harvard University, 1948.

Fig. 10.1.1. Energy Deposited by Protons Incident on NaI(Tl).

10.2. DETERMINATION OF COINCIDENCE-CIRCUIT EFFICIENCY BY VARYING THE INPUT SIGNAL DELAY¹

R. W. Peelle

Whenever an absolute coincidence rate is required in an experiment, the coincidence efficiency must be measured or proved to be unity. The purpose of the paper summarized here is to elucidate simple methods for the evaluation of twofold coincidence efficiency which have been useful to the author. Attention is confined to interpretation of delayed coincidence curves for which backgrounds and pulse pileup effects can be neglected. The resolving time of the circuit is assumed to be fixed and known from pulser or random coincidence studies.

Normally there is a marked distribution of time intervals between an event and the timing signal which reaches the coincidence circuit, and coincidence efficiency becomes less than unity whenever the breadth of this jitter distribution becomes comparable to the resolving time. Each counter has its jitter distribution arising from noise, statistical effects, and pulse-height dependencies, but, since only time differences are important to the circuit, the folded or combined jitter distribution is the important one. In terms of the normalized combined jitter distribution J the expression for the delayed coincidence curve becomes

$$C_{\tau}(T) = A H_{\tau}(T) = \int_{T-\tau}^{T+\tau} A J(t) dt, \quad (1)$$

where

A = mean rate of occurrence of simultaneous events;

τ = coincidence resolving time, or the mean of times τ_1 and τ_2 if different times are associated with the two channels;

T = mean difference between the event-to-signal time delays for the two information channels linking event detectors to the coincidence circuit; if $\tau_1 \neq \tau_2$, the zero of T is displaced so that maximum efficiency occurs for the delay setting $T = 0$;

$C_{\tau}(T)$ = observed mean coincidence rate for time difference T using resolving time τ ; random rates and backgrounds have been removed;

$H_{\tau}(T)$ = coincidence rate per simultaneous event of a desired class; thus $H(0)$ is the coincidence efficiency for the optimum electrical delay;

$J(t)$ = unit normalized distribution of time intervals t for a given system and source of events, where t is the difference between signal arrival times for a given pair of simultaneous events.

Examination of Eq. (1) shows that if the spread of J is large compared with τ , $H(T)$ will have the same shape as J , while in the limit of small spread H becomes a rectangle of unit height and width 2τ .

Equation (1) suggests that if A were known the efficiency could be determined from the largest value of $C_{\tau}(T)$ observed. The normalization of J implies that A is just the sum of the C 's observed at any series of points separated by 2τ , and if the efficiency is near unity only three to five such points contribute. The method based on these arguments is valid independent of the shape of the distribution J , but requires that delays as long as 2τ be introduced without serious signal distortion. Random backgrounds and the presence of true delayed components in the source can confuse interpretation of data by this method.

If a specific form can be assumed or demonstrated for the combined jitter distribution, the formula for $H(T)$ can be written in terms of the ratio of resolving time to breadth of the jitter. The regions of the curve near half the maximum $C(T)$ contain the information to determine the efficiency. If a normal combined jitter distribution with standard deviation s is assumed, the specific coincidence curve can be computed in terms of a difference of tabulated error integrals. This leads to characterization of a delay curve by the parameter F , where

$$F(\tau/s) \cong [\tau/C_{\tau}(0)] \left. \frac{dC_{\tau}(T)}{dT} \right|_{T=\pm\tau} = \frac{\tau[1 - \exp(-2\tau/s)]}{s\sqrt{2\pi}H_{\tau}(0)}. \quad (2)$$

¹Summarized from paper to be submitted to *Nuclear Instruments and Methods*.

The right side of Eq. (2) is a function of only τ/s , and the left side can be estimated by inspection of the experimental delay curve C and knowledge of the resolving time. Thus tabulation of the quantities involved can give by interpolation the

desired coincidence efficiency or the standard deviations of the jitter distribution.

Figure 10.2.1 gives values of τ/s as a function of $F(\tau/s)$, which are useful to determine whether sets of data obtained with different values of τ

Fig. 10.2.1. The Relative Jitter Parameter τ/s as a Function of the Delay Curve Parameter $F(\tau/s)$. Since τ is assumed to be known, this curve may be employed to estimate the standard deviation s of the combined jitter distribution from the slopes of the observed delayed coincidence curve $C_{\tau}(T)$ at $T = \pm\tau$. These values assume a normal jitter distribution.

correspond, as is expected, to the same underlying jitter distribution. Figure 10.2.2 gives the difference between the coincidence efficiency and unity as a function of the relative jitter parameter τ/s . This coincidence efficiency refers to that observed from optimum delay setting $T=0$. Figure 10.2.3 shows two of the delay curves obtained when coincident events of a fission chamber and a nearby scintillation detector² were observed and indicates the values

obtained from Fig. 10.2.1 and 10.2.2. Crossover pickoff timing circuits³ were employed, so that jitter distributions for limited height ranges might be expected to be nearly normal.

²T. A. Love, F. C. Maienschein, and R. W. Peelle, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1959*, ORNL-2842, p 93.

³R. W. Peelle and T. A. Love, *Appl. Nuclear Phys. Ann. Progr. Rept. Sept. 1, 1957*, ORNL-2389, p 249.

Fig. 10.2.2. Coincidence Efficiency as a Function of Relative Jitter. The difference between the efficiency and unity is plotted as a function of τ/s , where τ is the resolving time and s the standard deviation of the combined jitter distribution, which is assumed to be normal.

Fig. 10.2.3. Two Examples of Delay Curve Shape Analysis. These curves were obtained for different pulse-height regions of a scintillator output in coincidence with a fission chamber. Curve A was obtained using a 13% range of pulse heights at an energy loss of 25 kev, and curve B obtained using a 22% range at 85 kev. Sample computations indicate the shape parameter F , the jitter standard deviation s , and the optimum efficiency $H(0)$ for each edge of each curve. While s is poorly determined, only small efficiency uncertainties are implied.

10.3. CALCULATION OF THE EFFICIENCY AND RESOLUTION OF A PROTON RECOIL SPECTROMETER BY MONTE CARLO METHODS

W. E. Kinney and J. W. Wachter

Introduction

A valuable feature of the proton-recoil neutron spectrometer lies in the fact that its absolute efficiency can be calculated from a knowledge of the n,p scattering cross section, the dimensions of the proton radiator, and the geometry of the experimental arrangement. For thin radiators, the n,p scattering events can be considered as occurring at one face of the radiator rather than throughout its volume. Using numerical integration methods, Bame *et al.*¹ computed effi-

ciencies for thin-radiator telescopes for neutron energies of <30 Mev. Similar methods have been applied² to calculations of the resolution function, that is, the distribution in pulse height of the pulses from the detector resulting from monoenergetic neutrons incident on the radiator.

¹S. J. Bame *et al.*, *Rev. Sci. Instr.* **28**, 997 (1957).

²C. H. Johnson, p 256 in *Fast Neutron Physics*, J. B. Marion and J. L. Fowler, eds., Interscience, New York, 1960.

At higher energies, however, thick radiators are required for optimum balancing of efficiency and resolution, and neutron penetration of the radiator affects the geometry. When the incident-neutron energy is sufficiently high that the protons are not stopped within the scintillation detector, statistical fluctuations in the energy lost by protons as they pass through the scintillator (the Landau effect) cause an additional loss of resolution in the energy spectrum.

In view of the complexities and uncertainties inherent in an analytic or numeric approach to the analysis of thick-radiator telescopes, Monte Carlo methods have been employed to evaluate the efficiency and resolution functions for a recoil telescope operating in the high-energy neutron range.³ The computation allows radiators of arbitrary thicknesses, permits the consideration of distributed sources having isotropic, cosine, or other flux distributions, and takes account of energy losses in intervening counters or other materials.

The method has been used to calculate the efficiency of the proton recoil telescope described in Sec. 10.1, both to estimate experimental uncertainties and to prepare the experimental results for further analysis by unfolding techniques.

Method

The sequence of events in the neutron telescope is shown schematically in Fig. 10.3.1. A neutron is born in the source plane at $(x_0, y_0, 0)$ and collides with a proton in the radiator at (x_1, y_1, z_1) . The proton scatters, traverses the remainder of the radiator and the intervening detectors, and strikes the face of the dE/dx counter at (x_2, y_2, z_2) . The probability of this path is

$$p(x_0, y_0, E_0, x_1, y_1, z_1, x_2, y_2, z_2) dx_0 dy_0 dE_0 dx_1 dy_1 dz_1 dx_2 dy_2$$

$$= P(x_0, y_0, E_0, \bar{\Omega}_1) dx_0 dy_0 dE_0 \frac{\mu_1 dx_2 dy_2}{r_1^2}$$

$$\times \exp \left[-\Sigma_n(E_0) \frac{(z_1 - z_R)}{\mu_1} \right] \Sigma_{n,p}(E_0) \frac{dz_1}{\mu_1} P(\bar{\Omega}_2) \frac{\mu_2 dx_2 dy_2}{r_2^2} \times \exp \left[-\Sigma_p(E_p) \left(\frac{z_R + T - z_1}{\mu_2} \right) \right],$$

where

$P(x_0, y_0, E_0, \bar{\Omega}_1)$ = probability, per unit area per unit energy per unit solid angle, for a neutron being emitted from the source plane at dx_0 about x_0 and dy_0 about y_0 , with energy in dE_0 about E_0 and direction into $d\bar{\Omega}_1$ about $\bar{\Omega}_1$,

$P(\bar{\Omega}_2)$ = probability, per unit solid angle, that a proton recoils into $d\bar{\Omega}_2$ about $\bar{\Omega}_2$ in an n,p scattering event,

$\Sigma_n(E_0)$ = neutron macroscopic total cross section at energy E_0 ,

$\Sigma_{n,p}(E_0)$ = macroscopic n,p scattering cross section at energy E_0 ,

³The problem was suggested by C. F. Johnson, who assisted in its initial formulation. We are indebted to R. R. Coveyou for many suggestions and discussions concerning the Monte Carlo procedures.

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Fig. 10.3.1. Geometry of Monte Carlo Efficiency Calculation.

$\Sigma_p(E_p)$ = proton macroscopic total cross section at energy E_p ,

E_p = proton recoil energy,

z_R = z coordinate of the front face of the counter,

T = thickness of the radiator.

Proton nuclear interactions in the intervening detectors are neglected, and, with little error, the exponentials may be set equal to unity to give

$$p(x_0, y_0, E_0, x_1, y_1, z_1, x_2, y_2, z_2) \\ = P(x_0, y_0, E_0, \bar{\Omega}_1) P(\bar{\Omega}_2) \left[\frac{\Sigma_{n,p}(E_0) \mu_2}{r_1^2 r_2^2} \right].$$

The efficiency is the integral of p :

$$\epsilon = \int \dots \int p dx_0 dy_0 dx_1 dy_1 dz_1 dx_2 dy_2.$$

Protons, even those resulting from monoenergetic neutrons striking the radiator, arrive at the face of the dE/dx counter distributed in energy, because of the variation (1) of the recoil proton energy with angle of scattering and (2) in the ionization energy loss due to variations in the distance traveled by the proton in the radiator, the intervening detectors, and the air. Every path through the telescope is thus related to a unique value of energy. This factor permits the calculation of the energy resolution at the face of the dE/dx counter by sorting the path energies into energy intervals as indicated symbolically by

$$\overline{p_i(E)} \Delta E_i = \left\{ \int_{\text{appropriate ranges}} p(x_0, y_0, E_0, x_1, y_1, z_1, x_2, y_2, z_2) dx_0 dy_0 dE_0 dx_1 dy_1 dz_1 dx_2 dy_2 \right\} \Delta E_i,$$

where

$\overline{p_i(E)}$ = average probability, per unit energy, that a proton arriving at the face of the dE/dx counter has an energy falling in the i th energy interval,

ΔE_i = width of the i th energy interval.

Appropriate ranges cannot be defined but are such as to put the proton into the energy intervals. Any function of the energy may be averaged in this fashion.

The integral is solved by Monte Carlo methods, by regarding the integrand as a quantity whose expectation value is to be estimated. The value of the integral is then given by

$$\int \dots \int p dx_0 \dots dy_2 = \langle p \rangle \int \dots \int dx_0 \dots dy_2.$$

The estimation of the expectation value of the integrand proceeds by a random selection of both a point within the radiator and a point on the surface of the dE/dx counter. A source subroutine is then consulted to provide a point on the source plane selected from the desired source distribution. The required probabilities are then readily computed, the n, p differential cross sections being those used by Bertini.⁴ The energy of the proton arriving at the face of the dE/dx counter is computed by using range-energy tables constructed according to the Bethe-Block formula.⁵ This energy and the path length through the dE/dx counter are supplied to a subroutine which computes the magnitude of the light output number from the scintillation crystal. The computed probability is then stored in the appropriate channel counter, and another trial is made, the process being repeated until the desired number of paths has been traced.

The light output from the scintillator, L , can be obtained by integrating the value of dL/dE for protons traversing the detector material. In the proton energy range considered here, however, no data were available except those empirically obtained by differentiation of the experimentally

determined calibration curve of an actual telescope (see Sec. 10.1). Therefore the value of the light output for a proton path equal to the thickness of the crystal was taken from the calibration curve and extrapolated to values for longer path lengths by using the empirically obtained dL/dx . The light output was thus expressed directly in terms

⁴H. W. Bertini, *Monte Carlo Calculations on Intranuclear Cascades*, ORNL-3383 (Apr. 23, 1963).

⁵H. A. Bethe, *Z. Physik* **76**, 293 (1938).

of the channel number of the multichannel pulse-height analyzer.

Test Calculations

In order to provide a test of the method, the Monte Carlo code was used to calculate the efficiency of an infinitely thin radiator. A second calculation, considering the same parameters, was made with conventional numerical techniques. The geometry of both calculations is shown in Fig. 10.3.2. A comparison of the results as well as a comparison with data given by Johnson² is shown in Table 10.3.1. The quantity tabulated is $\epsilon/P\sigma$, the efficiency divided by the product of the number of hydrogen nuclei per square centimeter and the neutron cross section.

A test calculation of a practical problem was also made. A monoenergetic 50-Mev neutron source with a point isotropic distribution was assumed to be located 35 cm from the face of the telescope radiator. The telescope radius was 2.06 cm, with a radiator thickness of 0.532 cm. The dE/dx counter had a thickness of 0.399 cm, and its front surface was 13.22 cm from the front surface of the radiator. The intervening detectors were assumed to consist of a total thickness of 0.15875 cm of an organic, with the formula CH, and 2.54×10^{-3} cm of aluminum. The compositions, nuclear densities,

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Fig. 10.3.2. Parameters Used in Comparison of Monte Carlo with Numerical Integration Efficiency Calculations.

Table 10.3.1. Comparison of Monte Carlo and Numerically Calculated Efficiencies with Data Given by Johnson^a

Energy (Mev)	$\epsilon/P\sigma$		
	Monte Carlo	Numerical	Johnson
	($\times 10^{-3}$)	($\times 10^{-3}$)	($\times 10^{-3}$)
20	2.54 ± 0.02	2.57	2.56
30	2.54 ± 0.02	2.55	2.54

^aC. H. Johnson, p 256 in *Fast Neutron Physics*, J. B. Marion and J. L. Fowler, eds., Interscience, New York, 1960.

and mean excitation potentials of the telescope materials are given Table 10.3.2.

The results of the Monte Carlo calculation are shown in Figs. 10.3.3 and 10.3.4. Figure 10.3.3 shows the resolution function as a function of energy, with and without the energy variation due to the angle of scattering of the proton. The smearing resulting from this effect is evident. The resolution function is plotted vs channel number in Fig. 10.3.4. The results represent 5000 trials, which required 4 min of IBM-7090 computer time.

Conclusions

The solution of the integral describing the telescope efficiency by Monte Carlo techniques agrees within statistical error with that obtained by conventional numerical integration methods for equivalent expenditures of computer time. It is emphasized that, although not often quoted with results, the numerical methods must inherently contain errors, due to the nature of the integration process. These errors may be of equivalent magnitude to the Monte Carlo statistical errors.

The Monte Carlo calculation additionally gives the appropriate energy resolution functions evaluated at the surface of the detector and also at the output of the dE/dx counter. The single calculation thus provides a means of calibrating

the telescope for absolute differential cross-section measurements while also determining the resolution functions which can be applied to the measured data to enable the use of unfolding techniques.

As seen in the figures, the spread or smearing of the energy resolution may be further separated, in successive calculations, to that part resulting from proton energy degradation in the radiator and that resulting from kinematic effects.

Table 10.3.2. Composition, Nuclear Density, and Mean Excitation Potential of Telescope Materials

Element	Nuclear Density (atoms/cm ³) × 10 ⁻²⁴	Mean Excitation Potential (ev)
Radiator		
H	7.96 (-2) ^a	17.5
C	3.98 (-2)	74.44
Intervening Detectors		
Al	6.02 (-2)	150
H	4.91 (-2)	17.5
C	4.91 (-2)	74.44
Intervening Air Gaps		
O	2.26 (-5)	99
N	8.50 (-5)	86

^aDigit in parentheses denotes power-of-ten multiplier: 7.96 (-2) ≡ 7.96 × 10⁻².

Fig. 10.3.3. Resolution Function of Proton Recoil Telescope as a Function of Energy.

Fig. 10.3.4. Resolution Function as a Function of Channel Number.

10.4. SOME RECENT APPLICATIONS OF THE SLOP CODE FOR UNFOLDING INSTRUMENT RESPONSE

W. R. Burrus

Introduction

The SLOP code for unfolding a set of instrument readings, each typically a pulse-height distribution stored by a multichannel analyzer, to obtain a smoothed approximation to the desired gamma-ray or neutron spectrum was described previously,¹ and some early results of the application of the code to experimental data have been published.^{2,3} This paper describes the results obtained by using the code to unfold neutron spectra measured with liquid and plastic scintillators and gamma-ray spectra obtained with an anticoincidence-type multicrystal NaI(Tl) spectrometer. All spectra are shown as confidence bands corresponding to a confidence level of 68%.

Neutron Spectra

An organic liquid scintillator, NE-213, is used by the ORNL Tower Shielding Facility (TSF) for neutron spectroscopy.⁴ Pulse-shape discrimination is employed to reduce the effects of background from gamma rays. For the unfolding of the data obtained with NE-213, it was first necessary to obtain the response function $K_i(E)$ for the spectrometer. This function represents the counting rate in channel i of a multichannel analyzer for a unit-intensity source of energy E and was measured at several energies by using various neutron-producing reactions in a Van de Graaff accelerator. Intermediate-energy values were then obtained by interpolation. The resulting response function for a 2-in.-long, 2-in.-diam NE-213 cylinder, with neutrons incident from the side, is shown as a function of channel number in Fig. 10.4.1 for three energy values. As the figure shows, channels of the multichannel analyzer are combined into bins, with widths proportional to the pulse-

height resolution. Figure 10.4.2 shows $K_i(E)$ as a function of energy for representative bins.

A typical pulse-height distribution⁵ from the NE-213 scintillator exposed to Po-Be neutrons is shown in Fig. 10.4.3. Using this Po-Be pulse-height distribution and the response functions discussed above in the SLOP code yields the unfolded spectrum shown in Fig. 10.4.4. The energy resolution of the spectrum is about 20%. It should be pointed out, however, that the response functions used here may be in error by as much as 30 to 40%, owing to the effects of the pulse-shape discriminator used to reduce the effect of gamma-ray background. The spectrometer has been recalibrated against monoenergetic neutrons having energies as low as 300 keV, which will allow the effect of the pulse-shape discriminator to be taken into account more accurately. The data are still being analyzed.

⁵The data analyzed here were obtained by F. J. Muckenthaler and K. M. Henry.

Fig. 10.4.1. Pulse-Height Distributions for Monoenergetic Neutrons Incident on Side of 2-in.-diam, 2-in.-long Cylindrical NE-213 Liquid Scintillator.

¹V. D. Bogert and W. R. Burrus, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 22.

²W. R. Burrus, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1962*, ORNL-3360, p 19.

³W. R. Burrus, *Trans. Amer. Nucl. Soc.* 6, 173 (1963).

⁴The spectrometer was designed by V. V. Verbinski.

Fig. 10.4.2. Response Functions, $K_i(E)$, for NE-213 as a Function of Energy for Various Pulse-Height Bins.

A scintillator consisting of a 1.5-in.-diam by 1-in.-long cylinder of Pilot B plastic is used at the Massachusetts Institute of Technology in studies of the distribution of neutrons moderated in a small subcritical assembly pulsed with nano-second bursts of neutrons.⁶ Time-of-flight techniques are used to obtain the neutron spectra as a function of time after pulsing and to discriminate against gamma-ray background. A pulse-height distribution obtained by exposing this spectrometer to neutrons from the $\text{Li}^6(p,n)\text{Be}^6$ reaction, using first 2.8-Mev and then 3.1-Mev protons, is shown in Fig. 10.4.5. The spectrum as unfolded by the SLOP code is shown in Fig. 10.4.6. The two neutron peaks, at 1.04 and 1.36 Mev, are clearly distinguished, although the overall uncertainty is large.

Trouble has been encountered, however, in analyzing typical spectra obtained from the pulsed subcritical assembly. It is suspected that the cause may be a beating of the accelerator pulse repetition

⁶The spectrometer was designed by Prof. L. E. Beghian and associates, and the data are due to them.

Fig. 10.4.3. Pulse-Height Distribution for Po-Be Neutrons Incident on NE-213.

Fig. 10.4.4. Po-Be Neutron Spectrum Unfolded by SLOP Code.

Fig. 10.4.5. Pulse-Height Distribution of Neutrons from the $\text{Li}^6(p,n)\text{Be}^6$ Reaction, Using 2.8- and 3.1-Mev Protons, Incident on Pilot B Plastic.

Fig. 10.4.6. Spectrum of Neutrons Resulting from the $\text{Li}^6(p,n)\text{Be}^6$ Reactions, Using 2.8- and 3.1-Mev Protons, Unfolded by SLOP Code.

frequency with the storage dead time of the pulse-height analyzer, which produces significant oscillations in the pulse-height distribution.

Gamma-Ray Spectra

A multicrystal $\text{NaI}(\text{Tl})$ gamma-ray spectrometer chosen for certain measurements in the ORNL space shielding research program was described by Zobel.⁷ The response matrix for this spectrometer was generated analytically by assuming that its shape is given by a Gaussian full-energy peak plus a flat "tail" extending to lower energies. This treatment is within the accuracy of the experimental data.

A pulse-height distribution given by the multicrystal spectrometer for a Y^{88} calibration source is shown in Fig. 10.4.7, and the corresponding gamma-ray spectrum as unfolded by the SLOP code is shown in Fig. 10.4.8. The relation between the pulse-height distribution and the unfolded spectrum is more clearly evident in these

⁷W. Zobel, *Neutron Phys. Div. Ann. Progr. Rept.*, Sept. 1, 1962, ORNL-3360, p 306. The experimental data analyzed are due to Zobel, F. C. Maienschein, and R. J. Scroggs.

figures than in the neutron spectra previously shown because the positions of the peaks are linearly related to the corresponding gamma-ray energy. The energy resolution of the unfolded spectrum is substantially the same as that for the pulse-height distribution, the main difference being that the Compton contamination has been removed and the variation of spectrometer efficiency with energy has been corrected. The two high-energy peaks in the spectrum are due to Y^{88} , while the two low-energy peaks are apparently due to Y^{87} contamination in the source, which decayed out in a few days. The ratios and areas of the Y^{88} peaks reproduce the absolute source strength and the branching ratio information which went into setting up the response matrix.

Discussion

The rotation feature¹ of SLOP has failed to operate reliably because of computational diffi-

culties in obtaining the required eigenvector matrix; therefore, all the results shown above were obtained without using the rotation option of the code.

Owing to an occasional difficulty experienced with the least-squares portion of SLOP, the original least-squares algorithm has been replaced by a more accurate algorithm. Work is continuing on several advanced versions of the SLOP concept and on the related OPTIMO code.² Emphasis is being placed on the production of a trouble-free code written in FORTRAN IV/FORTRAN-63 language, which can be documented and made available for distribution.

In both gamma-ray and neutron calculations, problems of gain and zero shifts are dealt with when setting up the response matrix, rather than by applying corrections to the observed pulse-height distributions.

A typical computing time on the IBM-7090 computer, including input and output, was about 2 or 3 min per case.

Fig. 10.4.7. Pulse-Height Distribution from Y^{88} Gamma Rays Incident on NaI(Tl).

Fig. 10.4.8. Spectrum of Y^{88} Gamma Rays Unfolded by SLOP Code.

10.5. A CALCULATION OF THE PULSE-HEIGHT RESPONSE OF SCINTILLATORS TO HIGH-ENERGY ELECTRONS, POSITRONS, OR PHOTONS

C. D. Zerby and H. S. Moran

As the number of high-energy electron accelerators increases, interest grows in the design of scintillators for use in experiments with high-energy electrons, positrons, and photons. Although some experimental data are now available to help in determining the performance of scintillators, these data are not adequate for general application. For

this reason it was appropriate to modify the existing three-dimensional electron-photon cascade calculation described in Sec. 8.1 so that it would provide a useful research tool for calculating the pulse-height response of scintillation counters of arbitrary design. The modification was recently carried out and the new program now serves as a

versatile high-energy extension of a program previously developed for calculating the pulse-height response of scintillation counters to low-energy radiations.¹

As it is presently constructed, the computer program will consider a cylindrical detector of almost arbitrary composition with a source of positrons, electrons, or photons having energies up to 50 Gev. The source can be an isotropic point on the axis of the detector or a monodirectional source uniformly distributed over a circle which is concentric with the cylinder.

Following the methods of the previous work,¹ the new calculation assumes that the response of the scintillator is unique and proportional to the energy deposited in a given shower initiated by an incident particle. After the calculation is completed under this assumption, the pulse-height spectrum is spread out by a Gaussian broadening. The broadening introduced in this way is meant to include all line-broadening effects such as those introduced by uncertainties in the intensity of light produced in the detector, the transmission of the light to the photomultiplier, and the conversion of the light into an electrical pulse by the photomultiplier. The method used in the broadening calculation is to produce a broadened spectrum, $g(E)$, from the unbroadened spectrum, $k(E)$, by finding the integral

$$g(E) = \int_0^E k(E') F(E, E') dE', \quad (1)$$

where E is the pulse height and

$$F(E, E') = (\pi\sigma^2)^{-1/2} \exp \left[-\frac{1}{2}(E - E')^2 \sigma^{-2} \right]$$

is the Gaussian broadening factor. The term σ is empirically related to the pulse height by

$$\sigma = A\sqrt{E} + BE, \quad (2)$$

where A and B are constants that must be determined for each experimental apparatus. The quantity σ is related to the line width at half maximum, ΔE , by the relation $\Delta E = (8 \log_e 2)^{1/2} \sigma$.

The form of Eq. (2) is well established at low energies,¹ and is verified in one case at high energies in the experiment of Backenstoss *et al.*,² in which it was shown that $\Delta E/E = CE^{-1/2}$, where C is a constant, fits the experimental data very well.

Since the constants A and B in Eq. (2) will depend on the experimental apparatus, the computer program is arranged to print both the broadened and unbroadened pulse-height spectra.

To check the accuracy of the new program, a series of calculations were run for a 3-in.-diam by 3-in.-high NaI detector with an isotropic point source ranging in energy from 0.661 to 7.48 Mev. The results were compared with identical cases run with the old program.¹ In general it was found that for energies up to approximately 3 Mev the results of the two calculations agree extremely well. Above 3 Mev they show slight differences, which could be attributed to the approximations that were used in each case. For instance, the previous calculation neglected charged-particle migration and considered bremsstrahlung as a continuous process as the charged particles slowed down, while the new calculation includes electron migration and considers bremsstrahlung as a discontinuous process. As a result, the new calculation gives a slightly greater peak-to-total ratio at high energies than did the previous calculation: at 7.48 Mev the peak-to-total ratio in the new calculation is 0.085, while in the previous calculation it was 0.073. The shapes of the pulse-height curves are also slightly different in the two cases, because the effect of electron migration in the new calculation tends to increase the response at low pulse heights while the discontinuous bremsstrahlung processes tend to decrease the response at high pulse heights.

The new program has also been applied to one case of 129.4-Mev photons incident on a scintillator using polystyrene as the basic material. This was done to obtain a comparison with the experiment of Bowman, Carroll, and Poirier³ in which a 16-in.-diam by 80-in.-long detector was used to obtain the response from 129.4-Mev photons created by the capture of π^- in the reaction $\pi^- + p \rightarrow \gamma + n$.

¹C. D. Zerby and H. S. Moran, *Neutron Phys. Div. Ann. Progr. Rept. Sept. 1, 1960*, ORNL-3016, p 269; see also C. D. Zerby and H. S. Moran, *Nucl. Instr. Methods* 14, 115-124 (1961).

²G. Backenstoss *et al.*, *Nucl. Instr. Methods* 21, 155-160 (1963).

³W. C. Bowman, J. B. Carroll, and J. A. Poirier, *Rev. Sci. Instr.* 33, 741 (1962).

The photons passed through a 4-in.-diam collimator to reach the detector.

Figure 10.5.1 shows the calculated response before broadening in the high pulse-height region. The calculated peak-to-total ratio is 0.43 and the intrinsic efficiency is 0.95. The calculated response after broadening is compared with the experimental results in Fig. 10.5.2. For the purpose of broadening, the constants used in Eq. (2) were $A = 0.597 \text{ (Mev)}^{1/2}$ and $B = 0$. For the comparison the experimental data were normalized to the calculated data at the maximum of the total absorption peak and shifted slightly in energy

from the way they were originally presented. The experimental data go to zero in the low pulse-height region of Fig. 10.5.2 because of inaccuracies in peeling off the background caused by photons from the decay of π^0 mesons created in the reaction $\pi^- + p \rightarrow \pi^0 + n$.

Although a great deal cannot be concluded about the accuracy of the calculation at high incident energies from the comparison shown in Fig. 10.5.2, there is a striking similarity in the shapes of the two curves which tends to lend some credence to the applicability of the calculation.

Fig. 10.5.1. Calculated Unbroadened Pulse-Height Response of a Plastic Scintillator to 129.4-Mev Photons.

Fig. 10.5.2. Experimental and Calculated Response of a Plastic Scintillator to 129.4-Mev Photons. Calculated data are normalized to a total response of one count. Experimental data are normalized to the calculated data at the maximum of the total absorption peak.

10.6. PERFORMANCE CHARACTERISTICS OF MODULAR NANOSECOND CIRCUITRY EMPLOYING TUNNEL DIODES

N. W. Hill,¹ R. J. Scroggs,¹ and J. M. Madison¹

Introduction

In the somewhat complex electronics associated with the various high-energy particle experiments described in Chap. 9, much use has been made of modular circuits employing tunnel diodes. These solid-state devices have inherently high speed and a wide range of feasible operating temperatures, and they are reasonably resistant to radiation damage. Their unique current vs voltage response, shown in Fig. 10.6.1, makes them useful for current sensing and as active and memory-switching elements in nanosecond logical circuitry.

Various applications of tunnel diodes to high-speed circuitry have been described in the literature.²⁻⁸ In the present work a detailed study has been made of the response of several circuit modules, all employing tunnel-diode elements, to variations in operating temperature and input magnitude.

Discriminator Module

Figure 10.6.2 is a diagram of a typical discriminator module circuit which uses 10-ma gallium arsenide tunnel-diode univibrators based on a design by Whetstone.⁵ Operating on pulses from

a photomultiplier tube, this module performs the functions of lower-level discrimination, pulse-shaping, and "fan-out" output for counting purposes.

The individual univibrators of the discriminator module shown have a dead time, defined as the time separation between a pair of pulses that are just resolved when the second pulse has an amplitude 10% above threshold, of about 14 times the pulse width at half-height. This width, and therefore the pulse-pair resolution, is dependent upon the capacitance of the tunnel diode, the load (~ 13 ohms in the diagram), and the value of the inductance, L .

If it can be assured that all input pulses fall in an amplitude range from two to three times threshold, a significant reduction in dead time is achieved. If, on the other hand, the first pulse of a pair is 100 times threshold, the dead time is increased about 30% over the 14X factor noted

¹Instrumentation and Controls Division. The assistance of J. T. DeLorenzo, W. H. Williams, W. H. Houston, and A. E. Ball in various phases of this work is acknowledged.

²H. Ur, "Tunnel Diode High-Speed Circuits," *Proceedings of the Berkeley Conference on Instrumentation for High Energy Physics*, IIa.2, 45 (1960).

³R. H. Bergman, *IRE (Inst. Radio Engrs.) Trans. Electron. Computers*, EC9(4), 430 (1960).

⁴G. Infante and F. Pandarese, "The Tunnel Diode as a Threshold Device: Theory and Application," *Proceedings of the Conference on Nuclear Electronics*, Belgrade (1961).

⁵A. L. Whetstone and S. Kounosu, *Rev. Sci. Instr.* 33, 423 (1962).

⁶A. L. Whetstone, *IRE (Inst. Radio Engrs.) Trans. Nucl. Sci.* 9, 280 (1962).

⁷M. J. Morgan, *Semicond. Prod.* 5(7), 9 (1962).

⁸M. Cooperman and R. H. Bergman, *Electronics* 36(28), 42 (1963).

Fig. 10.6.1. Typical Current vs Voltage Plot for a Tunnel Diode.

Fig. 10.6.2. Discriminator Module Circuit.

above. The pulse width (full-width at half-maximum) observed for these univibrators is ~ 7 nsec/ μ h for a wide span of inductance values, while the amplitude of the output pulse is constant for constant input for all values of the inductance above about 0.3μ h. A modification of this circuitry to improve resolution significantly is discussed later in this paper. In this, as in most regenerative devices, there is an amplitude-dependent delay, or "walk," between the time the signal reaches the minimum triggering level and the time the discriminator fires. The delay

depends on how quickly the tunnel diode and stray capacitances can be charged; thus it depends on the percent of overdrive, or pulse amplitude above threshold, and the pulse rise time. As shown in Fig. 10.6.3, where the data are for a square input pulse with a rise time of < 1 nsec and a duration of 35 nsec, this delay decreases by about 4.5 nsec as the input pulse amplitude varies from the half-fire threshold (100 mv) to 120 times threshold (12 v). The delay was measured as the time between the 100-mv level of the driving pulse and the 100-mv level of the logic

output; thus it excludes input pulse time shifts. The "walk" from twice threshold to 120 times threshold is ~ 2.5 nsec.

The changes in output pulse width and amplitude resulting from overdrive are shown in Fig. 10.6.4. The maximum width change was 2.6 nsec, while the amplitude increased by 20%, both for an overdrive factor of 120X.

The behavior of the discriminator module when subjected to variations in temperature is of par-

ticular interest. Studies⁹ have indicated that neither the behavior of the peak current point of a tunnel diode nor the voltage at the peak current point can be reliably predicted as functions of temperature. Therefore individual testing and compensation of the three diodes in each module are required. However, some characteristics of the diodes do seem to vary reasonably with temperature. Figure 10.6.5 shows the variation in the half-fire threshold of a typical discriminator module with temperature. Over the range of temperature from 0 to 120°F, the voltage at the half-fire point decreases in a roughly linear fashion from 154.8 to 96.8 mv, a total decrement of 58 mv. The delay associated with the half-fire point, however, appears essentially unaffected by temperature, as is shown in Fig. 10.6.6.

The effect of temperature variations upon the logic output of the discriminator module is shown in the three parts of Fig. 10.6.7. Over the 120°F range covered in the figure, the full-width at half-maximum increases by roughly 5%, the output pulse amplitude increases by less than 6%, and the delay or walk is reduced by about 0.8 nsec. It is probable that the major portion of each of these variations is due to a change in the threshold level, since the constant input amplitude of 200 mv used for these tests represents an overdrive factor of 2 at 120°F.

Fig. 10.6.3. Discriminator Delay or Walk as a Function of Input Pulse Amplitude.

Fig. 10.6.4. Amplitude and Output Pulse Width of Discriminator Logic Output as Functions of Input Pulse Amplitude.

⁹These results are to be described in detail in ORNL-TM-615, in preparation.

Fig. 10.6.5. Variation of Discriminator Threshold Level with Temperature.

Fig. 10.6.6. Delay of Half-Fire Output with Temperature. Input changed to give half-fire from logic output.

Fig. 10.6.7. Variation of Discriminator Delay, Logic Output Pulse Amplitude, and Output Pulse Width with Temperature. Constant input pulse amplitude of 200 mv.

Fast Discriminator Module

In many experiments the pulse-pair resolution given by the module described above is inadequate. Although in principle the resolution is governed by the values of the loading resistor, R_L , and the inductance, L , in practice neither can be changed to

improve the resolution significantly over that obtained with values shown in Fig. 10.6.2. Changes in R_L produce instability, while making L too small ($<0.3 \mu h$) not only reduces the amplitude of the output pulse but also reduces sensitivity, especially to slowly rising input pulses. "Non-linear biasing," i.e., the substitution of a non-linear load for the linear load R_L , is, however, an excellent solution to the problem of obtaining improved resolution. Several slightly different nonlinear biasing elements, such as common-base transistors,^{10,11} tunnel rectifiers ("back" diodes),¹² germanium high-conductance diodes,¹³ and tunnel-diode resistors⁸ have been proposed. All of these elements operate in a "clamping" mode once the tunnel diode has switched over its peak.

A number of these nonlinear "clamps" were tested by operation in a high-speed univibrator. The number included a 2N976 germanium transistor connected as a diode, a BD-503 gallium arsenide back diode, a Q3-100T germanium diode, an MA-4121 silicon diode, and a common-base transistor. Following these tests, which will be described in detail in a later, expanded version of this paper, the 2N976 transistor "diode" clamp was chosen for nearly exclusive use. The choice was made using the criteria of economy, dependability, performance, and simplicity of utilization. A typical high-speed discriminator module using 2N976 transistors is shown in Fig. 10.6.8.

Some results of nonlinear biasing and linear biasing are compared in the oscilloscope traces of Fig. 10.6.9. It is apparent that the transistor clamp has a comparatively high resistance when the tunnel diode switches over the peak, and higher conductance than the linear load after switching. Thus the transistor does not act as a shunt path during switching and therefore requires much less input current, making it more sensitive to slower rise-time inputs. Since the voltage across the inductance, v_L , is much larger than it is with the linear load, the time required for recovery to the original bias point is much

¹⁰J. Amodei and W. F. Kosonocky, *R C A Rev.* 22, 669 (1961).

¹¹V. Radeka, *Nucl. Instr. Methods* 22, 153 (1962).

¹²R. H. Bergman, M. Cooperman, and H. Ur, *R C A Rev.* 23, 152 (1962).

¹³A. L. Whetstone, *Rev. Sci. Instr.* 34, 412 (1963).

Fig. 10.6.8. High-Speed Discriminator Module Circuit.

less with the transistor load, and because of the transistor's more nearly ideal switching characteristics, the recovery time is more clearly defined. In the high-voltage state, where v_L is much smaller for the nonlinear load, the pulse width is longer for a given value of L ; thus the nonlinear load provides a much faster recovery for a wider pulse. The sensitivity achieved for weak triggering

pulses, however, has been about one-fourth that of the circuit using a linear load. (This effect has been reported¹³ to disappear when the value of L is raised above $0.5 \mu\text{h}$.) Since the nonlinear load can result in recovery times shorter than 10 nsec, care must be exercised to ensure that broad input pulses, especially from overloads, do not result in multiple pulsing. In the circuit

shown in Fig. 10.6.8 the termination of the 125-ohm inputs by the 2:4 ratio transformer aids in reducing such multiple pulsing, since the transformer has insufficient low-frequency response to couple the slower component of the input pulses.

Some aspects of the variation in the response of the fast discriminator module with temperature have been examined. The half-fire threshold as a function of temperature is shown in Fig. 10.6.10.

Fig. 10.6.9. Current vs Voltage Curves for Linear and Nonlinear Discriminator Biasing.

Fig. 10.6.10. Half-Fire Threshold Stability with Temperature for Nonlinearly Biased Discriminator.

The drop in threshold over 120°F is about 100 mv, as compared to about 58 mv for the slower module previously described. A part or possibly all of this difference may be due to individual differences in tunnel-diode characteristics.

As was true for the slower module, the delay or walk associated with the half-fire point of the fast discriminator does not appear to be a function of temperature, as demonstrated by Fig. 10.6.11. The relative constancy of the data indicates that any walk due to temperature stems from the change in the trigger level point on a finite rise time pulse.

The output pulse amplitude as a function of temperature is shown in Fig. 10.6.12. Over the 120°F range the pulse amplitude decreases by about 11%, as seen with the coupling diode in series.

The effects produced at the logic output of the fast discriminator due to an increase in the input

Fig. 10.6.11. Delay of Half-Fire Point vs Temperature for Nonlinearly Biased Discriminator.

Fig. 10.6.12. Logic Output Amplitude Stability with Temperature for Nonlinearly Biased Discriminator.

pulse amplitude are shown in Fig. 10.6.13. The total delay change for inputs 1.25 times threshold to 15 times threshold is 2.9 nsec, while over the range from 2 to 15 times threshold the total change is ~ 1 nsec. These changes compare favorably with those observed with the linearly loaded discriminator. The amplitude stability with overdrive for the fast discriminator, however, is somewhat poorer than in the slower model, a result explained by the lower values of coupling resistances used between univibrator stages in the faster model. Output pulse width of the fast discriminator remains essentially constant for input amplitudes of from 0.5 to 4 v, becoming slightly broader from 4 to 10 v.

Coincidence Module

A diagram of a coincidence module employing tunnel-diode univibrators is shown in Fig. 10.6.14.

Fig. 10.6.13. Effects of Input Pulse Amplitude on Delay, Amplitude, and Pulse Width of Logic Output Pulse from Nonlinearly Biased Discriminator.

Standardized pulses from each of three discriminators are added linearly at the input univibrator, which is biased to trigger on a single pulse or any two or three input pulses in coincidence. The three 50-ohm inputs are terminated by the 1:3 transformers, which also provide d-c isolation between modules. Typical delayed-coincidence edges from pulses from a pulse generator are 0.1 nsec wide or less.

The behavior of this module with temperature is summarized in Table 10.6.1, which shows the results from temperature cycling a dual-input circuit. The variation in resolution is about 4%, while the change in edge timing is about 1 nsec.

Anticoincidence Module

A diagram of the anticoincidence module is shown in Fig. 10.6.15. The anticoincidence function is performed by a discriminator which feeds a modified scaler drive module. The width of the scaler drive pulse is accurately controlled by a delay line. Two 10-nsec 4-v pulses with 4-nsec edges can be produced within a period of 30 nsec, which is more than adequate for the resolution requirements of most of the experiments for which it is employed.

Scaler Driver Modules

At each logic step in the modules described above, a tunnel-diode fan-out output is provided for counting purposes. The nominal 1-v pulse of the gallium arsenide tunnel diodes, when used with an isolating coupling diode, had insufficient amplitude to reliably operate commercially available scalars. For this reason, and because of ≤ 40 -nsec resolution desired, several scaler driver modules were designed to drive scalars from either positive or negative tunnel-diode pulses. The positive-output driver is diagrammed in Fig. 10.6.16 and the negative-output driver in Fig. 10.6.17. The first delivers a 4-v pulse with 4-nsec edges into a 125-ohm resistance, and the second delivers a 4-v pulse with 7-nsec edges into a 125-ohm resistance. Both have been operated with delay lines for accurate and stable output widths for logic functions. The delay-time widths have

Fig. 10.6.14. Coincidence Module Circuit.

Table 10.6.1. Response of Coincidence Module
at Various Temperatures

Temperature (°F)	Half-Fire Point (nsec)		Resolution (nsec)
	Lower Pulse Edge	Upper Pulse Edge	
20	12.35	19.12	6.77
40	12.57	19.30	6.73
60	12.69	19.45	6.76
80	12.81	19.70	6.89
100	12.93	19.95	7.02
120	13.07	20.15	7.08

ranged from 10 to 90 nsec. More generally, however, the outputs have been controlled by the collector time constant in the trigger pair, which was usually set for an output pulse width of ~20 sec.

The behavior of both the positive and negative output scaler drivers as a function of temperature appears to be governed somewhat by the pulse width demanded at their outputs. The positive output scaler driver, without delay line, when set to produce a 60-nsec-wide pulse, showed a 19-nsec increase in width for a 122°F temperature change (31.7% or 0.16 nsec/°F). When set to produce a 490-nsec-wide pulse, however, the width increase for a 120°F temperature change was 53 nsec (11% or 0.44 nsec/°F). Over this same temperature range the amplitude change for the narrow pulse was only 2% and that of the wide pulse

Fig. 10.6.15. Anticoincidence Module Circuit.

was 3.3%. When the walk of the positive output scaler driver, driven by a linearly loaded discriminator set to trigger on a 100-mv input pulse, was measured as a function of input pulse amplitude, it was found to consist essentially of the walk due to the discriminator alone, with no change being added by the scaler driver.

With a delay line installed to produce a 17-nsec pulse, the positive output scaler driver again showed no more walk with overdrive than that due to the discriminator driving it. Its walk with temperature was ~ 2.3 nsec for a 127°F temperature change (1.3 nsec from 75 to 122°F , of

which 0.3 nsec comes from the discriminator). The amplitude increase was 5% for a 122°F range, and the width change was 0.75 nsec or 4.5% for a temperature change of 125°F .

Tests similar to the above performed on the negative output scaler driver showed that its general reaction to changes in temperature and drive was essentially the same as that of the positive output module. Figure 10.6.18 shows the variation with temperature of the resolution, amplitude, and walk of the negative output scaler driver when it was delay-line-controlled to produce an 18-nsec pulse.

Fig. 10.6.16. Positive-Output Scaler Driver Circuit.

Fig. 10.6.18. Variation of Delay, Amplitude, and Pulse Width of Output Pulse from Negative Output Pulse Scaler Driver with Temperature.

Scaler Modifications

Modifications have been made to the input gate, limiter, and pulse shaper of the CMC scalers used in these experiments in order to ensure reliable operation under conditions not within the manufacturer's¹⁴ specifications. The redesigned circuit is shown in Fig. 10.6.19. With this circuit these scalers have a pulse-pair resolution of 40 nsec or less for input pulses having widths of from 6 to 20 nsec and rise times of from 2 to 8 nsec. The required input amplitude for the 15-nsec width is 1.5 v. A continuous counting rate in excess of 12 Mc is possible. However, this circuit does not respond to pulses with rise times slower than 1.5 μ sec, and a modification, to be reported in a later paper,⁹ has been developed.

¹⁴Computer Measurements Corp. Model No. 1217A.

The modified circuit has a pulse-pair resolution of 35 nsec for 1-v input pulses having 8-nsec rise times.

100-Mc Scaler Driver

The experiments described in Secs. 9.2 and 9.8 required resolution capabilities greater than those of the scaler-driver module described above. To fulfill these needs, the circuit shown in Fig. 10.6.20 was designed. It is capable, in conjunction with the nonlinearly loaded univibrators described above, of pulse quintuplicate resolution at a rate of 50 kc into a 50-ohm resistance. It will deliver a 3.5-v 4-nsec pulse. The behavior of one such unit at various temperatures is shown in Fig. 10.6.21.

Fig. 10.6.19. Input Gate, Pulse Shaper, and Limiter for Computer Measurements Corp. Scaler.

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