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EXPERIMENTAL NUCLEAR CROSS SECTIONS FOR SPACECRAFT SHIELD ANALYSIS*

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EXPERIMENTAL NUCLEAR CROSS SECTIONS FOR SPACECRAFT SHIELD ANALYSIS*

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Experiments have been performed to validate and to supplement the intranuclear cascade model as a method for estimating cross sections of importance to spacecraft shield design. The experimental situation is inconclusive particularly for neutron-producing reactions, but is relatively sound for reaction cross sections and for proton spectra at several hundred MeV at medium forward angles. Secondary photon contributions are imprecisely known.

INTRODUCTION

This paper tries to outline the purpose, scope, and main qualitative results of a decade of effort for our group working on nuclear cross sections relevant to spacecraft shield design. A large share of our effort went toward the invention of experimental methods which are not discussed here.

Our crewman face in space the cosmic ray sources and, for space stations, the trapped radiation belts. We must be concerned about reactions of primaries in tissue (if $[QF]_{av.} \gg 1$) and about interactions in tissue of secondary neutrons and gamma rays from nuclear reactions in the spacecraft's shell. For heavy primaries, attenuation in the spacecraft may markedly influence hazard levels. The radiation problem is inherent in the manned exploration of space; its severity from an engineering point of view depends on the radiation tolerances assigned by the authorities and on the thickness otherwise required for the craft's exterior structure. If nuclear rockets or nuclear auxiliary power are used, the shield design should be studied as a unit. Radiation problems will require continuing surveillance so long as manned flight is contemplated; maintaining the underlying competence will require continued development of analysis techniques.

First-order shielding calculations are made by considering only the "continuous" energy loss by charged particles, while nuclear reaction products are ignored. The ability to continue to carry out such calculations in practical geometries is important and must be maintained. As the shield structure thickens for longer missions, more primary particles traverse a large fraction of their interaction length in the shield or in the astronaut's body, and the first approximation becomes less and less satisfactory. The knowledge of differential cross sections for nuclear interactions is needed to obtain correct results. Using current analyses, about one half the biologically equivalent (rem) dose from an 80-MV flare behind 20 gm/cm² of aluminum arises from secondaries produced in the shield and in tissue.[1] Unfortunately, one is so far quite unsure what LET-dependent quality factors should be utilized in making such estimates.

We accept the idea that radiation penetration studies can be done better by calculation than by experiment, provided that the necessarily huge supply of cross-section information is available. In the energy regions of interest here we assume the preferred strategy will always be to depend on calculated cross sections or at least on high-class interpolations that take into account theoretical ideas. The question for the experimenter becomes: Do the available cross-section estimation methods work well enough for the space shielding problem? If not, in what directions should one seek improvement? Answering these simple questions, an effort which must be shared with shield analysts, has been difficult because of the lack of satisfactory criteria and because of the complexity of the necessary experiments.

So far, as expected a decade ago, all higher-order methods of spacecraft shield analysis are based on cross sections provided by some intranuclear cascade model. Cascade reactions are usually followed in the model by successive evaporation of fragments until only gamma radiation is allowed by the conservation rules. To date, the cascade model receives its most productive expression in the work of Bertini[2] and in the application of the resulting model cross sections to transport calculations.[3]

Clarification of the validity restrictions on this model has been the objective for our experimental work. The model is restricted to incident neutrons or protons, and offers a little help for incident alpha particles.[4] So far, it has not led to very good estimates of gamma-ray production.[5]

The model itself assumes that the reaction within a real nucleus can be replaced in the cascade or pre-equilibrium phase by a series of nucleon-nucleon interactions and, at higher energies, meson-nucleon interactions. The cascade of successive intranuclear collisions is followed by Monte Carlo using experimental free-particle nucleon-nucleon cross sections until the cascade terminates when no more nucleons can escape the model potential which holds the target nucleus together. The model is conceptually strong at energies of several hundred MeV, but as one goes below 100 MeV it is used at risk because the binding of nucleons is no longer so small compared to the incident energy, the deBroglie wave-length of the incident particle is no longer very short, and the ignored distortions of the incident "wave" by the nuclear potential might be thought to have a strong influence. Also, Coulomb effects and differences

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in binding energy from one nucleus to the next start to become important. So, we must be cautious in accepting predictions of the cascade model in the region where the model was never meant to produce answers. Most of the problems with the model arise at the lowest incident energies, where there is great intensity of solar and trapped protons. Above 1 GeV, there are technical problems of what to use for the intranuclear cross sections, but this paper is not concerned with energies that high. At all energies, there is a 10% to 20% weakness that while the model deals with direct reactions, it does not allow production of deuterons etc. by such reactions even though experiments always show considerable deuteron intensity. We can hope for such an improvement in the model; no strong effort has yet been made.

STATUS OF EXPERIMENTS

Here I will concentrate on contributions by our group, but mention the other experiments which have been most influential. Table 1 outlines the main cross-section publications that have arisen from our work.

Reaction Cross Sections

Reaction cross sections give the probability of occurrence of some nonelastic nuclear reaction, and therefore are of prime importance. These cross sections are somewhat available from various physics groups for both neutrons and protons, since they are also of great importance in the optical model of the nucleus or any other reaction model. The comparisons which have been presented show the Bertini cascade model to be within experimental uncertainty (~10%) over the energy range 30 to 1000 MeV.[2,6] This success gives the cascade model a remarkably good start toward overall validity.

Measurements of Dose

Observations of absorbed energy have been made from proton beams in bulk absorbers by Tanner, Bailey, and Hilbert and by Blosser and Maienschein, and in phantoms from scattered reaction products by Blosser and Maienschein.[7] These results have produced a substantial challenge to the combined calculation of cross sections and radiation transport. Since the most thorough methods involve Monte Carlo, the cost of computing integral checks in the latter case was too great to allow a complete comparison with the data. Figure 1 shows the two checks that have been performed in the work of Irving and Alsmiller.[8] Unfortunately, when such integral results do not check, it is difficult to infer what characteristics of the calculation (or experiment) is imperfect and whether indeed the disagreement is representative of practical situations.

Gamma-Ray Spectra

Zobel and Maienschein[9] obtained photon spectra from protons in the energy range 15 to 150 MeV on typical targets. The results have not proved uniformly predictable,[9] partly because the calculated results were based on the residual energy following nucleon evaporation while many of the important excited states are collective levels excited by direct reactions. Nevertheless, current opinion holds that for flare spectra as hard as P_0 = 100 MV, gamma rays from the reactions cannot compete with the primary dose component.[10] For sufficiently soft flares of high intensity, this conclusion may not be valid.[11] Figure 2 shows a typical photon spectrum for oxygen which exhibits different structure from that calculated with the help of the cascade model. Figure 3 shows the energy dependence of the photon production cross sections observed and calculated for four target materials.

Secondary Neutron Production (from protons)

Insofar as secondaries produced in the spacecraft are concerned, neutrons are felt to be the most important, and so a large fraction of our effort has been spent in neutron spectroscopy. Wachter and Gibson have observed spectra of secondary neutrons for incident 160- and 450-MeV protons for a variety of targets, some thick enough to allow a little testing of transport codes.[12,13] Agreement of this data with theory is only moderate[12,14] even after account is taken of the broad resolution of the spectrometers. Figure 4 illustrates typical results obtained at 450 MeV at forward angles for rather thin targets. Figures 5 and 6 illustrate that at 160 MeV the thick-target yields more nearly agreed with theory for bismuth than for aluminum. The source of the difficulties is not clear; theorists are understandably reluctant to modify the model until the experiments are independently confirmed, and also it is not clear from the data what modifications should be made.

Essentially no competing neutron data exists for protons in this energy range except for the measurements by Bowen et al. of neutrons at 2° from ~140-MeV protons on various targets.[15] Figure 7 is a typical example of the 140-MeV results, none of which have ever been properly explained. Not only must the peak at the high energies contain excitation of the target's isobaric analog as well as any contribution from quasifree scattering, but the continuum region (at 1/4 to 3/4 the incident energy) is underestimated by the cascade model for each target studied. Extreme forward angles are expensive to study by present Monte Carlo techniques.

Verbinski and Burrus looked in a brief but productive experiment at neutron spectra above 1 MeV from 14- to 18-MeV protons on a series of targets.[16] Figure 8 shows the results obtained as a function of angle for an aluminum target. Some targets both lighter and heavier than Al yielded greater anisotropy. As suggested by Fig. 9, where the same results integrated over angle are compared with theory, this experiment showed that the angle-integrated spectra in this energy range are better fitted by the cascade (+ evaporation) model than by evaporation alone; the latter idea had previously been accepted. The latest interpretation of Verbinski's data by Alsmiller and Hermann[17] has shown that a simple low-energy modification of the cascade model, which takes into account the Q-value for the (p,n) reaction, is required to give the theory some validity for neutron energies near the incident beam energy.

J. W. Wachter is now analyzing the experimental results he, Santoro, Love, and Zobel obtained for neutron spectra from 40- and 60-MeV protons.[18] These data were obtained in the region where the cascade model is expected to be failing and in which marked angular distributions can be expected. These data should help greatly to clarify our ideas about reactions in this region in which the other reaction products have been studied so thoroughly (see below). Figure 10 shows preliminary results for 39-MeV protons on carbon, while Fig. 11 shows the 0° spectrum from a lead target. The peak in Fig. 11 corresponds to excitation of the isobaric

analog of the target, and cannot be given by the cascade model. Similar experimental capability for measuring neutron spectra is apparently being developed at other isochronous cyclotrons, notably Texas A. and M. and University of California at Davis, and scattered results are also available showing the behavior of the peak from excitation of the isobaric analog state.

Secondary Protons, Deuterons, Alpha Particles

Secondary proton experiments by Cladis, Hess, and Moyer[19] motivated the early development of the cascade model, and most of the nucleon data against which the model can be tested are still for protons rather than neutrons. Unfortunately, the latter are of more shielding interest, though at some hundreds of MeV the charged-particle spectra are of importance in estimating tissue dose from protons. The work of Ashgirey et al.[20] observing protons from 660-MeV protons on nuclei, though it covered only small angles, has had a strong effect on the development of the theory because it showed approximate validity of the theory in this region provided that meson production was included. (See Fig. 12.) Similar comparisons[2c] for secondary energies above 800 MeV are available from the work of Corley and Wall[21] with 1-GeV protons.

At lower energies the situation becomes more confused. The results of Wachter, Gibson, and Burrus[13] from 450-MeV protons on nuclei included the proton spectra illustrated in Fig. 13. Agreement seems to improve as the angle is increased toward 60°, but consistent differences between experiment and theory appear in the 30° and 45° data.

In the 150- to 200-MeV region real disagreements appear between various experiments. It is impossible to decide, for instance, if the quasifree scattering peak appears clearly in the data as expected from model calculations. The experimental results are generally confused by multiple-scattering effects, failure to separate explicitly the deuteron contribution, and in some cases by broad resolution. Figure 14 illustrates this discrepancy of spectral shape between the experiments of Wall and Roos[22] and those of Peelle.[23] At 60°,[12] the experiments of Peelle and of Wachter et al.[12] (see Fig. 15) are in rough agreement with the cascade model,[2b] while the results of Roos and Wall still show maxima in the spectra. At backward angles the experimental cross section is much larger than the predicted one. We conclude that above 100 MeV the cascade model gives about the right magnitude of differential cross section except at backward angles, but the quasifree structure in the energy spectrum must remain in doubt for energies less than a few hundred MeV until more precise experiments are performed. Since the spectrum affects the energy balance, we can assume that from the evaporation phase of the reaction intensities are also in doubt.

For the last few years results have been appearing from an exhaustive experiment by Bertrand and myself to look at complete spectra of hydrogen and helium ions from 30- to 60-MeV protons on a series of nine targets from carbon through bismuth.[24] Figure 16 illustrates the type of data available for each target, angle, and incident energy, while Fig. 17 shows some proton results from 62-MeV protons on ^{120}Sn. To state the qualitative results briefly, cross sections in the continuum regions do vary slowly with mass number (Figs. 18 and 19), alpha-particle production is not entirely explained by the evaporation model (Fig. 16), the mass 2 and 3 isotopes comprise 15% to 20% of the observed cross section and emitted energy (Fig. 19) and have spectra which completely differ from that predicted by the evaporation phase of the model (Fig. 16), at higher energies the back angle intensity is higher than estimated (Fig. 17), and the quasifree scattering peak is not seen (Fig. 20). Figure 21 illustrates the progressive shift in the accuracy of cascade model predictions at a given angle as the incident energy is lowered, while Fig. 22 illustrates that predictions of the angle-integrated spectra behave much more stably at the low energy. Some results have also been obtained for incident 59-MeV alpha particles;[25] Fig. 23 illustrates that the experimental results from the ^{nat}Pt(α,xp) reaction cannot be explained on the basis of a simple nuclear evaporation model.[26]

Most of the data from this charged-particle experiment is now publicly available, but much interpretive work remains to be done. If the data can be complemented with good neutron differential cross sections in the same energy region for some of the same targets, the data base will be sufficiently complete to allow productive theoretical efforts.

STATUS OF THE THEORY

Theory is important, since we expect to derive a complete set of usable cross sections from it rather than directly from experiment. I will try to summarize my view of the utility of present theories for computing cross sections for incident energies below 1 GeV. 1) Optical model (elastic) and distorted-wave approximation cross sections could be computed for excitation of discrete levels in residual nuclei, based on the work of many physics groups. These reactions become increasingly important for incident energies below 50 MeV as seen in Fig. 21, but they have not yet been included in shielding computations. To do so would require due respect for the detailed literature but some simplification of level schemes while keeping the main features. We do not quite know how this "collective" share of the reactions should be meshed with the rest.

2) The nuclear fragment evaporation theory itself is seldom completely valid, except for perhaps some reactions with incident heavy nuclei. In combination with the cascade theory, it has enjoyed some success. With incident particles in the 30- to 60-MeV range, the competition between alphas and protons in the Dostrovsky model now used[24] is always wrong by a factor of two or more; we do not know whether the neutron intensity shares this difficulty. Part of the difficulty lies in the unrealistic inverse cross sections used in the model, and failure to consider angular momentum may also be important.

3) The cascade model[2] gives satisfactory (~10%) nonelastic cross sections over the whole range of interest, if the uncertainty of the literature values is taken into account. So far the model fails to predict the 10% to 15% contribution of deuterons which seem to be produced by direct reactions. For 60-MeV incident protons the model gives cascade proton spectra integrated over angle which are within about 20% of experiment, but too few cascade protons are emitted at large angles. The energy distribution of protons at moderately forward angles are similarly good at the highest energies considered here, but at low energies show too much quasifree scattering structure. We do not know for sure the behavior in the 100- to 200-MeV

region. The best available comparisons for neutron spectra show disagreements larger than 30%, but so far the data are a bit inconclusive. (Comparison with a Cosmotron experiment to check neutron production in very thick samples encourages the belief that on some energy-angle average the neutron production is within 30% of the correct value.[27]) Extensive (p,2p) coincidence experiments in the physics community indicate that distortion of the incident nucleon wave by the nuclear-force field of the nucleus must be taken into account for energies below 100 MeV.[28] Since (p,2p) experiments study the intranuclear nucleon-nucleon reaction which underlies the cascade model, their conceptual results should be folded into the cascade theory. No real competitor for the intranucleon cascade theory has yet appeared, so the course must be to improve what we have. The cascade cross sections vary slowly with angle, target mass, and incident and outgoing energy, so it seems conceptually hopeful that a clever computational method could be found to reduce greatly the number of histories required for precise estimation of a broad range of results.

SUMMARY OF WORK NEEDED TO BE DONE

If man is to spend extended periods in space, more details should be worked out on the effects of nuclear reactions on his radiation environment. More experimental information should be obtained on the production of low-energy neutrons in the reactions of protons, and experiments like that of Wachter should be extended to more targets. Some additional experimental assurance on secondary gamma rays would be wise, for instance by measurement of the photon energy released by stopping 15- to 30-MeV protons in appropriate targets. Large efforts are needed to make available to the space shielding analyst improved cross-section codes which take account of the major findings of incident-proton experiments, and to continue the exploration of the consequences of these reactions for spacecraft design. Beyond the work with incident protons, experimental and theoretical exploration of the reactions of alpha particles and heavier primaries are surely in order, since the available experiments barely sample the problem and no really applicable general theory is available. The immediate problem is that current fiscal plans provide for but a small fraction of the needed effort.

The primary author wishes to acknowledge the forbearance of most of the associate authors, who had no chance to review the manuscript which depended so heavily of their long efforts.

Table 1. ORNL Space Shielding Experiment Program

Observed	Incident Particle (MeV)	Type	Targets	Angle Range (deg)	Secondary Energy Range (MeV)	Principal Authors	Reference
dose in phantom	160	p	C,Al,Cu, Bi	0,45	N.A.	Blosser, Maienschein, Freestone	7
γ	16–160 59	p α	Be,B,C, O,Al,Fe	50,90, 135	0.7–10	Zobel, Maienschein, Todd,Chapman	9
p	160	p	Be,C,O, Al,Co,Bi	30–120	20–160	Peelle,Love, Hill,Santoro	23
p	160	p	Be,C,O, Al,Cu,Co, Bi	10,45 60,135	50–160	Wachter, Burrus,Gibson	12
n	160	p	C,O,Al, Cu,Co,Bi	10,45	50–160	Wachter, Burrus,Gibson	12
p	450	p	Be,C,Al, Cu,Co,Pb, Bi	20,30, 45,60	120–450	Wachter, Gibson,Burrus	13
n	450	p	C,Al,Co	10,20 30,45	120–450	Wachter, Gibson,Burrus	13
n	14–18	p	Be,N,Al, Fe,In,Ta, Pb	0–170	1–15	Verbinski, Burrus	16
p,d,T, ^{3}He,α	30–60	p	C,O,Al, Fe,Y,Sn, Au,Bi	15–160	2–60	Bertrand, Peelle	24
p,d,T, α	58	α	C,O,Fe,	20–120	2–60	Bertrand, Peelle	25
n	40–60	p	C,Al,Fe, Pb	0–120	5–60	Wachter, Santoro,Love	18

REFERENCES

1. SCOTT, W. W.: Estimates of Primary and Secondary Particle Doses Behind Aluminum and Polyethylene Slabs Due to Incident Solar-Flare and Van Allen Belt Protons, Oak Ridge National Laboratory Document, ORNL-RSIC-18, 1967. IRVING, D. C.; ALSMILLER, R. G.; ALSMILLER, F. S.; and MORAN, H. S.: Nucl. Sci. Eng., vol. 25, 1966, p. 373.
2. BERTINI, H. W.: (a) Phys. Rev., vol. 131, 1963, p. 1801; Phys. Rev., vol. 138, AB2, 1965. (b) Phys. Rev., vol. 162, 1967, p. 976. (c) Phys. Rev., vol. 188, 1969, p. 1711.
3. COLEMAN, W. A.; and ALSMILLER, R. G., Jr.: Nucl. Sci. Eng., vol. 34, 1968, p. 104.
4. GABRIEL, T. A.; SANTORO, R. T.; and ALSMILLER, R. G., Jr.: An Approximate High-Energy Alpha-Particle-Nucleus-Collision Model, Oak Ridge National Laboratory Document, ORNL-TM-3153, 1970, to be published in Nucl. Sci. Eng.
5. SHIMA, Y.; and ALSMILLER, R. G., Jr.: Nucl. Sci. Eng., vol. 41, 1970, p. 47.
6. Private communications from E. Gross and H. W. Bertini (1970) indicate that most of the yet-unpublished data of the former for proton reaction cross sections between 30 and 60 MeV lie within 5% of the Bertini predictions (about 1/3 of the differences lie just outside of 10%).
7. TANNER, R. L.; BAILEY, N. A.; and HILBERT, J. W.,: Rad. Res., vol. 32, 1967, p. 861. BLOSSER, T. V.; MAIENSCHEIN, F. C.; and FREESTONE, R. M.: Health Phys., vol. 10, 1964, p. 743.
8. IRVING, D. C.; ALSMILLER, R. G., Jr.; and MORAN, H. S.: Nucl. Sci. Eng., vol. 37, 1969, p. 304. Comparisons against this data have also been performed by LILEY, B.; and DUNEER, A. G., Jr.: Nucl. Sci. Eng., vol. 29, 1967, p. 189.
9. ZOBEL, W.; MAIENSCHEIN, F. C.,; TODD, J. H.; and CHAPMAN, G. T.,: Nucl. Sci. Eng., vol. 32, 1968, p. 392.
10. HILL, C. W.; and SIMPSON, K. M., Jr.: Proc. Second Symp. on Protection Against Radiations in Space, NASA SP-71, 1965, p. 351.
11. PEELLE, R. W.: Proc. Special Sessions on Protection Against Space Radiation, NASA SP-169 (ANS-SD-5) 1968, p. 434 or Nuclear Reaction Cross Sections for Spacecraft Shield Design, Oak Ridge National Laboratory Document, ORNL-TM-1892, 1967, p. 8.
12. WACHTER, J. W.; BURRUS, W. R.; and GIBSON, W. A.: Phys. Rev., vol. 161, 1967, p. 971.
13. WACHTER, J. W.; GIBSON, W. A.; and BURRUS, W. R.: Neutron and Proton Spectra from Targets Bombarded by 450-MeV Protons, Oak Ridge National Laboratory Document, ORNL-TM-2253, submitted to Phys. Rev.
14. ALSMILLER, R. G., Jr.; WACHTER, J. W.; and MORAN, H. S.: Nucl. Sci. Eng., vol. 36, 1969, p. 291.
15. BOWEN, P. H.; COX, G. C.; HUXTABLE, G. B.; SCANLON, J. P.; THRESHER, J. J.; and LANGSFORD, A.: Nucl. Phys., vol. 30, 1962, p. 475.
16. VERBINSKI, V. V.; and BURRUS, W. R.,: Phys. Rev., vol. 177, 1969, p. 1671.
17. ALSMILLER, R. G., Jr.; and HERMANN, O. W.: Nucl. Sci. Eng., vol. 40, 1970, p. 254.
18. WACHTER, J. W.; LOVE, T. A.,; SANTORO, R. T.; and ZOBEL, W.: Neutron Physics Division Annual Progress Report for Period Ending May 31, 1970, Oak Ridge National Laboratory Document, ORNL-4592, p. 104.
19. CLADIS, J. B.; HESS, W. N.; and MOYER, B. J.: Phys. Rev., vol. 87, 1952, p. 425.
20. AZHGIREY, L. S.; VZOROV, I. K.; ZRELOV, V. P.; MESCHERYAKOV, M. G.; NEGANOV, B. S.; RYNDIN, R. M.; and SHABUDIN, A. F.: Nucl. Phys., vol. 13, 1959, p. 258.
21. CORLEY, D. M.: Ph.D. Dissertation, University of Maryland, 1968.
22. WALL, N. S.; and ROOS, P. R.: Phys. Rev., vol. 150, 1966, p. 811.
23. PEELLE, R. W.; LOVE, T. A.; HILL, N. W.; and SANTORO, R. T.: Phys. Rev., vol. 167, 1968, p. 981.

REFERENCES (Continued)

24. BERTRAND, F. E.; and PEELLE, R. W.: Oak Ridge National Laboratory Documents as follows: ORNL-4274, 60-MeV protons on C, Fe, and Bi.; ORNL-4450, 62-MeV protons on ^{89}Y; ORNL-4455, 62- and 28-MeV protons on ^{27}Al; ORNL-4456, 61-MeV protons on ^{56}Fe; ORNL-4460, 62- and 29-MeV protons on ^{197}Au; ORNL-4469, 62-, 39-, and 29-MeV protons on ^{54}Fe; ORNL-4471, 62- and 29-MeV protons on ^{120}Sn; ORNL-4638, 62- and 39-MeV protons on ^{209}Bi, and Neutron Physics Division Annual Progress Report for Period Ending May 31, 1970, ORNL-4592, p. 98.
25. BERTRAND, F. E.; and PEELLE, R. W.: Cross Sections for Hydrogen and Helium Particles Produced by 59-MeV Alpha Particles on ^{12}C, ^{16}O, and ^{54}Fe, Oak Ridge National Laboratory Document, ORNL-4670, to be published.
26. DOSTROVSKY, I.; et al.: Phys. Rev., vol. 116, 1959, p. 683; vol. 118, 1960, p. 781; vol. 118, 1960, p. 791. The program used is from DRESNER, L.: EVAP - A Fortran Program for Calculating the Evaporation of Various Particles from Excited Nuclei, Oak Ridge National Laboratory Document, ORNL-TM-196, 1961.
27. COLEMAN, W. A.; and ALSMILLER, R. G., Jr.: Nucl. Sci. Eng., vol. 34, 1968, p. 104.
28. RIOU, M.; and RUHLA, Ch.: Progress in Nuclear Physics, vol. 11, p. 195, D. M. Brink and J. H. Mulvey, Eds., Pergamon Press, 1970.

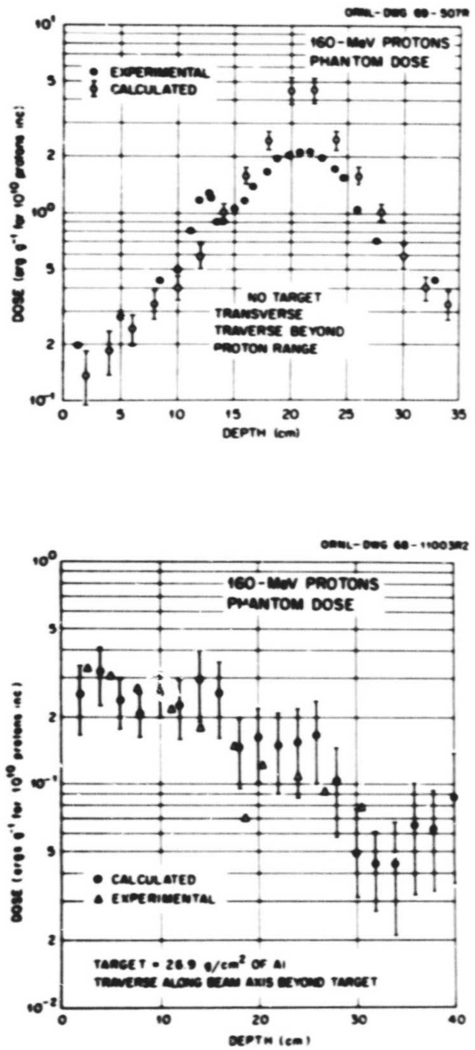

FIGURE 1.—Absorbed dose observed as a function of position in a spherical water phantom (ref 7), compared to a Monte Carlo nucleon transport calculation of Irving and Alsmiller (ref 8). For the results illustrated at the top (a), the beam was incident on the phantom in a direction perpendicular to the traverse, while in the work illustrated below (b), an aluminum target thick enough to stop the incident 160-MeV proton beam was interposed.

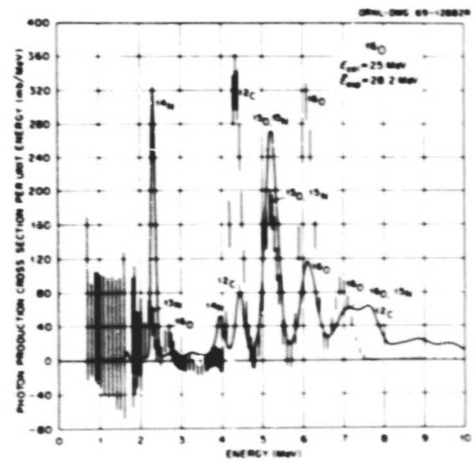

FIGURE 2.—Photon-production cross section per unit energy vs photon energy for protons on ^{16}O (ref 9). The solid line represents the cross section calculated by Shima and Alsmiller (ref 5) for 25-MeV protons and the vertical lines represent the 67% confidence limits on the experimental data for an average proton energy of 28 MeV.

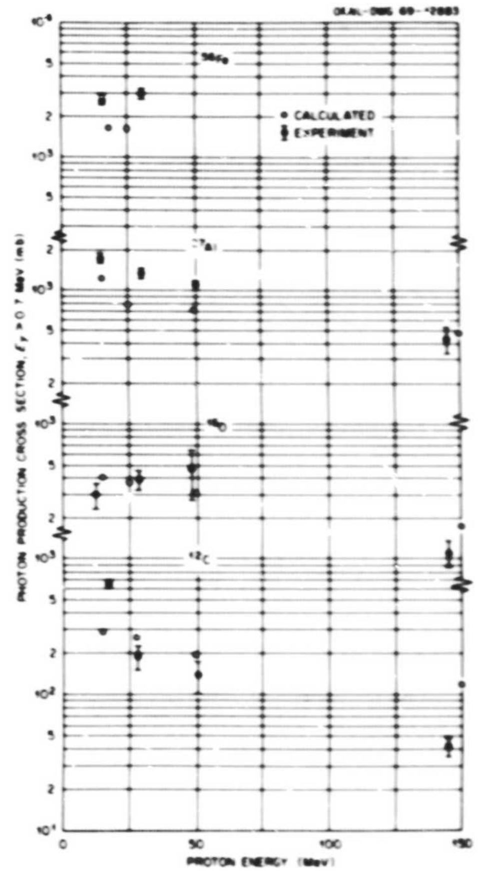

FIGURE 3.—Production cross section for photons with energy >0.7 MeV vs incident proton energy. The experimental values (ref 9) are 4π × (mb/sr observed at 135°), though the experimental results as a function of angle were sometimes inconsistent with isotropy. The calculated values are from Shima and Alsmiller (ref 5).

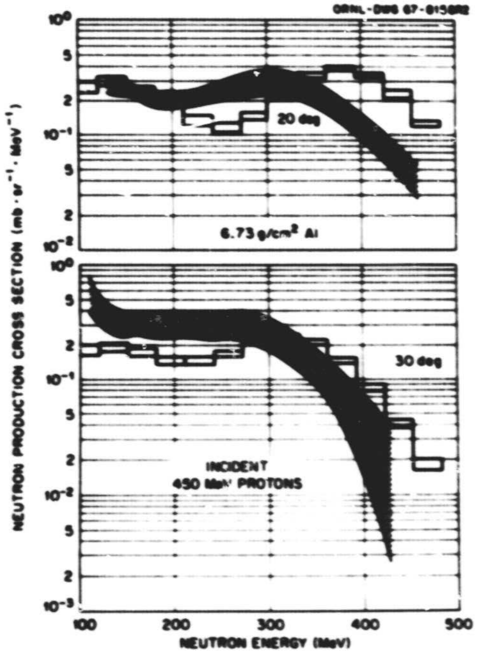

FIGURE 4.—The hatched areas are the experimental confidence intervals for the differential neutron cross sections at 20° and 30° from 450-MeV protons on aluminum (see ref 13). The histogram shows the estimated cross section from the Bertini intranuclear cascade model, smeared by the experimental resolution, for the surrounding angle intervals (ref 2c).

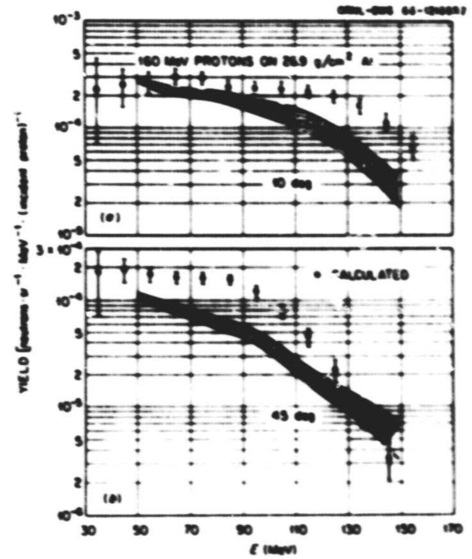

FIGURE 5.—Experimental (ref 12) and calculated neutron yields as a function of energy at 10° and 45° to a 27-g/cm²-thick aluminum target, which is thick enough to stop the incident beam of 160-MeV protons. The calculated points were obtained using the Monte Carlo transport codes of Kinney (predecessors to the work of ref 3) which employed the cross sections of Bertini (ref 2). The calculated values were smeared using a Gaussian energy resolution so that they correspond to the resolution associated with the experimental curves.

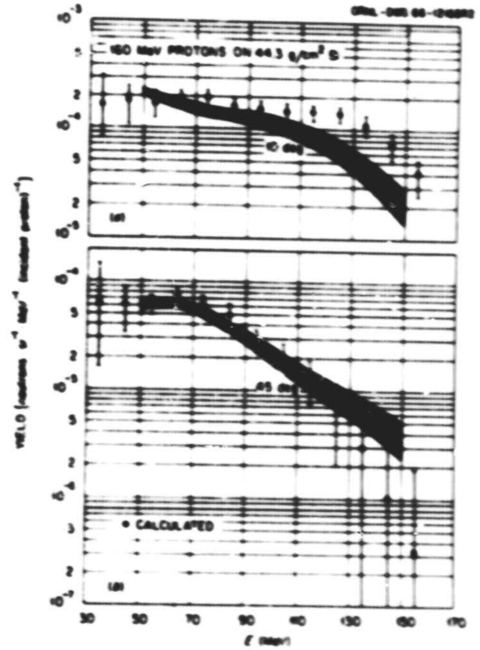

FIGURE 6.—Experimental and calculated neutron yields at 10° and 45° from a 44.3-g/cm²-thick bismuth target. (See Fig. 5 for explanation.)

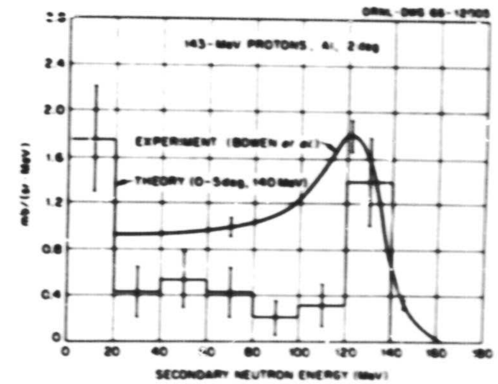

FIGURE 7.—Secondary-neutron spectrum at 2° from 143-MeV protons on aluminum. Smooth curve: experimental results of P. H. Bowen et al. (ref 15). histogram: calculated spectrum by the intranuclear cascade model (ref 2b) of neutrons emitted into the angular interval 0° to 5° from 140-MeV incident protons.

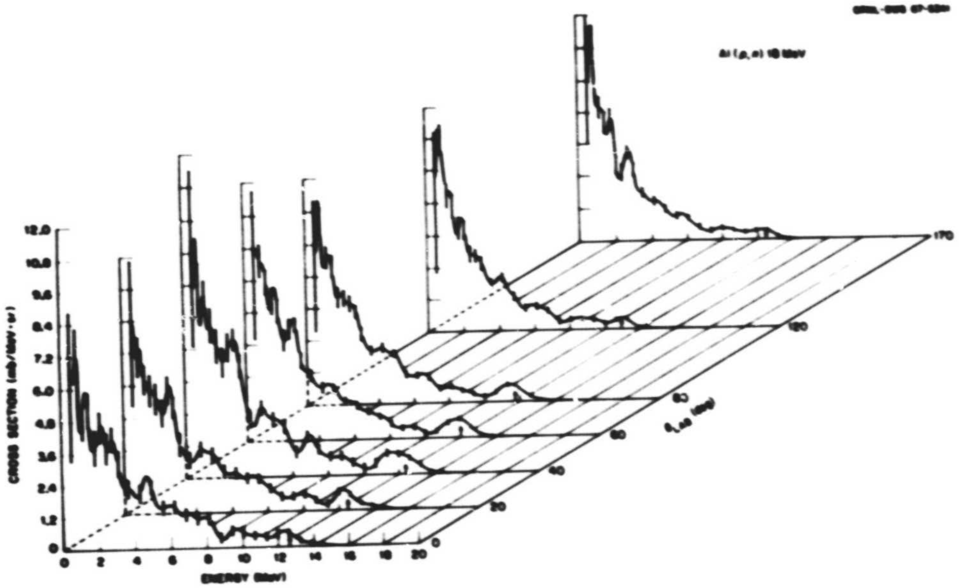

FIGURE 8.—Neutron differential cross sections vs energy and angle for $^{27}Al(p,xn)$ reactions at E_p = 18 MeV. (See ref 16.)

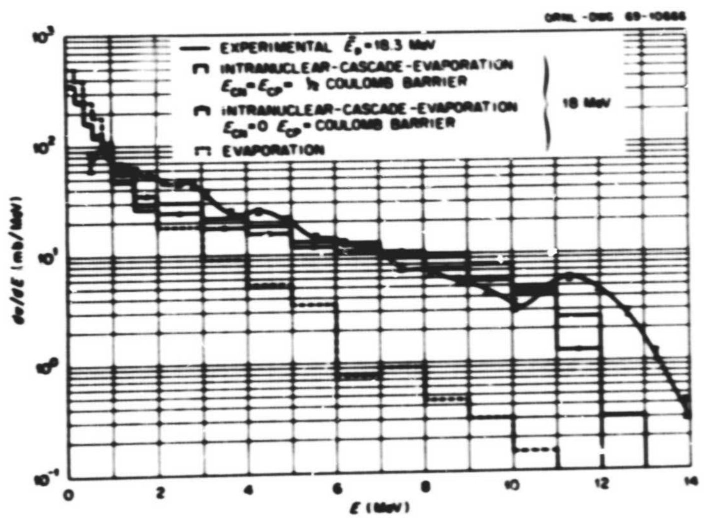

FIGURE 9.—Angle-integrated differential cross section for neutron emission from 18-MeV protons on ^{27}Al. The experimental values of Verbinski and Burrus (ref 16) are compared with the theoretical values due to Alsmiller and Hermann (ref 17).

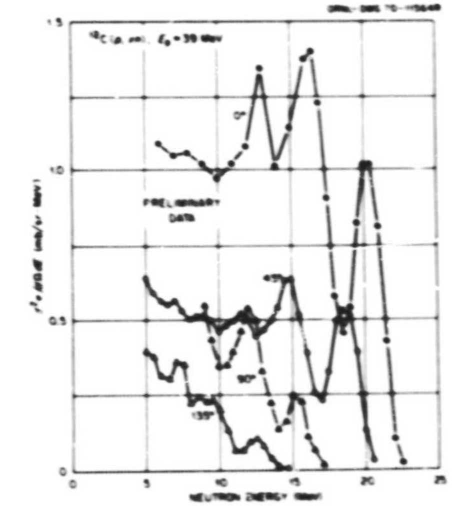

FIGURE 10.—Preliminary differential cross sections of Wachter et al. (ref 18) for differential neutron cross sections from 39-MeV protons on carbon at various detector angles.

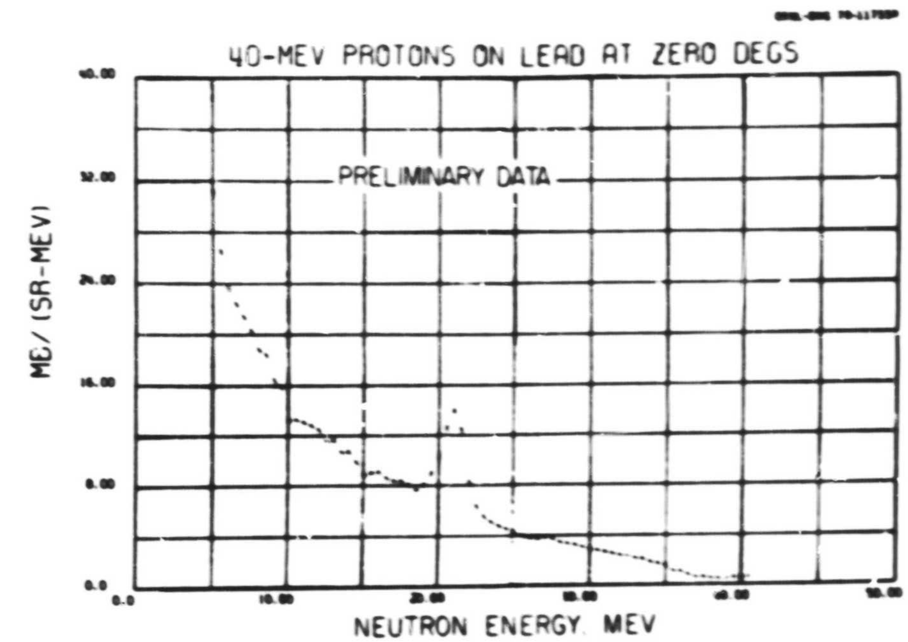

FIGURE 11.—Preliminary differential cross sections of Wachter et al. (ref 18) for neutrons at 0° from 39-MeV protons on lead.

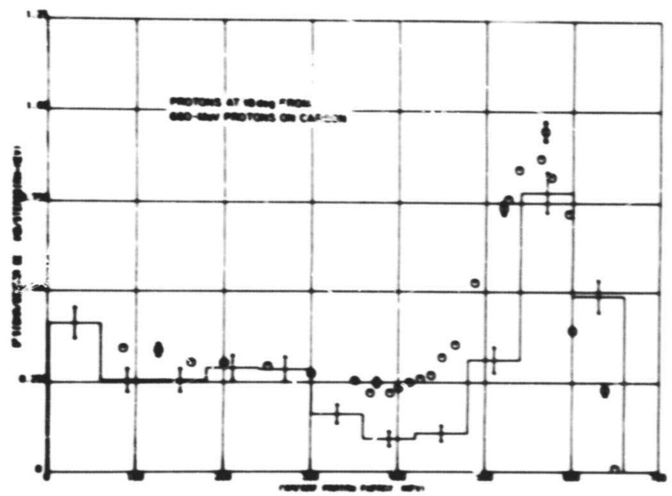

FIGURE 12.—Energy spectrum of protons emitted at a laboratory angle of 18° from 660-MeV protons on carbon. Histogram: calculated values by Bertini (ref 2c) for the angular interval 13° to 23°; circles: experimental data of Azhgirey et al. (ref 20).

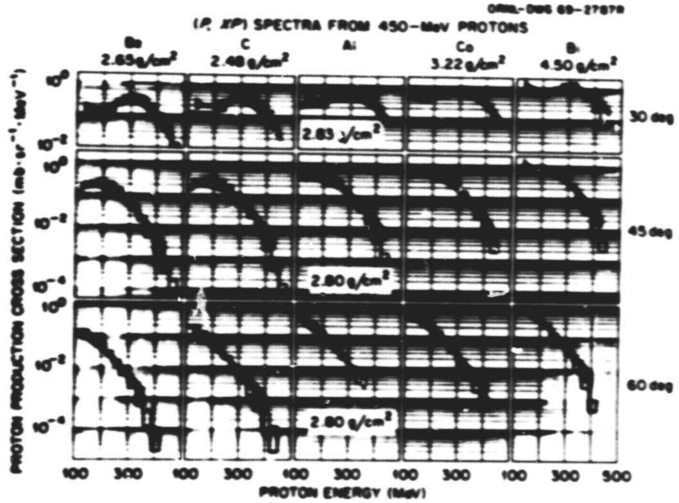

FIGURE 13.—The shaded areas are the experimental proton spectra of Wachter et al. (ref 13) for 450-MeV protons at the energies and angles indicated. The histograms give the resolution-smeared results of the Bertini cascade model (ref 2c) for appropriate angle intervals.

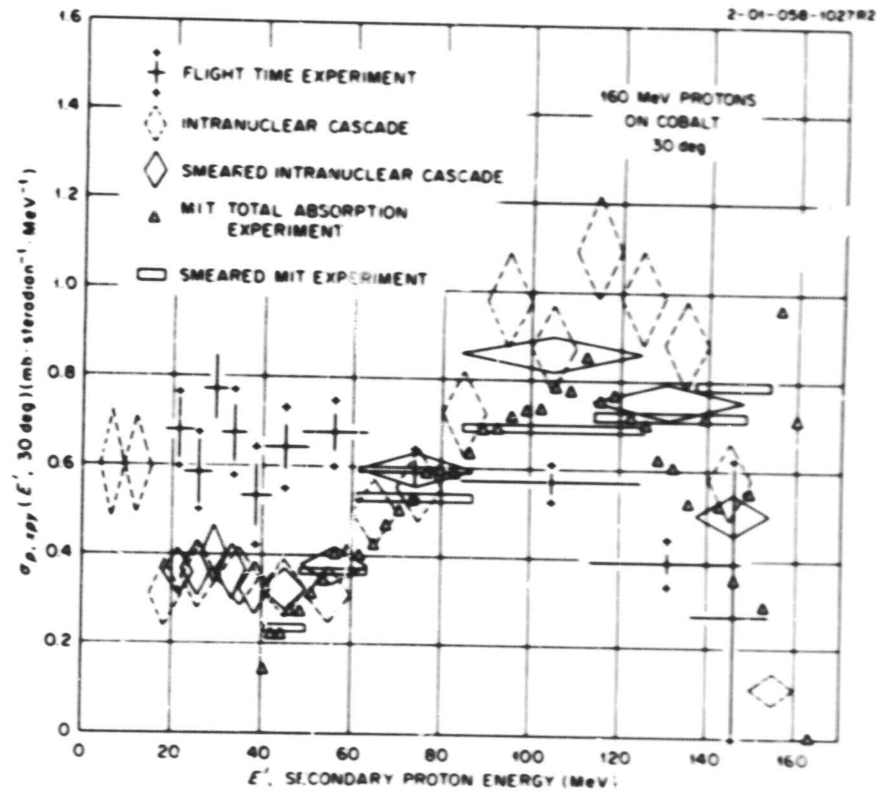

FIGURE 14.—Differential cross sections at 30° for protons from 158-MeV protons on Co. Comparisons of the flight-time data of Peelle et al. (ref 23) with the experiment of Wall and Roos (ref 22) and with the intranuclear-cascade estimates of Bertini (ref 2b) are exhibited with and without resolution smearing according to the calculated detector-response functions (of Peelle et al.).

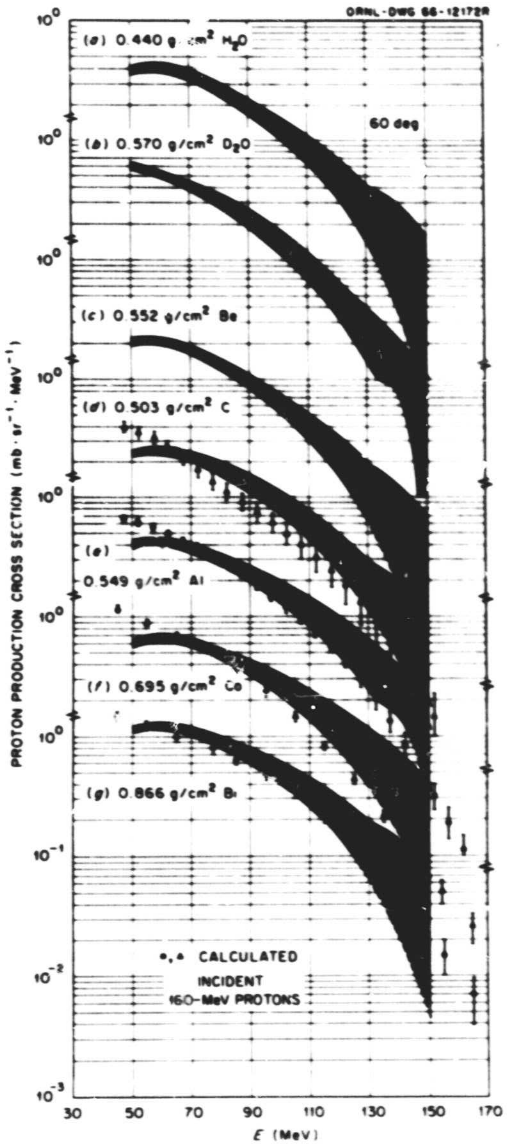

FIGURE 15.—Experimental and calculated proton cross sections (ref 12) at 60° for 160-MeV protons on a variety of elements. The points are the calculated cross sections of Bertini (ref 2b) smeared with a 15% Gaussian energy resolution so as to correspond to the energy resolution associated with the experimental results.

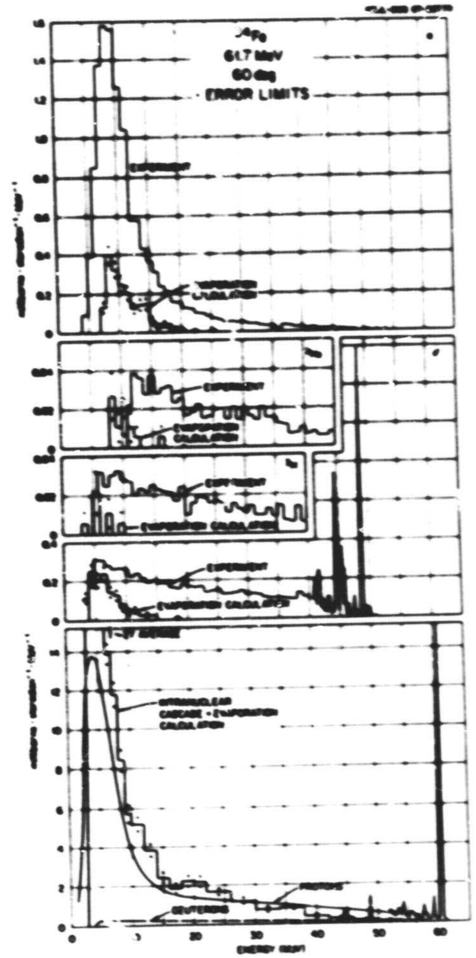

FIGURE 16.—Shown are 60° differential cross sections for hydrogen and helium particles from 62-MeV protons on ^{54}Fe (ref 24) compared with the results of Bertini's intranuclear cascade model with evaporation (ref 2). Note the shapes of the observed spectra for d, T, and ^3He and the relative intensities and shapes of observed and predicted alpha-particle spectra. The vertical scales differ from particle to particle.

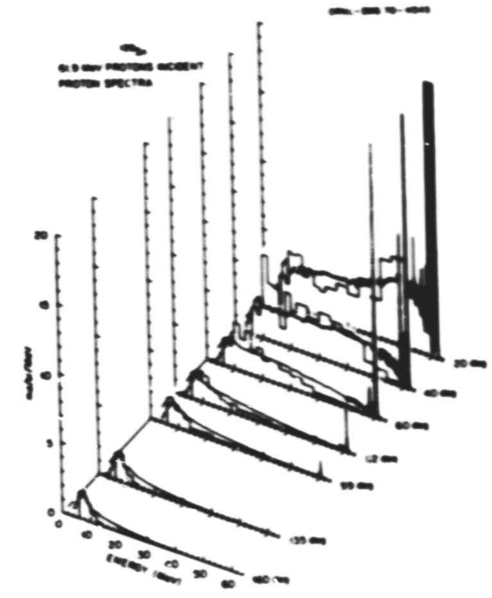

FIGURE 17.—Proton spectra as a function of angle for 62-MeV protons on ^{120}Sn (ref 24), compared to the predictions of the intranuclear cascade model (ref 2). Note that for backward angles the computed spectrum contains too few particles above the "evaporation" region.

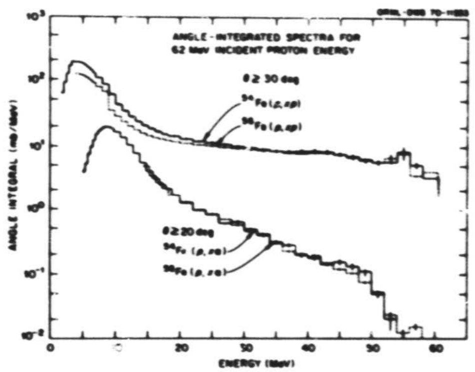

FIGURE 18.—A comparison of angle-integrated differential cross sections for protons and alpha particles from targets of ^{54}Fe and ^{56}Fe bombarded by 62-MeV protons. The results are consistent with the observed cross section being nearly independent of detailed nuclear level structure. Elastic scattering has been removed.

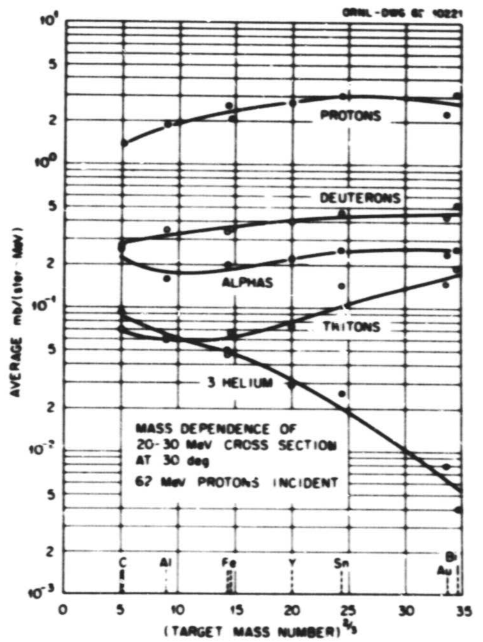

FIGURE 19.—Dependence on target mass number of the average cross sections for production by 62-MeV protons of medium energy (20 to 30 MeV) particles at 30° (ref 24). Note the relative deuteron/proton intensity, the generally smooth behavior of the cross sections, and the T/^{3}He ratio as a function of mass number.

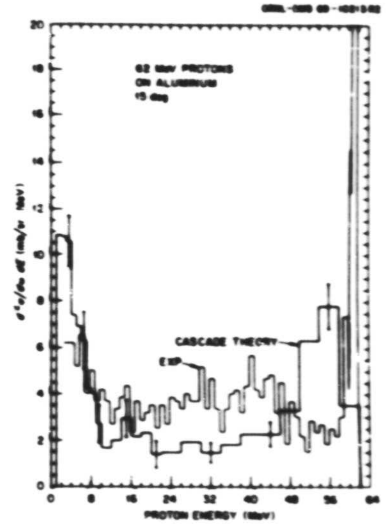

FIGURE 20.—Experimental differential proton cross section observed at 15° for 62-MeV protons on aluminum (ref 24), compared with intranuclear cascade theory (ref 2). In this energy range the theory always overestimates the quasifree scattering peak, seen here at about 54 MeV, which arises in the model from single collisions between the incident nucleon and a (moving) bound one.

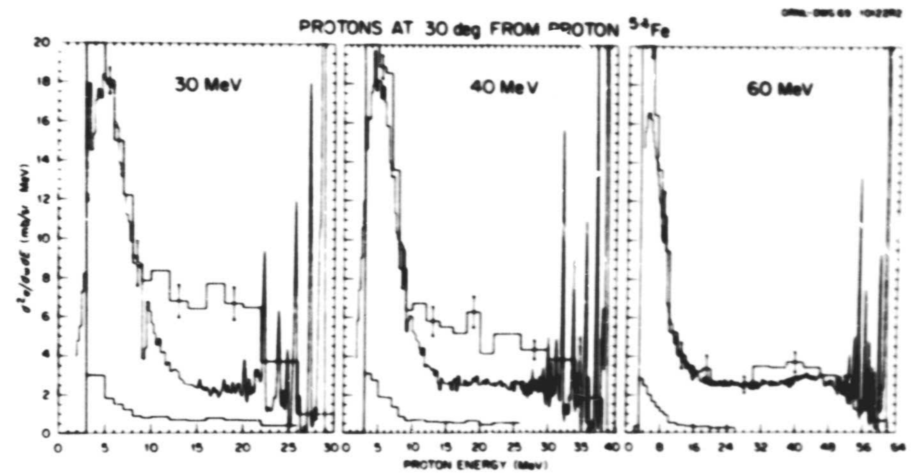

FIGURE 21.—Comparison of observed differential proton cross sections at 30° from ^{54}Fe as a function of incident energy (ref 24) compared to the corresponding predictions of the cascade model (ref 2) shown by broad-stepped histograms. (The lower histogram is 1/10 the computed cross section.)

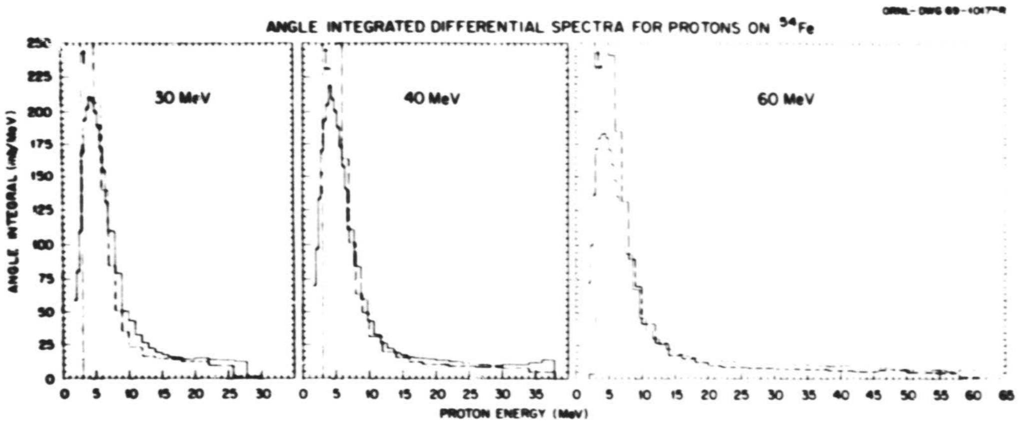

FIGURE 22.—Comparison of observed angle-integrated differential spectra from protons of various energies on ^{54}Fe (ref 24), compared with the corresponding predictions of the cascade model (ref 2). The degree of agreement is nearly independent of incident energy. Note in all cases the "evaporated" proton intensity is overestimated.

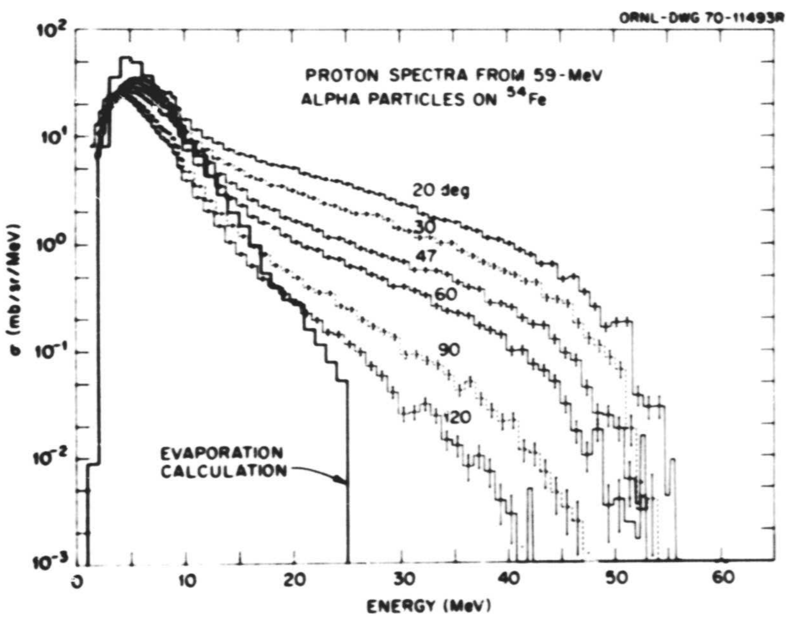

FIGURE 23.—Observed differential proton cross sections from 59-MeV alpha particles on ^{54}Fe. The evaporation calculation, using the method of Dresner and of Dostrovski (ref 26), is based on a reaction cross section of 1.7 barns; the sharp cutoff at 25 MeV is an artifice of the utilized program.

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