14

ORNL-TM-2752

A Facsimile Report

Reproduced by
UNITED STATES
ATOMIC ENERGY COMMISSION
Division of Technical Information
P.O. Box 62 Oak Ridge, Tennessee 37830

FACILITY FORM 602

N71-11786 (ACCESSION NUMBER)	(THRU)
24 (PAGES)	G3 (CODE)
CR-111411 (NASA CR OR TMX OR AD NUMBER)	24 (CATEGORY)

SQT-63441R

MASTER

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

ORNL - TM - 2752
COPY NO. -
DATE - September 15, 1969

Neutron Physics Division

CALCULATION OF THE NEUTRON SPECTRA FROM PROTON-NUCLEUS NONELASTIC COLLISIONS IN THE ENERGY RANGE 15-18 MeV AND COMPARISON WITH EXPERIMENT*

R. G. Alsmiller, Jr. and O. W. Hermann†

Abstract

The energy distribution of neutrons from proton-nucleus nonelastic collisions for 18-MeV protons on ^{14}N, ^{27}Al, ^{56}Fe, ^{181}Ta, and ^{208}Pb and for 15-MeV protons on ^{27}Al and ^{208}Pb have been calculated with the intranuclear-cascade-evaporation model of nuclear reactions and with the evaporation model of nuclear reactions. Comparisons between the calculated neutron spectra and experimental data are presented, and it is shown that neither model is entirely reliable in the energy region considered but that the intranuclear-cascade-evaporation model is the more reliable of the two.

NOTE:
This Work Partially Funded by
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Under Order H-38280A

---

*To be submitted for journal publication.

†Computing Technology Center, Union Carbide Corporation, Oak Ridge, Tennessee.

BLANK PAGE

TABLE OF CONTENTS

I. INTRODUCTION

In carrying out nucleon-transport calculations for shielding spacecraft and accelerators, it is necessary to consider particle production from nucleon-nucleus nonelastic collisions over a wide range of energies. At energies of the order of 50 MeV and above, the intranuclear-cascade-evaporation model of nuclear reactions is usually used to describe particle production from such collisions. At quite low energies (∿ 15 MeV), on the other hand, it is usually assumed that the evaporation model may be used.[1,2] In the intermediate-energy range, it is not clear which model is applicable. Of course, neither model may give reliable results in this energy range, but, since these are the only sufficiently general models that are readily available, one or the other is usually used.

In a recent paper Verbinski and Burrus[3] presented experimental data on the differential cross section for neutron production when protons in the energy range 15–18 MeV interact with a variety of nuclei. In their paper Verbinski and Burrus compared their experimental data with calculated results obtained with the intranuclear-cascade-evaporation model and with the evaporation model. The comparisons using the intranuclear-cascade-evaporation model were not definitive, as pointed out in the paper, because a constant binding energy of 7 MeV per nucleon was used in the intranuclear-cascade portion of the calculations, and discrepancies between the calculated and experimental results which could presumably be ascribed to this approximation were clearly evident. In this paper intranuclear-cascade-evaporation calculations that take into account approximately the true binding energies are presented and compared with the angle-integrated experimental data of Verbinski and Burrus. It must be emphasized that the method of including

the binding energy employed here is only approximate and is valid only because of the very low incident energy being considered.

Comparisons are also presented between the experimental data and calculated results obtained with the type of evaporation model developed by Dostrovsky *et al.*[4-6] The evaporation calculations were carried out using the code written by Dresner[7] and modified by Guthrie.[8] These calculations differ from the evaporation calculations given by Verbinski and Burrus in that the approximation introduced by LeCouteur and Lang[9,10] which they used is not employed.

In Section II the details of the calculations are described. In particular the method used to account for the correct binding energies in the intranuclear-cascade calculations is discussed. In Section III the results are presented and discussed.

II. METHOD OF CALCULATION

The intranuclear-cascade-evaporation calculations of Bertini have been described in detail previously[11,12] so only those aspects of the calculations which have been changed in obtaining the results presented here will be discussed. In the intranuclear-cascade portion of the Bertini calculations, it is usually assumed that the binding energy of the most loosely bound neutron and proton in any nucleus is 7 MeV. This approximation is not valid at the very low incident energies considered so corrections for this approximation have been introduced.

The intranuclear-cascade calculations are carried out using Monte Carlo methods. For each incident proton history, other than those which pass through the nucleus without a collision, the cascade code gives the type, energy, and angles of the cascade particles which emerge from the nucleus, as well as the type and excitation energy of the intermediate residual nucleus. This intermediate residual nucleus and excitation energy are then used in conjunction with an evaporation code to predict the "evaporation" particles which escape from the nucleus and the final residual nucleus. The procedure followed here is to introduce corrections into each intranuclear-cascade history and then perform the evaporation calculations using the corrected intermediate residual nucleus and excitation energy. The correct binding energies have always been used in the evaporation calculations, so no additional corrections are needed.

The only case considered here is the nonelastic collision between an incident proton, with kinetic energy E_p, and a nucleus with nucleon number A and charge number Z. To understand the manner in which the intranuclear-cascade histories are corrected, consider first those incident particles that collide with the nucleus but give rise to no cascade particles. For these histories the intermediate residual nucleus is the target nucleus with one additional proton and the excitation energy is the incident proton kinetic energy plus the binding energy of the most loosely bound proton in the nucleus that has nucleon number A + 1 and charge number Z + 1. In the calculations reported here, this excitation energy is obtained using the correct binding energy rather than 7 MeV. It must be understood that this procedure is only approximate because the information that in a given history no cascade particle is emitted is obtained from the intranuclear-cascade code, and in generating this information the approximate 7-MeV binding energy was used. Throughout this paper the binding energies used are taken from the work of Mattauch, Thiele, and Wapstra.[13]

Consider next those histories in which a single cascade proton, with kinetic energy E'_p, is emitted. The intermediate residual nucleus in this case is the same as the target nucleus, and the excitation energy of this nucleus, E^*, as calculated by Bertini and as used in the calculations reported here, is

$$E^* = E_p - E'_p \; . \tag{1}$$

That is, for these histories no correction is applied because the binding energy does not occur in the expression for the excitation energy. This procedure, however, is only an approximation because the approximate binding energy of 7 MeV was used in the intranuclear-cascade calculations which gave the value E'_p.

Consider next those histories in which one cascade neutron with kinetic energy E'_n is emitted. The intermediate residual nucleus in this case has nucleon number A and charge number Z + 1, and the excitation energy is given by

$$\begin{aligned} E^* &= E_p + m_p + M(A, Z) - E_n - m_n - M(A, Z + 1) \\ &= E_p - E'_n + B(A, Z + 1) - B(A, Z) \; , \end{aligned} \tag{2}$$

where

m_p = the proton rest energy,

m_n = the neutron rest energy,

$M(A, Z)$ = the rest energy of nucleus with nucleon number A and charge number Z,

$B(A, Z)$ = the total binding energy of nucleus with nucleon number A and charge number Z.

In the Bertini calculations it is assumed that

$$B(A, Z + 1) - B(A, Z) = 0 \qquad (3)$$

and

$$E^{*} = E_{p} - E'_{nB} , \qquad (4)$$

where

E'_{nB} = the kinetic energy of the emitted neutron as calculated.

This has the consequence that in some histories E'_{nB} may be nearly equal to E_p and thus neutrons are emitted with energies which are not physically allowed, that is, with energies which would not be allowed by the correct binding energies.[3] In the calculations reported here, all histories in which one cascade neutron was emitted were corrected by taking the energy of the emitted neutron E'_n to be

$$E'_{n} = E'_{nB} + B(A, Z + 1) - B(A, Z) \qquad (5)$$

and the excitation energy of the intermediate residual nucleus to be

$$E^{*} = E_{p} - E'_{nB} . \qquad (6)$$

This procedure has the consequence that neutrons with kinetic energies that are physically not allowed are not obtained in the calculation, but this manner of correction is still only approximate. It has the further consequence that cascade neutrons which were emitted in the original calculations are no longer emitted. In the calculations of Bertini, the separation between the cascade and evaporation phase of the calculations is determined by an energy parameter E_c.[11] When the energy of a cascade collision product with respect to the outside of the nucleus falls below the energy E_c, it is assumed that this particle can no longer escape from the nucleus as a cascade

particle but rather its energy becomes part of the excitation energy of the intermediate residual nucleus. When the correction given by Eq. 5 is applied to an emitted cascade neutron, it is possible that the kinetic energy E'_n is below the energy E_c, and thus by the standard criterion this neutron should not have escaped from the nucleus. When this occurs, it is assumed that for this history no cascade particle was emitted and the intermediate residual nucleus and excitation energy are calculated as in the case when no cascade particles are emitted.

Consider next those histories in which more than one cascade nucleon is emitted. At the energies of interest here, the probability of emission of more than one cascade nucleon is very unlikely, and in those few histories where this does occur no correction is made. It should be noted that a correction procedure such as that given in Eq. 5 cannot unambiguously be applied to those histories in which more than one cascade particle is emitted because the manner in which the binding energy correction is to be split between the kinetic energies of the several emitted particles is not clear.

After the corrections described above had been made in the intranuclear-cascade histories, the evaporation calculations were carried out using the code EVAP-3.[8] In this portion of the calculations, the excitation energy and intermediate residual nucleus are obtained in the manner described above and not in the manner described in ref. 8. In the large majority of calculations that have been done with the intranuclear-cascade-evaporation model and in most of the calculations reported here, the cutoff energy E_c, which determines when a nucleon can no longer be emitted from the nucleus as a cascade particle, has been taken to be the same for neutrons and protons and has been taken to be 1/2 the Coulomb potential at the surface of the nucleus. Bertini[b] has recently modified his code so that it is now possible to specify separate neutron and proton cutoff energies. To test the sensitivity of the calculations to the cutoff energies, a few calculations have been carried out with the cutoff energy for neutrons, E_{cn}, set equal to zero and the cutoff energy for protons, E_{cp}, set equal to the Coulomb potential at the surface of the nucleus.

In contrast to the intranuclear-cascade-evaporation model of nuclear reactions, one may use the evaporation model by itself to predict the emission spectra of particles from proton-nucleus nonelastic collisions. In this case, one assumes that all incident-particle collisions produce an excited compound nucleus and the evaporation calculations always start from a nucleus with nucleon number $A + 1$, charge number $Z + 1$, and with an excitation energy given by the incident proton kinetic energy in the center-of-mass system plus the binding energy of a proton in the nucleus with nucleon number $A + 1$ and charge number $Z + 1$. The calculated results presented in the next section of this paper using the evaporation model by itself were obtained with the code EVAP-3.[8]

One significant point to be noted is that the intranuclear-cascade-evaporation model is capable of giving an estimate of the total nonelastic cross section, but the evaporation model alone gives no such estimate; that is, the evaporation model predicts the particle spectra but does not predict the total nonelastic cross section. In the comparisons presented in this paper, the nonelastic cross section calculated with the intranuclear-cascade-evaporation model has also been used with the spectra obtained from the evaporation model. That is, the same total nonelastic cross section has been used with both of the calculational models employed.

III. RESULTS AND DISCUSSION

Calculations with the two models have been carried out for 18-MeV protons on ^{14}N, ^{27}Al, ^{56}Fe, ^{181}Ta, and ^{208}Pb and for 15-MeV protons on ^{27}Al and ^{208}Pb. In the cases of 15- and 18-MeV protons on ^{27}Al and 15-MeV protons on ^{208}Pb, the intranuclear-cascade-evaporation calculations have been carried out with two different sets of cutoff energies, as explained in Section II. The calculated differential cross sections for neutron production are compared with the experimental data of Verbinski and Burrus[3] in Figs. 1 to 7. Because in the experiment the incident protons lost energy in the targets, the data do not correspond to a single proton energy but rather to a small range of energies. In each of the figures the average energy of the protons in the experimental target, $\overline{E}_p$, and the proton energy used in the calculation are given.

In Fig. 1 the comparisons are given for 18-MeV protons on ^{14}N. In this case, both calculational models underestimate the low-energy portion of the differential production cross section. The cascade-evaporation model overestimates and the evaporation model seriously underestimates the high-energy portion of the cross section. The calculated spectrum has not been spread to account for spectrometer resolution, and this is presumably the reason why there are a few neutrons emitted experimentally at higher energies (> 12 MeV) than the highest energy given by the calculation. The total cross section that was used with the evaporation model is somewhat arbitrary (see Section II), and the agreement at the lower energies obtained with this model could be improved by the use of a more appropriate cross section, but this would not appreciably improve the agreement at the higher energies.

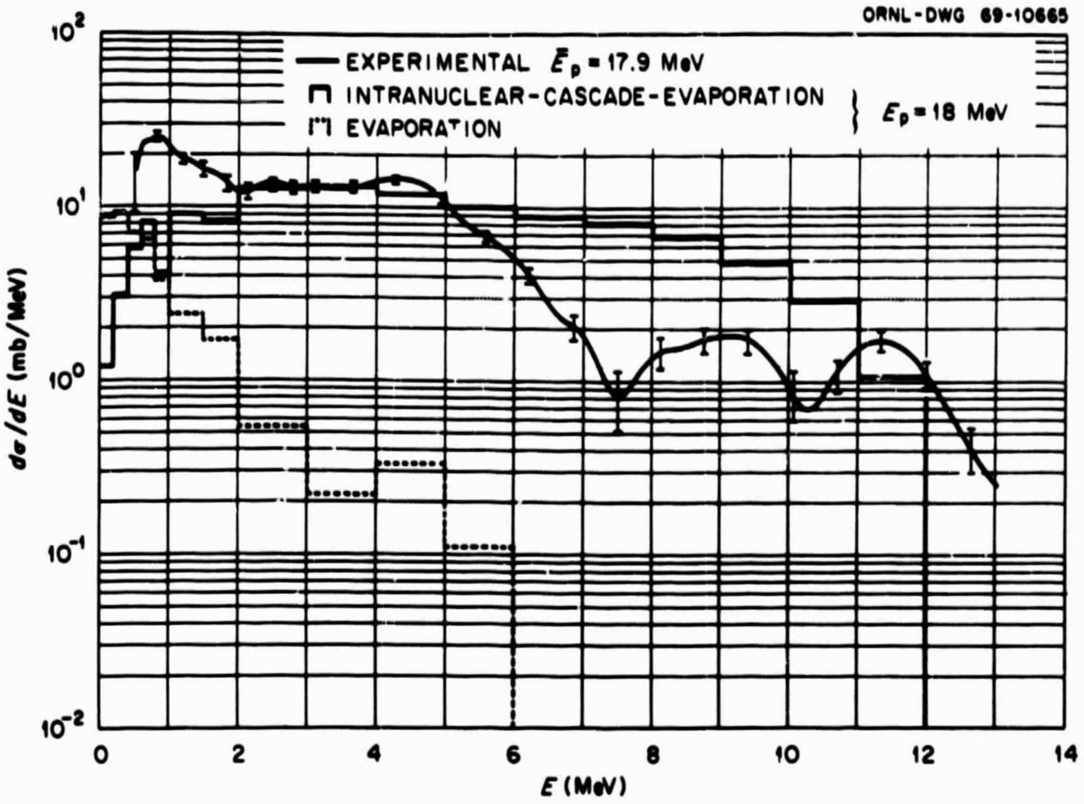

Fig. 1. Differential Cross Section for Neutron Emission from 18-MeV Protons on ^{14}N.

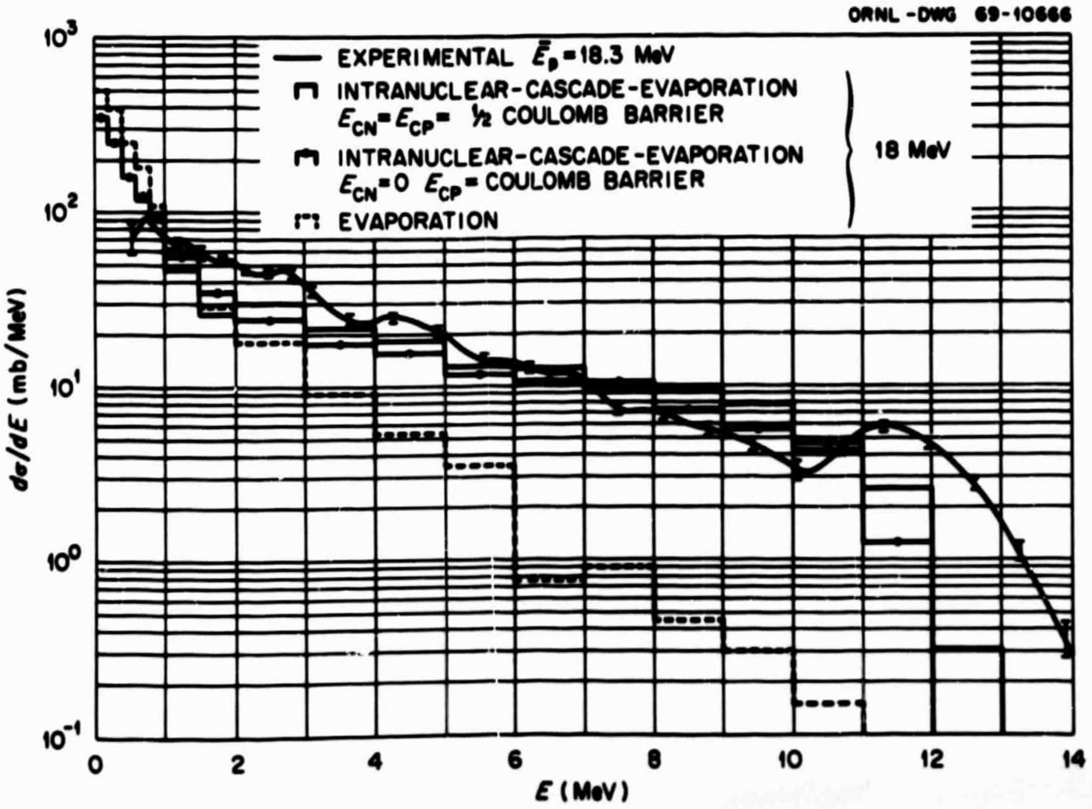

Fig. 2. Differential Cross Section for Neutron Emission from 18-MeV Protons on ^{27}Al.

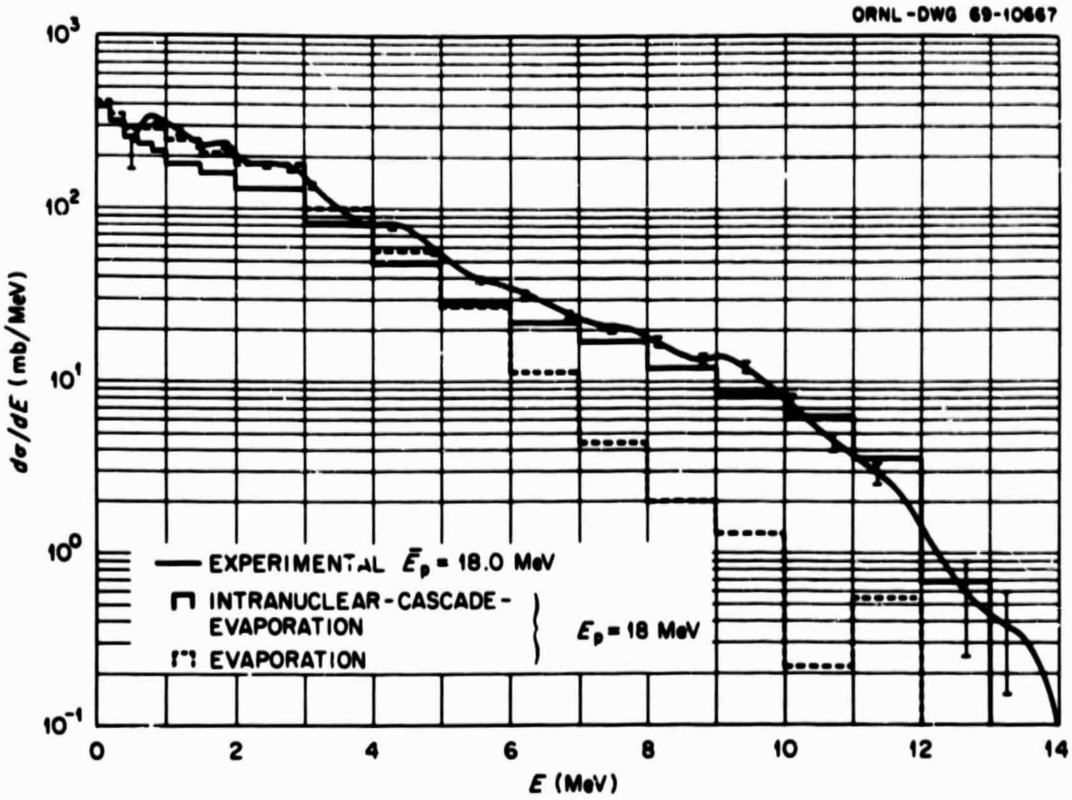

Fig. 3. Differential Cross Section for Neutron Emission from 18-MeV Protons on ^{56}Fe.

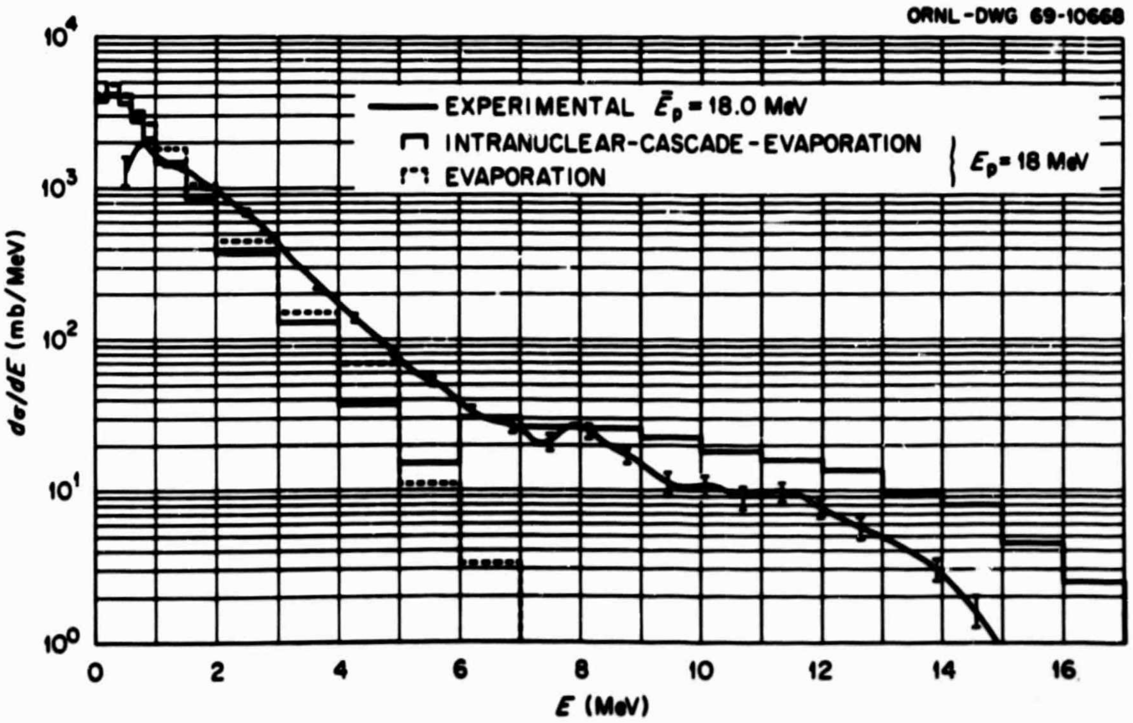

Fig. 4. Differential Cross Section for Neutron Emission from 18-MeV Protons on ^{181}Ta.

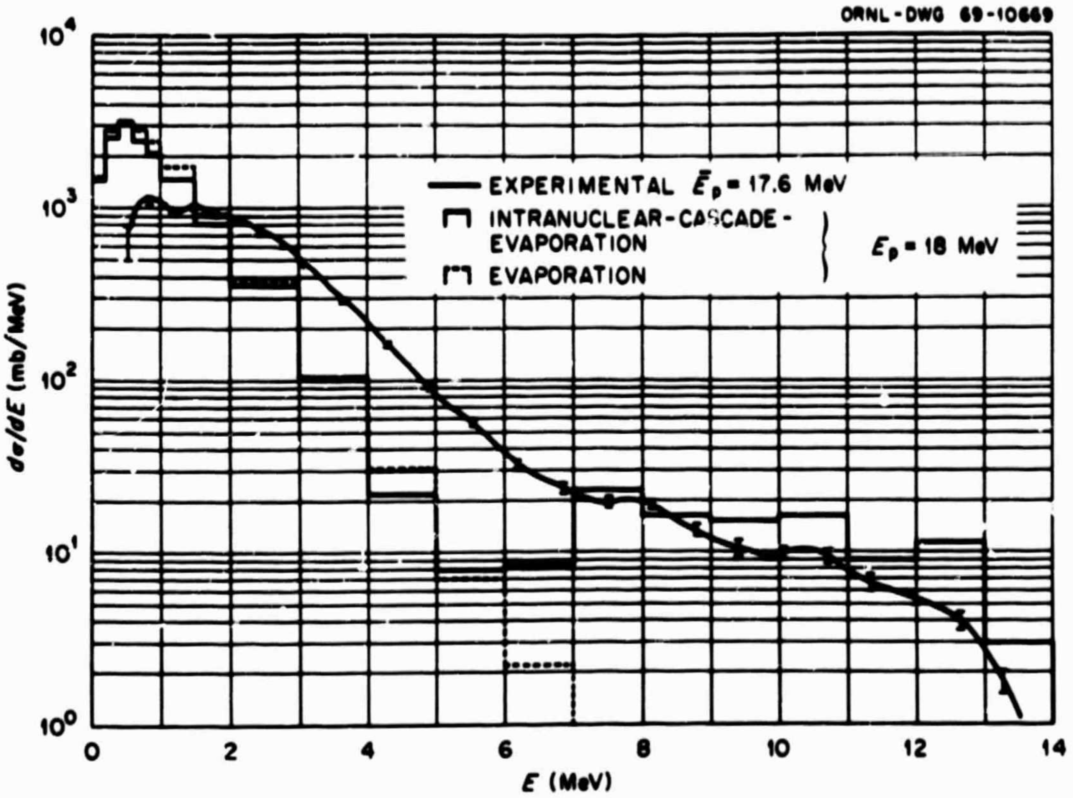

Fig. 5. Differential Cross Section for Neutron Emission from 18-MeV Protons on ^{208}Pb.

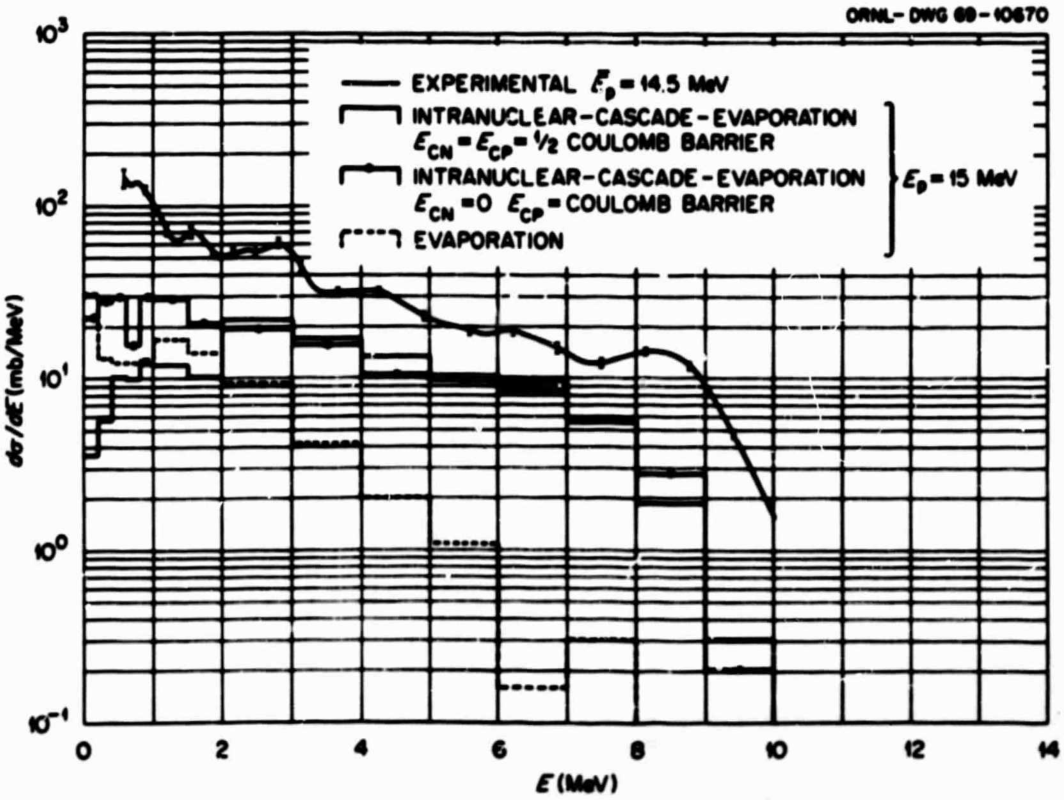

Fig. 6. Differential Cross Section for Neutron Emission from 15-MeV Protons on ^{27}Al.

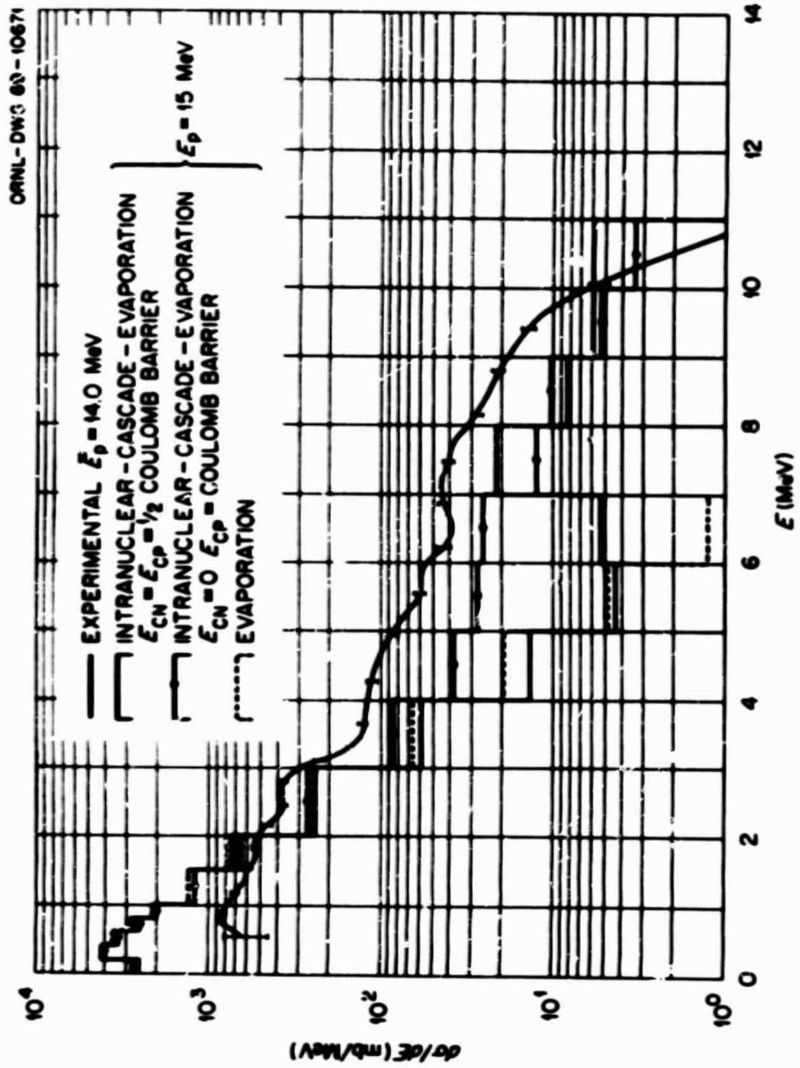

Fig. 7. Differential Cross Section for Neutron Emission from 15-MeV Protons on ^{208}Pb.

In Fig. 2 the comparisons are given for 18-MeV protons on ^{27}Al. The intranuclear-cascade-evaporation calculations have been carried out using the two different sets of cutoff energies, as explained in Section II, and, as indicated in the figure, the results in this case are insensitive to the cutoff energies. The results from the cascade-evaporation model are in substantial agreement with the experimental data over much of the energy range. The results from the evaporation model do not agree at all well with the experimental data.

In Fig. 3 the results are given for 18-MeV protons on ^{56}Fe. At the lower energies the cascade-evaporation results underestimate the cross section, but the agreement at the higher energies is quite good. The evaporation results agree with the experimental data at the lower energies but underestimate seriously the cross section at the higher energies.

In Figs. 4 and 5 the comparisons for 18-MeV protons on ^{181}Ta and ^{208}Pb, respectively, are shown. The results here are similar to those given in the previous figures except that in the case of ^{181}Ta the cascade-evaporation calculations give an overestimate of the high-energy portion of the cross section.

In Figs. 6 and 7 the comparisons are presented for 15-MeV protons on ^{27}Al and ^{208}Pb, respectively. In these cases, the intranuclear-cascade-evaporation calculations have been carried out using the two different sets of cutoff energies, as explained in Section II. The calculated results in Al are insensitive to the cutoff energies used except at the lower emission energies. The calculated results in ^{208}Pb are reasonably insensitive to the cutoff energies except in the 4- to 6-MeV region. In this energy range the spectrum obtained with the values E_{cn} = 0 and E_{cp} = the Coulomb potential at the surface of the nucleus is in much better agreement with the experimental data than is the spectrum obtained with the values $E_{cn} = E_{cp} = 1/2$ the Coulomb potential at the surface of the nucleus. In Fig. 6 all of the calculated results seriously underestimate the experimental data, but it is clear that the shape of the spectrum given by the cascade-evaporation model is more realistic than that given by the evaporation model. In Fig. 7 it is again clear that the cascade-evaporation model is to be preferred to the evaporation model.

IV. CONCLUSIONS

Neither the intranuclear-cascade evaporation model nor the evaporation model gives entirely reliable results in the energy region considered here. However, if one or the other of these models must be used at the low energies considered here, it seems clear from the comparisons presented that the intranuclear-cascade-evaporation model is to be preferred. In this conclusion it is assumed, of course, that the correct binding energies or corrections such as those applied here are used in the cascade calculations.

On the basis of the few cases considered here, it is not possible to draw any general conclusions concerning the most appropriate cutoff energies to be used in the intranuclear-cascade-evaporation calculations, but the indications are that the values $E_{cn} = 0$ and E_{cp} = the Coulomb potential at the surface of the nucleus give a more reliable spectrum than do the values $E_{cn} = E_{cp} = 1/2$ the Coulomb potential at the surface of the nucleus. This is to some extent to be expected since the values $E_{cn} = 0$, E_{cp} = the Coulomb potential at the surface of the nucleus are physically more realistic than the values $E_{cn} = E_{cp} = 1/2$ the Coulomb potential at the surface of the nucleus.

ACKNOWLEDGMENT

We are indebted to Dr. H. W. Bertini for many helpful discussions concerning the intranuclear-cascade-evaporation model of nuclear reactions.

FOOTNOTES

a. This work partially funded by National Aeronautics and Space Administration (Order H-38280A) under Union Carbide Corporation's contract with the U. S. Atomic Energy Commission.

b. We thank Dr. H. W. Bertini for making this revised code available to us.

REFERENCES

1. C. D. ZERBY and W. E. KINNEY, "Calculated Tissue Current-to-Dose Conversion Factors for Nucleons Below 400 MeV," Nucl. Instr. Methods 36, 125 (1965).
2. D. C. IRVING, R. G. ALSMILLER, Jr., and H. S. MORAN, "Tissue Current-to-Dose Conversion Factors for Neutrons with Energies from 0.5 to 60 MeV," Nucl. Instr. Methods 51, 129 (1967).
3. V. V. VERBINSKI and W. R. BURRUS, "Direct and Compound-Nucleus Neutrons from 14-18-MeV Protons on ^{9}Be, ^{14}N, ^{27}Al, ^{56}Fe, ^{115}In, ^{181}Ta, and ^{208}Pb and from 33-MeV Bremsstrahlung on ^{27}Al, ^{206}Pb, ^{208}Pb, and ^{209}Bi," Phys. Rev. 177, 1671 (1969).
4. I. DOSTROVSKY, Z. FRAENKEL, and G. FRIEDLANDER, "Monte Carlo Calculations of Nuclear Evaporation Processes. III. Applications to Low-Energy Reactions," Phys. Rev. 116, 683 (1959).
5. I. DOSTROVSKY, Z. FRAENKEL, and L. WINSBERG, "Monte Carlo Calculations of Nuclear Evaporation Processes. IV. Spectra of Neutrons and Charged Particles from Nuclear Reactions," Phys. Rev. 118, 781 (1960).
6. I. DOSTROVSKY, Z. FRAENKEL, and P. RABINOWITZ, "Monte Carlo Calculations of Nuclear Evaporation Processes. V. Emission of Particles Heavier Than He^4," Phys. Rev. 118, 791 (1960).
7. L. DRESNER, "EVAP - a FORTRAN Program for Calculating the Evaporation of Various Particles from Excited Nuclei," ORNL-TM-196, Oak Ridge National Laboratory (1961).
8. M. P. GUTHRIE, "EVAP-2 and EVAP-3: Modifications of a Code to Calculate Particle Evaporation from Excited Compound Nuclei," ORNL-4379, Oak Ridge National Laboratory (1969).

9. K. J. LeCOUTEUR, *Nuclear Reactions*, ed. P. M. Endt and M. Demeur, Vol. I, Chapter VII, North Holland Publishing Co., Amsterdam (1959).

10. K. J. LeCOUTEUR and D. W. LANG, "Neutron Evaporation and Level Densities in Excited Nuclei," *Nucl. Phys.* 13, 32 (1959).

11. H. W. BERTINI, "Monte Carlo Calculations on Intranuclear Cascades," ORNL-3383, Oak Ridge National Laboratory (1963).

12. H. W. BERTINI, "Low Energy Intranuclear Cascade Calculations," *Phys. Rev.* 131, 1801 (1963); with erratum, *Phys. Rev.* 138, AB2 (1965).

13. J. H. E. MATTAUCH, W. THIELE, and A. H. WAPSTRA, "1964 Atomic Mass Table," *Nucl. Phys.* 67, 1 (1965).