Odd-Even Dependence of Nuclear Level Density Parameters*

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Previously reported experimental (n,p) and (n,α) cross-section data have been analyzed to determine nuclear level density parameters for the Fermi gas model which best fit the experimental data for target nuclei ranging in mass number from 9 to 64. Level density parameters for odd-odd and even-even nuclei are obtained in terms of those for the better-known odd-A values. The results of this analysis are $\frac{1}{2}C_{\text{odd-odd}} = C_{\text{odd }A} = 5C_{\text{even-even}}$. Brief mention is made of the direct-interaction contribution in (n,p) reactions. Experimental measurements which would be most beneficial for further theoretical analysis are suggested.

1. INTRODUCTION

IT appears that the complexity of a strongly bound many-body system precludes the possibility of obtaining an exact representation for the nuclear level density. Many attempts[1] have been made, however, to deduce approximate expressions which do not represent all of the irregularities actually appearing in the level density but which do provide smooth curves that are representative of the true density averaged over many levels. One such representation, which is most often used, is based on the statistical model[2] of nuclear reactions. The Fermi gas expression for the nuclear level density is

$$\rho(E) = C \exp[2(aE)^{\frac{1}{2}}], \tag{1}$$

where C and a are parameters which depend upon the nuclear charge and mass number. Unfortunately, the exact variation of the parameters C and a with the nuclear properties is not yet well known.

Much consideration has been given to the study of the parameter a and its variation, in particular, with the nuclear mass number. Only limited data are available, and they do not seem to be in complete agreement. Igo and Wegner[3] point out that the values obtained from the analysis of γ ray, neutron, and charged-particle data are relatively independent of A (in disagreement with the Fermi gas model) and are abnormally small for large A. Other data, e.g., certain reaction and inelastic scattering data,[4,5] do show a dependence upon mass number. In their study of the photocapture process, Heidmann and Bethe[6] deduced values of the parameter a for odd mass numbers in the range $15<A<70$ which leads to an approximate expression of the form

$$a = 0.035(A-12) \text{ Mev}^{-1}. \tag{2}$$

Very little is known on the subject concerning even-A nuclei. The results of Heidmann and Bethe[6] are consistent with those reported by Blatt and Weisskopf,[7] who also emphasize that the parameters which they list apply only to odd values of A. A summary of the variety of a values which can be obtained from the analysis of various reaction data has been given by Dostrovsky, Rabinowitz, and Bivins.[8]

Somewhat less work has been reported on the parameter C. Blatt and Weisskopf[7] report values for odd-A nuclei. Though not much is known on the subject, it appears[9,10] that the values of C for a given odd-even character are related to the values of C for other odd-even configurations by a constant multiplicative factor. The value of this factor is not well known. This lack of data for even-A nuclei together with the fact that little quantitative information exists relating the values of C for different odd-even combinations suggested that a study be made to determine these level density parameters. The present paper describes an attempt to extract this information from an analysis of experimental (n,p) and (n,α) cross-section data.

2. METHOD OF ANALYSIS

The computations reported in this paper were performed on the IBM 704 in the Convair-Fort Worth computing laboratory. The calculations were based on the compound nucleus model using the methods

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[1] H. A. Bethe, Phys. Rev. **50**, 332 (1936); Revs. Modern Phys. **9**, 69 (1937). I. N. Sneddon and B. F. Touschek, Proc. Cambridge Phil. Soc. **44**, 391 (1948); C. Block, Phys. Rev. **93**, 1094 (1954); T. D. Newton, Can. J. Phys. **36**, 804 (1956); and N. Rosenzweig, Phys. Rev. **108**, 817 (1957).
[2] D. C. Peaslee, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1955), Vol. 5, p. 99. K. J. LeCouteur, *Nuclear Reactions*, edited by P. M. Endt and M. Demeur (North Holland Publishing Company, New York, 1959).
[3] G. Igo and H. E. Wegner, Phys. Rev. **102**, 1364 (1956).
[4] J. M. B. Lang and K. J. LeCouteur, Proc. Phys. Soc. (London) **A67**, 586 (1954).
[5] M. El-Nadi and M. Wafik, Nuclear Phys. **9**, 22 (1959); *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 14, p. 54.
[6] J. Heidmann and H. A. Bethe, Phys. Rev. **84**, 274 (1951).
[7] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, New York, 1952).
[8] I. Dostrovsky, P. Rabinowitz, and R. Bivins, Phys. Rev. **111** 1659 (1958).
[9] E. Segrè *Experimental Nuclear Physics* (John Wiley & Sons, New York, 1953), Vol. II, p. 45.
[10] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940); V. F. Weisskopf, Atomic Energy Commission Report MDDC-1175, 1945 (unpublished).

described by Moore,[11] namely

$$\sigma(n,\alpha)=\sigma_c(n)F_\alpha{}^*/\textstyle\sum_i F_i, \qquad (3.a)$$

$$\sigma(n,p)=\sigma_c(n)F_p{}^*/\textstyle\sum_i F_i, \qquad (3.b)$$

where $\sigma_c(n)$ is the cross section for formation of the compound nucleus by neutrons. The quantities F_i give a measure of the probability of emission of particle i (regardless of whether or not a secondary particle follows the emission of i), and the $F_i{}^*$ give a measure of the emission of particle i (and only particle i). The F_i are given by

$$F_n=\frac{2m_n}{\hbar^2}\int_0^{E_n} E_n'\sigma_c(E_n')\rho(E_n-E_n')dE_n', \qquad (4.a)$$

$$F_p=\frac{2m_p}{\hbar^2}\int_0^{E_n+Q_{np}} E_p'\sigma_c(E_p') \times\rho(E_n+Q_{np}-E_p')dE_p', \qquad (4.b)$$

$$F_\alpha=\frac{2m_\alpha}{\hbar^2}\int_0^{E_n+Q_{n\alpha}} E_\alpha'\sigma_c(E_\alpha') \times\rho(E_n+Q_{n\alpha}-E_\alpha')dE_\alpha', \qquad (4.c)$$

in which $\sigma_c(E_i')$ is the cross section for formation of the compound nucleus by particle i incident upon the residual nucleus, and $\rho(U)$ is the nuclear level density evaluated at excitation energy U. The $F_i{}^*$ are given by

$$F_p{}^*=\frac{2m_p}{\hbar^2}\int_{\epsilon_p}^{E_n+Q_{np}} E_p'\sigma_c(E_p') \times\rho(E_n+Q_{np}-E_p')dE_p', \qquad (5.a)$$

$$F_\alpha{}^*=\frac{2m_\alpha}{\hbar^2}\int_{\epsilon_\alpha}^{E_n+Q_{n\alpha}} E_\alpha'\sigma_c(E_\alpha') \times\rho(E_n+Q_{n\alpha}-E_\alpha')dE_\alpha'. \qquad (5.b)$$

In Eqs. (5), the quantity ϵ_i denotes the minimum energy with which particle i may be emitted without leaving sufficient excitation energy to subsequently emit a neutron. For an incident neutron energy below the threshold E_i^* for the $(n;i,n)$ reaction, $\epsilon_i=0$. For an incident neutron energy equal to or greater than this threshold, $\epsilon_i=E_n-E_i^*$. The threshold energy E_i^* is equal to the binding energy of the last ith particle in the target nucleus, which is also equivalent to $(\mathrm{BE})_n-Q_{ni}$, where $(\mathrm{BE})_n$ is the neutron binding energy in the residual nucleus after emission of the particle i, and Q_{ni} is the Q value for the (n,i) reaction. If the $F_i{}^*$ are taken equal to the F_i, then competition from the $(n;i,n)$ reaction has been ignored. The calculations reported herein use compound nucleus cross sections based on the continuum model and were taken from the tables given by Blatt and Weisskopf for $r_0=1.5$ fermis.[7] Terrell and Holm[12] have pointed out that results are not significantly altered if optical model cross sections are used. The Q values were taken from the compilation of Howerton.[13] The conventional assumption is made that

$$C_{\text{odd-even}}=C_{\text{even-odd}}=C_{\text{odd }A}, \qquad (6)$$

where $C_{\text{odd }A}$ is known and is that reported by Blatt and Weisskopf.[7] It is further assumed that both C and a are energy-independent,[5] and that the excitation energy is measured from the ground state.[5,14–15a]

An initial calculation was made using the values of a and C reported in reference 7, in which no regard is made for the odd-even structure of the nucleus. A comparison of the results of the initial calculations with experimental cross section data showed certain systematic disagreement between theory and experiment. The (n,p) calculations were low for even-A target reactions and high for odd-A target reactions, while the (n,α) calculations were low for odd target nuclei and appeared to be low for even target nuclei. These results are summarized in Table I. These comparisons suggest that the odd-even nature of the nucleus should be taken into account in the level density parameters.

Target nuclei must be one of four types $({}_ZX^A)$:

(a) ${}_{\text{odd}}X^{\text{odd}}$,
(b) ${}_{\text{even}}X^{\text{odd}}$,
(c) ${}_{\text{even}}X^{\text{even}}$,
(d) ${}_{\text{odd}}X^{\text{even}}$.

Essentially no (n,p) nor (n,α) cross-section data are available for nuclei in classes (b) and (d). Hence, an analysis of (n,p) and (n,α) data must be based primarily on ${}_{\text{odd}}X^{\text{odd}}$ and ${}_{\text{even}}X^{\text{even}}$ target nuclei measurements. The residual nuclei have the odd-even (neutron-proton) structure shown in Table II. Since case (a) involves only one even-A residual nucleus, we consider it first. For this case, the residual nuclei for neutron

TABLE I. Systematics of initial calculations.

Target type	$\sigma(n,p)_{\text{calc.}}/\sigma(n,p)_{\text{expt.}}$	$\sigma(n,\alpha)_{\text{calc.}}/\sigma(n,\alpha)_{\text{expt.}}$
Odd target nuclei	>1	<1
Even target nuclei	<1	<1

[11] R. G. Moore, Jr., Revs. Modern Phys. **32**, 101 (1960).

[12] J. Terrell and D. M. Holm, Phys. Rev. **109**, 2031 (1958).

[13] R. J. Howerton, University of California Radiation Laboratory Report UCRL-5351, 1958 (unpublished).

[14] H. Hurwitz, Jr., and H. A. Bethe, Phys. Rev. **81**, 898 (1951).

[15] A. G. W. Cameron, Can. J. Phys. **35**, 666 (1957).

[15a] *Note added in proof.*—The analysis is currently being extended to include the odd-even effect in the exponent of the level density expression in order to further improve agreement between theory and experiment. This effect is being accounted for by introducing an effective excitation energy U' related to the excitation energy U in the following way: $U'=U-\delta$, where δ depends upon the odd-even character of the nucleus. See for example: Dostrovsky, Fraenkel, and Friedlander, Phys. Rev. **116**, 683 (1959); S. Kaufman, Phys. Rev. **117**, 1532 (1960).

and proton emission are odd-A (see Table II), whereas the residual nuclei for alpha-particle emission are even-A. Since it was believed that the level density parameters used were not applicable for even mass nuclei, the discrepancy between calculated and experimental curves for ${}_{\text{odd}}X^{\text{odd}}$ target nuclei may be attributed to the use of incorrect parameters for even residual nuclei. The relative probability for alpha-particle emission becomes larger with increasing level density; therefore, an increase in the level density for the residual nuclei in the alpha-particle emission process (i.e., the odd-odd nuclei) would raise the calculated (n,α) cross section while lowering the calculated (n,p) cross section and, hence, give better agreement with experimental results. This finding appears to be in agreement with the belief that odd-odd nuclei may have higher level densities than odd-A nuclei.[14]

The experimental data thus seem to indicate that ignoring odd-even effects underestimates the level density for odd-odd nuclei. The calculated cross sections seem to differ from the experimental values by approximately a constant multiplicative factor. We seek this factor by which C for odd-A nuclei can be multiplied to obtain those for odd-odd nuclei so as to predict results in agreement with the measurements for ${}_{\text{odd}}X^{\text{odd}}$ reactions. Before determining this constant factor, one must first investigate the level structures of the residual nuclei. Reactions in which the decay can proceed only to a few low-lying levels of the residual nucleus cannot justifiably be used to fit a compound nucleus calculation, for according to Butler,[16] the direct-interaction process may constitute a significant contribution to the yield of the reaction in such cases. The only measured (n,p) or (n,α) cross sections whose residual nuclei have level structures which suggest a direct interaction are F^{19} and O^{16}. This point will be discussed later.

The analysis of target nuclei of the form ${}_{\text{even}}X^{\text{even}}$ proceeds by using the results of the analysis of ${}_{\text{odd}}X^{\text{odd}}$ data, where the residual nuclei have the structures shown in Table II. Constants are now assumed to be known for all but the even-even nuclei and $C_{\text{even-even}}$ is adjusted to fit the data.

3. DISCUSSION

The values of a used in the present analysis were taken from the table given by Blatt and Weisskopf,[7] ignoring the odd-even character of the nucleus. The parameter a may vary linearly with the atomic mass number. The results reported by Blatt and Weisskopf[7] do not show a linear relationship in the high-mass region; therefore, it may be that for heavier nuclei ($A>70$), the curve given by El-Nadi and Wafik,[5] for example, better represents the true level density. The curves given in references 5 and 7 do not differ significantly for $A<70$. An analysis in the high mass region could aid in increasing our knowledge of the parameter a. Since (n,p) and (n,α) cross-section data are not available in this region, it may be that an analysis of $(n,2n)$ data could be very useful in such a study.

The calculated curves are shown in Figs. 1 to 15; these figures contain several theoretical curves for which no measurements are available. The experimental data were taken from the compilation due to Howerton[17] unless otherwise stated. In the figures, the solid curves denote (n,p) cross sections, and the dashed curves denote (n,α) cross sections. The curves labeled (A) are based on both a and C values given by Blatt and Weisskopf,[7] in which no account is taken of the odd-even dependence of C. Curves labeled (B) are based on a values from Blatt and Weisskopf[7] and C values from Eq. (7). The experimental curves are shown by data points connected by solid or dashed lines as above.

The results of the analysis[18] are given by the equation

$$\tfrac{1}{2}C_{\text{odd-odd}}=C_{\text{even-odd}}=C_{\text{odd-even}}=5C_{\text{even-even}}, \qquad (7)$$

in which the factor $\frac{1}{2}$ was obtained from ${}_{\text{odd}}X^{\text{odd}}$ target data and the factor 5 from ${}_{\text{even}}X^{\text{even}}$ target data. These results appear to be in agreement with the suggestion of Hurwitz and Bethe.[14]

The values of C deduced in the present study are based on the choice of the values of a discussed above, and a different selection for a would likely yield different results for C. The reactions used in the analysis are shown in Table III.

Certain of these reactions, however, were not used in obtaining the factors in Eq. (7). In group A, the data for three target nuclei were not used, namely F^{19}, Na^{23}, and Cl^{35}. The Na^{23} data were in doubt at the time these calculations were made. The data reported by Williamson et al.[19] revealed decimal errors in earlier work.[20] In reference 19, however, the units of the cross section were millibarns/steradian but were reported as millibarns with the result that the correct $Na^{23}(n,p)Ne^{23}$

TABLE II. Odd-even structure of residual nuclei.

Target type	n	p	α
(a) ${}_{\text{odd}}X^{\text{odd}}$	even-odd	odd-even	odd-odd
(b) ${}_{\text{even}}X^{\text{odd}}$	odd-even	even-odd	even-even
(c) ${}_{\text{even}}X^{\text{even}}$	even-even	odd-odd	odd-even
(d) ${}_{\text{odd}}X^{\text{even}}$	odd-odd	even-even	even-odd

[16] S. T. Butler, Phys. Rev. **106**, 272 (1957). N. Austern, S. T. Butler, and H. McManus, Phys. Rev. **92**, 350 (1953).

[17] R. J. Howerton, University of California Radiation Laboratory Report UCRL-5226, 1958 (unpublished).

[18] Equivalent results have been obtained by G. Brown and H. Muirhead, Phil. Mag. 2, 473 (1957) using a different approach. The results reported in the present paper were arrived at independently of the work of Brown and Muirhead, which was called to the authors' attention after the completion of the present analysis.

[19] C. F. Williamson, E. L. Hudspeth, I. L. Morgan, and R. G. Moore, Jr., Phys. Rev. **110**, 139 (1958); also private communication from C. F. Williamson.

[20] *Neutron Cross Sections*, compiled by D. J. Hughes and R. Schwartz, Brookhaven National Laboratory Report BNL-325, Suppl. No. 1 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1957).

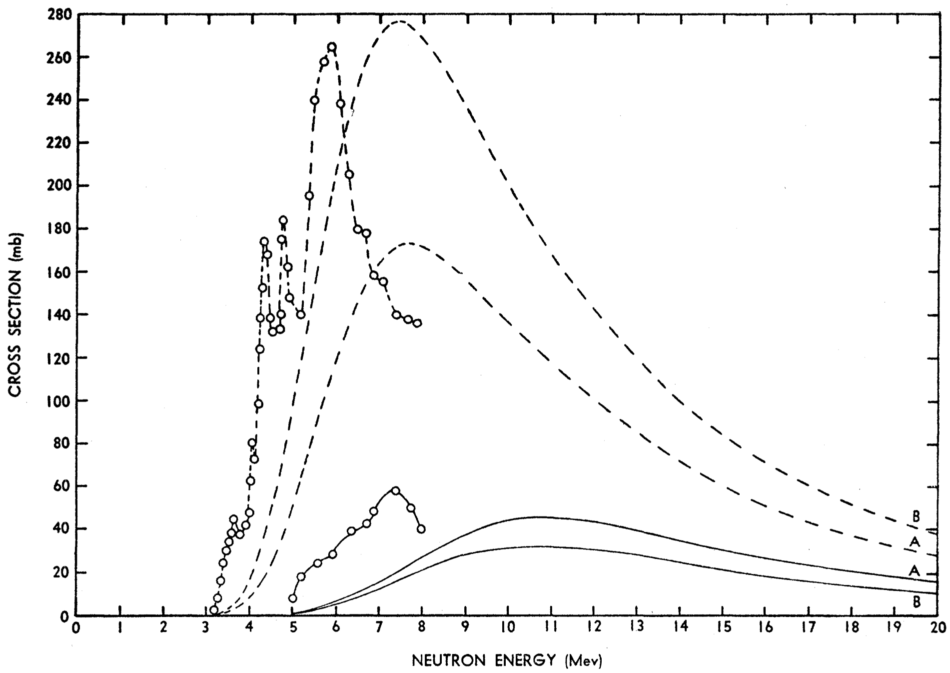

FIG. 1. Cross sections for (n,p) and (n,α) reactions in fluorine. The solid curves are (n,p) cross sections; the dashed curves are (n,α) cross sections. Curves labeled (A) are theoretical curves using level density parameters from reference 7, while the curves labeled (B) are theoretical curves based on Eq. (7). The experimental curves are shown as data points connected by solid lines or dashed lines, as above. This notation is used for Figs. 1 through 15.

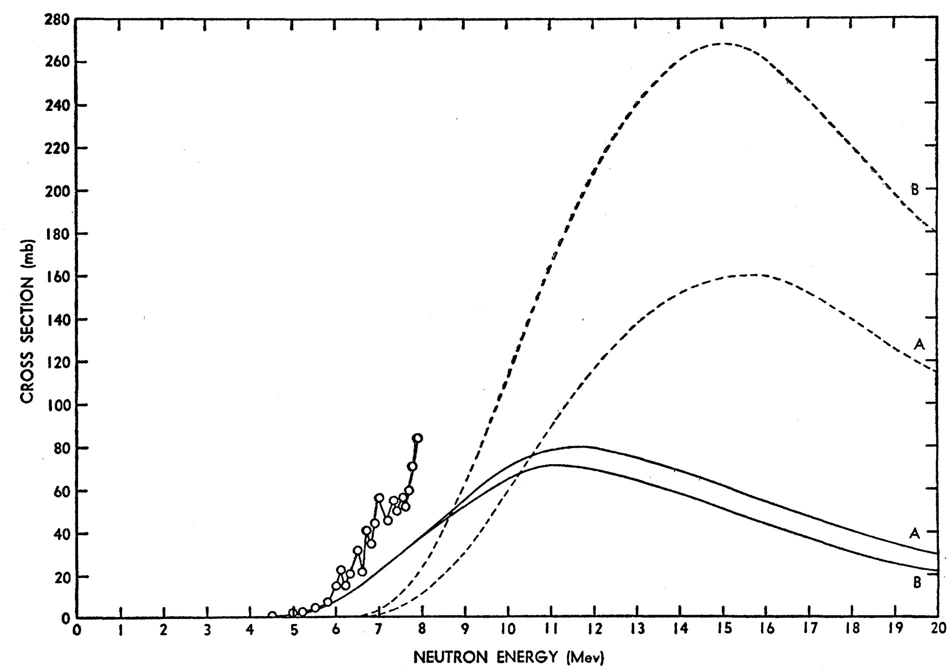

FIG. 2. Cross sections for (n,p) and (n,α) reactions in sodium. The experimental curve is taken from Fig. 6 of reference 19 with the ordinate of that figure multiplied by 4π. See text.

cross section is that shown in Fig. 6 of reference 19 with the ordinate of that figure multiplied by 4π. It is this result that is plotted in Fig. 2 as the experimental cross section for the (n,p) reaction in sodium. The agreement between the corrected experimental curve and the theoretical curve (solid curve B) is quite good, in particular when one notes that more recent data on the $N^{14}(d,n)$ reaction indicate that the cross section

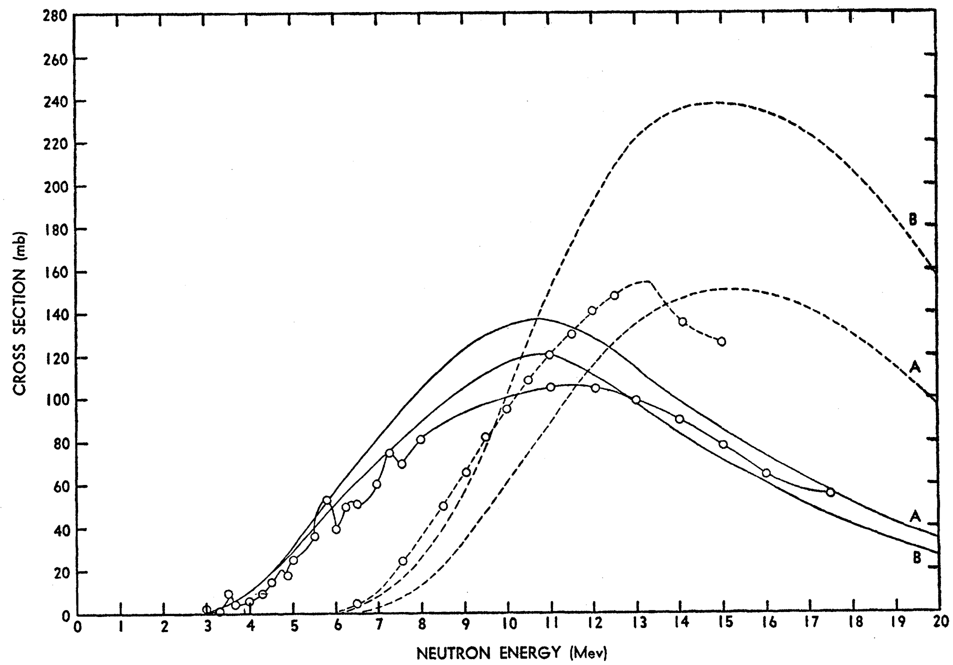

FIG. 3. Cross sections for (n,p) and (n,α) reactions in aluminum. Low-energy experimental data are from BNL-325 and reference 17; high-energy experimental data are from O. M. Hudson, Jr., and I. L. Morgan, Bull. Am. Phys. Soc. 4, 97 (1959)

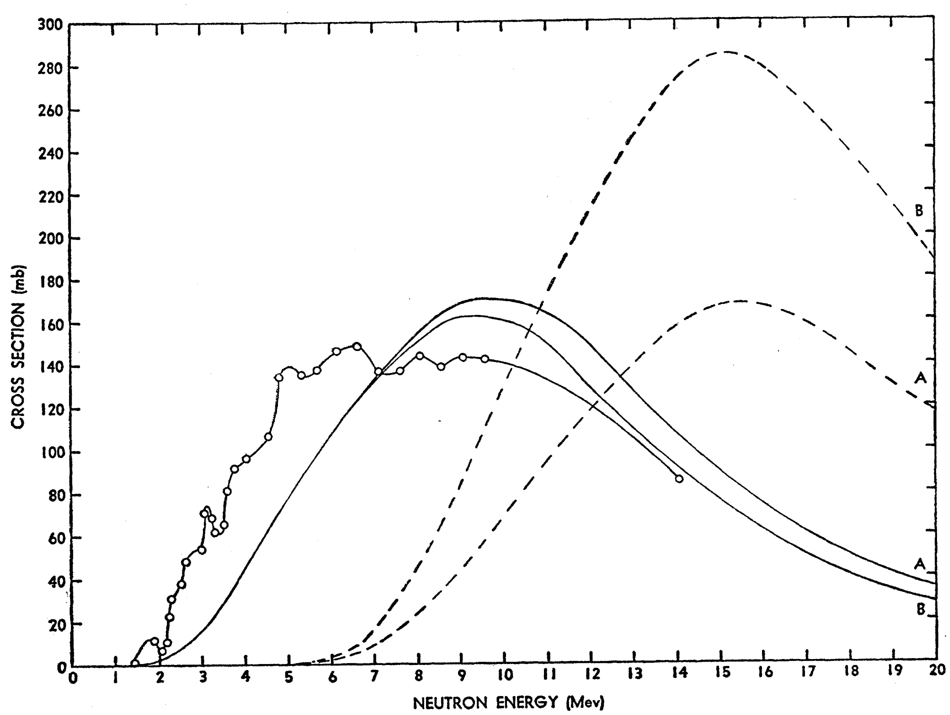

FIG. 4. Cross sections for (n,p) and (n,α) reactions in phosphorus.

may be nearly twice as great as that used in processing the Na^{23} data.[19] Use of this new N^{14} data would tend to lower the (n,p) cross section by about 50% for those cases in which $N^{14}(d,n)$ was used as a source, i.e., above about 6.5 Mev. The Cl^{35} data were not used, as the energy range for which measurements have been made was considered too small to justify a detailed analysis; however, the factors do give results which are not inconsistent with the measured curve.

The F^{19} case merits further comment. The level structures of the residual nuclei O^{19} and N^{16} have only a few excited levels, all at low-lying energies. According

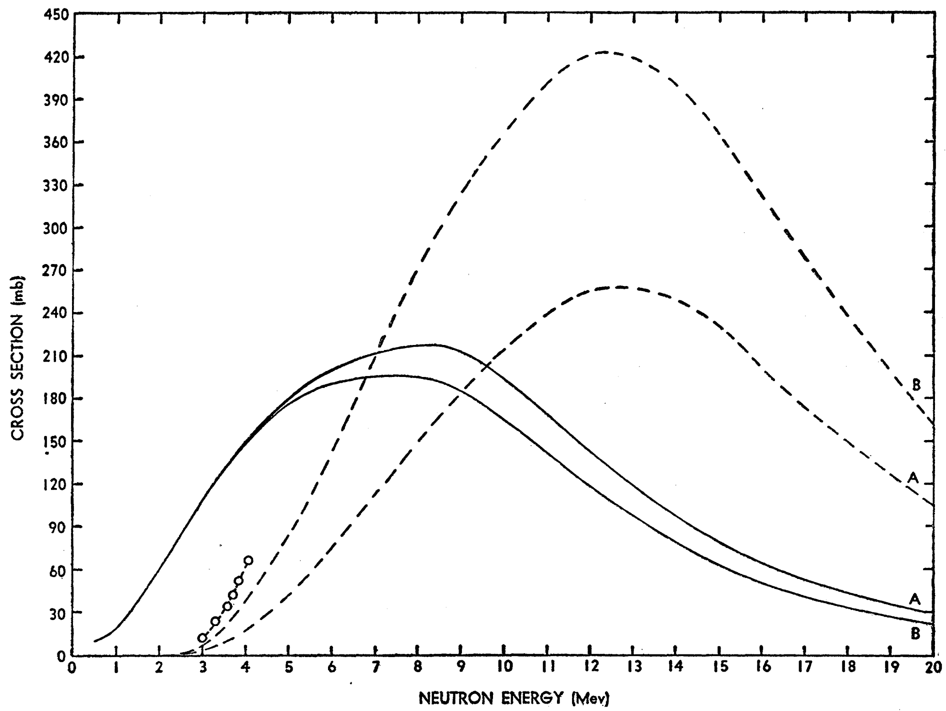

FIG. 5. Cross sections for (n,p) and (n,α) reactions in chlorine.

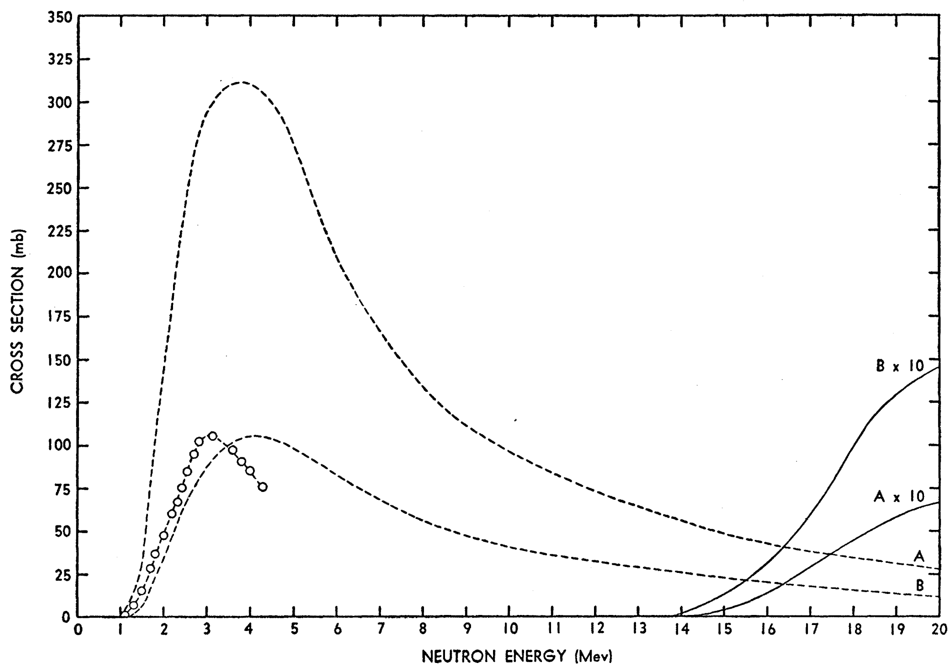

FIG. 6. Cross sections for (n,p) and (n,α) reactions in beryllium.

to Butler,[16] at a neutron energy of 14 Mev an important contribution to the yield of an (n,p) reaction is due to neutron interaction at the nuclear surface, where the final nucleus is left in a state of low excitation, i.e., reactions which proceed to a low-lying level of the final nucleus receive predominant contributions from a direct process which does not involve the compound nucleus as an intermediate step. It would thus seem that F^{19} would be a likely candidate for the direct-interaction process. In their calculations for neutron-induced reactions in F^{19}, Kondaiah, Iyengar, and Badrinathan[21] have estimated the direct-interaction contribution to the (n,p) cross section. According to their results, this contribution is of the order of twice as important as the compound nucleus process, since the ratio of calculated $\sigma(n,\alpha):\sigma(n,p)$ is approximately 3.5 while the

[21] E. Kondaiah, K. V. K. Iyengar, and C. Badrinathan, Nuclear Phys. **5**, 346 (1958).

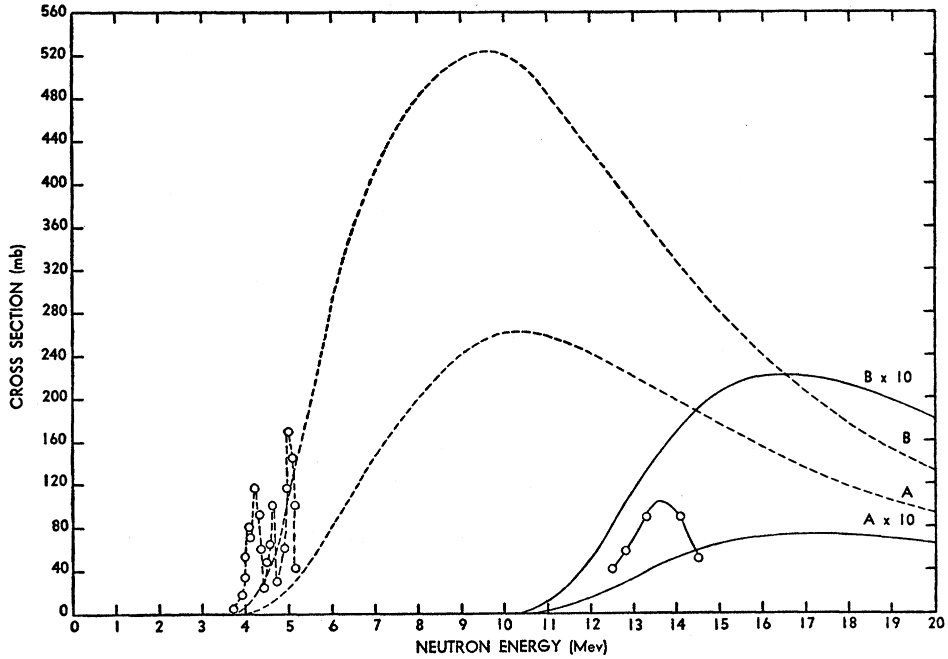

FIG. 7. Cross sections for (n,p) and (n,α) reactions in oxygen.

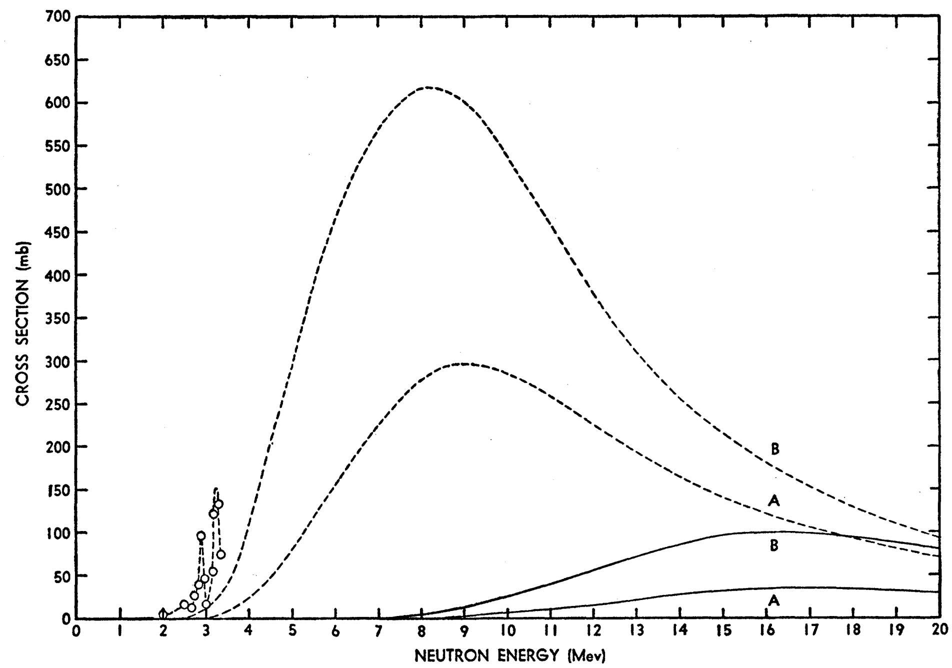

FIG. 8. Cross sections for (n,p) and (n,α) reactions in neon.

experimental ratio is 1.2. This may be considered to be a lower limit, as mentioned by these authors, since N^{16} (the residual nucleus for the (n,α) reaction) is odd-odd; hence, its level density is believed to be higher than estimated, thereby increasing the calculated ratio. Table IV shows a compairson of the results of the present study with those obtained in reference 21. Including the factors in Eq. (7) increases the calculated $\sigma(n,\alpha):\sigma(n,p)$ ratio with the result that the direct-interaction contribution appears to be somewhat greater than that indicated by the results of reference 21. For cases in which a direct interaction is significant, we should expect a compound nucleus calculation to predict a result less than the measured value. This is the case for $F^{19}(n,p)O^{19}$ as shown in Fig. 1.

Since such a limited amount of suitable data are available for ${}_{\text{odd}}X^{\text{odd}}$ target reactions, the result of the first step in the analysis, namely $C_{\text{odd-odd}}=2C_{\text{odd }A}$, does not necessarily constitute a final and unique relationship. It is consistent, however, with the suggestion of Weisskopf.[9,10] It would be very helpful to have additional (n,p) or (n,α) cross-section measure-

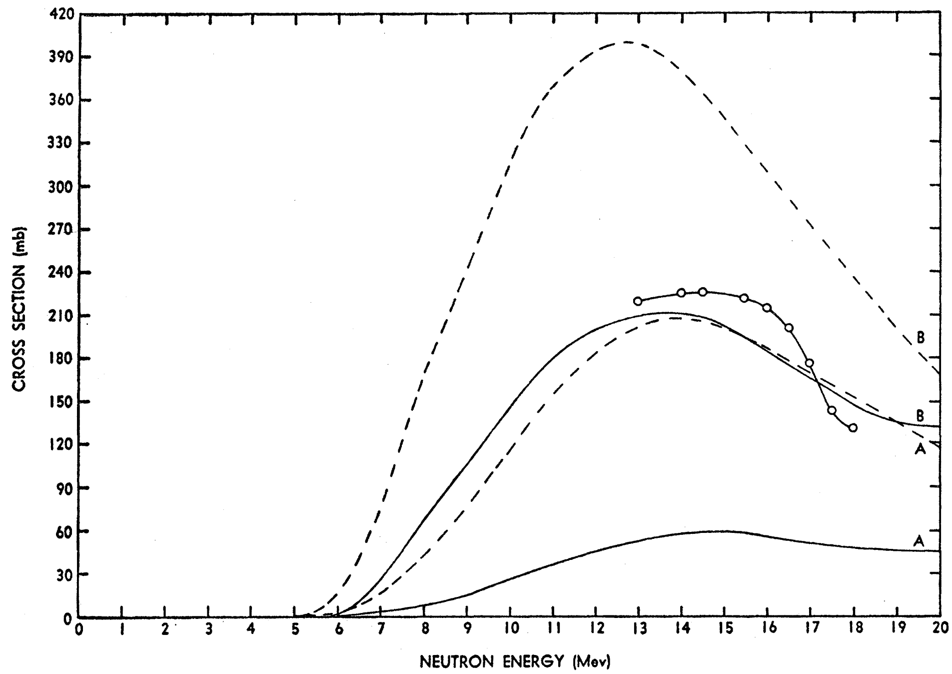

FIG. 9. Cross sections for (n,p) and (n,α) reactions in magnesium. Experimental data are from reference 20.

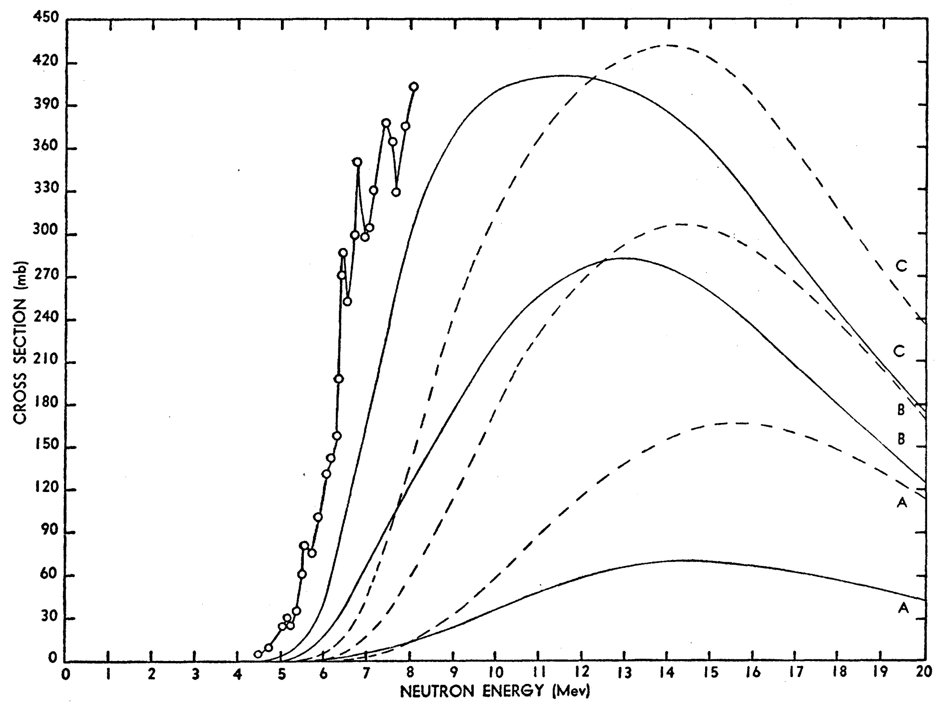

FIG. 10. Cross sections for (n,p) and (n,α) reactions in silicon. The theoretical curve (C) is based on level density parameters believed to be suitable for magic nuclei. See text.

ments for ${}_{\rm odd}X^{\rm odd}$ target nuclei such as $Na^{23}(n,\alpha)$ or $P^{31}(n,\alpha)$. The (n,α) cross sections would yield more helpful information in this case, since $F_\alpha{}^*$ (involving $C_{\text{odd-odd}}$) appears in the numerator of the branching ratio of Eq. (3.a); hence, the calculation is quite sensitive to $C_{\text{odd-odd}}$. If such data were available, further theoretical analysis could substantiate (or modify) this result.

The remaining C value, namely $C_{\text{even-even}}$, has been adjusted to fit the ${}_{\rm even}X^{\rm even}$ target curves by making use of the relationship previously obtained for $C_{\text{odd-odd}}$. These values of $C_{\text{even-even}}$ depend upon the accuracy of results based on ${}_{\rm odd}X^{\rm odd}$ target data, which further emphasizes the need for additional information on ${}_{\rm odd}X^{\rm odd}$ target reactions. The ${}_{\rm even}X^{\rm even}$ target reactions not used in the analysis were O^{16}, Ne^{20}, Si^{28}, and Zn^{64}.

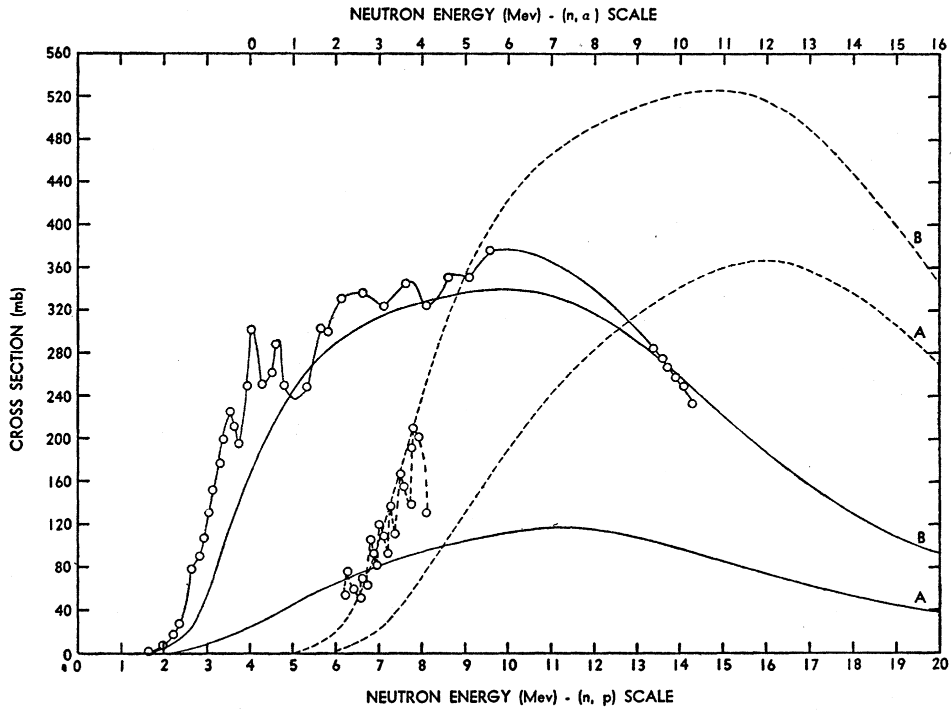

FIG. 11. Cross sections for (n,p) and (n,α) reactions in sulfur.

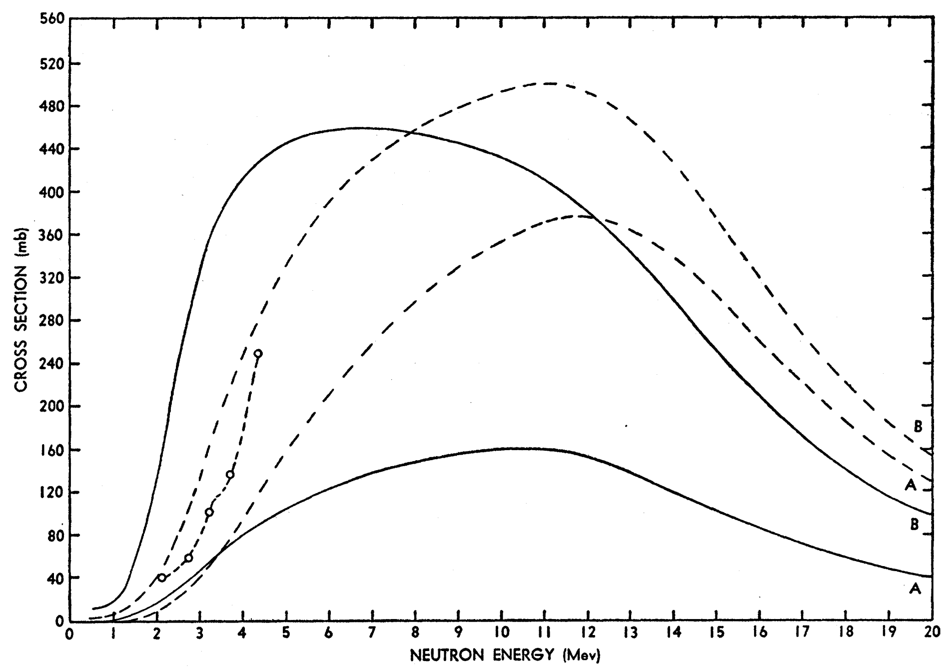

FIG. 12. Cross sections for (n,p) and (n,α) reactions in argon.

The Ne^{20} and Zn^{64} data were considered too limited to include in the analysis. The residual nucleus N^{16} for the (n,p) reaction in oxygen has only a few low-lying levels, in which case the mechanism of direct interaction may be a significant contribution to the measured cross section. If this is the case, the O^{16} calculations should be expected to be similar to those for F^{19}, namely good agreement with measured (n,α) data, but rather poor agreement with the (n,p) data for which the calculated curve is low; this is indeed the case. Further, O^{16} and Si^{28} are both doubly magic. It appears[6] that for nuclei as light as oxygen, the parameters may well be the same as those for nonmagic nuclei. For Si^{28}, however, this may not be the case. If one estimates the parameter a for magic nuclei from the curve given by Heidmann and Bethe,[6] he obtains the result shown in curve C, Fig. 10, which may account for the rapid rise of the $Si^{28}(n,p)$ cross section. The experimental Fe^{56}

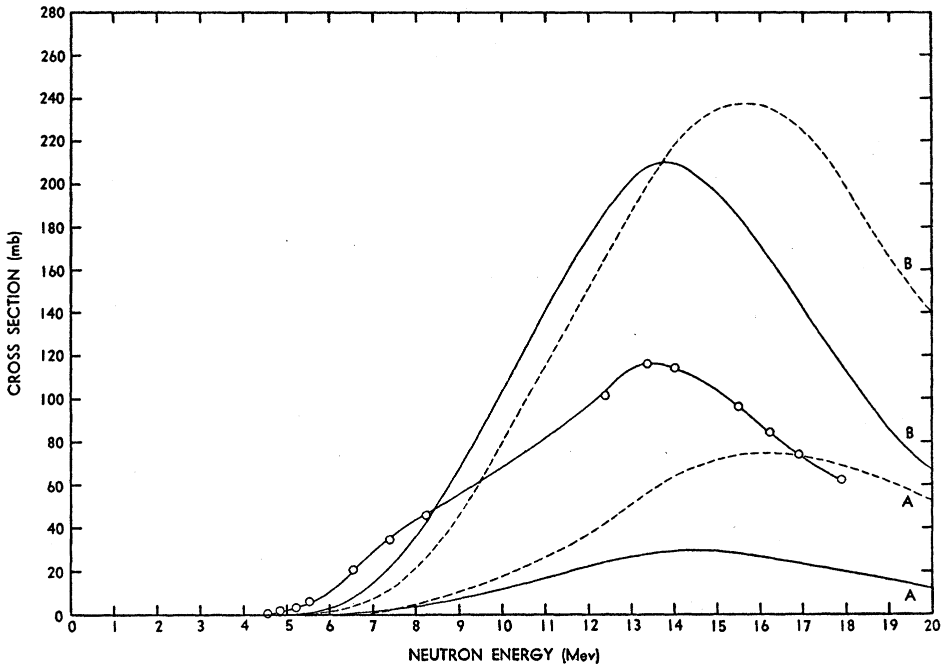

FIG. 13. Cross sections for (n,p) and (n,α) reactions in iron.

data shown in Fig. 13 were measured on an arbitrary scale by Terrell and Holm[12] and normalized at 14.3 Mev to a cross-section value of 110 mb, which was obtained by averaging early data. The resulting experimental curve is then significantly lower than our calculated curve in this energy range. More recent data show this cross section to be of the order of 190 mb. If the relative experimental data of Terrell and Holm are normalized to this value, the agreement with our calculated curve is much improved.

The case of ${}_{\text{even}}X^{\text{odd}}$ target nuclei is particularly interesting. Only one excitation curve in this category has been reported, namely Be^9. Even though this is rather light for satisfactory analysis, a theoretical calculation did seem to be of value, since the residual nucleus for alpha-particle emission is even A while those for neutron and proton emission are both odd A, so that the ${}_{\text{even}}X^{\text{odd}}$ data determine $C_{\text{even-even}}$ in which no assumptions need be made about $C_{\text{odd-odd}}$. The Be^9 measurement could thus serve as an independent check of the value of $C_{\text{even-even}}$ which was obtained from ${}_{\text{even}}X^{\text{even}}$ target analysis. The calculations do support the $C_{\text{even-even}}$ result which was obtained independently from the ${}_{\text{even}}X^{\text{even}}$ reactions (see Fig. 6). Several ${}_{\text{even}}X^{\text{odd}}$ nuclei exist in the intermediate mass range for which excitation curves might be measured, e.g., $Mg^{25}(n,p)$, $Mg^{25}(n,\alpha)$, $Si^{29}(n,p)$, $Si^{29}(n,\alpha)$, $Cr^{53}(n,p)$, $Cr^{53}(n,\alpha)$. The (n,α) cross-section data would yield more useful information in this case, since the alpha-particle emission channel contains the even A residual nucleus.

There have been no measurements made for ${}_{\text{odd}}X^{\text{even}}$ target nuclei in the intermediate and heavy-mass range. Such measurements are difficult since few stable ${}_{\text{odd}}X^{\text{even}}$ nuclei exist in this mass range, and those which do exist occur in very small percent abundance. There are a few light ${}_{\text{odd}}X^{\text{even}}$ nuclei (e.g., Li^6, B^{10}, and N^{14}) which do exist in sufficient abundance to make measurements feasible. Even though such light nuclei are not well suited for extracting level density parameters, we have made theoretical calculations for N^{14}. This (n,p) cross section is characterized by a resonance structure in the low-energy region, but the calculation does show that the parameters deduced in the earlier analyses give qualitative agreement with measurements. The $N^{16}(n,\alpha)$ calculation is also in good qualitative agreement with the measured curve.

TABLE III. Experimental (n,p) and (n,α) cross-section data.

Target nucleus type	Reaction	Target nucleus type	Reaction
A. ${}_{\text{odd}}X^{\text{odd}}$	${}_9F^{19}(n,p)$	C. ${}_{\text{even}}X^{\text{even}}$	${}_8O^{16}(n,p)$
	${}_9F^{19}(n,\alpha)$		${}_8O^{16}(n,\alpha)$
	${}_{11}Na^{23}(n,p)$		${}_{10}Ne^{20}(n,\alpha)$
	${}_{13}Al^{27}(n,p)$		${}_{12}Mg^{24}(n,p)$
	${}_{13}Al^{27}(n,\alpha)$		${}_{14}Si^{28}(n,p)$
	${}_{15}P^{31}(n,p)$		${}_{16}S^{32}(n,p)$
	${}_{17}Cl^{35}(n,\alpha)$		${}_{16}S^{32}(n,\alpha)$
			${}_{18}A^{36}(n,\alpha)$
			${}_{26}Fe^{56}(n,p)$
			${}_{30}Zn^{64}(n,p)$
B. ${}_{\text{even}}X^{\text{odd}}$	${}_4Be^9(n,\alpha)$	D. ${}_{\text{odd}}X^{\text{even}}$	${}_7N^{14}(n,p)$
			${}_7N^{14}(n,\alpha)$

TABLE IV. Ratios of $\sigma(n,\alpha)$ to $\sigma(n,p)$.

E_n (Mev)	KIB[a] expt.	KIB[a] calc.	Present study
8	3.2	7.1	12.78
14.5	1.2	3.5	3.96

[a] See reference 21.

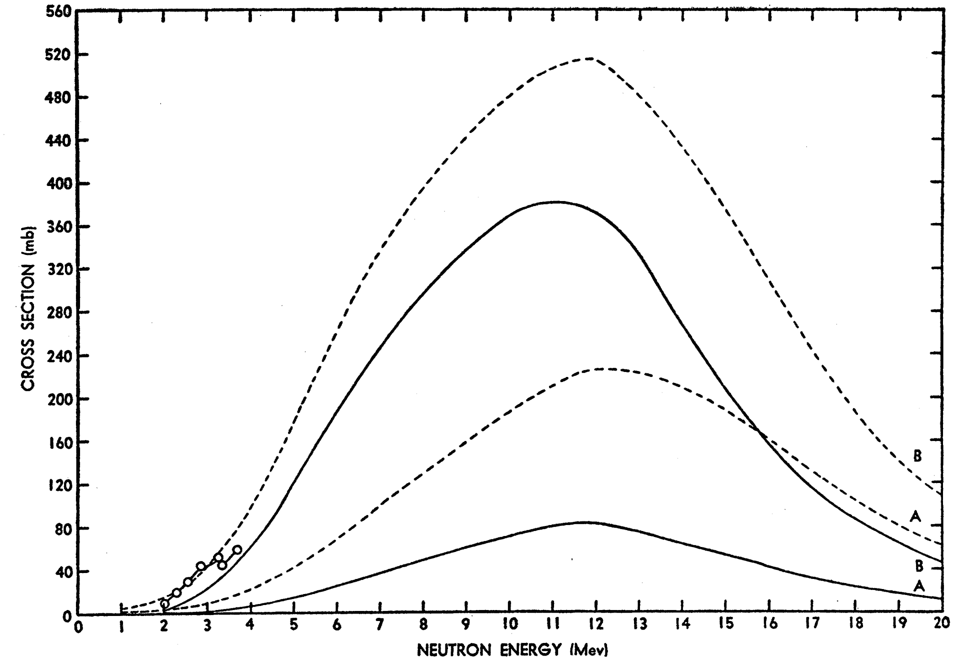

FIG. 14. Cross sections for (n,p) and (n,α) reactions in zinc. Experimental data are from J. Rapaport and J. J. van Loef, Phys. Rev. **114**, 567 (1959).

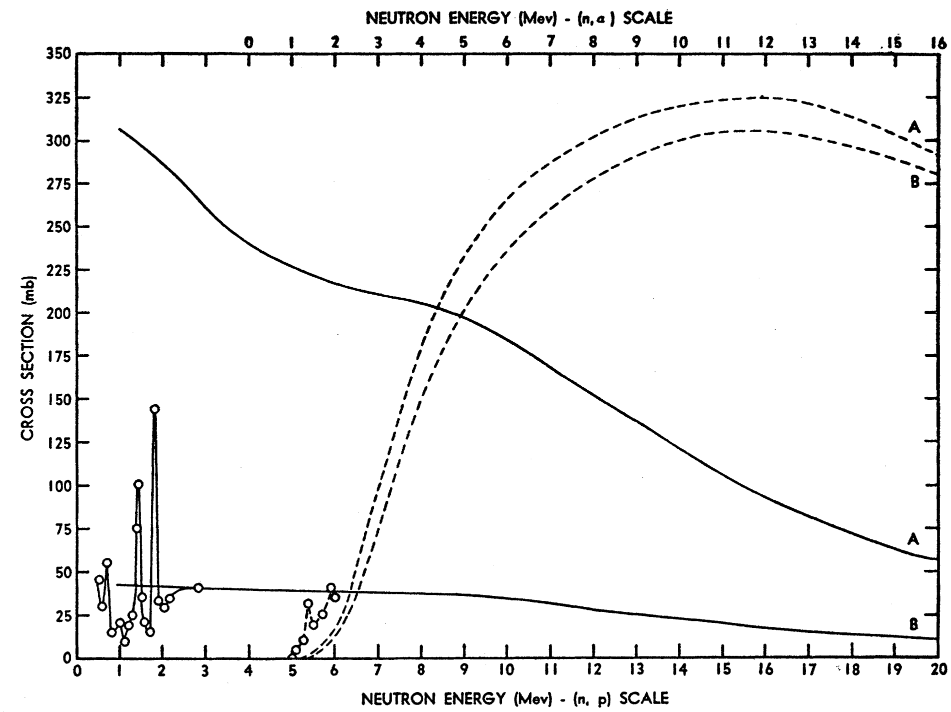

FIG. 15. Cross sections for (n,p) and (n,α) reactions in nitrogen.

4. CONCLUSIONS

Agreement between experimental and theoretical cross section curves for (n,p) and (n,α) reactions is very good if the values of C are those given by Eq. (7) and the values of a are those given by Blatt and Weisskopf[7] for low mass-numbered nuclei. Further analysis is required before any quantitative conclusions can be made concerning the values of a for heavy nuclei. Additional experimental data (particularly for ${}_{\text{even}}X^{\text{odd}}$ target nuclei) could aid significantly in improving our knowledge of the odd-even dependence of the C values.