measured in the present experiment under exactly the same experimental conditions, and the relative values are accurate to within about 15 percent. It seems reasonable that the difference of a factor of 1.5 in the relative (d,p) and (d,n) cross sections may be accounted for by Coulomb effects,[37] without indicating a larger spatial extension in the nucleus for neutrons than for protons.

The gamma-ray yields from the $B^{10}(d,p)B^{11}$ and $B^{10}(d,n)C^{11}$ reactions show a strange result. The 7.30-Mev line from B^{11} is stronger than the 6.77-Mev line from the mirror level of C^{11}, whereas the 6.50-Mev line from C^{11} is stronger than the 6.75-Mev mirror line from B^{11}. This discrepancy might be explained by assuming that the reaction leaving B^{11} and C^{11} excited in the 7.3- and 6.77-Mev states, respectively, is mainly a stripping reaction, whereas the reaction leading to the 6.75- and 6.50-Mev states goes mainly by compound nucleus formation. The low (d,p) cross section for the 6.75-Mev state relative to the (d,n) cross section for the 6.50-Mev state might then be explained by the effect of the Coulomb barrier on the proton emitted from the compound nucleus.

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[37] D. C. Peaslee, Phys. Rev. 74, 1001 (1948).

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(p,pn) and $(p,2n)$ Cross Sections in Medium Weight Elements

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The quantity F_p/F_n, the ratio of probabilities for proton and neutron emission from nuclear reactions in the statistical region, is determined from measurements of (p,pn) and $(p,2n)$ cross sections induced by 21.5-Mev protons bombarding nuclei of masses 48 to 71. The results are then compared with determinations of F_p/F_n from reactions induced by lower-energy protons and 14-Mev neutrons. Both the absolute values of F_p/F_n and their variation with bombarding energy are very difficult to explain by usual nuclear reaction theories.

INTRODUCTION AND THEORY

In studies of nuclear reactions in the statistical region, considerable attention has been given to the quantity F_p/F_n, the relative probability of proton and neutron emission from nuclear reactions.[1] In particular, interest was aroused by the fact that the experimental determinations[2] were in disagreement with the theoretical estimates[1] from the statistical theory of nuclear reactions, and several attempts have been made to revise the theoretical estimates by modifying the statistical theory,[3] or by introducing direct interactions.[4]

In the experiments described in this paper, a much more serious difficulty with the behavior of F_p/F_n seems to be uncovered. Measurements are reported of F_p/F_n from 21.5-Mev proton-induced reactions in the iron-copper mass region, and these are then compared with determinations at lower incident proton and neutron energies. It is found that F_p/F_n increases by well over an order of magnitude within a few Mev, and attains values considerably larger than unity.

In order to demonstrate how difficult these facts are to reconcile, a simple but quite general treatment of the theory is given. Since a compound nucleus model is the most familiar and the most easily handled, it is used here, but other possibilities will be discussed later. It is further assumed that equal energies are available for both proton and neutron emission; while this is not the usual case, the experimental results for various differences in these energies may be extrapolated to it.

A straightforward application of the reciprocity theorem to the decay of the compound nucleus gives[5]

$$\frac{F_p}{F_n}=\frac{\int_0^{E_0}\sigma_p\eta_p E\omega_p(E_0-E)dE}{\int_0^{E_0}\sigma_n\eta_n E\omega_n(E_0-E)dE}, \tag{1}$$

where E_0 is the maximum energy available for neutron or proton emission, σ_p is the cross section for capture of a proton of energy E, assuming unit sticking probability (tables of σ_p are given in reference 1), $\omega_p(E_0-E)$ is the density of states of the residual nucleus after proton emission [it is a function of (E_0-E), its excitation energy], η_p is a quantity that takes into account selection rules in the nuclear transitions from compound nucleus to residual nucleus plus proton, and the corresponding quantities with subscript n refer to neutrons. While ω_p and ω_n may be different in any particular case,

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* Present address: U. S. Army.

[1] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

[2] E. B. Paul and R. L. Clarke, Can. J. Physics 31, 267 (1953).

[3] D. B. Beard, Phys. Rev. 94, 738 (1954); V. F. Weisskopf (private communication).

[4] H. McManus and W. T. Sharp, Phys. Rev. 87, 188 (1952); R. M. Eisberg, Phys. Rev. 94, 739 (1954).

[5] B. L. Cohen, Phys. Rev. 92, 1245 (1953).

on a statistical basis there clearly can be no consistent difference between them. There is evidence[5] that η may be a function of E and E_0, but a consistent difference between η_p and η_n would be a clear violation of charge independence of nuclear forces (charge independence is well substantiated at these energies). σ_p differs from σ_n only by a Coulomb factor, so let us define such a factor, P_c, as

$$P_c=\sigma_p/\sigma_n. \tag{2}$$

Since the integrand in the denominator of Eq. (1) is just the energy spectrum of emitted neutrons, Eq. (1) may be written

$$F_p/F_n=\bar{P}_c, \tag{3}$$

where $\bar{P}_c$ is the average value of P_c, the average being taken over the energy spectrum of the emitted neutrons.

If this energy spectrum is assumed to be Maxwellian with a temperature of 2 Mev, application of Eq. (3) gives $F_p/F_n=0.07$ in the mass region of interest here; if the temperature is raised to 5 Mev, Eq. (3) gives $F_p/F_n=0.2$, and even if the Maxwellian energy distribution is abandoned and the energy distribution is chosen to maximize F_p/F_n in these experiments, the result would only yield $F_p/F_n=0.4$.

EXPERIMENTAL

The quantities directly measured in these experiments were ratios between pairs of activation cross sections; by combining these, the relative cross sections of all reactions were obtained, and these were made absolute by use of known absolute cross sections as has been described previously.[6] Most cross sections were determined by ratios to at least two others independently, and many cross checks were made.

The procedure most generally used for measuring the ratio between two cross sections was to bombard a finely ground chemical compound (or, in a few cases, a mixture) of the two elements, and count the induced beta activities under an end-window Geiger counter. Bombardments were sufficiently intense that it was necessary to count only a very small mass of material, thus eliminating beta self-absorption and self-scattering corrections. Corrections for backscattering, window and air absorption, etc., were made by the methods of Zumwalt.[7] In the few cases where the materials were available as foils, foil combinations were bombarded behind a "window frame"[6] instead of using chemical compounds. Corrections for self-absorption and self-scattering were then applied.

The activation cross sections for the long-lived gamma-emitting isotopes Cr^{51}, Mn^{54}, and Co^{58} were obtained relative to the $Fe^{56}(p,2n)Co^{55}$ cross section by bombarding mixtures containing iron oxide and counting both these activities and the Co^{55} activity on their respective gamma-ray peaks with a scintillation spectrometer. The spectrometer efficiencies for the long-lived isotopes were obtained by use of accurately assayed standards.[8] The Co^{55} spectrometer efficiency was measured by determining absolute disintegration rates by beta counting, with a phosphorous-32 standard[8] for the Geiger counter calibration. As a check on the entire method, the cross section for production of Na^{22} from Na^{23} was measured by both this method and the usual beta-counting-ratio method; the agreement was excellent.

The cross section for $Fe^{56}(p,pn)Fe^{55}$ relative to that of $Fe^{56}(p,2n)Co^{55}$ was obtained by absolute beta counting one aliquot for the Co^{55} activity, and then determining the absolute disintegration rate in another of the pure electron-capturing isotope Fe^{55} by counting the x-rays under an end-window Geiger counter calibrated with a standard Fe^{55} source.[8] Chemical purification of the iron was carried out, and the fact that the samples were free of betas (which are counted with very much higher efficiency) was checked by comparing their absorption characteristics with those of the standard by the use of thin silver foils. (The inverse mass absorption coefficient of silver for the manganese x-ray is about 1.5 mg/cm^2.)

The cross section for $Zn^{68}(p,2n)Ga^{67}$ relative to that of $Zn^{64}(p,pn)Zn^{63}$ was obtained by absolute beta counting an aliquot for the Zn^{63} activity, and then determining the Ga^{67} disintegration rate by comparing its counting rate with that of a Ga^{67} standard[8] on a scintillation spectrometer set on the 110-kev gamma-ray peak.

Every cross-section ratio was measured independently at least five times. (Those used most frequently in combining ratios were measured at least ten times.) The general reproducibility of the data and the consistency of the cross checks indicates an uncertainty in the raw data of about 7%; considering errors due to beta counting corrections, the relative cross sections may be uncertain by as much as 15%. In addition, the absolute calibration of all cross sections[6] may be in error by about 15%, but this has little effect on the theoretical interpretation, since only cross-section ratios are used.

RESULTS

The measured (p,pn) and ($p,2n$) cross sections are listed in Table I, along with the energetic thresholds of the pertinent reactions and the character of the final nuclei involved. Table I also lists ratios of (p,pn) to ($p,2n$) cross sections, although both cross sections were measured in only four of the twelve cases. In the other eight cases, the estimates were arrived at by using our recent measurements of (p,pn)+($p,2n$) cross sections.[9]

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[6] Cohen, Newman, Charpie, and Handley, Phys. Rev. **94**, 620 (1954); G. H. McCormick and B. L. Cohen, Phys. Rev. **96**, 722 (1954).

[7] L. R. Zumwalt, U. S. Atomic Energy Commission Report, MDDC 1346 (unpublished).

[8] We are greatly indebted to Mr. W. S. Lyon of the Analytical Chemistry Division, Oak Ridge National Laboratory for supplying and assaying these standards.

[9] Cohen, Newman, and Handley, following paper [Phys. Rev. **99**, 723 (1955)].

TABLE I. (p,pn) and $(p,2n)$ cross sections and related information.

Initial nucleus	Thresholds (Mev) (p,n)	(p,pn)	$(p,2n)$	Cross sections (mb) (p,pn)	$(p,2n)$	$\frac{\sigma(p,pn)}{\sigma(p,2n)}$	Favoring by $o-o$ vs $e-e$ $\frac{(p,n)}{(p,p)}$	$\frac{(p,np)}{(p,2n)}$
$_{22}Ti^{48}$	4.7	11.7	15.3	···	120	5.8	x	
$_{24}Cr^{52}$	5.4	12.0	16.0	425	155	2.8	x	
$_{25}Mn^{55}$	0.9	10.3	10.4	620	···	3.5		x
$_{26}Fe^{56}$	5.3	11.5	15.7	760	105	7.2	x	
$_{27}Co^{59}$	1.0	10.9	10.8	540	···	2.7		x
$_{28}Ni^{62}$	5	10.6	13.5	···	385	1.4	x	
$_{29}Cu^{63}$	4.2	11.0	13.4	590	100	5.9		x
$_{29}Cu^{65}$	2.1	10.4	10.5	500	···	1.7		x
$_{30}Zn^{68}$	3.6	8.9	10.7	···	780	0.20[a]	x	
$_{31}Ga^{69}$	4.1	10.4	11.0	360	360	1.0		x
$_{31}Ga^{71}$	1.0	9.0	8.0	260	···	0.37		x
$_{33}As^{75}$	1.6	10.3	10.9	350	···	0.70		x

[a] See reference 10.

In no case do these estimates introduce sufficient uncertainty to qualitatively affect the ensuing discussion.

The most striking observation from Table I is that (p,pn) cross sections are considerably larger than $(p,2n)$ cross sections in eight of the twelve cases, and about equal to them in two of the other four. On the other hand, there is one anomalous case, Zn^{68}, where the $(p,2n)$ cross section is by far the larger.[10] The ratio of (p,pn) to $(p,2n)$ cross sections is very much less in all of the four heaviest isotopes studied than in any of the eight lighter ones. Data for the heavier isotopes are therefore indicated by open symbols in the figures and are considered separately.

Before proceeding with a detailed analysis of the data, it is important to establish that (p,pn) reactions consist principally of (p,p) reactions followed by neutron "boil off." The most important alternative process to be considered is (p,n) reactions followed by proton emission.

In such a process, the energy available for proton emission is in the region 0–10 Mev, with about 7 Mev representing a fair average. These excitations are exactly the same as those encountered in measurements of (p,n) cross sections by Blaser *et al.* and by Blosser.[11] In those experiments it was found that neutron emission even predominates over proton emission when the former is energetically possible by only 1 Mev while the latter is energetically possible by as much as 5 Mev. Proton emission following a (p,n) reaction is therefore very unlikely so long as neutron emission is energetically possible. There are cases, of course, where the emission of the first neutron leaves the nucleus with too little excitation for neutron emission but still with enough for proton emission, so that the latter should take place with high probability. However, calculations based on measured neutron energy spectra[12] indicate that such situations arise relatively seldom.

Another approach to this problem is to compare these data with data on the relative probability for (x,np) and $(x,2n)$ reactions in cases where x is a neutron rather than a proton. Assume, temporarily, that the observed (p,pn) cross sections are entirely due to (p,n) reactions followed by proton emission, and consider the ratio $\sigma(x,np)/\sigma(x,2n)$. This ratio may be estimated[13] for 14-Mev neutron-induced reactions from the ratio of observed to calculated $(n,2n)$ cross sections from the data of Paul and Clarke.[3] Figure 1 shows it plotted against the difference between the energetic thresholds of (x,np) and $(x,2n)$. It is quite evident that $\sigma(x,np)/\sigma(x,2n)$ is greater by at least an order of magnitude in the proton-induced reactions. Actually, this method of comparison grossly underestimates the discrepancy; the proton-induced reactions are carried out with bombarding energies much further above threshold so that situations where emission of a second neutron is energetically forbidden arise much less frequently. In the only neutron-induced reaction where $\sigma(n,np)$ is apparently quite large, the bombarding energy is only 2 Mev above the $(n,2n)$ threshold, but 6 Mev above the (n,np) threshold. It thus seems quite evident that (p,n) reactions followed by proton "boil off" cannot explain the large observed (p,pn) cross sections.[14]

Another process that would lead to the same residual nucleus as a (p,pn) reaction is the simultaneous emission of a proton and a neutron, or "three-body breakup."[15] However, all the arguments about the ratio F_p/F_n apply equally to F_{pn}/F_{2n}, and in fact even more strongly since there is less energy available for the latter processes.

A final possibility is the (p,d) reaction which is essentially a special case of three-body breakup except

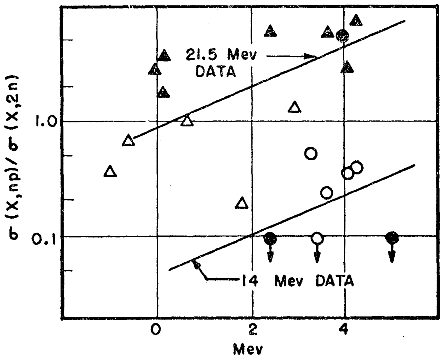

FIG. 1. $\sigma(x,np)/\sigma(x,2n)$ *vs* difference in the energetic thresholds for (x,np) and $(x,2n)$. Triangles are from 21.5-Mev proton data and circles are from 14.5-Mev neutron data. Open points are for $30 \leqslant Z \leqslant 33$, and solid points are for $22 \leqslant Z \leqslant 29$.

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[10] There is evidence from the lower-energy work (reference 11) that the reaction cross section from Zn^{68} is abnormally large. This would increase the $(p,pn)/(p,2n)$ ratio to about 0.5.

[11] Blaser, Boehm, Marmier, and Peaslee, Helv. Phys. Acta **24**, 3, 441 (1951); H. G. Blosser (to be published).

[12] P. C. Gugelot, Phys. Rev. **81**, 51 (1951).

[13] This method is very inaccurate for large values of observed-to-calculated $(n,2n)$ cross sections. When such values occur, it is assumed here that the ratio is greater than 0.9. These points are designated with a vertical arrow in Fig. 1.

[14] In the three cases with high $(p,2n)$ thresholds, as much as 25% of the (p,n) reactions may lead to (p,np) reactions. This would decrease F_p/F_n by only about 35%, which is quite negligible.

[15] Good, Kunz, and Moak, Phys. Rev. **94**, 87 (1954).

that an additional 2.2-Mev energy is available from the binding energy of the deuteron. However, it is difficult to see how that amount of energy can materially affect matters. Furthermore, experiments to detect deuterons directly[6,16] have shown that they are not common reaction products in proton-induced reactions in this energy region.

It therefore seems probable that the predominant reaction contributing to the (p,pn) cross section is inelastic scattering followed by neutron emission. Calculations based on the energy spectra of the emitted particles,[12,17] indicate[9] that actually somewhat less than 75% of all (p,p) reactions become (p,pn), whereas a considerably greater fraction of all (p,n) reactions in the elements considered here become ($p,2n$); but these corrections will be neglected since they are difficult to apply and only accentuate an effect which is already overwhelmingly large. We therefore assume that $\sigma(p,pn)/\sigma(p,2n)$ is an experimental determination of F_p/F_n.

Figure 2 shows F_p/F_n plotted *vs* the difference in energy available for emission of protons and neutrons. It appears that there is little dependence on the abscissa (in agreement with the Hurwitz-Bethe proposal[18]), and that the average value of F_p/F_n is about 2.5 for the lighter elements and 0.5 for the heavier ones.

In accordance with usual nuclear reaction theories,[1] F_p/F_n should depend on the nature of the nuclei involved. If the residual nuclei after proton and neutron emission are even-even and odd-odd, respectively, neutron emission should be favored by about a factor of four; then, in such cases, observed values of F_p/F_n should be multiplied by four to put them on an equal basis with reactions where the residual nuclei are odd-even or even-odd. This has been done in Fig. 3. A noticeable dependence on the abscissa is introduced, and a line through the data crosses zero abscissa at about F_p/F_n equal 1.5 for the lighter elements and 0.4 for the heavier ones. The difference between the two methods of extrapolation is thus relatively minor.

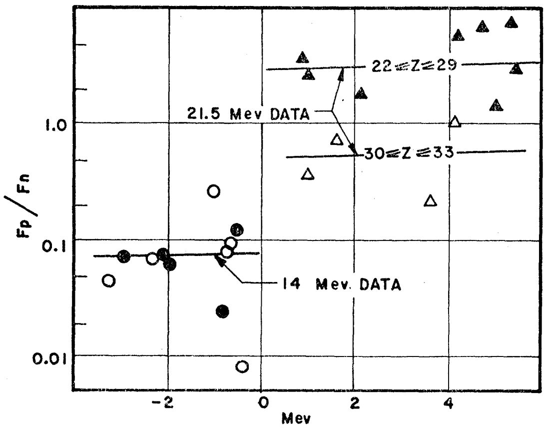

FIG. 2. F_p/F_n *vs* difference in energies available for proton and neutron emission. See caption for Fig. 1.

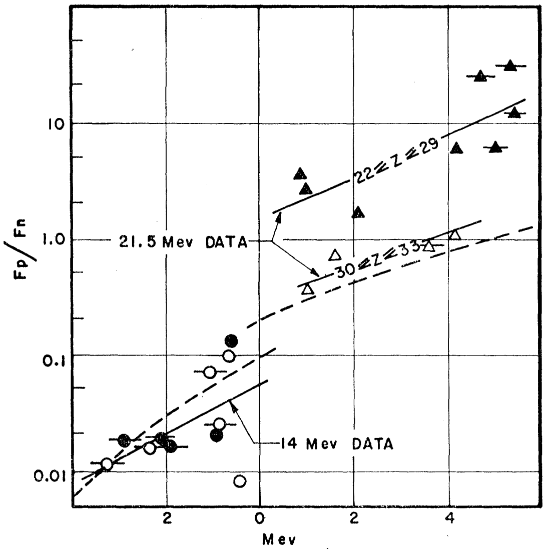

FIG. 3. F_p/F_n *vs* difference in energies available for proton and neutron emission. Data has been corrected for odd-odd *vs* even-even level density differences. Points so corrected are crossed with horizontal lines. See caption for Fig. 1. Dashed lines are predictions of statistical theory (reference 1).

For purposes of reference, the theoretical curves calculated from statistical theory are shown as dashed lines in Fig. 3. However, the authors feel that much more can be learned by comparing these data with other data rather than with the very adjustable predictions of statistical theory.

CONCLUSIONS AND DISCUSSION

At least two other experiments give estimations of F_p/F_n at lower energies. The most directly comparable work is the measurements of (p,n) cross sections at 11.5 Mev by Blosser.[11] He finds that they account for essentially the complete reaction cross section, and in fact, uses the data to determine the nuclear radius. It is estimated that the upper limit to F_p/F_n from his work is ~0.2. It includes many cases where the energy available for neutron emission is considerably less than that available for proton emission.

Another experiment that may be compared with this is the measurements of (n,p) cross sections by Paul and Clarke.[2] This comparison has the disadvantage that, since the target nuclei must be beta stable, neutron emission is always energetically favored in neutron-induced reactions whereas proton emission is always energetically favored in proton-induced reactions, so that the two sets of data must be extrapolated in opposite directions. However, this could hardly cause a very large discrepancy. The data from reference 2 are shown in Figs. 2 and 3 where in each case the data are plotted in the same way as the 21.5-Mev proton data.

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[16] R. M. Eisberg and G. Igo, Phys. Rev. **93**, 1039 (1954); J. B. Reynolds and K. G. Standing, Phys. Rev. **95**, 639 (1954).

[17] P. C. Gugelot, Phys. Rev. **93**, 425 (1954).

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

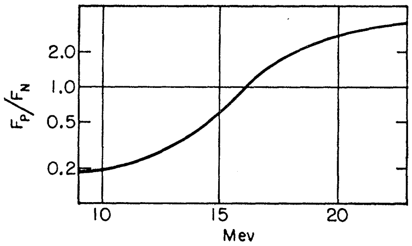

FIG. 4. F_p/F_n for Cu^{63} *vs* proton bombarding energy.

The observed value of F_p/F_n extrapolated to zero difference in energy available to neutrons and protons is about 0.05, and there is apparently no important difference between data for elements with $Z<30$ and with $Z \geqslant 30$.

In summary then, the observed values of F_p/F_n are 0.05 from 14.5-Mev neutrons, <0.2 from 11.5-Mev protons, and about 2.0 and 0.5 for the lighter and heavier elements respectively from 21.5-Mev protons. The manner in which F_p/F_n increases with incident proton energy for Cu^{63} can be determined from the excitation function measurements of Ghoshal[19]; this is shown in Fig. 4. The low-energy portion is calculated by subtracting two large and nearly equal numbers, each of which is quite uncertain, so that the values plotted are roughly upper limits for energies below 15 Mev.

These results are somewhat unique in two ways—in the large absolute values of F_p/F_n, and in its rather strange energy dependence. Other experiments[2] have found unexpectedly large values for F_p/F_n, but it has always been possible to explain them consistently with Eq. (3) by introducing distortions in the energy spectra of emitted particles.[3,4] The values of F_p/F_n from this experiment, however, are very much too large to be explained by any such distortions. The dependence of F_p/F_n on bombarding energy is also completely unexplainable by Eq. (3).

Before considering alternative theories, account must be taken of the measurements of energy distributions of inelastically scattered protons carried out by Gugelot[16] with 18.3-Mev incident protons. They indicate that the energy distributions are approximately Maxwellian with temperatures of about 2 Mev, and that for protons below 10 Mev (the highest energy that could lead to a (p,pn) reaction in these experiments), the angular distributions are not strongly anisotropic ($\sim$20% higher at 60 deg than at 150 deg). Figure 4 indicates that there is no drastic change in F_p/F_n between 18.3-Mev and 21.5-Mev, and this is further supported by measurements of (p,pn) and $(p,2n)$ excitation functions.[6,20]

The fact that most of the protons are emitted with relatively low energy [as evidenced by Gugelot's measurements and the very fact that (p,pn) reactions are observed] would seem, at first thought, to exclude the possibility that the effect observed here is due to reemission of the incident proton. Weisskopf has pointed out,[21] however, that in considering collisions within the nucleus, the binding energy of the incident particle should be added before the collision, and subtracted when a particle emerges from the nucleus. Furthermore, refraction effects occur at the nuclear boundary. Thus, the low energy and relatively isotropic angular distributions of the emitted protons are not inconsistent with reemission of the incident particle. The question can best be settled by investigating the quantity F_p/F_n in reactions induced by other bombarding particles. In the two cases of alpha-particle-induced reactions that have been reported,[19,22] very large values of F_p/F_n were found. In the single neutron-induced reaction that has been investigated in this mass region,[23] the observed value of F_p/F_n was relatively small. Further investigations would be very desirable.

Wigner has suggested[24] that proton emission in this mass region may be favored by a "giant resonance" of the type introduced by his "intermediate coupling" theory. However, it is his opinion that this could not explain so large an effect.

The most difficult to explain of the large observed (p,pn) cross sections are the cases of Mn^{55}, Co^{59}, and Cu^{65} where the energetics of neutron and proton emission are quite equivalent. If these could be explained, the extrapolations in Figs. 2 and 3 might be sufficiently altered to remove the other discrepancies. One possibility for explaining them lies in the fact that (p,np) reactions in these cases lead to odd-odd residual nuclei. The data could be reasonably explained, for example, if level densities in odd-odd nuclei were assumed to be larger than those in even-even nuclei by a factor of 20.

In order to investigate this possibility, horizontal lines are drawn through the data points for even-even nuclei in Fig. 3. To conform with our assumption, values of F_p/F_n for circles so marked should be decreased at least an order of magnitude, and for triangles so marked should be increased by that amount. It is readily evident that this would clearly introduce a large discrepancy between the data for even and odd mass nuclei. This discrepancy could not easily be explained by differences in Q values, because the data for the various even-mass nuclei does not show such a sensitivity to the Q of the reaction (i.e., the abscissa in Fig. 3). Our assumption would also introduce great difficulties into the explanation for the small observed $(p,pn)+(p,2n)$ cross sections[9] in Zn^{64}, Ni^{58}, and Ti^{46}, the small $(p,\alpha n)$ cross section[6] in Zn^{64}, and the similarities between (p,n) excitation functions[11] for the copper isotopes and the isotopes of nickel and zinc,

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[19] S. N. Ghoshal, Phys. Rev. **80**, 939 (1950).

[20] Rough measurements of several (p,pn) and $(p,2n)$ excitation functions have been made by the authors and by R. A. Charpie.

[21] V. F. Weisskopf (private communication).

[22] Miller, Friedlander, and Markowitz, Phys. Rev. **98**, 1197(A) (1955).

[23] Brolley, Fowler, and Schlacks, Phys. Rev. **88**, 618 (1953).

[24] E. P. Wigner (private communication).

and between the (p,pn) excitation functions[6,19] for Cu^{63} and Cu^{65}.

We might note two other indications that the reactions observed are probably not proton emission following (p,n) reactions. Firstly, Gugelot's measurements[16] indicate that the energy spectra of emitted protons are the same in copper as in nickel and iron. Measurements at higher energies[9] clearly show that the first particle emitted in nickel is a proton, and it seems relatively certain from the preceding discussion that the same is true for iron.

Secondly, a remeasurement was made of the excitation functions in Cu^{63}, and it was found that $[\sigma(p,n)+\sigma(p,2n)+\sigma(p,pn)]/\sigma_p$ decreases by 15% as the energy is increased from 11 to 15 Mev. This indicates that the (p,n) cross section probably drops off from competition with the unobserved (p,p') reaction rather than from competition with (p,np).

The conclusions of this paper that F_p/F_n is abnormally large is also supported by two other experiments:

(1) Meadows,[25] in measuring excitation functions in copper with high-energy protons, found that not only are the (p,pn) cross sections much larger than the $(p,2n)$'s, but $(p,p2n)$ and $(p,p3n)$ cross sections are much larger than the $(p,3n)$'s and $(p,4n)$'s.

(2) In the following paper,[11] it is shown that $(p,2p)$ cross sections are very large in this mass region, and in slightly lighter nuclei, commonly are the most probable of all reactions.

In spite of these arguments, it should always be borne in mind, of course, that we are dealing here with a statistical phenomenon; as such, it is subject to wide fluctuations, as can be seen directly from the data. It would be essentially impossible to prove that the effects found here cannot be explained by a combination of these fluctuations, the Wigner effect,[24] large differences between level densities in even-even and odd-odd nuclei, and contributions from (p,d) "pickup" reactions. Certainly any isolated piece of data can easily be explained in that way. However, after prolonged consideration of the various aspects of the problem, the authors have reached the opinion that the large ratio of proton to neutron emission cannot be explained by the usual nuclear reaction theories. Experiments are being undertaken to further study the problem by observing energy distributions and angular distributions of the emitted protons as a function of bombarding energy.

Before concluding, it is interesting to note that the large (p,pn) cross sections indicate that the neutron energy spectra measured by Gugelot[12] are greatly distorted by neutrons from those reactions.

ACKNOWLEDGMENTS

The authors are greatly indebted to Professor E. P. Wigner and Professor V. F. Weisskopf for their very valuable suggestions, to R. S. Livingston for his continual encouragement, and to J. A. Martin for his stimulating discussions. The As(p,pn) cross section was measured by A. Timnick.

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[25] W. Meadows, Phys. Rev. **91**, 885 (1953).

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$(p,pn)+(p,2n)$ and $(p,2p)$ Cross Sections in Medium Weight Elements*

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Several $(p,pn)+(p,2n)$ and $(p,2p)$ cross sections of nuclei of mass 19 to 69 were measured with 21.5-Mev incident protons. For all elements with mass less than 55 and for Ni^{58}, the $(p,pn)+(p,2n)$ cross section is very much less than the total reaction cross section. Detailed analysis of the data indicates that this is largely due to competition from $(p,2p)$ reactions. The conclusion from the previous paper that the ratio of probabilities for proton and neutron emission is much larger than expected seems to be confirmed and extended to lighter nuclei.

INTRODUCTION

In planning our recent survey of activation cross sections for various types of nuclear reactions in medium weight elements, little attention was at first given to the relatively large number of cases where the sum of the $(p,pn)+(p,2n)$ cross sections can be conveniently measured. It was assumed that, apart from small corrections, these would add up to the total reaction cross section (σ_R).[1] It was soon found, however, that this was not by any means the case. In many of the early measurements, values very much less than σ_R were obtained, and as the data were extended, it turned

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* The "$(p,pn)+(p,2n)$ cross section" is used here to mean the sum of the $(p,2n)$, (p,pn), (p,np) and (p,d) cross sections, all of which lead to the same radioactive nucleus (after a beta decay in the first case).

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[1] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).