are less accurate, the correction to the inverse matrix is

$$A_{ij}'=-A_{ik}\alpha_{kl}'A_{lj}+A_{ik}\alpha_{kl}'A_{lr}\alpha_{rs}'A_{sj}-\cdots,$$

where A_{ik} is the old inverse matrix and α_{kl}' is the new contribution to the matrix from the new data and summation is carried out over repeated suffixes. It is believed that this series oscillates infinitely in the only useful case, i.e., when the new data are more accurate. However the first term points the direction for corrections to the inverse matrix though it overcorrects.

PHYSICAL REVIEW VOLUME 99, NUMBER 3 AUGUST 1, 1955

Gamma Rays from the Deuteron Bombardment of Be^9, B^{10}, N^{14}, and F^{19}†

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(Received April 18, 1955)

A magnetic lens pair spectrometer has been used to study the radiations produced by the bombardment of certain light nuclei with deuterons from a Van de Graaff accelerator. Gamma rays from the bombardment of Be^9 with 2.5-Mev deuterons were observed at 6.00±0.06, 5.10±0.1, and 4.52±0.1 Mev. At 3.85-Mev bombarding energy no lines were observed between 6.5 and 8.0 Mev with an intensity as great as 5 percent of that of the 6.0-Mev line. Gamma rays from the bombardment of B^{10} with 2.0-Mev deuterons were observed at 8.93±0.04, 8.57±0.04, 7.30±0.03, 6.75±0.03, 6.50±0.03, 5.03±0.03, 4.73±0.03, and 4.49±0.05 Mev. Gamma rays from the bombardment of N^{14} with 4.0-Mev deuterons were observed at 10.73±0.08, 10.04±0.04, 9.13±0.06, 8.33±0.04, 7.31±0.04, 6.81±0.04, 6.33±0.05, 6.12±0.06, and 5.26±0.04 Mev. Gamma rays from the bombardment of F^{19} with 3.6-Mev deuterons were observed at 11.51±0.2, 10.61±0.1, 9.97±0.1, and 9.34±0.1 Mev. All the energies of gamma rays given above are corrected for Doppler shifts.

A comparison is made for some of the reactions of the relative (d,p) and (d,n) cross sections.

I. INTRODUCTION

In an earlier paper,[1] a report was given on the radiations from the Li^7+d, $B^{11}+p$, $C^{12}+d$, $C^{13}+d$, and $F^{19}+p$ reactions as observed with a lens-type pair spectrometer. As a continuation of this work, the present paper gives the results of measurements of the gamma rays from the Be^9+d, $B^{10}+d$, $N^{14}+d$, and $F^{19}+d$ reactions. The apparatus and experimental procedures used to make these measurements have been previously described.[1] Most of the experiments have been carried out with either 2.5 or 3.6 percent energy resolution, but in the case of the complicated gamma-spectra from $B^{10}+d$ a resolution of 1.8 percent was used. Plastic scintillators are currently being used for detection of the positrons and electrons instead of stilbene crystals, since larger clipped pulses are obtained from the plastic and it can be more easily machined to the desired shapes.

II. SPECTROMETER EFFICIENCY

The gamma-ray energies and yields were obtained in most of the experiments from measurements of the internal pair spectra. The number of internal pairs which are transmitted by the spectrometer and detected in coincidence, per quantum, is a function of the gamma-ray energy and multipolarity. In order for a pair to be detected in coincidence, the positron and electron must have nearly the same energy, and they must both be emitted within the acceptance solid angle of the spectrometer. The angular correlation of the positrons and electrons, i.e., the number of pairs per quantum, per $d\theta$, per unit energy interval where the positron and electron have nearly the same energy, was calculated from the expressions given by Rose[2] for gamma rays of different energies and multipolarities. The peak number of pairs transmitted by the spectrometer, per quantum, was then calculated numerically with an acceptance solid angle equal to 8.7 percent of the total sphere (maximum acceptance half-angle = 47°, minimum acceptance half-angle = 31°, energy resolution = 2.5 percent), assuming that the gamma-ray angular distributions were isotropic with respect to the beam. The results are shown in Fig. 1.

The efficiency of the spectrometer for detecting gamma rays of different energies was determined experimentally by comparing the pair yields obtained with the spectrometer from the $C^{13}+d$ reaction with the absolute gamma-ray yields given for this reaction by Baggett and Bame,[3] and Thomas and Lauritsen.[4] The experimentally determined peak number of coincidence counts per quantum was less than the calculated number of transmitted pairs per quantum by about a factor of 3 at 9 Mev, and a factor of 10 at 4 Mev. This can be explained in the following ways. (1) Half of the transmitted pairs are not detected in coincidence since in half of the cases the positron and electron both strike the same scintillator. (2) The alignment of the spec-

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† Supported in part by the U. S. Atomic Energy Commission.

[1] Bent, Bonner, and Sippel, Phys. Rev. **98**, 1237 (1955).

[2] M. E. Rose, Phys. Rev. **76**, 678 (1949).

[3] L. M. Baggett and S. J. Bame, Phys. Rev. **84**, 154 (1951).

[4] R. G. Thomas and T. Lauritsen, Phys. Rev. **88**, 969 (1952).

trometer and choice of baffle widths are not exactly optimum, so that some of the electrons emitted within the acceptance solid angle do not pass through the intermediate baffle. (3) In order to minimize background effects due to the scattering of high-energy gamma rays and neutrons from the walls and coils of the spectrometer, the detectors were chosen to be somewhat smaller than the spot size at the exit end of the spectrometer. (4) At the fastest resolving times (2×10^{-9} sec) some of the true coincidences are missed because of random delays in the photomultipliers and associated electronics. (5) In order to bias out as much background as possible, only the largest coincidence pulses are counted. Thus coincidences due to electrons and positrons passing through the edges of the crystals are missed. It is hoped to minimize this loss by the proper shaping of the detecting scintillators. Losses due to the use of too large a bias are probably more important at low gamma-ray energies than at high energies.

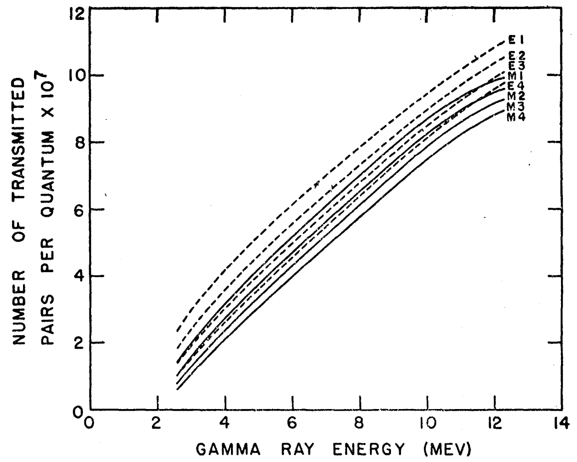

Fig. 1. Spectrometer efficiency.

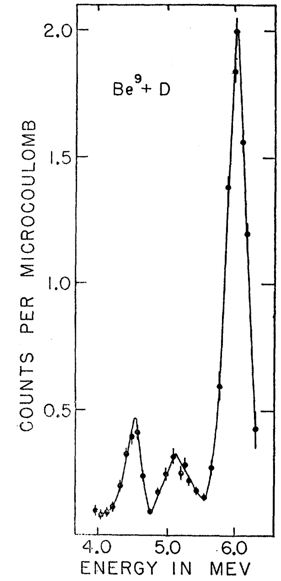

Fig. 2. Internal pair spectrum from the bombardment of a 25-mg/cm² metallic beryllium target with 2.5-Mev deuterons. Spectrometer resolution = 5.5 percent.

III. RESULTS AND DISCUSSION

A. Be^9+H^2

The internal pairs from the bombardment of a 25-mg/cm² metallic beryllium target with 2.50- and 3.85-Mev deuterons were observed with 5.5 percent resolution. The results obtained at 2.5-Mev bombarding energy are shown in Fig. 2. They have been corrected for a background observed with zero magnetic field, which is due to true coincidences from scattered gamma radiation and neutrons, equal to about 35 percent of the 4.54-Mev peak and for an accidental coincidence rate equal to about 4 percent of this peak. At 3.85-Mev bombarding energy, the internal pair spectrum was observed up to 8.0-Mev gamma-ray energy, but no lines were observed between 6.5 and 8.0 Mev with an intensity as great as 5 percent of that of the 6.00-Mev line. The gamma-ray energies and yields are given in Table I.[5–7] An attempt was made to observe the internal pair spectrum below 6 Mev with 2.5 percent resolution. However, the transmission of the spectrometer for pairs is reduced by about a factor of 10 in going from 5.5 percent to 2.5 percent resolution, whereas the background with no magnetic field is not affected. Hence at 2.5 percent resolution this background was five times larger than the 4.5-Mev pair peak. This background was worse for the Be^9+d reaction than for any of the other reactions studied.

When Be^9 is bombarded with deuterons the following reactions, which could account for the gamma rays, occur:

$$Be^9(d,p)Be^{10},\quad Q=4.59\text{ Mev},$$
$$Be^9(d,n)B^{10},\quad Q=4.36\text{ Mev}.$$

Energy levels of Be^{10} have been reported at 3.37, 5.96, 6.18, 6.26, 7.37, and 7.54 Mev by Jung and Bockelman,[5] and Bockelman *et al.*[6] from measurements

Table I. Energies and yields of the gamma rays from the deuteron bombardment of Be^9.

Uncorrected energy (Mev)	Doppler corrected energy (Mev)	Yield (γ/deut. ×10⁶)	Total cross section[a] (mb)	Assignment	Reference
6.03 ±0.05	6.00 ±0.06	0.70	1.4	Be^{10}(5.96)	5, 6
5.13 ±0.09	5.10 ±0.1	0.13	0.2	B^{10}(5.16)	7
4.54 ±0.09	4.52 ±0.1	0.23	0.4	B^{10} cascade (5.16 to 0.72)	7

[a] Average value, $E_d=0$ to 2.5 Mev.

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[5] J. J. Jung and C. K. Bockelman, Phys. Rev. **96**, 1353 (1954).

[6] Bockelman, Browne, and Buechner, Massachusetts Institute of Technology Progress Report, May, 1954 (unpublished).

[7] F. Ajzenberg, Phys. Rev. **82**, 43 (1951); Phys. Rev. **88**, 298 (1952); A. J. Dyer and J. A. Bird, Australian J. Phys. **6**, 45 (1951); Bockelman, Browne, Sperduto, and Buechner, Phys. Rev. **90**, 340 (1953); Phys. Rev. **92**, 665 (1953); Pruitt, Swartz, and Hanna, Phys. Rev. **92**, 1456 (1953); T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954).

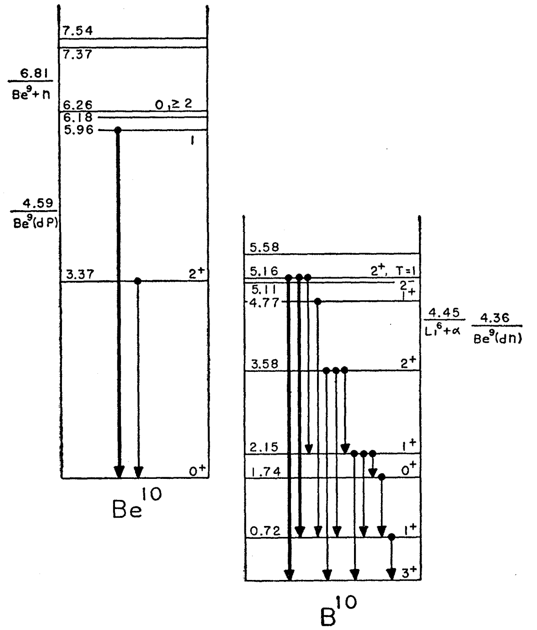

FIG. 3. Energy levels and decay schemes of Be^{10} and B^{10}. Gamma rays observed in the present experiment are represented by heavy vertical lines.

of the proton groups from the $Be^9(d,p)Be^{10}$ reaction. B^{10} has known levels at 0.72, 1.74, 2.15, 3.58, 4.77, 5.11, 5.16, 5.58, 5.93, 6.06, 6.16, 6.40, 6.58 Mev,[7] and higher levels.

Previous measurements of the gamma rays from the Be^9+d reaction have been made by Rasmussen, Hornyak, and Lauritsen[8]; Chao, Lauritsen, and Rasmussen[9]; Shafroth and Hanna[10]; and Mackin.[11] Gamma rays from the $Li^6(\alpha,\gamma)B^{10}$ reaction have been studied by Jones and Wilkinson.[12] The 6.00-, 5.10-, and 4.52-Mev gamma rays observed in the present experiment probably correspond to the gamma rays reported at 4.47 and 5.20 Mev by Chao *et al.*,[9] and at 4.44 and 5.98 Mev by Mackin.[11]

The 6.00-Mev gamma ray is assigned to a ground-state transition from the 5.96-Mev state in Be^9 since states in this energy region in B^{10} probably break up by alpha emission much faster than by gamma emission. The 5.10- and 4.52-Mev gamma rays are assigned to transitions from the 5.11- or 5.16-Mev state in B^{10} to the ground and 0.72-Mev states, respectively. Within the experimental errors of the present experiment, it is not possible to tell which member of the pair of states at 5.1 Mev is involved. However, according to the arguments of Jones and Wilkinson[12] the 5.16-Mev state is a 2^+, $T=1$ state, and the 5.11-Mev state is 2^-, $T=0$, and so these two lines probably are due to transitions from the 5.16-Mev state, the breakup into $Li^6+\alpha$ being slowed down by the isotopic spin selection rule.

Energy-level diagrams and decay schemes of Be^{10} and B^{10} are shown in Fig. 3. Spin and parity assignments of B^{10} are given which are consistent with the neutron angular distributions of Ajzenberg[7] and the gamma-ray measurements.[8–12] The spin and parity of the 3.37-Mev state of Be^{10} have been shown to be 2^+.[13] The fact that the 5.96-Mev state in Be^{10} decays predominantly to the 0^+ ground state rather than to the 2^+, 3.37-Mev state, suggests that the angular momentum of this state is 1. Measurements of the proton groups from the $Be^9(d,p)Be^{10}$ reaction by Bockelman *et al.*[7] at 5.4- to 7.4-Mev bombarding energies and by Phillips and Windham[14] at 3.85-Mev bombarding energy have shown that the proton group leaving Be^{10} in the 6.26-Mev level has about the same intensity as the proton group leading to the excitation of the 5.96-Mev level. The absence of a ground-state transition from the 6.26-Mev state suggests that the angular momentum of this state is 0 or ≥ 2.

$B^{10}+H^2$

The gamma rays from the deuteron bombardment of B^{10} were first investigated with 2.5 percent resolution. The internal pair spectrum obtained was complicated and most of the lines were not well resolved, making the interpretation of the data difficult. The pair spectrum between 5.8 and 9.2 Mev was therefore reinvestigated with 1.8 percent resolution. The results obtained are shown in Fig. 4, corrected for a zero magnetic field

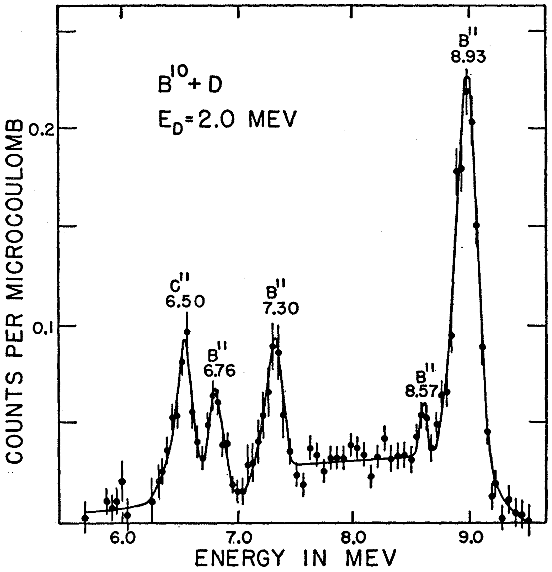

FIG. 4. Internal pair spectrum from the bombardment of thick B^{10} targets with 2.0-Mev deuterons. Spectrometer resolution = 1.8 percent.

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[8] Rasmussen, Hornyak, and Lauritsen, Phys. Rev. **76**, 581 (1949).

[9] Chao, Lauritsen, and Rasmussen, Phys. Rev. **76**, 582 (1949).

[10] J. M. Shafroth and S. S. Hanna, Phys. Rev. **95**, 86 (1954).

[11] R. J. Mackin (private communication).

[12] G. A. Jones and D. H. Wilkinson, Phys. Rev. **90**, 722 (1953); Phys. Rev. **91**, 1575 (1953).

[13] Cohen, Hanna, and Class, Phys. Rev. **94**, 419 (1954).

[14] G. C. Phillips and P. M. Windham (private communication).

background which was equal to about 20 percent of the 7.3-Mev peak and for an accidental rate equal to about 8 percent of the 7.3-Mev peak. A 45 mg/cm^2 96 percent B^{10} target pressed onto a 21 mg/cm^2 copper foil was used for the region between 7.5- and 9.3-Mev gamma-ray energy and a 99.5 percent B^{10} target about 6 mg/cm^2 thick was used for the region between 6 and 7.5 Mev. The 99.5 percent B^{10} was used to minimize the accidental rate due to the beta rays from B^{12} resulting from the B^{11}(d,p)B^{12} reaction. The internal pair spectrum of the low-energy gamma rays taken at 2.5 percent resolution is shown in Fig. 5, corrected for a zero magnetic field background equal to about 7 percent of the 4.73-Mev peak and an accidental rate equal to about 20 percent of this peak. The lower energy gamma rays were not investigated with 1.8 percent resolution because of the low yields in this region.

Because of uncertainties in determining the thicknesses of the boron targets, this spectrum was calibrated on the lines which were identified as being from the B^{10}(d,p)B^{11} reaction, since the energy levels of B^{11} have been accurately determined by Van Patter, Buechner, and Sperduto[15] from measurements of the proton groups. In doing this it was assumed that each pair line experienced the maximum possible Doppler shift. The gamma-ray yields and Doppler corrected energies are listed in Table II.[15,16]

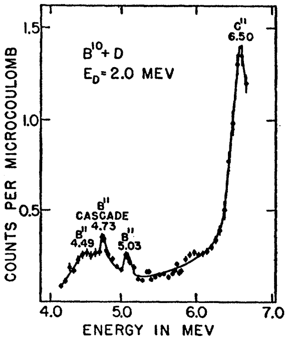

FIG. 5. Internal pair spectrum from the bombardment of a 45-mg/cm^2, 96 percent B^{10} target with 2.0-Mev deuterons. Spectrometer resolution =2.5 percent.

The main features of the present results are in agreement with earlier pair spectrometer measurements of the gamma rays from the deuteron bombardment of B^{10} which were carried out with poorer resolution.[17]

When B^{10} is bombarded with deuterons, the following reactions, which could account for the gamma rays, occur:

$$B^{10}(d,p)B^{11}, \quad Q= 9.23 \text{ Mev},$$
$$B^{10}(d,n)C^{11}, \quad Q= 6.47 \text{ Mev},$$
$$B^{10}(d,\alpha)Be^{8}, \quad Q=17.81 \text{ Mev}.$$

TABLE II. Energies and yields of the gamma rays from deuteron bombardment of B^{10}.

Doppler corrected energy (Mev)	Yield (γ/deut. $\times 10^6$)	Total cross section[a] (mb)	Assignment	References
8.93±0.04	2.6	8.1	B^{11}(8.93)	15
8.57±0.04	0.6	1.8	B^{11}(8.57)	15
7.30±0.03	1.9	6.0	B^{11}(7.30)	15
6.75±0.03	1.7	5.4	B^{11}(6.76)	15
6.50±0.03	2.6	8.0	C^{11}(6.40)	16
5.03±0.03	0.9	3.0	B^{11}(5.03)	15
4.73±0.03	2.0	6.3	B^{11} cascade (9.19→4.46)	15
4.49±0.05	1.6	5.0	B^{11}(4.46)	15

[a] Average value $E_d=0$ to 2.0 Mev.

The excited states of Be^8 probably break up into two alpha particles and hence would not contribute to the pair spectrum.

Accurate measurements of the proton groups from the B^{10}(d,p) reaction by Van Patter *et al.*[15] and Elkind[18] have established the existence of levels in B^{11} at 9.28, 9.19, 8.92, 8.57, 7.99, 7.30, 6.81, 6.76, 5.03, 4.46, and 2.14 Mev. A comparison of the gamma-ray energies and intensities with these results leads to the assignment of the 8.93-, 8.57-, 7.30-, 6.75-, 5.03-, and 4.49-Mev lines to ground state transitions in B^{11}. The 4.73-Mev line is assigned to a transition between the 9.19- and 4.46-Mev levels of B^{11}. The 6.50-Mev line is assigned to a ground state transition in C^{11} corresponding to the level at 6.40 in C^{11} reported by Johnson[16] from measurements of the neutron groups from the B^{10}(d,n)C^{11} reaction.

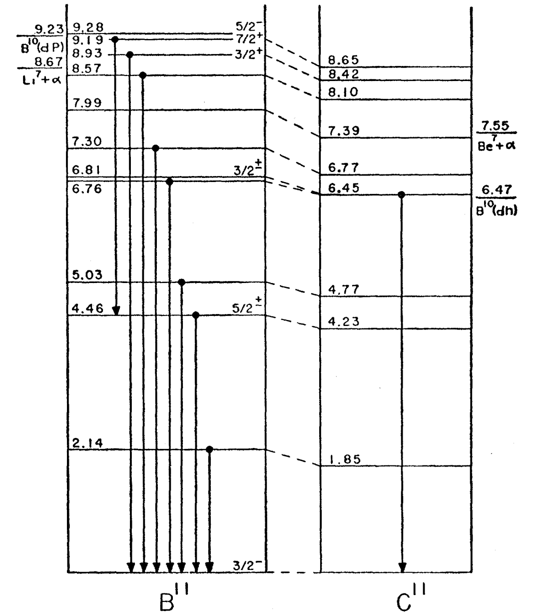

FIG. 6. Energy levels of B^{11} and C^{11} and the gamma rays from B^{10}+d.

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[15] Van Patter, Buechner, and Sperduto, Phys. Rev. **82**, 248 (1951).

[16] V. R. Johnson, Phys. Rev. **86**, 302 (1952).

[17] J. Terrell and G. C. Phillips, Phys. Rev. **83**, 703 (1951); S. J. Bame and L. M. Baggett, Phys. Rev. **84**, 891 (1951); Rutherglen, Rae, and Smith, Proc. Phys. Soc. (London) **A64**, 906 (1951).

[18] M. M. Elkind, Phys. Rev. **92**, 127 (1953).

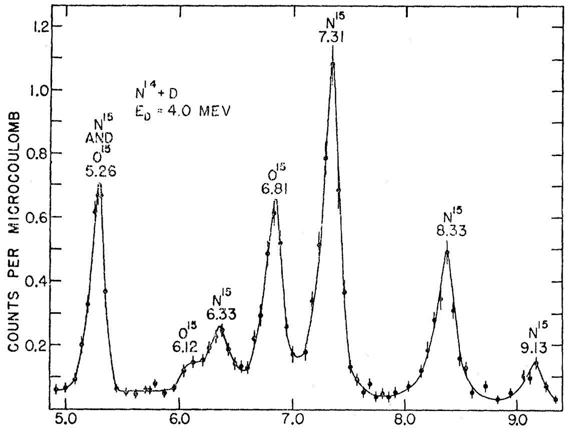

FIG. 7. Internal pair spectrum from the bombardment of an 18-mg/cm^2 CrN target with 4.0-Mev deuterons. Spectrometer resolution = 2.5 percent.

Energy level diagrams of B^{11} and C^{11} showing the gamma rays from $B^{10}+d$ are given in Fig. 6. The energies of the B^{11} levels are due to the proton group measurements.[15,18] The 1.85, 4.23, 4.77, 6.77, and 7.39 energies for C^{11} are due to Johnson.[16] The 6.45-Mev value is an average of the gamma-ray and neutron group measurements. The 8.10-, 8.42-, and 8.65-Mev values are from the neutron threshold measurements of Marion, Cook, and Bonner.[19] Spin and parity assignments have been given which are consistent with the present gamma-ray measurements, the angular distributions of Evans and Parkinson,[20] and the $\alpha-\gamma$ and $\gamma-\gamma$ angular correlations of Jones and Wilkinson.[21]

In addition to the transitions shown in Fig. 6, it is likely that a number of other transitions occur which are either too weak to observe or are unresolved in the present experiment. It is expected from the charge symmetry hypothesis of nuclear forces that the spins and parities of the corresponding levels of the mirror nuclei B^{11} and C^{11} are the same, and that the decay schemes of these two nuclei should therefore be the same. Transitions in C^{11} corresponding to transitions from the 8.57-, 8.93-, and 9.19-Mev levels of B^{11} would be expected to be weak because these states in C^{11} can break up into $Be^7+\alpha$. However, weak lines between 7.5 and 8.5 Mev may be present. A 6.77-Mev gamma ray from C^{11} would not have been distinguishable from the 6.76-Mev gamma ray of B^{11}. There is a slight indication of 4.9-Mev gamma radiation since the spectrum does not fall as low in this region as it should were there only lines at 4.73 and 5.03 Mev, which might be due to a ground state transition from the 4.77-Mev state of C^{11}. Similarly, there is a slight indication for a line at 4.3 Mev, which might be due to a ground-state transition from the 4.23-Mev state of C^{11}. In general it is seen that at 2.0-Mev bombarding energy the lines from the $B^{10}(d,n)C^{11*}$ reaction are weaker than the lines from the $B^{10}(d,p)B^{11*}$ reaction. The only exception is the 6.50-Mev line from C^{11} which is stronger than the 6.75-Mev line from the mirror level in B^{11}. In an attempt to explain this exception, the spectrum between 6 and 7.5 Mev was also observed at 4.0-Mev bombarding energy. It was found that the relative intensities of the 6.50-, 6.76-, and 7.30-Mev gamma rays are about the same at 4.0 Mev as at 2.0-Mev bombarding energy. This point is discussed further in Sec. IV.

There is indirect evidence that the 4.46-Mev state of B^{11} cascades partly to the 2.14-Mev level, since if the 4.73-Mev line is due to a transition from the 9.19 to the 4.46-Mev level, then the 4.46-Mev line should be at least as intense as the 4.73-Mev line if the 4.46-Mev state decayed 100 percent to the ground state.

C. $N^{14}+H^2$

An 18-mg/cm^2 CrN target pressed onto a 20-mg/cm^2 copper foil was bombarded with 4.0-Mev deuterons and the internal pair spectrum was observed between 5 and 9.2 Mev with 2.5 percent resolution. The results are shown in Fig. 7, corrected for zero magnetic field and chance backgrounds which were about 10 and 40 percent, respectively, of the lowest points. Because of power limitations, the intermediate image spectrometer arrangement giving 2.5 percent resolution could not be used to measure gamma-ray energies greater than 9.3 Mev. In order to look for higher energy gamma rays from the $N^{14}+d$ reaction, a ring focus arrangement was used. The internal pair spectrum obtained from the bombardment of a 25-mg/cm^2 ZrN target with 4.25-Mev deuterons is shown in Fig. 8, uncorrected for background effects. The instrument resolution for this experiment was 3.6 percent. ZrN was found to be a more stable target than CrN. The gamma-ray energies and yields are given in Table III.[22,23]

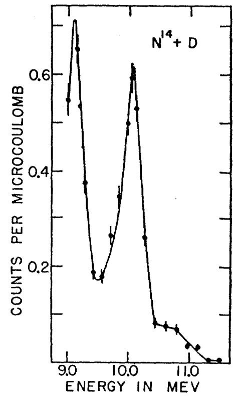

FIG. 8. Internal pair spectrum from the bombardment of a 25-mg/cm^2 ZrN target with 4.25-Mev deuterons. Spectrometer resolution = 3.6 percent.

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[19] Marion, Cook, and Bonner (private communication).

[20] N. T. S. Evans and W. C. Parkinson, Proc. Phys. Soc. (London) **A78**, 684 (1954).

[21] G. A. Jones and D. H. Wilkinson, Phys. Rev. **88**, 423 (1952).

[22] Sperduto, Buechner, Bockelman, and Browne, Phys. Rev. **96**, 1316 (1954).

[23] Evans, Greene, and Middleton, Proc. Phys. Soc. (London) **A66**, 108 (1953).

When N^{14} is bombarded with deuterons the following reactions, which could account for the gamma rays, occur:

$$N^{14}(d,p)N^{15},\quad Q=8.61\text{ Mev},$$
$$N^{14}(d,n)O^{15},\quad Q=5.12\text{ Mev},$$
$$N^{14}(d,\alpha)C^{12},\quad Q=13.57\text{ Mev}.$$

The 10.73-, 10.04-, 9.13-, 8.33-, 7.31-, and 6.33-Mev lines are all assigned to N^{15} since they correspond to ground-state transitions from known excited states of N^{15}.[22] Similarly, the 6.81- and 6.12-Mev lines are assigned to O^{15}. The 5.26-Mev peak is too broad for a single line indicating that gamma rays from both N^{15} and O^{15} contribute to this peak. There is no evidence for a nuclear pair line from the $N^{14}(d,\alpha\pi)C^{12}$ reaction at 7.65 Mev.

These results are in agreement with other measurements of the gamma rays from the $N^{14}+d$ reaction by Terrell and Phillips[17] who observed lines at 4.4, 5.33, 6.4, 7.40, and 8.46 Mev, and with the neutron capture gamma-ray measurements of Kinsey, Bartholomew, and Walker[24] who reported gamma rays from N^{15} at 4.48, 5.29, 5.55, 6.32, 7.16, 7.36, 8.28, 9.15, and 10.82 Mev. The gamma rays reported at 5.55 and 7.16 Mev by Kinsey *et al.* were not observed in the present experiment. The 7.31- and 8.33-Mev values from the present experiment disagree with the corresponding values given by Kinsey *et al.* by amounts larger than the estimated experimental errors, but agree with the proton group values of Sperduto *et al.*[22] Within the experimental errors, the 10.82-Mev line observed by Kinsey *et al.* and the 10.73-Mev line observed in the present experiment may be due to the same gamma ray.

Energy level diagrams of N^{15} and O^{15} showing the gamma rays from $N^{14}+d$ are given in Fig. 9. The energies of the levels of N^{15} have been accurately determined by Sperduto *et al.*[22] from measurements of the proton groups from the $N^{14}(d,p)N^{15}$ reaction. The 6.12- and 6.81-Mev values of O^{15} are from the present gamma-ray measurements and are 70 and 30 kev, respectively, lower than the values given for these levels by Evans, Greene, and Middelton.[23] The 5.29-Mev value is from Evans *et al.* In view of the proton group intensities of Sperduto *et al.*,[22] the absence of ground-state transitions from the 7.16- and 7.57-Mev levels of N^{15} suggests that these levels decay by cascades to lower levels. A 1.88-Mev gamma ray reported by Thompson[25] from the $N^{14}+d$ reaction has been interpreted as being the result of a transition from the 7.16-Mev state to the 5.28- or 5.30-Mev state of N^{15}. Spin and parity assignments are given which are consistent with the gamma-ray measurements together with the angular distributions of Gibson and Thomas[26] and Evans, Greene, and Middleton.[23]

TABLE III. Energies and yields of the gamma rays from the deuteron bombardment of N^{14}.

Uncorrected energy (Mev)	Doppler corrected energy (Mev)	Yield (γ/deut. ×10⁶)	Total cross section[a] (mb)	Assignment	Reference
10.77 ±0.07	10.73 ±0.08	0.02	0.1	$N^{15}(10.70)$	22
10.08 ±0.03	10.04 ±0.04	0.14	0.8	$N^{15}(10.07)$	22
9.17 ±0.05	9.13 ±0.06	0.15	0.9	$N^{15}(9.16)$	22
8.37 ±0.03	8.33 ±0.04	0.71	4.3	$N^{15}(8.32)$	22
7.34 ±0.03	7.31 ±0.04	2.3	14	$N^{15}(7.31)$	22
6.84 ±0.03	6.81 ±0.04	1.6	9.7	$O^{15}(6.84)$	23
6.36 ±0.04	6.33 ±0.05	0.75	4.5	$N^{15}(6.33)$	22
6.15 ±0.05	6.12 ±0.06	0.50	3.0	$O^{15}(6.19)$	23
5.29 ±0.03	5.26 ±0.04	3.3	20	$N^{15}(5.29)$	22
				and $O^{15}(5.29)$	23

[a] Average value $E_d=0$ to 4 Mev.

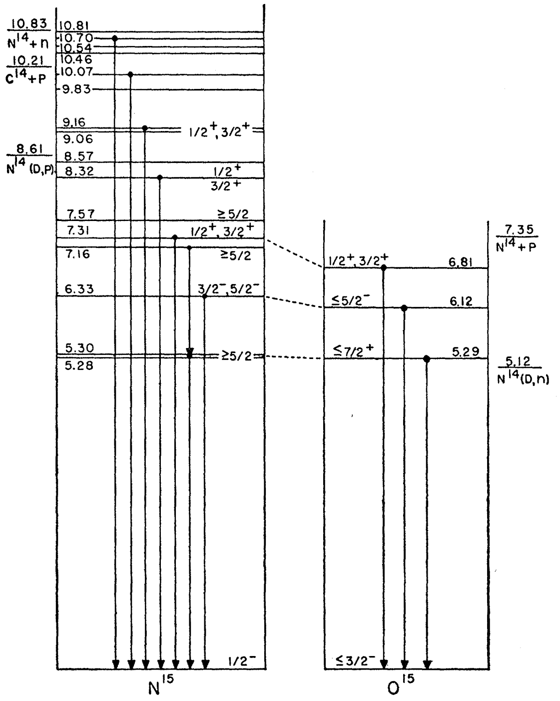

FIG. 9. Energy levels of N^{15} and O^{15} and gamma rays from $N^{14}+d$.

The decay schemes of the two mirror nuclei N^{15} and O^{15} appear to be the same where comparisons can be made. Levels above 7.4 Mev in O^{15} can break up into $N^{14}+p$ and hence would be expected to give only weak gamma rays. Also, the spin and parity measurements which have been made seem to indicate that the spins and parities of the corresponding levels are the same.

A comparison of the gamma-ray yields from the corresponding levels shows that the gamma rays from the $N^{14}(d,p)N^{15*}$ reaction are about 1.5 times stronger than the gamma rays from the $N^{14}(d,n)O^{15*}$ reaction.

D. $F^{19}+H^2$

First attempts to measure the internal pair spectrum from the deuteron bombardment of F^{19} were unsuccessful because of the large accidental coincidence rate due

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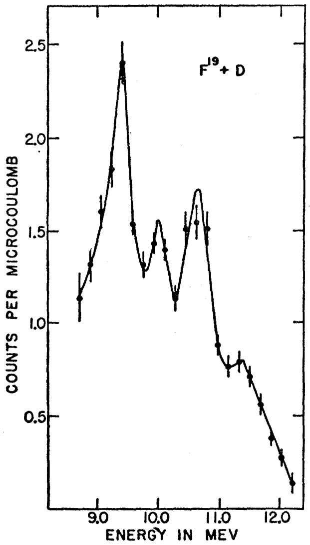

FIG. 10. External pair spectrum from the bombardment of a thick CaF_2 target with 3.6-Mev deuterons. A 77-mg/cm^2 lead converter 9 mm in diameter was separated from the target by 5 mm of aluminum absorber.

to the beta rays from F^{20}. However, the maximum energy of these beta-rays is 5.4 Mev, so by placing a 5-mm aluminum absorber between the target and a 77-mg/cm^2 lead converter it was possible to look at the external pair spectrum down to 8.5-Mev gamma-ray energy. The results obtained from the bombardment of a thick CaF_2 target with 3.6-Mev deuterons are shown in Fig. 10, uncorrected for background effects. A ring focus spectrometer arrangement giving 3.6 percent resolution was used. The energies of the lines were calculated from the peak positions using the 6.05-Mev nuclear pair line from the $F^{19}(p,\alpha\pi)O^{16}$ reaction for calibration assuming that each external pair peak was shifted down by an amount equal to the most probable energy lost by a single electron in passing through the 77-mg/cm^2 lead converter. This shift was calculated to be 0.154 Mev. The gamma-ray energies and yields are summarized in Table IV.

When F^{19} is bombarded with deuterons the following reactions occur:

$$\begin{aligned} &F^{19}(d,n)Ne^{20}, && Q=10.65 \text{ Mev},\\ &F^{19}(d,p)F^{20}, && Q=\ \ 4.37 \text{ Mev},\\ &F^{19}(d,\alpha)O^{17}, && Q=10.04 \text{ Mev}.\end{aligned}$$

States above 4.2 Mev in O^{17} can break up into $O^{16}+n$ and hence would not be expected to give rise to intense gamma radiation. Because of the low Q value for the $F^{19}(d,p)F^{20}$ reaction, F^{20} cannot give rise to gamma rays with energies greater than 7.7 Mev. The gamma rays that are observed between 8 and 12 Mev must therefore be from Ne^{20}.

The 9.34- and 9.97-Mev gamma rays are assigned to ground-state transitions from the levels reported at 9.0 and 10.1 Mev from measurements of the neutron groups from the $F^{19}(d,n)Ne^{20}$ reaction.[27] The 11.51-Mev gamma ray is also assigned to a ground-state transition from an excited state in Ne^{20} at this energy since this line was also observed by Terrell and Phillips[17] at 1.56-Mev bombarding energy where it is energetically impossible that it could be due to a transition from a higher level in Ne^{20} to the 1.63-Mev level. The 10.61-Mev gamma ray is assigned to a ground-state transition from a level in Ne^{20} at this energy although this line could also be due to a transition to the 1.63-Mev level from a level at 12.28 Mev in Ne^{20}. A gamma-ray line has been reported at 8.1 Mev by Terrell and Phillips,[17] which may correspond to a ground-state transition from the level reported at 7.3 Mev by Bonner,[27] or to a cascade transition from the 9.97-Mev level to the 1.63-Mev level.

The 9.34-Mev state must have odd angular momentum and even parity, or *vice versa*, since otherwise it could break up into $O^{16}+\alpha$ much faster than it could emit a gamma ray. Since this state decays predominantly to the ground state rather than to the 2^+, 1.63-Mev[28] state, the spin and parity are probably either 1^+ or 2^-. A 2^- assignment is possible because of the isotopic spin selection rule discouraging an $E1$ transition to the 1.63-Mev level. The same arguments may be applied to the 9.97- and 10.61-Mev gamma emitting states; however, since the difference in energies of these two states is very nearly the same as the excitation energy of the first excited state of F^{20}, and since the first $T=1$ state of Ne^{20} is expected to be at about 10.2 Mev,[29] the 9.97- and 10.61-Mev levels might be $T=1$ states corresponding to the ground and first excited states of F^{20}. The spins and parities of these two states in Ne^{20} would then have to be 1^+ to be consistent with the decay scheme. This assignment is in agreement with the 1^+ ground state of F^{20} and the first excited state of F^{20}, which has been reported to have even parity and a spin of 1, 2, or 3.[30] Similar arguments suggest that the spin and parity of the 11.51-Mev state of Ne^{20} are 1^+ or 2^-. The fact that the 11.51-Mev gamma radiation is weaker than the other lines may be due to the competition with alpha emission, since states above 10.9 Mev in Ne^{20} can break up into $O^{16}+\alpha$ leaving O^{16} excited in the 3^- state at 6.14 Mev.

An energy level diagram of Ne^{20} showing the gamma rays from $F^{19}+d$ is given in Fig. 11. The energies, spins,

TABLE IV. Energies and yields of the gamma rays from the deuteron bombardment of F^{19}.

Uncorrected energy (Mev)	Doppler corrected energy (Mev)	Yield (γ/deut. $\times 10^6$)	Total cross section[a] (mb)	Assignment
9.38±0.09	9.34±0.1	0.48	1.7	Ne^{20}
10.01±0.09	9.97±0.1	0.29	1.0	Ne^{20}
10.65±0.09	10.61±0.1	0.32	1.1	Ne^{20}
11.56±0.19	11.51±0.2	0.14	0.5	Ne^{20}

[a] Average value $E_d=0$ to 3.6 Mev.

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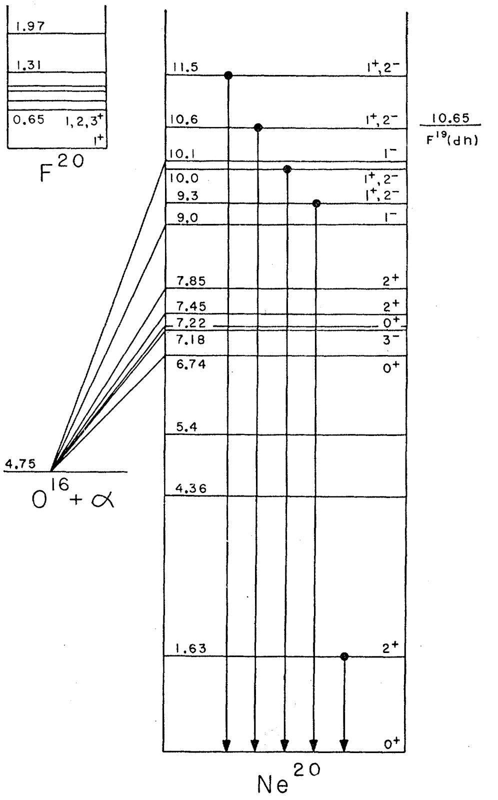

FIG. 11. Energy levels of Ne^{20} and gamma rays from $F^{19}+d$.

and parities of the levels at 6.74, 7.18, 7.22, 7.45, and 7.85 Mev have been reported by Cameron[31] from measurements of resonances in the scattering of alpha particles from O^{16}. The energies, spins, and parities of the 9.0- and 10.1-Mev levels are due to Ferguson and Walker[32] from measurements of the $O^{16}(\alpha,\alpha')$ reaction. The 9.3- and 10.0-Mev values are from the present gamma-ray measurements. Within the experimental errors the energies of these gamma-emitting states are the same as the energies of the alpha-emitting states at 9.0 and 10.1 Mev. However, the states observed from resonances in the scattering of alpha particles from O^{16} cannot be the same as the states giving rise to the strong gamma rays since gamma emission is much less probable than particle emission. Since the energies of the two levels near 9 Mev and the two levels near 10 Mev are only known to within a few hundred kilovolts, the energy separation and relative positions of the levels may not be significant. The existence of pairs of levels with very nearly the same energies but different parities might result from an alpha particle model of Ne^{20} due to the tunneling motion.[33] The similar case of O^{16} has been worked out in some detail by Dennison.[33]

IV. RELATIVE (*d,p*) AND (*d,n*) CROSS SECTIONS

It has been pointed out by Cooper and Tobocman[34] that measurements of cross sections for deuteron stripping reactions can provide direct experimental measurements of the relative neutron and proton distributions within the nucleus. The results of the present paper and an earlier paper[1] of the gamma rays from the reactions $B^{10}(d,p)B^{11}$, $B^{10}(d,n)C^{11}$, $C^{13}(d,p)C^{14}$, $C^{13}(d,n)N^{14}$, and $N^{14}(d,p)N^{15}$, $N^{14}(d,n)O^{15}$ show that, except for the 6.50-Mev line from the $B^{10}(d,n)C^{11}$ reaction, the gamma rays from the (d,p) reactions are more intense than the gamma rays from the (d,n) reactions. For two of the reactions, $B^{10}+d$ and $N^{14}+d$, the residual nuclei are mirror nuclei. The decay schemes of mirror nuclei should be the same and hence the relative gamma-ray intensities should give the relative (d,p) and (d,n) cross sections. A comparison of the $N^{14}(d,p)N^{15}$ and $N^{14}(d,n)O^{15}$ cross sections for two corresponding states is given in Table V, which shows that the (d,p) cross section is about 1.5 times greater than the (d,n) cross section.

A comparison of the cross sections of the $Mg^{24}(d,p)Mg^{25}$ and $Mg^{24}(d,n)Al^{25}$ reactions for the three lowest states has been made by Goldberg[35] which shows that the (d,p) cross sections at 8.0-Mev bombarding energy are 4 to 6 times larger than the (d,n) cross sections at 4.0-Mev bombarding energy. Using these data Fujimoto, Kikuchi, and Yoshida[36] calculated the reduced widths for three corresponding levels in the mirror nuclei Mg^{25} and Al^{25} neglecting Coulomb effects, and found that the reduced widths for Mg^{25} were about 10 times greater than the reduced widths for Al^{25}. It is expected from the charge symmetry of nuclear forces that the reduced widths of corresponding levels in mirror nuclei should be the same; however, a difference of a factor of 10 seems to be too large to be accounted for by the fact that Coulomb effects were neglected in these calculations, and it was suggested that it might be due to the protons occupying a smaller volume than neutrons in the nucleus.[34,36] Part of this discrepancy may also be due to uncertainties in the absolute (d,p) and (d,n) cross sections.

The $N^{14}(d,p)N^{15}$ and $N^{14}(d,n)O^{15}$ cross sections were

TABLE V. Cross sections of the $N^{14}(d,p)N^{15}$ and $N^{14}(d,n)O^{15}$ reactions.

$N^{14}(d,p)N^{15}$		$N^{14}(d,n)O^{15}$	
E_x (Mev)	Total cross section[a] (mb)	E_x (Mev)	Total cross section[a] (mb)
6.33	4.5	6.12	3.0
7.31	14	6.81	9.7

[a] Average values $E_d=1.6$ to 4.0 Mev. Accuracy of relative values is about 15 percent. Absolute values are accurate to within about a factor of 4.

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

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(Received March 7, 1955)

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]

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

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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