(d,n) Reactions in O^{16} and N^{14}†

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(Received June 6, 1955)

The technique of observing neutron thresholds in (p,n) and (d,n) reactions has been applied to the reactions $O^{16}(d,n)F^{17}$ and $N^{14}(d,n)O^{15}$. A nuclear resonance absorption magnetometer, in conjunction with a 90° magnetic analyzer, was used to accurately measure the bombarding energies. The $Li^7(p,n)Be^7$ threshold was used as the primary calibration. The energy of the first excited state of F^{17} was found to be 0.499 ± 0.003 Mev; excited states in O^{15} were found at 6.20 ± 0.03, 6.841 ± 0.009, and 6.909 ± 0.009 Mev. Ten broad resonances in the forward yield of neutrons from the reaction $O^{16}(d,n)F^{17}$ have been found in the range of bombarding energies from 1.8 to 4.3 Mev. The cross section for the $N^{14}(d,n)O^{15}$ reaction increases with the deuteron energy in the range 1.1 to 4.5 Mev; a sharp rise in the cross section begins at a bombarding energy of 2.1 Mev. The absolute cross sections for the $O^{16}(d,n)F^{17}$ and $N^{14}(d,n)O^{15}$ reactions were measured.

I. INTRODUCTION

THERE is at present considerable interest in the similarity of the level structure of pairs of mirror nuclei, since the hypothesis of the charge symmetry of nuclear forces predicts that these structures should be identical, except for Coulomb effects. Theoretical analysis of the energy shifts of mirror excited states has met with success only in a qualitative manner.[1] Both theoretical and experimental difficulties are present: the magnitude of the energy shifts are critically dependent on the nuclear radius, and the radius varies with excitation energy in an unknown manner. Also, accurate determinations of the energy levels of both members of a mirror pair have been made in only a few cases. Magnetic analysis of inelastically scattered charged particles and of charged-particle groups from nuclear reactions allow accurate measurements of the energies of excited states. The levels of many nuclei, however, are inaccessible with this technique, and in most cases the best present information is derived from measurements of the energies of neutron groups or of γ rays from various reactions. Since these types of measurements are difficult to make with great accuracy, the level structures of some nuclei are known only to an order of magnitude less accurately than those of the mirror partners.

By measuring, as a function of bombarding energy, the ratio of the number of slow neutrons to the number of fast neutrons emitted in (p,n) and (d,n) reactions, it is possible to detect neutron thresholds corresponding to the ground states or to excited states of the residual nuclei. This technique[2] has been supplemented with a means of precisely determining the bombarding energy. In this manner, it is possible to accurately measure the excitation energy of the residual nucleus and thus provide information which may be used in the comparison of the level structures of pairs of mirror nuclei.

The method of measuring the ratio of the number of slow neutrons to fast neutrons with two paraffin-moderated BF_3 counters, one sensitive preferentially to slow neutrons ("slow counter") and the other almost energy-insensitive ("modified long counter"), is called the "counter ratio" technique, and it is applied here in the measurement of neutron thresholds in the reactions $O^{16}(d,n)F^{17}$ and $N^{14}(d,n)O^{15}$.

II. PRECISION MEASUREMENT TECHNIQUE

In order to establish the level structures of nuclei with considerable accuracy by measuring neutron threshold energies with the "counter ratio" technique, it is necessary to know precisely the energy of the bombarding particles. Since magnetic analysis of the charged-particle beam is used with the Rice Institute 6-Mev Van de Graaff accelerator, measurements of the radius of curvature of the particle orbit and the magnetic field strength suffice to determine the particle energy. A Pound magnetometer[3] is used to measure the field strength. This instrument utilizes a proton resonance absorption signal for field strengths up to about 7000 gauss and a lithium signal for higher strengths. The oscillator unit supplies a signal that is beat against the signal from a frequency meter,[4] and the beat frequency is displayed on an oscilloscope along with the resonance absorption signal in the conventional manner. The probe, which is fitted between the pole pieces of the analyzing magnet close to the accelerator vacuum tube, is connected by short leads to the oscillator. The frequency tuning and the operation of the frequency meter and the oscilloscope are carried out at the accelerator's remote control station.

The radius of curvature was determined by measuring the field strength at the threshold for the reaction $Li^7(p,n)Be^7$. The threshold energy for this reaction is

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[1] J. B. Ehrman, Phys. Rev. **81**, 412 (1951); R. G. Thomas, Phys. Rev. **88**, 1109 (1952).
[2] T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954).
[3] Manufactured by the Laboratory for Electronics, Inc., Boston, Massachusetts; Model 101.
[4] Manufactured for the U. S. Army Signal Corps by the Zenith Radio Corporation, Chicago, Illinois; Model BC-221-K.

1.8811±0.0005 Mev.[5] Over a period of several days, no change in the calibration could be detected which corresponded to an energy shift of more than 0.5 kev at the $Li^7(p,n)Be^7$ threshold. A typical calibration threshold is shown in Fig. 1. The deviation from linearity on the low-energy side of the threshold is due to the energy spread of the beam.

Since the average field strength experienced by a particle is not exactly that measured by the magnetometer, a systematic error could be introduced by using the calibration deduced from the $Li^7(p,n)Be^7$ threshold measurement over a large range of field strengths. In order to determine the magnitude of this systematic error, a number of well-known (p,n) thresholds[5–7] were measured. The difference between the known and the observed threshold energy [based on the $Li^7(p,n)Be^7$ calibration] was found to be an increasing function of field strength. Six (p,n) threshold measurements were made, which are listed in Table I, and the energy difference was plotted as a function of $H\rho$. For a given field strength, the energy correction for protons is twice that necessary for deuterons. The correction curve for protons determined in this manner is shown in Fig. 2. The correction at the highest field strengths used amounted to about 17 kev for protons, 9 kev for deuterons.

TABLE I. (p,n) Threshold calibration points.

	Target nucleus	Threshold energy (Mev)	Reference	Approximate $H\rho$ (Kilogauss-cm)	Mass No. of beam	Correction (kev)
A	Li^7	1.8811±0.0005	5	198	1	standard
B	Be^9	2.059 ±0.002	6	208	1	2
C	B^{11}	3.015 ±0.003	6	250	1	6.5
D	C^{13}	3.236 ±0.003	6	260	1	6
E	H^3	1.0203±0.0015	7	295	2	12
F	Li^7	1.8811±0.0005	5	398	2	16

Small errors in the application of this correction, together with the energy spread of the beam and the uncertainty in extrapolating the leading edge of a threshold to determine the threshold energy, limits the accuracy of the absolute measurement of energies to about ±4 kev. Energy differences of less than a few hundred kev may be measured somewhat more accurately.

Each of the measurements of the threshold energies reported herein was carried out on at least two different occasions, with separate calibrations of the radius of curvature. In no case was an energy spread of more than 3 kev noted among the runs, and in most cases non-systematic shifts of about 1 kev were observed.

III. $O^{16}(d,n)F^{17}$

The energy of the first excited state of F^{17} has been measured with an accuracy of about 15 kev by two different methods. Ajzenberg[8] obtained an energy of 0.536±0.010 Mev for this level from the observation in a photographic plate of the ranges of the recoil protons from the reaction $O^{16}(d,n)F^{17}$ at a bombarding energy of 8 Mev. Warren *et al.*,[9] observed the γ radiation from this state in the reaction $O^{16}(p,\gamma)F^{17}$, and obtained a value of 0.487±0.015 Mev. In view of the rather large discrepancy between these two measurements, the $O^{16}(d,n)F^{17}$ reaction was investigated with the "counter ratio" technique.

An oxygen target of about 25-kev thickness at a deuteron energy of 2 Mev was prepared by heating a clean tungsten blank at a temperature of 600°–800°C in an induction heater in the presence of tank oxygen at a pressure of about 25 mm of Hg. The counter ratio and the neutron yield in the forward direction were

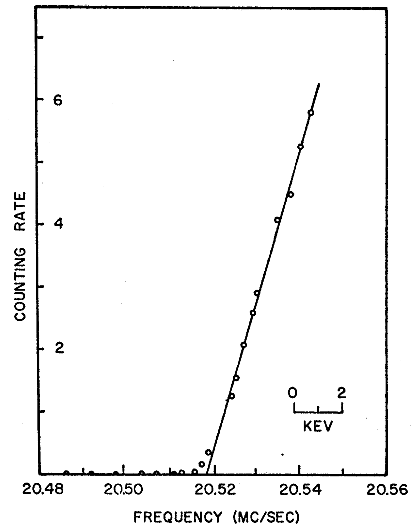

FIG. 1. Typical $Li^7(p,n)Be^7$ threshold calibration.

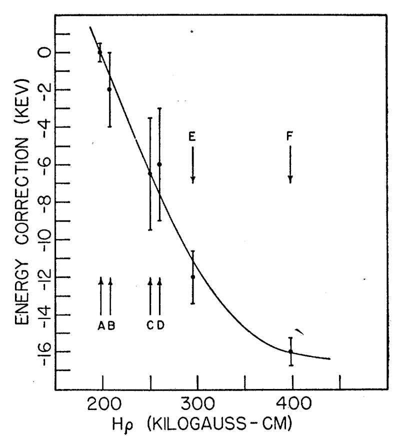

FIG. 2. Experimentally determined curve of the energy correction for protons.

[5] Jones, Douglas, McEllistrem, and Richards, Phys. Rev. **94**, 947 (1954).

[6] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).

[7] T. W. Bonner and J. W. Butler, Phys. Rev. **83**, 1091 (1951).

[8] F. Ajzenberg, Phys. Rev. **83**, 693 (1951).

[9] Warren, Laurie, James, and Erdman, Can. J. Phys. **32**, 563 (1954).

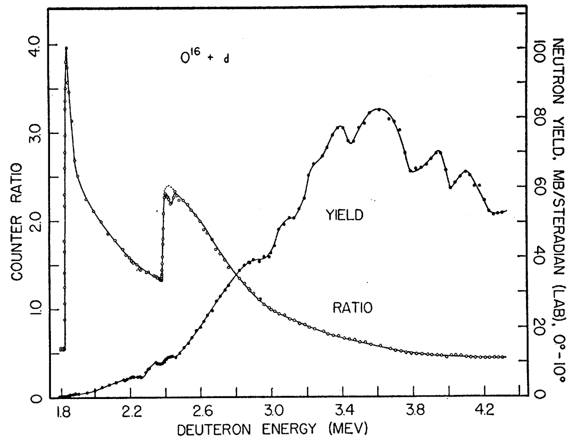

FIG. 3. $O^{16}(d,n)F^{17}$. Counter ratio and yield of neutrons in the forward direction as a function of bombarding energy.

measured in the range of deuteron energies from 1.8 to 4.3 Mev. The results are presented in Fig. 3, which shows the two thresholds that were observed and a number of resonances in the neutron yield. At a bombarding energy of 1.830±0.004 Mev, threshold neutrons corresponding to the ground state of F^{17} were observed, and a sharp rise in the counter ratio results. The curve rises until the target thickness is reached and then decreases in the expected manner. The second sharp increase in the ratio, at a bombarding energy of 2.393 ±0.004 Mev, is due to the emission of threshold neutrons leaving F^{17} in the first excited state.

For cases in which the number of neutrons emitted at an excited state threshold is large, it is possible to use either the counter ratio curve or the plot of the counting rate in the "slow counter" to determine the threshold energy. Figure 4 shows the extrapolation of the leading edge of the 2.393-Mev threshold observed with the "slow counter" to determine the threshold energy. These two thresholds establish the energy of the first excited state of F^{17} to be 0.499±0.003 Mev.

The calculated Q-value for the ground state threshold is −1.626±0.004 Mev, which is to be compared with a value of −1.622±0.004 Mev, obtained by Bonner and Butler,[7] when their value is corrected for the most

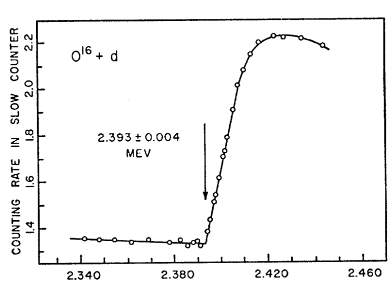

FIG. 4. $O^{16}(d,n)F^{17}$. Counting rate in the "slow counter" as a function of bombarding energy, showing the extrapolation of the leading edge of the 2.393-Mev threshold to obtain the threshold energy.

recent determination of the $Li^7(p,n)Be^7$ threshold.[5] The threshold energies, Q-values, and the excitation energies in F^{17} are summarized in Table II.

The slow decrease of the counter ratio above the second threshold is probably due to the emission of slow neutrons with $l=1$. The yield of such neutrons continues to rise for a greater energy interval than that for s-wave neutrons. Since the first excited state of F^{17} is $\frac{1}{2}^+$, s-wave neutron emission to this state would be possible only if the states of the compound nucleus were either 0^+ or 1^+. The resonance structure of the yield curve suggests that compound nucleus formation plays an important role at these low bombarding energies. Therefore, if 0^+ or 1^+ states are present in this energy region of the compound nucleus, they must be weak. At the peak of the ratio curve, at 2.42 Mev, a dip in the ratio occurs. That such a shape of the ratio curve should not be interpreted as an additional threshold may be seen by noting that only a single level occurs in the mirror nucleus, O^{17}, in this energy region. This dip is probably not the result of a decrease in the number of slow neutrons emitted, but of an increase of the number of fast neutrons at the corre-

TABLE II. Neutron thresholds in the reaction $O^{16}(d,n)F^{17}$.

Threshold energy (Mev) Present work	Threshold energy (Mev) Other measurement	Q-value (Mev)	Excitation in F^{17} (Mev) Present work	Excitation in F^{17} (Mev) Other measurement
1.830±0.004	1.835±0.005[a]	−1.626±0.004	0	0
2.393±0.004		−2.125±0.004	0.499±0.003	0.536±0.010[b]
				0.487±0.015[c]

[a] See reference 7. The published value has been corrected; see text.
[b] See reference 8.
[c] See reference 9.

sponding resonance in the yield of neutrons in the forward direction. This dip in the ratio is taken to imply that neutron emission to the ground state is favored over emission to the excited state at the 2.42-Mev resonance. This would occur if s-wave emission were possible to the ground state at resonance, while it were not favored to the excited state. Since the ground state of F^{17} has spin $5/2^+$, this effect would result from the compound nucleus being in either a 2^+ or a 3^+ state, with an additional assumption that deuterons with $l \geqslant 4$ are ineffective. Therefore, it is probable that the 9.7-Mev state of F^{18}, which is formed at the 2.42-Mev resonance, is a 2^+ or 3^+ state.

Figure 5 shows the level schemes of the mirror nuclei, O^{17} and F^{17}, up to excitations of 2 Mev. The O^{17} energies are from Sperduto *et al.*,[10] and the F^{17} energies are the values of Table II. The extreme downward shift in energy of the first excited state of F^{17}, compared with that of O^{17}, is probably associated with the change in boundary conditions on the wave

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

functions at the nuclear surface as a result of the anomalously low particle dissociation energy in F^{17}.[11]

The neutron yield in the forward direction from three separate runs, is shown in Fig. 3. The background, obtained by bombarding a clean tungsten blank, has been subtracted. The percentage background counting rate in the modified long counter decreased from 37% at 2.4 Mev to 6% at 4.0 Mev. Ten broad resonances were found between threshold and 4.3 Mev, some of which agree with those observed in the $O^{16}(d,p)O^{17}$ reaction.[12,13] The flattening of the yield curve immediately above the threshold for the F^{17} ground state was also observed by Bonner and Butler.[7] This effect is probably due to the resonance at 1.7 Mev, below the threshold for neutron emission, which is known from the $O^{16}(d,p)O^{17}$ reaction.[12] A summary of the resonances found, together with the corresponding excitation energies in F^{18} is given in Table III.

IV. $N^{14}(d,n)O^{15}$

The reaction $N^{14}(d,n)O^{15}$ has been studied with the "counter ratio" technique described above. The target

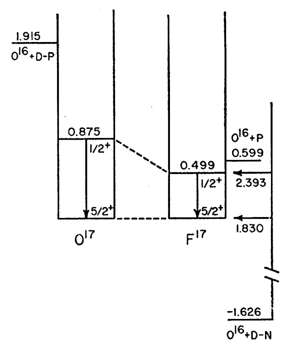

FIG. 5. Energy level diagrams for the first 2 Mev of excitation of the mirror nuclei, O^{17} and F^{17}.

was prepared by absorbing nitrogen gas in tantalum. This was accomplished by heating a 40-mil tantalum disk in an induction heater to about 1300°C for several minutes in the presence of 1 atmosphere of nitrogen. This target was approximately 60 kev thick at a deuteron energy of 1.9 Mev.

The counter ratio and the forward yield of neutrons is given in Fig. 6 for deuteron energies from 1.1 to 4.5 Mev. The counter ratio curve indicates thresholds at bombarding energies of 1.24±0.02 and 1.967±0.004 Mev. A closer examination of the region near 2.0 Mev was made with a 20-kev target and the results are shown in Fig. 7. An additional threshold was observed at 2.044±0.004 Mev. The threshold energies, Q-values, and excitation energies in O^{15} are listed in Table IV. The large error in determining the energy of the 1.24-

[11] T. Lauritsen, Ann. Rev. Nuc. Sci. 1, 67 (1952).
[12] N. P. Heydenburg and D. R. Inglis, Phys. Rev. **73**, 230 (1948).
[13] Van Patter, Simmons, Stratton, and Zipoy, Phys. Rev. **96**, 825(A) (1954).

TABLE III. Resonances in $O^{16}+d$.

$O^{16}(d,n)$; $\theta=0°–10°$ E_d (Mev)	$O^{16}(d,p)$ E_d (Mev)	*F^{18} (Mev)
	1.7[a]	9.0
2.22	2.2[a]	9.5
2.34		9.6
2.42		9.7
	2.65[b]	9.9
2.89		10.1
	3.0[a]	10.2
	3.01[b]	
3.07		10.3
3.22	3.25[b]	10.4
3.38	3.43[b]	10.6
3.62		10.8
3.94		11.0
4.10		11.2

[a] See reference 12. Resonances in the integrated cross section.
[b] See reference 13. Resonances in the cross section at 50°.

Mev threshold was due to the large background counting rate at this low bombarding energy.

The threshold at 1.24±0.02 Mev implies an energy level in O^{15} at 6.20±0.03 Mev. This is in agreement with the determination of Evans, Green, and Middleton[14] using photographic plates (6.19±0.16 Mev), and with that by Bent *et al.*,[15] obtained from a pair-spectrometer investigation of the γ radiation from the deuteron bombardment of N^{14} (6.12±0.06 Mev). With the photographic plate method it was not possible to resolve the neutron groups corresponding to the 6.841- and 6.909-Mev states. The pair-spectrometer measurements indicated a single line at 6.81±0.04 Mev.

Table V lists the relative intensities of protons, neutrons, and γ rays from the deuteron bombardment of N^{14}. The bombarding energy at which the intensity was measured is given in each case. The relative intensities will be influenced by differences in angular distribution since the intensities are taken from measurements made at a single angle. Also, comparison of relative intensities from reactions produced at

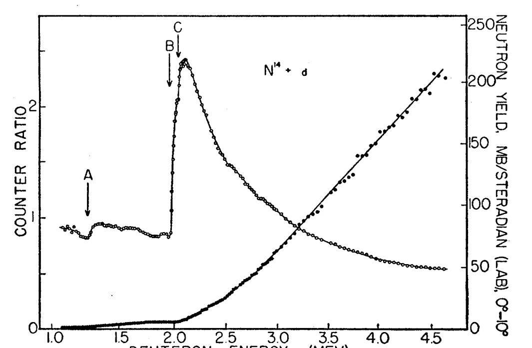

FIG. 6. $N^{14}(d,n)O^{15}$. Counter ratio and yield of neutrons in the forward direction as a function of bombarding energy.

[14] Evans, Green, and Middelton, Proc. Phys. Soc. (London) **A66**, 108 (1953).
[15] Bent, Bonner, McCrary, Ranken, and Sippel, Phys. Rev. **99**, 710 (1955).

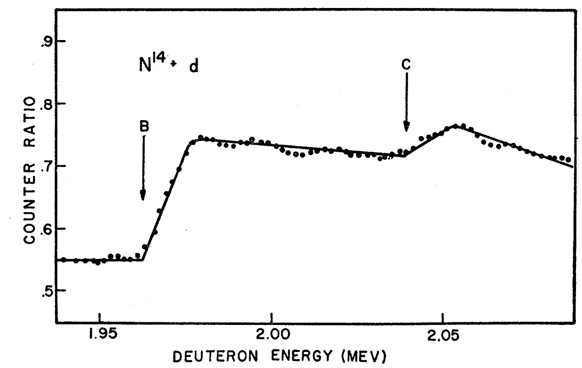

FIG. 7. $N^{14}(d,n)O^{15}$. Counter ratio as a function of bombarding energy near 2.0 Mev, showing the 1.967- and 2.044-Mev thresholds.

different bombarding energies is probably not valid in a quantitative sense, but the comparison should be at least qualitatively correct.

The N^{15} level at 7.314 Mev and the O^{15} level at 6.841 Mev appear to be the most intensely produced levels in these reactions. Because of this fact, it may be reasonable to associate these two states as mirror levels. If this is the case, the N^{15} level at 7.575 Mev and the O^{15} level at 6.909 Mev are also mirror states, and the O^{15} level corresponding to the 7.165-Mev state in N^{15} has not yet been detected. Such a level to which neutron emission near threshold is less than about 0.3 as intense as at the 2.044-Mev threshold (6.909-Mev state in O^{15}), would not have been detected in this experiment. The indication of a weak threshold at about 1.83 Mev (see Fig. 6) attributed to a small oxygen, contamination, could possibly be due to this missing state.

The yield of neutrons in the forward direction from the $N^{14}(d,n)O^{15}$ reaction is shown in Fig. 6. The background, obtained by bombarding a clean tantalum blank, has been subtracted. The background was 33% of the total counting rate in the modified long counter at 1.1 Mev and decreased to 3% at 4.5 Mev. The cross section increases smoothly up to 2.1 Mev where there is a sharp rise in the yield. It is probable that at energies above 2.1 Mev a large part of the neutron yield consists of neutrons leaving O^{15} in the 6.841-Mev state. This is consistent with the intensity measurements of Evans, Green, and Middleton,[14] made at a bombarding energy of 7.7 Mev.

TABLE IV. Neutron thresholds in the reaction $N^{14}(d,n)O^{15}$.

	Threshold energy (Mev)	Q-value (Mev)	Excitation of O^{15} (Mev) Present work	Other measurements
A	1.24 ±0.02	−1.08 ±0.02	6.20 ±0.03[a]	6.19±0.16[c] 6.12±0.06[b]
B	1.967±0.004	−1.719±0.004	6.841±0.009[a]	6.81±0.04[c] 6.84±0.16[b]
C	2.044±0.004	−1.787±0.004	6.909±0.009[a]	

[a] The error assignment includes the uncertainty in the ground state Q-value, calculated from the mass defect uncertainties listed by J. E. Drummond, Phys. Rev. **97**, 1004 (1955).
[b] See reference 14.
[c] See reference 15.

V. MEASUREMENT OF ABSOLUTE CROSS SECTIONS

Since very little information is available concerning the absolute cross sections for the emission of neutrons in nuclear reactions, measurements were made to obtain this information for the reactions $O^{16}(d,n)$ and $N^{14}(d,n)$. It was necessary to determine the absolute cross section for each reaction at one or more bombarding energies, thereby calibrating the relative yield curve. This entails a knowledge of two factors: (1) the absolute number of neutrons emitted from the target per unit solid angle and microcoulomb of beam current, and (2) the number of target nuclei per cm^2 on the target.

The first factor was determined by comparing the counting rate from the target with that from a calibrated[16] Ra-Be source with a "long counter" of the type described by Hanson and McKibben.[17] The current integrator was calibrated by measuring the time necessary to record an integrating pulse when a known current was passed through the circuit. The amount of current was determined by measuring the voltage drop across a precision, wire-wound resistor with a Leeds and Northrup potentiometer.

TABLE V. Relative reaction intensities in $N^{14}+d$.

$*N^{15}$ (Mev)	Protons[a] ($E_d=7.0$ Mev)	Gamma rays[b] ($E_d=4$ Mev, thick target)	$*O^{15}$ (Mev)	Neutrons (threshold)	Neutrons[c] ($E_d=7.7$ Mev)	Gamma rays[b] ($E_d=4$ Mev, thick target)
5.280	0.8	~1.5[d]				
5.305	0.6	~1.5[d]	5.29	...	0.4	~1.5[d]
6.330	1	1	6.20	1	1	0.7
7.165	1.3	...	...	...		...
7.314	2.7	3.2	6.841	4.6	2.4	2.2
7.575	1.7	...	6.909	0.9		...

[a] See reference 10.
[b] See reference 15. Intensities of γ radiation from both $*N^{15}$ and $*O^{15}$ are relative to the 6.33-Mev γ ray from $*N^{15}$.
[c] See reference 14.
[d] These three γ rays could not be resolved; the total intensity was 4.4, given an intensity of ~1.5 for each if they are equally intense.

The determination of the number of target nuclei per cm^2 was simplified by using a gas target for the absolute cross section measurements. The target chamber was 0.5 inch in diameter and 1.5 inches in length and was constructed of iron; a 2.58 mg/cm^2 nickel foil covered the entrance hole to the chamber. Gas pressures of about $\frac{1}{3}$ atmosphere were used. Since the deuteron bombardment of nickel produces an appreciable number of neutrons, backgrounds were taken with the gas removed from the target chamber.

The absolute cross sections were determined at a

[16] Calibrated to an accuracy of 4% by the U. S. Bureau of Standards, September, 1954.
[17] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

deuteron energy of 3.33 Mev. The yield curves shown in Figs. 3 and 6 were normalized to the absolute values at this energy. The curves have not been corrected for the variation of the sensitivity of the modified long counter with neutron energy. The efficiency of the modified long counter in its position behind the "slow counter," is a maximum for neutrons with an energy of about 1.5 to 2 Mev and it has a lower efficiency for both lower and higher energy neutrons. The decrease in efficiency is about 40% for 5-Mev neutrons and is slightly greater for neutrons of energy less than about 0.3 Mev. Since the correction is complicated by the existence of more than a single neutron energy group, such a correction has not been attempted.

The estimated accuracy to which the absolute cross sections have been determined is ±50%.

PHYSICAL REVIEW VOLUME 100, NUMBER 1 OCTOBER 1, 1955

Isotopic Spin Impurity in Light Nuclei. I. Core Impurity

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(Received April 25, 1955)

The introduction of isotopic spin impurity by the Coulomb mixing of different nuclear eigenstates of T^2 can occur both through the perturbation of the wave function for nucleons in a J, $T=0$ core by the Coulomb interaction of nucleons in the core, and through the perturbation of the wave function for nucleons outside the core by their Coulomb interaction with nucleons in the core and with each other. In this paper the core impurity, the sum of the squared amplitudes of higher isotopic spin eigenstates ($T\neq 0$), is calculated for the ground state of $N=Z$ even-even nuclei on the Fermi gas model. The core impurity is found to exceed by a large factor the isotopic spin impurity in the wave function for nucleons outside the core.

I. INTRODUCTION

THE total isotopic spin quantum number T^2 exists under the assumption of a "charge-independent" interaction between nucleons of the form $\sum'(a+b\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j)$, where a and b are functions of space and spin and $\boldsymbol{\tau}_i$ is the isotopic spin vector for the ith nucleon. The primed summation indicates that one sums over $i\neq j$. The present active interest in the isotopic spin quantum number for nuclei began primarily among the experimentalists and among those interested in cataloging and understanding the large amount of experimental information on light nuclei which is being accumulated at an increasing rate. For this purpose the isotopic spin quantum number provides selection rules on each of three types of nuclear reactions: (1) reactions involving absorption and emission of heavy particles, (2) β-decay, and (3) isomeric transitions. Selection rules for processes of type (1) are usually simple and forbid such reactions as (d,α) going from the ground state of an $N=Z$ nucleus to the $T=1$ states of the final $N=Z$ nucleus. Selection rules for the second process were given by Wigner[1] and are different for the Fermi and Gamow-Teller matrix elements.

$$\text{Fermi: } \quad \Delta T=0,$$
$$\text{Gamow-Teller: } \quad \Delta T=0, \pm 1, \quad 0 \not\rightarrow 0.$$

Finally selection rules for electric dipole transitions were recently derived by Trainor[2] in supermultiplet theory and more generally by Christy,[3] Radicati,[4] and Gell-Mann and Telegdi.[5] We have discussed this selection rule in some detail and have shown it to be a sensitive test of the validity of the isotopic spin quantum number.[6]

The validity of the selection rules is affected only by a nuclear interaction which does not commute with T^2; i.e., by a "charge-dependent" nuclear potential, or by the Coulomb interaction. Consequently, before any conclusions can be drawn about the nuclear potential, the quantitative effect of the Coulomb force on the isotopic spin quantum number must be determined. The possibility of accounting for any observed violations of the above selection rules by ascribing them to the Coulomb potential would strongly suggest a nuclear interaction of the form $\sum'(a+b\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j)$. Conversely, the observation of large departures from the isotopic spin selection rules which could not be explained by the Coulomb force would certainly imply the existence of charge-dependent nuclear interactions. Of course, in case Coulomb forces should be shown to give rise to considerable mixing of the states of different isotopic spin, the usefulness of the isotopic spin quantum number would be destroyed.

We are therefore interested in the extent to which one can assign a total isotopic spin quantum number T to the states of light nuclei for which $A\leq 20$. Specifically we want to know how much admixture (sum of the

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