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Deuteron-Induced Reactions from N^{14}, N^{15}, and He^4†

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A study has been made of the reactions $N^{14}(d,p)N^{15}$, $N^{14}(d,t)N^{13}$, $N^{15}(d,p)N^{16}$, $N^{15}(d,\alpha)C^{13}$, and $He^4(d,p)He^5$ using 14.8-Mev deuterons. Angular distributions and stripping reduced widths were obtained for five proton groups leading to energy levels in N^{15}. The stripping reduced widths for the first two negative parity levels of N^{15} were used to gain information concerning the N^{14} ground state wave function. The absolute differential cross sections obtained for the $N^{14}(d,t)N^{13}$ reaction were compared to theoretical predictions. Nine proton groups observed from the $N^{15}(d,p)N^{16}$ reaction were assigned to levels in N^{16} at 0, 0.126±0.015, 0.303±0.009, 0.403±0.015, 3.980±0.02, 4.80±0.05, 5.25±0.05, and possibly at 3.53±0.03 and 5.01±0.05 Mev. Angular distributions were obtained for the first four levels, which have been previously reported. The four angular distributions yielded $l=2, 0, 2, 0$ and "reduced widths" of $(2J+1)\Theta^2=0.27, 0.19, 0.33, 0.54$ for the 0-, 0.12-, 0.30-, and 0.40-Mev levels, respectively. The results of the angular distributions were combined with theoretical predictions to give most probable values of $J^\pi=2^-$, 0^-, 3^-, and 1^-, respectively. Ten alpha-particle groups were observed from the $N^{15}(d,\alpha)C^{13}$ reaction corresponding to previously reported C^{13} levels. The stripping reduced width obtained for the $He^4(d,p)He^5$ ground state reaction was $\Theta^2=0.05$, and the center-of-mass half-width of the He^5 ground state was measured to be 0.55±0.030 Mev.

I. INTRODUCTION

The apparatus used has been previously described.[1] A collimated beam of 14.8-Mev deuterons was incident upon a target placed at the center of the scattering chamber. Outgoing particles were magnetically analyzed and were detected by a CsI(Tl) crystal.

The reactions investigated were $N^{14}(d,p)N^{15}$. $N^{14}(d,t)N^{13}$, $N^{15}(d,p)N^{16}$, $N^{15}(d,\alpha)C^{13}$, and $He^4(d,p)He^5$. Angular distributions were obtained for some of the proton groups and were analyzed by the stripping theory of Butler[2] to determine the spins and parities of the states of the residual nuclei. Absolute differential cross sections were measured for all the reactions. For the (d,t) and (d,α) reactions, qualitative comparisons are made between the experimental cross sections and predictions based on shell model theory. For the (d,p) reactions, comparison of the cross sections with theoretical predictions are made in terms of the stripping reduced widths.[3]

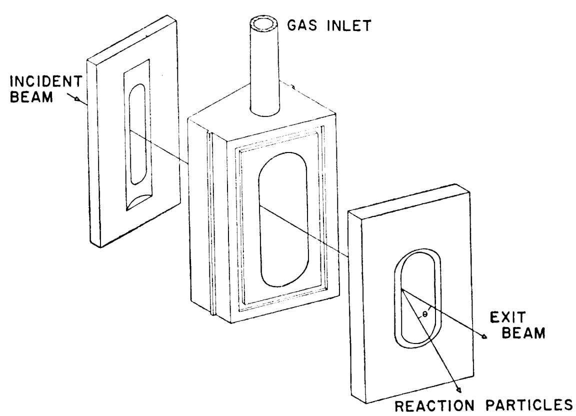

FIG. 1. Two-window gas cell used for scattering angles from 0° to 60°. The window frames are shown separated from the cell. The vacuum seal between the frames and the cell was effected by O-rings.

II. EXPERIMENTAL PROCEDURE

Most of the observations were made using gas targets. The two gas target cells used are shown in Figs. 1 and 2. The cell windows consisted of 0.0001-in. nickel foils cemented with Gelva V-7 on a cylindrical surface of $\frac{3}{16}$ to $\frac{1}{4}$ in. radius of curvature. The target volume viewed by the reaction-particle analyzing magnet was defined by a movable slit placed directly outside the reaction-particle window. For scattering angles less than 10° the Faraday cage normally used for beam collection was pulled down out of the beam and the beam intensity was monitored with a zinc sulfide scintillation counter placed

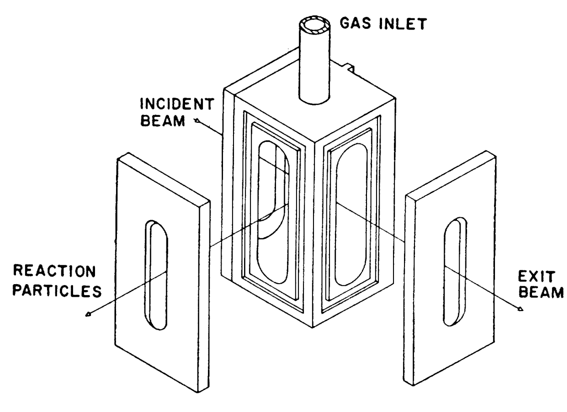

FIG. 2. Three-window gas cell used for scattering angles from 60° to 90°. The window frames are shown separated from the cell. The vacuum seal between the frames and the cell was effected by O-rings.

† Work done in the Sarah Mellon Scaife Radiation Laboratory and assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
* Now at Brookhaven National Laboratory, Upton, New York.
[1] Bender, Reilley, Allen, Ely, Arthur, and Hausman, Rev. Sci. Instr. 23, 542 (1952).
[2] S. T. Butler, Proc. Roy. Soc. (London) A208, 559 (1951).
[3] The definition of the reduced width used in this paper is $\Theta^2=2Mr_0\gamma^2/3\hbar^2$, where γ^2 is the usual reduced width.

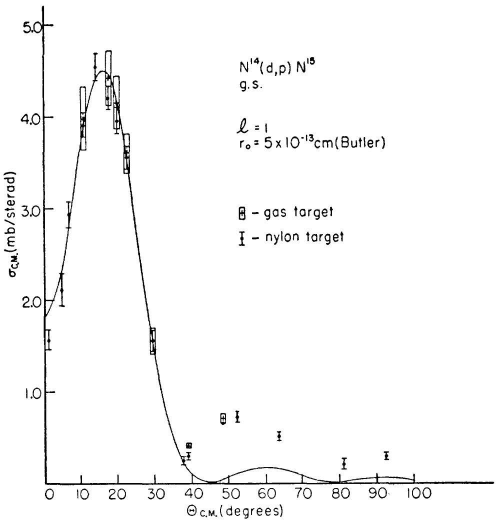

FIG. 3. Angular distribution of the $N^{14}(d,p)N^{15}$ ground state.

at 50° to the incident beam. By inserting a foil (just thick enough to stop 14.8-Mev deuterons) ahead of the reaction particle detector, (d,p) data were obtained down to 0° despite the large deuteron background. The major source of error associated with cross-section measurements at scattering angles close to 0° was a high proton background which was ascribed to deuteron interactions in this foil and in the various apertures and baffles of the detecting system.

The gases used as targets were nitrogen, ammonia, helium, nitrogen enriched[4] to 98% in N^{15}, and ammonia enriched to 62% in N^{15}. The enriched ammonia was

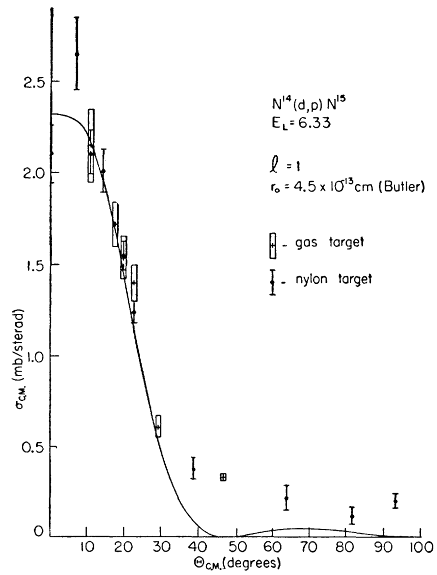

FIG. 4. Angular distribution of the $N^{14}(d,p)N^{15}$ 6.33-Mev level.

[4] We are indebted to Professor T. I. Taylor for supplying the $(N^{15})_2$. See W. Spindell and T. I. Taylor, J. Chem. Phys. **23**, 1318 (1955).

made from ammonium nitrate[5] enriched to 62% in the ammonium radical only. A pressure of approximately one atmosphere was employed for all gas targets except the 98% $(N^{15})_2$ which, because of the limited supply, was maintained at a pressure of 50–100 mm Hg.

III. RESULTS AND DISCUSSION OF REACTIONS

A. $N^{14}(d,p)N^{15}$

Results

A thin nylon target prepared after the method of Sperduto *et al.*[6] and an ammonia gas target were used to obtain angular distributions for proton groups corresponding to the N^{15} ground state and the 6.33-, 7.58-, 8.32-, and 8.57-Mev levels.[7] Figures 3 through 7 show the observed angular distributions, the solid curves being the Butler curves which best fit the data. The

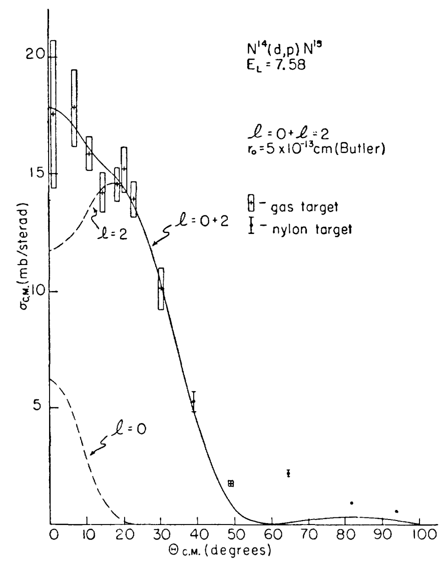

FIG. 5. Angular distribution of the $N^{14}(d,p)N^{15}$ 7.58-Mev level.

results for the N^{15} ground state, 6.33-Mev level, and 8.32-Mev level are in agreement with previous angular distributions.[7] For the 7.58-Mev level, a superposition of $l=0$ and 2 provided the best fit; however, the $l=0$ component of the angular distribution is considered to be doubtful for the following reasons: (a) the large uncertainties in the low-angle data, (b) the possibility that the Butler theory does not give an adequate description of the stripping process near 0°, and (c) the proton group corresponding to the O^{17} 0.872-Mev level could not be separated from the N^{15} 7.58-Mev level proton group at angles less than 30°. The $O^{16}(d,p)O^{17}$ 0.872-Mev level reaction is known to be an intense $l=0$

[5] Obtained from Distillation Products Industries, Eastman Organic Chemicals Department.

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

[7] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

transition and it is possible that the $l=0$ component of Fig. 5 arises in whole or part from a small oxygen contamination of the NH_3 target.[8] A superposition of $l=0$ and 2 for the observed 7.58-Mev level transition is in agreement with previous work[9,10]; however, Green and Middleton[10] assign the $l=0$ component to the $O^{16}(d,p)O^{17}$ 0.872-Mev reaction. For the 8.57-Mev level a theoretical fit was obtained for a superposition of $l=0$ and 2 in agreement with the MIT group.[9] Green and Middleton[10] report $l=1$, but they regard this assignment as doubtful. The Butler curve for $l=1$ is shown for comparison in Fig. 7.

When the NH_3 gas target was used, absolute differential cross sections were obtained in terms of the known differential cross sections for the scattering of deuterons by hydrogen. The d-p scattering differential cross sections were determined at 14.8-Mev deuteron energy

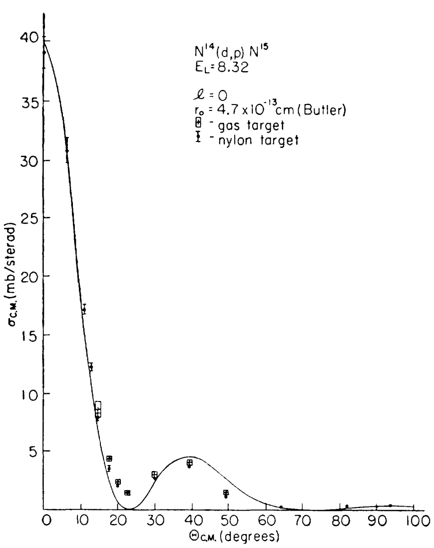

FIG. 6. Angular distribution of the $N^{14}(d,p)N^{15}$ 8.32-Mev level.

by interpolation of experimental data for deuteron energies of 9.94, 10.04, 15.70, and 19.4 Mev.[11–14] In Figs. 3 through 7, the standard deviation in the absolute differential cross section is shown for the gas target data, and the standard deviation in the relative cross section is shown for the nylon data.

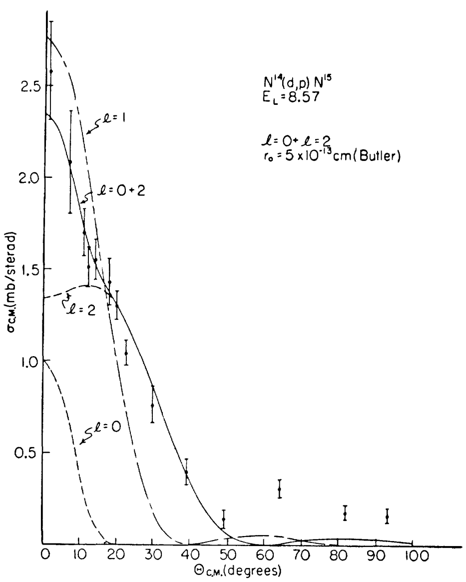

FIG. 7. Angular distribution of the $N^{14}(d,p)N^{15}$ 8.57-Mev level.

Discussion

N^{14} ground-state wave function.—Reduced widths were calculated for the five angular distributions of Figs. 3 through 7 from Butler's theory and the observed differential cross sections. The reduced widths for the $N^{14}(d,p)N^{15}$ ground state and the 6.33-Mev level were found to be $(2J+1)\Theta^2=0.097$ and 0.030, respectively. The two possible states for the configuration s^4p^{11}, which represents a hole in the p shell, are $(p^{-1})_{\frac{1}{2}}$ and $(p^{-1})_{\frac{3}{2}}$. The ground state may be identified as the $(p^{-1})_{\frac{1}{2}}$ state, and the 6.33-Mev level as the $(p^{-1})_{\frac{3}{2}}$ state.[15] In the notation of French, the quantities S_1 and $S_1{}^*$ are defined by

$$S_1=\Theta^2/\Theta_0{}^2, \quad S_1{}^*=\Theta^2/\Theta_0{}^2, \tag{1}$$

where Θ^2 and Θ^{*2} are the stripping reduced widths for the $N^{14}(d,p)N^{15}$ ground state and the 6.33-Mev state, respectively, and $\Theta_0{}^2$ and $\Theta_0{}^{*2}$ are single-particle reduced widths. There is evidence[16] that for the nuclear p shell $\Theta_0{}^2$ is probably constant to within 15%, at least for bound states. Within this uncertainty,

$$\Theta^2/\Theta^{*2}=S_1/S_1{}^*. \tag{2}$$

French[15] has shown that, insofar as the N^{14} ground state belongs to the configuration s^4p^{10} and the N^{15} ground state and 6.33-Mev level belong to s^4p^{11}, S_1 and $S_1{}^*$ are related by

$$2S_1{}^*=\tfrac{3}{2}-S_1. \tag{3}$$

Combining Eqs. (2) and (3) gives

$$\Theta^2/\Theta^{*2}=2S_1/(\tfrac{3}{2}-S_1). \tag{4}$$

[8] An upper limit of 1% was estimated for the oxygen contamination of the NH_3 for the low-angle observations; this places an upper limit of approximately 2.5 mb/sterad to the contribution of the O^{17} 0.872-Mev level to the $l=0$ transition at 0°.

[9] R. D. Sharp and R. Sperduto, Massachusetts Institute of Technology, Laboratory for Nuclear Science Progress Report, May, 1955 (unpublished).

[10] T. S. Green and R. Middleton, Proc. Phys. Soc. (London) **A69**, 28 (1955).

[11] Rodgers, Leiter, and Kruger, Phys. Rev. **78**, 656 (1950).

[12] L. Rosen and J. C. Allred, Phys. Rev. **82**, 777 (1951).

[13] Brolley, Putnam, and Rosen, Bull. Am. Phys. Soc. Ser. II, **1**, 246 (1956); also private communication.

[14] Allred, Armstrong, Bondelid, and Rosen, Phys. Rev. **88**, 433 (1952).

[15] J. B. French, Phys. Rev. **103**, 1391 (1956).

[16] The measurement of the stripping reduced widths for $N^{14}(d,p)N^{15}$ ground state and 6.33-Mev level, as well as the treatment that follows, were suggested by J. B. French.

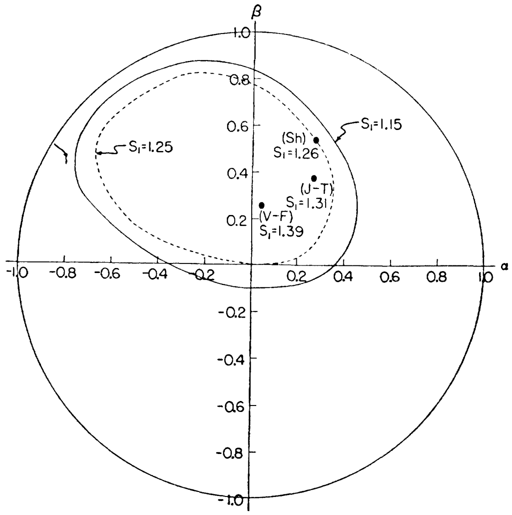

FIG. 8. Contours representing the conditions imposed on the amplitudes α and β, where $\psi(\mathrm{N}^{14}\,\mathrm{g.s.})=\alpha\psi(^3S_1)+\beta\psi(^1P_1)+\gamma\psi(^3D_1)$, by the equation $2S_1=1+\frac{3}{2}\gamma^2+2\beta[\gamma\sqrt{\frac{5}{6}}-\alpha\sqrt{\frac{2}{3}}]$. Both contours are drawn for γ positive.

The ratio Θ^2/Θ^{*2} obtained from the experimental cross-section ratio was 6.5±0.4. From this value, S_1 is calculated to be 1.15±0.02. The reduced widths are rather insensitive to the value of r_0 used in the Butler theory, so that S_1 would not be significantly different if the same value of r_0 were used for the angular distributions of both the N^{15} ground state and 6.33-Mev level.

The absolute value of the stripping reduced width for the $\mathrm{N}^{14}(d,p)\mathrm{N}^{15}$ ground-state reaction provides an independent check on the value of S_1 obtained. For the N^{15} ground state, $J=\frac{1}{2}$ and $\Theta^2=0.097/(2J+1)=0.049$. For the nuclear p shell there is evidence[16] that $0.045\lesssim\Theta_0^2\lesssim0.060$. From the definition of S_1 then, $0.82\lesssim S_1\lesssim1.08$ which agrees fairly well with the more accurate determination from the relative reduced widths.

With the N^{14} wave function written in the notation of Jancovici and Talmi,[17]

$$\Psi(\mathrm{N}^{14}\,\mathrm{g.s.})=\alpha\Psi(^3S_1)+\beta\Psi(^1P_1)+\gamma\Psi(^3D_1), \tag{5}$$

S_1 is given[15] by

$$2S_1=1+\tfrac{3}{2}\gamma^2+2\beta[\gamma\sqrt{\tfrac{5}{6}}-\alpha\sqrt{\tfrac{2}{3}}]. \tag{6}$$

If γ is eliminated from Eq. (6) by the normalization condition, a contour representing the relation between α and β can be drawn for a particular value of S_1. Figure 8 shows the contours for $S_1=1.15$ and $S_1=1.25$. The values for α and β given by Jancovici and Talmi[17] (J-T), Visscher and Ferrell[18] (V-F), and Sherr *et al.*[19] (Sh) are shown together with the associated values for S_1.

Positive parity states of N^{15}.—Halbert and French[20] have made a complete calculation of the wave functions for the positive-parity states of N^{15} belonging to the configurations $s^4p^{10}s$, $s^4p^{10}d$, and s^3p^{12}. Twelve of the states obtained were identified with the twelve known positive-parity states of N^{15} (most of whose spins are unknown) largely by demanding that the values of $S(=\Theta^2/\Theta_0^2)$ and J be consistent with the experimental results of stripping and resonance reactions. The values of S calculated by Halbert and French for the lower levels were converted to approximate stripping reduced widths by assuming that $\Theta_0^2=0.32$ for $l=0$, and $\Theta_0^2=0.11$ for $l=2$, which were deduced by Halbert and French from the $\mathrm{O}^{16}(d,p)\mathrm{O}^{17}$ ground state ($l=2$) and 0.872-Mev level ($l=0$) stripping reactions[10,21] (assumed to be single-particle reactions). In Table I the results of Halbert and French are compared to the results for the three positive-parity states examined in the present experiment.

TABLE I. Comparison of experimental and theoretical results for three positive parity states of N^{15}.

Level (Mev)	J [a]	l [a]	l [b]	$(2J+1)\Theta^2$ Halbert and French	$(2J+1)\Theta^2$ Present expt.
7.575	5/2	2	0(?), 2	0.40	0.06(?), 0.40
8.316	$\frac{1}{2}$	0	0	0.49	0.47
8.571	$\frac{3}{2}$	0, 2	0, 2	0.015, 0.11	0.018, 0.031

[a] Halbert and French.
[b] Present experiment.

TABLE II. Differential cross sections for the $\mathrm{N}^{14}(d,t)\mathrm{N}^{13}$ reaction.

N^{13} level (Mev)	$\sigma(\theta)$ mb/sterad θ(lab) = 18°	θ(lab) = 24°
ground state	4.0 ±0.5	1.6 ±0.5
2.37	0.01±0.005	0.02±0.01
3.51, 3.56	0.2 ±0.05	0.2 ±0.05

Except for the doubtful $l=0$ component of the 7.575-Mev level reaction which Halbert and French predict to be spin forbidden, the experimental and calculated results are in better agreement than should be expected. If, in actual fact, further experiments should establish the $l=0$ component of the 7.575-Mev level reaction, it would establish a serious objection to their predictions.

B. $\mathrm{N}^{14}(d,t)\mathrm{N}^{13}$

Results

A search was made for triton groups up to an excitation of approximately 7 Mev in N^{13} at scattering angles of 18° and 24° using an $(\mathrm{N}^{14})_2$ gas target at 760 mm Hg. Only three triton groups were observed, corresponding to the N^{13} ground state, the 2.37-Mev level, and the unresolved 3.51- and 3.56-Mev levels. The cross sections, obtained at 18° and 24° by comparison with the proton group from the $\mathrm{N}^{14}(d,p)\mathrm{N}^{15}$ ground-state reaction, are

[17] B. Jancovici and I. Talmi, Phys. Rev. 95, 289 (1954).

[18] W. M. Visscher and R. A. Ferrell, Phys. Rev. 99, 649(A) (1955).

[19] Sherr, Gerhart, Horie, and Hornyak, Phys. Rev. 100, 945 (1955).

[20] E. C. Halbert and J. B. French, Phys. Rev. (to be published).

[21] Burge, Burrows, Gibson, and Rotblat, Proc. Roy. Soc. (London) A210, 534 (1951).

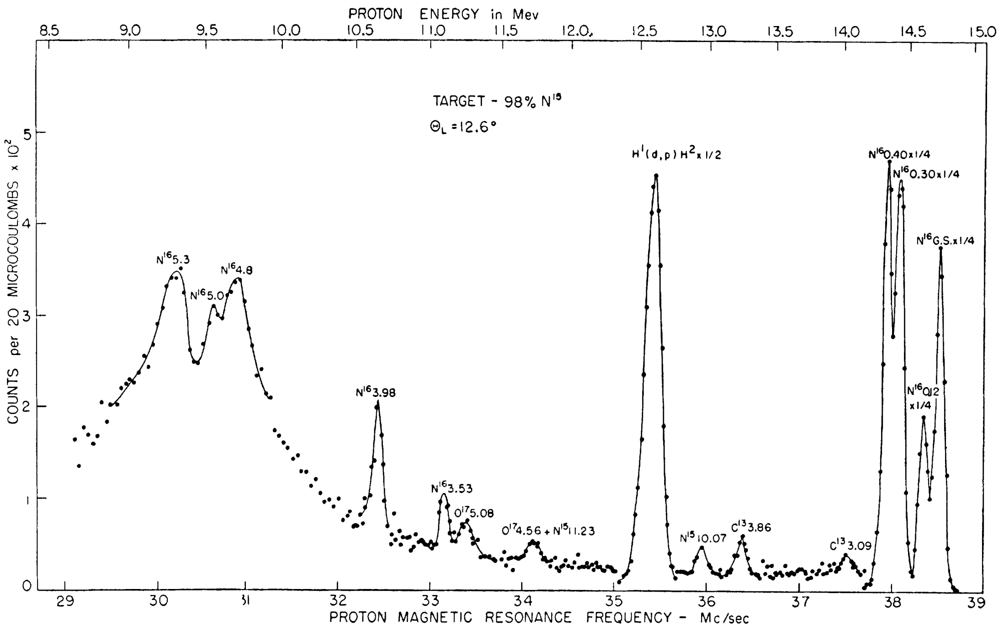

FIG. 9. Proton spectrum observed at 12.6° from a 98% $(N^{15})_2$ gas target bombarded by 14.8-Mev deuterons. The peaks are labeled by the state of the residual nucleus to which they belong.

given in Table II. The comparatively large uncertainties in the cross sections arise mainly from the presence of a deuteron background which was not completely separated from the triton channel. An upper limit to $\sigma(\theta)$ of 0.05 mb/sterad may be placed on transitions to any other levels in N^{13} between 0- and 7.0-Mev excitation at both angles.

Discussion

The first four levels of N^{13} are thought to have the configurations[22] s^4p^9, s^4p^8s, s^4p^9, and s^4p^8d, respectively. Since the N^{14} ground state is largely an s^4p^{10} configuration, the $N^{14}(d,t)N^{13}$ transitions to the second and fourth levels involve a change in orbit of two particles and are shell model forbidden. Therefore, the cross sections for the 2.37- and 3.56-Mev levels are expected to be small. The results for the 2.37-Mev level transition are consistent with Standing's[23] observation of the $N^{14}(p,d)N^{13}$ reaction, while the results for the 3.56-Mev level reinforce Standing's argument that the N^{14} ground state is rather pure s^4p^{10}.

TABLE III. Excitation energies and differential cross sections obtained for the $N^{15}(d,p)N^{16}$ reaction at 12.6°.

N^{16} level (Mev)	$\sigma(\theta)$ mb/sterad
ground state	
0.126±0.015	
0.303±0.009	
0.403±0.015	
3.53 ±0.03	0.90±0.25
3.980±0.02	2.4 ±0.3
4.80 ±0.05	~13
5.01 ±0.05	~ 4
5.25 ±0.05	~13

[22] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).
[23] K. G. Standing, Phys. Rev. **101**, 152 (1956).

The 3.51-Mev transition is not shell-model-forbidden; however, for the intermediate coupling which gives the best agreement with the level spacings of N^{13}, calculations of Auerbach and French[24] predict the 3.51-Mev level transition to be ~0.1 as intense as the ground-state transition, in fair agreement with the results given in Table II.

C. $N^{15}(d,p)N^{16}$

Results

Energy levels.—The proton spectrum obtained from the 98% $(N^{15})_2$ gas target[25] at 12.6° is shown in Fig. 9. The N^{16} levels at 0, 0.12, 0.30, and 0.40 Mev have been previously reported.[7] Five proton groups were identified with previously unreported levels in N^{16}. Surveys were made at scattering angles of 12.6°, 18°, 30°, and 60° up to 9-Mev excitation in N^{16}. All five groups peaked in the forward direction. At 30° the 3.53-Mev and 5.0-Mev levels were not seen and at 60° none of the five levels were seen. Identification of the peaks was made only by comparison with the proton spectra obtained from nickel, carbon, nylon, and O_2 targets. It is concluded that the 3.98-, 4.8-, and 5.3-Mev levels are definitely established; while the N^{16} 3.53- and 5.0-Mev levels are

[24] T. Auerbach and J. B. French, Phys. Rev. **98**, 1276 (1955).
[25] A mass spectographic analysis made after the work was completed showed the composition of the gas to be:

Mass No.	Identification	Percent
18	H_2O	1.7
28	$(N^{14})_2$	0.7
29	$N^{14}N^{15}$	1.6
30	$(N^{15})_2$	95
40	A	0.05
44	CO_2	1.0
46	$(N^{15})_2O^{16}$	<1

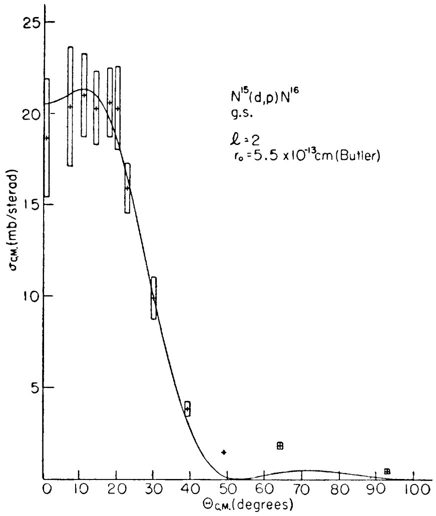

FIG. 10. Angular distribution of the $N^{15}(d,p)N^{16}$ ground state.

somewhat doubtful because they were observed at only two angles and had relatively low intensities. The 4.8- and 5.0-Mev levels were observed to have widths greater than the instrumental resolution. The c.m. widths were 0.23±0.04 and 0.29±0.05 Mev, respectively, after correction for instrumental contributions.

The results obtained with the 98% $(N^{15})_2$ target are summarized in Table III. The Q values and excitation energies were obtained by calculating the incident deuteron energy from the Q of −0.034±0.005 Mev obtained by Malm and Beuchner[26] for the 0.30-Mev level. The ground-state Q value was calculated to be 0.269±0.010 Mev. Cross sections (at 12.6°) are given for the five new levels only since cross sections for the other four levels were determined with the enriched ammonia as discussed below. The cross sections given for the last three levels may be too small by a factor of two because these peaks were superimposed on a large background. Upper limits for any other N^{16} levels were estimated to be 0.1 mb/sterad between 0.4-Mev and 1.6-Mev excitation, 0.2 mb/sterad between 1.6 and 4.0 Mev, 1.0 mb/sterad between 4.0 and 4.8 Mev, and 2.0 mb/sterad between 4- and 9-Mev excitation.

Angular distributions.—Angular distributions were obtained for the four low levels by using the enriched NH_3 gas so that cross sections could be obtained by direct comparison with the differential cross sections for

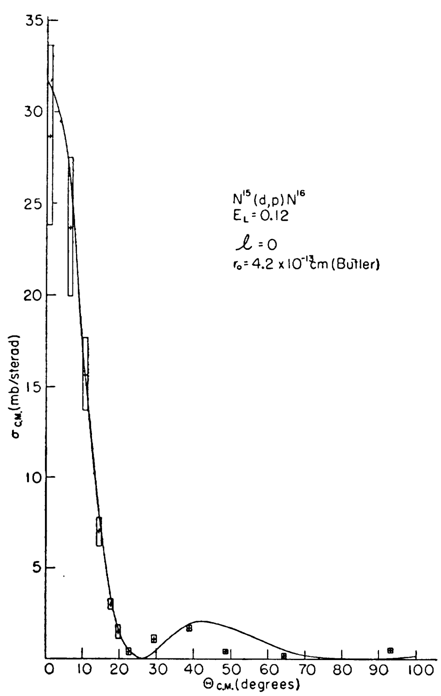

FIG. 11. Angular distribution of the $N^{15}(d,p)N^{16}$ 0.12-Mev level.

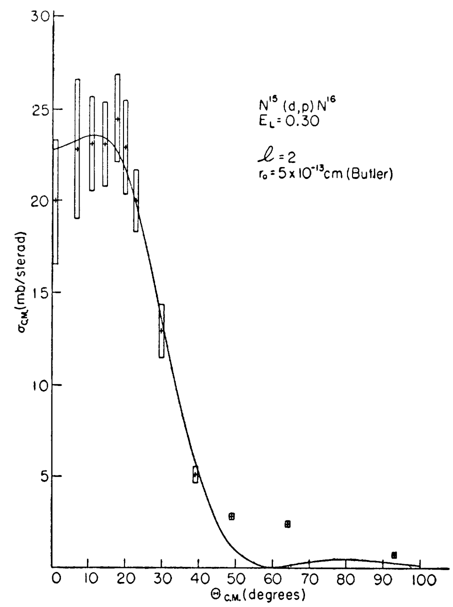

FIG. 12. Angular distribution of the $N^{15}(d,p)N^{16}$ 0.30-Mev level.

the scattering of deuterons by hydrogen. The angular distributions are shown in Figs. 10 through 13 with the Butler curves which best fit the data. The standard deviations in the absolute differential cross sections are shown; the relative errors are smaller. The angular distributions for the three excited states are in agreement with the work of Zimmerman[27] at a deuteron energy of 2.75 Mev. Zimmerman did not obtain an angular distribution for the ground-state transition because of interference with the $N^{14}(d,p)N^{15}$ 8.32-Mev level transition.

Discussion

Elliott[28] has done an intermediate coupling calculation for N^{16}. He included all states of the configurations $s^4p^{11}s$

[26] R. Malm and W. W. Buechner, Phys. Rev. **80**, 771 (1950).
[27] W. Zimmerman, Jr., Phys. Rev. **104**, 387 (1956).
[28] J. P. Elliott (private communication to E. U. Baranger).

and $s^4p^{11}d$ in the calculation which predicts four low-lying states with $J^\pi=0^-$, 1^-, 2^-, 3^- (not necessarily in that order). The four states are all predicted to have single-particle stripping reduced widths and the 1^- state (for which $l=0$ and $l=2$ are allowed by the selection rules) is predicted to have a small reduced width for $l=2$. The calculation also predicts that the next level in N^{16} will occur at least several Mev higher in excitation. These predictions are in agreement with the results of the present experiment. All four levels were found to have negative parity and none of the angular distributions demanded a superposition of $l=0$ and 2.

The single-particle reduced widths derived from the $O^{16}(d,p)O^{17}$ reaction are $\Theta^2=0.32$ for $l=0$ and $\Theta^2=0.11$ for $l=2$. The reduced widths for the four low levels of N^{16} are expected to be equal to or less than these values. If the assumption is made that the four states do have spins 0, 1, 2, and 3 then the two states with $l=2$ must

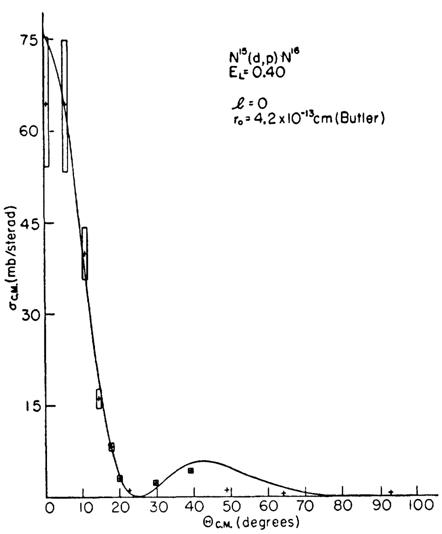

FIG. 13. Angular distribution of the $N^{15}(d,p)N^{16}$ 0.40-Mev level.

have $J=2$ and 3. The N^{16} ground state is almost certainly a 2^- state,[7,29] and thus the 0.30 Mev level should be the 3^- state. The stripping reduced widths are then 0.054 and 0.046, respectively. The reduced width for the 0.40-Mev level would be larger than expected if this state were $J^\pi=0^-$, and thus $J^\pi=1^-$ is indicated for the 0.40-Mev level (with or without the assumption that the four states have spins of 0, 1, 2, and 3). These assignments leave $J^\pi=0^-$, $\Theta^2=0.19$ for the 0.12-Mev level. The foregoing assignments are consistent with Wilkinson's[30] work on the de-excitation gamma rays following the $N^{15}(d,p)N^{16}$ reaction.

The results for the angular distributions, including the most probable values for J and Θ^2, are given in Table IV.

[29] B. J. Toppel, Phys. Rev. **103**, 141 (1956).
[30] D. H. Wilkinson, Phys. Rev. **105**, 686 (1957), this issue.

TABLE IV. Results of the $N^{15}(d,p)N^{16}$ angular distributions.

N^{16} level (Mev)	l	$r_0\times10^{-13}$ cm	Spin(parity)	$(2J+1)\Theta^2$	Θ^2 [a]	J [a]
ground state	2	5.5	$1^-, 2^-, 3^-$	0.27	0.05	2
0.12	0	4.2	$0^-, 1^-$	0.19	0.19	0
0.30	2	5.0	$1^-, 2^-, 3^-$	0.33	0.05	3
0.40	0	4.2	$0^-, 1^-$	0.54	0.18	1

[a] Most probable value.

D. $N^{15}(d,\alpha)C^{13}$

Results

Alpha-particle groups corresponding to energy levels in C^{13} up to 9.9-Mev excitation were observed simultaneously with and were identified in the same manner as the proton groups from $N^{15}+d$. No levels were looked for at excitations higher than 9.9 Mev. The alpha-particle spectrum observed at a scattering angle of 12.6° is shown in Fig. 14. The C^{13} 9.0-, 9.5-, and 9.9-Mev levels were not looked for at other scattering angles. The other levels shown in Fig. 14, as well as the 6.87-Mev level (which was not looked for at 12.6°), were also observed at 18° and 30°. All the levels observed have been previously reported.[7,31,32]

The slight asymmetry in the 3.68-Mev level peak (Fig. 14) may arise from a weak group corresponding to the 3.86-Mev level. The relative intensities for the C^{13} levels at 0, 3.09, 3.68, and 3.86 Mev are in qualitative agreement with the results of Malm and Buechner.[33] The alpha-particle group between 36 and 37 Mc/sec was ascribed to the unresolved 7.53- and 7.64-Mev levels by its width and mean energy. This group could also contain a small contribution from the 7.47-Mev level reported by McGruer, Warburton, and Bender.[32] The excitation energy of the 9.0-Mev level was calculated to be 8.80 ± 0.04 Mev by comparison with the accurately known N^{14} 3.95-Mev level which was identified by the increased intensity of the group upon addition of $(O^{16})_2$ to the target. The broad C^{13} level at 8.4-Mev excitation observed[32] through the $C^{12}(d,p)C^{13}$ reaction was not seen in the present experiment. The cross

TABLE V. Differential cross sections for the $N^{15}(d,\alpha)C^{13}$ reaction obtained at 12.6°.

C^{13} level (Mev)	$\sigma(\theta)$ mb/sterad
ground state	0.85 ± 0.09
3.09	0.18 ± 0.03
3.68	$2.4\ \pm0.3$
3.86	<0.3
6.87	$1.3\ \pm0.2$[a]
7.47, 7.53, 7.64	$1.1\ \pm0.2$
8.4	not observed
8.80 ± 0.04	0.56 ± 0.11
9.5	0.15 ± 0.04
9.9	0.26 ± 0.06

[a] Measured at a scattering angle of 18°.

[31] Bigham, Allen, and Almqvist, Phys. Rev. **99**, 631(A) (1955).
[32] McGruer, Warburton, and Bender, Phys. Rev. **100**, 235 (1955).
[33] R. Malm and W. W. Buechner, Phys. Rev. **81**, 519 (1951).

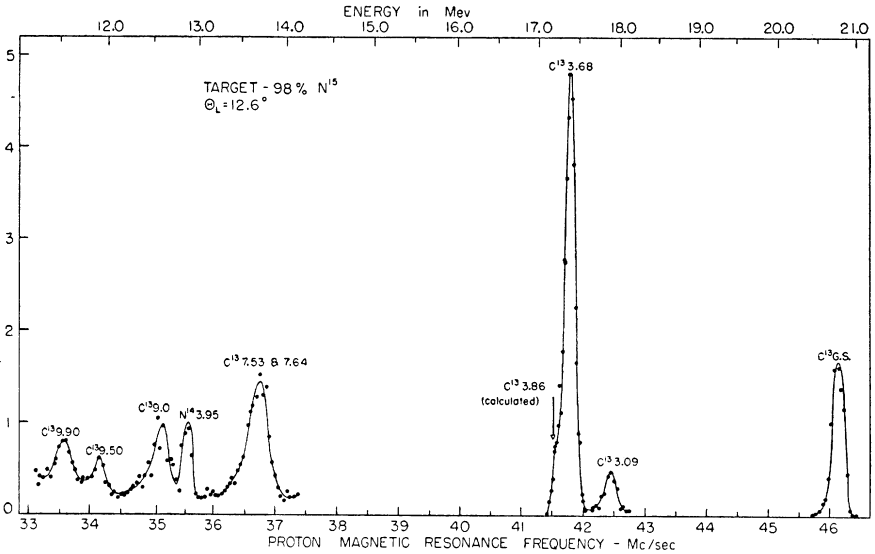

FIG. 14. Alpha-particle spectrum observed at 12.6° from a 98% $(N^{15})_2$ gas target bombarded by 14.8-Mev deuterons. The peaks are labeled by the state of the residual nucleus to which they belong.

sections obtained for the $N^{15}(d,\alpha)C^{13}$ reaction at 12.6° are given in Table V.

Discussion

It is interesting to note that, if the $N^{15}(d,\alpha)C^{13}$ reaction is considered to proceed by a direct interaction, the relative intensities of the first four levels and the 8.4-Mev level are in qualitative agreement with the results which are predicted by a naive consideration of the shell model. The first four levels are generally considered to belong[22] to the configurations s^4p^9, s^4p^8s, s^4p^9, and s^4p^8d, respectively, while Lane[34] has suggested that the 8.4-Mev level belongs to the configuration s^4p^8d. The N^{15} ground state is s^4p^{11}, and thus direct (d,α) transitions to the configurations s^4p^8s and s^4p^8d are shell-model-forbidden, while transitions to the s^4p^9 configuration are allowed.

E. $He^4(d,p)He^5$

The proton spectrum obtained from deuteron bombardment of He^4 gas target at a scattering angle of 19.5° is shown in Fig. 15. Other spectra were obtained at 18° and 24°. No evidence was seen for an excited state of He^5; however, the proton background from the reactions $He^4(d,p)He^5(n)He^4$ and $He^4(d,pn)He^4$ ($Q=-2.23$ Mev) would have obscured a broad and/or weak proton group. The proton group corresponding to the He^5 ground state was broad and had an asymmetrical shape.

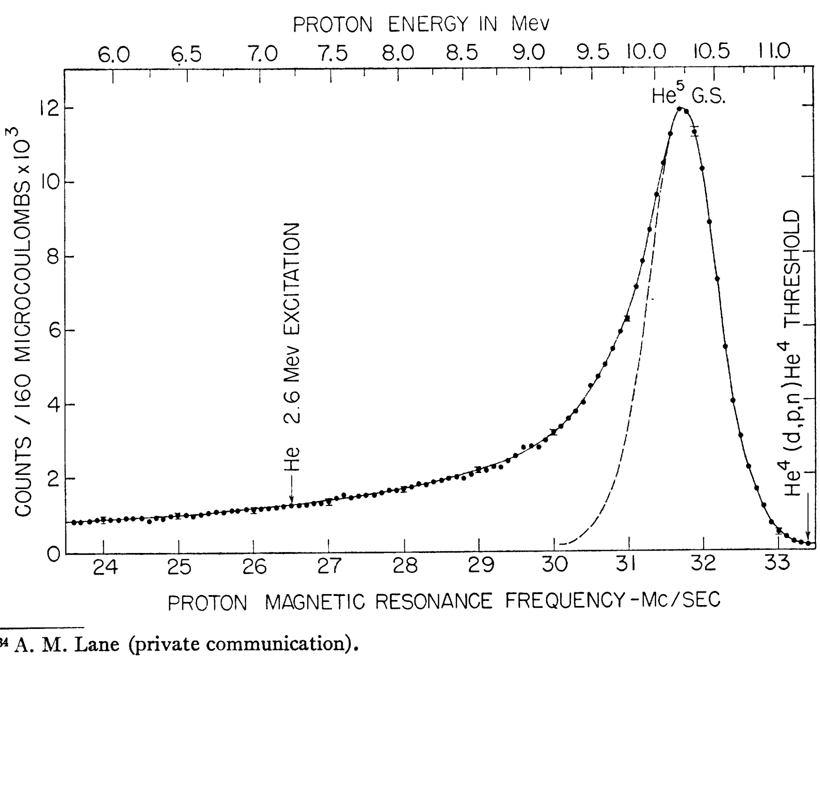

FIG. 15. Proton spectrum observed at 19.5° from a He^4 gas target bombarded by 14.8-Mev deuterons. The dashed line is the continuation of a Gaussian curve fitted to the high-energy side of the He^5 ground-state proton peak.

[34] A. M. Lane (private communication).

The half-width of the He^5 ground state was determined by fitting a Gaussian curve to the high-energy side of the proton peak after background was subtracted out. The c.m. half-width was 0.55 ± 0.030 Mev after correction for instrumental contributions.[35]

The cross section for the $He^4(d,p)He^5$ ground state was obtained from the area under the Gaussian curve (Fig. 15) which gave 25 ± 5 mb/sterad and 15 ± 4 mb/sterad at 18° and 24°, respectively. He^4 has the configuration $s^4(J^\pi=0^+)$, while the He^5 ground state has the configuration $s^4p(J^\pi=\frac{3}{2}^-)$; therefore, the stripping reaction $He^4(d,p)He^5$ ground state is expected to be an $l=1$ transition with a single-particle reduced width. By fitting an $l=1$, $r_0=4.5\times10^{-13}$ cm Butler curve to the observed cross sections, a reduced width of 0.05 was determined for this reaction. This value is within the range observed empirically[16] for $l=1$ single-particle stripping reduced widths of bound states, but is approximately a factor of ten smaller than the reduced width obtained from the resonant reaction[36] $He^4(n,n)He^4$.

[35] Other experimental values for the He^5 ground-state half-width are tabulated by Craig, Cross, and Jarvis, Phys. Rev. **103**, 1427 (1956).

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Radioactive Decay of Ne^{23}†

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The beta and gamma radiations of 38-sec Ne^{23} have been studied by means of scintillation spectrometer techniques. Beta transitions were found to the ground, first, and second excited states of Na^{23} with end-point energies equal to 4.39 ± 0.05, 3.95 ± 0.05, and 2.4 ± 0.1 Mev, respectively. Their percent intensities and log *ft* values are: 67 ± 3, 5.25; 32 ± 3, 5.38; and 1.00 ± 0.15, 5.88, respectively. Gamma rays are coincident with the latter two beta transitions and with one another; their energies and percent relative intensities are: 436 ± 4 kev; 100; 1647 ± 16 kev, 3.0 ± 0.3, respectively. Higher energy gamma radiation was present in less than 0.2% of all decays. No beta transitions with log *ft* values in the superallowed group were found. A decay scheme based on the above data is proposed.

The half-life of Ne^{23} was remeasured together with the half-lives of O^{15} and Ne^{19}. The results are: Ne^{23}, 37.6 ± 0.1 sec; O^{15}, 123.95 ± 0.50 sec; Ne^{19}, 17.7 ± 0.1 sec.

INTRODUCTION

INTEREST in the decay characteristics of the $N-Z=3$ nuclides was stimulated recently by speculations of King,[1] and of Feenberg,[2] into the origin of the reported[3] superallowed transition in Ne^{23}. In this work of Brown and Perez-Mendez[3] the beta spectrum of Ne^{23} was found to consist of two groups with end-point energies of 4.21 ± 0.15 and 1.18 ± 0.04 Mev, and with relative intensities of 93 and 7%, respectively. The log *ft* value for the lower energy group was given as 3.8, which places the transition in the superallowed class.

In their review of the energy levels of light nuclei Endt and Kluyver[4] pointed out that the end-point energy of the high-energy beta group in the decay of Ne^{23}, as determined by Brown and Perez-Mendez,[3] was in disagreement with the value of 4.388 ± 0.007 Mev which was calculated from Li's[5] compilation of the masses of light nuclei.

For the above reasons we undertook a reexamination of the Ne^{23} decay. A preliminary account of our work has been published in abstract form.[6] Concurrently, Gerber, Muñoz, and Maeder[7] also reinvestigated this radioisotope. Our results are in substantial agreement for the more intense radiations. However, in the work of Gerber *et al.*, contamination from other activities obscured gamma radiation of low intensity above about 500 kev. Nevertheless, they were able to quote a lower limit of 5.0 on the log *ft* value associated with the beta decay of Ne^{23} to the 3.0-Mev state of Na^{23}.

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