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Authors
Harvey, Bernard G.
Cerny, Joseph.
Pehl, Richard H.
et al.

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Ernest O. Lawrence Radiation Laboratory

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ABSTRACT

The two-nucleon α, d stripping reaction has been studied for targets of C^{12}, N^{14}, N^{15}, and O^{16}. In each case, strong levels believed to correspond to insertion of the captured nucleons into a $(d_{5/2})^2$ $J = 5$ configuration are observed. In N^{14} and F^{18}, single levels are observed at 9.0 and 1.1 MeV respectively; in O^{16} and O^{17} the level is split into a triplet (O^{16}) and a doublet (O^{17}) by coupling with the spin of the target core. In O^{16} the levels lie at 14.7, 16.2, and 17.2 MeV; in O^{17} they are at 7.6 and 9.0 MeV.

By inelastic helium ion scattering the following parities were measured for levels in N^{14}: 3.95 and 7.03 MeV, positive; 4.91, 5.10, 5.69, and 5.83 MeV, negative.

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1. INTRODUCTION

Recent investigations of two-nucleon transfer reactions such as α, d or He^3, p show that they usually proceed mainly by a direct-interaction mechanism$^{1-5}$). Therefore it is reasonable to expect that the levels formed in high yields will be those representable in j-j coupling shell-model language as $\left[J_T+(j_p j_n)_{J'}\right]_J$. Here J_T is the angular momentum of the target nucleus, j_p and j_n are the total angular momenta of the added proton and neutron, coupled to J'. J_T and J' couple to the angular momentum J of the particular level. It is here assumed that the configuration of the target core is unchanged in the interaction. More complex core-excited states should be formed in lower yield.

In an experimental study of the reactions $C^{12}(\alpha, d)N^{14}$, $N^{14}(\alpha, d)O^{16}$, $N^{15}(\alpha, d)O^{17}$, and $O^{16}(\alpha, d)F^{18}$, we have observed the appearance of a strong level or levels in the product nuclei which we believe can be associated with the configurations $\left[J_T+(d_{5/2})^2_5\right]_J$. The experimental results for the C^{12} and N^{14} targets have already been published.^{1,4}).

2. EXPERIMENTAL PROCEDURE

Bombardments with 47-MeV helium ions were made in a 91-cm scattering chamber at the Crocker Laboratory 152-cm cyclotron. Particles were identified by means of an E - dE/dx counter telescope system and analog pulse multiplier. Multiplied pulses, corresponding to deuterons, were used to trigger a pulse-height analyzer which recorded the energy spectrum of the deuterons. The apparatus has already been described[1,4]). In the earlier experiments, scintillation counters were used. These have been recently replaced with diffused phosphorous p-n junctions (for the dE/dx counter) and lithium-drifted diodes (for the E counter). By adding the pulses from the two counters and using the sum pulse for energy analysis, the effects of nonuniformity and energy straggling in the dE/dx counter were eliminated. This improved the experimental energy resolution so that it was entirely determined by energy dispersion in the cyclotron beams. This dispersion was about 0.9% of the particle energy.

N_2^{15} and O_2^{16} were contained in the gas-holder target assembly which had previously been used for the investigation of N_2^{14} [4]). Separated N_2^{15} of 94.6 and 97.6% purity (Isomet Corporation) was used.

3. RESULTS

Typical deuteron energy spectra obtained from the four targets are shown in figs. 1 through 4. Virtually identical spectra of protons were obtained from the reactions $C^{12}(He^3,p)N^{14}$ and $O^{16}(He^3,p)F^{18}$, using 31-MeV He^3 accelerated in the Hilac (heavy-ion linear accelerator).

The angular distributions of the deuteron groups corresponding to the 9.0-MeV level in N^{14}, the 14.7- and 16.2-MeV levels in O^{16}, the 7.6- and 9.0-MeV levels in O^{17}, and the 1.1-MeV level in F^{18} are shown in figs. 5-8. A level at 17.2 MeV is perhaps the third member of a triplet in O^{16}, but in only a few of the experiments was the deuteron spectrum measured to such high excitation energies. In no case is there any evidence of diffraction-like oscillations, but the distributions are all strongly peaked in the forward direction, and closely resemble one another.

4. DISCUSSION

The levels whose angular distributions are shown in figs. 5 through 8 are in each case formed in higher yields than any other levels in their respective nuclei. The integrated cross sections are shown in table 1.

The first evidence that all the levels shown in table 1 might be of similar configuration was obtained when the Q values for their formation were plotted as a function of the mass number A of the product nucleus. As fig. 9 shows, the (negative) Q values decrease in a regular way with increasing A. This, and the fact that in F^{18} the strong level is only 1.1 MeV above the ground state, suggest that the two added nucleons are in shell-model states not far above the $1p_{1/2}$ subshell: the $1d_{5/2}$ and $2s_{1/2}$ shells are obvious candidates. There is in fact a 5+ level in F^{18} at 1.125 MeV^{6}), which must be of pure $(d_{5/2})^2_5$ configuration. Shell-model calculations by True place the $(d_{5/2})^2_5$ level in N^{14} at about 9 MeV^{7}), just where the strong α, d level is observed.

It seems reasonable that the dynamics of the reaction should favor the formation of the J = 5 levels of the $(d_{5/2})^2$ configuration. The wave functions of the odd nucleons will have maximum overlap when the vector sum of the orbital angular momenta is either a maximum or a minimum, and of these two the maximum value (L = 4) is most likely to be produced in a grazing collision on the nuclear surface. The captured nucleons then "go round the core in the same direction," looking as much as possible like a deuteron.

The $(d_{5/2})^2$ configuration can belong to levels of spins from 0 to 5. The reaction should favor the level with the greatest ^3G component—i.e., the level for which $\ell_n + \ell_p = 4$ and in which the two nucleons preserve the triplet configuration they had in the incident helium ion. For the various spin states of $(d_{5/2})^2$, the amplitudes of the possible L-S components (obtained by expansion of the j-j wave function) are summarized in table 2. The spin-5 level is the only one with a strong ^3G component.

The spin of N^{15} is 1/2 - . Hence two levels of the configuration $(d_{5/2})^2_5$ should exist in O^{17}, with spins 9/2 - and 11/2 - . It seems very likely that the observed levels at 7.6 and 9.0 MeV correspond to this doublet. The measured splitting is 1.4 MeV. A calculation by Glendenning using the Ferrell-Visscher force gave a splitting of 3.16 MeV, the 11/2 - level lying lower$^{8)}$. The Serber force (zero in triplet odd and singlet odd states) gave 2.1 MeV. (The Serber force was also used by True.)

Since the spin of the N^{14} core is 1+, the configuration $(d_{5/2})^2_5$ in O^{16} should lead to three levels with spins 4+, 5+, and 6+. Two strong deuteron groups corresponding to O^{16} levels at 14.7 and 16.2 MeV are clearly seen: in many spectra there was a third weaker group corresponding to a level at 17.2 MeV. Unfortunately, at many angles this group fell below the deuteron energy range investigated, so that it is not possible to be sure that it is the third member of a triplet. There is a known 4+ level in O^{16} at 14.94 MeV[9]), but no known high spin levels at 16.2 or 17.2 MeV.

The $(d_{5/2})^2_5$ levels in F^{18} and N^{14} should be single, since the cores are 0+. In F^{18}, this level is well known. In N^{14}, no such level has been observed at 9 MeV, but True's shell-model calculations predict that it should lie at about this energy[7]). The level at 8.99 MeV is reported to be 1+[6]), and even if it is of strong $(d_{5/2})^2$ character it should not have been strongly populated, since the 1+ ground state of F^{18} was not, even though it contains a substantial $(d_{5/2})^2$ component. The observed level must therefore be a new one. It is not surprising that a level of pure $(d_{5/2})^2_5$ character should have been missed. The region was previously explored by the reactions $C^{13}(p,\gamma)N^{14}$ and $C^{13}(p,p)C^{13}$, and such a level could be made only by simultaneous promotion of the $p_{1/2}$ neutron in C^{13} to the $d_{5/2}$ shell and capture of the incident proton in the same shell. The probability seems feeble that such an interaction occurs.

Further confirmation (of a negative nature) of the proposed $(d_{5/2})^2_5$ configuration of the 9.0-MeV level in N^{14} was obtained by a study of the reactions $N^{14}(\alpha,\alpha')N^{14}$ and $O^{16}(d,\alpha)N^{14}$ [10]). Inelastic α scattering should populate strongly those levels in N^{14} that can be made by promotion of a single nucleon from its ground-state configuration[11]). The results are everywhere in agreement with this hypothesis and with the configurations proposed by Warburton and Pinkston[11]), and by True[7]). For example, the well known levels at 3.95 and 7.03 MeV, which can be made by the promotion $p_{3/2} \rightarrow p_{1/2}$, are both strongly populated. Their angular distributions and absolute cross sections are virtually identical. (This result, incidentally, establishes the parity of the 7.03-MeV level as positive.) The 4.91 -, 5.10 -, 5.69 -, and 5.83-MeV levels, all of which can be made by the promotion $p_{1/2} \rightarrow 2s_{1/2}$ or $p_{1/2} \rightarrow d_{5/2}$, are strongly populated and have very similar angular distributions and cross sections. Their angular distributions oscillate in phase with the elastic cross section, so that all four levels are of negative parity.

On the other hand the levels at 6.23 and 6.44 MeV are made in about one-tenth the yield; they require the double promotions $(p_{1/2})^2 \rightarrow (s_{1/2})^2$, or $(p_{1/2})^2 \rightarrow (s_{1/2}d_{5/2})$, according to the configurations assigned by True7). The level at 9.0 MeV was not observably populated in $N^{14}(\alpha, \alpha')$, as shown in fig. 10. It too could be made only by promotion of two nucleons, if it has a $(d_{5/2})^2$ configuration.

In $O^{16}(d, \alpha)N^{14}$, the strong N^{14} levels should be those that can be made by simply removing two nucleons from O^{16}. The 9.0-MeV$(d_{5/2})^2_5$ level is not of this type, and it is not strongly populated by bombardments with 24-MeV deuterons, as fig. 11 shows. The energy of the He^4 ion corresponding to this level is nearly the same as the energy of the He^3 ion corresponding to the ground state of the $O^{16}(d, He^3)N^{15}$ reaction. The development of very thin dE/dx counters12) enabled us to differentiate between He^3 and He^4 ions with the pulse multiplier and consequently to obtain "pure" He^4 energy spectra such as shown in fig. 11.

5. CONCLUSIONS

The configuration $(d_{5/2})^2_5$ coupled to an unchanged target core produces the levels summarized in table 3.

A preliminary study of the elastic and inelastic scattering of helium ions from N^{14} showed that the 3.95- and 7.03-MeV levels have positive parity; the 4.91-, 5.10-, 5.69-, and 5.83-MeV levels have negative parity. Assignments were made on the basis of the phase rule.

It is a pleasure to thank Professor W. W. True and Dr. N. K. Glendenning for most stimulating discussions, and for the communication of results prior to publication. We also wish to thank the crew of the Crocker Laboratory cyclotron for their most efficient operation of the machine. We are most grateful to J. H. Elliott for supplying the lithium-drifted silicon particle detectors which were used in many of the experiments.

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REFERENCES

[†] Now at Aberdeen Proving Ground, Maryland

1) B. G. Harvey and J. Cerny, Phys. Rev. 120, (1960) 2162

2) H. C. Newns, Proc. Phys. Soc. (London) 76, (1960) 489

3) N. K. Glendenning, Nuclear Phys. 29, (1962) 109

4) J. Cerny, B. G. Harvey, and R. H. Pehl, Nuclear Phys. 29, (1962) 120

5) S. Hinds and R. Middleton, Proc. Phys. Soc. (London) A73, 721 (1959)

6) F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. 11, (1959) 1; unpublished revision by the authors, Energy Levels of Light Nuclei, dated August 1960

7) W. W. True (University of California at Davis), private communication

8) N. K. Glendenning (Lawrence Radiation Laboratory), private communication, March 1962

9) S. Bashkin, R. R. Carlson, and R. A. Douglas, Phys. Rev. 114, (1959) 1543

10) R. H. Pehl, B. G. Harvey, E. Rivet and J. Cerny (work in progress)

11) E. K. Warburton and W. T. Pinkston, Phys. Rev. 118, (1960) 733

12) J. H. Elliott and R. H. Pehl, The Thin Semiconductor Transmission Counter System for Nuclear Particle Detection (to be published in Rev. Nuclear Sci.).

Table 1

Energies, Q values, and integrated cross sections for strong levels formed in α, d reactions

Nucleus	Level energy (MeV)	Q value (MeV)	Cross section (mb)	Range of integration in deg (c. m.)
N^{14}	9.0±0.2	-22.6	7.0	20.4 - 78.2
O^{16}	14.7±0.3	-17.8	7.1	11.3 - 73.4
	16.2±0.3	-19.3	5.2	11.5 - 74.0
	(17.2 ±0.3)	(- 20.3)	---	-----
O^{17}	7.6±0.2	-17.4	6.4	11.2 - 66.6
	9.0±0.2	-18.8	3.1	11.3 - 67.0
F^{18}	1.1+0.1	-17.4	11.2	14.9 - 72.7

Table 2

j-j wave functions of $(d_{5/2})^2$ configurations

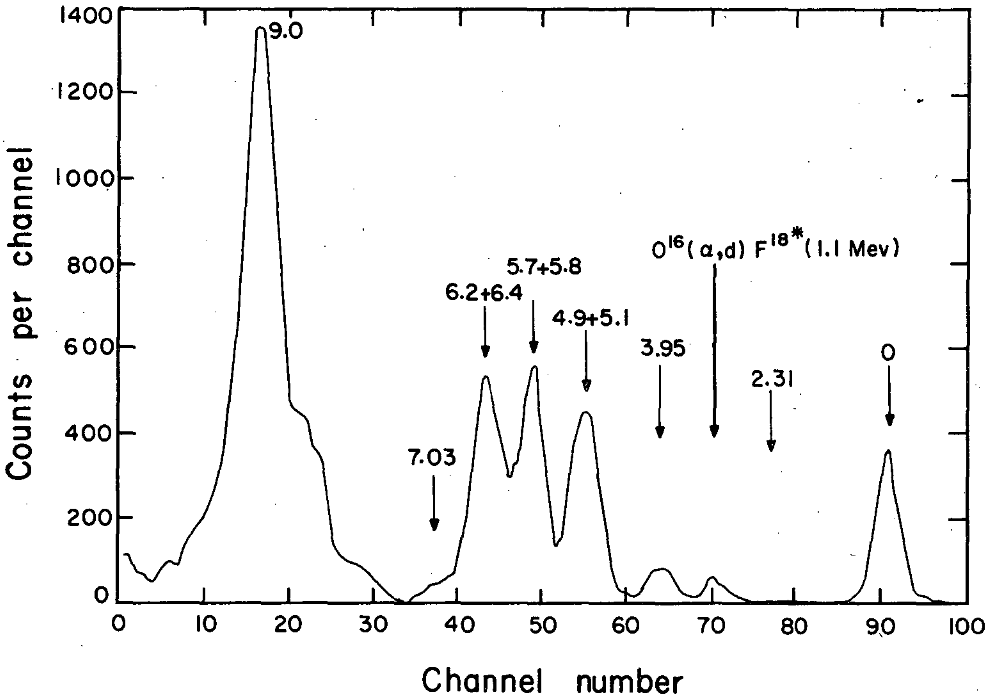
Level spin	L-S components
5	$1.00\ {}^3G$
4	$\sqrt{\frac{4}{5}}\ {}^3F + \sqrt{\frac{1}{5}}\ {}^1G$
3	$\sqrt{\frac{108}{175}}\ {}^3D - \sqrt{\frac{4}{175}}\ {}^3G + \sqrt{\frac{63}{175}}\ {}^1F$
2	$\sqrt{\frac{56}{125}}\ {}^3P - \sqrt{\frac{9}{125}}\ {}^3F + \sqrt{\frac{60}{125}}\ {}^1D$
1	$\sqrt{\frac{7}{25}}\ {}^3S - \sqrt{\frac{4}{25}}\ {}^3D + \sqrt{\frac{14}{25}}\ {}^1P$
0	$\sqrt{\frac{2}{5}}\ {}^3P + \sqrt{\frac{3}{5}}\ {}^1S$

Table 3

Summary of energies, spins, and parities of $(d_{5/2})^2_5$ levels in N^{14}, O^{16}, O^{17}, and F^{18}

Nucleus	Energy	$J^{\pi}T$
N^{14}	9.0±0.2	5 + 0
O^{16}	14.7±0.3	(4)+ 0
	16.2±0.3	(5, 6)+ 0
	(17.2±0.3	(5, 6)+ 0)
O^{17}	7.6±0.2	11/2- 0
	9.0±0.2	9/2- 0
F^{18}	1.1±0.1	5 + 0

The 14.7-MeV level in O^{16} is assigned spin 4 only because there is a previously known (4+) level at this energy. 6).



MU-26781

Fig. 1. Deuteron energy spectrum at 15 deg (lab) for the reaction $C^{12}(\alpha, d)\,N^{14}$.

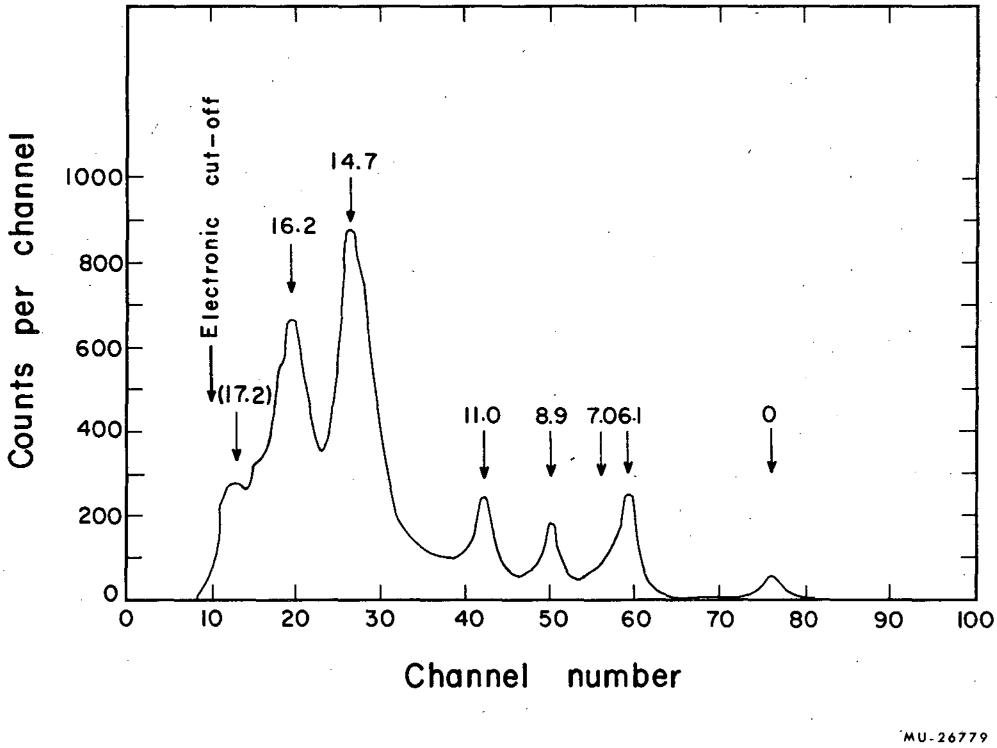


Fig. 2. Deuteron energy spectrum at 15 deg (lab) for the reaction $N^{14}(\alpha, d)\ O^{16}$.

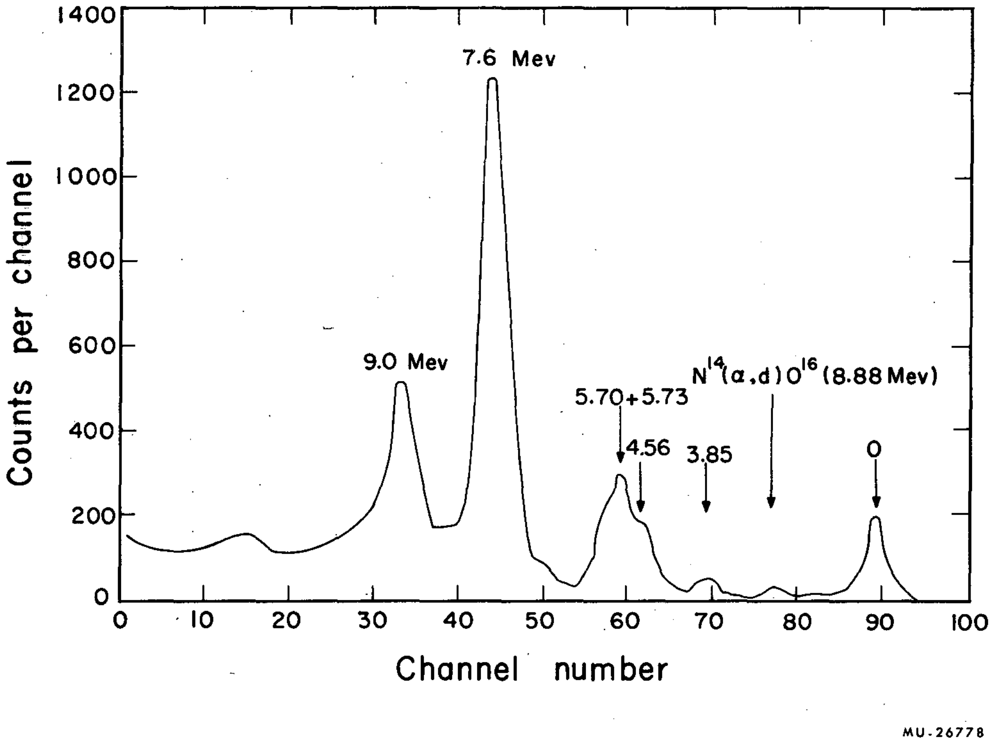


Fig. 3. Deuteron energy spectrum at 15 deg (lab) for the reaction $N^{15}(\alpha, d)\ O^{17}$.

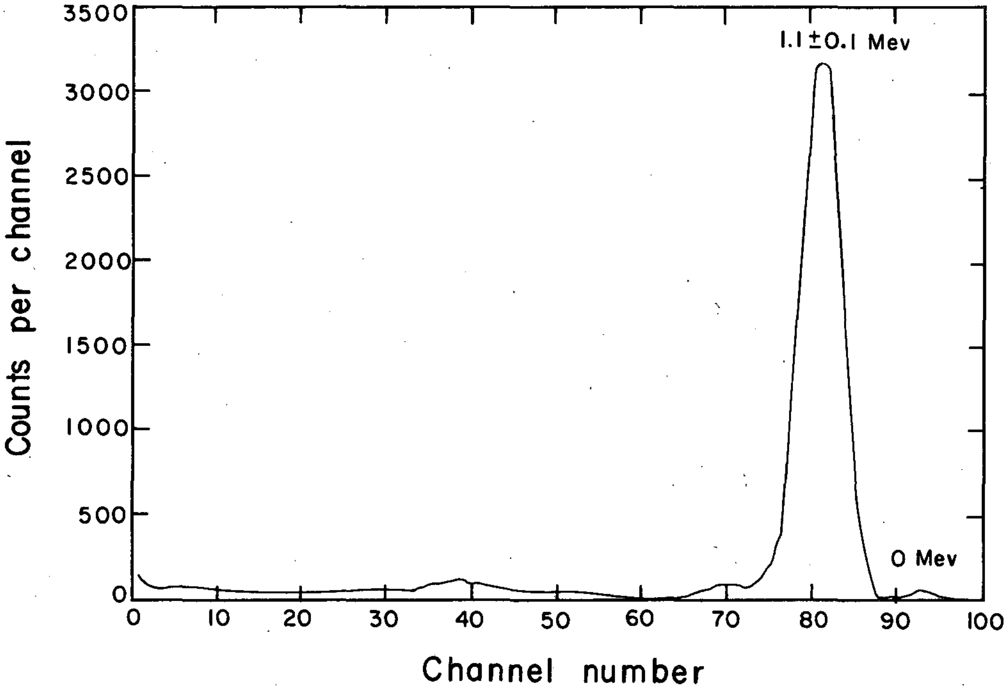


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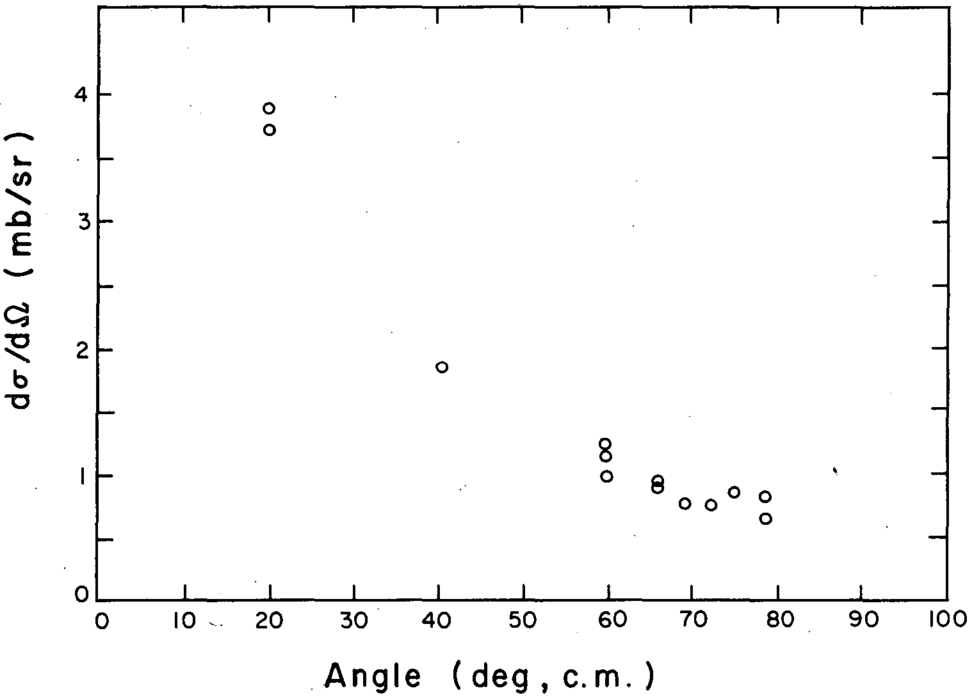
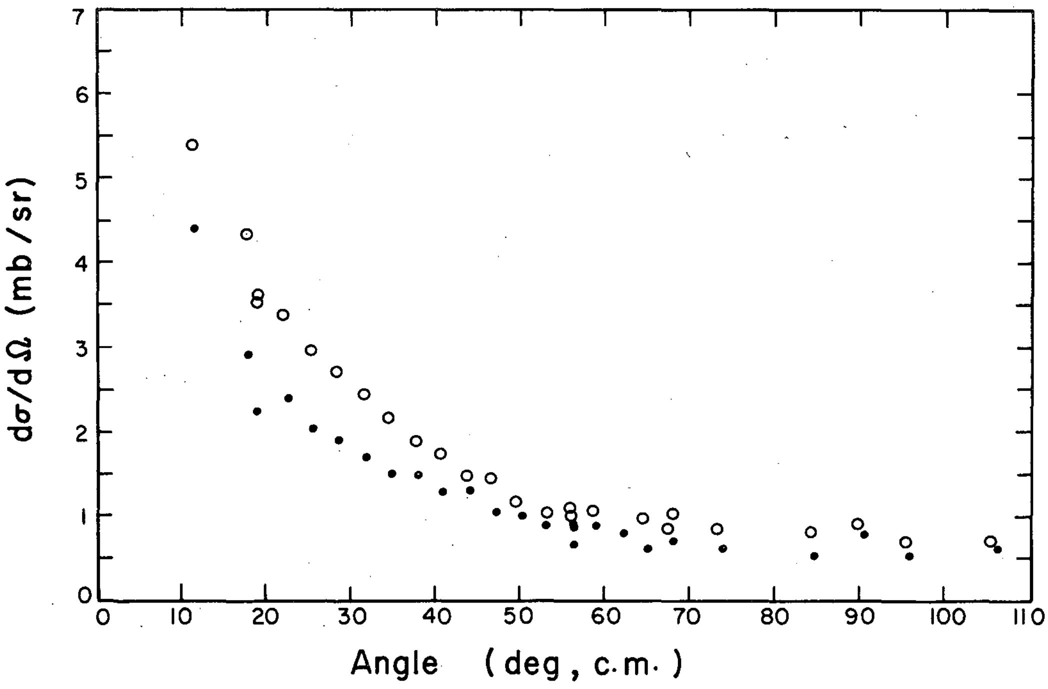
Fig. 4. Deuteron energy spectrum at 15 deg (lab) for the reaction $O^{16}(a, d) F^{18}$.



MU-26784

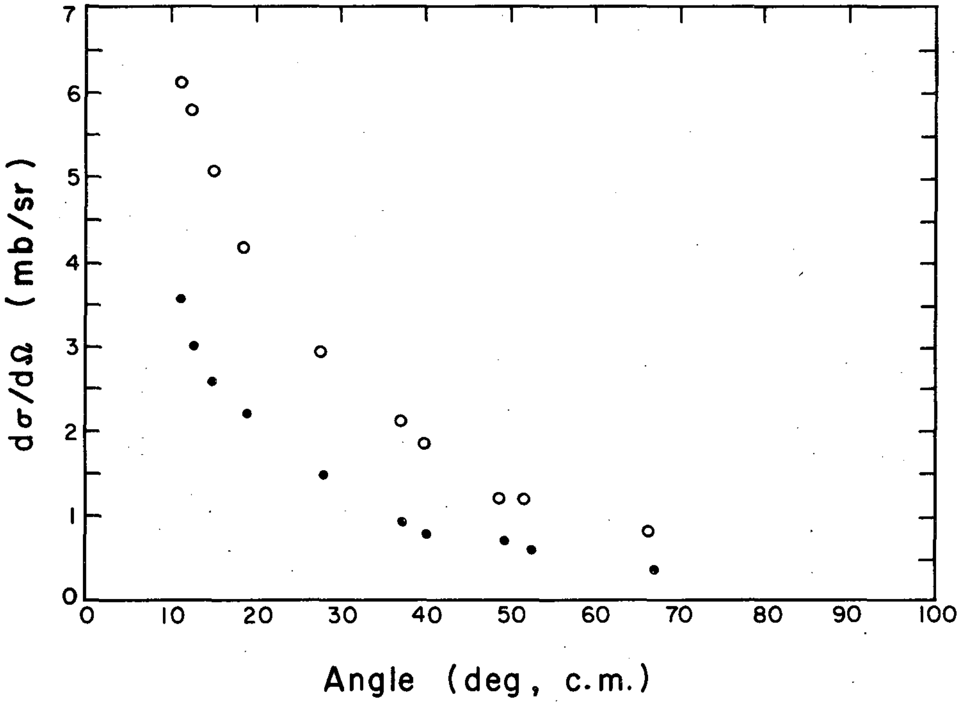
Fig. 5. Angular distribution of deuterons from $C^{12}(\alpha, d)\ N^{14}$ (9.0-MeV level).



MU-26785

Fig. 6. Angular distribution of deuterons from $N^{14}(\alpha, d)\ O^{16}$:

○ 14.7-MeV level
● 16.2-MeV level .



MU-26780

Fig. 7. Angular distribution of deuterons from $N^{15}(\alpha, d)\ O^{16}$:

○ 7.6-MeV level
● 9.0-MeV level .

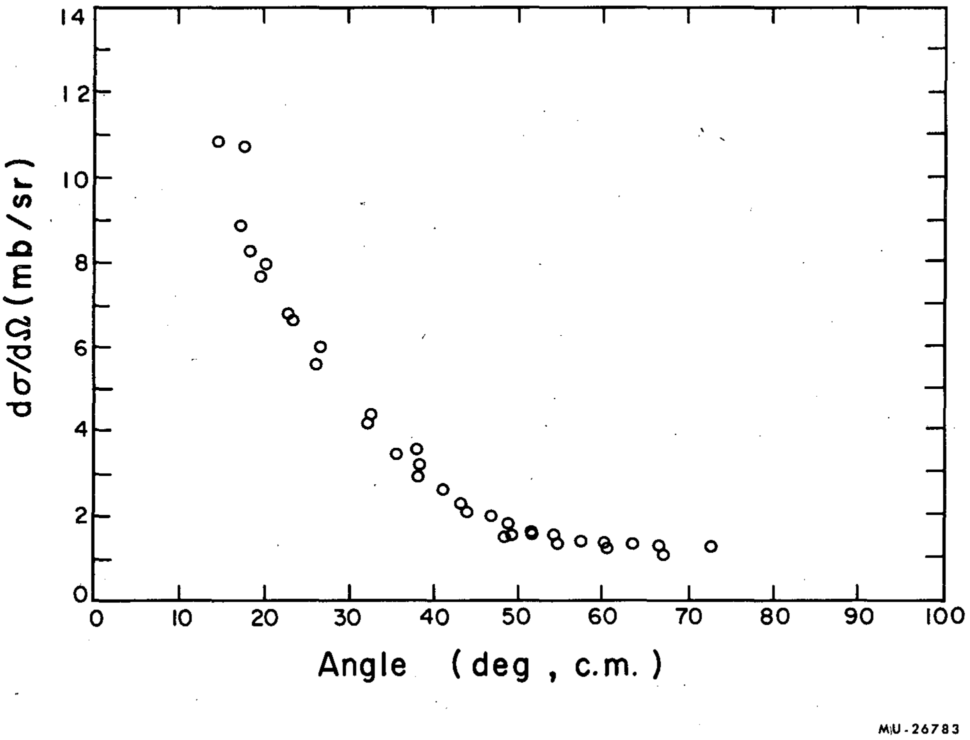
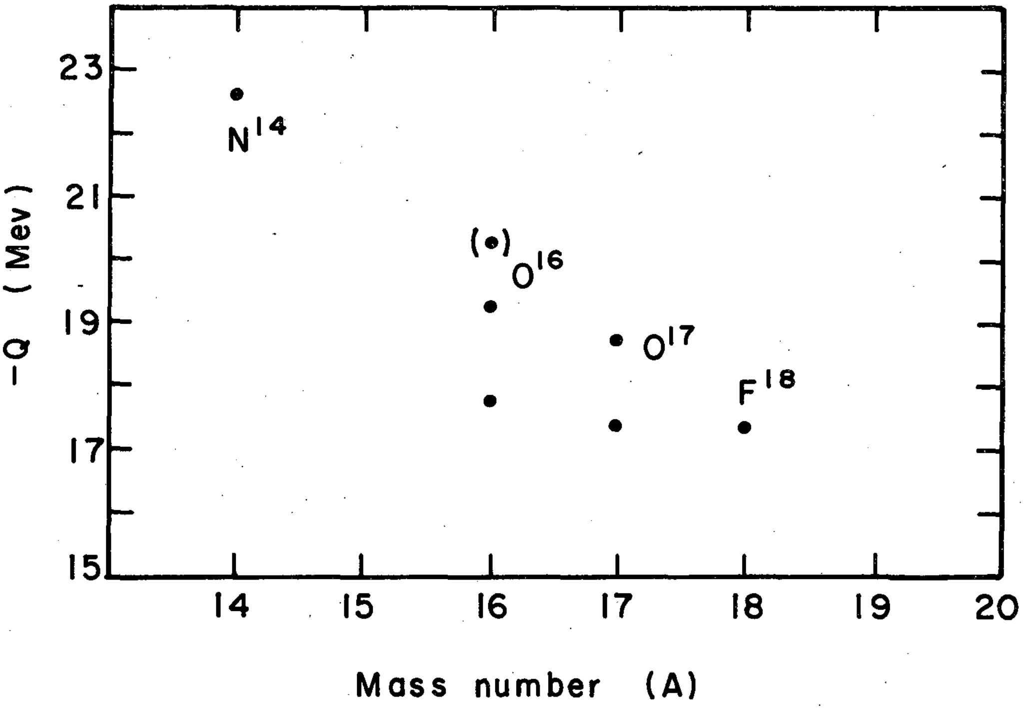


Fig. 8. Angular distribution of deuterons from $O^{16}(\alpha, d)\ F^{18}$ (1.1-MeV level).



MU-26782

Fig. 9. Dependence of Q on Mass Number A, for (α, d) reaction to $(d_{5/2})^2_5$ levels.

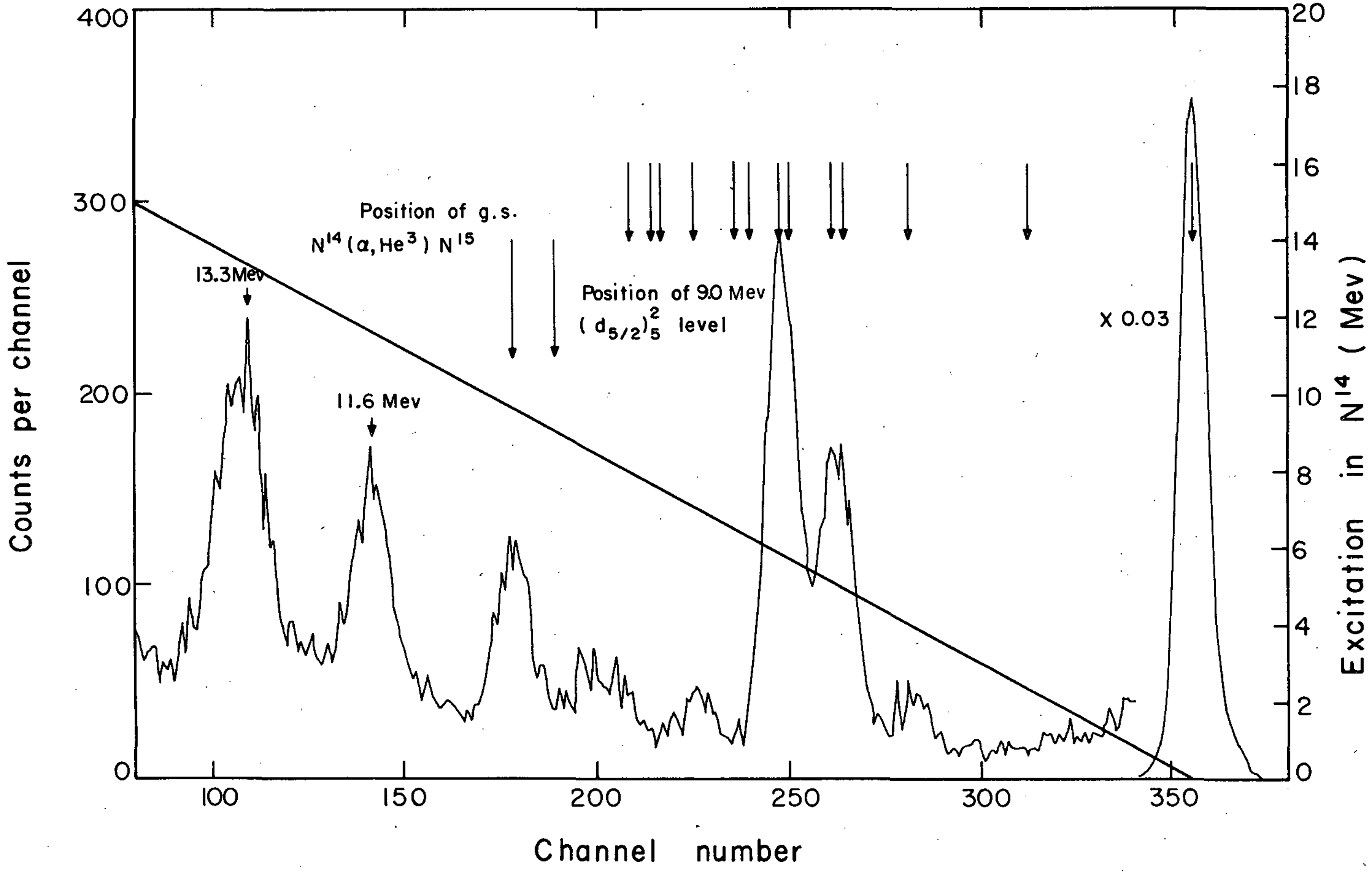


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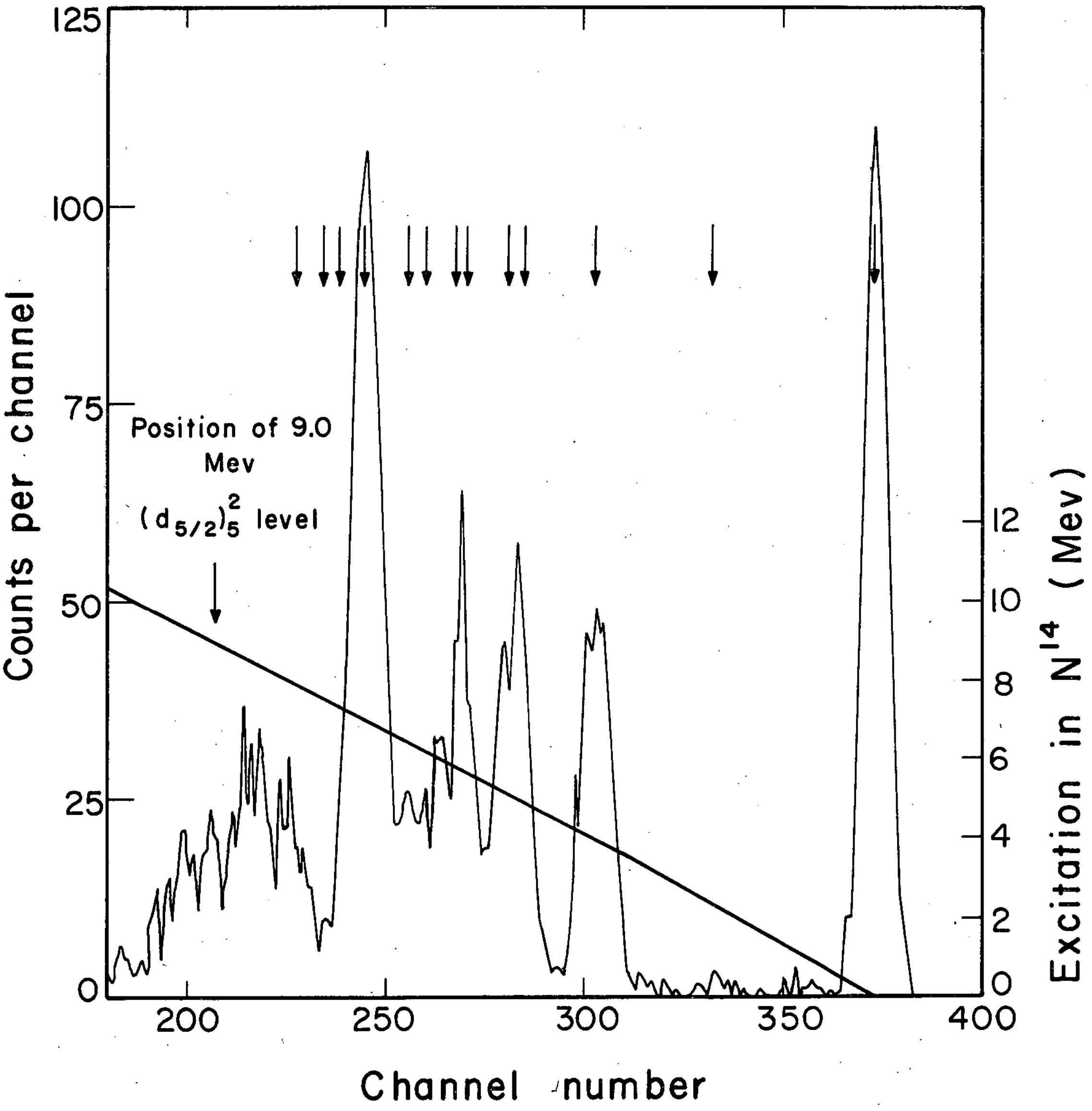
Fig. 10. Helium ion energy spectrum at 18.8 deg (lab) for the reaction $N^{14}(\alpha, \alpha') N^{14*}$. Arrows indicate the position of known levels.



MUB-1075

Fig. 11. Helium ion energy spectrum at 18.8 deg (lab) for the reaction $O^{16}(d,\alpha)N^{14}$. Arrows indicate the position of known levels.