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Isotopic-Spin* Selection Rule Violation in the $O^{16}(d,\alpha)N^{14}$ Reaction†

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The $O^{16}(d,\alpha)N^{14}$ reaction has been observed to proceed to the first excited state of N^{14} in violation of the isotopic-spin selection rule. The yields of this alpha group and the alpha groups leading to the ground state and second excited state have been measured from 5.5- to 7.5-Mev bombarding energy. At 7.03 Mev, the angular distributions of the three groups have been measured from 15 to 130 degrees. An absolute cross section has been obtained by comparison with the known proton elastic scattering from O^{16}. The observed isotopic-spin selection rule violation is of the order of magnitude predicted by theory on the basis of Coulomb-force mixing of states of different isotopic spin.

I. INTRODUCTION

ON the assumption of charge independence of nuclear forces, an isotopic spin quantum number, T, may be defined such that $2T+1$ is the number of possible isotopic spin states for a given space and spin configuration, and the component $T_z=\frac{1}{2}$ (number of protons–number of neutrons) indicates the particular isobar in question. In a nuclear reaction, the total isotopic spin should be conserved, and hence a selection rule should apply. The $O^{16}(d,\alpha)N^{14}$ reaction is one of the classical examples of the operation of this selection rule.[1] Because the ground state of O^{16}, the deuteron, and the alpha particle each has $T=0$, if the total T is to be conserved, the only states in N^{14} that can be formed in this reaction are those with $T=0$.

Experiments at many energies and angles of observation[2] have failed to show the first state in N^{14} at 2.31-Mev excitation, and this has been explained by assuming the state to have $T=1$. Other evidence that the first excited state has $T=1$ comes from its position corresponding to the ground states of the neighboring isobars, C^{14} and O^{14}, and from the fact that it is not observed with inelastic deuteron scattering.[3]

A failure of the selection rule might be caused either by a lack of charge independence of nuclear forces or by an isotopic spin impurity of the nuclear states arising from operation of Coulomb and magnetic forces.

The selection rule violation reported here was discovered through the appearance of an unknown group of alpha particles from the deuteron bombardment of a target of magnesium evaporated onto Formvar. A preliminary identification of the group as coming from the $O^{16}(d,\alpha)N^{14}$ reaction was reported in a paper on the $Mg^{24}(d,\alpha)Na^{22}$ reaction,[4] and many of the results presented here were briefly reported later.[5]

II. PROCEDURE

Deuterons from the MIT-ONR electrostatic accelerator were used to bombard targets of magnesium, lithium, iron, and silicon dioxide all evaporated onto Formvar. Natural oxidation of the first three elements gave a usable amount of oxygen in the targets. The alpha particles from the targets were analyzed with the MIT broad-range spectrograph.[6]

For the identification runs, the angular distributions, and the yield curve of the first and second excited-state groups, nuclear-track plates were used for recording the alpha particles. For the yield curve of the ground-state group, a scintillation counter mounted at a fixed position on the focal surface was used in addition to the nuclear plates.

The position on the plate of every group used in the data was accurately measured, and the Q value for $O^{16}(d,\alpha)N^{14}$ was calculated. This served to confirm the identification of the group. The SiO_2 targets were used for most of the data; therefore, calculations were made for the $Si^{28}(d,\alpha)Al^{26}$ reaction, using the known Q values to assure that no alpha groups from this reaction overlapped the oxygen groups in question. This was always true for the low-intensity forbidden group. In the case of the intense second excited-state group, there is a possibility of overlap of groups corresponding to excitations in Al^{26} above the known levels. The groups seen in the neighborhood of the group from oxygen are all of about equal size and much smaller than the group from oxygen at all bombarding energies used. It is estimated therefore that any overlapping group could contribute at most 5% to the observed intensity of the second excited-state group.

* *Note added in proof.*—The author feels that the term isobaric-spin is much to be preferred over the old isotopic-spin for this quantum number which distinguishes isobars. At the request of the editor the old term is used here to conform to the rules of this Journal.

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[1] R. K. Adair, Phys. Rev. **87**, 1041 (1952).

[2] Van de Graaff, Sperduto, Buechner, and Enge, Phys. Rev. **86**, 966 (1952); Craig, Donahue, and Jones, Phys. Rev. **88**, 808 (1952); A. Ashmore and J. F. Raffle, Proc. Phys. Soc. (London) **A64**, 296 (1952); Burrows, Powell, and Rotblat, Proc. Roy. Soc. (London) **A209**, 478 (1951); Freemantle, Gibson, Prowse, and Rotblat, Phys. Rev. **92**, 1268 (1953).

[3] Bockelman, Browne, Buechner, and Sperduto, Phys. Rev. **92**, 665 (1953).

[4] C. P. Browne and W. C. Cobb, Phys. Rev. **99**, 644(A) (1955).

[5] C. P. Browne, Phys. Rev. **100**, 1253(A) (1955).

[6] C. P. Browne and W. W. Buechner, Rev. Sci. Instr. (to be published).

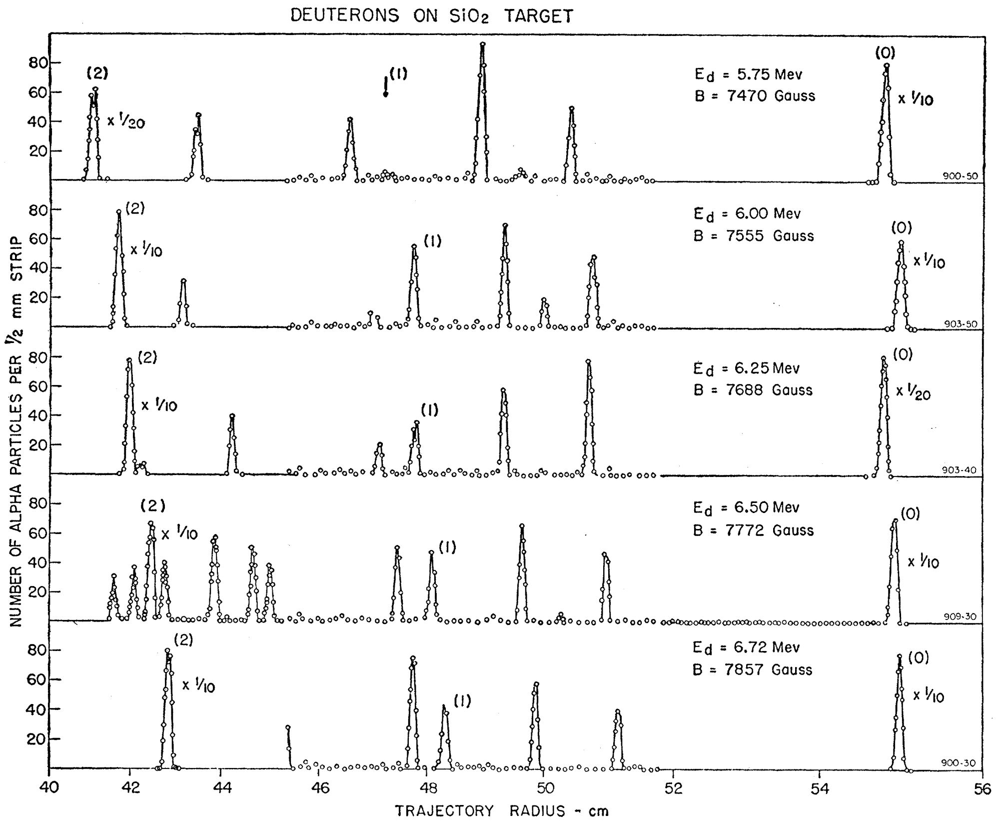

FIG. 1. Alpha-particle groups observed at 30 degrees from a SiO_2 target bombarded with deuterons. Plots are shown of exposures made at the five different energies indicated on the drawing. All groups were counted only on the exposure at 6.50 Mev. The numbered groups arise from the $O^{16}(d,\alpha)N^{14}$ reaction, leading to the ground state and first and second excited states, respectively. The other groups arise from the $Si^{28}(d,\alpha)Al^{26}$ reaction.

Identification

In order to prove that the observed alpha groups actually came from the oxygen and not some other material in the target, two procedures were used.

First, the ratio of the intensity of the unknown group to the $O^{16}(d,\alpha)N^{14}$ ground-state group was measured at 90 degrees and 7.0-Mev deuteron energy for LiOH targets and two oxidized magnesium targets made at different times. This ratio was constant within the experimental error (20%).

Second, the excitation energy of the state in N^{14} was calculated, using the measured Q value for the known ground-state group and the measured Q values for the unknown group, assuming the latter to be from the $O^{16}(d,\alpha)N^{14}$ reaction. This was done for thirty-five runs on silicon-dioxide and iron-oxide targets at energies from 5.5 to 7.5 Mev and angles from 15 to 130 degrees. Typical results are shown in Table I. The constancy of the excitation rather than its absolute value is the important thing for identification. The fact that the alphas passed through the target backing at 30 degrees accounts for the small discrepancy with the known excitation energy of 2.313 Mev.[3] The results shown in Table I give conclusive identification of the group, because an error of one mass unit in assignment of the nucleus responsible would have caused a discrepancy of 11 kev in excitation between the 5.5- and 7.5-Mev runs. Since the nearest possible contaminant mass is two mass units away, the discrepancy would be 22 kev, which is well outside the experimental error.

Figure 1 shows a typical set of plots of number of alpha particles *versus* trajectory radius for a series of energies. Most of the peaks arise from the $Si^{28}(d,\alpha)Al^{26}$ reaction, but the strongest groups are the $O^{16}(d,\alpha)N^{14}$ groups leading to the ground state and second excited state (both $T=0$). The forbidden group, marked by (1) on the plot, leading to the first excited state is clearly seen at most of the energies but obviously varies in intensity. An analysis of the silicon reaction will appear soon.[7]

TABLE I. Data for identification of the forbidden group.

Deuteron energy	Angle	Excitation in N^{14} (Mev)
5.50	30°	2.321
6.00	30°	2.322
6.25	30°	2.320
6.50	30°	2.321
6.72	30°	2.323
7.01	30°	2.320
7.50	30°	2.321
7.03	15°	2.313
7.03	30°	2.319
7.03	50°	2.322
7.03	70°	2.318
7.03	80°	2.318

[7] C. P. Browne (to be published).

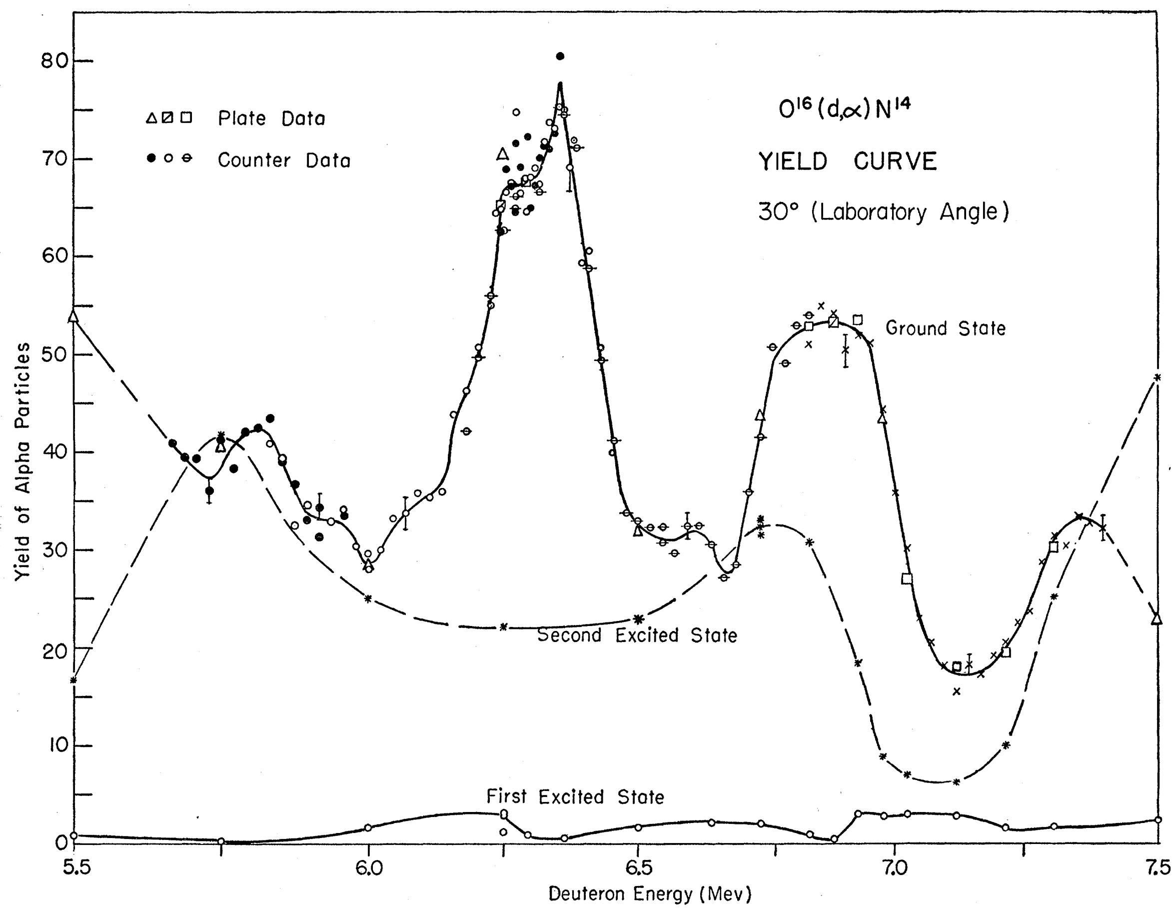

FIG. 2. Yield of alpha particles from the reaction $O^{16}(d,\alpha)N^{14}$ as a function of bombarding energy. The yields of the groups leading to the ground state and to the first and second excited states are shown. For the ground state, both a scintillation counter and nuclear-track plates were used to record the alphas, as indicated by the various symbols. The other two groups were recorded on the plates.

Yield Curves

The SiO_2 targets were used to measure the yield of the ground-state group at a laboratory angle of 30 degrees with bombarding energies ranging from 5.5 to 7.5 Mev. From 5.7 to 7.4 Mev, points were taken every 20 kev, using a scintillation counter to count the alphas. The amplified pulses were fed to two scalers with biases set to give a single channel. Pulses from any proton groups having the same momentum as the alphas were approximately twice as high and fell outside the channel. Pulses from deuterons were about the same height and were counted with the alphas. Slit-edge scattering of the incident beam gave a small deuteron background at all momenta, but this background along with background caused by gamma rays and neutrons was counted and subtracted from the total counts.

The gross structure of the yield function was measured with a series of runs using nuclear-track plates for recording. These were taken every 250 kev and at more frequent intervals over part of the range. As alpha-particle tracks could be distinguished from deuteron or neutron recoil tracks, the background was essentially zero. With the plates, it was practical to use long exposure times and obtain a sufficient number of tracks to make statistical uncertainties negligible. The plate data were used for normalization of the different counter runs, so that, in a sense, the counter data served as an interpolation between the plate data points of the yield curve. The results are shown as the curve labeled "ground state" in Fig. 2. The various symbols indicate different runs with plates and counter as noted on the figure.

Once the ground-state yield was measured, the yield of the groups leading to the first and second excited states could be plotted from the ratios of the intensities of these groups to the ground-state group. Since the three groups appeared on a single plate, the only uncertainty in the ratios, aside from statistical, is the small uncertainty ($\pm 3\%$) in the variation of solid angle of the spectrograph as a function of position on the plate. The resulting yield curves are plotted in Fig. 2.

Judging from the structure of the ground-state yield, it is felt that the second-excited-state yield would show many fluctuations if measured at smaller energy intervals. For this reason, the dashed curve drawn through the data points should be considered only a rough approximation to the true yield curve. It serves, however, to give the order of magnitude relative to the other groups. For the reason stated under "Discussion" it is thought that the forbidden-group yield probably does not fluctuate more rapidly than shown. Figure 3 shows the forbidden-group yield plotted on a larger scale to emphasize the resonance structure.

Angular Distripution

The yields of the three alpha groups were measured as a function of angle from 15 to 130 degrees at a bombarding energy of 7.03 Mev. This energy was chosen because it appears from the yield curve to give a maximum intensity for the forbidden group. Nuclear plates were used for recording, and, as in the case of the yield curve, the ground-state distribution was first plotted and then the yield of the other groups was plotted from the measured ratios of intensities. Repeat runs were made to check target stability.

The SiO_2 targets were used for all the data except the yield of the forbidden group at angles greater than 70 degrees. In this case, the iron-oxide target was used to avoid confusion with alpha groups from silicon. The results are shown in Fig. 4, where the relative differential yield in the center-of-mass system is plotted against center-of-mass angle.

Absolute Cross Section

In order to convert the measured angular distribution to cross section, the yield from the (d,α) reaction was compared with the known yield[8] of elastically scattered protons from the same target. With the target fixed, the proton yield and the alpha yield were successively measured at 131.7 degrees (lab), by using

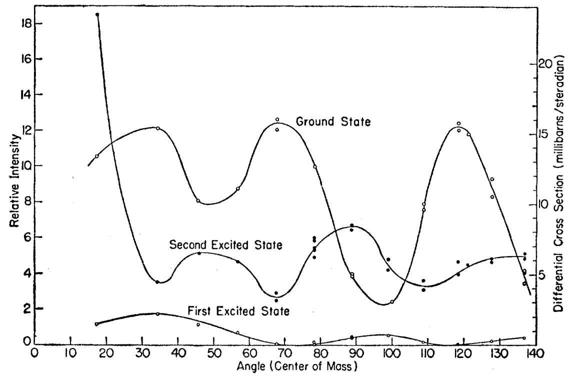

FIG. 4. Angular distribution of alpha particles from the $O^{16}(d,\alpha)N^{14}$ reaction leading to the ground state and first two excited states. The left-hand ordinate scale is in arbitrary units; the right-hand scale is absolute cross section, based on the known $O^{16}(p,p)O^{16}$ cross section.

an H_2^+ beam energy of 6.00 Mev and a deuteron energy of 7.03 Mev. An exposure was then made to check the contamination of the H_2^+ ions in the deuteron beam. Next, the yield of alphas at 30 degrees and 6.00 Mev was measured, and, finally, a second measurement of proton yield at 131.7 degrees was made.

At a laboratory angle of 30 degrees and 6.00-Mev bombarding energy, the center-of-mass cross section was found to be 14.6 millibarns per steradian, while at 131.7 degrees and 7.03-Mev bombarding energy, $\sigma_{\mathrm{c.m.}}=3.69$ millibarns per steradian. The result of the 131.7-degree measurement has been used to label the right-hand ordinate scale in Fig. 4.

Using the angular distribution curve to give a ratio between cross sections at 131.7 degrees and 30 degrees and the yield curve to give a ratio between 7.03 and 6.00 Mev at 30 degrees, a ratio of the yield at 131.7 degrees and 7.03 Mev to the yield at 30 degrees and 6.00 Mev may be obtained to compare with the ratio measured directly as stated above. The agreement is about 1%, indicating excellent over-all consistency in the data. The ratios of the (d,α) cross section to the (p,p) cross section are felt to be good to about 10%, and the latter is known to better than 2%.[8]

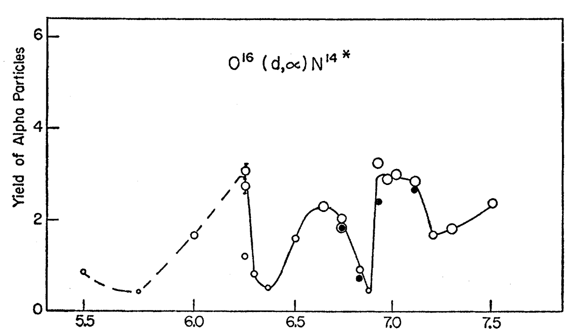

FIG. 3. Yield of alphas to the first excited state of N^{14} (forbidden group) as a function of energy. The same data shown in Fig. 2 are plotted on a larger scale to show the resonance structure.

III. DISCUSSION

From the yield curve, it is obvious that, although the $O^{16}(d,\alpha)N^{14}$ reaction can lead to the first excited state of N^{14}, the yield to this state is much less than the yield to the ground state or second excited state. The angular distribution suggests that the ratios of the total cross sections are even smaller than the ratio of the differential cross sections measured at 30 degrees. Of course, the angular distribution would be expected to change with energy, so that one gets a quantitative comparison of cross section at only one energy even from the present data.

The curves show that measurements taken at only one energy and angle give little information on the

[8] F. J. Eppling, Ph.D. thesis, University of Wisconsin (unpublished), and private communication.

validity of the selection rule. In fact, the most desirable data would be total cross sections for each group as a function of energy.

The present data, however, give a good estimate of the order of magnitude of the violation of the selection rule. Over the range of angles covered at 7.03-Mev bombarding energy, the average yield of the forbidden group is about 7% of the average yield of the ground-state group. From the yield curve, it is seen that this energy is at a maximum in the forbidden group yield and near a minimum in the ground-state yield. so that on the average the intensity of the forbidden group is only a few percent of the intensity of the allowed groups.

To attempt to explain the appearance of the forbidden group, one must consider the isotopic spin purity of the initial state, intermediate state, and final state. It has been suggested by Lane[9] that a breakdown of the selection rule might be expected in cases where the compound system was in a sufficiently highly excited state to have appreciable overlapping of states of different isotopic spin and yet existed long enough as a system to permit Coulomb forces to mix the states. The excitation energy of F^{18} ranges from 12.4 Mev to 14.2 Mev in the present experiment, which is in the region where this process might be expected. This does not, however, explain the resonance-like yield of the forbidden group as seen in Fig. 3.

It seems probable that $T=1$ levels exist in F^{18} at energies corresponding to the maxima of the forbidden group yield. Once formed, such a level would decay preferentially to the $T=1$ state of N^{14} rather than to the $T=0$ state. It is perhaps suggestive that the allowed group yields tend to be lower near the maxima of the forbidden group. Of course, one expects an abundance of $T=0$ levels in this region of the compound nucleus. The varying widths, spins, and parities of these levels will give complicated angular distributions and yield functions tending to mask the effect of the $T=1$ levels on the allowed groups.

[9] A. Lane (to be published).

It is to be noted that the angular distributions of the allowed groups are complicated, but the distribution of the forbidden group is reasonably symmetric about 90 degrees, consistent with the hypothesis of a single $T=1$ level being responsible for the appearance at this bombarding energy.

The question of the formation of the $T=1$ level in the first place is still to be explained. An estimate of the extent to which Coulomb forces may be expected to mix $T=1$ and $T=0$ states of O^{16} may be obtained from MacDonald's[10,11] calculations. Using the Fermi gas model and an estimate of 13 Mev for the spacing between the ground state and the first $T=1$ state with the same real spin and parity as the ground state, MacDonald[10] finds an isotopic spin impurity of about 2% for the ground state. Using *jj* coupling shell-model wave functions and an energy difference of 16 Mev, the impurity is given[11] as 0.67%. Similarly, the impurity for the ground state of N^{14} is calculated as 0.3%, and it is expected that the impurity of the low-lying excited states will be of nearly the same magnitude. The isotopic spin impurity of the more highly excited intermediate states in F^{18} is probably much larger.

It is seen that the expected impurity of the initial and final state is of the order of magnitude of the observed violation of the selection rule. Certainly, then, the combination of these Coulomb-force impurities with mixing in the intermediate state gives sufficient reason for the appearance of the forbidden group.

The present results, therefore, in no way contradict the hypothesis of charge independence of nuclear forces.

The author wishes to thank Miss Estelle Freedman and Miss Sylvia Darrow, who faithfully counted more than half a million alpha-particle tracks in the nuclear emulsions. Mr. David Douglass did most of the work on reducing the track-count data to the final plot for the angular distribution. The SiO_2 targets were prepared by Dr. C. K. Bockelman.

[10] W. M. MacDonald, Phys. Rev. **100**, 51 (1955).
[11] W. M. MacDonald, Phys. Rev. **101**, 271 (1956).