Isotopic-Spin Selection-Rule Violation in the $Ne^{20}(d,\alpha)F^{18}$ Reaction*

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A large isotopic-spin violation was observed in the $Ne^{20}(d,\alpha)F^{18}$ reaction. The yield to the second $T=1$ level (3.063 MeV) in F^{18} was measured and compared with the yield to an adjacent (3.133 MeV) $T=0$ level. The ratio of the yields to these two levels, averaged over angles from 50° to 140°, for an input energy of 4.00 MeV, was found to be 0.40. A value of approximately 1 was found for this ratio using the $O^{16}(He,p)F^{18}$ reaction. The isotopic-spin selection-rule breakdown is attributed to Coulomb mixing of states in the compound nucleus Na^{22} and in the residual nucleus F^{18}. Angular distributions of 11 proton groups from the $O^{16}(He^3,p)F^{18}$ reaction and of seven alpha groups from the $Ne^{20}(d,\alpha)F^{18}$ reaction are presented.

INTRODUCTION

VIOLATIONS of the isotopic-spin selection rule have been observed in (d,α) reactions[1–5] with the intensity of the forbidden group varying from 5% to 10% of the intensity of an adjacent allowed group. Violations of this order can be explained by Coulomb force mixing of $T=0$ and $T=1$ states. As has been pointed out by Hashimoto and Alford[4] however, in all of these cases the violation may be more severe than the simple forbidden-to-allowed intensity ratio indicates. In all cases the forbidden transition proceeded from a $J^\pi=0^+$ target nucleus to a $J^\pi=0^+$ ($T=1$) level in the residual nucleus. This will result in a reduction in intensity because of statistical weight factors on angular momentum and parity, assuming many levels in the pertinent region of the compound nucleus with a range of spins. Thus the isotopic-spin selection rule may be reducing the intensity of the forbidden group by only a factor of 2 or 3. A more recent study of the $B^{10}(d,\alpha)Be^8$ reaction reported a near 100% violation of the isotopic-spin selection rule.[6] The 16.623- and the 16.921-MeV levels of Be^8, one of which must be the $T=1$ level, are excited with comparable intensity.

To test the selection rule further, the $Ne^{20}(d,\alpha)F^{18}$ reaction was chosen because the second $T=1$ level should be a 2^+ level, and is low enough in excitation to be studied with an input energy of 4.00 MeV. In previous work on this reaction, the levels of interest were unresolved.[7]

The $O^{16}(He^3,p)F^{18}$ reaction was studied to provide a comparison. The region of excitation in F^{18} near 3 MeV was carefully studied for possible unreported levels, but none were found. Seventeen levels have previously been reported[8] using this reaction, and angular distributions of the first five groups were measured at input energies of 5.90 and 9.16 MeV.

EXPERIMENTAL PROCEDURE

The $O^{16}(He^3,p)F^{18}$ reaction was studied using the Notre Dame broad-range magnetic spectrograph, with the incident beam obtained from the 4.5-MeV electrostatic accelerator. This apparatus has been described elsewhere.[9] O^{16} targets were made by evaporating silicon

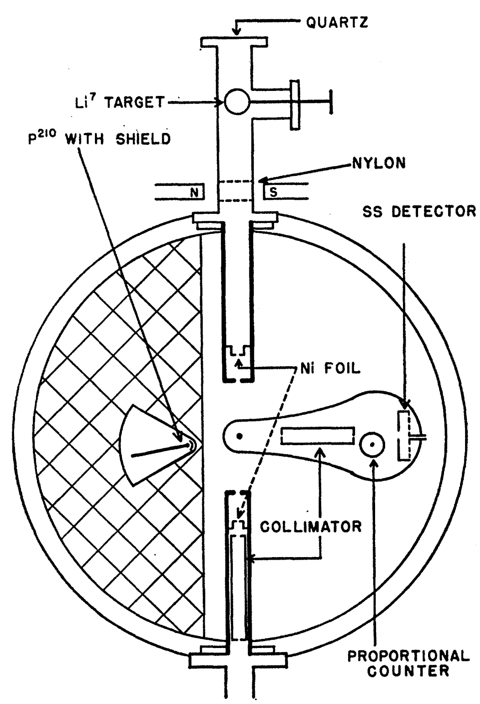

FIG. 1. Schematic top-view drawing of the gas scattering chamber.

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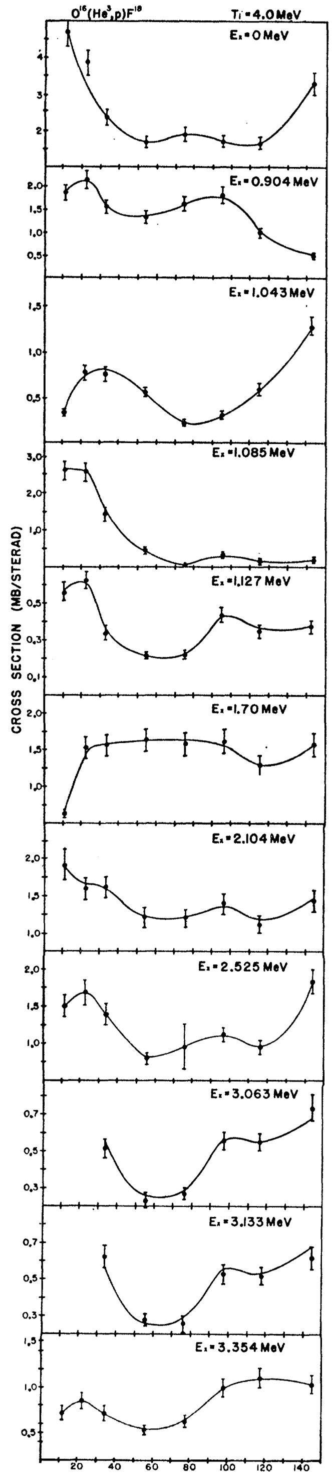

FIG. 2. Angular distributions of protons from the $O^{16}(He^3,p)F^{81}$ reaction. The data are for protons leading to the ground state and first-ten excited states of F^{18} at an input energy of 4.00 MeV.

dioxide onto thin Formvar films. The absolute differential cross section of the $O^{16}(He^3,p)F^{18}$ reaction was measured by comparing the yield with the yield to the ground state in the $O^{16}(d,p)O^{17}$ reaction.[10]

A gas chamber was constructed to study the $Ne^{20}(d,\alpha)F^{18}$ reaction. Figure 1 gives a schematic of the chamber used. Input foils were made of 4×10^{-6}-in.-thick nickel foil, affixed over a circular 7/64-in. hole. A gas pressure of 16 oz/in.^{2} (1/15 atmos) was used. 99.9% enriched Ne^{20} was used with an addition of 1% of propane. The propane was used because the target gas also served as counter gas for the proportional counter. A special effort was put into collimation in order to reduce background and energy spread. Both electric and magnetic suppression were used on the outgoing beam before it entered the integration cup. The reaction products were energy analyzed with a solid-state detector, and a proportional counter was used as a dE/dx detector. The proportional counter was made of stainless-steel tubing, $\frac{3}{8}$ in. in diameter. The inside was bored out and carefully polished to obtain a smooth surface. Glass-insulated high-voltage feedthroughs were soft-soldered into the ends, and a 0.055-in. off-axis hole drilled through the side of the cylinder. Care was taken to have the beam pass along a chord at a distance $R/2$ from the high-potential center wire, where R is the radius of the cylinder. Polished, chemically pure nickel wire, 0.0045 in. in diameter, was inserted through the high-voltage feedthroughs and soft-soldered into place. This proportional counter operated satisfactorily as a dE/dx detector with a voltage in the neighborhood of 290 V. Pulses from this detector were used to gate a 256-channel analyzer. This system had the great advantage that the reaction products did not pass through any window. Since the groups of interest are low-energy alpha particles, separated by about 60 keV, this feature is of great importance. The total resolution of the system was 50 keV. This included straggle in the input foil and target gas, resolution of the input beam, detector resolution, and electronic noise. The resolution for a Po^{210} alpha energy of 5.305 MeV (full width at half-maximum) was 20 keV.

In an attempt to measure the angular distributions of as many levels as possible, it was necessary to take both a gated and an ungated spectrum. In the ungated runs, the ground-state and several excited-state groups were separated from the background. These groups were used to normalize the gated spectrum data. In this way it was not necessary to rely on intensity measurements in the gated runs. The absolute differential cross sections were measured by comparing with the known cross section of the $He^4(d,d)He^4$ reaction at an input energy of 2.48 MeV over the angular spread from 50° to 110°.[11]

RESULTS

$O^{16}(He^3,p)F^{18}$ Reaction

Angular distributions were obtained of groups leading to the ground state and first-ten excited states of F^{18}

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using the $O^{16}(He^3,p)F^{18}$ reaction. Figure 2 gives the results of the measurements. The similarity of the angular distributions of groups leading to the 3.063- and the 3.133-MeV levels is striking, and suggests that the spin and parity of the levels may be the same. Angular distributions of the ground-state group and first-four excited-state groups for this reaction have previously been reported at input energies of 5.9 and 9.16 MeV.[8] A fit to the data was obtained by Hinds and Middleton using the double-stripping calculations of H. C. Newns. The present data indicate a trend which is consistent with the change observed in going from 9.16 to 5.9 MeV. The most significant change is a general shift away from direct interaction toward a compound nucleus type of behavior as the input energy is decreased. For this reason no attempt was made to fit the present data with a double-stripping theory. Some discrepancy exists between the present data and that of Hinds and Middleton for the second and third excited states. The present data shows the 1.085-MeV group with the $l=0$ stripping type of angular distribution and the 1.04-MeV level being only weakly excited. For this reason and because there is disagreement on the identification of the first $T=1$ level,[8,12] a careful study of this region of excitation is being carried out.

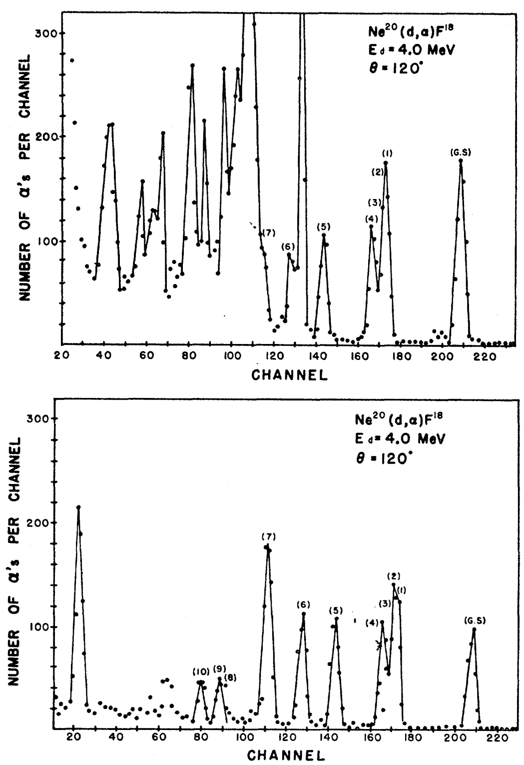

FIG. 3. Gated and ungated spectra of alpha particles at 120° and input energy of 4.00 MeV from the $Ne^{20}(d,\alpha)F^{18}$ reaction.

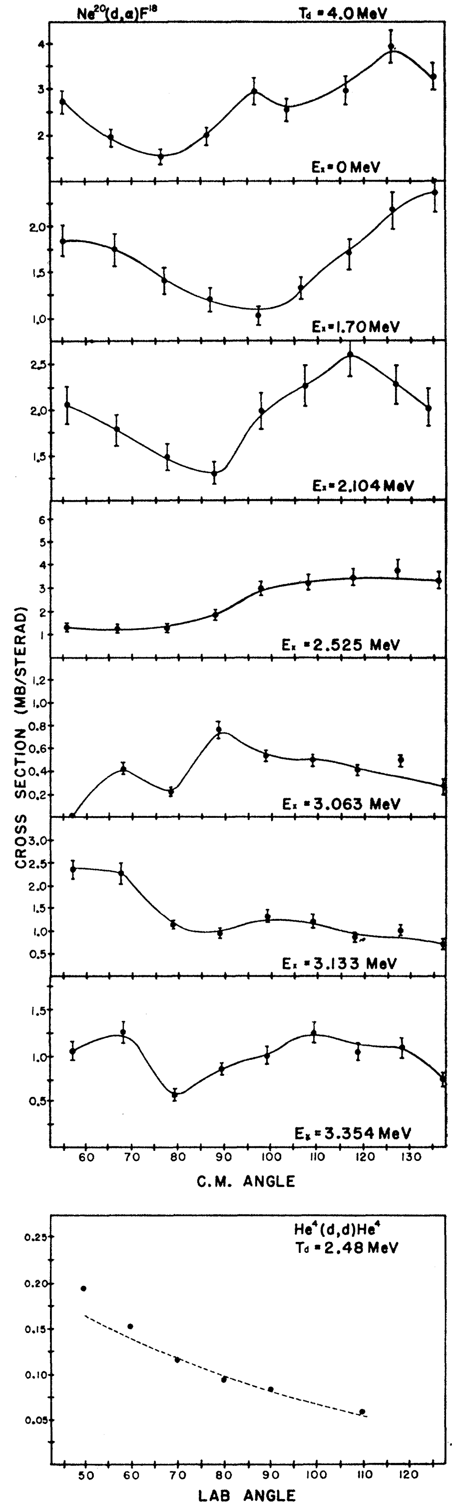

FIG. 4. Angular distributions of alpha particles from the $Ne^{20}(d,\alpha)F^{18}$ reaction. The data are for alpha particles leading to the ground state and six excited states of F^{18} at an input energy of 4.00 MeV. The last curve is the cross section for elastic deuteron scattering off He^4 for an input energy of 2.48 MeV.

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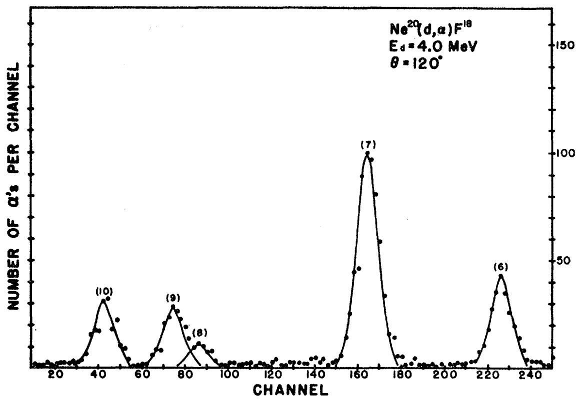

FIG. 5. Spectrum of alpha particles at 120° from the $Ne^{20}(d,\alpha)F^{18}$ reaction at an input energy of 4.00 MeV. Groups leading to the 2.104-MeV (6), 2.525-MeV (7), 3.063-MeV (8), 3.133-MeV (9), and the 3.354-MeV (10) levels in F^{18} are shown.

TABLE I. For the $O^{16}(He^3,p)F^{18}$ and $Ne^{20}(d,\alpha)F^{18}$ reactions the ratio of the differential cross sections leading to the 3.063-MeV level in F^{18} to the differential cross section leading to the 3.133-MeV level in F^{18}. The ratio is given for an input energy of 4.00 MeV and laboratory angles from 30° to 140°.

Angle (deg)	$O^{16}(He^3,p)F^{18}$ Ratio	$Ne^{20}(d,\alpha)F^{18}$ Ratio
30	0.80	
40	0.58	
50	0.86	0
60		0.23
70	1.17	0.19
80	1.55	0.81
90	1.06	0.40
100	1.03	0.41
110	1.05	0.46
120	1.06	0.49
130	1.09	0.35
140	1.22	

$Ne^{20}(d,\alpha)F^{18}$ Reaction

Angular distributions of seven groups leading to levels in F^{18} from the $Ne^{20}(d,\alpha)F^{18}$ reaction were obtained. Figure 3 gives a comparison of typical spectra with gate and without gate. The four levels near 1-MeV excitation were not completely resolved. Angular distributions of the ground-state and six excited-state groups, for an input energy of 4.00 MeV, are given in Fig. 4. It is perhaps significant to point out that the angular distributions of groups leading to the 3.063- and the 3.133-MeV levels are not at all similar for this reaction. This is in sharp contrast with the $O^{16}(He^3,p)F^{18}$ results, and is surprising if the spin and parity of the two levels are the same. However, this could be an isotopic-spin effect and does not necessarily mean that the spins are not the same. It would be of interest to measure angular distributions at more energies. The $He^4(d,d)He^4$ data used to normalize the angular distributions are shown in the lower part of Fig. 4. The dashed curve is from data by Blair *et al.*, and the points are from data taken with the present setup. A deviation occurs at forward angles, but this can be accounted for by stopping in the input foil. Since the energy of the input beam is less than 2.48 MeV when it reaches the scattering area, the angular distribution should be larger at the forward angles.

The widths of the levels in F^{18} are negligible compared to the resolution of the equipment. For this reason, all of the peaks should have essentially the same width. Figure 5 gives a plot of the type of data used to obtain the ratio of the intensity of the 3.063-MeV group to that of the 3.133-MeV group. All of the peaks in the spectrum have Gaussian distributions whose width at half-maximum is 10 channels. This gives a total resolution of 50 to 60 keV. The separation between the 3.063- and the 3.133-MeV group varies between 55 and 60 keV. Figure 6 gives plots of the two groups in question at several angles and input energies. Table I gives the ratio of the 3.063- to the 3.133-MeV group as a function of angle for an input energy of 4.00 MeV as measured for the $O^{16}(He^3,p)F^{18}$ and $Ne^{20}(d,\alpha)F^{18}$ reactions. Table II gives the same ratio for the $Ne^{20}(d,\alpha)F^{18}$ reaction at an input energy of 4.50 MeV. Table III gives the ratio for the $Ne^{20}(d,\alpha)F^{18}$ reaction at a laboratory angle of 120° for input energies from 3.50 to 4.50 MeV. The average yield (averaged over the angles shown) to the forbidden 3.063-MeV level is 40% of the average yield to the 3.133-MeV level at an input energy of 4.00 MeV, and 60% at an input energy of 4.50 MeV.

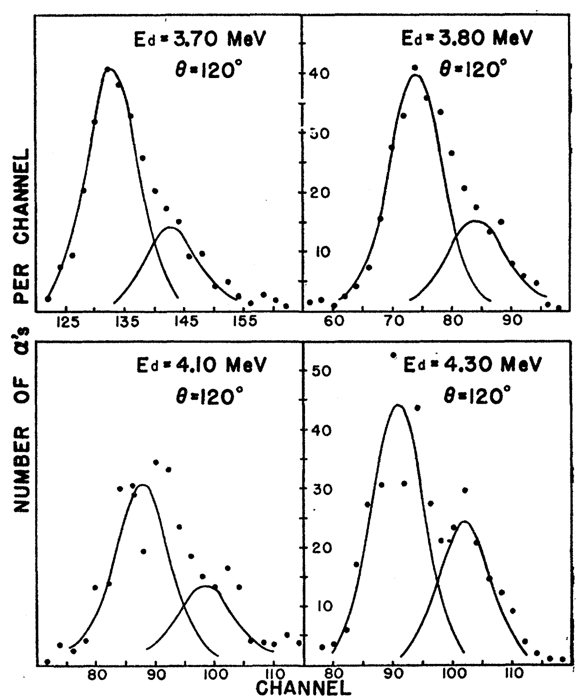

FIG. 6. Spectrum of alpha particles at 120° from the $Ne^{20}(d,\alpha)F^{18}$ reaction. Groups leading to the 3.063 and 3.133-MeV levels in F^{18} at input energies of 3.70, 3.80, 4.10, and 4.30 MeV are plotted. The solid curves are Gaussians with widths of 10 channels.

DISCUSSION

The method suggested by Wilkinson[13] was used to calculate the position of corresponding $T=1$ levels in the mass-18 triad. The ground state of O^{18} and the 1.043-MeV level of F^{18} correspond to within 19 keV (1.024 MeV calculated). Also the 1.982-MeV level of O^{18} and the 3.063-MeV level of F^{18} agree to within 57 keV (3.006 MeV calculated). The discrepancy between the 1.982-MeV level of O^{18} and the 3.133-MeV level of F^{18} is 111 keV. This strongly suggests that the 3.063-MeV level of F^{18} is the second $T=1$ level corresponding to the first excited state of O^{18}. Studies of the $C^{14}(\alpha,\gamma)O^{18}$ reaction[14] have established the 1.982-MeV level of O^{18} as having spin and parity of 2^+. The (p,γ)-coincidence experiments of Kuehner, Almqvist, and Bromley[12] while unable to resolve the 3.063- and the 3.133-MeV groups, set limits on the possible spins of the two levels as $J<3$ and $J>0$ and possibly $J>1$. Since their estimates apply to both levels, an assignment of 2^+ for both levels is not at all inconsistent with their data.

A comparison of the angular distributions of the groups leading to the 3.063- and the 3.133-MeV levels of the $O^{16}(He^3,p)F^{18}$ reaction indicates the same J for both and hence makes the assignment of $J^\pi=2^+$ to both levels very plausible. The average value of the yield to the 3.063-MeV level divided by the yield to the 3.133-MeV level is very close to 1 for the $O^{16}(He^3,p)F^{18}$ reaction, and both exhibit the same angular distribution. In the $Ne^{20}(d,\alpha)F^{18}$ reaction the ratio of the yields to the same two levels at 4.00 MeV and also the yield at input energies from 3.50 to 4.50 MeV at an angle of 120°, all indicate that the 3.063-MeV group is suppressed by 50 to 60%. If the spin and parity of the two levels are the same then one might expect, since the two levels are so closely spaced, that this ratio in the absence of isotopic spin would be close to 1 for both reactions. This indicates an isotopic-spin selection-rule violation of approximately 40%.

TABLE II. For the $Ne^{20}(d,\alpha)F^{18}$ reaction the ratio of the differential cross section of alpha particles going to the 3.063-MeV level in F^{18} to the differential cross section of alpha particles going to the 3.133-MeV level in F^{18}. The ratio is given for an input energy of 4.50 MeV and laboratory angles from 50° to 120°.

Angle (deg)	$Ne^{20}(d,\alpha)F^{18}$ Ratio
50	0.26
60	0.31
70	0.48
80	0.65
90	0.71
110	0.94
120	0.88

TABLE III. For the $Ne^{20}(d,\alpha)F^{18}$ reaction ratio of the differential cross section of alpha particles going to the 3.063-MeV level in F^{18} to the differential cross section of alpha particles going to the 3.133-MeV level in F^{18}. The ratio is given for input energies from 3.50 to 4.50 MeV and laboratory angle of 120°.

Ti (MeV)	$Ne^{20}(d,\alpha)F^{18}$ Ratio
3.50	0.19
3.60	0.24
3.70	0.35
3.75	0.25
3.80	0.38
3.90	0.23
4.00	0.49
4.10	0.43
4.20	0.25
4.25	0.42
4.30	0.55
4.50	0.87

Explanation of the Selection-Rule Violation in the $Ne^{20}(d,\alpha)F^{18}$ Reaction

In attempting to explain the 40% selection-rule violation that has been observed, one must look at three different possible sources of isotopic-spin impurity. The first place where isotopic-spin mixing may occur is in the ground state of the target nucleus Ne^{20}. The ground state of Ne^{20} is a $J^\pi=0^+$, $T=0$ state. In order to get a good estimate of isotopic-spin impurity in the ground state, a knowledge of the spin, parity, and isotopic spin of the excited states is needed. Calculations of the mass-20 triad predict that the first $T=1$ level in Ne^{20} should be at 10.20 MeV. A look at the decay scheme of Ne^{20} supports this result.[15] The means of decay of Ne^{20} from the level at 6.745 MeV to and including the 9.11-MeV level is by alpha emission. The next 11 levels, from the 9.34- to the 12.51-MeV level, decay by gamma emission. Thus, these 11 levels probably correspond to the first 11 levels in F^{20}, from the ground state to the 2.966-MeV level, and have $T=1$. Some of these levels of F^{20} have tentative assignments of $J^\pi=0^+$. So the energy separation over which the Coulomb force must mix states of $T=0$ and $T=1$, is at least 9.34 MeV or more. The statistical model estimates of isotopic-spin impurity in the ground state of Ne^{20}, using an energy separation of 10.1 MeV give 3.9%.[16] Calculations using jj-coupling shell-model wave functions[17] give results which are a factor of 2 or 3 smaller, if an account is taken of the fact that the two calculations employed different energy separations. Hence the amount of impurity in the initial state seems to be about an order of magnitude too small to explain the present data.

The next possibility for mixing to occur is in the compound nucleus Na^{22}. The region of excitation in the compound nucleus is about 10 MeV. This region of

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[16] W. M. MacDonald, Phys. Rev. **100**, 51 (1955).

[17] W. M. MacDonald, Phys. Rev. **101**, 271 (1956).

excitation in Na^{22} has not been extensively studied, and it is difficult to make estimates of expected isotopic-spin mixing. Also it is important to remember that time can play an important part in mixing states in the compound nucleus. Even for cases where the levels with the same spin and parity but different isotopic spin are very close, if the compound nucleus lives for only a short time, not much mixing of states can occur. The first $T=1$ state in Na^{22} was observed with the $Mg^{24}(d,\alpha)Na^{22}$ reaction to be at 0.661 MeV.[18] Hence the possibility of mixing in the compound nucleus does exist.

In discussing the possibility of violation in the final state, much depends on the spin and parity of the 3.133-MeV level. If $J^\pi \neq 2^+$, then one must look for other levels with $J^\pi = 2^+$ and $T=0$. Both the 2.525- and the 2.104-MeV levels are reported as possibly 2^+, $T=0$ states. Using an energy separation of 0.50 MeV one gets estimates of isotopic-spin impurity of approximately 20%. Using this as an estimate of the amount of mixing in the final nucleus for the case $J^\pi \neq 2^+$ for the 3.133-MeV state, and assuming that the effects of isotopic-spin impurity in the three regions simply add, one would attribute approximately 18% impurity to the compound nucleus at 4.00-MeV input energy. This amount is needed to explain the 40% violation observed at 4.0 MeV, assuming a 2% impurity in the ground state of Ne^{20}. Since the isotopic-spin impurity in the final states is not expected to depend strongly on the input energy, about 40% isotopic-spin impurity must be attributed to the compound nucleus at 4.50-MeV input energy in order to explain the 60% violation observed at that energy. The variation of violation as a function of input energy from 3.50 to 4.50 MeV also tends to indicate that a large part of the violation is due to the mixing of states in the compound nucleus.

It has already been argued from the similarity of angular distributions of groups leading to the 3.063 and the 3.133-MeV levels that probably $J^\pi = 2^+$ for both levels. If this is the case, considering only the effect of the small energy separation, one might expect a complete breakdown of the selection rule. However, the requirement that two levels have the same J^π and a small energy separation must be considered a necessary but not sufficient condition for mixing to occur. Given these conditions, it is still possible that the two levels arise from quite different configurations and the amount of mixing is much smaller.[17] However, even in such a case, the levels are close enough that an appreciable amount of mixing could still occur. One might be inclined to attribute all of the selection-rule violation to mixing in the final state, but the rather large dependence of the violation on input energy tends to make this assignment unlikely.

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SUMMARY

An isotopic-spin selection-rule violation of the order of 50% has been established for the second $T=1$ level in the $Ne^{20}(d,\alpha)F^{18}$ reaction. The angular distributions of protons leading to the 3.063- and 3.133-MeV levels of F^{18} from the $O^{16}(He^3,p)F^{18}$ reaction strongly suggest that both levels have $J^\pi = 2^+$. This could lead to a large breakdown of the isotopic-spin selection rule due to mixing of states in the final nucleus. However, if the spins of the 3.063- and the 3.133-MeV levels are not the same, there are other levels with tentative assignments of the proper spin and parity which are close enough in energy to account for the observed violation.

The dependence of the amount of violation on input energy indicates that at least part of the violation is due to mixing of different isotopic spin states in the compound nucleus.

It is not possible to make a definite assignment of the mixing to either the compound nucleus or the final state. However, a comparison of the present data with previous experiments would tend to indicate that an appreciable amount of mixing occurs both in the compound nucleus Na^{22} and in the final state F^{18}.

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