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Two-nucleon transfer to T-mixed states in ^{16}O

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In a comparison of the reactions ^{14}N(t,p) to the g.s. quadruplet of ^{16}N and ^{14}N$(^3$He$,p)$ to the dominantly $T = 1$ analogs in ^{16}O, only the 2^- levels have the expected cross-section ratio: $\sigma(^3\mathrm{He},p)/\sigma(t,p) = 0.5$. The cross sections for 0^- and 3^- levels of ^{16}O are reduced by a further factor of 2. Direct-reaction calculations are unable to reproduce the results.

[NUCLEAR REACTIONS ^{14}N(t,p), ^{14}N$(^3$He$,p)$, $E=15.0$ MeV; measured $\sigma(E_p,\theta)$. T mixing effect on reaction mechanism.]

We report here on a comparison of the reactions ^{14}N$(t,p)^{16}$N to the low-lying quadruplet[1] in ^{16}N and ^{14}N$(^3$He$,p)^{16}$O to the (dominantly) $T=1$ analogs[1] in ^{16}O near 13-MeV excitation (see Fig. 1). The bombarding energy for both experiments was 15 MeV, and the target in both cases was ^{14}N gas contained in a gas cell. Protons were momentum analyzed in a multiangle spectrograph and detected in nuclear emulsions. Absolute cross sections were computed from gas cell pressure and measured charge integration and are believed accurate to 10%. Relative cross sections between the two experiments should be even more accurate.

If the states of ^{16}O were pure $T=1$ and if the reaction were direct two-nucleon transfer, then we would expect[2]

$$\sigma(^3\mathrm{He},p)=\tfrac{1}{2}\sigma(t,p)$$

for each pair of levels in ^{16}O and ^{16}N. (This simple relationship ignores kinematic effects but the outgoing momenta in this case are virtually identical.) However, the states of ^{16}O are known[3,4] to have admixtures of $T=0$. Even though these admixtures are small ($\leq 20\%$) we might expect their presence to cause deviations from the above rule. Similar effects have been observed recently[4] in a comparison of ^{17}O(d,t) and ^{17}O$(d,^3$He$)$ leading to the same final states as discussed herein.

Spectra for the two reactions are displayed in Fig. 2. It is already apparent from this figure that the simple relationship between cross sections does not hold. The 12.97-MeV 2^- state in ^{16}O is about one-half as strong as the 2^- g.s. in ^{16}N, as expected, but all the other $T=1$ levels in ^{16}O are weaker than they should be. The 1^- $T=1$ level of ^{16}O is not resolvable from nearby $T=0$ levels (see Fig. 1), but if it had one-half the strength of the 1^- state in ^{16}N, it would be apparent in the spectrum. The 0^- and 3^- states, which are resolvable from other levels, are much weaker than the parent states in ^{16}N.

This reduction in $(^3$He$,p)$ strength is even more readily observed from the angular distributions, which are displayed in Fig. 3. The data points here are for the reaction ^{14}N$(^3$He$,p)^{16}$O and the lines are smooth curves drawn through the data points for the reaction ^{14}N$(t,p)^{16}$N. The (t,p) curves have been multiplied by the factors indicated.

Thus, it is seen that the 2^- ratio is about right: $\sigma(^3\mathrm{He},p)/\sigma(t,p)=0.47$, compared to the expected value of 0.50. But the 0^- and 3^- levels of ^{16}O are only about one-fourth as strong as the corresponding ^{16}N states. Even for the 2^- state, the agreement begins to break down for angles greater than

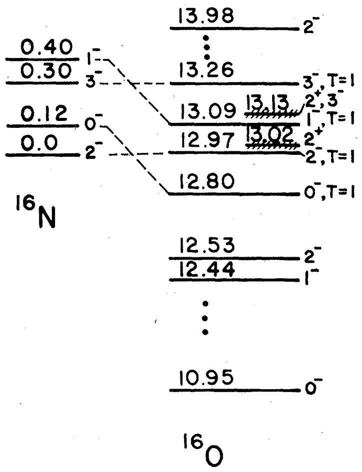

FIG. 1. Energy levels of ^{16}N (left) and ^{16}O (right) from Ref. 1. Dominantly $T=1$ levels of ^{16}O are connected to their parents in ^{16}N by dashed lines.

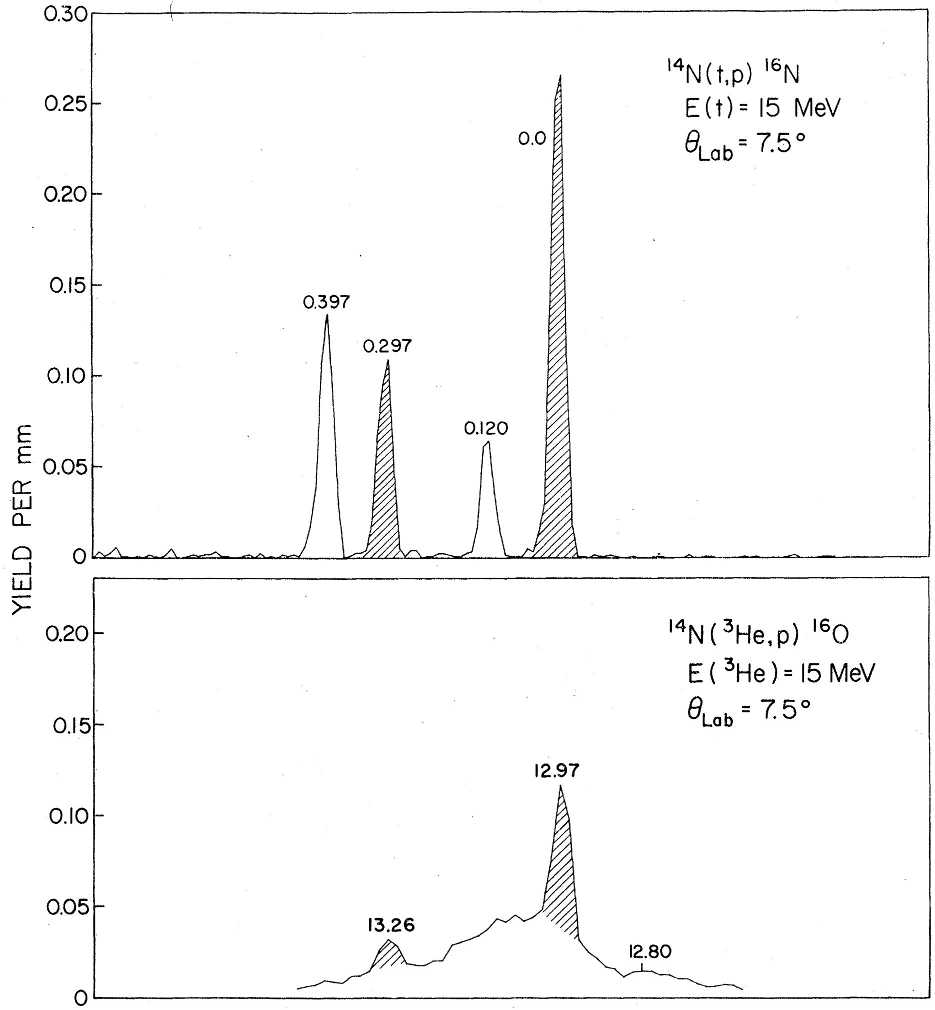

FIG. 2. Spectra of the reactions ^{14}N(t,p)^{16}N (top) and ^{14}N(^{3}He,p)^{16}O (bottom) leading to the g.s. quadruplet in ^{16}N and the region around 13-MeV excitation in ^{16}O. Bombarding energy is 15.0 MeV and laboratory angle is 7.5° in both cases. The 2^- and 3^- levels in ^{16}N and their analogs in ^{16}O are shown hatched.

about 60°.

At first sight, the observed deviations might be attributed to isospin mixing. However, this can not be so in the usual context of direct two-nucleon transfer theory, as outlined below. If a state of ^{16}O is a linear combination of two pure isospin states — one with $T=1$ and the other with $T=0$, i.e., $\Psi(^{16}\text{O}) = \alpha|T=1\rangle + \beta|T=0\rangle$, then in the usual treatment of (^{3}He,p) reactions, the $S+T=1$ selection rule (brought about by the internal structure of ^{3}He) causes the cross sections for $T=1$ ($S=0$) and $T=0$ ($S=1$) transfer to be incoherent.[2] Spin-orbit potentials for ^{3}He and p can cause some coherence, but this effect is calculated to be very small. Thus,

$$\sigma(^3\text{He},p) = \alpha^2\sigma_{T=1} + \beta^2\sigma_{T=0},$$

where $\sigma_{T=1} = \frac{1}{2}\sigma(t,p)$. Then, even if $\sigma_{T=0}=0$, $\sigma(^3\text{He},p) = \frac{1}{2}\alpha^2\sigma(t,p)$, and for all four states the isospin mixing is reasonably small[3,4] — $\alpha^2 > 0.8$. So 20% T mixing can cause at most a 20% reduction in (^{3}He,p) cross section. The effect is even less because the nearby $T=0$ states (Fig. 1) that presumably mix with the $T=1$ levels are observed,[5,6] and predicted, to have sizable cross sections — though not as large as for the $T=1$ states.

The reduction is not due to Coulomb effects in the distorting potentials. The Coulomb potential in the entrance channel ^{14}N + ^{3}He is somewhat different from that in the ^{14}N + t entrance channel, and likewise for ^{16}O + p and ^{16}N + p. But the effect of these differences is calculated to be small. We display in Fig. 4 the distorted-wave Born-approximation (DWBA) predictions (using the code DWUCK[7]

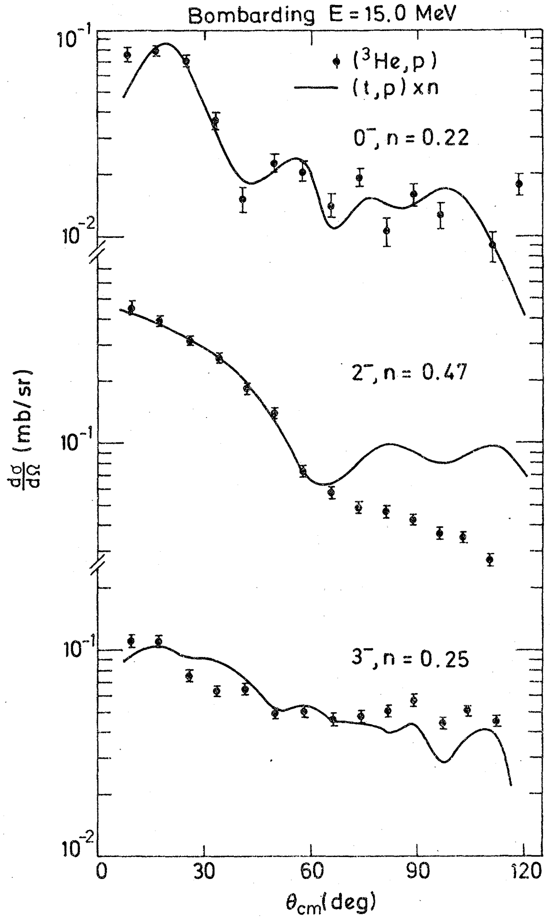

FIG. 3. Angular distributions for $^{14}N(^3He,p)$ to the dominantly $T=1$, 0^-, 2^-, and 3^- levels of ^{16}O (points) and for $^{14}N(t,p)$ to the parent states in ^{16}N (curves). The ^{16}N data have been multiplied by the factors shown.

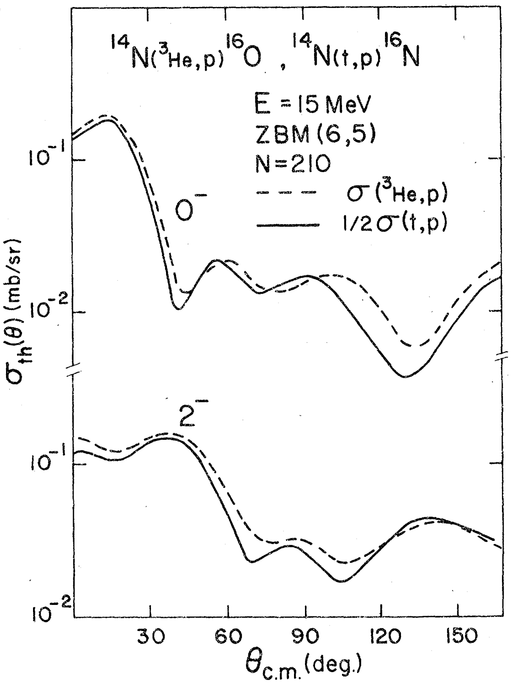

FIG. 4. Distorted-wave calculations for $^{14}N(t,p)$ (solid) and $^{14}N(^3He,p)$ (dashed) reactions leading to 2^- and 3^- $T=1$ levels. Optical-model parameters were taken from Ref. 8, and transfer amplitudes from the wave functions of Ref. 10.

and standard optical-model parameters[8]) for the 2^- and 0^- levels in both reactions. The differences are very small and in the wrong direction and not significantly greater for the 0^- levels than for the 2^- levels. Since the 2^- states have about the right ratio and the 0^- states do not, this cannot be the explanation.

For these calculations, we took two-nucleon transfer amplitudes[9] from the work of Zuker, Buck, and McGrory.[10] The transferred nucleons were each bound by one-half the $2n$ (or np) separation energy. Dividing the binding energy up differently between the two transferred nucleons might be appealing, since one goes into the $1p$ shell and one into the sd shell. And, indeed, changing the binding energies does cause changes in the absolute cross sections, but if the change is made consistently for (t,p) and $(^3He,p)$, the calculated $\sigma(^3He,p)/\sigma(t,p)$ ratio is little affected.

We are thus forced to seek the explanation elsewhere, viz. in the reaction mechanism. The mechanism might be suspect, since the cross sections are rather small — those for the 0^- and 3^- states in ^{16}O are less than about 100 μb/sr at all angles and that for the 2^- is smaller than 100 μb/sr at angles beyond about 50°. These are to be compared with typical (t,p) and $(^3He,p)$ cross sections in this mass region[11-14] of 1–20 mb/sr. Indeed, at larger angles where the 2^- cross section is small, it becomes increasingly weaker than expected. At 90°, the reduction factor for it is about the same as for the other two states.

Further evidence for a complicated reaction mechanism comes from inspection of the angular-distribution shapes. The 2^- and 3^-, since they are reasonably pure $(1p_{1/2})^{-1}(1d_{5/2})$ states,[10] should both be populated with $L=3$ only, even though the macroscopic selection rules allow also $L=1$ for the 2^- state. And yet the shapes for the 2^- and 3^- states are very different. It has been reported[8] that an admixture of $L=1$ and 3 can account for the shape of the 2^- angular distribution in $^{14}N(t,p)$ at a somewhat lower bombarding energy, but mixing $L=1$ and 3 does not produce the difference in shapes for (t,p) and $(^3He,p)$ that is observed.

The difference in shapes is more easily seen if we plot the $\sigma(2^-)/\sigma(3^-)$ ratio as a function of angle,

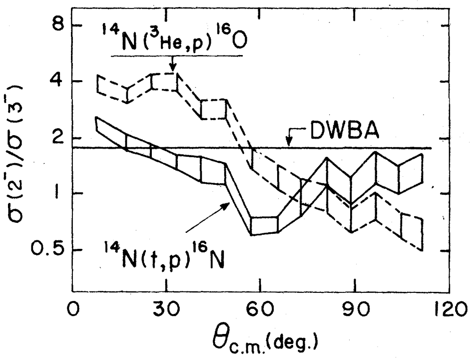

FIG. 5. Observed cross-section ratios, $\sigma(2^-)/\sigma(3^-)$, plotted vs angle, for ^{14}N(t,p) (solid) and ^{14}N(^{3}He,p) (dashed). The DWBA ratio is shown as a horizontal line.

as is done in Fig. 5. Not only is the ratio not constant with angle, but the angular dependence of the ratio is quite different in ^{16}O and ^{16}N. The deviations are well outside the error bars, which represent the sum of the percentage errors for each cross section separately. The angle-averaged $2^-/3^-$ ratio for ^{16}N is very close to the value of 1.73 predicted by DWBA using microscopic wave functions of Zuker, Buck, and McGrory,[10] whereas in ^{16}O the ratio is about twice what is predicted. This is further independent evidence that the 3^- is too weak in ^{16}O rather than too strong in ^{16}N.

It must be that an appreciable compound, or intermediate, process is present in the reaction mechanism. Evidence for such a mechanism has been pointed out previously[15] for the ground-state transition in ^{14}N(^{3}He,p)^{16}O, which is also weak. That work suggested that the nondirect and direct processes were interfering. Such appears to be also the case here. If the amplitudes add coherently, the nondirect contribution need not be large in order to cause a factor-of-2 reduction in cross section. Also, compound processes to a T-mixed state in ^{14}N(^{3}He,p)^{16}O can contribute coherently to the $T=0$ and 1 parts while still conserving isospin in each step of the reaction, since a $T=\frac{1}{2}$ level in ^{17}F can decay by proton emission to either a $T=0$ or $T=1$ final state.

If it is only the $T=0$ and $T=1$ compound nuclear components that interfere, then the observed reduction in cross section for the 3^- and 0^- levels can arise from such interference only if the angle-integrated compound cross section dominates the measured angle-integrated cross section. If the compound and direct amplitudes also interfere, then the compound contribution need not be so large. There is independent evidence[5] from a study of the reaction ^{14}N(^{3}He,p)^{16}O to the low-lying $T=0$ levels that an angle integrated (0–90°) compound cross section as large as $\sigma_{\mathrm{CN}}/2J_f+1=40\ \mu$b could be present. This is almost as large as the measured cross section for the 3^- state, but less than one-third of the measured cross section for the 0^- level. The fact that the 0^- state of ^{16}O has an angular distribution that looks very much like a direct transfer one (forward angle to 90° ratio is almost 10) and like that measured in (t,p) is further evidence that the direct and nondirect processes are coherent. If they were incoherent, we would expect the cross-section reduction to be larger at larger angles.

Of course, if the ^{16}O levels were pure $T=1$, and the two reaction mechanisms were incoherent, the cross sections would still be in the ratio 1:2 if each of the reactions themselves is isospin conserving. But it is not clear if the effects of coherence that are observed can be sufficiently accounted for solely by interference between compound processes to the $T=0$ and $T=1$ components of the ^{16}O final states. That remains for detailed calculations that treat isospin correctly throughout the reaction, step by step. To our knowledge, such calculations have not yet been done.

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