Violation of Isospin Conservation in Two-Nucleon Pickup Reactions*

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(Received 5 April 1973)

The analog $(p,{}^3\mathrm{He})$ and (p,t) reactions on $^{16}\mathrm{O}$ have been compared at 27.0 MeV incident proton energy. In contrast to previous results at higher energies (≥ 43.7 MeV), the intensity ratio predicted by isospin conservation was satisfied only at small angles.

The analog $(p,{}^3\mathrm{He})$ and (p,t) reactions on $^{16}\mathrm{O}$ have been the classic example of isospin conservation in transfer reactions since they were first compared in 1964 by Cerny and Pehl[1] and found to have similar angular distributions and the expected relative intensity. Subsequently, the many similar tests[2-4] for other targets at comparable proton energies (40–55 MeV) have shown no significant deviations from isospin conservation. Since such comparisons are often viewed[2,5] as testing the details of reaction models rather than overall isospin conservation, the simple derivation of the intensity prediction is given here. In *any* isospin-conserving theory, the transition operator will have matrix elements (squared) in the ratio

$$\frac{|T_{p,{}^3\mathrm{He}}|^2}{|T_{p,t}|^2}=\frac{\langle T_fT_{fz}T_{^3\mathrm{He}}T_{^3\mathrm{He}z}|T_i+\frac{1}{2},T_{iz}+T_{pz}\rangle^2}{\langle T_fT_{fz}T_tT_{tz}|T_i+\frac{1}{2},T_{iz}+T_{pz}\rangle^2}=\tfrac{1}{2}(2T_i+1)$$

for analog $(p,{}^3\mathrm{He})$ and (p,t) reactions on the same target [of isospin $T_i=(N-Z)/2$], provided the analog residual nuclei have isospin $T_f=T_i+1$. [The restriction $T_f=T_i+1$ ensures that only the value of total isospin $T_i+\frac{1}{2}$ is common to initial and final states, which generally are superpositions of isospins $T_i\pm\frac{1}{2}$ and $T_f\pm\frac{1}{2}$, respectively. Accordingly, with the assumption of isospin conservation, the final-state amplitudes (Clebsch-Gordan coefficients) for this isospin determine the relative strength, giving the ratio indicated when explicitly evaluated.] Each differential cross section further involves an available phase-space factor proportional to the final momentum, so that differential cross sections are predicted to have the ratio

$$\left.\frac{(p,{}^3\mathrm{He})}{(p,t)}\right|_{T_f=T_i+1}=\frac{k_{^3\mathrm{He}}}{k_t}\frac{|T_{p,{}^3\mathrm{He}}|^2}{|T_{p,t}|^2}=\frac{k_{^3\mathrm{He}}}{k_t}\frac{2T_i+1}{2}. \quad (1)$$

Since this relation arises so generally from overall isospin conservation, as just shown, without further perturbation-theory or microscopic-reaction assumptions, its experimental confirmation cannot establish the validity of more detailed assumptions. It is only when the assumption of overall isospin conservation is *not* sufficient (because of important Coulomb effects, for example), that ratio measurements for analog processes can begin to test such details. In standard distorted-wave calculations for higher energies it was found[3,4] that known isospin-nonconserving Coulomb (and Q-value) effects did not cause important modifications of the simple isospin prediction at those energies. In the present investigation, however, the simple prediction, Eq. (1) above, is in fact violated, and in a way not immediately reproduced by Coulomb effects in standard distorted-wave calculations.

The reactions $^{16}\mathrm{O}(p,{}^3\mathrm{He})^{14}\mathrm{N}^*(2.31\ \mathrm{MeV},\ T=1)$ and $^{16}\mathrm{O}(p,t)^{14}\mathrm{O}(0.00\ \mathrm{MeV},\ T=1)$ were observed at 27.0 MeV, a much lower energy than before.[2,4,5] Particle identification was optimized for the rather low-rate $A=3$ products by using the $A=3$ range-table-lookup method of Hird and Ollerhead,[6] with 51- and 152-μm Si surface-barrier detectors in a standard telescope arrangement. A third (veto) detector rejected long-range events. A 6100-μm Si(Li) monitor detector fixed at 90° was used to observe protons elastically scattered from $^{16}\mathrm{O}$ in the 0.48 mg/cm^2 $C_{10}H_8O_4$ (Mylar) target, and thereby correct for target deterioration. This was necessary for accurate angular distribution measurements (Fig. 1, upper part), but not for the ratio measurements (Fig. 1, lower part), since the $^3\mathrm{He}$ and t were observed simultaneously. The low particle energies, small cross sections, and an intense α-particle background frustrated attempts to measure beyond 40°.

For the present experiment, the ratio prediction becomes

$$(p,{}^3\mathrm{He})/(p,t)=\tfrac{1}{2}k_{^3\mathrm{He}}/k_t=0.63.$$

As seen in Fig. 1, this prediction is remarkably well satisfied at the most forward angles (7.5° to

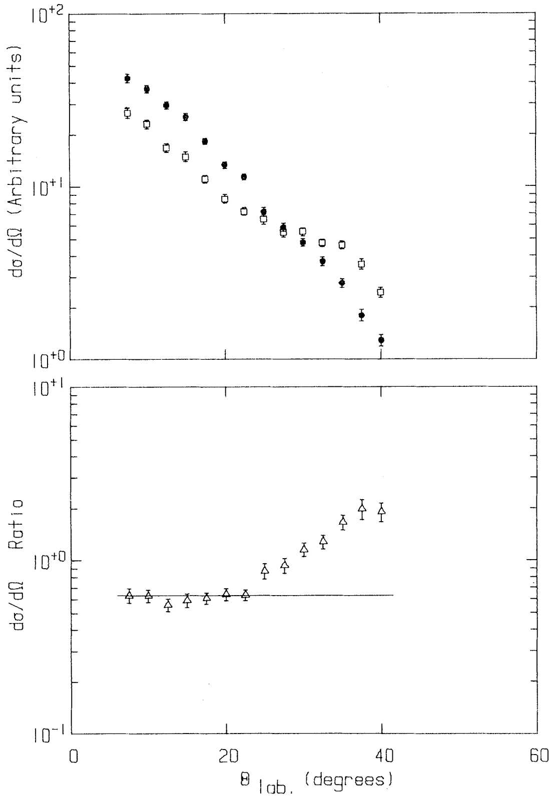

FIG. 1. Differential cross sections for the analog $(p, {}^3\mathrm{He})$ and (p,t) reactions on ^{16}O at 27.0 MeV, and their ratio. Upper part: open squares, $^{16}\mathrm{O}(p, {}^3\mathrm{He})$-$^{14}\mathrm{N}^*$(2.3 MeV, $T=1$); closed circles, $^{16}\mathrm{O}(p,t)^{14}\mathrm{O}$(0.0 MeV, $T=1$); 27.0-MeV protons. Lower part: open triangles, observed $(p, {}^3\mathrm{He})/(p,t)$ ratio. The horizontal line indicates the ratio predicted by isospin conservation, $(p, {}^3\mathrm{He})/(p,t) = (k_{^3\mathrm{He}}/k_t)\frac{1}{2}(2T_i+1) = 0.63$.

22.5°), but is then increasingly violated (by up to 300%) at larger angles, where the experimental ratio rises abruptly. This is the first significant violation of the simple isospin intensity rule for isospin-raising two-nucleon pickup reactions. Until now, the success of the isospin intensity rule for such $(p, {}^3\mathrm{He})$ and (p,t) reactions has stood in sharp contrast to the systematic violation of the similar rules for one-nucleon transfer reactions. For isospin-raising $(d, {}^3\mathrm{He})$ and (d,t) reactions or $(\alpha, {}^3\mathrm{He})$ and (α, t) reactions, isospin conservation predicts differential cross sections in the ratio

$$\left.\frac{(d, {}^3\mathrm{He})}{(d,t)}\right|_{T_f=T_i+\frac{1}{2}} = \left.\frac{(\alpha, {}^3\mathrm{He})}{(\alpha,t)}\right|_{T_f=T_i+\frac{1}{2}} = \frac{k_{^3\mathrm{He}}}{k_t}(2T_i+1).$$

In each case this rule is increasingly violated[7] as the charge of the target nucleus increases, even for relatively high-energy outgoing particles.

These violations generally take a particularly simple form, with similar ^{3}He and t angular distributions, which do not, however, have the predicted ratio, even at forward angles. The strong angle dependence observed in the present experiment certainly does not fit that pattern.

It is of interest to see if known isospin-nonconserving Coulomb effects (and associated Q-value effects) in available reaction models are helpful in understanding the observed violation of the isospin intensity rule. Although the distorted-wave treatment of two-nucleon transfer reactions has not had great success in the energy and mass region of this experiment, several pairs of $(p, {}^3\mathrm{He})$ and (p,t) calculations were made to assess the importance of Coulomb effects as treated in this widely used model. Rather standard local, zero-range direct two-nucleon pickup calculations using the form factor prescription of Bayman and Kallio were made.[8] As in the successful higher-energy calculations,[3] the ^{3}He and t optical-model parameters are the same except for the Coulomb potentials, which differ explicitly. In addition, Coulomb effects (and, conceivably, other small charge-dependent effects) are included implicitly in the differing experimental Q values and nucleon-pair separation energies appropriate to the two reactions. Optical-model parameters were taken from the previous 43.7-MeV investigation[5] of these same reactions, as well as from sets which have had some success for 19–27-MeV (p,t) investigations on heavier targets.[9,10]

The results of these calculations are not shown in detail, as they were too sensitive to parameter choices to be useful. The calculated $(p, {}^3\mathrm{He})/(p,t)$ ratios ranged from 1.0 to 3.2 at small angles, and were both larger and smaller, depending on parameters used, at larger angles. In none of these calculations was a constant $(p, {}^3\mathrm{He})/(p,t)$ ratio preserved in the forward direction, much less the ratio predicted by isospin conservation and observed experimentally. It must be concluded that at present we lack a useful way to treat Coulomb and Q-value effects at these energies. It is remarkable that the experimental results tend to preserve the simple isospin result (at small angles), in spite of all real complications in the reaction mechanism, yet simple model calculations employing only Coulomb violations of isospin conservation do not. However, this emphasizes again that the ratio prediction arises more from simple symmetry considerations than from the details of distorted-wave calculations. Perhaps the present results, showing experimentally the onset of isospin nonconservation, will be a useful guide for improving the treatment of Coulomb and Q-value effects in future reaction calculations.

*Work supported in part by the U. S. Atomic Energy Commission.

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Feasibility of α-Transfer Studies via the (α, ^{8}Be) Reaction at High Energies*

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Using a new ^{8}Be identifier of high detection efficiency, we observed the (α, ^{8}Be) reaction on targets of ^{11}B, ^{12}C, and ^{16}O at 65 MeV. Differential cross sections (~ 1–60 μb/sr) were measured from $\theta_{c.m.} = 20°-80°$. The only states strongly populated were those predicted to have large α-structure amplitudes, implying that direct processes dominate at $E_\alpha = 65$ MeV.

Although it has been apparent for some time that the (α, ^{8}Be$_{g.s.}$) reaction is potentially one of the least controversial α-pickup reactions, the original experiments by Brown *et al.*[1] employing α-α coincidence techniques showed that at 35.5–41.9 MeV bombarding energies, nondirect processes appeared predominant. We wish both to show that direct processes appear to dominate at higher bombarding energies, and to present a new technique which greatly enhances the experimental feasibility of such studies. The large α-structure amplitude of ^{8}Be should make (α, ^{8}Be$_{g.s}$) a most useful spectroscopic reaction with which to investigate theoretical α-structure amplitudes in nuclei, such as those for the p shell given by Kurath[2] and Rotter.[3]

To study the (α, ^{8}Be) reaction, one must detect the particle-unstable ^{8}Be nucleus. Usually this is done either by coincidence techniques[1] or by the detection of both breakup α particles in a single counter telescope.[4] Since the cross section is small (~ 1–60 μb/sr) at 65 MeV, we have developed a new ^{8}Be detection technique with an appreciable probability of detecting the two breakup α particles by using a position-sensitive counter telescope with an angular acceptance larger than that of the ^{8}Be breakup cone.

Our approach is illustrated in Fig. 1(a). The ^{8}Be identifier[5] employs a circular collimator, divided into two open segments by a solid post, followed by a counter telescope consisting of a ΔE detector backed by a position-sensitive E detector (PSD).[6] As will be seen, the presence of the post can be used to select ^{8}Be events.

Consider two α particles from the decay of a ^{8}Be$_{g.s.}$ passing through the divided collimator on either side of the post, as shown in Fig. 1(a). These traverse the ΔE detector and stop in the E detector. In a PSD both an energy signal (E) and a signal proportional to the distance of the detected particle from the grounded end times the energy of the particle (XE) are generated. Since the center-of-mass breakup energy of the two α particles is small (92 keV) compared to