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[8]It will be seen that this is, in fact, a "quadruple-scattering" experiment involving the sequence $(e,\gamma) \to (\gamma,n) \to (n,n_{pol}) \to (n_{pol},n_{pol})$.

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α Pickup in the $A = 90$ Region

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The (^{3}He, ^{7}Be) reaction was observed for targets of ^{92}Zr and ^{93}Nb at 41 MeV. The reaction displays features expected from the pickup of an α-like fragment. The values of the cross sections agree with a prediction based on known proton spectroscopic factors. Contrary to current shell-model predictions, the trend of (^{3}He, ^{7}Be) cross sections does not require that the α spectroscopic factors change by more than 1 order of magnitude from ^{12}C to ^{93}Nb.

Whether four-nucleon transfer reactions can be described simply as an α-transfer process is a matter of current interest. Experimentally it has been shown[1] that the (^{3}He, ^{7}Be) reaction is dominated by the transfer of a $J^\pi = 0^+$ α-like fragment. This is not surprising since L-S coupling closely describes the structure of the ^{7}Be nucleus, and most of the possible configurations of the four transferred nucleons have the same quantum numbers as an α particle. However, for four-nucleon transfer reactions involving heavier projectiles which are largely j-j coupled, such a selectivity may not occur.

We have undertaken a study of the (^{3}He, ^{7}Be) reaction in the zirconium region to see if this reaction, in spite of its small cross section, could be used to investigate α structures in nuclei with large neutron excess. The reactions ^{92}Zr(^{3}He, ^{7}Be)^{88}Sr and ^{93}Nb(^{3}He, ^{7}Be)^{89}Y were induced by a 41.3-MeV ^{3}He beam from the University of Colorado cyclotron with a typical intensity on target of 1.2 μA. The experimental apparatus has been described elsewhere.[2] The ^{7}Be energy spectra are shown in Fig. 1 and the angular distributions pertinent to the following discussion appear in Fig. 2.

The strong forward peaking of the angular distributions cannot be of a statistical nature since the energy definition is larger than the coherence width of the possible compound states. It is a definite indication of the direct character of the reaction mechanism.

From ^{12}C to ^{40}Ca, (^{3}He, ^{7}Be) ground-state cross sections decreased by a factor of about 40,[1,3] but the ^{92}Zr cross section is half as large as that of ^{40}Ca and actually more than 2 times *larger* than that of ^{58}Ni.[3,4] Therefore (^{3}He, ^{7}Be) measurements remain within the limits of experimental feasibility for nuclei far heavier than calcium.

This variation of the (^{3}He, ^{7}Be) cross section has been investigated using a fixed-range approximation[2,5] for the distorted-wave Born-approximation (DWBA) factor of the cross section.[6] On the one hand, in a reaction such as (^{3}He, ^{7}Be) where absorption plays an important role, the mere increase in radius of the target nucleus reduces the cross section sharply.[1] For example, using a 3S bound-state wave function for the

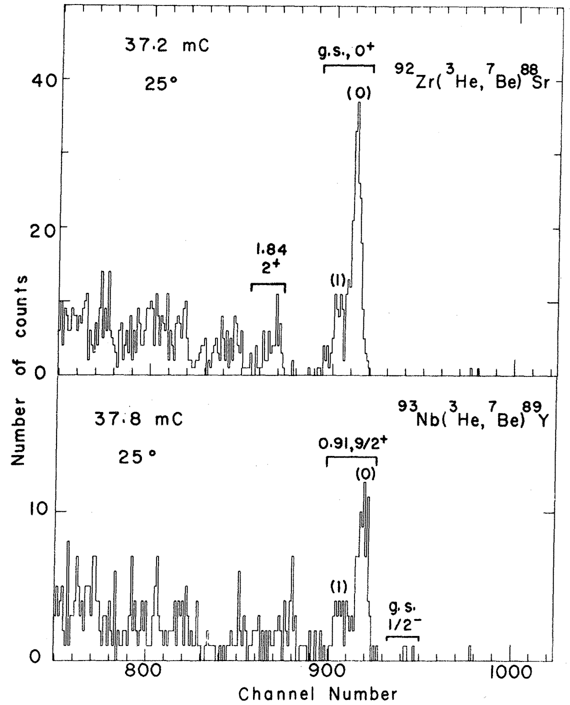

FIG. 1. Energy spectra of ^{7}Be particles from ^{92}Zr and ^{93}Nb targets under bombardment by 41.3-MeV $^{3}He^{++}$ ions. The peaks are labeled by the excitation energy of the residual nucleus. Since the ^{7}Be nucleus has two bound states (the ground state and the 0.431-MeV state), each state of the residual nucleus appears as a doublet of peaks labeled (0) and (1).

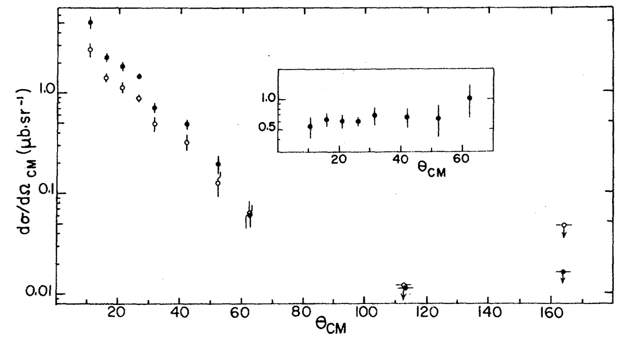

FIG. 2. Angular distributions of the cross sections of the reactions ^{92}Zr(^{3}He, ^{7}Be)^{88}Sr (filled circles) and ^{93}Nb(^{3}He, ^{7}Be)^{89}Y* (0.91 MeV, $\frac{9}{2}^+$) (open circles). The cross sections for the two bound states of ^{7}Be have been summed. The upper limits indicated at $\theta_{c.m.} = 113°$ and 164° correspond to two events, although none was actually observed. The insert gives the angular distribution of the ratio of the ^{93}Nb and ^{92}Zr cross sections. The weighted average of this ratio is 0.64.

transferred α fragment, DWBA calculations indicate a decrease of 2 orders of magnitude between ^{12}C and ^{40}Ca, and the same decrease again from ^{40}Ca to ^{92}Zr.

However, for heavier target nuclei, the availability of more energy quanta for the four transferred nucleons dampens this effect. Since the transferred fragment is in the internal quantum state of an α particle, all the energy quanta are carried by the relative motion of the fragment in the nucleus.[7] For a $0^+ \rightarrow 0^+$ transition, the transferred α particle is in a 3S state in ^{12}C, a 5S state in ^{40}Ca, and an 8S state in ^{92}Zr. All other parameters being left unchanged, the pickup from ^{92}Zr of an α fragment in 3S, 5S, and 8S bound states results in relative DWBA cross sections of 1, 5, and 40, respectively. This effect is responsible for the leveling off of the DWBA-calculated cross sections for heavier target nuclei. Since the combined effect of the increases in the radius of the nucleus and in the number of nodes of the wave function correctly predicts the magnitude of the variations of σ(^{3}He, ^{7}Be), large changes of the spectroscopic factors S_α are not indicated.[8] Unfortunately, this conclusion is only qualitative, as σ(DWBA) is extremely sensitive to the choice of the bound-state radius r_0 in the case of a wave function with many nodes (σ changes by nearly 1 order of magnitude for a 10% change of r_0 in the case of an 8S bound state).

The last factor which governs the magnitude of σ(DWBA) is the Q value of the reaction. von Oertzen[9] has recently pointed out the importance of Q-value dependence in (^{16}O, ^{12}C) reactions. We observe that σ(^{3}He, ^{7}Be) also depends on the Q value (Fig. 3), although not as severely as do heavy-ion reaction cross sections. A point of interest is that good matching (hence maximum cross section) requires a positive Q value for the (^{12}C, ^{16}O) α-pickup reaction.[9] However, a *negative* Q value is required for (^{3}He, ^{7}Be) (see Fig. 3). This results from the fact that in the second case the incoming and outgoing waves, corresponding to particles with lesser electric charges, are less distorted by the Coulomb field. As a result, the momentum-matching conditions are closer to those of the plane-wave approximation which require a smaller energy for the heavier particle. As all α-pickup reactions of interest have negative Q values, this effect represents a decisive advantage of the (^{3}He, ^{7}Be) or (d, ^{6}Li) reactions over their heavy-ion counterparts.

Since the magnitude of the DWBA term remains so uncertain, it is impossible to extract reliable values for the spectroscopic factors S_α. However, in a given region of the mass table, comparison of (^{3}He, ^{7}Be) cross sections can provide

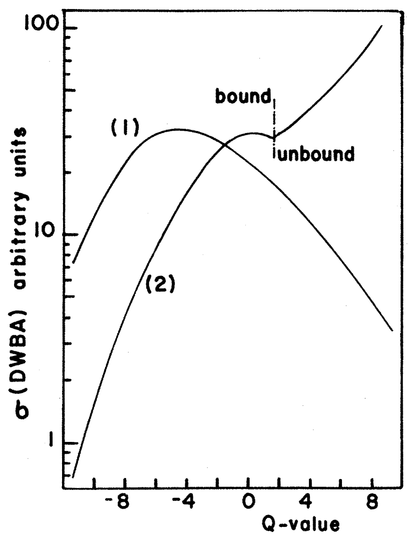

FIG. 3. Q-value dependence for $\sigma_{\rm DWBA}(^3\text{He}, {}^7\text{Be})$ calculated in the fixed-range approximation for the case of the reaction $^{92}\text{Zr}(^3\text{He}, {}^7\text{Be})^{88}\text{Sr}$ at 41.3 MeV. Curve (1) shows the effect of the change in Q value, with a fixed binding energy for the α-particle in ^{92}Zr. Curve (2) corresponds to the case where the Q value and the α binding energy are correctly correlated. For Q values larger than 1.8 MeV, the DWBA calculations predict an increase in cross section, but there the α particle is unbound. The Q values of the two transitions discussed in the text are both close to -1.3 MeV.

valuable spectroscopic information. An example is given by a previous study of α clustering in the $A=40$ nuclei.[10] Analysis of $(^3\text{He}, d)$ data[11,12] has established that the structure of the ^{93}Nb ground state and the 0.91-MeV $\frac{9}{2}^+$ state of ^{89}Y is well accounted for by a weak-coupling model. In that model, ^{93}Nb consists of a $g_{9/2}$ proton coupled to a ^{92}Zr core; and the 0.91-MeV ^{89}Y state, of a $g_{9/2}$ proton coupled to a ^{88}Sr core. As a result the two transitions, $0^+ \to 0^+$ on ^{92}Zr and $\frac{9}{2}^+ \to \frac{9}{2}^+$ on ^{93}Nb, should be essentially identical. They would both consist of the pickup of the same $J^\pi = 0^+$ four-nucleon fragment from ^{92}Zr.

The corresponding angular distributions in Fig. 2 are indeed very nearly parallel. Although the cross sections themselves decrease by almost 2 orders of magnitude between 10° and 62°, their ratio R remains constant within the experimental uncertainties (see insert of Fig. 2). The value of R is 0.64 ± 0.10, where the error includes the uncertainty in the ratio of the ^{92}Zr and ^{93}Nb target thicknesses. This departure from unity results from the fact that the addition of a $g_{9/2}$ proton to ^{92}Zr and ^{88}Sr does not account for the entire wave function of ^{93}Nb and $^{89}\text{Y}^*(\frac{9}{2}^+)$, respectively. Since the neutron number is the same in both targets, our number R is primarily a measure of the product of the proton spectroscopic factors, $S_p(^{93}\text{Nb}) \times S_p(^{89}\text{Y}^*{}_{9/2^+})$. From the $(^3\text{He}, d)$ data,[11,12] this product is $0.79 \times 0.88 = 0.69$, which is certainty compatible with $R = 0.64 \pm 0.10$.

As can be seen in Fig. 1, the $\frac{9}{2}^+ \to \frac{1}{2}^-$ ground-state transition on ^{93}Nb is strongly inhibited (it is at least 30 times smaller than that of the $\frac{9}{2}^+ \to \frac{9}{2}^+$ transition). This reduction is not due to the different L-transfers involved, according to our DWBA calculations. Therefore, this strong inhibition illustrates the spectroscopic selectivity of the $(^3\text{He}, {}^7\text{Be})$ reaction, since the $(g_{9/2}, p_{1/2})$ proton pair transferred in that transition cannot have the 1S relative motion of a proton pair in an α particle.

In conclusion, the present results indicate that the $(^3\text{He}, {}^7\text{Be})$ reaction can still be used as a spectroscopic tool for nuclei as heavy as zirconium. The quantitative agreement of the ratio between the ^{92}Zr and ^{93}Nb cross sections with known proton spectroscopic factors, and all the other qualitative indications provided by the data and discussed above, confirm that the simple picture of a direct α-transfer process describes the $(^3\text{He}, {}^7\text{Be})$ reaction.

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Deuteron Alignment in Deuteron-Proton Elastic Scattering at 3.6 GeV/c*

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We have performed a deuteron-proton double-scattering experiment with a 3.6-GeV/c deuteron beam to study the spin alignment of the elastically scattered deuterons. We observed scattered beams of polarized deuterons and have measured the spin alignment and vector polarization in the four-momentum–transfer interval of $\Delta^2 = 0.13$ to 0.54 (GeV/c)^2. Multiple-scattering model fits are presented to our alignment and polarization data as well as to existing differential-cross-section data.

An important ingredient in the Glauber model[1] for p-d and π-d forward differential cross sections above 1 GeV is the D-state deuteron form factor which fills in a dip in the cross section near $|\Delta|^2 = 0.3$ (GeV/c)^2 to give the experimentally observed shoulder in the interference region between single and double scattering. It was shown by Franco and Glauber[2] that the D-state form factor should lead to a strong dependence of the p-d differential cross section on the deuteron spin direction. Harrington[3] has pointed out that this spin dependence could also be studied in a double-scattering experiment in which a high-energy deuteron beam was scattered from two hydrogen targets in succession.

In a double-scattering experiment in which a deuteron beam is polarized by the first scatterer and analyzed by the second scatterer, the differential cross section of the second scattering can be written $I = I_0[1 + a_1 b_1 + a_2 b_2 \cos 2\varphi + (a_3 b_3 - a_4 b_4) \times \cos\varphi]$, where I_0 is the unpolarized differential cross section, φ is the azimuthal angle, a_i describe the deuteron polarization in the first scattering, and b_i describe the analyzing power in the second scattering. The terms $a_1 b_1$, $a_2 b_2$, and $a_3 b_3$ are due to alignment, or tensor polarization, while $a_4 b_4$ is the usual vector-polarization term. For elastic scattering, $a_i = b_i$ assuming time-reversal invariance. The $a_i(\Delta)$ are functions of the spin expectation values.[4] In Harrington's model the coefficients a_1, a_2 depend upon the quadrupole form factor of the deuteron, and the coefficients a_3, a_4 vanish. In the experiment reported here the azimuthal asymmetry $N(\varphi)$ was measured, and it was compared to the formula $N(\varphi) = N_0(1 + A\cos 2\varphi + B\cos\varphi)$, where allowance has been made for nonzero coefficients a_3, a_4.

Figure 1 shows the configuration for the first and second scatterings. The external deuteron beam of the Princeton-Pennsylvania Accelerator at 3.6 GeV/c [5] was aligned by the first scattering at momentum transfer Δ_a and formed a secondary scattered beam. Deuterons in the scattered beam had a momentum higher than that kinematically allowed for any contamination, so the beam-line magnets served to furnish a pure deuteron beam incident on the second target. The momentum transfer Δ_a was varied by moving the position of the first target T_a and retuning the magnet system. Some data were also taken at higher and lower incident momenta than 3.6 GeV/c to obtain extreme values of momentum transfer. Typical external deuteron beam intensity was 8×10^{11} d/sec which gave about 10^4 aligned deuterons in a 5-cm-diam circle at the second scattering target T_b. The slit system defined $|\Delta|^2$ to ± 0.01 (GeV/c)^2.