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PHYSICAL REVIEW C VOLUME 6, NUMBER 2 AUGUST 1972

Asymmetric Proton Yields from the Sequential Reaction ^{6}Li(^{3}He, αp)^{4}He†

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(Received 24 February 1972)

Measurements have been made of the asymmetric proton yields about the ^{5}Li recoil direction using the sequential reaction ^{6}Li(^{3}He, αp)^{4}He for both the ground and first excited states of ^{5}Li at a beam energy of 1.54 MeV. Measurements were made out of the reaction plane, and the results are in qualitative agreement with the predictions of a model proposed by Reimann, Martin, and Vogt. Distorted-wave Born-approximation stripping theory may also be capable of explaining the asymmetric results.

I. INTRODUCTION

Reactions between light nuclei which produce three particles at low bombarding energy have been the subject of considerable experimental and theoretical investigation since about 1965.[1,2] Even though these experiments are complicated by difficult kinematics and experimental uncertainties, it has recently been possible to observe some important phenomena and to extract quantitative results concerning nuclear structure[3-5] and nuclear reactions.[6-8]

This paper will be concerned with a sequential reaction leading to three final-state particles of the general form

$$B+T\rightarrow 1+I\rightarrow 1+2+3, \qquad (1)$$

where B represents the beam nucleus, T the target nucleus, 1 the first-emitted particle, and 2 and 3 the particles resulting from the spontaneous breakup of the intermediate nucleus I. The form of (1) implies that the reaction proceeds through a stripping or a pickup process, as opposed to the reaction

$$B+T\rightarrow C\rightarrow 1+I\rightarrow 1+2+3,$$

in which a compound-nucleus C is formed.

There are three coordinate systems which must be defined: (1) The laboratory system (lab) is the coordinate system in which the target nucleus is at rest; (2) the system center-of-mass (scm) system is the coordinate system in which the vector momentum of the beam and target nuclei is zero; and (3) the recoil center-of-mass system (rcm) is the coordinate system in which the recoil nuclus I is at rest.

The transformations and kinematic correction factors among these coordinate systems have been previously derived[4,8-10] and will not be presented here. Throughout this discussion spherical polar coordinates will be used with the polar axis parallel with and in the direction of the beam.

The particular reaction which is the object of this study is the reaction

$$^3\text{He}+{}^6\text{Li}\rightarrow \alpha_1+\alpha_2+p\,.$$

Measurements of two of the final-state particles in coincidence are kinematically restricted to certain loci in the E_1-E_2 plane as shown in Fig. 1. Since this reaction has previously been determined[11-13] to proceed sequentially via the states of ^{8}Be and ^{5}Li which are kinematically allowed, the open three-body channels are

$$^3\text{He}+{}^6\text{Li}\rightarrow \alpha_1+{}^5\text{Li(g.s.)} \qquad Q=14.9137\text{ MeV}, \qquad (2a)$$

$$^3\text{He}+{}^6\text{Li}\rightarrow \alpha_1+{}^5\text{Li}^*(7.5) \qquad Q=7.4\text{ MeV}, \qquad (2b)$$

$$^3\text{He}+{}^6\text{Li}\rightarrow p+{}^8\text{Be(g.s.)} \qquad Q=16.7869\text{ MeV}, \qquad (2c)$$

$$^3\text{He}+{}^6\text{Li}\rightarrow p+{}^8\text{Be}^*(2.9) \qquad Q=13.9\text{ MeV}, \qquad (2d)$$

$$^3He + {^6Li} \rightarrow p + {^8Be^*}(11.5) \quad Q = 5.3\,MeV, \qquad (2e)$$

$$^3He + {^6Li} \rightarrow p + {^8Be^*}(16.63) \quad Q = 0.15\,MeV. \qquad (2f)$$

Masses, energy levels, spin and parity assignments, etc., were taken from the tabulations of Ajzenberg-Selove and Lauritsen.[14,15] The distribution of the various channels along the kinematic loci is controlled by the kinematics for any given geometry, as shown in Fig. 1.

Measurements previously performed[12] for the ground state of ^5Li have been extended to measurements out of the reaction plane for both the ground and first excited states of ^5Li. This experiment not only confirms previous measurements, but provides more detailed data which can be used to test various theories applicable to reactions involving short-lived nuclei.

II. RMV MODEL

Reimann[12] has measured the reaction (2a) and observed that the distribution of protons from the decay of ^5Li(g.s.) is not symmetric about the scm direction of the recoil nucleus. Since the first-emitted α particle is unpolarized, one would expect the recoil nucleus ^5Li(g.s.) to also be randomly oriented, thus producing an isotropic distribution of protons in the rcm, i.e., a symmetric yield of protons about the recoil direction in the scm. Based upon Reimann's measurements, Reimann, Martin, and Vogt[16,17] proposed a simple semiclassical model, which will be abbreviated as the RMV model, whose assumptions are based upon the short lifetime of the state.

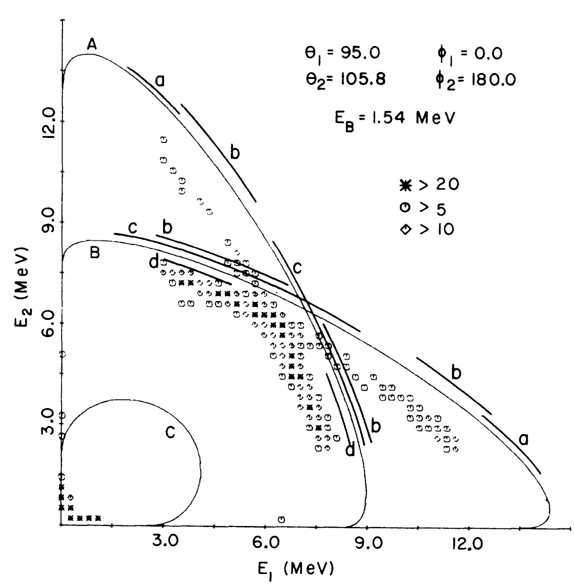

FIG. 1. Typical dual parameter spectrum. The locus labeled A is the (α,p) locus (α energy stored along the horizontal axis, proton energy along the vertical axis); B is the (p,α) locus; and C is the (α,α) locus. The curves labeled a represent the expected positions of the 2.9-MeV state of ^8Be; c represents the 11.5-MeV state of ^8Be; and d represents the ground state of ^5Li. This geometry represents data taken at the point A of Fig. 2.

The RMV model is presented with the aid of Fig. 2. There is strong evidence that ^6Li has an $\alpha + d$ cluster structure.[18-21] Thus, in a simple-minded picture of the ^6Li nucleus the α-particle nucleons are tightly bound and localized in a small region of space and the nucleons of the large and loosely bound deuteron form a diffuse cloud about the α-particle core. An incoming ^3He nucleus is more likely, then, to interact with the nucleons of the deuteron, since it is these nucleons which occupy most of the volume of the ^6Li nucleus. These ideas are supported by the experimental evidence, and the initial reaction mechanism is almost certainly a pickup reaction. The experimental facts which point to a peripheral process are the large amounts of energy released (14.9 MeV), which indicates that the initial reaction takes place quickly, and the lack of resonant structure in the single-parameter excitation spectra.[12] The RMV model assumes that the proton is uniformly distributed about the α-particle core and that there are no neutron-proton correlations in the ^6Li nucleus. This assumption does not violate the $\alpha + d$ structure of the ^6Li nucleus, since the deuteron is so loosely bound. A very crude estimate of the asymmetry can be gained if it is assumed that the proton may have one of two positions relative to the axis of transfer. If the proton is localized in the opposite hemisphere to that from which the

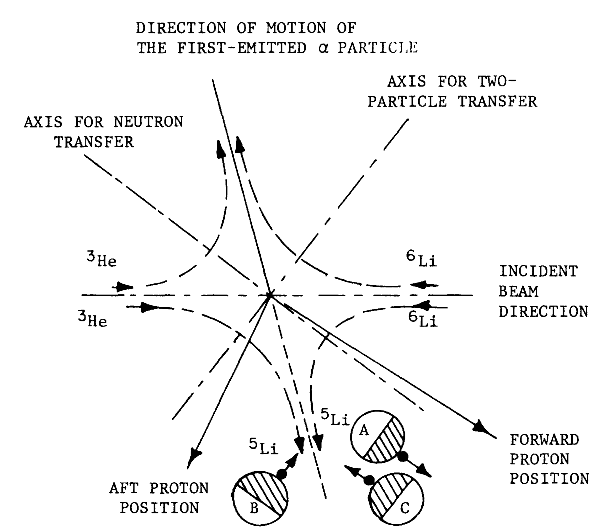

FIG. 2. Schematic diagram of the reaction mechanism for the RMV model in the scm.

neutron is picked up, case A in Fig. 2 results (the black dot on the ^{5}Li nucleus represents the proton, and the arrow represents the preferred direction of emission of the proton) provided that the proton does not have time to change its relative position before the ^{5}Li nucleus breaks up. Case A applies only to neutron transfer, since deuteron pickup is unlikely if the neutron and proton are localized on opposite sides of the α-particle core. If the proton is localized in the same hemisphere from which the neutron is picked up, it is assumed that neutron (single-particle transfer) and deuteron pickup (two-particle transfer) are equally likely. Case C results if only the neutron is transferred and case B if the deuteron is picked up. With the above assumptions, and with A occurring 50% of the time and B and C each occurring 25% of the time, it is easily seen that the forward detector position would be more favorable for detecting protons.

At its present stage of development, the RMV model is not capable of quantitative predictions. It is possible, however, to predict the relative degree of asymmetry for the ^{5}Li*(7.5) state. The central argument here is that the proton, for both the ground and first excited states, has a velocity in the ^{5}Li nucleus which does not allow it to change its relative position before the ^{5}Li decays. Clearly this assumption depends quite critically upon

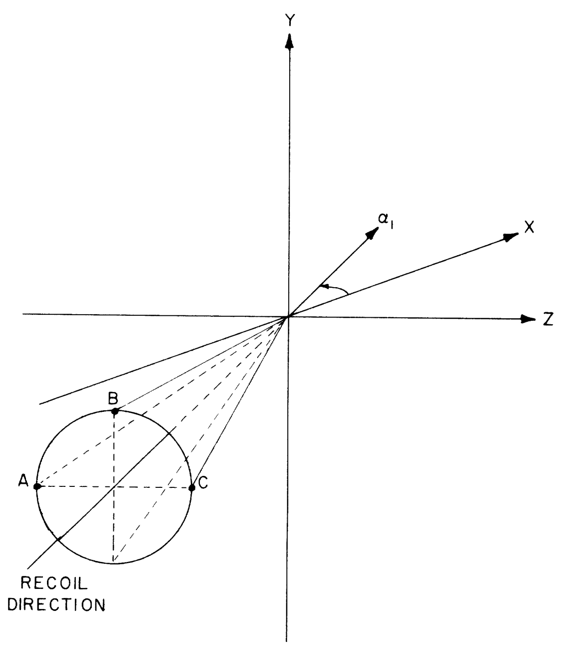

FIG. 3. Experimental geometry in the center-of-mass system. The z-axis is the polar axis and is coincident with the beam direction, and the x-z plane is the horizontal plane.

the lifetime of the state, and, according to this, the excited state, which has a shorter lifetime, should then exhibit stronger asymmetry than the ground state. Moreover, a measurement of the asymmetry at a point out of the reaction plane directly above the recoil axis should yield an asymmetry ratio smaller than the ratio observed on alternate sides of the recoil axis. In fact, one might expect one half the yield at a point out of the plane directly above the recoil direction.

III. EXPERIMENTAL TECHNIQUE

A beam of singly ionized ^{3}He ions was obtained from the Washington State University 2-MeV Van de Graff accelerator. The beam energy was calibrated by using the Al(p,γ)Si threshold reaction, and was accurate to ± 5 keV. The beam incident on the target was collimated by two slits, and antiscattering devices were used to protect the detectors from beam particles scattered from the collimating slits.

The scattering chamber was constructed specifically for the study of multiparameter reactions, and has been described in detail elsewhere.[22] One detector holder is confined to move in a horizontal plane, and the other detector may be placed at any point on a hemisphere above the horizontal plane. The scattering chamber, detector assemblies, and collimators were optically aligned using a precision cathetometer.

Two silicon surface-barrier detectors of thicknesses 1000 and 1500 μ were used for these measurements. The thick detector was capable of stopping the most energetic protons, but protons whose energy was greater than 12 MeV could exceed the depletion depth of the 1000-μ detector. Care was taken so that these fold-over events did not occur in the regions of interest.

The targets were constructed by evaporating ^{6}LiF salt on commercially prepared carbon foils of thickness 15 ± 2 μg/cm^2. Targets of total thickness 40–50 μg/cm^2 were used throughout the experiment. Targets of this thickness did not produce significant kinematic broadening or distortion of the loci.

The electronics used was a standard configuration for coincidence measurements and has been adequately described elsewhere.[3,13] The energy output of the detector (E_1) in the horizontal position and the energy output of the vertical detector (E_2) were stored in a 64×64 array using a dual parameter analyzer. A typical dual parameter spectrum is shown in Fig. 1. The electronics was calibrated by observing the α particles from a standard (thin) ^{241}Am source. Normalization of the the spectra was accomplished by monitoring the elastic events from the ^{19}F contained in the ^{6}LiF salt.

Three-body final-state reactions at low bombarding energies in which two or more of the final-state particles are nonidentical have received relatively little attention because it is difficult to separate events which fall in regions where the kinematic loci interfere. The feasibility of an experimental procedure to separate these events has been demonstrated by the authors,[23] but the technique was not yet adequately refined for use in this study, so that it was necessary to choose the experimental geometry so that the events of interest were separated from interference from other loci. In order to determine the number of events corresponding to a particular isolated state the expected position of the state on the locus was calculated. Using the calculated values and accounting for shifts in the data due to energy loss in the target, the group of data corresponding to the state involved could be identified and counted. Figure 1 displays the calculated positions and experimental data for a particular geometry.

Reimann made measurements at the points A and C in Fig. 3 for the ground state of ^{5}Li. The measurements presented herein were made at the points A and B in Fig. 3 for the ground and first excited states of ^{5}Li.

IV. RESULTS AND DISCUSSION

Contrary to Reimann's assumptions, significant contributions due to the first excited state of ^{5}Li and the second excited state of ^{8}Be were observed. The degree to which the $^{8}Be^{*}(11.5)$ state can contribute to the triple-correlation cross section can be estimated by looking at the yield in a region where only the $^{8}Be^{*}(11.5)$ state populates the (α, p) locus and also where there is freedom from interference from the (p, α) locus. At best only a crude estimate can be made, but the $^{8}Be^{*}(11.5)$ contribution is certainly more than 5% and probably less than 15% in the region of the ^{5}Li ground state. The contribution of the $^{5}Li^{*}(7.5)$ state in the regions of interest of the ^{5}Li(g.s.) state cannot be estimated by any reliable procedure, and no correction for this has been made. Happily, the $^{5}Li^{*}(7.5)$ state on the upper portion of the (α, p) locus is separated nicely from competing reactions, and the absolute accuracy for this state is much better.

Define the asymmetry ratio at the position x of Fig. 3 to be

$$a_{\mathrm{x}} = \frac{Y_{\mathrm{x}}}{Y_{\mathrm{A}}} ,$$

where Y_{x} is the normalized yield at the point x and Y_{A} is the yield at the point A of Fig. 3. Clearly, $a_{\mathrm{A}} = 1$. Table I gives the results of the measurements and the errors associated with them. In Table I the subscripts L, S, and R indicate the coordinate system to which the quantity of interest is referred. The absolute error in the asymmetry ratio includes estimated effects resulting from competing reactions such as the $^{8}Be^{*}(11.5)$ state problem discussed above and also estimated normalization and data handling errors. The absolute errors given are necessarily subjective, but the statistical error analysis has been carried out rigorously.

The asymmetry ratios agree quite well with the qualitative predictions of the RMV model. The asymmetry measured for the first excited state of ^{5}Li is significant not only because it confirms the predictions of the RMV model, but also because the measurement is free from interference due to other reaction channels.

A more quantitative model may be applicable to this problem. Angular-correlation measurements on the $(d, p\gamma)$ stripping reaction have shown asymmetric yields of γ rays about the recoil direction. This has been explained using distorted-wave Born-approximation (DWBA) theory.[24] At least one attempt has been made to adapt this theory to particle-particle angular-correlation data.[5]

TABLE I. Measurement results.

State	Asymmetry ratio	Total error	Statistical error	Position	$\frac{d^3\sigma}{dE_{1L}\,d\Omega_{1L}\,d\Omega_{2L}}$ (b)	$\frac{d^3\sigma}{dE_{1S}\,d\Omega_{1S}\,d\Omega_{2R}}$ (b)
^{5}Li(g.s.) (Reimann)	$a_c = 2.0$	±0.3				
^{5}Li(g.s.)	$a_B = 1.23$	±0.2	±0.08	A	4.6×10^{-4}	6.4×10^{-5}
				B	5.7×10^{-4}	8.2×10^{-5}
$^{5}Li^{*}(7.5)$	$a_B = 1.89$	±0.4	±0.32	A	1.5×10^{-4}	3.6×10^{-5}
				B	2.9×10^{-4}	6.4×10^{-5}

The effect of DWBA stripping theory is a possible destruction of the symmetry about the recoil direction. Whether or not a reasonable set of DWBA parameters could account for all of the experimental features given in Table I should be the object of further theoretical investigation. The fact that DWBA theory makes no assumptions concerning the lifetime of the state seems to be in conflict with the basic assumptions of the RMV model.

ACKNOWLEDGMENTS

The authors would like to thank W. P. Copple for his assistance during the acquisition of the data for this experiment. Computer time was contributed by the Washington State University Computing Center.

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†Work supported in part by the Research Committee and the Nuclear Radiation Center of Washington State University.

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