Reaction ^{6}Li(p, pt) at 590 MeV

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The cross section ($d^5\sigma/d\Omega_p d\Omega_t dT_p$) for the reaction ^{6}Li(p, pt) has been measured in a kinematically complete experiment. The energy resolution did not allow for an identification of the final-state residual nucleus. The cross-section data obtained, when analyzed in terms of the recoil momentum of the three-nucleon residual system, has the shape characteristic of an S state for the relative motion of the triton. If the cross section is fitted with a Gaussian the width at $1/e$ is $\Gamma = 100 \pm 20$ MeV/c, and the cross section at zero recoil is 490 ± 120 nb/sr^2 MeV. The width observed is twice as large as obtained in previous, lower-energy experiments, but only slightly larger than predicted by ^{6}Li-cluster-model calculations.

A lithium target enriched to 95.6% of ^{6}Li and 0.685 cm thick was bombarded in the 590-MeV proton beam of the National Aeronautics and Space Administration synchrocyclotron at the Space Radiation Effects Laboratory.

Coincident events were detected in a double telescope arrangement (an illustration of the arrangement can be found in a previous paper, Kitching *et al.*[1]). The momentum and time of flight of a particle scattered at 43° were measured using a combination of spark chambers and scintillators with a bending magnet. The invariant mass was calculated event by event from these two quantities and was used in the identification of tritons in this arm. However, the identity of the particle could be obtained with very good reliability from the time of flight alone. Trajectories through the magnetic spectrometer were reconstructed assuming an homogeneous field; they were required to satisfy a number of criteria to give an acceptable reconstructed event. These criteria were: target intercept, alignment of sparks in three different chambers before and after the magnet, and smooth connection of the trajectories at the edge of the homogeneous field. A resolution of 100 MeV full width at half maximum (FWHM) on the invariant mass of a triton was achieved for those events with trajectories satisfying all criteria. The sample of identified tritons to be discussed here contains 79 tritons; the estimated deuteron contamination is less than two events.

The energy of a particle scattered at 66° on the other side of the beam and in coincidence with a triton was measured by stopping the particle in a telescope with 11 scintillation counters loaded with 10 copper plates, each 0.315 cm thick. A main copper absorber 8.25 cm thick preceeded the stopping counters and provided a selection of the proper energy window for protons. Heavier particles could not penetrate through the main absorber. The total energy acceptance of the range stack was 90 MeV. Spark chambers in this arm were used to measure the scattering angle.

The two angles chosen, as well as the range energy window, correspond to 90° c.m. scattering for a free proton-triton collision; all three parameters were maintained throughout the experiment.

For each event the following characteristics of the unobserved three-nucleon residual system were calculated:

(i) missing energy

$$T_{\text{miss}} = T_o - (T_t + T_p), \tag{1}$$

where T_o, T_t, and T_p are the kinetic energies of the incident proton, the triton, and scattered proton, respectively;

(ii) longitudinal recoil

$$q_{\parallel} = p_o - (p_t \cos\theta_t + p\cos\theta_p); \tag{2}$$

and

(iii) transverse recoil

$$q_\perp = p_t \sin\theta_t - p \sin\theta_p , \quad (3)$$

where p_o is the beam momentum, p_t and p are the momenta, and θ_t and θ_p the laboratory angles of the triton and scattered protons.

Largely because of the unfavorable ratio of proton-triton events to uncorrelated particle fluxes through the front spark chambers, the reconstruction efficiency was poor (15 events from the sample of 79 tritons were entirely reconstructed). The efficiency of the system was verified in a low background experiment, ^{6}Li(p, pd); the cross section for 90° c.m. was found in agreement with the result of a previous experiment by Alder *et al.*[2] at a total recoil momentum of 40 MeV/c. It is to be noted that the cross sections measured in the present experiment are about 160 times smaller than those of Ref. 2.

Because of the unique signature provided by a triton in the magnetic spectrometer, it was assumed that incomplete events—for which either the momentum of the triton or the kinetic energy of the proton or one of the angles could not be reconstructed—could be saved with assumed values of the missing quantity, at no other cost than increased over-all resolution.

The missing energy spectrum was centered around 16 MeV, but its width was about twice as large as obtained in calibration runs using the elastic (p, d) reaction. It is assumed that this widening is the result of the different corrections applied. The distribution of the longitudinal recoil momentum was observed to be about triangular, with a base width of ±100 MeV/c, in good agreement with the result of a Monte Carlo simulation of the experiment including multiple scattering in the target and scintillation counters. The simulation assumed no angular correlation of the proton and triton but energy conservation was required. According to this simulation, the recoil distribution out-of-the-reaction plane should have been rectangular in shape, with a basis width of ±50 MeV/c; the out-of-plane distribution was not observed in the present experiment. The Monte Carlo calculation indicated also that the transmission of the system was flat for values of the transverse recoil momentum up to ±120 MeV/c.

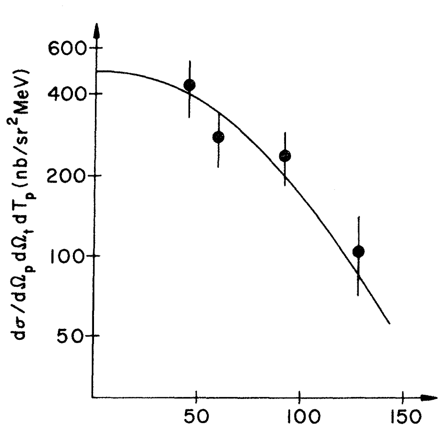

FIG. 1. Cross-section data, as a function of the magnitude q of the recoil momentum.

The events in the longitudinal distribution were then summed over 40-MeV/c bins, without distinction of the sign of the recoil. The cross-section data obtained are shown in Fig. 1. The cross section is calculated from

$$\frac{d^5\sigma}{d\Omega_p d\Omega_t dT_p} = \frac{(\text{events in } \pm 20 \text{ MeV}/c \text{ around } q)}{[\Delta\Omega_p \Delta\Omega_t (nI) \Delta T_p \epsilon]} , \quad (4)$$

where $\Delta T_p = \Delta q_\perp / 3.06$ at $q_\parallel = 0$, as can be calculated from formula (3), assuming energy conservation (namely, $\Delta T_t = -\Delta T_p$); nI is the number of target nuclei times the number of incident protons; ϵ is the combined efficiency arising from the range telescope efficiency (evaluated at 0.63 for 8.25 cm of copper in the main absorber, scintillation counters included), and from the efficiency in range decoding (evaluated at 0.86).

The cross-section data in Fig. 1 indicate that zero recoil momentum for the unobserved three-nucleon recoil system is the most likely situation. Examination of the transverse momentum distribution further supports this observation. The width of the missing energy distribution is much larger than would be required to separate ground state helium-3 recoil nuclei from breakup ones (the separation energy for a proton in ^{3}He is 5.5 MeV). Hence the data do contain events with a ^{3}He in the final state as well as broken-up ^{3}He with relative kinetic energies of the components up to 30 MeV. A recent estimate of the breakup contribution in a similar reaction reinforces the expectation that such a contribution can be large [see a theoretical analysis of the ^{3}He($p, 2p$) reaction by Lehman[3]]. However, for the sake of obtaining an upper limit for the apparent number of tritons n_t in the ^{6}Li ground state, it will be assumed that all events observed were due to ^{6}Li(p, pt)^{3}He (ground state). Furthermore assuming the validity of the plane-wave impulse approximation, the following relation obtains:

$$\frac{d^5\sigma}{d\Omega_p d\Omega_t dT_p}(q) = (\text{kinematics}) \left(\frac{d\sigma}{d\Omega}\right)_{pt}^{90^\circ \text{c.m.}} n_t \, |\phi(q)|^2 , \quad (5)$$

where the kinematic factor has the value 4.05×10^6

TABLE I. Comparison of experimental results and cluster-model calculations.

Reaction	Beam energy	Recoil width MeV/c FWHM	Reference
^{6}Li(α, α^{3}He)	50	44	Lambert *et al.* (Ref. 6)
^{6}Li(α, αd)	50	62	Lambert *et al.* (Ref. 6)
^{6}Li(p,p^{3}He)	156	80	Bachelier *et al.* (Ref. 7)
^{6}Li(p,pd)	156	68 ± 8	Ruhla *et al.* (Ref. 8)
^{6}Li(p,pt)	590	168 ± 34	This work
^{6}Li(p,pd)	590	124 ± 4	Alder *et al.* (Ref. 2)
Cluster model			
^{3}He-t cluster		128, 156	Kudeyarov *et al.* (Ref. 5)
α-d cluster		118, 130	Kurdyumov *et al.* (Ref. 9)

MeV^2 at $q=0$, and $(d\sigma/d\Omega)_{pt}^{90^\circ\text{c.m.}}$ is the presently unknown elastic proton-triton cross section taken at 90° c.m. scattering angle. $|\phi(q)|^2$ is the probability for a relative internal momentum q between a triton and a ^{3}He in the ^{6}Li ground state.

If we assume that the kinematic factor and the proton-triton elastic cross section are both constant over the relatively small range of q values detected in the present experiment, then the shape of the experimental cross section in Fig. 1 is directly related to the internal momentum distribution $|\phi(q)|^2$, suggesting an S state of relative motion for the triton-helium-3 system in ^{6}Li. A Gaussian fit through the cross-section data

$$\frac{d^5\sigma}{d\Omega_p\, d\Omega_t\, dT_p} \propto \exp(-q^2/\Gamma^2)$$

gives $\Gamma = 100 \pm 20$ MeV/c, corresponding to 168 MeV/c (FWHM). If we then use for $|\phi(q)|^2$ a Gaussian normalized to 1 when integrated over d^3q, we obtain for the product

$$\left(\frac{d\sigma}{d\Omega}\right)_{pt}^{90^\circ\text{c.m.}} \times n_t = (0.68 \pm 0.16) \times 10^{-30}\ \text{cm}^2.$$

To gain any information on n_t a guess of the value of the proton-triton elastic cross section at 90° c.m. is needed. Based on the CERN data and the Space Radiation Effects Laboratory data[4] for elastic proton-helium-3, it may be reasonable to assume that $(d\sigma/d\Omega)_{pt}^{90^\circ\text{c.m.}}$ is anywhere between 10^{-30} and 10^{-32} cm^2. Although it is not possible to give a value of n_t at this time, the results above indicate that n_t is probably larger than 0.68.

It is interesting to compare the results above with those of previous experiments and cluster-model calculations.[5] This is done in Table I. The width of the distribution observed in the present experiment is about twice as large as found in similar experiments[6-8] with lower-energy incident particles. A similar discrepancy has been noted previously from (p, pd) data (see Ref. 2). This observation may be related to the smaller absorption and distortion occurring when high-energy particles are used. The width from the present experiment is consistent with the prediction of the cluster model, as worked out by Kudeyarov *et al.*[5] (see also Kurdyumov *et al.*[9]). In these calculations the two free parameters are fitted to the ^{6}Li Coulomb elastic and inelastic form factors.

Previous experiments have given $n_t \sim 0.7$ from the reaction ^{3}He + ^{3}H → ^{6}Li + γ (Young *et al.*,[10] Ventura *et al.*[11]), and $n_t/n_d \sim 0.4$ from a comparison of the reactions ^{6}Li(p, pd) and ^{6}Li(p, pt) (Bachelier *et al.*[7]). Our present limit for n_t will have to be reinterpreted when the elastic p-t cross section becomes available.

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