Reaction ^{6}Li(p, pd)^{4}He at 590 MeV and α-d Clustering in ^{6}Li

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The cross section for the reaction ^{6}Li(p, pd)^{4}He(g.s.) has been measured in a kinematically complete experiment with 590-MeV protons. Reactions with recoil momenta of the residual ^{4}He nucleus up to 120 MeV/c have been detected. The results are interpreted in terms of the plane-wave impulse approximation and the α-d cluster model. It is found that the reaction occurs with a cross section 0.8 times as large as the free elastic pd cross section at the same average c.m. scattering angle. The width of the momentum distribution for the motion of a deuteron in ^{6}Li is observed to be 124 ± 4 MeV/c (full width at half maximum), a value considerably larger than had been observed before in similar experiments at lower energies.

An enriched ^{6}Li target (95.6% of ^{6}Li), 0.685 cm thick, was bombarded by 590-MeV protons in the external beam of the National Aeronautics and Space Administration synchrocyclotron at the Space Radiation Effects Laboratory.[1] The beam intensity was monitored with two telescopes viewing a second target located 5 m downstream from the ^{6}Li target. The monitor was calibrated by activation from the reaction ^{12}C(p, pn)^{11}C.

Coincident signals from seven scintillation counters in a double telescope arrangement triggered eight spark chambers, with magnetostriction readout, interfaced to an IBM 360-44 computer for online analysis. Six of the spark chambers were used with a 0.90-m H magnet as a magnetic spectrometer on one side of the beam. The magnetic field was chosen so as to preferentially select deuterons. The momentum of a particle and its time of flight provided a determination of the invariant mass, insuring an excellent rejection of protons or $A \geq 3$ reaction products. The width at half maximum of the "deuteron" invariant mass spectrum was 10%. On the other side of the beam, the energy of the particles was determined from their stopping range. The range telescope consisted of four 16-MeV energy channels. A minimum range was required to generate a triggering signal for the spark chambers, resulting in the elimination of all particles heavier than a proton.

The ^{6}Li(p, pd)^{4}He(g.s.) reactions were selected in the analysis from the reconstructed missing energy defined by $E_{\text{miss}} = E_0 - (E_p + E_d + E_{\text{rec}})$, where E_0 is the incident, E_p and E_d the scattered proton and deuteron energies, respectively, and E_{rec} the recoil energy. Figure 1 shows the observed missing-energy spectrum. The separation energy for a deuteron in ^{6}Li being 1.5 MeV, the main peak around $E_{\text{miss}} \sim 0$ was interpreted as originating from quasielastic interactions of the incident protons with a deuteron in ^{6}Li. The second, broader peak is probably associated with breakup of the ^{4}He. The events with a missing energy between −40 and +10 MeV were kept for further analysis.

The laboratory angles of the deuteron and proton telescopes were 43 and 58°, respectively, corresponding to 90° c.m. scattering angle for free elastic pd scattering. For each event the recoil momentum $\vec{q}$ of the ^{4}He nucleus was calculated from the measured angles θ_p and θ_d, momentum p_d and kinetic energy E_p. The chosen momentum and angular acceptance of the two telescopes resulted in the transmission of the system being constant for transverse components $q_\perp$ of the ^{4}He recoil momentum between −40 and +105 MeV/c. Therefore, this experiment was of the energy-sharing type in the sense that nonzero recoil momenta were observed because of the wide momentum acceptance of both telescopes, which were thus maintained at the same angle throughout the experiment.

A Monte Carlo computer routine was written to calculate the transmission of the apparatus as a function of $\vec{q}$, the total recoil momentum of the ^{4}He nucleus. Events were simulated by selecting randomly the incoming and outgoing proton momenta from uniform distributions, and calculating the corresponding deuteron momentum from energy conservation. The interaction point in the target and the horizontal angles of proton and deuteron were also taken at random. Multiple scattering corrections in the target and counters were made and the trajectories followed along the two telescopes to check acceptance. The accepted simulated events were then classified and summed in the same way as the experimental ones. If $T(E_{miss}, \vec{q})$ is the calculated transmission of the system for events with missing energy within given limits and within a given recoil momentum bin around $\vec{q}$, the cross section is given by

$$\frac{d\sigma(E_{miss}, \vec{q})}{d\Omega_p d\Omega_d dE_p} = \frac{N(E_{miss}, \vec{q})}{T(E_{miss}, \vec{q})\Delta\Omega_p \Delta\Omega_d \Delta E_p} \frac{1}{nI\epsilon},$$

where $N(E_{miss}, \vec{q})$ is the number of experimental events within defined energy and recoil momentum intervals, $\Delta\Omega_p$ and $\Delta\Omega_d$ are the geometrical solid angles of the defining counters, and ΔE_p is the total energy acceptance of the range telescope. n is the number of ^{6}Li nuclei in the target and I the number of incident protons. ϵ is a correction factor for the efficiency of the range detector; a value of $\epsilon = 0.67$ was used. Writing as $q_\parallel$ and q_{out} the components of the ^{4}He recoil momentum along the beam and out of the horizontal plane, respectively, the cross sections were calculated by summing events in bins of $q_\perp$ 30 MeV/c wide, and over all values of q_{out}. In the final result only events with $q_\parallel$ between −30 and 0 MeV/c were kept. A positive value of any of the recoil projections obtains when the corresponding deuteron momentum component is larger than the proton one. The total recoil momentum was then calculated from

$$q = (q_\perp^2 + q_\parallel^2 + \langle q_{out}^2 \rangle)^{1/2},$$

where $\langle q_{out}^2 \rangle$ is the average square of q_{out}. The resulting cross sections are plotted as a function of q in Fig. 2(a); in this figure the errors shown are statistical only.

The cross section can be interpreted in terms of the plane-wave impulse approximation, assuming that the reactions selected were quasielastic and the distortion due to the interaction of the reaction participants with the spectator recoil nucleus is negligible. With these assumptions the recoil momentum q can be assumed to be the negative of the internal motion momentum of the deuterons knocked out. The cross section can be written as

$$\frac{d\sigma(q)}{d\Omega_p d\Omega_d dE_p} = k \left(\frac{d\sigma}{d\Omega}\right)_{pd} n_{\alpha d}\, \rho(q),$$

where k is a kinematical factor, $(d\sigma/d\Omega)_{pd}$ is the 90° c.m. elastic pd cross section,[2] $n_{\alpha d}$ is the number of α-d clusters in the ground state of ^{6}Li, and $\rho(q)$ is the internal momentum distribution of the deuteron relative to the ^{4}He spectator.

The values of $\rho(q)$ calculated for the six recoil momenta for which a cross section has been obtained in this experiment, are shown normalized to $\rho(q=0) = 1.0$ in Fig. 2 (b). The distribution has a full width at half maximum of 124 ± 4 MeV/c when a fit is made with various model distribu-

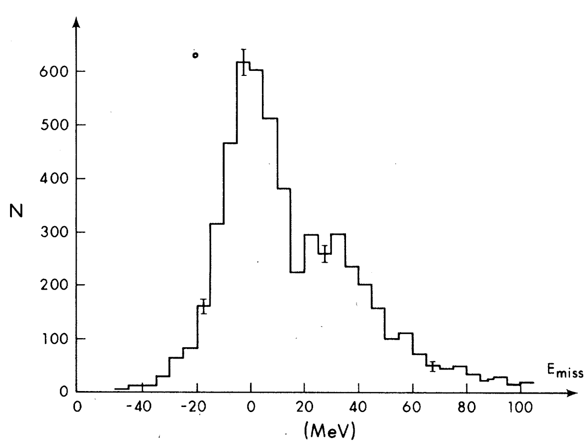

FIG. 1. Spectrum of the events reconstructed in the experiment, plotted as a function of the missing energy $E_{miss} = E_0 - (E_p + E_d + E_{rec})$.

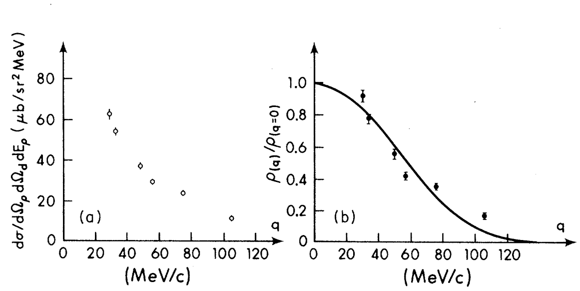

FIG. 2. (a) The cross sections $(d\sigma/d\Omega_p d\Omega_d dE_p)$ shown as a function of the total recoil momentum q of the residual ^{4}He nucleus, for the reaction ^{6}Li(p,pd)^{4}He(g.s.). (b) Momentum distribution $\rho(q)$ calculated from the cross-section data, assuming the validity of the plane-wave impulse approximation. The distribution has been normalized to $\rho(q=0) = 1.0$. The solid line is the theoretical distribution of Kudeyarov *et al.*(Ref. 4), fitted in absolute value only to the results of the present experiment.

TABLE I. Measured widths of the ^{4}He(g.s.)-d momentum distribution and clustering probabilities.

Reaction	Energy (MeV)	FWHM of $p(q)$ (MeV/c)	n_d	Reference
^{6}Li(p,pd)^{4}He	30	42 – 64	0.04 ± 0.12	a
	55	64 ± 4	0.15 ± 0.07	b
	155	68 ± 8	0.31 ± 0.15	c
	590	124 ± 4	0.80 ± 0.06	This experiment
^{6}Li(π^-,nn)^{4}He	Rest	122	0.37 ± 0.04	3

[a] D. W. Devins, B. L. Scott, and H. H. Forster, Rev. Mod. Phys. 37, 396 (1965).
[b] D. L. Hendrie *et al.*, UCRL Report No. 16580, 1960 (unpublished), p. 146.
[c] C. Ruhla, M. Riou, M. Gusakow, J. C. Jacmart, M. Liu, and L. Valentin, Phys. Letters 6, 282 (1963).

tions. This result is compared in Table I with previous ones obtained from the same reaction although at lower energies, or in a π^--absorption experiment by Davies *et al.*[3] The present result for the momentum distribution width is larger than observed so far at lower energies. This larger width may be the result of weaker nuclear distortion effects when 600-MeV protons are used, although the agreement with Davies's result is not obviously compatible with this assumption. Also shown in Fig. 2(b) is a theoretical distribution due to Kudeyarov, Kurdyumov, Neudatchin, and Smirnov.[4] In the ^{6}Li cluster model of these authors, the configuration ^{4}He(g.s.)-d in the fractional-parentage expansion of the ^{6}Li ground state has a momentum distribution given by

$$\rho(q) \sim \left| \sum_{i=0,1,2} (a_i + b_i q^2) e^{-c_i q^2} \right|^2 .$$

The numerical values of the nine parameters are given in Table II.[4,5] The two free parameters of Kudeyarov's model have been determined by fits to elastic electron-Coulomb form factors (see Ref. 4). The theoretically expected value of $n_{\alpha d}$ is near 1.0. As the Kudeyarov model has no free parameter, we merely fitted the absolute value of the theoretical momentum distribution to our data and found a value $n_{\alpha d} = 0.8 \pm 0.06$. The error quoted on $n_{\alpha d}$ includes an estimate of systematic errors in the experiment. Comparing that result with others listed in Table I again shows that higher energy protons give larger clustering probabilities than lower energy ones, in agreement with the assumption of reduced nuclear distortion.

TABLE II. Coefficients in the momentum distribution of Kudeyarov *et al.* (see Refs. 4 and 5).

Index i	a_i (fm$^{3/2}$)	b_i (fm$^{7/2}$)	c_i (fm$^{7/2}$)
0	−7.50	10.90	2.170
1	2.36	−0.239	1.050
2	−1.449	0.534	1.073

A Gaussian fit to the experimental momentum distribution, of the form $e^{-(q/q_0)^2}$, gives a width parameter $q_0 = 74.5 \pm 3.7$ MeV/c and a cluster number $n_{\alpha d} = 0.75 \pm 0.13$; the larger error is related to the fact that the Gaussian fit involves two free parameters, rather than one in Kudeyarov's fit. However, as pointed out by Tang, Wildermuth, and Pearlstein,[6] the exclusion principle requires the lowest state of relative motion of the αd system to be 2S. A 2S-momentum distribution for ^{6}Li has a characteristic secondary peak near 200 MeV/c, unfortunately outside the recoil domain of the present experiment. A Gaussian fit corresponds to a 1S state and is, therefore, not of much value, other than providing a comparison with other experiments.

In conclusion, the results of the present experiment indicate that the cross section for the scattering of protons by deuterons within the ^{6}Li ground state and leaving a ^{4}He nucleus in its ground state amounts to 0.80 times the free elastic *pd* scattering cross section, after integration over the final states in momentum space of the recoiling nucleus. This value is significantly higher than all those observed in lower energy experiments and close to theoretical expectation from a model that reproduces the elastic electron scattering form factor of ^{6}Li.

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[1]The preliminary results of this experiment have been presented by J. C. Alder, W. Kossler, C. F. Perdrisat, W. K. Roberts, P. Kitching, G. Moss, W. C. Olsen, and J. R. Priest, Bull. Am. Phys. Soc. 16, 132 (1971).

[2]A value of $(d\sigma/d\Omega)_{pd} = 0.050 \pm 0.002$ mb/sr was used; see J. S. Vincent, W. K. Roberts, E. T. Boschitz, L. S. Kisslinger, K. Gotow, P. C. Gugelot, C. F. Perdrisat, L. W. Swenson, and J. R. Priest, Phys. Rev. Letters 24, 236 (1970).

[3]H. Davies, H. Muirhead, and J. N. Woulds, Nucl. Phys. 78, 663 (1966).

[4]Yu. A. Kudeyarov, I. V. Kurdyumov, V. G. Neudatchin, and Yu. F. Smirnov, Nucl. Phys. A163, 316 (1971).

[5]I. V. Kurdyumov, Ph.D. thesis, Nuclear Research Institute, Moscow State University, 1971 (unpublished); and private communication with V. G. Neudatchin.

[6]Y. C. Tang, K. Wildermuth, and L. D. Pearlstein, Phys. Rev. 123, 548 (1961).

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$^{19}F(d, p)^{20}F$ and the Nuclear Structure of ^{20}F†

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The reaction $^{19}F(d, p)^{20}F$ has been studied with 16-MeV deuterons. Outgoing protons were detected in photographic emulsions in a magnetic spectrograph. Spectroscopic factors were extracted and combined with previous information and compared with results of shell-model calculations performed in a complete *sd*-shell basis. Of the previously known 25 states below $E_x = 4.5$ MeV, angular distributions measured at 14 angles were obtained for all but the 5 at $E_x = 1.824$, 2.871, 3.761, 4.20, and 4.21 MeV. Strong stripping angular distributions were observed for 10 states – 6 dominated by $l = 2$, and 4 by $l = 0$. These 10 states agree reasonably well in position and strength with the 10 lowest shell-model states predicted to have appreciable amounts of the configuration $[^{19}F(\text{g.s.}) \otimes 1d_{5/2}$ or $2s_{1/2}$ neutron)].

I. INTRODUCTION

The spectroscopy of ^{20}F is typical of non-self-conjugate odd-odd nuclei; the knowledge about it is extremely scant in view of the effort that has been expended. The most notable early work on its structure was that of El Bedewi[1] in 1956. Using an 8.9-MeV deuteron beam and one of the first heavy-particle spectrographs, he was able to obtain excitation energies and angular distributions for a great many of the states in ^{20}F. His analysis of the angular distributions was limited by the use of the plane-wave Born approximation (PWBA). However, as we shall see below, his results for the few strong states were qualitatively correct.

Accurate excitation energies have been measured[2] up to $E_x = 6.043$ MeV by use of the reactions $^{18}O(^3He, p)^{20}F$ and $^{19}F(d, p)^{20}F$ at low bombarding energies. Information on the γ decay of levels of ^{20}F has been obtained in studies of the reactions $^{18}O(^3He, p\gamma)^{20}F$,[3-7] $^{19}F(d, p\gamma)^{20}F$,[3,8] $^{19}F(n, \gamma)^{20}F$,[9-12] and $^{18}O(t, n\gamma)^{20}F$.[13] Further studies include measurements of lifetimes[13-16] of excited ^{20}F levels, angular-distribution measurements of the reaction $^{19}F(d, p)^{20}F$ obtained with a polarized deuteron beam,[17] and a study of the reaction $^{22}Ne(p, ^3He)$-^{20}F.[18] Studies of the reactions $^{18}O(^3He, p)^{20}F$ and $^{22}Ne(d, \alpha)^{20}F$ have also been reported recently.[19] The experimental results concerning ^{20}F are excellently summarized in the review by Ajzenberg-Selove.[20]

Directional-correlation measurements[7] in the re-