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Spectral function of p-n pairs in ^{6}Li, from the ^{6}Li(p,$p\alpha$)pn reaction at 200 MeV

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The spectral function for p-n pairs in the ^{6}Li ground state (i.e., the distribution in p-n relative momentum $\hbar k$ for pairs whose c.m. is at rest in the laboratory) was measured for k ranging from 0.6 to 1.5 fm^{-1}, using the ^{6}Li(p,$p\alpha$)pn reaction at 200 MeV. These and earlier 120 MeV ^{6}Li(α,2α)pn measurements show that, when k increases from 0.1 to 1.5 fm^{-1}, this function decreases by 4 orders of magnitude and is predicted within a factor of 2 by the plane-wave impulse approximation. The asymmetry for the ^{6}Li(p,$p\alpha$)pn reaction induced with polarized protons was measured at 56° c.m. and found to have the same bombarding-energy dependence as that for p-α elastic scattering. The d-α cluster probability of ^{6}Li, determined by the ^{6}Li(p,$p\alpha$)d reaction, was consistent with that found in other intermediate-energy experiments.

I. INTRODUCTION

The two-body cluster structures (α-d and ^{3}He-t) of ^{6}Li are reasonably well understood and have, for example, been studied experimentally with knockout reaction measurements[1] interpreted through the distorted-wave impulse approximation.[2] Microscopic theoretical models[3,4] now successfully predict and correlate the ground-state properties of this nucleus including its α-d cluster structure. Moreover, since a Faddeev treatment of the three-body αpn cluster mode is in progress,[5] experimental data for this mode are now needed. The momentum distribution for three-body clusters also can be investigated through knockout measurements, in which two momenta must be determined: the momentum $\hbar Q$ of the p-n c.m., and the momentum $\hbar k$ of each nucleon relative to it. The distribution in k, for $Q=0$, is called the spectral function. It is related to the overlap of the ^{6}Li ground state with an αpn final state in which the p-n c.m. is at rest.

Measurements of the ^{6}Li spectral function, using the ^{6}Li(α,2α)pn reaction at 120 MeV, are available[6] for k ranging from 0.1 to 0.8 fm^{-1}. We now report additional measurements of this quantity, obtained from ^{6}Li(p,$p\alpha$)pn studies at 200 MeV, for k between 0.5 and 1.5 fm^{-1}. The combined measurements show that the ^{6}Li spectral function falls by 4 orders of magnitude in this range of k. They are fitted within about a factor of 2, and without renormalization, by a plane-wave theory previously presented.[6,7] Other experimenters[8] are now measuring the spectral function for this nucleus, using the ^{6}Li(e,$e'\alpha$)pn reaction.

II. EXPERIMENTAL PROCEDURE

A 200-MeV polarized-proton beam from the TRIUMF accelerator was used to bombard a 95.45% enriched ^{6}Li target of thickness 10.5 ± 1.0 mg/cm^2. The beam was about 80% polarized and was periodically cycled between up and down polarization states. Elastic scattering in a CH$_2$ polarimeter of analyzing power 0.285, 11.5 m upstream from the target, monitored the beam intensity and polarization.

Protons and α particles from the ^{6}Li(p,$p\alpha$)pn reaction were detected in coincidence by two telescopes coplanar with, and on opposite sides of, the beam. Angle pairs were selected for which the c.m. of the undetected *p-n* pair could be at rest in the laboratory when the detected proton was scattered through 56° in the *p*-α c.m. system. The α-particle telescope consisted of two Si detectors, 0.1 and 5 mm thick (called ΔE and E). Its solid angle of 1.22 msr was defined by a brass collimator. A vacuum chamber held both this telescope and the target, which was turned 30° from the beam direction to reduce the energy loss of the α particles. Protons left this chamber through a thin Kapton window and were detected by two plastic scintillators (each 0.63 cm thick) and a 12.7-cm-diam × 15.2-cm-thick NaI(Tl) crystal 2 m from the target. One plastic detector (called TOF), just outside the Kapton window, provided time-of-flight information; the other (Ω), 1.4 cm ahead of the NaI detector, defined the 1.14 msr solid angle. A trigger signal was derived from fast coincidences between ΔE, E, and Ω detectors, and timing and analog signals were recorded in event mode on magnetic tape.

All analyzed events are believed to have come from the ^{6}Li$(p,p\alpha)pn$ reaction. The energy coordinates (E_p,E_α) of four-body breakup events with $Q=0$ were well displaced from both kinematic branches of the ^{6}Li$(p,p\alpha)d$ three-body breakup reaction, and E_p+E_α was large enough to exclude all pion production reactions. Both random coincidences and events from the 4.55% ^{7}Li in the target were subtracted. Short, separate runs with an enriched ^{7}Li target showed that this contaminant never exceeded 3% of the yield from the reaction of interest. Random coincidences were always less than 4% of true coincidences except for our most inelastic event sample ($k=1.53$ fm^{-1}) where they were 14%. Counting losses due to dead time of the electronics and data-acquisition computer were negligible ($\leq 0.1\%$).

Coincidence measurements of elastic *p-d* scattering from a CD$_2$ target provided energy calibration and determined the response function of the NaI detector at a proton kinetic energy of 156 MeV. Further energy calibration data came from analysis of the ^{6}Li$(p,p\alpha)d$ three-body reaction data.

Two-dimensional spectra of the ΔE vs $(\Delta E+E)$ and Ω vs $(\Omega+\text{NaI})$ signals were used to identify α particles and protons, respectively. Additional TOF vs $(\Omega+\text{NaI})$ two-dimensional spectra were used to select protons. Proton energy spectra were obtained for events which survived these cuts and for which the α-particle energy allowed the final *p-n* c.m. to be at rest in the laboratory. Events were subtracted from those in each proton energy bin to eliminate the remaining reaction tail from higher-energy protons, as determined from the previously mentioned response function. A second correction was made to recover the events which should have appeared in that bin, but were lost through nuclear reactions in NaI.

The running conditions selected, and the results obtained for the four-body breakup reaction, are given in Table I. The widths of the energy bins used to determine the cross sections and analyzing powers are indicated in the table, and were chosen to obtain reasonable statistics.

III. RESULTS AND DISCUSSION

A. The *p-n* spectral function

Measured four-body cross sections for the ^{6}Li$(p,p\alpha)pn$ reaction at 200 MeV are shown in Fig. 1 and compared with plane-wave impulse approximation predictions[6,7] using the equation

$$\frac{d^4\sigma}{d\Omega_p d\Omega_\alpha dE_p dE_\alpha}=\frac{v_{0,2}}{v_{0,4}}\frac{\rho_4}{\rho_2}\left[\frac{d\sigma}{d\Omega}\right]_{p\alpha}4\pi|\langle Q,k|^6\text{Li}\rangle|^2 \ . \tag{1}$$

The $(d\sigma/d\Omega)_{p\alpha}$ of Eq. (1) were evaluated at the energies and scattering angles of the final *p*-α system, using the final-state energy prescription. The projectile velocity and density of final states for *p*-α elastic scattering under such conditions are $v_{0,2}$ and ρ_2, respectively. The similar quantities $v_{0,4}$ and ρ_4 are evaluated for four-body breakup at $E_0=200$ MeV. The momentum $\hbar Q$ of the *p-n* c.m. is zero for these measurements.

The spectral function (or overlap) $4\pi|\langle Q,k|^6\text{Li}\rangle|^2$ was calculated using the following assumptions.[6,7] The ^{6}Li ground state contains a *p-n* pair (with $S=1$, $L=0$) moving in a harmonic-oscillator potential with a range parameter chosen to reproduce the ^{6}Li charge radius. The final *p-n* pair is in a scattering state described by a Yamaguchi[9] wave function, and all other unbound particles are described by plane waves. The impulse approximation is used to relate the *p*-α interaction causing four-body quasielastic breakup to the *p*-α elastic-scattering cross section.

The final-state energy prescription for $(d\sigma/d\Omega)_{p\alpha}$ required *p*-α elastic-scattering cross sections for incident proton energies from 73 to 177 MeV. These were obtained as follows. For six bombarding energies between 72 and 200 MeV, measured[10-15] elastic cross sections were plotted versus momentum transfer, since it is

TABLE I. Laboratory experimental conditions and results for ^{6}Li$(p,p\alpha)pn$ reaction at 200 MeV. The detected proton scatters at 56° in the *p*-α c.m. system, and the undetected *p-n* pair is left at rest in the laboratory.

k (fm^{-1})	θ_p (deg)	θ_α (deg)	E_p (MeV)	E_α (MeV)	σ (μb sr^{-2} MeV^{-2})	A
0.58	44.3	58.0	154.1	28.4	0.71±0.06	−0.52±0.08
0.80	43.7	55.3	142.5	27.2	0.19±0.04	+0.03±0.19
1.03	43.2	51.1	126.3	26.2	0.086±0.022	−0.10±0.22
1.28	41.9	44.8	104.4	24.9	0.035±0.011	−0.08±0.26
1.53	40.0	35.9	77.9	24.4	0.013±0.008	+0.55±0.40

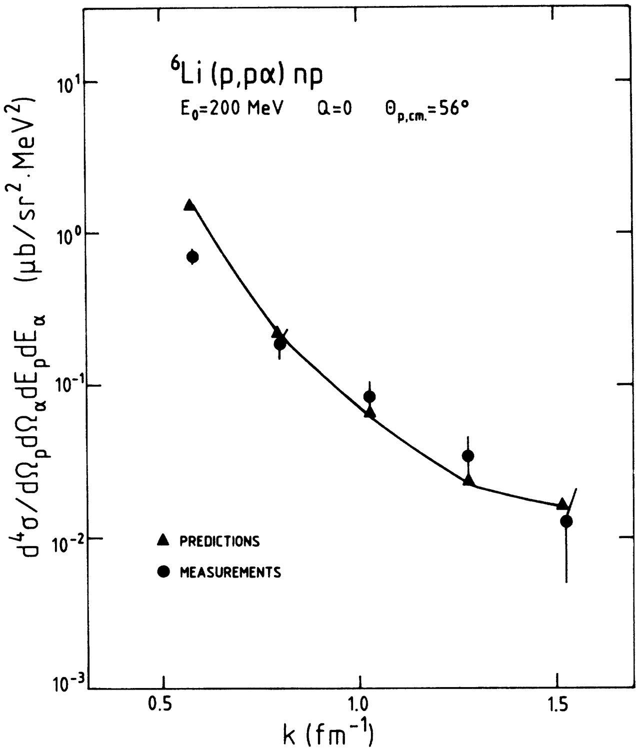

FIG. 1. Cross sections vs p-n internal momentum k, for the reaction ^{6}Li$(p,p\alpha)pn$ at 200 MeV. The proton and α-particle energies and angles were chosen so that the proton quasielastically scattered at 56° in the p-α c.m. system and the final p-n c.m. had zero laboratory momentum ($Q=0$). Triangles show cross sections predicted using Eq. (1) and published p-α elastic-scattering data. The dashed curve only guides the eye between predictions.

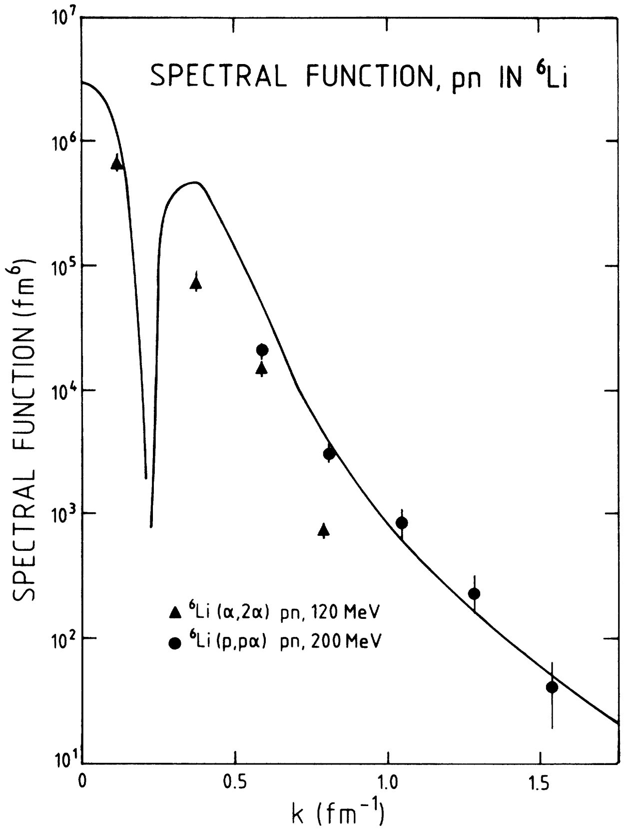

FIG. 2. Spectral function vs k for p-n pairs in ^{6}Li, as measured in the present study of the ^{6}Li$(p,p\alpha)pn$ reaction at 200 MeV and in the ^{6}Li$(\alpha,2\alpha)pn$ reaction at 120 MeV (Ref. 6). The curve shows the predictions of the plane-wave theory of Refs. 6 and 7.

known[13] that for fixed momentum transfer the dependence upon bombarding energy is weak. These plots provided interpolated cross sections at these six energies for the five momentum transfers (ranging from 1.4 to 2.15 fm^{-1}) corresponding to the p-α quasifree scattering conditions of Table I. Plots for these five momentum transfers then allowed the cross sections at our quasifree scattering energies to be interpolated. Since these results were within 10% of those obtained from direct plots of interpolated 56° c.m. elastic cross sections versus energy, we concluded that this double-interpolation procedure is accurate to at least 10%.

In Fig. 2 we present spectral functions determined by solving Eq. (1) for $4\pi|\langle Q,k|^6\text{Li}\rangle|^2$ and substituting our measured ^{6}Li$(p,p\alpha)pn$ breakup cross sections and the existing p-α elastic scattering data.[10-15] Values of this quantity similarly obtained from the 120-MeV ^{6}Li$(\alpha,2\alpha)pn$ data[6] are shown on the same graph. These deduced values are compared with predictions obtained from the plane-wave model.[6,7] It is noteworthy that, even though the p-α and α-α quasifree scattering experiments are at such different energies (200 and 120 MeV, respectively) and scattering angles (56° and 90° c.m., respectively), the downward trend of the predictions with increasing k is followed by the data over 4 orders of magnitude. Most of the data agree with the predictions within a factor of 2. This may be as much as one can expect of the plane-wave model, considering that neither the data nor the predictions have been renormalized.

The large deviation of the $(\alpha,2\alpha)$ datum at $k=0.78$ fm^{-1} may indicate deviations of the off-energy-shell α-α interaction from that given by the final-state energy prescription. The α-α data are more sensitive than the p-α data to the prescription used, since the α-α elastic cross sections used to obtain the data of Fig. 2 vary by a factor of 100 while those for the p-α cross section vary by only a factor of 5.

Other large deviations occur below $k=0.5$ fm^{-1} in the region where the theory predicts a deep minimum, caused by interference between plane-wave and scattering terms in the Yamaguchi function. This minimum is expected to be absent from Faddeev model calculations,[5] and one could expect a proper microscopic treatment to show large corrections at nearby k, as well.

B. Asymmetry of the ^{6}Li$(p,p\alpha)pn$ reaction

Our measured asymmetries for the ^{6}Li$(p,p\alpha)pn$ reaction are plotted versus bombarding energy (deduced with the final-state energy prescription) in Fig. 3. There they

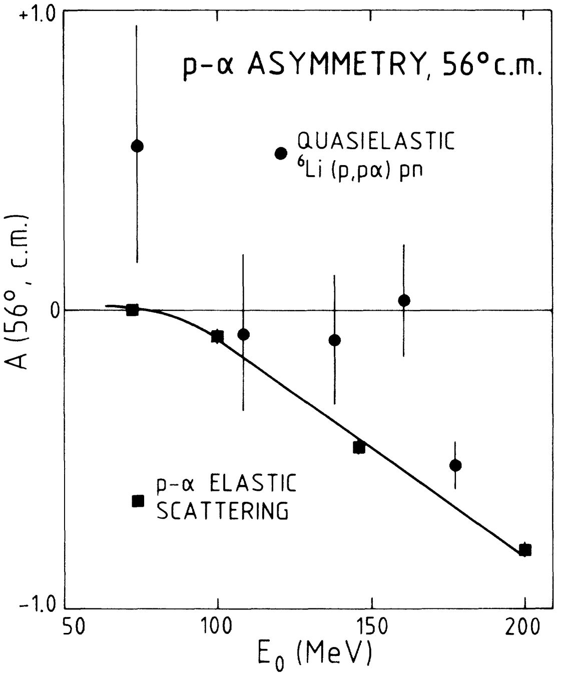

FIG. 3. Asymmetry versus equivalent bombarding energy (final-state energy prescription) for quasifree p-α scattering in the reaction ^{6}Li($p,p\alpha$)pn at 200 MeV (round data points). Proton and α-particle energies and angles were selected as described in Fig. 1 caption. Square data points show measured asymmetries for 56° c.m. elastic p-α scattering at laboratory energies of 72 through 200 MeV (Refs. 10, 13, 15, and 16); these are connected by a smooth curve to guide the eye.

are compared with asymmetries measured[10,13,15,16] for p-α elastic scattering. Our data have large statistical uncertainties, but they nevertheless establish an energy dependence for quasielastic scattering at least as steep as that of the elastic data. Asymmetries in nucleon-nucleon quasifree scattering are also of high current interest. At high intermediate energies, where exchange contributions are small, they are generally suppressed[17] relative to elastic asymmetries. Better statistical accuracy for quasifree p-α asymmetries are clearly needed to determine the systematics. This might establish whether the apparent shift of our data toward positive values, as compared with those for elastic p-α scattering, results only from statistical fluctuations, or from exchange effects or failure of the final-state energy prescription to describe adequately the off-shell p-α interaction. In the latter case, the quasielastic scattering may behave as if it took place at energies slightly lower than those given by this prescription. Quasielastic-scattering asymmetries may also differ from those for elastic scattering as a result of the spin-dependent terms in the optical potentials which determine the distorted waves. Such effects, however, are largest at low bombarding energies.

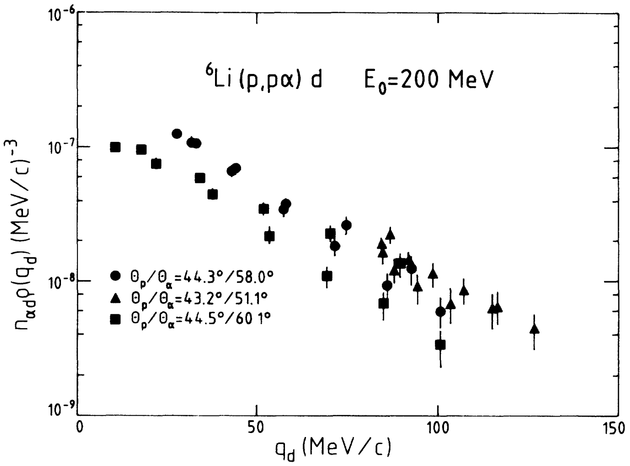

FIG. 4. Data for ^{6}Li($p,p\alpha$)d reaction at 200 MeV. Ordinate is described in text [Eq. (2)]; abscissa is final deuteron laboratory momentum.

C. The ^{6}Li($p,p\alpha$)d reaction

Events from the three-body reaction ^{6}Li($p,p\alpha$)d also were analyzed to test the energy calibration and beam normalization. These data, for three geometries, are presented in Fig. 4. When they are interpreted[18] using the plane-wave impulse approximation, the cross section for this reaction can be written as

$$\frac{d^3\sigma}{d\Omega_p d\Omega_\alpha dE_\alpha} = \text{KF} \left[\frac{d\sigma}{d\Omega} \right]_{p\alpha} \eta_{\alpha d}\rho(q_d) , \tag{2}$$

where KF is the kinematical factor and $\eta_{\alpha d}$ is the α-d clustering probability for the ^{6}Li ground state. The p-α elastic cross section[15] at 200 MeV and 56° c.m. was taken to be 0.52 mb/sr. The distribution $\rho(q_d)$ in the momentum q_d of the spectator deuteron has been calculated by Kudeyarov *et al.*[19] who find $\rho(0)=4.2\times10^{-7}$ (MeV/c)$^{-3}$sr^{-1}. Our 200-MeV quasielastic ^{6}Li($p,p\alpha$)d data then yield a cluster probability $\eta_{\alpha d}$ of (0.4±0.1). This is consistent with the systematics established by the quasielastic ^{6}Li(p,pd)α measurements of Ruhla *et al.*[20] and Alder *et al.*,[18] who find $\eta_{\alpha d}=(0.31\pm0.15)$ and (0.80 ± 0.06) at 155 and 590 MeV, respectively. The data of Fig. 4 indicate normalization uncertainties of about ±40% in this experiment.

IV. CONCLUSIONS

Our data for the ^{6}Li($p,p\alpha$)pn reaction at 200 MeV, combined with the earlier ^{6}Li($\alpha,2\alpha$)pn data,[6] determine the spectral function for p-n pairs in ^{6}Li with relative momenta between 0.1 and 1.5 fm^{-1}. Within this range, this function drops by more than 4 orders of magnitude. The function and its energy dependence are fitted remarkably well (usually within a factor of 2, without renormalization) by a simple plane-wave model, except near $k=0.2$ fm^{-1} where a minimum is predicted.

Data simultaneously obtained for the ^{6}Li($p,p\alpha$)d reaction yield a ^{6}Li ground-state d-α clustering probability consistent with the systematics of those obtained from other intermediate-energy measurements. This procedure verifies the normalization of the ^{6}Li($p,p\alpha$)pn cross sections.

Measured asymmetries for the $^6\mathrm{Li}(p,p\alpha)pn$ reaction at 56° c.m. have roughly the same bombarding-energy dependence as those for p-α elastic scattering, which indicates that quasielastic scattering is the principal reaction mechanism for four-body breakup. This comparison uses the final-state energy prescription to find the equivalent bombarding energy for the four-body reaction. The statistical uncertainties for the four-body data are large, precluding a sensitive test of this prescription.

The success of our very simple model in interpreting these data adds interest to the anticipated Faddeev calculations[5] of the ^{6}Li ground-state spectral function. They, in particular, are expected to fill in the minimum near $k=0.2\ \mathrm{fm}^{-1}$ which the simple theory predicts. More generally, we expect that measurements of greater precision and at higher bombarding energies (where a larger range of p-n internal momenta k can be investigated) will then be needed to fully exploit the predictions of a more sophisticated theoretical model.

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