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LARGE-ANGLE QUASI-FREE SCATTERING IN $^{6}Li(p,pd)\,^{4}He$ AT 670 MeV

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V.I.Petrukhin, Z.Seres,[1] L.Végh[2]

LARGE-ANGLE QUASI-FREE SCATTERING IN ^{6}Li(p,pd) ^{4}He AT 670 MeV

Submitted to "Nuclear Physics"

[1] On leave from the Central Research Institute for Physics of the Hungarian Academy of Sciences, Budapest, Hungary.

[2] On leave from the Institute of Nuclear Research of the Hungarian Academy of Sciences, Debrecen, Hungary.

Альбрехт Д. и др. E1 - 12727

Квазисвободное рассеяние на большие углы в реакции $^6Li(p,pd)^4He$ при 670 МэВ

Экспериментально исследована реакция $^6Li(p,pd)^4He$ в геометрии рассеяния на большие углы с регистрацией совпадений вторичных частиц. Измерены распределения энергии между продуктами реакции и их угловые корреляции и определены импульсные распределения продуктов реакции для переходов, приводящих к образованию остаточного ядра в основном и возбужденных состояниях. Результаты анализируются в рамках импульсного приближения с использованием кластерной модели и трехтельных волновых функций. Переходы в основное и возбужденные состояния α-частицы имеют характеристики квазисвободного рассеяния на дейтронных кластерах, соответственно в p- и s-оболочке. Импульсное распределение p-n пары в p-оболочке ^6Li хорошо описывается расчетами по трехтельной модели, однако спектроскопический множитель больше предсказанного теорией.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Albrecht D. et al. E1 - 12727

Large-Angle Quasi-Free Scattering in $^6Li(p,pd)^4He$ at 670 MeV

The $^6Li(p,pd)^4He$ reaction was investigated at 670 MeV by coincidence experiment at large-angle scattering geometry. Energy sharing and angular correlation of the reaction products were measured and momentum distribution of the recoil nucleus was determined for transitions leading to residual nucleus in ground and excited states, respectively Results were analysed in terms of a simplified distorted wave impulse approximation using cluster model and three-body wave functions. The observed momentum distribution of the p-n pair in the p-shell of ^6Li is in agreement with three-body calculations, the spectroscopic factor is larger than predicted by theory. Transitions to breakup states of the α-particle also have the characteristics of quasi-free scattering on deuteron clusters.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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1. INTRODUCTION

The study of the quasi-free scattering at high energies has /1-4/ the advantage that distortion effects are reduced and the comparison with theoretical predictions is more reliable. The large width of the momentum distribution above 500 MeV, being in contradiction with realistic intercluster wave functions /5/, raises therefore the question about the adequacy of describing ^6Li as a simple $\alpha-d$ system. Further experimental and theoretical investigations are of interest because the simple structure of the p-shell in ^6Li gives the hope of finding an accurate wave function for the proton-neutron pair and thereby to understand the interaction of protons with this system.

In the present work the $^6Li(p,pd)^4He$ reaction was measured at 670 MeV in a kinematically complete experiment. Large-angle scattering geometry was used because the mechanism of the backward p-d scattering is well investigated at intermediate energies and the interaction is sensitive to the short range behaviour of the two-particle wave function owing to the large momentum transfer. Experimental results will be presented for momentum densities of the deuteron clusters in the p- and s-shell of ^6Li and they will be compared with predictions from conventional cluster models and from three-body calculations.

2. THEORETICAL CONSIDERATIONS

The cross section of the quasi-free scattering is described by the distorted wave impulse approximation as /6/

$$\frac{d^5\sigma}{d\Omega_d\, d\Omega_p\, dT_p} = KS\left(\frac{d\sigma}{d\Omega}\right)_0 P(q). \qquad (1)$$

In this formula K is kinematic factor and S stands for the spectroscopic factor of the deuteron component in the target nucleus. The cross section of the quasi-free p-d scattering, denoted by $(d\sigma/d\Omega)_0$, is usually taken equal to $(d\sigma/d\Omega)_{pd}$, the cross section of the free p-d scattering. The quantity P(q) is the momentum distribution of the cluster in the target modified by distortion effects. The momentum $\vec{q}$ is connected with that of the recoil nucleus $\vec{p}_B$ by the relation $\vec{q} = -\vec{p}_B$. The quantity

$$\rho(q) = \frac{d^5\sigma}{d\Omega_d d\Omega_p dT_p} / K\left(\frac{d\sigma}{d\Omega}\right)_{pd} = SP(q) \qquad (2)$$

is the so-called experimental momentum density. In experiments detecting only the deuterons [1] the inclusive cross section of the quasi-free scattering $d^3\sigma/d\Omega_d dp_d$ is obtained by integrating expression (1) for all proton directions and summation is to be performed for the partial cross sections related to different final states of the residual nucleus.

3. MEASUREMENT AND EXPERIMENTAL RESULTS

The reaction $^6Li(p,pd)^4He$ was investigated in coplanar geometry detecting the deuterons at θ_d=6.5°. The protons were detected at eight different angles near θ_p=147°, the corresponding kinematic lines are illustrated in fig. 1 by heavy lines labelled (1-8). To get information about the large recoil momentum region, measurement was made at θ_p=110° too (curves labelled (9-12)). The end points of the lines in the figure represent experimental limits where the efficiency of the detector system falls below 50%. The experimental arrangement was similar to that described in a previous paper [7].

Before measuring the $^6Li(p,pd)^4He$ reaction, the apparatus was calibrated using deuterons and protons from the free p-d scattering. In this measurement LiD was used as the deuteron target, the correction for the lithium content was made by an additional measurement with natural lithium. For the cross section of the free p-d scattering at θ = 6.5°, $(d\sigma/d\Omega)_{lab}$ = 510 ± 50 μb/sr was obtained corresponding to $(d\sigma/d\Omega)_{c.m.}$ = 110 ± 11 μb/sr at $\theta_{c.m.}$=165° in agreement with the value 115 μb/sr obtained by extrapolating the data of other measurements to 670 MeV.

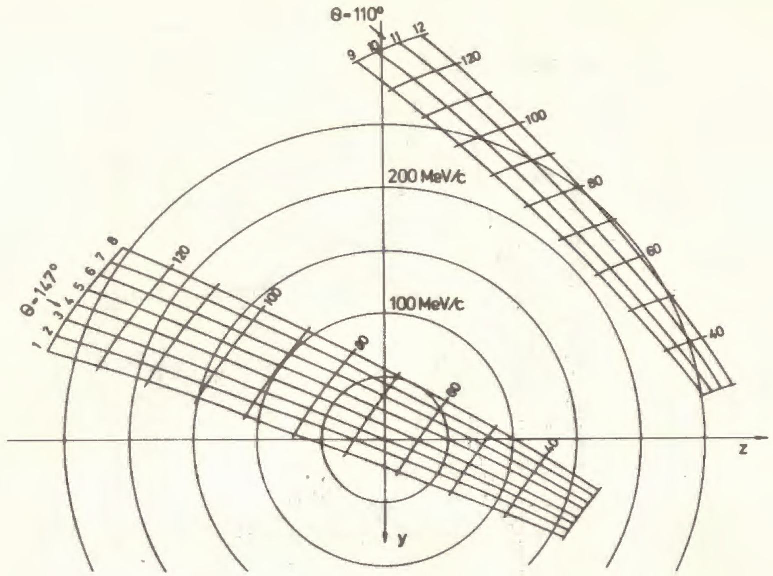

Fig.1. The kinematic conditions in the experiment. Heavy lines show the recoil momentum region where the efficiency of the detector system was larger than 0.5. The indices (1-12) refer to the position of the array detectors; numbers (40-120) denote the corresponding energy of the protons; the circles give the value of the recoil momentum.

The missing energy spectrum measured at θ_p=147° is presented in fig. 2. The large peak at E_{miss}=1.47 MeV is related to interactions with the deuteron cluster in the p-shell leaving the α-particle in its ground state. The width of the peak reflects the experimental resolution (ΔE_{miss} =17 MeV FWHM). Missing energies for the different break-up of the α-particle range from 25.2 MeV ($\alpha \to d+d$) to 29.7 MeV ($\alpha \to 2p+2n$). The bump around 27 MeV is connected with these processes while the tail above 40 MeV probably comes from secondary interactions.

To separate the three different groups the spectrum was decomposed by two Gaussian distributions of 17 MeV FWHM having maxima at 1.5 MeV and 27.5 MeV and the remainder

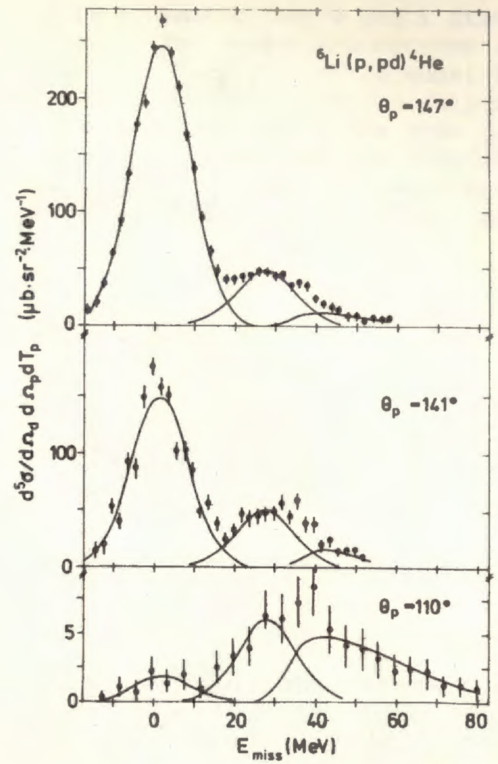

Fig. 2. Missing energy spectra at proton angles θ_p=147°, 141° and 110°. Curves are fitted Gaussian distributions related with the experimental resolution (see text).

was described by an asymmetric Gaussian peaking at 40 MeV as is shown in the figure by thin lines. As illustration, missing energy spectra at angles θ_p=141° and 110° are also shown in the figure demonstrating the rapid fall of the ground state peak with proton angle.

The energy distribution of protons for the ground state transition was determined from the energy-sharing data taking into account only events with missing energy E_{miss} < 4 MeV in order to exclude any contribution from the excited states. The differential cross section $d^5\sigma/d\Omega_d d\Omega_p dT_p$ measured at θ_p=147° is presented in fig. 3 by points with error bars.

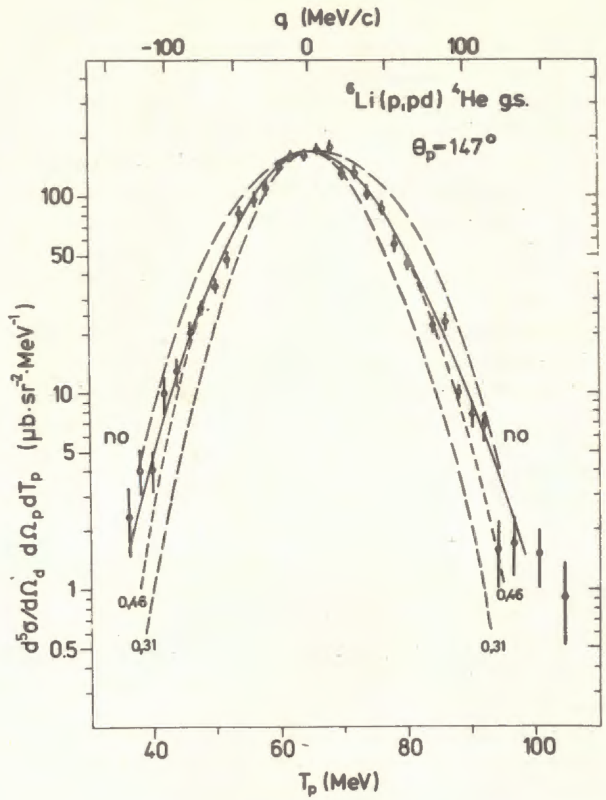

Fig.3. Energy distribution of the protons from the ground state transition at θ_p =147° in coincidence with the deuterons at θ_d =6.5°. Upper scale denotes the corresponding recoil momentum. Broken lines are calculated distributions using cluster model wave function given in ref. /9/ (no) and its modified form with different exponential tails (κ =0.31 fm^{-1} and 0.46 fm^{-1}). Full line is based on three-body calculation of Rai et al /10/.

To determine the width of the momentum distribution the fitting procedure was restricted to the low momentum region of the spectrum ($q < 70$ MeV/c). For the sake of technical simplicity Gaussian distributions $P(q) \sim \exp(-q^2/q_0^2)$

where assumed with various q_0. The best fit was obtained at q_0=51.5 ± 2.5 MeV/c corresponding to half width $q_{1/2}$ =86 ± ±4 MeV/c (FWHM). The chisquare per degree of freedom was χ^2/N =2.2 taking into account statistical errors only. The quoted uncertainty refers to confidence interval with $\chi^2/N < 3$. The experimental momentum density at zero momentum is $\rho(0) = (8.5 \pm 0.8)\cdot 10^{-7}$ (MeV/c)$^{-3}$. In fig. 3 the full line and the three dashed lines are calculated distributions using different wave functions and will be discussed further below.

Energy distributions of the protons related to the break-up of the α-particle are presented in fig. 4. They were measured at θ_p=147° and 110° for events in missing energy ranges $16 < E_{miss} < 30$ MeV and $10 < E_{miss} < 30$ MeV, respectively. Best fit was obtained at both angles assuming Gaussian momentum distribution with q_0 =133 MeV/c providing $q_{1/2}$ =220 ± 15 MeV/c (FWHM). The curves in the figure are the calculated cross sections using the same normalization for both angles. The corresponding density at zero momentum is $\rho(0) = (8.1 \pm 0.8)\cdot 10^{-8}$ (MeV/c)$^{-3}$.

The integrated cross sections measured at different angles are given in the table for the ground state, the break-up and the large missing energy groups, respectively. The numbers in the first column refer to the labels of the kinematic lines in fig.2. The angular distribution of the ground state group is presented in fig. 5, the full line is the result of calculation with Gaussian momentum distribution (q_0 =51.5 MeV/c). The experimental data are well reprodiced showing that the angular dependence of the cross section is in accordance with the energy-sharing measurement.

The calculated angular distribution of the break-up group varies only ~5% in the central region, this is within the error of the experimental data. The cross section of the large missing energy group is approximately constant in the whole angular range up to 110°.

The momentum distribution of the forward going deuterons (θ_d =6.5°) measured without coincidence condition is represented in fig. 6. Owing to the large difference between the binding energies of the deuterons in the s- and p -shells the momentum spectra belonging to the ground state and the break-up transitions are separated quite well allowing one to estimate their relative weights. The dashed lines in the figure are the results of calculations with ap-

Table

Angular distribution of protons

No.	Θ_p	$\frac{d^4\sigma}{d\Omega_d d\Omega_p}$ (mb·sr^{-2}) ground state	break-up	large missing energy
1	151.6	3.54 ± 0.14	0.83 ± 0.07	0.25 ± 0.05
2	150.0	4.23 ± 0.15	0.78 ± 0.07	0.11 ± 0.05
3	148.4	4.84 ± 0.16	0.91 ± 0.07	0.33 ± 0.05
4	146.9	4.37 ± 0.15	0.88 ± 0.07	0.23 ± 0.05
5	145.1	3.80 ± 0.13	0.81 ± 0.07	0.22 ± 0.05
6	143.6	3.20 ± 0.12	0.89 ± 0.07	0.12 ± 0.05
7	142.0	2.44 ± 0.11	0.87 ± 0.07	0.21 ± 0.05
8	140.4	1.96 ± 0.09	0.90 ± 0.07	0.15 ± 0.05
9-12	110.0	0.033 ± 0.004	0.105 ± 0.006	0.149 ± 0.015

propriate normalization to fit experimental data, the solid line is their sum. The excess at deuteron momenta comes from the tail of the ^{6}Li(p,πd) reaction[/1/] peaking

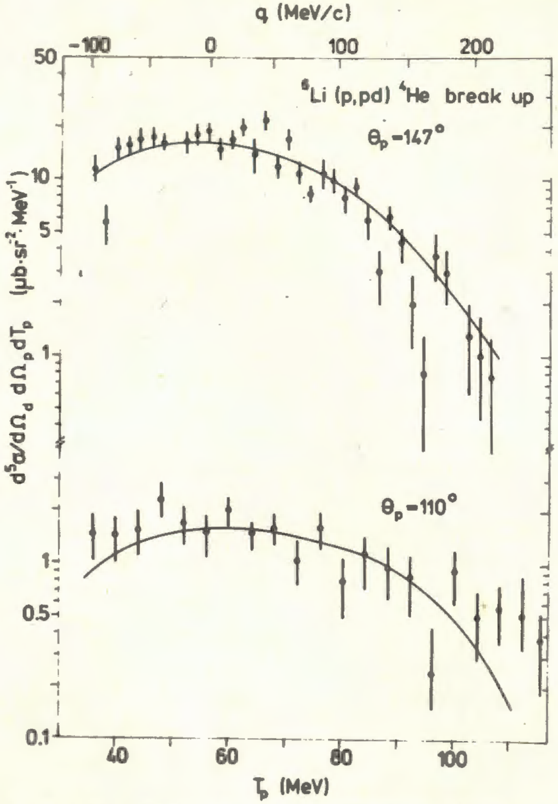

Fig.4. Energy distributions of protons from break-up prosses at θ_p =147° and 110° in coincidence with deuterons at θ_d =6.5°. Upper scale denotes the corresponding recoil momentum. The lines are calculated distributions using Gaussian distribution function with q_0 =133 MeV/c.

at 1375 MeV/c and due to events having large missing energy. The small bump at large momenta is associated probably with the puck-up reaction. The arrow in the figure points to the maximum possible momentum of the deuterons from this process. The inclusive cross section integrated for

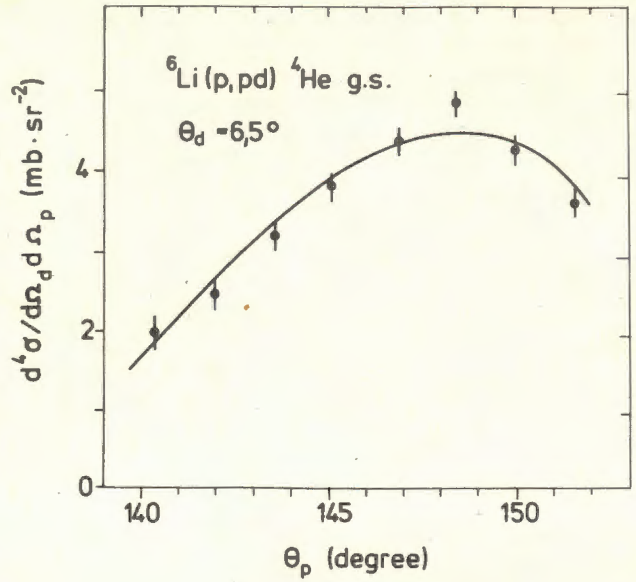

Fig.5. Angular distribution of protons from the ground-state transition. The line is the calculated distribution using Gaussian momentum distribution (q_0 =51.5 MeV/c).

momenta between 1500 MeV/c and 1650 MeV/c is $(d\sigma/d\Omega)_{incl.}$ = =2.1 ± 0.2 mb/sr. This value is near to that given in ref.[/1/] at θ_d=9.5°(1.7 ± 0.2 mb/sr). The partial inclusive cross sections for the ground state and the break-up groups obtained by integrating the calculated spectra are 0.56 ± ±0.09 mb/sr, respectively.

4. DISCUSSION

4.1. Ground State Transitions

In the experiment reported in ref.[/2/] the ^{6}Li(p,pd)^{4}He reaction was measured at 590 MeV in symmetric geometry and $q_{1/2}$ =122 ± 3 MeV/c was found for the width of the ground state momentum distribution. Various intercluster wave functions were used to describe the experimental momentum distribution: among them the cluster model wave function

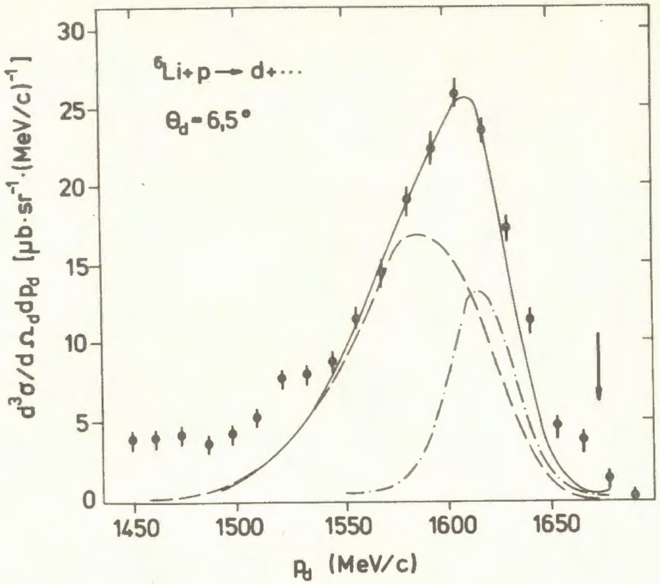

Fig.6. The inclusive cross section of the deuterons at $\theta_d = 6.5°$ as a function of the deuteron momentum. The broken lines were calculated for the ground state and the break-up transitions, the full line is their fitted sum. The arrow points to the maximum deuteron momentum allowed in the (p,d) pick-up reaction.

of Kurdyumov et al. /8/ without exponential tail predicts $q_{1/2}$=110 MeV/c, close to the experimental value. In a subsequent work /3/, however, the same experiment was analysed in terms of pole approximation and best fit was obtained with κ =0.34 fm^{-1} corresponding to $q_{1/2}$ =84 MeV/c (FWHM). The ambiguity is caused probably by the absence of experimental data at low recoil momenta.

The half width determined in the present experiment ($q_{1/2}$ =86 MeV/c) is in accordance with the result given in ref. /3/, however, it is definitely larger than widths associated with cluster model wave functions having the desired asymptotics (see the table). Proton energy distributions were calculated using the wave function given

by Kudeyarov et al. /9/ with an exponential tail and without it. They are represented in fig. 3 by lines labelled (0.31) and (no), respectively. The deviation from the experimental points is obvious. By varying κ in the exponential function a good fit was obtained with κ =0.46 fm^{-1} (dashed line labelled (0.46)) describing the energy distribution in almost the whole investigated energy range. In fig. 7 the dashed line represents the momentum density

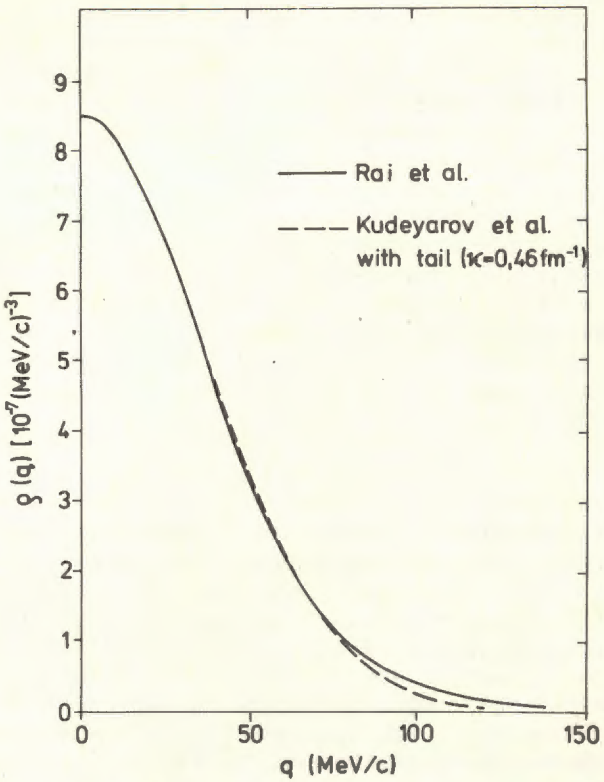

Fig.7. Momentum distributions used in calculations giving best fit to the experiment. Full line: three-body calculation (ref. /10/); broken line: cluster model wave function (ref. /18/) with exponential tail (κ= 0.46 fm^{-1}).

associated with this wave function and normalized to the experimental value at $q=0$. In spite of the good fit this wave function may be regarded only as a phenomenological one and not as a correct intercluster wave function because it has no the desired asymptotic behaviour.

The fact that the experimental data inconsistent with calculations based on realistic cluster model wave functions suggests that the (p,pd) reaction at high energies cannot be interpreted satisfactorily by assuming for the ^{6}Li nucleus a simple α-d structure. In contrast to the cluster model, three-body calculations (describing ^{6}Li as alpha-core plus two nucleons) provide more sophisticated treatment for the two particle wave function. Rai et al.[10] in their calculations determined the momentum distribution of the deuteron component and gave it in the form of a Chew-Low plot. The width $q_{1/2}=85$ MeV/c, as obtained from the plot, is in excellent agreement with the present experimental value and calculation using momentum distribution of the form reconstructed from the Chew-Low plot reproduces well the experimental energy distribution as shown in fig. 3 by the full line. This momentum distribution normalized to the experiment is shown in fig. 7 by full line. The three-body calculation of Rai et al. predicts momentum density $\rho^{th}(0) = 6.33 \cdot 10^{-7}$ (MeV/c)$^{-3}$ for the deuteron component at $q=0$ and the value $S^{th}=0.65$ for the spectroscopic factor. Calculations presented in the very recent work of Bang and Gignoux[11] support the results given in ref.[10] and predict the spectroscopic factor $S^{th}=0.52$.

The experimental spectroscopic factor can be obtained from the measured momentum density, according to eq. (2), as $S=\rho(0)/P(0)$. In this expression $P(0)$ is the distorted distribution function at $q=0$ and includes the effect of the absorption. The calculation gives $P(0) = 7.84 \cdot 10^{-7}$ (MeV/c)$^{-3}$ and the corresponding spectroscopic factor is $S = 1.08 \pm 0.10$. When calculating in plane wave approximation $P^{PW}(0) = 10.2 \cdot 10^{-7}$ (MeV/c)$^{-3}$ was obtained, i.e., the absorption reduces by 25% the distribution function at zero momentum. The spectroscopic factor is related to the inclusive cross section too. The calculated deuteron spectrum in fig. 6 was obtained by integrating eq. (1) for all proton directions taking into account only the deuteron absorption when constructing P(q). The fit to the experiment provided $S = 1.31 \pm 0.18$ which is close to the value obtained in the coincidence measurement. If we neglect the absorption the calculated inclusive cross section increases by 12% and the spectroscopy factor correspondingly decreases by the same amount.

The difference between experimental and theoretical spectroscopic factors may have different origins. Besides the quoted errors an additional uncertainty comes from the approximations when determining $P(0)$, especially due to the simple way of handling the absorption. The theoretical S^{th} may also be uncertain. In this respect we refer to article [9] where a spectroscopic factor near unity has been reported, although values around 0.6 seem more acceptable for the percentage of the d-α component[12] in ^{6}Li. Finally, it is also possible that $(d\sigma/d\Omega)_0$, the cross section of the elementary quasi-free scattering, is larger than that of the free p-d scattering. This may be the consequence of the large-angle scattering geometry used in the present experiment as at backward angles the exchange mechanism by virtual pion production proposed by Craigie and Wilkin[13] seems to have a dominating role in the p-d scattering around 670 MeV and this mechanism is sensitive to the actual form of the proton-neutron relative wave function[14]. Any deformation of the deuteron cluster, may be reflected in the change of the elementary cross section.

4.2. Break-up of the Alpha-Core

Above the ground state peak the missing energies are near the break-up energy of the alpha-core (see fig. 2) and we associate these events with the quasi-free scattering of protons on deuteron clusters in the s-shell. For these events the internal kinetic energy of the residual four-nucleon system is small in accordance with the assumptions of the quasi-free scattering approximation, and the validity of this model is supported also by the fact that the energy distribution of the protons may be described by formula (1). The width of the momentum distribution ($q_{1/2}=220$ MeV/c) is equal (within error limits) with $q_{1/2}=210$ MeV/c obtained in the case of free alpha particle[15] in reaction ^{4}He(p,pd)^{2}H at 156 MeV. The experimental momentum density at zero momentum [$\rho(0) = 8.1 \times 10^{-8}$ (MeV/c)$^{-3}$] is more than two times larger than the value $\rho(0) = 3 \cdot 10^{-8}$ (MeV/c)$^{-3}$ reported in ref.[15]. The difference may be accounted for by the increased absorption at 156 MeV.

The observed spectroscopic factor of the deuteron component in the alpha-core is $S^{obs} = 0.90 \pm 0.10$ as obtained from $\rho(0)$ if Gaussian momentum distribution was assumed with $q_0 = 133$ MeV/c and the absorption was neglected, whereas the inclusive deuteron cross section gives $S^{obs}_{incl} = 2.7 \pm 0.5$. The difference between the two values suggests that the transmission probability of protons originating in the s-shell is $T_p \approx 0.3$, a reasonable value being in rough agreement with the calculated $T_p^{calc} \approx 0.33$ obtained simply by integrating the absorption in the residual nucleus along the radius. To get the spectroscopic factor $S = S^{obs}_{incl}/T_d$ the transmission probability of the deuteron (T_d) was calculated and it was found to be $T_d \approx 0.45$. With this transmission probability we get $S \approx 6$ which is too large when keeping in mind the value 2.4 predicted by Kudeyarov et al. /9/ for transitions above the ground state of the residual nucleus.

5. SUMMARY

In this work the cluster structure of ^6Li has been investigated in the $^6Li(p,pd)^4He$ reaction with 670 MeV protons at large scattering angles associated with large momentum transfer. In the ground state transition the momentum distribution of the recoil nucleus is only slightly modified by distortion effects at energies above 600 MeV. The experimental width of the distribution is larger than predicted by the cluster model if realistic intercluster wave functions are used with correct exponential asymptotics; three-body calculations, however, provide a momentum distribution which is in very good agreement with experiment. The experimental momentum density of the deuteron component in the p-shell is larger than given by the three-body model and provides a spectroscopic factor near unity instead of the theoretically estimated value near 0.6. Besides taking into account experimental as well as theoretical uncertainties in determining this quantity a possible explanation of the deviation may be given by assuming different cross sections for the proton scattering on free deuterons and on p-n pairs in ^6Li, respectively.

Interactions followed by the break-up of the residual nucleus have also a quasi-free character and can be interpreted as scatterings on quasi-deuterons in the alpha-core. The absorption of the secondary protons in the residual nucleus was determined experimentally and agreements was found with the calculated absorption. The spectroscopic factor of the deuteron component in the alpha-core was found to be larger than the theoretical prediction when the absorption of the deuteron is taken into account.

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