

## Quasifree Scattering in the ${}^6\text{Li}(\alpha, 2\alpha){}^2\text{H}$ Reaction at $E_\alpha=118$ MeV

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Three body breakup cross sections for the  ${}^6\text{Li}(\alpha, 2\alpha){}^2\text{H}$  reaction were measured at  $E_{inc}=118$  MeV in coplanar symmetric geometry. In spectra projected on the energy axis ( $E_1$ ) for one scattered  $\alpha$ -particle, quasifree scattering enhancements were seen at the points of minimum recoil deuteron energy ( $E_d$ ). The recoil deuteron momenta at these minima varied from  $-120$  MeV/c to  $+226$  MeV/c. DWIA calculations were used to analyze the experimental data. Except at  $\theta_\alpha=35^\circ$  and  $50^\circ$ , good fits to the data were obtained. The width of the QFS peak was 71 MeV/c (FWHM) and the spectroscopic factor  $C_{ad}$  was 0.82. These results were consistent with those obtained from the  ${}^6\text{Li}(p, pd){}^4\text{He}$  reaction.

KEYWORDS: Nuclear reactions  ${}^6\text{Li}(\alpha, 2\alpha){}^2\text{H}$ ,  $E=118$  MeV/ Measured three body breakup cross sections/ Compared with distorted wave impulse approximation calculations/ Enriched  ${}^6\text{Li}$  target.

### 1. INTRODUCTION

${}^6\text{Li}$  is loosely bound and breaks easily into a tightly bound alpha particle and a deuteron or two nucleons. Therefore, the low energy properties of  ${}^6\text{Li}$  can be treated as the  $\alpha-d$  and  $\alpha-N$  or  $\alpha-N-N$  cluster models. In our recent papers, three body breakup channel ( $\alpha-p-n$ ) of  ${}^6\text{Li}$  has been discussed.<sup>1)</sup> In the present study, we will discuss about the  $\alpha-d$  cluster model of  ${}^6\text{Li}$ . According to the recent microscopic theories,<sup>2,3)</sup>  $\alpha-d$  component of  ${}^6\text{Li}$  ground state wave function can be calculated exactly from the  $\alpha-N-N$  three body model. Therefore, to study  $\alpha-d$  cluster structure experimentally is of great interest. Many experimental studies of  ${}^6\text{Li}$  cluster structure have been done. Distorted Wave Impulse Approximation (DWIA) calculations are often used to analyze these experimental data. In applying the DWIA to analyze data, good probes and high enough energies must be chosen in order that the knockout process is the dominant reaction mechanism. According to the DWIA analyses by Chant and Roos,<sup>4)</sup> at incident energies between 100–200 MeV, the  $(p, p\alpha)$  knockout reaction is a suitable tool to study nuclear structure, whereas for the  $(\alpha, 2\alpha)$  reaction, higher energies are more appropriate.

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However their studies were restricted to nuclei heavier than  $^{12}\text{C}$ . Therefore studies of the  $(\alpha, 2\alpha)$  reaction for light nuclei like  $^6\text{Li}$  are of interest.

The  $^6\text{Li}(p, p\alpha)$  reaction was studied at  $E=100$  MeV by Roos et al.<sup>5)</sup> and the spectroscopic factor  $N=0.58$  was deduced from the DWIA analysis. On the other hand, studies of the  $^6\text{Li}(p, pd)$  reaction at  $E=120$  and  $200$  MeV<sup>6)</sup> give spectroscopic factors 0.76 and 0.84, respectively. These values are consistent with the results (0.69–0.76) of a microscopic calculation by Kukulin et al.,<sup>2)</sup> and higher than that (0.65) by Lehman and Rajan.<sup>3)</sup> In general, DWIA calculations are strictly factorable for  $(p, p\alpha)$  and  $(\alpha, 2\alpha)$  reactions, but not for  $(p, pd)$ . Therefore, it is quite interesting to study  $^6\text{Li}$  clustering with the  $(\alpha, 2\alpha)$  reaction and to compare the results with those deduced from the  $(p, pd)$  and  $(p, p\alpha)$  reactions. Watson et al.<sup>7)</sup> studied the  $^6\text{Li}(\alpha, 2\alpha)$  reaction in detail at 50 to 80 MeV bombarding energies. Their analysis with the Plane Wave Impulse Approximation (PWIA) gives an  $\alpha + d$  clustering probability for the  $^6\text{Li}$  ground state ( $N_{eff}$ ) of 0.08. This result suggests that since the reaction mechanism is more complicated at these low bombarding energies, the PWIA is not applicable for the  $(\alpha, 2\alpha)$  reaction. At the higher bombarding energy of  $E=700$  MeV, Dollhopf et al. deduced  $N_{eff}=0.98$  from the  $^6\text{Li}(\alpha, 2\alpha)$  reaction by using a PWIA calculation.<sup>8)</sup> This value was compatible with the one deduced from the  $^6\text{Li}(p, pd)$  reaction at  $E=600$  MeV.<sup>9)</sup> Therefore at such high energies, the knockout reaction is dominant and the distortion effect can be neglected for  $(p, pd)$  and  $(\alpha, 2\alpha)$  reactions. So it is very interesting to determine at what energy the PWIA becomes valid. In the present study,  $^6\text{Li}$  clustering is investigated by using the  $(\alpha, 2\alpha)$  reaction at the bombarding energy  $E=118$  MeV, in the recoil deuteron momentum region from  $-120$  MeV/c to  $+226$  MeV/c. For the  $(p, pd)$  reactions at  $E=120$  and  $200$  MeV, DWIA calculations succeeded for small deuteron momenta in  $^6\text{Li}$ , but in the region larger than  $100$  MeV/c they gave a poor fit. So it is interesting to study the large momentum region. The present data are analyzed with a DWIA calculation, using a  $2S$  Woods-Saxon  $^6\text{Li}$  bound state wave function which is same as the one used for the above  $(p, pd)$  and  $(p, p\alpha)$  studies. The results are compared with those from the  $(p, pd)$  reaction at  $120$  MeV, and from  $(p, p\alpha)$  at  $100$  MeV.

## 2. EXPERIMENTAL PROCEDURE

An alpha particle beam accelerated by the AVF cyclotron at the Research Center for Nuclear Physics (RCNP) of Osaka University bombarded a  $^6\text{Li}$  target (95.45% enrichment). The target thickness was  $5$  mg/cm<sup>2</sup> and the energy at the target center was  $117.7$  MeV. The beam current was kept between  $20$  and  $40$  nA to limit the random coincidence rate. Coincident  $\alpha$ -particles were detected by two pairs of telescopes set in coplanar symmetric geometry. One telescope pair, consisting of  $150$   $\mu\text{m}$   $\Delta E$  and  $5$  mm  $E$  silicon detectors, was used for the measurements at forward angles from  $35^\circ$  to  $44.4^\circ$ . The other pair consisted of  $100$   $\mu\text{m}$   $\Delta E$  and  $3$  or  $5$  mm  $E$  silicon detectors and was used for the backward angle measurements (angles larger than  $50^\circ$ ). The  $E$ ,  $\Delta E$  and time signals were transmitted through a raw data processor to a PDP 11 computer. The offline analyses were done with the computers FACOM 380 at RCNP, FACOM 360R at Kyoto University of Education, and VAX 8300 at Kernfysisch Versneller Instituut (KVI). Measurements at six angle pairs were made in the recoil momentum region between  $-120$  MeV/c and  $+226$  MeV/c. We define a negative (positive) deuteron momentum as one when the deuteron moves parallel (antiparallel) to the beam direction. Integrated

### Quasifree Scattering in the ${}^6\text{Li}(\alpha, 2\alpha)$ Reaction at 118 MeV

charges of about  $10^{-3}\text{C}$  were accumulated at each of six angle pairs. The detectors were calibrated in energy both by measuring  $\alpha + d$  and  $\alpha + {}^6\text{Li}$  elastic scattering and by fitting the three body kinematic loci of the  ${}^6\text{Li}(\alpha, 2\alpha){}^2\text{H}$  and  ${}^9\text{Be}(\tau, 2\alpha){}^4\text{He}$  reactions. Events from the  ${}^7\text{Li}$  contaminants in the  ${}^6\text{Li}$  target were found to be 5–10% of the  ${}^6\text{Li}$  yield, and were subtracted by measuring the  ${}^7\text{Li}(\alpha, 2\alpha){}^3\text{H}$  reaction with an enriched  ${}^7\text{Li}$  target. The yields from  ${}^{16}\text{O}$  and  ${}^{12}\text{C}$  contaminants were negligibly small. (For details, see our other papers.<sup>1)</sup>) Particle identification and random event subtraction were made by analyzing both an two-dimensional  $E - \Delta E$  spectra of  $2\text{K} \times 2\text{K}$  channels and a  $2\text{K}$  time spectrum. Separations between  ${}^3\text{He}$  and  ${}^4\text{He}$  and between total and random events were adequate. Both  $64 \times 64$ - and  $128 \times 128$ -channel coincidence spectra were obtained for each angle pair and the three body breakup loci were identified. Separation from the continuum region was sufficient to cause negligible uncertainty in the cross sections determined for the three-body reaction. The three body loci were projected onto the energy axis ( $E_1$ ) for one alpha-particle detector.

The overall energy uncertainty of the present experiment was about 1 MeV and only statistical uncertainties of the cross section values were considered.

### 3. DWIA CALCULATIONS

The Distorted Wave Impulse Approximation (DWIA) method was summarized by Chant and Roos.<sup>4)</sup> In this method, the three body breakup cross section for the  ${}^6\text{Li}(\alpha, 2\alpha){}^2\text{H}$  reaction is described as follows.

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1} = S_{\alpha d} \times KF \times |\Phi(p_3)|^2 \times \left. \frac{d\sigma}{d\Omega} \right|_{\alpha\alpha}$$

$S_{\alpha d}$  is a spectroscopic factor (or the deuteron clustering probability in  ${}^6\text{Li}$ ) and  $KF$  is the kinematic factor.  $|\Phi(p_3)|^2$  is the deuteron momentum distribution in  ${}^6\text{Li}$  distorted by the initial and final potentials and  $p_3$  is the deuteron recoil momentum.  $\left. \frac{d\sigma}{d\Omega} \right|_{\alpha\alpha}$  is the  $\alpha - \alpha$  elastic scattering cross section at the final state  $\alpha - \alpha$  relative energy, used instead of a half off shell cross section. To obtain the deuteron momentum distribution distorted by the initial and final potential, Woods-Saxon type optical potentials were used. In Table 1, the potential parameters are listed. The notation is the conventional one. For the initial  $\alpha + {}^6\text{Li}$  system, parameters at  $E_\alpha = 104$  MeV by Devries et al.<sup>10)</sup> were used. Strictly, the initial channel distorting potential is the optical potential for scattering from the core averaged over the target.<sup>4)</sup> Therefore these potentials were modified by multiplying the depths of the real and imaginary potentials by 1/3 to reproduce the optical potential for scattering from the deuteron core averaged over the  ${}^6\text{Li}$  target. For the two final  $\alpha + d$  systems, the potential by Gross et al.<sup>11)</sup> was used. For the  ${}^6\text{Li}$  bound state wave function, both  $1S$  and  $2S$  functions have been used. Watson et al. assumed a  $1S$  state.<sup>7)</sup> However, in the cluster models, antisymmetrization leads to an effective  $\alpha - d$  wave function with  $2S$  form regardless of whether  $1S$  or  $2S$  is chosen initially.<sup>12)</sup> Therefore the  $2S$  Woods-Saxon

Table 1. Optical potential parameters.

Reaction	$E$ (MeV)	$V_0$ (MeV)	$r_0$ (fm)	$a_0$ (fm)	$W_0$ (MeV)	$W_0'$ (MeV)	$r'$ (fm)	$a'$ (fm)	$r_c$ (fm)
$\alpha + {}^6\text{Li}$	104	29.62	0.991	0.807	1.65	0.0	3.006	0.577	1.2
$\alpha + d$	58	78.1	1.32	0.620	0.0	2.03	3.23	0.65	1.3
$\alpha + d$		76.6	1.47	0.71					1.47

bound state wave function<sup>13)</sup> was used in this study. The potential depth was adjusted to fit the deuteron separation energy from  ${}^6\text{Li}$ ; its derived value was consistent with the one found by Roos et al.<sup>5)</sup> The elastic  $\alpha-\alpha$  cross section was calculated from phase shifts interpolated from those found by Darriulat et al.<sup>14)</sup> for the 53 and 120 MeV region. The scattering angles and energies of  $\alpha-\alpha$  scattering were calculated with the final state energy prescription which was thought to be a better approximation than the initial state prescription.<sup>7)</sup>

#### 4. EXPERIMENTAL RESULTS

Projected three body breakup cross sections are shown in Fig. 1. The detector angles are

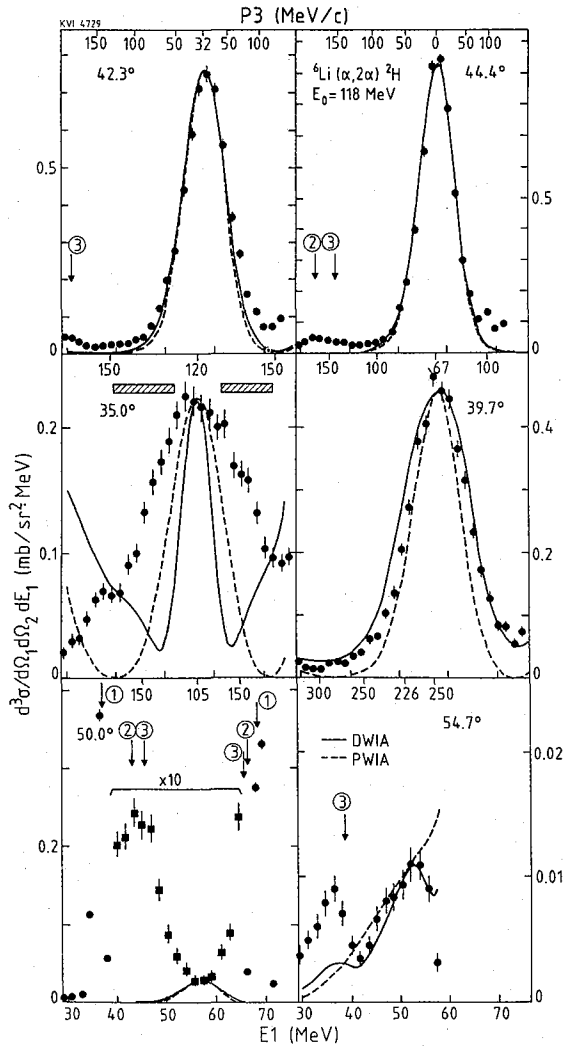


Fig. 1. Projected three body breakup cross sections for the  ${}^6\text{Li}(\alpha, 2\alpha){}^2\text{H}$  reaction at  $E = 118$  MeV. Solid curves show the DWIA calculations and dashed curves the PWIA ones. Some arrows and hatched rectangles in the figure show the  ${}^6\text{Li}$  excitation energies. For details, see the text.

## Quasifree Scattering in the ${}^6\text{Li}(\alpha, 2\alpha)$ Reaction at 118 MeV

given in the figure. Absolute values of the deuteron recoil momenta are represented in the upper scale of each figure. For all angle pairs except  $50^\circ$ , enhancements were seen at the points of minimum recoil momentum. These correspond to quasifree scattering with a deuteron spectator in an initial  $S$  state. Some arrows in the figure show the energy corresponding to sequential decay of low-lying  $T=0$  excited states of  ${}^6\text{Li}$ . Arrows labeled 1 correspond to the 2.19 MeV, 2 to the 4.31 MeV, and 3 to the 5.65 MeV excited states. At  $44.4^\circ$ , the small bump to the left of the quasifree peak corresponds to sequential decay from the 4.31 MeV and 5.65 MeV states. Some enhancement from the 5.65 MeV level is also seen in the  $42.3^\circ$  spectrum. Hatched rectangles at  $35^\circ$  show the region of  ${}^6\text{Li}$  excitation energy between 20 MeV and 30 MeV; in fact, these are the lowest  ${}^6\text{Li}$  excitations observable at this geometry. According to the  $d+\alpha$  elastic scattering analyses,<sup>14)</sup> there may be some  $T=0$  excited states of  ${}^6\text{Li}$  in this energy region. The width of the quasifree peak in this spectrum is extremely broad compared with those in our other data; thus it appears that excitation of 20 to 30 MeV levels is responsible for this anomalous width. At  $39.7^\circ$ , only the quasifree peak is seen. At  $50^\circ$ , the data around the minimum recoil momentum are multiplied by 10 and presented with closed squares. In this spectrum, at low  $E_1$ , a sharp peak correspond to the 2.19 MeV state and there is a broad bump corresponding to the 4.31 MeV and 5.65 MeV states. At high  $E_1$ , the curvature of the three body locus places the contributions of the three levels so close together that they cannot be resolved. Thus at  $50^\circ$ , the minimum recoil momentum point is at the valley of these strong excited states. At  $54.7^\circ$ , except for the quasifree peak, only the bump corresponding to the 5.65 MeV level can be seen.

### 5. ANALYSES AND DISCUSSIONS

The results of the DWIA/PWIA calculations are shown in Fig. 1. Solid curves show the DWIA calculations, and dashed curves the PWIA ones. The spectroscopic factors depend on the type of  ${}^6\text{Li}$  bound state wave function; therefore in the present study, a similar DWIA analysis was done and the same  $2S$  Woods-Saxon potential was used as in the case of the  ${}^6\text{Li}(p, pd){}^4\text{He}$  studies at  $E = 120$  and  $200$  MeV<sup>6)</sup> and the  ${}^6\text{Li}(p, p\alpha){}^2\text{H}$  reaction at  $E = 100$  MeV.<sup>5)</sup> Spectroscopic factors were determined by normalizing the calculated peaks to the maxima of the QFS peaks. For each angle, the obtained spectroscopic factor is listed in Table 2. In the small recoil momentum region ( $|\Phi(p_3)| \leq 100$  MeV/c) such as in the measurements at  $44.4^\circ$ ,  $42.3^\circ$  and  $39.7^\circ$ , the DWIA calculations reproduced the experimental data fairly well. The absolute spectroscopic factors obtained are reasonably consistent, and the average value of them is 0.82. This value is consistent with 0.75 and 0.84 obtained from the  ${}^6\text{Li}(p, pd)$  reaction.<sup>6)</sup> It also agrees with the three body theory by Kukulin et al. (0.70–0.75),<sup>2)</sup> but is larger than the results from the  ${}^6\text{Li}(p, p\alpha){}^2\text{H}$  reaction (0.45–0.72). In the measurement at  $44.4^\circ$ , where the data include zero recoil momentum, the width of the quasifree peak is 71 MeV/c in FWHM. This value is

Table 2. Spectroscopic factors.

Angle (deg)	44.4	42.3	39.7	50.0	35.0	54.7
Minimum recoil momentum (MeV/c)	0	32	67	105	120	226
DWIA	0.85	0.79	0.81	0.055	0.75	3.1
PWIA	0.35	0.38	0.28	0.049	0.59	0.75

consistent with those deduced from both the  ${}^6\text{Li}(p, pd){}^4\text{He}$  and  ${}^6\text{Li}(p, p\alpha){}^2\text{H}$  data (73 MeV/–76 MeV/c). It is also consistent with the one deduced from the three body theory by Lehman and Rajan.<sup>3)</sup> The PWIA calculation also gave reasonable fits to the data as regards to the shape. Compared with the DWIA calculations, the PWIA ones gave a slightly narrower width an about twice as large absolute values. These results are consistent with the conclusions from studies of the  ${}^6\text{Li}(p, pd)\alpha$  reaction at 155 MeV by Jain et al.<sup>16)</sup> At  $44.4^\circ$  the deduced spectroscopic factor is 0.35. Compared to the lower energy results of Watson et al. (0.08), this value is very large. This inconsistency seems to come from the use of different bombarding energies and different wave functions for the  ${}^6\text{Li}$  ground state. In the region of large recoil momenta ( $|\Phi(p_3)| \geq 100$  MeV/c) such as in the measurements at  $35^\circ$ ,  $50^\circ$  and  $54.7^\circ$ , there are some problems in reproducing the experimental data. At  $35^\circ$ , although a reasonable spectroscopic factor (0.75) was deduced, a poor fit to the spectrum was obtained. The width of the peak was about three times as wide in alpha energy as that of the DWIA calculation, and also was twice as wide as that of the PWIA calculation. Compared with our other data such as at  $44.4^\circ$ ,  $42.3^\circ$  and  $39.7^\circ$ , this experimental width is extremely broad. Moreover, the width deduced from the DWIA calculation is narrower than the one from PWIA. This relation between the results by DWIA and PWIA is opposite to that in case of other data. As a reason for this inconsistency, the energy dependence of the final state optical potential was considered. The effect of it was checked at this angle and pair  $44.4^\circ$ . Since the recoil deuteron energy changes by about 5 MeV in the quasifree peak, two additional  $d-\alpha$  potentials were investigated. In one, the real and imaginary potentials were made shallower by 10 MeV, and the other potentials deeper by 10 MeV. The predicted cross sections at both angles of  $35^\circ$  and  $44.4^\circ$  were changed by no more than 5%. Therefore this effect could not explain the poor fit. Both sides of the peak correspond to the region of  ${}^6\text{Li}$  excitation energy between 20 MeV and 30 MeV. Broad  $T=0$  levels have been reported at 26.6 MeV<sup>17)</sup> and at 23, 24 and 27 MeV.<sup>15)</sup> Apparently sequential decay from these levels broadens the peak. At  $50^\circ$ , no enhancement could be seen at the minimum recoil momentum. So our calculations set only an upper limit on the yield. Three strong excited states of  ${}^6\text{Li}$  appear twice on the locus for this kinematical condition. The 2.19 MeV state ( $3^+$ ) is most strong and sharp. The 4.31 MeV ( $2^+$ ) and 5.65 MeV ( $1^+$ ) states are broad (1.5 MeV width). These enhancements seem to account for most of the structure in our spectrum. Moreover since the  ${}^6\text{Li}$  wave function has a node at some momentum between 100 MeV/c and 150 MeV/c, i.e., for the range of deuteron recoil momenta we observe at this geometry. Presumably these two reasons account for the absence of QFS enhancements. At  $54.7^\circ$ , the DWIA calculation gave a good fit to the data except below  $E_1=40$  MeV where the 5.65 MeV state is observed. However for the absolute value, the DWIA calculation gave the unphysically large spectroscopic factor 3.1. The PWIA calculation also gave a poor fit. Its cross section varied monotonically and the enhancement was not produced. According to the DWIA theory, the deuteron momentum distribution is obtained from the three body cross section divided by the phase space factor and the free  $\alpha-\alpha$  cross section. These were calculated at the minimum recoil momentum for each angle pair, and are shown in Fig. 2. The solid curve represents the DWIA calculation multiplied by 0.85, and the dashed curve the PWIA one multiplied by 0.35. For our symmetric geometries, all minimum recoil momenta occur for the symmetric condition  $E_1=E_2$  and  $\theta_1=\theta_2$ . Then the deuteron momentum has only a component in the beam direction, and no perpendicular component. So the momentum distribution in regard to the

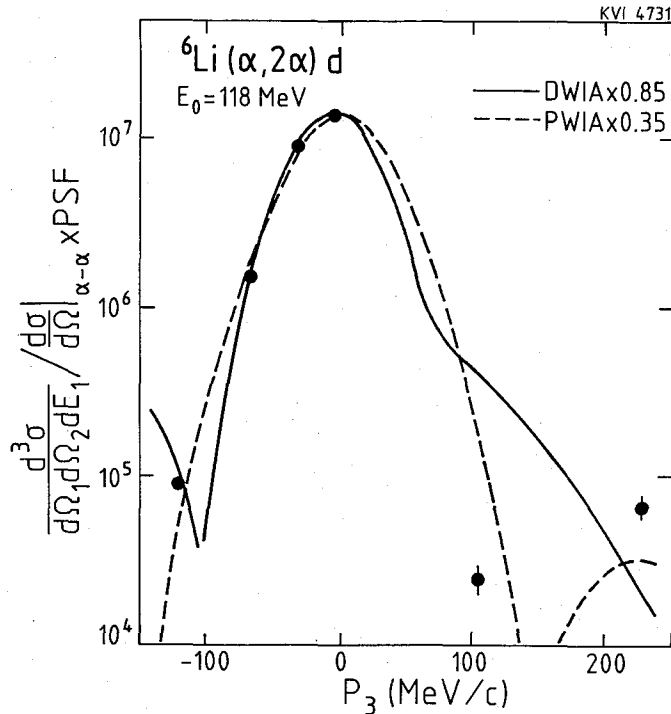


Fig. 2. The three body cross section as a function of spectator deuteron momenta, divided by the phase space factor and the free  $\alpha-\alpha$  cross section. The solid curve represents the DWIA calculation multiplied by 0.85, and the dashed curve the PWIA one multiplied by 0.35.

beam direction is shown in this figure. The DWIA calculation gave good fits in the negative momentum region, but poor fits to two positive momentum data. A noticeably asymmetric result about zero recoil momentum was obtained. In the absence of rescattering, the momentum distribution is symmetric about zero recoil momentum. These data are obtained for different kinematic conditions, so distortion effects are different for different momenta. In contrast, the PWIA calculation gives a symmetric momentum distribution. Figure shows that, overall, the PWIA gives a better fit than the DWIA to the momentum distribution. On the positive momentum side, the PWIA calculation has a dip at about 150 MeV/c, but the DWIA prediction fills in the valley. This situation is quite consistent with the results<sup>5,18</sup> from the  ${}^6\text{Li}(p, p\alpha){}^2\text{H}$  and  ${}^6\text{Li}(e, e'd){}^4\text{He}$  reactions. On the negative momentum side, the DWIA calculation has a dip at about  $-100$  MeV/c and fits the data well.

In summary, DWIA calculations gave fits to the experimental data in the region of small recoil momenta for the  ${}^6\text{Li}(\alpha, 2\alpha)d$  reaction at 118 MeV. They gave a reasonable  $\alpha+d$  spectroscopic factor of 0.82, consistent with the results from the  ${}^6\text{Li}(p, pd)$  reaction at  $E=120$  and 200 MeV. These results are surprising considering the less penetrability of alpha particle. However this value depends on the cross sections of the  $\alpha-\alpha$  scattering interpolated from the previous data. There is a large ambiguity about this interpolation. It may cause the spectroscopic factor of 0.6 in minimum. This value is closer the result for  $(p, p\alpha)$  than the one for  $(p, pd)$ . In the region of recoil momenta larger than 100 MeV/c, however, DWIA

calculations could not reproduce the experimental spectra successfully. The  $(\alpha, 2\alpha)$  reaction at 118 MeV appears to be as suitable a probe for studying  ${}^6\text{Li}$  clustering as the  $(p, pd)$  and  $(p, p\alpha)$  reactions at similar energy.

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