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The ^{6}Li exclusive breakup on ^{28}Si at 13 MeV

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Abstract

We have undertaken the study of ^{6}Li breakup on a ^{28}Si target near the Coulomb barrier through an angular distribution measurement. Alpha particles were recorded in coincidence with deuterons in order to determine exclusively the breakup of lithium. The results are analysed and are discussed, in a continuum discretized coupled channel framework (CDCC).

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For light–heavy ion collisions at low bombarding energies, the emission of light particles is the most usual feature and is associated with various compound or direct reaction channels. For stable nuclei, at near and below barrier energies, the compound mechanism is the most dominant, in contrast to the weakly bound nuclei, where direct processes like transfer and breakup, play the most important role [1,2]. In recent years, much effort has been devoted in disentangling these processes by particle–particle, particle–gamma correlations and in determining their relative importance in the total reaction cross section [3–15].

The study of the breakup of light-ion projectiles like ^{6}Li is of special interest since its cluster nature simplifies calculations which can corroborate experimental results and therefore enlight this subject. The nucleus ^{6}Li is a weakly bound nucleus ($^6\mathrm{Li} \to \alpha + d$, $S_\alpha = 1.471$ MeV), which resembles the halo nucleus ^{6}He. In this context, a study of its direct and sequential breakup may help in understanding the resonant and non-resonant breakup process in halo nuclei [16]. Moreover, the breakup of ^{6}Li, as a coupled channel effect, is directly connected with the anomalous behaviour of the optical potential around barrier with consequences on sub-barrier fusion.

We have studied recently the α-particle yield, produced by the scattering of ^{6}Li on a ^{28}Si target at near barrier energies [2]. According to our study which included CDCC calculations, the yield was attributed to breakup and transfer reactions. As it was

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suggested, the two processes had to be unfolded in order to draw valuable conclusions about the reaction mechanisms in this interesting energy region. In this context, we report in this Letter a study of the exclusive breakup of ^{6}Li on ^{28}Si, in a complete coincidence experiment.

Our experimental setup has been described in detail in a previous work [17] and only a short summary pertinent in this work, will be given here. In principle, we follow the experimental technique of the work outlined in [5,6]. A $^6\mathrm{Li}^{+3}$ beam at 13 MeV, was delivered by the TN11/25 HVEC 5.5 MV Tandem accelerator of the National Research Center of Greece-DEMOKRITOS. Beam currents were of the order of 30 nA. The beam impinged on a 210 μg/cm^2 thick, self supported natural silicon target, tilted by $\pm 45°$ (depending on the detector position) and the reaction products were detected by three telescopes set ~ 13 to 17 cm far from the target. Telescope 1 ($\Delta E = 100$ μm, $E = 1500$ μm) was set on the upper rotating table and used to detect deuterons. In this telescope lithium ions and some of the α's were stopped in the first detector, while deuterons were well discriminated from protons with the $\Delta E - E$ technique (see Fig. 1). Telescopes 2 and 3 ($\Delta E = 10$ μm, $E = 200$ μm) were set on a bottom rotating table, concentric to the top one and were used to detect α's. These telescopes were separated by 20 degrees from each other and were able to discriminate between alphas and elastic lithium elastic scattering events. Elastic lithium was accepted in the acquisition occasionally, for normalisation purposes. In the main runs, it was gated out electronically in order to minimise the dead-time of the acquisition system. In that way the higher energy part of the alpha particles were also gated out. This was not a problem however, since the phase space, for the detection of the two fragments in coincidence, was limited due to ΔE restrictions, as will be explained later. An additional Si detector of 200 μm was set in an arm fixed at 40° to be used also for normalisation. Telescope 1 was kept fixed at four positions, that is at 30°, 40°, 60° and 70°, while telescopes 2 and 3 were rotated in order to obtain the following

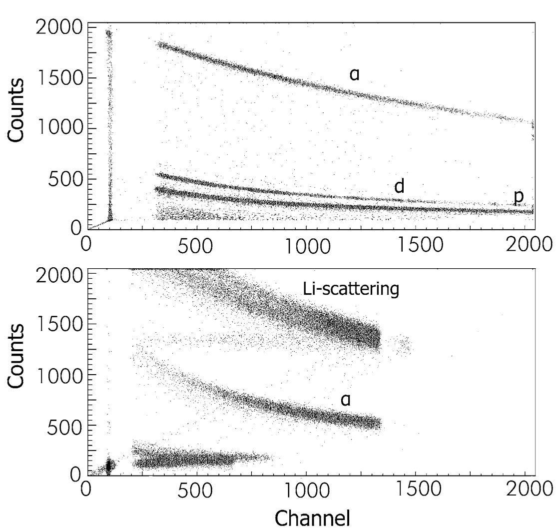

Fig. 1. Two-dimensional, $\Delta E - E$, spectra taken at 13 MeV, with telescope 1 (top) and telescope 2 (bottom).

pair of angles: $\theta_d/\theta_\alpha = 30/20$, $30/40$, $40/30$, $40/50$, $60/30$, $60/50$, $70/40$, $70/60$, $30/55$, $30/75$. These pairs correspond to the following angles of $^6\mathrm{Li}^*$ in the center-of-mass system, $\theta_{\mathrm{c.m.}} = 29°$, 45°, 41°, 56°, 49°, 64°, 60°, 76°, 57° and 75°, correspondingly [18] (see also similar plots of kinematics in [5,6], appropriate also in the present work). Data in single, and coincidence mode between telescopes 1 and 2 and telescopes 1 and 3, were simultaneously recorded in our acquisition. Finally, the exclusive results (coincidence α–d events) were determined off line. Our analysis was found to be consistent with our previous α-production measurements [2] giving support to our normalisation.

The breakup fragments α and d, may originate either by a sequential or/and a direct process. Events due to sequential decay of $^6\mathrm{Li}^*$ are confined to cones of angular width, which are determined by their relative energy $E_{\alpha,d}$ and the laboratory energy of the projectile [19]. Due to the fixed relative energy between the fragments in sequential-decay events, the fragments are confined to cones with a given maximum opening angle. For the first excited state of Li-6 at 2.18 MeV, the maximum separation is $\Delta\theta \sim 32°$. Therefore, most of our exclusive measurements are confined inside this sequential cone and the obtained breakup cross sections are due to a sum of all the sequential and direct processes. On the other hand, the measurement with the pair of detectors at 30/75 is well out of the sequential cone and the breakup events are due to all direct and sequential processes, except for the sequential via the first excited state of ^{6}Li. Since the sequential decay due to the 3^+ state is the most dominant (see calculations later in the text), this measurement gives an upper limit for the non-resonant breakup.

For each of the above mentioned telescope positions, exclusive yields (Fig. 2) are determined and transfered to laboratory double differential cross sections ($d^2\sigma/d\Omega_\alpha/d\Omega_d$) using a detection efficiency estimated through a MONTE CARLO code [20]. Two types of breakup processes are considered; sequential (via the 3^+, 1^+, 2^+ excited states of ^{6}Li, adopting a Lorentzian distribution probability) and direct (excitation energy width 1.47 to 10.6 MeV). In all simulations the breakup fragments are assumed to be emitted isotropically in the rest frame of ^{6}Li. Assuming isotropic decay in the rest frame of Li, may not completely account for the efficiency for each of the different angular momentum states. But since the beam is not polarized, then the changes with angle are small and smooth over the small range of angles covered by our detectors. At an angle where the effect can be greatest, an error at most of 3% is estimated. Subsequently laboratory cross sections are transferred to center-of-mass ones by using the code RELKIN [21]. Finally, the results are corrected for the limited phase space (accounting to $\sim 50\%$), seen by the two fragments due to the thickness of the ΔE detectors of the telescopes and the coincidence requirements between the two telescopes. Kinematics for the two fragments and their phase space are calculated according to Ohlsen [18]. The low and high energy limits of the alphas and deuterons are determined taking into account the stopping powers of Ziegler [22]. The results, are presented in Fig. 3, where they are compared with CDCC calculations. At one angle, namely $\theta_{\mathrm{c.m.}} = 75°$, the datum designated with a star,

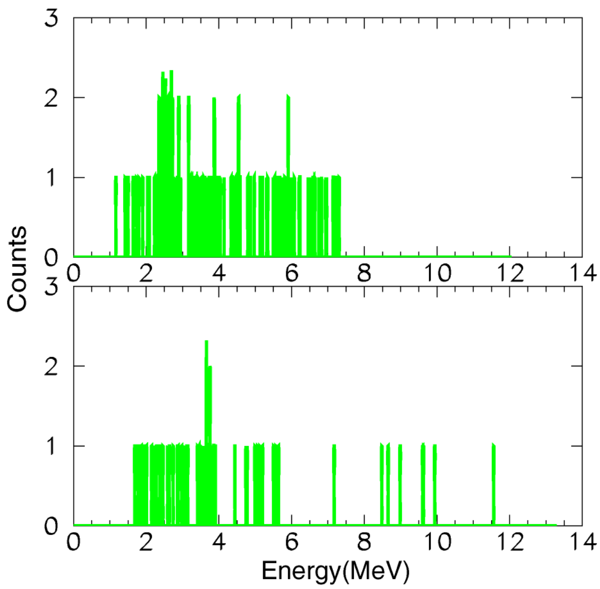

Fig. 2. Exclusive breakup spectra. Top figure: Alpha particles detected at 20° in coincidence with deuterons detected at 30°. Bottom figure: deuterons detected at 30° in coincidence with α's detected at 20°. The peak in both figures corresponds to sequential breakup via the 3^+ excited state of lithium. This is the low energy solution. The high energy solution is cut off due to the limited phase space seen in this experiment. Finally, it has to be noted that for a better display of the data, due to the choice of counts binning as a function of energy, the y axis presents fraction of counts.

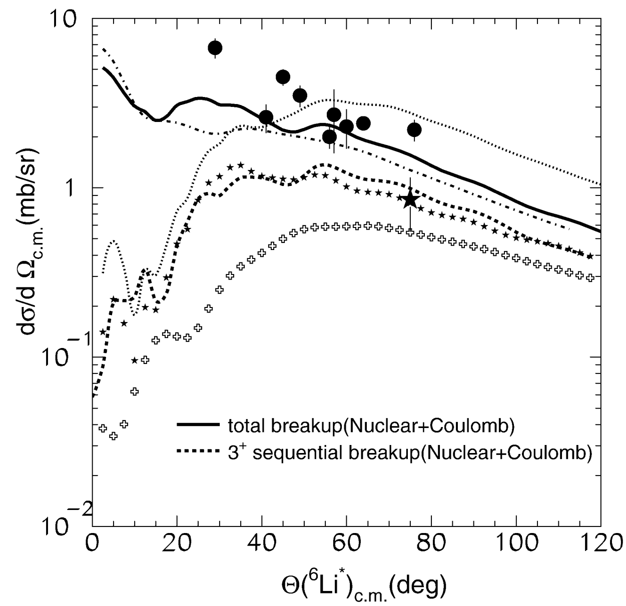

Fig. 3. Experimental and theoretical angular distributions in the center of mass, for the breakup of ^{6}Li on ^{28}Si. The experimental data, referring to total breakup, are designated with filled circles, while the datum referring to direct breakup with a star (see text). The associate errors are due to statistics. CDCC cross section calculations for total breakup are presented with the solid line (nuclear contribution with the dotted-dashed line and the Coulomb contribution with the dotted line), while for a sequential breakup via the 3^+ state with a dashed line (nuclear contribution with the open cross line and the Coulomb contribution with the little star line).

refers to data collected outside the sequential cone for the decay of ^{6}Li from the 3^+ excited state, and therefore this data point refers mainly to direct breakup.

CDCC calculations were performed using version FRXP.18 of the code FRESCO [23]. The model used is very close to that of Ref. [24]. It is assumed that the nucleus ^{6}Li has a two-body $\alpha + d$ cluster structure. Couplings to the 3^+ ($E_{\alpha,d} = 0.704$ MeV), 2^+ ($E_{\alpha,d} = 2.834$ MeV) and 1^+ ($E_{\alpha,d} = 4.154$ MeV) resonant states are included, as well as couplings to the non-resonant α–d continuum. The resonant states are treated as momentum bins, with widths corresponding to 0.1, 2.0 and 3.0 MeV. The continuum is truncated at an excitation energy of about 10.6 MeV, corresponding to the relative momentum of the two clusters $k = 0.78\ \mathrm{fm}^{-1}$. It is discretized into bins of equal width, $\Delta k = 0.26\ \mathrm{fm}^{-1}$. In the presence of resonances, the discretisation is slightly modified in order to avoid double counting. Couplings between all the cluster states corresponding to the α–d relative orbital angular momentum $L = 0, 1, 2$ are included. The $\alpha + d$ binding potential is of Woods–Saxon shape, with parameters $R = 1.9$ fm and $a = 0.65$ fm [25]. All the diagonal and coupling potentials include Coulomb and nuclear components and are calculated from empirical $\alpha + {}^{28}$Si [26] and $d + {}^{28}$Si [27] optical model potentials by means of the single-folding technique. It can be noted that, CDCC calculations describe well the measured angular distribution of the differential cross sections for ^{6}Li + ^{28}Si elastic scattering. The results of the calculation for the angular distribution of total breakup cross sections are presented in Fig. 3 with the solid line. This distribution leads to a total breakup cross section equal to $\sigma_b = 16.8$ mb. In the same figure, the angular distribution of cross section due to sequential breakup via the 3^+ state is also presented with the dashed line. According to our calculation, this is the most dominant resonant process. This fact is demonstrated in Fig. 4, where the ratio of the resonant breakup via the 3^+ state over the sum of all resonant processes (3^+, 1^+, 2^+) is plotted as a function of the ^{6}Li* angle in the center-of-mass. It is seen that breakup due to the 3^+ sequential decay is the most dominant at forward angles (at 30 deg 97% of total resonant breakup), while it declines slightly at backward angles (at 80 deg by $\sim 87\%$ of total resonant breakup). It should be noted that the 3^+ dominance is partly supported by our experimental spectra (Fig. 2) where only an energy peak appears associated with the 3^+ decay. However, the statistics are very poor to support fully that view. In the same figure, the ratio of the direct breakup (non-resonant continuum) over total breakup (resonant + non-resonant) is also shown as a function of the angle. The last ratio is compared with one experimental point (ratio of the cross section at $\theta_{\mathrm{c.m.}} = 75°$ obtained with the pair of detectors at 30°–75°, over the cross section at $\theta_{\mathrm{c.m.}} = 76°$, obtained with the pair of detectors at 70°–60° that is outside and inside the sequential cone of the 3^+ excited state of ^{6}Li) which represent an upper limit to the direct part and includes a small part due to sequential breakup via the 2^+ and 1^+ resonant states. It is seen that both theory and experiment point out that the direct contribution to breakup is substantial with increasing trend to forward angles, as expected. Additionally to that, we present in Fig. 3 our calculations in respect with the Coulomb and nuclear contribution for the total breakup as well as the sequential via the 3^+ ex-

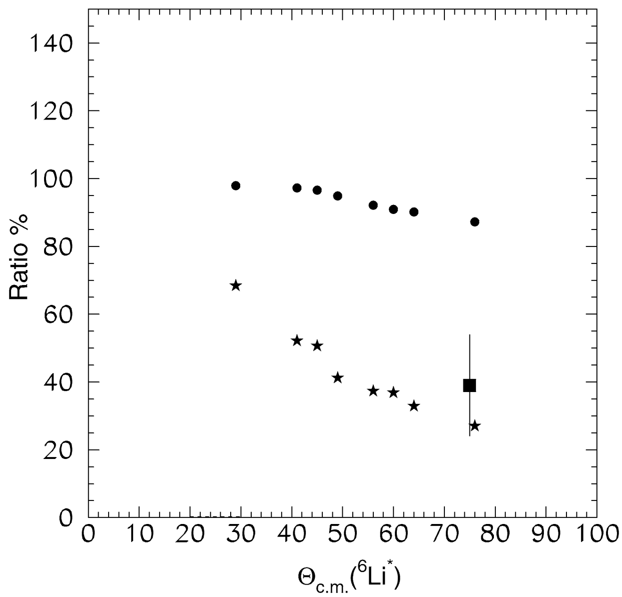

Fig. 4. The predominance of the 3^{+} sequential breakup in the resonant part of the breakup is displayed in this figure with calculated ratios of sequential breakup via the 3^{+} state over total resonant breakup(sequential via 3^{+}, 1^{+} and 2^{+}) as a function of the ^{6}Li* center of mass angle (filled circles). Moreover, the existence of a substantial direct breakup component is outlined with the calculated ratios of direct breakup over the total breakup which are presented with solid stars. With the latter ratios, one experimental point at $\theta_{\mathrm{c.m.}}$ is compared, designated with a square. This point is not purely direct, including at least 10% of sequential breakup via the second and third resonant state of ^{6}Li. As it is seen however from the first plot, the correction is small and if it will be applied will bring the datum closer to the calculation.

cited state. It is seen that the Coulomb contribution is stronger in the sequential decay while at forward angles the nuclear contribution is the strongest in the non-resonant breakup. This last result is supported by the experimental point at $\theta_{\mathrm{c.m.}} = 29$ deg. A large nuclear breakup contribution at forward angles was observed previously by Hirabayashi and Sakuragi [28], but at much higher energies.

In general, as it can be seen from Figs. 3 and 4, the experimental results support the theory in a satisfactory way, both quantitatively and qualitatively, although theory shows a slight trend to underestimate the data. It has to be noted however, that this comparison is liable to the following shortcomings. The range of angles where data exist is narrow and moreover, due to the adopted technique, the phase space seen by the detected fragments is limited to 50% of the true phase space. The correction for the phase space increases the statistical error reported in the figures by a factor of most of 3% due to the error assigned in the phase correction, ranging from 5% to 8%. In any case, the experimental data show that the theoretical calculation for a total breakup cross section of ~ 17 mb is a very good prediction. Taking into account the α-production cross section and total reaction cross section obtained previously [17] as 533 and 954 mb, respectively, we conclude that the reaction channel of breakup at near barrier energies is negligible. Therefore, the variation of the optical potential anomaly at barrier between ^{6}Li and stable projectiles has to be sought elsewhere, and particularly in the transfer channels as it was underlined recently [2,29]. On the other hand in a previous exclusive breakup measurement of $^{6}\mathrm{Li} + {}^{208}\mathrm{Pb}$ [4] the obtained cross section is higher by almost a factor of 5, indicating a strong target dependence. We would like also to draw attention to the following point. Our laboratory coincidence cross sections, except the datum at forward angles ($\theta_{\mathrm{c.m.}} = 29°$), can be factorized into a product of inclusive alpha and inclusive deuteron cross sections [15] $(d^{2}\sigma/[d\Omega(\alpha)\,d\Omega(d)](\text{exclusive}) = K \cdot [d\sigma/d\Omega(\alpha\text{-inclusive})] \cdot [d\sigma/d\Omega(d\text{-inclusive})])$ with a factor $K = (1.1 \pm 0.3) \times 10^{-3}$. This value is in fair agreement with a factor of $K = 4.5 \times 10^{-3}$ obtained for $^{6}\mathrm{Li} + {}^{120}\mathrm{Sn}$ previously [15]. This may indicate that most of the breakup fragments, α and d, observed in the present experiment at backward angles might be thought of as arising by a two step process where after the ^{6}Li breakup, one of the fragments undergoes a further inelastic interaction with the target (e.g., incomplete fusion-ICF), while subsequently it is re-emitted. It should be noted however that according to the authors of [15] this factorization is true for in plane data, as is the present case and not for data observed out of plane. Further investigation into that direction should be pursued, while it becomes obvious, once more, that the reaction mechanisms at barrier is a very complicated subject which has a long way still to go in order to become fully understood.

In summary, we have presented results both experimental and theoretical, on the breakup of ^{6}Li on ^{28}Si at 13 MeV. Experiment and theory show a satisfactory compatibility and predict a very low total breakup cross section. This result calls for further work in the direction of other direct reaction channels, like transfer reactions in order to enlight the controversy of the optical potential anomaly between weakly bound and stable nuclei. We have attempted also to unfold the resonant from the non-resonant part of the breakup as a function of angle. It can be concluded that the direct breakup is substantial, accounting for almost $\sim 50\%$ of the total breakup. Moreover, at forward angles the direct breakup has a strong nuclear contribution.

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References

[1] A. Pakou, et al., Phys. Rev. C 71 (2005) 064602.
[2] A. Pakou, et al., Phys. Rev. Lett. 90 (2003) 202701.
[3] G.R. Kelly, et al., Phys. Rev. C 63 (2000) 024601.
[4] C. Signorini, et al., Phys. Rev. C 67 (2003) 044607.
[5] D. Gupta, et al., Nucl. Phys. A 646 (1999) 161.
[6] D. Gupta, et al., Nucl. Phys. A 683 (2001) 3.
[7] D. Scholtz, et al., Nucl. Phys. A 288 (1977) 351.
[8] R. Ost, et al., Z. Phys. 266 (1974) 266.
[9] R. Kanungo, et al., Nucl. Phys. A 599 (1996) 579.

[10] Y. Leifels, H. Freiesleben, L. Ricken, Z. Phys. A 351 (1995) 43.
[11] A.C. Xenoulis, A.E. Aravantinos, Phys. Lett. B 364 (1995) 143.
[12] R. Raabe, et al., Nature 431 (2004) 823.
[13] E.F. Aguilera, et al., Phys. Rev. Lett. 84 (2000) 5058.
[14] J. Hesselbarth, K.T. Knopfle, Phys. Rev. Lett. 67 (1991) 2773.
[15] I. Yorkston, et al., Nucl. Phys. A 524 (1991) 495.
[16] I. Tanihata, Prog. Part. Nucl. Phys. 35 (1995) 505.
[17] A. Pakou, et al., Phys. Lett. B 556 (2003) 21.
[18] G.G. Ohlsen, Nucl. Instrum. Methods 37 (1965) 240.
[19] G. Baur, C.A. Bertulani, H. Rebel, Nucl. Phys. A 458 (1986) 188.
[20] E.W. MacDonald, MONTE CARLO computer code UNIMONTE, 1992, University of Edinburg, unpublished.
[21] J. Lilley, B.R. Fulton, relativistic code RELKIN, unpublished.
[22] J.F. Ziegler, Stopping Cross Sections of Energetic Ions in all Elements, Pergamon, 1980.
[23] I.J. Thompson, Comput. Phys. Rep. 7 (1988) 167.
[24] N. Keeley, K. Rusek, Phys. Lett. B 427 (1998) 1.
[25] K.-I. Kubo, M. Hirata, Nucl. Phys. A 187 (1972) 186.
[26] H. Lacek, U. Strohbusch, Z. Phys. 233 (1970) 101.
[27] W. Whur, A. Hofmann, G. Philipp, Z. Phys. 269 (1974) 365.
[28] Y. Hirabayashi, Y. Sakuragi, Phys. Rev. Lett. 69 (1992) 1892.
[29] A. Pakou, et al., J. Phys. G: Nucl. Part. Phys. 31 (2005) S1723.