Quasi-elastic scattering in the ^{6}Li + ^{232}Th reaction

S. Mukherjee,[1,*] B. K. Nayak,[2] D. S. Monteiro,[3] J. Lubian,[3] P. R. S. Gomes,[3] S. Appannababu,[1] and R. K. Choudhury[2]
[1] *Physics Department, Faculty of Science, The M. S. University of Baroda, Vadodara 390 002, India*
[2] *Nuclear Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085, India*
[3] *Instituto de Fisica, Universidade Federal Fluminense, Av. Litorânea s/n, Niterói, R. J., CEP 24210-340, Brazil*
(Received 6 January 2009; revised manuscript received 12 June 2009; published 14 July 2009)

Quasi-elastic scattering measurements at large backward angles have been carried out for the ^{6}Li + ^{232}Th system at energies around the Coulomb barrier. Barrier distribution has been obtained from the excitation function data. Coupled channel calculations using a double-folding potential as the bare potential have been performed. The disagreement between data and theoretical predictions shows a large breakup effect in the quasi-elastic scattering of a weakly bound projectile on a deformed target.

DOI: 10.1103/PhysRevC.80.014607 PACS number(s): 25.70.Mn, 25.70.Bc, 24.10.Eq

Investigation of the effect of low threshold energy against breakup of some projectiles on reaction mechanisms has been a subject of great interest in the past several years [1]. The derivation of fusion barrier distributions from very precise fusion excitation function measurements has shown to be a powerful and sensitive tool for the investigation of the importance of channel couplings at energies around the Coulomb barrier in fusion reactions. Thus the barrier distribution method has opened up the possibility of using the heavy-ion fusion reaction to investigate both the static and dynamical properties of atomic nuclei involved in the collision process. Fusion barrier distributions involving weakly bound projectiles ^{6,7}Li, and ^{9}Be on heavy targets have been reported [2–4]. However, there are difficulties associated with the derivation of fusion barrier distributions, such as the low fusion cross sections and the fact that one must use the second derivative of the fusion excitation function to obtain these [5]. Since the channel coupling also affects the scattering process, it has been suggested [6,7] that the barrier distribution can also be obtained from the excitation function of quasi-elastic scattering (QES) (a sum of elastic, inelastic, transfer, and other direct reaction cross sections) at backward angles. It has been proposed that the first derivative of the ratio of the quasi-elastic cross section $\sigma_{\rm qel}$ to the Rutherford cross section $\sigma_{\rm Ruth}$ with respect to energy, $-d(d\sigma_{\rm qel}/d\sigma_{\rm Ruth})/dE$, be used as an alternative representation of the barrier distribution [8].

Whereas fusion is related to transmission through the barrier, large-angle quasi-elastic scattering is related to reflection at the barrier. So, because of conservation of the reaction flux, these two processes may be considered as complementary to each other, and one may obtain information concerning one of them by investigating the other. The QES is usually much simpler to investigate experimentally than fusion. Furthermore, the QES barrier distribution at backward angles is obtained from the first derivative of the quasi-elastic excitation function. It has been shown [9,10] that the two representations of the barrier distribution are equivalent.

So far, QES barrier distributions have not been widely investigated for systems involving weakly bound nuclei [11–13]. For such systems, breakup must be included as one of the quasi-elastic processes. Noncapture breakup (NCBU) is defined as the breakup in which neither of the fragments fuses with the target. If the incomplete fusion (ICF) part of the projectile fusion with the target is not included in the QES, this later process will be complementary to the total fusion, defined as the sum of the complete fusion (CF) of the projectile with the target and ICF. Otherwise, QES will be complementary to CF. With the aim to further investigate the effect of projectile breakup on fusion, we have carried out measurements on fusion barrier distribution by quasi-elastic scattering at extreme back angles for the ^{6}Li + ^{232}Th system.

The experiment was performed at the 14 UD Pelletron accelerator facilities, BARCTIFR, Mumbai, India. The measurements were carried out using a loosely bound stable ^{6}Li (1.47-MeV) beam. A self-supporting ^{232}Th target of 2.0 mg/cm^2 thickness was used in the experiment. The measurements were performed in the beam energy range of $E_{\rm lab} = 24$–38 MeV in steps of 1.0 MeV. The bombarding energies have been corrected for the energy loss in half the target thickness, which is in the range 0.27–0.21 MeV. A silicon surface barrier detector telescope $\Delta E(50.0\ \mu{\rm m}) - E(1.0\ {\rm mm})$ was placed at an angle of 157° to the beam direction to detect projectile-like fragments. Two silicon surface barrier detectors were placed at angles of ±10° with respect to beam direction to measure Rutherford scattering events for normalization. A typical two-dimensional ΔE-E scatter plot from the detector telescope at backward angles showing elastic + target inelastic scattering and various transfer or breakup products (^{2}H,^{4}He) at $E_{\rm lab} = 38$ MeV is shown in Fig. 1. The $Z = 3$ events correspond to the elastic scattering of ^{6}Li plus the unresolved ^{232}Th inelastic excitations. The outgoing projectile-like fragments (PLF) of various charges are observed to be clearly separated. All projectile-like fragments, including ^{6}Li (elastic and inelastic), α particles, and deuterons (from breakup, ICF, and transfer) have been identified and selected from ΔE-E scatter plots. The quasi-elastic to Rutherford excitation functions were determined by using the expression given by Sahu *et al.* [14].

Possible double-counting in the quasi-elastic cross section, owing to the ^{6}Li breakup into an α particle and a deuteron, does not occur, because the α-d maximum opening angle for

*Corresponding author: smukherjee_msuphy@yahoo.co.in

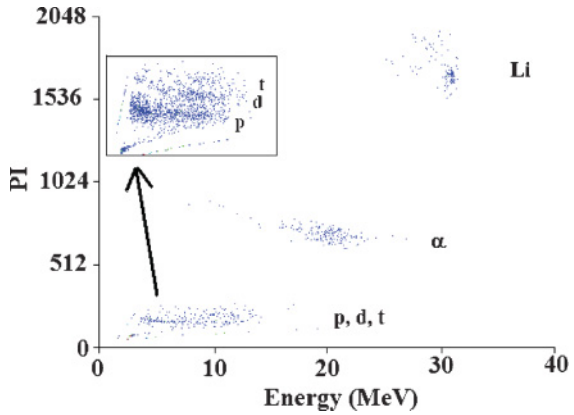

FIG. 1. (Color online) A typical ΔE versus E scatter plot for the ^{6}Li + ^{232}Th reaction, in which the outgoing projectile-like fragments (p, d, t, α, and ^{6}Li) are identified. The inset shows $Z = 1\,(p, d, t)$ events separated from each other.

the ^{6}Li unbound 3^+ state at 2.186 MeV is $-20°$, whereas the opening angle of our particle telescope is only 1.2°. So, α and deuteron fragments from the same projectile cannot reach the detector simultaneously. Even if by any chance the α particle and the deuteron from the same event simultaneously reached the detector, this simultaneous event would be identified as the $\alpha + d$ band between the α and the ^{6}Li bands in ΔE-E scatter plots [15]. As expected we do not observe any extra band corresponding to $\alpha + d$ in Fig. 1.

From Fig. 1. one can observe a very intense proton group that might be thought as originating from other mechanisms such as the ^{6}Li breakup into $\alpha + n + p$ (3.7 MeV) or evaporation of the compound nucleus. We checked these two hypotheses. For the first case corresponding proton energies would be too high for the highest bombarding energies, where the protons are also observed. The second possibility is ruled out by the predictions from the evaporation code PACE2 [16]. Furthermore, there is a possibility that low-energy protons might originate in reactions with light impurities (carbon and oxygen) present in the target. In a previous work [17] we have shown that α and deuteron projectile-like fragments peak around Q- optimum in ^{6}Li + ^{232}Th reactions and are free from contamination of light impurities. We also observe tritons at higher bombarding energies coming from the breakup of $^6\text{Li} \rightarrow {}^3\text{He} + {}^3\text{H}$ ($BE = 2.4$ MeV) with very few events. Hence, we have only considered ^{6}Li, α, and deuteron projectile-like-fragments as quasi-elastic events in the present analysis.

The quasi-elastic excitation function measured at an angle of 157° was used to determine the quasi-elastic barrier distribution $D_{\text{qe}}\,(E_{\text{eff}})$ using a point-difference formula with a step of 2.0 MeV in the laboratory frame [18]. To convert the results of $D_{\text{qe}}\,(E, 157°)$ to that of $D_{\text{qe}}\,(E, 180°)$, an effective energy was introduced into the cross section such that $\sigma_{\text{qe}}(E_{\text{eff}}) \approx \sigma_{\text{qe}}\,(E_{\text{c.m.}}, 157°)$, where $E_{\text{eff}} = 2E_{\text{c.m.}}/[1 + \text{cosec}(\theta_{\text{c.m.}}/2)]$. This corrects for centrifugal effects [8].

The experimental results of QES excitation functions for ^{6}Li, $^6\text{Li} + \alpha$, and $^6\text{Li} + \alpha + \text{d}$ outgoing channels in ^{6}Li + ^{232}Th reactions are shown in Fig. 2, and the corresponding quasi-elastic barrier distribution (D_{qe}) derived from the QES data is shown in Fig. 3. The ^{6}Li channel is the sum of elastic scattering

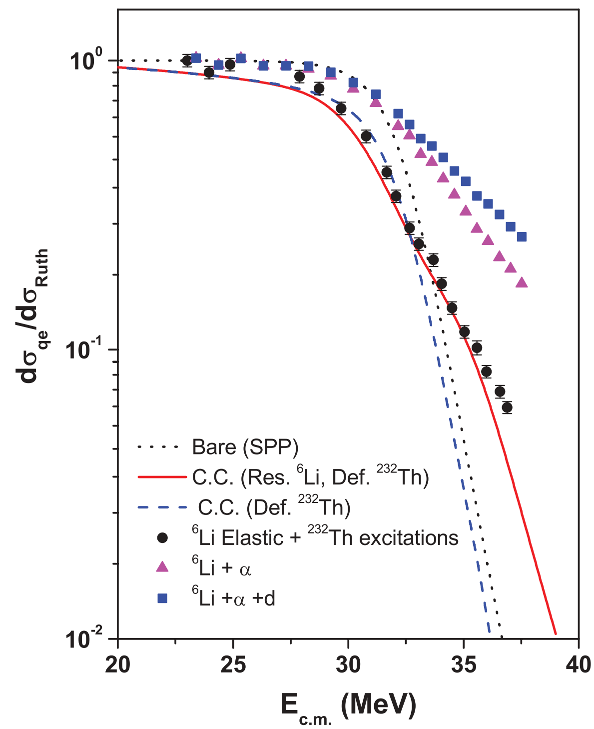

FIG. 2. (Color online) Quasi-elastic scattering excitation function. The curves are the results of various coupling schemes in CC calculations. In the figure, Res. ^{6}Li, Def. ^{232}Th means that the resonance states of ^{6}Li and inelastic states of the deformed ^{232}Th were included in the CC calculations. Def. ^{232}Th means that only inelastic states of ^{232}Th were included in the CC calculations.

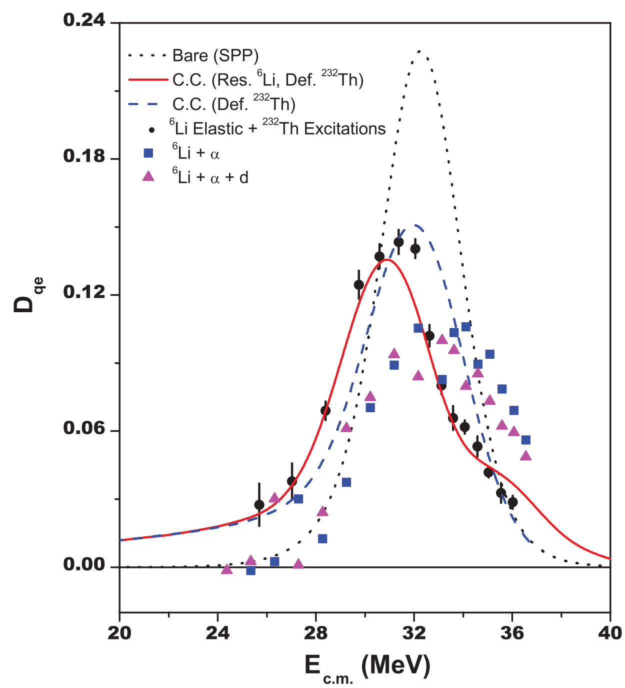

FIG. 3. (Color online) Quasi-elastic scattering barrier distribution. The curves are the results of CC calculations. (Terms are the same as in Fig. 2.)

plus inelastic excitations of the target. It can be observed that there is a significant contribution of α and d transfer/breakup channels in the QES excitation function at higher energies. The D_{qe} values for ^{6}Li + α and ^{6}Li + α + d channels are shifted to high energy around 1.9 MeV as compared to the ^{6}Li channel. The experimental average fusion barrier energy is 30.3 ± 0.06 MeV for the ^{6}Li channel, whereas it is 32.2 ± 0.18 MeV for the ^{6}Li + α + d channel. This observation shows that inclusion of breakup/transfer channels shifts the fusion barrier to a higher energy value, which can lead to suppression of the fusion cross section both above and below the Coulomb barrier energies.

The predictions of quasi-elastic excitation functions and their corresponding barrier distributions for various channel couplings in the ^{6}Li + ^{232}Th reaction are shown in Figs. 2 and 3 using the FRESCO code [19]. In the present calculations the reliable parameter-free double-folding São Paulo potential (SPP) was used as a bare potential [20,21]; it has been able to predict different reaction mechanisms in a wide energy range for several systems [22,23], including weakly bound systems [24]. The curves are predictions from calculations with this bare potential, without any fit search. The dotted curve (black) is the result of the calculations without any coupling. The dashed curve (blue) is the result of a coupled channel (CC) calculations when the inelastic excitations of the ^{232}Th target are considered in the coupling scheme. The ground-state rotational band of the target up to the 6+ excited state was included, with deformation parameter $\beta_2 = 0.261$ [25] for both Coulomb and nuclear interaction. The full curve (red) is the result when the 3^+ resonance state of the ^{6}Li projectile at 2.18 MeV (the threshold breakup energy for ^{6}Li being 1.47 MeV) and $\beta_3 = 0.87$ [3] is also included in the coupling scheme. As we are not including the nonresonant states of the projectile, we do not include any continuum-continuum coupling of this state with the other states of the continuum. One can observe that the coupling of the ^{6}Li resonance, corresponding to the sequential breakup, leads the calculations in the correct direction, but an agreement with the data is still far away.

It is important to mention that in the calculations just described, no surface imaginary potential was used, but rather a real nucleus-nucleus interaction without any fit to the data was used. The only imaginary potential considered is internal to the barrier Woods-Saxon potential with small diffuseness (0.2 fm), which guaranties the absorption of the flux that passes the Coulomb barrier. Those calculations should agree with the data if all relevant channels were included in the CC calculations. It should be pointed out that for this specific system the ICF cross sections cannot be estimated by continuum discretized coupled channel (CDCC) calculations, since for this kind of calculation the CF cross section can only be estimated for systems where almost all the mass of the projectile is concentrated in the core [26]. In the present case, CDCC calculations would provide only the TF cross sections and what we are plotting is the QES, which is equivalent to CF rather than to TF, as explained before.

Figure 3 shows the QES barrier distribution derived from the experimental QES data. The curves are theoretical results using the same procedure as was done for the excitation function. The coupling of the target excited states and the ^{6}Li resonance improves the agreement with the experimental barrier distribution, but no good agreement is actually obtained without the inclusion of the direct breakup process. This is quite evident from the figure and the calculations do not match with the ^{6}Li + α and ^{6}Li + α + d channels. This is because breakup effects are not included in the present calculations.

In most of the reported works on the investigation of the effect of breakup of a weakly stable projectile on CF cross sections with a heavy target, a spherical target has been chosen, with the purpose of isolating the effect of breakup. Recent work on the study of the presence of the usual threshold anomaly (TA) of the elastic scattering of weakly bound systems [27–32] has shown that the polarization potentials from breakup and inelastic excitation of the projectile have opposite signs. In some situations the repulsive polarization potential has roughly the same absolute value as the attractive one, leading to the vanishing of the TA, which is present at near-barrier energies for tightly bound heavy-ion reactions. For some systems the repulsive polarization potential is even larger than the attractive one, leading to the breakup threshold anomaly (BTA) [27,28].

For the system studied in the present work, with a heavy target with large deformation, one should not expect any significant enhancement or hindrance of the CF cross section, when compared with the large sub-barrier enhancement resulting from target deformation, since the attractive polarization potential should predominate over the breakup repulsive polarization potential. However, there is a strong and predominant effect of the repulsive Coulomb breakup, as shown in Fig. 3, where one can observe that the experimental barrier position is higher than the calculated one without the direct breakup effect. Recently it has been shown by means of CDCC calculations that the effect of the direct breakup is to increase the barrier to higher energies [12]. One should point out that by studying the QES barrier distribution one cannot access the effect of the breakup on different energy regimes, but rather only the shift of the height of the Coulomb barrier by the coupling effects.

We would like to emphasize that in our calculations we have not included any sequential breakup processes that could be responsible also for the disagreement between the CC predictions and the experimental data. Besides the one-step breakup of the ^{6}Li projectile into a deuteron and an α particle ($BE = 1.47$ MeV) there are other possible sequential breakup reactions such as, $^6\text{Li} \rightarrow p + {}^5\text{He}$ ($BE = 4.59$ MeV) $\rightarrow p + n + {}^4\text{He}$ and $^6\text{Li} \rightarrow n + {}^5\text{Li}$ ($BE = 5.66$ MeV) $\rightarrow n + p + {}^4\text{He}$. Nevertheless, as the breakup energies of these two processes is much higher that the one-step breakup they should not be important. Besides, there are other sequential processes that could be important for the present system, for example the transfer reactions of $1n(Q = -0.88$ MeV), $1p(Q = 0.66$ MeV) to the target followed by the breakup of the unstable ^{5}Li and ^{5}He nuclei. These α events are included in our experimental α cross sections. Another sequential reaction may be the transfer of one neutron from the target to the projectile ($Q = 0.81$ MeV) and a sequential breakup of the ^{7}Li into an α particle and a triton.

In summary, the quasi-elastic excitation function has been measured at backward angles and the representation of the fusion barrier distribution is obtained for the ^{6}Li + ^{232}Th system. It is observed that D_{qe} consists of a single peak for this system. The experimental fusion barrier distribution has been compared with the FRESCO code calculations using the parameter-free São Paulo potential. The agreement between experiment and prediction improves by including the coupling of the ^{6}Li resonance, corresponding to the sequential breakup, in the calculations. This resonance state is an important coupling to be considered, but it is not enough to explain the data. The direct noncapture breakup, nonresonant sequential breakup and transfer, not included in the calculations, affects significantly the QES excitation functions and barrier distributions at near-barrier energies. As QES is complementary to CF, the present results indicate that the direct noncapture breakup should affect CF significantly.

The authors acknowledge the support of CNPq, FAPERJ. S.M. is grateful to IUAC, New Delhi, and BRNS-DAE, Mumbai, for financial support. S.M. also thanks TWAS-UNESCO, Trieste, Italy, for financial support for three years.

[1] L. F. Canto, P. R. S. Gomes, R. Donangelo, and M. S. Hussein, Phys. Rep. **424**, 1 (2006).
[2] M. Dasgupta *et al.*, Phys. Rev. Lett. **82**, 1395 (1999).
[3] M. Dasgupta *et al.*, Phys. Rev. C **66**, 041602(R) (2002).
[4] M. Dasgupta *et al.*, Phys. Rev. C **70**, 024606 (2004).
[5] N. Rowley, G. R. Satchler, and P. H. Stelson, Phys. Lett. **B254**, 25 (1991).
[6] A. T. Kruppa, E. Romain, M. A. Nagarajan, and N. Rowley, Nucl. Phys. **A560**, 845 (1993).
[7] M. V. Andres, N. Rowley, and M. A. Nagarajan, Phys. Lett. **B202**, 292 (1988).
[8] H. Timmers *et al.*, Nucl. Phys. **A584**, 190 (1995).
[9] H. Timmers *et al.*, Phys. Lett. **B399**, 35 (1997).
[10] H. Timmers *et al.*, Nucl. Phys. **A633**, 421 (1998).
[11] C. J. Lin *et al.*, Nucl. Phys. **A787**, 281c (2007).
[12] J. Lubian, T. Correa, P. R. S. Gomes, and L. F. Canto, Phys. Rev. C **78**, 064615 (2008).
[13] D. S. Monteiro *et al.*, Phys. Rev. C **79**, 014601 (2009).
[14] P. K. Sahu *et al.*, Phys. Rev. C **73**, 064604 (2006).
[15] C. Signorini *et al.*, Phys. Rev. C **67**, 044607 (2003).
[16] A. Gavron, Phys. Rev. C **21**, 230 (1980).
[17] B. K. Nayak *et al.*, Phys. Rev. C **78**, 061602(R) (2008).
[18] B. K. Nayak *et al.*, Phys. Rev. C **75**, 054615 (2007).
[19] I. J. Thompson, Comput. Phys. Rep. **7**, 167 (1988); www.fresco.org.uk.
[20] L. C. Chamon *et al.*, Phys. Rev. C **66**, 014610 (2002).
[21] M. A. G. Alvarez *et al.*, Nucl. Phys. **A723**, 93 (2003).
[22] L. R. Gasques, L. C. Chamon, P. R. S. Gomes, and J. Lubian, Nucl. Phys. **A764**, 135 (2006).
[23] J. J. S. Alves *et al.*, Nucl. Phys. **A748**, 59 (2005).
[24] E. Crema, L. C. Chamon, and P. R. S. Gomes, Phys. Rev. C **72**, 034610 (2005).
[25] S. Raman, C. W. Nestor, Jr., and P. Tikkanen, At. Data Nucl. Data Tables **78**, 1 (2001).
[26] A. Diaz-Torres and I. J. Thompson, Phys. Rev. C **65**, 024606 (2002).
[27] M. S. Hussein *et al.*, Phys. Rev. C **73**, 044610 (2006).
[28] P. R. S. Gomes *et al.*, J. Phys. G **31**, S1669 (2005).
[29] J. Lubian *et al.*, Phys. Rev. C **64**, 027601 (2001).
[30] J. M. Figueira *et al.*, Phys. Rev. C **73**, 054603 (2006).
[31] J. Lubian *et al.*, Nucl. Phys. **A791**, 24 (2007).
[32] H. Kumawat *et al.*, Phys. Rev. C **78**, 044617 (2008).