Breakup vs fusion inhibition of Li-induced reactions at low energies

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A critical analysis of the cross sections for the characteristic γ rays of the residual nuclei following ^{6}Li + ^{16}O and ^{7}Li+ ^{16}O reactions shows that if the breakup mechanism is supposed to be responsible for the limitation of fusion cross sections for these systems, then the large magnitude of the cross sections for the γ rays cannot be accounted for.

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Very recently we have measured the fusion cross sections for a number of reactions induced by ^{6,7}Li projectiles, by the characteristic γ-ray yield method [1–3]. These cross sections are found to be nearly equal to the total reaction cross sections at energies below $2B_C$ (where B_C is the Coulomb barrier energy), which shows that fusion is the dominant reaction mechanism for these systems at low energies.

The fusion cross sections for the same systems have earlier been measured at energies around and above $2B_C$ by the evaporation residue detection technique [4–7]. Takahashi *et al.* [8] have extended the measurement for the ^{6,7}Li + ^{12}C reactions down to energies $\sim B_C$ using a similar technique. As can be seen in Fig. 1, there is a clear discrepancy in the cross sections measured by the two techniques. This is very puzzling since both the techniques are rather well established and have been used extensively for the measurements of cross sections involving several systems. It is well known that the γ-ray method is more suitable for measurements at lower bombarding energies while the evaporation residue method works better at higher energies. On the other hand, for the systems, such as ^{12}C+ ^{13}C [9,10] and ^{11}B + ^{12}C [11,12], fusion cross sections have been measured using both techniques and good agreement has been observed in the corresponding data in the overlapping energy region [3]. Therefore, the disagreement between the results obtained for all the Li-induced reactions investigated by the two methods is very surprising.

Takahashi *et al.* [8] correlated the reduction of fusion cross sections to the small separation energies of the nuclei ^{6,7}Li and ^{9}Be which presumably break up instead of going to fusion. The breakup particles, however, have been detected in some of the systems only at considerably higher bombarding energies [7]. In fact it is generally believed that the breakup effects are stronger at high incident energies and to our knowledge so far no measurements of the breakup cross sections have been done for such low heavy-ion systems at subbarrier energies. In view of this, the suppression of the fusion cross sections by a factor of 3–6 for the systems studied by Takahashi *et al.* at low energies by this process appears rather strange.

In the measurement of γ-ray cross sections, the angular distribution effects, which are supposed to be minimized because of the extensive cascading [13], were further reduced by taking the measurement at 125° to make $P_2(\cos\theta)=0$ [14]. Special care was taken in the absolute efficiency calibration of the detector by making calibrated sources of ^{60}Co and ^{137}Cs on the tantalum frames having the same configurations as those for the targets. The measurements of different quantities and their uncertainties from different sources, in the determination of the γ-ray cross sections, have been discussed in details earlier [1–3]. The total uncertainty in the γ-ray cross sections is found to be $\sim$11% in the present case.

The main objection to the application of the γ-ray method to determine the fusion cross sections is that it uses a statistical model for the evaluation of the branching factors $\sigma_\gamma/\sigma_{ch}$ to obtain the channel and fusion cross sections from the experimental γ-ray cross sections. However, it is possible to justify the use of this procedure by determining the cross sections for a specific channel using more than one γ ray emitted from the same residual nucleus [15]. Figure 2 shows the comparison of cross sections for some of the channels, namely, ^{21}Ne+pn, ^{20}Ne+pn, ^{15}N+αn, and ^{14}N+α in ^{7}Li+ ^{16}O, ^{6}Li+ ^{16}O, ^{7}Li+ ^{13}C, and ^{6}Li+ ^{12}C reactions, respectively, using the characteristic γ rays. The agreement in most of the cases is within $\sim$10%. It is worthwhile to note that a similar comparison is not possible with the evaporation residue technique.

A serious discrepancy between the two types of measurements becomes apparent when one compares the cross sections for the individual mass groups obtained by the evaporation residue detection method with the corresponding channel cross sections obtained by the γ-ray method [1]. To illustrate this more clearly the cross sections for the mass groups $A=20$ in the ^{6}Li+ ^{16}O reaction and $A=21$ in the ^{7}Li+ ^{16}O reaction obtained by these two methods are shown in Fig. 3. The cross sections for these two mass groups constitute $\sim$30% and $\sim$40% of the total fusion cross sections for ^{6}Li+ ^{16}O and ^{7}Li+ ^{16}O reactions, respectively [3]. Besides channel cross sections, we have also shown in this figure the cross sections for the 1.634 MeV γ ray (1.634 MeV→g.s.) of ^{20}Ne in the ^{6}Li+ ^{16}O reaction and the 0.351 MeV γ ray (0.351 MeV→g.s.) of ^{21}Ne in the ^{7}Li + ^{16}O reaction. To facilitate the comparison the cross sections obtained for $A=20$ and $A=21$ mass groups by the statistical model calculations (using the code CASCADE) are also shown.

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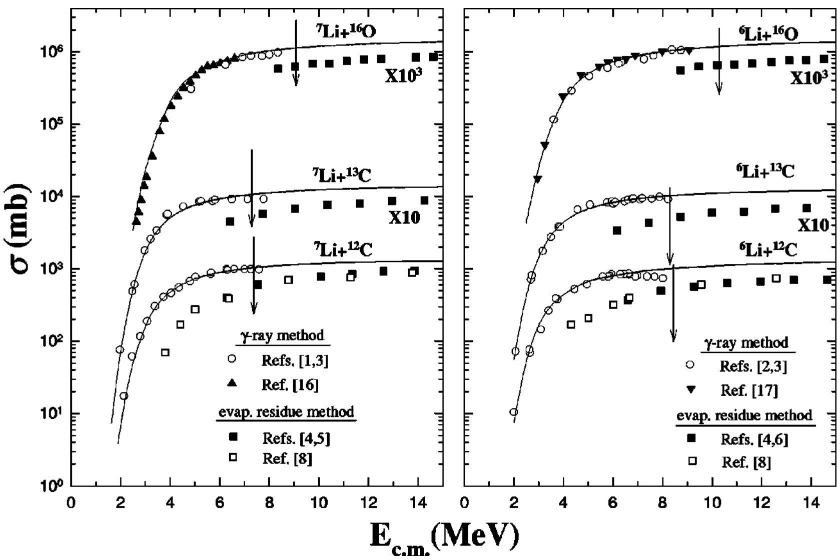

FIG. 1. Total fusion cross sections for ^{6,7}Li + ^{12,13}C and ^{6,7}Li+ ^{16}O reactions, measured by the γ-ray method and the evaporation residue detection method. The solid lines represent the total reaction cross sections calculated using optical model potential with parameters obtained from fitting the elastic scattering data [24]. The arrows indicate the positions of 2 times the Coulomb barrier energy, $2B_C$ [where $B_C = Z_1 Z_2 e^2 / 1.70(A_1^{1/3} + A_2^{1/3})$] up to which the fusion cross sections are usually observed to be $\approx$ total reaction cross sections.

It is observed that in the energy region of overlap, the cross sections for $A=20$ and $A=21$ obtained by the evaporation residue method are smaller by a factor of ~ 2.7 compared to those obtained by the γ-ray method. It is surprising to note that the former cross sections are also smaller (by a factor of ~ 2) than those for the 1.634 MeV γ ray (^{20}Ne) and 0.351 MeV γ ray (^{21}Ne), respectively.

It is difficult to think of any contaminants which could give such a large yield of the 0.351 and 1.634 MeV γ rays. Nevertheless, the contribution of these two γ rays from the background were obtained by allowing the beam to pass through an empty hole in place of the target for the same beam dose and exposure time [3]. As can be observed from Fig. 4, the yield from the background is too small to account for the observed discrepancy in Fig. 3. It is also observed that the peaks corresponding to the above two γ rays in the spectrum are very intense and the evaluation of the area under the peaks poses no problem. Furthermore, the measurements have been done using different targets and setup [3,16,17], giving consistent results.

That the breakup process cannot account for the inhibition of fusion cross sections together with the observation of large γ-ray cross sections mentioned above will be evident from the following discussions. There are essentially two basic mechanisms of the breakup reactions: (i) sequential breakup mechanism and (ii) spectator breakup mechanism [18]. In the former the projectile is excited to a continuum state upon collision with the target nucleus. It subsequently breaks into two (or more) pieces after traversing the interaction region. In the latter case, the projectile breaks up instantaneously in the interaction region and one of the fragments may be absorbed by the target nucleus.

Now, according to Takahashi *et al.*, if we consider the breakup process to be responsible for the smaller cross sections obtained by the evaporation residue method, then the sequential breakup mechanism, though it can explain the

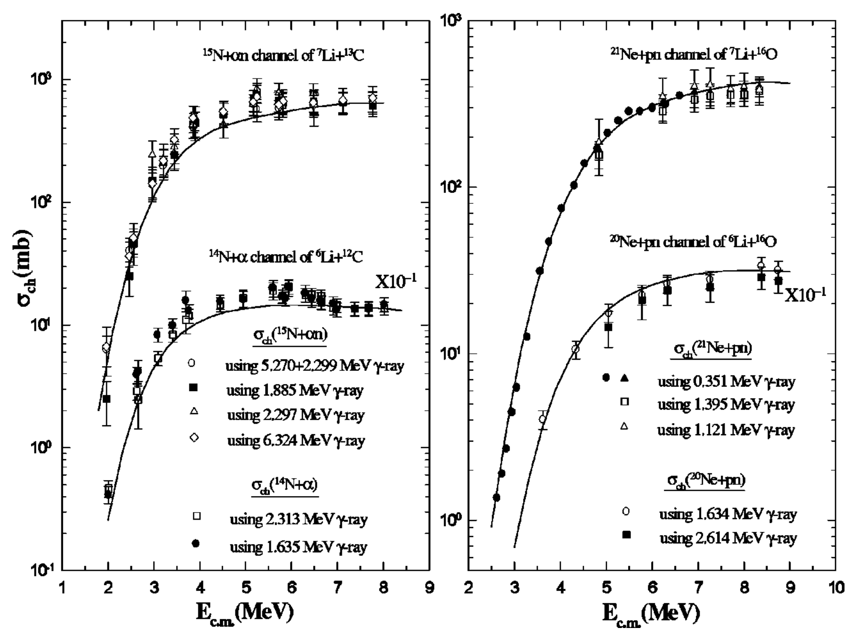

FIG. 2. Cross sections for the ^{15}N$+\alpha n$, ^{14}N $+\alpha$, ^{21}Ne$+pn$, and ^{20}Ne$+pn$ channels from different characteristic γ rays of the relevant residual nuclei following ^{7}Li+ ^{13}C, ^{6}Li+ ^{12}C, ^{7}Li+ ^{16}O, and ^{6}Li+ ^{16}O reactions, respectively. The solid curves represent the statistical compound nucleus calculations performed with the code CASCADE. The error bars show the total error.

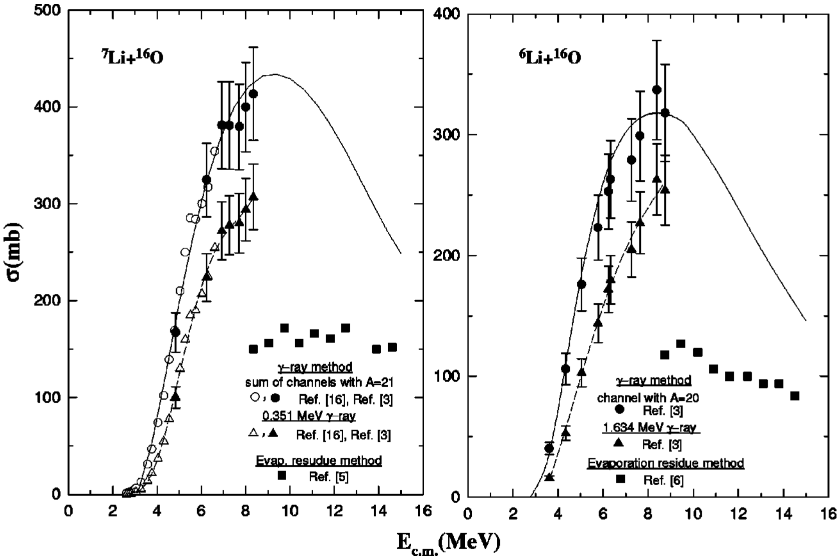

FIG. 3. Cross sections for the mass group $A=21$ in ^{7}Li+ ^{16}O reaction and $A=20$ in ^{6}Li + ^{16}O reaction obtained from the evaporation residue method [5,6] are compared with the corresponding channel cross sections obtained by the γ-ray method [3,16]. The cross sections for the 0.351 MeV γ ray of ^{21}Ne and 1.634 MeV γ ray of ^{20}Ne are also plotted. The solid lines represent the statistical model calculations performed with the code CASCADE and the dotted lines through the γ-ray cross section data are drawn only to guide the eye. The error bars show the total error.

small fusion cross sections, cannot explain the large yield of the γ-ray cross sections mentioned above. The only way in which we can get more 1.634 MeV γ rays of ^{20}Ne in the ^{6}Li+ ^{16}O reaction is when the breakup proceeds through the spectator mechanism. In this process, the nucleus ^{6}Li breaks up into α and d ($Q=-1.5$ MeV); the α particle is captured by ^{16}O to form ^{20}Ne in some excited state which subsequently decays to the 1.634 MeV state and emits the 1.634 MeV γ ray. However, in the evaporation residue method these ^{20}Ne residual nuclei, somehow, are not detected. In this explanation it is inherently assumed that the residual nuclei

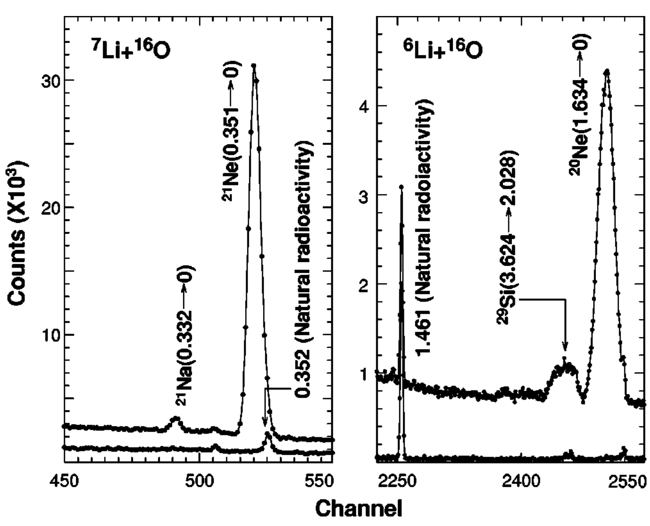

FIG. 4. Parts of the γ-ray spectra of ^{6}Li+ ^{16}O and ^{7}Li+ ^{16}O reactions at $E_{lab}(^{6}\mathrm{Li},^{7}\mathrm{Li})=12$ MeV obtained with a SiO_2 target. The lower spectrum in each case is obtained with the equal beam dose and exposure time at the same bombarding energy but allowing the beam to pass through an empty hole in place of the target. Note the broadening and shift of γ-ray peaks in the upper spectra due to recoil of the residual nuclei and placement of the HPGe detector at 125° with respect to the beam direction. For comparison two γ-ray peaks 0.352 MeV (^{226}Ra) and 1.461 MeV (^{40}K) of natural radioactivities in the background are also shown. ^{29}Si(3.624 →2.028) is from the ^{6}Li+ ^{28}Si→ ^{29}Si+ αp reaction.

(^{20}Ne) do not come out of the target. If it were so, it would lead to the formation of a large unshifted and sharp 1.634 MeV γ-ray peak contrary to the observed shifted and broad peak (Fig. 4). Even this way of describing the reaction process seems to be more difficult to explain the ^{7}Li+ ^{16}O → ^{21}Ne+pn reaction. To get ^{21}Ne following breakup one will have to consider ^{7}Li to break into ^{5}He+d ($Q=-9.6$ MeV) or ^{5}He+n+p ($Q=-11.8$ MeV). However, the breakup thresholds for both these processes are much higher than that for ^{7}Li breaking into $\alpha+t$ ($Q=-2.5$ MeV) and hence the former two processes should have very small cross sections compared to the latter. Thus such a large cross section for the 0.351 MeV γ ray of ^{21}Ne compared to that for the mass group $A=21$ obtained by the evaporation residue technique cannot be explained by the breakup phenomenon.

It may be worthwhile to mention here that the noninhibition of fusion cross sections has also been observed, using γ-ray method, for systems such as ^{9}Be+ ^{64}Zn [19] at energies near and above the barrier and ^{9}Be+ ^{9}Be [15] and ^{9}Be+ ^{16}O [20] systems at sub-barrier energies despite the fact that ^{9}Be is a loosely bound ($S_n=1.67$ MeV) nucleus. On the other hand, the evaporation residue measurements for systems such as ^{9}Be+ ^{28}Si [21] and ^{9}Be+ ^{29}Si [22] at energies well above the barrier and the α activity measurement for the ^{9}Be+ ^{208}Pb system [23] at energies near and above the barrier show strong inhibition of fusion cross sections.

Summing up we can conclude that there is a serious discrepancy between the cross sections obtained by the evaporation residue method and the γ-ray method at sub-barrier energies for the Li-induced reactions. The difference appears to reduce with the increasing bombarding energy. It is impossible to reconcile the two sets of data considering the breakup process as suggested in a recent reference [8]. Measurements using both the techniques simultaneously may help to resolve the discrepancy.

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[1] A. Mukherjee, U. Datta Pramanik, M. Saha Sarkar, A. Goswami, P. Basu, S. Bhattacharya, S. Sen, M.L. Chatterjee, and B. Dasmahapatra, Nucl. Phys. **A596**, 299 (1996).
[2] A. Mukherjee, U. Datta Pramanik, S. Chattopadhyay, M. Saha Sarkar, A. Goswami, P. Basu, S. Bhattacharya, M.L. Chatterjee, and B. Dasmahapatra, Nucl. Phys. **A635**, 205 (1998).
[3] A. Mukherjee, U. Datta Pramanik, S. Chattopadhyay, M. Saha Sarkar, A. Goswami, P. Basu, S. Bhattacharya, M.L. Chatterjee, and B. Dasmahapatra, Nucl. Phys. **A645**, 13 (1999).
[4] L.C. Dennis, K.M. Adbo, A.D. Frawley, and K.W. Kemper, Phys. Rev. C **26**, 981 (1982).
[5] J.F. Mateja, J. Garman, D.E. Fields, R.L. Kozub, A.D. Frawley, and L.C. Dennis, Phys. Rev. C **30**, 134 (1984).
[6] J.F. Mateja, A.D. Frawley, L.C. Dennis, and K. Sartor, Phys. Rev. C **33**, 1649 (1986).
[7] S.L. Tabor, L.C. Dennis, and K. Abdo, Nucl. Phys. **A391**, 458 (1982).
[8] J. Takahashi, K. Munhoz, E.M. Szanto, N. Carlin, N. Added, A.A.P. Suaide, M.M. de Moura, R. Liguouri Neto, and A. Szanto de Toledo, Phys. Rev. Lett. **78**, 30 (1997).
[9] R.A. Dayras, R.G. Stokstad, Z.E. Switkowskii, and R.M. Wieland, Nucl. Phys. **A265**, 153 (1976).
[10] D.G. Kovar *et al.*, Phys. Rev. C **20**, 1305 (1979).
[11] R.A. Dayras, R.G. Stokstad, Z.E. Switkowski, and R.M. Wieland, Nucl. Phys. **A261**, 478 (1976).
[12] J.F. Mateja, A.D. Frawley, L.C. Dennis, K. Abdo, and K.W. Kemper, Phys. Rev. C **25**, 2963 (1982).
[13] C.A. Barnes, S. Trentalange, and S.-C. Wu, in *Treatise on Heavy Ion Science*, edited by D.A. Bromley (Plenum, New York, 1985), Vol. 6, p. 3.
[14] C.T. Papadopoulos, R. Vlastou, E.N. Gazis, P.A. Assimakopoulos, C.A. Kalfas, S. Kossionides, and A.C. Xenoulis, Phys. Rev. C **34**, 196 (1986).
[15] A. Mukherjee and B. Dasmahapatra, Nucl. Phys. **A614**, 238 (1997), and references therein.
[16] C.J.S. Scholz, L. Ricken, and E. Kuhlman, Z. Phys. A **325**, 203 (1986).
[17] K. Glasner, L. Ricken, and E. Kuhlmann, Nucl. Phys. **A452**, 150 (1986).
[18] G. Baur, F. Rosel, D. Trautmann, and R. Shyam, Phys. Rep. **111**, 333 (1984), and references therein.
[19] S.B. Moraes, P.R.S. Gomes, J. Lubian, J.J.S. Alves, R.M. Anjos, M.M. Sant'Anna, J. Padron, and C. Muri, Phys. Rev. C **61**, 064608 (2000).
[20] B. Cujec, S.-C. Wu, and C.A. Barnes, Phys. Lett. **89B**, 151 (1979).
[21] J.S. Eck, J.R. Leigh, T.R. Ophel, and P.D. Clark, Phys. Rev. C **21**, 2352 (1980).
[22] M.C.S. Figueira, E.M. Szanto, R.M. Anjos, N. Added, N. Carlin, L. Fante, Jr., R. Matheus, and A. Szanto de Toledo, Nucl. Phys. **A561**, 453 (1993).
[23] M. Dasgupta *et al.*, Phys. Rev. Lett. **82**, 1395 (1999).
[24] J.E. Poling, E. Norbeck, and R.R. Carlson, Phys. Rev. C **13**, 648 (1976).