Fusion cross sections for ^{7}Li+^{16}O at energies above barrier

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Measurement of fusion cross sections for the ^{7}Li+^{16}O reaction by the γ-ray method has been done in the energy interval $E_{\mathrm{c.m.}}$=12.5–23.6 MeV (where c.m. means center-of-mass). The γ-ray data obtained at high bombarding energies are found to be in agreement with those obtained by the evaporation residue method. The present data, together with the previous γ-ray data, show that there is no fusion suppression at energies below and near the Coulomb barrier.

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Influence of breakup of weakly bound stable/radioactive nuclei on the fusion process, at energies around Coulomb barrier, has been extensively investigated in recent years both theoretically [1–9] and experimentally [10–31], but still it is not well understood. There are theoretical works which predict either suppression of the complete fusion cross sections [1–5] due to the breakup of the loosely bound nucleus or enhancement of the same due to the coupling of the relative motion of the colliding nuclei to the breakup channel. Very recently coupled channels calculations [8] have been performed which suggest that a combination of all these effects essentially leads to enhancement of fusion cross sections at sub-barrier energies and reduction of the same at above barrier energies. Fusion cross section measurements of ^{9}Be +^{208}Pb [18], ^{9}Be+^{209}Bi [21], and ^{6,7}Li+^{209}Bi [19] show substantial fusion suppression at energies above the fusion barrier V_b. No fusion suppression around the barrier has been observed for the reaction of ^{9}Be with ^{64}Zn [24]. Also recent measurements of ^{6,7}Li and ^{9}Be with ^{27}Al [31,30] show that the total fusion cross sections (complete+incomplete) are not inhibited due to breakup effects.

For the light mass systems ^{6,7}Li+^{12,13}C and ^{6,7}Li+^{16}O, measurements with controversial results have been reported in the literature. Measurements done by the direct detection of evaporation residues [10–12,15] show large reduction of cross sections at energies above V_b. Inhibition of fusion cross sections in the ^{7}Li+^{16}O reaction at low energies was also reported [14], using light charged particles detection method. But measurements carried out using the characteristic γ-ray technique [25–28] show fusion cross sections to be almost equal to the total reaction cross sections, at energies below and around V_b. One of the measurements using the evaporation residue technique was pushed down to energies below the Coulomb barrier [15]. The measurements at low bombarding energies mentioned in this work show reduction of fusion cross sections by a factor of ~3–6 compared to the total reaction cross section, in contradiction to the results of the γ-ray measurements [25,26]. This inhibition of fusion cross sections, according to the authors, is due to the breakup of the weakly bound projectiles without going to fusion. In our earlier works [25–28], we pointed out that this discrepancy could be due to the underestimation of the yield of the evaporation residues, because of their low kinetic energy particularly at low bombarding energies, in the evaporation residue detection technique. In the light charged particle detection work [14], since only a very small fraction of the total fusion cross sections was measured and the justification of the use of a low angular momentum cutoff was based on the evaporation residue data [11], it is perhaps difficult to make any definite conclusion regarding fusion suppression from these measurements.

As the evaporation residue measurements could not be pushed down to lower energies, and the light charged particle method is limited to the measurement of a very small fraction of the total fusion cross sections, besides being difficult to use at higher bombarding energies (because of multiparticle emission), the alternative suggestion would be to apply the γ-ray method to higher bombarding energies covered by the evaporation residue method.

The principal disadvantage of the γ-ray method is its dependence on a statistical model calculation to obtain channel and fusion cross sections from the observed γ-ray cross sections. Moreover, the γ-ray technique works well at lower bombarding energies when the residues formed are relatively smaller in number and Doppler broadening of the γ rays is small due to the small recoil velocities of the residues. But γ-ray measurements normally become difficult owing to the complexity of the spectra with the increase of incident energy. Also, at incident energies far above the barrier, total ground state populations increases because of the opening of more evaporation channels. Nevertheless, there are certain reactions, e.g., ^{16}O+^{16}O [32], ^{12}C+^{16}O [33,34], where the γ-ray measurements have been pushed to much higher energies because of the population of not too many channels. It appears that ^{7}Li+^{16}O is one such reaction where also γ-ray measurements can be extended to much higher energies. So in the present work, fusion cross section measurements, using the γ-ray technique for the system ^{7}Li+^{16}O, have been extended to higher energies (E_{lab}=18–34 MeV) with an aim to investigate the existing discrepancy between the γ-ray method and the evaporation residue method conclusively.

The measurements were carried out with ^{7}Li beam in the energy region, E_{lab}=18–34 MeV, from the 14UD Pelletron accelerator at the Nuclear Science Centre, New Delhi. The target was SiO_2 (self-supporting) having oxygen content $(18.0\pm1.1)\times10^{17}$ nuclei/cm^2, measured from the elastic scattering data obtained with heavy ion detectors. The beam current was measured using a Faraday cup in the form of a long insulated metallic cylinder and a standard current integrator. The characteristic γ rays emitted by the fusion evaporation residues were detected using an HPGe detector of 25% relative efficiency, placed at 90° with respect to the beam axis. The details of the measurement of efficiency of the detector have been described earlier [25,28]. The anisotropy of the angular distribution of the γ rays used in the determination of fusion cross section was investigated, and was found to be negligible. The measurement of different quantities and their uncertainties in the determination of γ-ray cross sections have been discussed in Refs. [25–27]. The total uncertainty in the γ-ray cross section is found to be ~11%. The total γ-ray yield was obtained by summing the cross sections of 0.332 (^{21}Na), 0.351, 1.121, 1.395 (^{21}Ne), 0.937 (^{18}F), 1.634 (^{20}Ne), and 5.270+5.299 (^{15}N) MeV γ rays. The total fusion cross sections were obtained from the total γ-ray cross sections, dividing the latter by the correction factor F_γ, as described in Ref. [27]. The factor F_γ in the present work has been calculated using the code CASCADE. [35] and is found to vary from ~60% to ~30% in the energy region $E_{c.m.}$ =12.5–23.6 MeV (where c.m. means center-of-mass). The dependence of F_γ on various parameters of the calculation using a code has been investigated by several authors including us. It is found that except for very weak γ rays F_γ is not much sensitive to the reasonable variation of these parameters and the uncertainty in F_γ is estimated to be $\leqslant$10% [36–39]. The consistency of such calculation is further checked by the evaluation of cross sections for a particular channel from two or more γ rays of the same residual nucleus. The agreement, in general, is found to be within 10% [25–28,37]. The uncertainty in F_γ (10%) has been added in quadrature to the total uncertainty ($\simeq$11%) in γ-ray cross sections resulting in $\approx$15% uncertainty in the total fusion cross section. The fusion cross sections are shown (with solid circles) in Fig. 1. In the earlier γ-ray measurements [27,28] as there was very little energy overlap of the γ-ray data with those of the evaporation residue data, it was not clear up to which energy the discrepancy between the two sets of measurements remains. With the present measurement at higher bombarding energies, it is well visible that the two sets of measurements agree with each other for energies $E_{c.m.}\geqslant$14 MeV.

Recently Keeley *et al.* [40] have calculated the fusion cross sections for the ^{6,7}Li+^{16}O systems using a combination of CDCC/CF (continuum discretized coupled channels/cluster folding) and BPM (barrier penetration model) techniques which agree well with the γ-ray measurements [13,27,28] rather than the evaporation residue measurements [11,12]. These calculations were carried out in the framework of a relatively realistic inclusion of lithium breakup using the CDCC method. The calculated values are shown by triangles in Fig. 1 and can be seen to be in fairly good agreement with the γ-ray measurements both at low and high bombarding energies. The total reaction cross sections, calculated using optical model potential obtained from fitting the elastic scattering data by Poling *et al.* [41], are shown by the solid line in Fig. 1. The onset of reduction of fusion cross sections from the total reaction cross sections appears to occur at $E_{c.m.}$~8 MeV, which is well above the Coulomb barrier (~5 MeV) for this system. This is quite expected due to the opening of other reaction channels, thereby reducing the fusion cross sections. It was pointed out in the CDCC calculations of Keeley *et al.* [40] that this reduction of fusion cross sections at higher energies is mainly due to the break up of the loosely bound lithium nuclei.

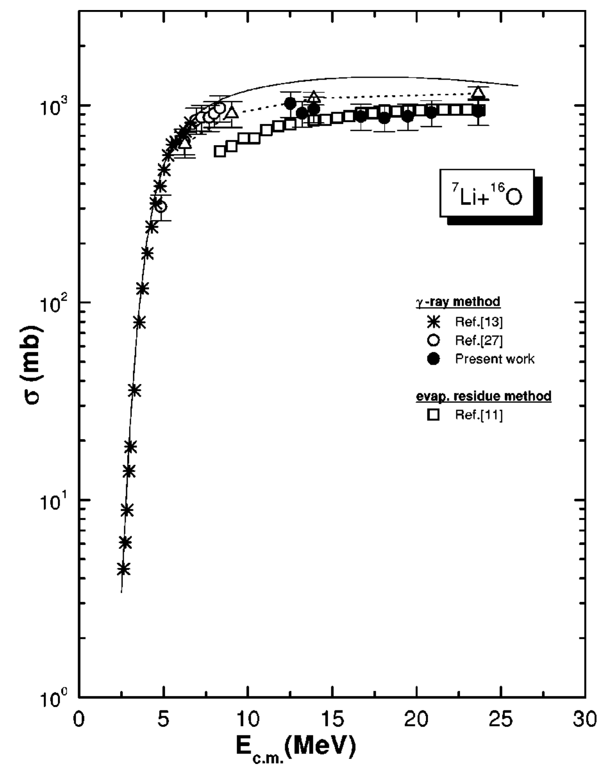

FIG. 1. Total fusion cross sections for the ^{7}Li+^{16}O reaction, measured by the γ-ray method and the evaporation residue method. The solid line represents the total reaction cross sections calculated using optical model potential (for details see Refs. [27,41]). The CDCC calculations of Keeley *et al.* [40] are shown by the symbol "Δ" and are joined by dotted line to guide the eyes.

At low bombarding energies the measured fusion cross sections are observed to be almost equal to the total reaction cross sections. This is due to the absence or very weak excitation of possible quasielastic reactions. The work of Leifels *et al.* [14] shows that although α- and t-transfer reactions dominate for a few low lying states of ^{20}Ne and ^{19}F the magnitude of their cross sections (~2.5–7.0 mb and ~3–8 mb, respectively) is very much less compared to the total fusion cross section (~180–850 mb) in the energy region $E_{c.m.}$=4–7 MeV. Furthermore, cross sections for most of these states, according to them, contain contribution of compound nucleus reaction. The γ-ray data (which also contain contributions of both compound nucleus and transfer reactions) when compared with statistical model calculations show that only ~2–10 mb in the case of ^{20}Ne and ≃0 in the case of ^{19}F contribute as transfer cross section in the low energy region. Since spectroscopic amplitudes for one particle configuration in $^{7}\mathrm{Li}\rightarrow{}^{6}\mathrm{Li}+n$ and $^{6}\mathrm{He}+p$ are smaller by a factor of ~0.05 compared to $\alpha+t$ [42], one would expect the cross sections for these reactions to be much smaller than those for α- and t-transfer reactions. This appears to be corroborated by the γ-ray work at low energies [27], where we do not observe any γ rays of ^{17}O and ^{17}F following n- and p-transfer reactions, respectively.

At high bombarding energies (E_{lab}~36 MeV), on the other hand, the total reaction cross sections for a number of ^{6,7}Li-induced reactions are found to be nearly equal to the sum of fusion and breakup reactions cross sections [43]. This shows that other quasielastic reactions, such as transfer and inelastic scattering, have negligible contributions to the total reaction cross sections. It is expected that the same should be true for the $^{7}\mathrm{Li}+{}^{16}\mathrm{O}$ reaction also.

Very recently Mukherjee *et al.* [44] have measured the fusion cross sections for the $^{7}\mathrm{Li}+{}^{12}\mathrm{C}$ reaction in inverse kinematics using the evaporation residue method at $E_{c.m.}$ =3.7 MeV. The measured fusion cross sections agree with the γ-ray measurement [25], in contradiction to the work of Ref. [15] where substantial inhibition of fusion cross section was observed. Moreover, it has been shown in Ref. [44] that this inhibition is not due to the breakup of the loosely bound ^{7}Li nucleus but arises because of not considering the contribution of the residues with kinetic energies below the detection threshold. It is very likely that like $^{7}\mathrm{Li}+{}^{12}\mathrm{C}$ reaction, all the Li and Be induced reactions including $^{7}\mathrm{Li}+{}^{16}\mathrm{O}$ investigated previously by the evaporation residue method suffer from the same drawback, i.e., underestimation of the yield of the low energy residues.

Considering all these facts together, it can be concluded that for the $^{7}\mathrm{Li}+{}^{16}\mathrm{O}$ system, the fusion cross sections are almost equal to the total reaction cross sections at $E_{c.m.}$ ≤8 MeV and start decreasing from it above this energy mainly due to the breakup process, with other quasielastic reactions such as transfer and inelastic scattering making negligible contribution.

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