PHYSICAL REVIEW C **76**, 027603 (2007)

Experimental investigation of fusion of ^{7}Li+^{28}Si above the Coulomb barrier

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(Received 8 May 2007; published 20 August 2007)

Excitation functions for the above-barrier fusion cross sections are measured for the first time for the ^{7}Li+^{28}Si system by two methods—the characteristic γ-ray method and the evaporation α measurement method—in the energy range $E_{\text{lab}} = 11.5$–26 MeV. Experimental results are consistent and agree with each other, and the one-dimensional Barrier Penetration Model (BPM) predictions describe the data well up to twice the Coulomb barrier, but they overestimate the data by about 15–20% at higher energies.

DOI: 10.1103/PhysRevC.76.027603 PACS number(s): 25.60.Pj, 25.70.Gh, 25.70.Jj

Understanding the reaction dynamics of loosely bound stable projectiles at near-barrier energies have attracted much interest in recent years not only because of the new insights provided by them into the mechanisms but also because these nuclei are viewed as precursors to more exotic radioactive nuclei with "haloes" or "skins." Some of the novel experimental information obtained involving weakly bound nuclei are fusion enhancement or suppression, increase of breakup cross sections compared with tightly bound stable projectiles, weakening or absence of a threshold anomaly, or the occurrence of a new type of threshold anomaly related to the energy dependence of optical model potentials in the neighborhood of the barrier [1–10].

Theoretical studies [11–15] have also investigated the correlation between the weakly bound cluster structure of these nuclei and the dynamics of the reactions. These studies present a somewhat conflicting picture regarding the magnitude of fusion cross section (enhancement/suppression) at near-barrier energies and their dependence on the bombarding energy above the barrier. Besides the subbarrier and near-barrier fusion and the associated controversies, the scenario of fusion reaction involving weakly bound projectiles at above-barrier energies is also not clear and conclusive. One of the observations is that the breakup does not affect fusion [16] at above-barrier energies. The argument is that for breakup to affect fusion, it has to occur at a lower partial wave region. However, in this angular momentum region, breakup is followed by incomplete fusion (ICF) at higher energies, and the sum of complete fusion (CF) and incomplete fusion (ICF), i.e., the total fusion, remains unaffected. The total fusion (ICF+CF) agrees well with the well-accepted barrier penetration model prediction. This observation, however, does not really corroborate the results of Refs. [17–19]. The general finding in these investigations points toward an overall inhibition of fusion cross section at above-barrier energies, especially for light mass targets. It is to be emphasized, in this context, that the ICF contribution for medium mass targets at above-barrier energies was found to be negligible [20].

There have been a number of complementary experimental investigations on scattering, e.g., for ^{6,7}Li+^{27}Al and^{28}Si [21–23], and on reaction and fusion, e.g., for ^{6,7}Li+^{27}Al [16,24], ^{6}Li+^{28}Si [25,26], ^{9}Be+^{27}Al, ^{28}Si [25,27], and ^{6,7}Li+^{59}Co [6], in the target mass range $A \sim 20$–60. But these measurements are mainly confined to the Coulomb barrier probing the effect of breakup on scattering and fusion in the near-barrier energies. Very few of these data extend beyond twice the barrier energy. However, no fusion measurement exists for the ^{7}Li+^{28}Si system. We present in this article our measurement of fusion cross sections for the ^{7}Li+^{28}Si system at several energies extending from the Coulomb barrier to well above twice the barrier value.

The total fusion excitation function of the ^{7}Li+^{28}Si system was measured using the characteristic γ-ray method. The experiment was carried out at the Bhabha Atomic Research Centre -Tata Institute of Fundamental Research (BARC-TIFR) 14UD Pelletron accelerator with a ^{7}Li (3^+) beam at the energies $E_{\text{lab}} = 11.5, 12.5, 14, 16, 18, 20, 22, 24$, and 26 MeV. Beam intensity was of the order of 5–20 pnA. A small thin-walled aluminum chamber was used to house the target, which consisted of 192 μg/cm^2 natural silicon sandwiched between two thin gold layers (40 and 100 μg/cm^2) to prevent oxidation and was prepared using a vacuum evaporation technique. The average energy loss in the target is about 200 keV. The characteristic γ rays emitted from the evaporation residues were detected using a Compton suppressed Clover detector placed at 55° with respect to the beam direction. Efficiency runs were taken at both the beginning and the end of the main experiment with a number of standard sources, i.e. ^{152}Eu, ^{133}Ba, and ^{207}Bi, spanning the energy range 85–1770 keV. The absolute efficiency in the add-back mode of the detector was measured with ^{152}Eu and ^{133}Ba standard radioactive calibrated sources placed at the target position. Target thickness was measured with the α energy loss method with a three-line α source, and the estimated uncertainty was about 5%. The background was measured at each energy with and without beam using a blank tantalum frame in place of the target.

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These data were used to subtract or correct for background γ rays and γ rays arising out of beam impingement (if any) on the slit, beamline, or Faraday cup. The cross sections were obtained in a manner as described in Ref. [28].

The residues from the fusion of ^{7}Li+^{28}Si at above-barrier energies ($E_{\rm lab} = 11.5$–26 MeV), identified by the characteristic γ-ray spectra, were ^{29}Si, ^{30}Si, ^{32}S, ^{33}S, ^{30}P, and ^{33}P. However, the main contributions to fusion came from αd+^{29}Si, pn+^{33}S, dn+^{32}S, and αp+^{30}Si channels. Some of the prominently identified γ rays were 2.028 (^{29}Si), 1.273+1.263 (^{29}Si+^{30}Si), 2.235+2.230 (^{30}Si+^{32}S), 1.967 (^{33}S), 0.677 (^{30}P), and 1.847 MeV (^{33}P). The total γ-ray cross section was obtained by summing over all the above-mentioned γ-ray cross sections. The total fusion cross section was then estimated as the ratio of the total γ-ray cross section and the branching factor F_γ. This factor was estimated considering the relative population of different bound states of the nuclei under consideration, their branching ratios, and the known deexcitation schemes in a detailed statistical model calculation using CASCADE [29]. The calculated value of F_γ varies from 30% to 48% in the energy region under review. It is also found that F_γ is not as sensitive to small parameter changes, and the estimated uncertainty of the F_γ was found to be within 10%. The contributions of ^{29}Si and ^{30}Si in the natural Si target were taken into account, and their effect yielded an error of only about 5%. Finally, the total uncertainty of the fusion cross section was estimated to be about 14% considering statistical γ-ray yield, absolute efficiency of the detectors, and systematic error in target thickness measurement and integrated beam current.

We compared our fusion results with the one-dimensional Barrier Penetration Model (BPM) predictions of the code CCFULL [30] in the no-coupling mode (see Fig. 1). The potential parameters V_0, r_0, and a_0 were found by fitting the high energy experimental fusion data of the nearest tightly bound projectile-target system, ^{11}B+^{27}Al [31]. The final parameters used in the calculation were $V_0 =$ 130 MeV, $r_0 = 0.97$ fm, and $a_0 = 0.63$ fm. The CCFULL calculation yielded a value for the barrier of $V_b =$ 6.79 MeV produced by the best fit potential parameters. On the lower energy side, up to twice the barrier, the prediction agrees well with the experimental excitation function. But beyond $2V_b$, there is an overprediction of about 15–20% by the 1D BPM model calculation. We checked the sensitivity of the 1D BPM estimation to changes of optical model parameters by keeping V_b fixed but varying the diffuseness parameter a_0 and, accordingly, r_0 by ±10% from their best fit values. The maximum change in fusion cross sections above $2V_b$ is seen to be marginal. If the diffuseness is further increased or decreased, it results in poor fitting. In the high energy side, the fusion cross sections change rather slowly with increasing bombarding energies. Similar observations were reported by Kovar *et al.* [32] while studying systematics of ^{12}C and ^{16}O induced fusion on targets with $12 \leqslant A \leqslant 19$ and by Takahashi *et al.* [5] for the ^{6,7}Li+^{9}Be systems. The theoretical calculation (CDCC) of the fusion cross section for ^{6,7}Li+^{59}Co by Diaz-Torres *et al.* [33] also overestimated the experimental values at energies well above the barrier. In this region, it seems the fusion behavior is no longer dominated by the interaction barrier.

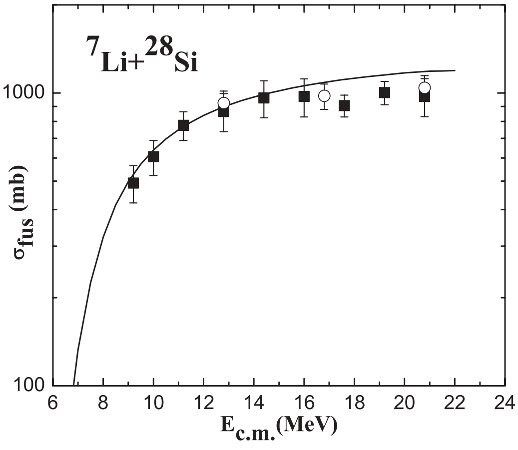

FIG. 1. Fusion cross section for ^{7}Li+^{28}Si system. Experimental results obtained by the γ method (solid rectangles) and α method (open circles) are compared with theoretical estimates (solid line).

To further investigate the fusion mechanism here, we undertook another experiment with the same target-projectile system. Angular distributions of evaporation α particles at the backward directions were measured at 16, 21, and 26 MeV using two silicon telescopes (25, 300 μm). Two monitors were placed at forward angles (±9.8°) for beam normalization purposes. Evaporation α cross sections were measured from the α spectra at different angles, and these were analyzed with the statistical model code PACE2 [34]. The evaporation α's in the backward angles might arise from mainly two sources: (a) CF residues and (b) ICF preceded by breakup and or transfer. Now the α contribution from process (b) seems to be very small at lower energy, as per the study of Pakou *et al.* [35]. At higher energy, though there might be appreciable breakup/transfer events, the backward angle α contributions of this secondary process (each followed by fusion) will be insignificant. This leads us to assume that the α particle contributions in the backward angles are mostly due to CF residues. In our analysis with PACE2, we treated the fusion cross section as input and varied it such that the theoretical α energy and angular distributions gave the best fit to the corresponding experimental α distributions. Typical experimental α energy distributions and energy integrated α angular distributions in some selected backward angles at three higher projectile energies are shown in Figs. 2 and 3, respectively, along with the theoretical best fit estimates from PACE2. The nature of the fits confirms our conjecture that α evaporations in the backward hemisphere are mainly from CF events. The relevant PACE2 parameters used are $a = A/8$ and l-diffuseness $= 0.6$ (obtained from CCFULL estimates of σ_l vs l). The estimated fusion cross sections thus obtained from the best fit are also shown in Fig. 1 (open circles). It is apparent that our fusion measurements with two different experimental techniques mutually agree with each other. The γ measurement usually yields the total fusion cross section (TF) consisting of CF and ICF components. We could not experimentally distinguish between CF and ICF events (occurring from breakup/transfer followed by fusion) because there is overlapping residual nuclei produced in CF and ICF.

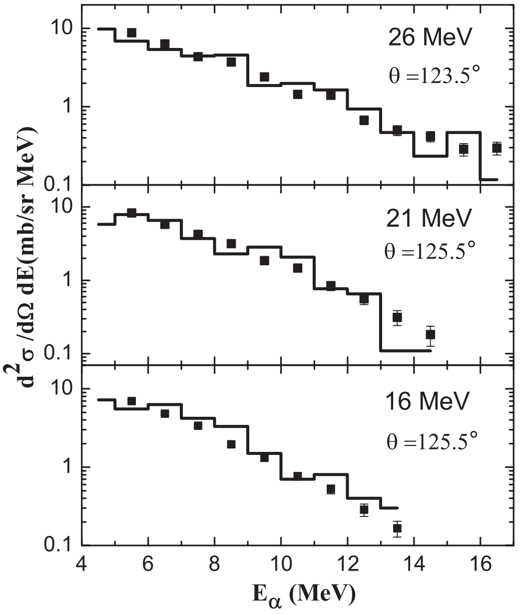

FIG. 2. α energy distributions at three projectile energies. Experimental values (solid rectangles) are compared with best fit PACE2 estimates (solid lines).

In Fig. 4, we compare our results with those of the nearest projectile-target systems ^{7}Li+^{27}Al [16], ^{11}B+^{27}Al [31], and ^{6}Li, ^{9}Be+^{28}Si [25],^{9}Be+^{29}Si [19], following the prescription of Gomes *et al.* [36] so as to eliminate the geometrical effects and thus including the real physical effects embodied in the reduced radii. Though the effect of loose structure is visible, the reduction procedure is not a foolproof prescription, as is obvious from the results from the ^{9}Be+^{29}Si system. Here an increase of target mass by one unit (from ^{28}Si) artificially decreases the ordinate value and shifts the corresponding abscissa to a larger value, finally presenting an overall lowering of the curve compared to ^{9}Be+^{28}Si data. However, as is pointed out in Ref. [36], the usual reduction procedure (either by scaling $E_{\mathrm{c.m.}}$ by V_b or taking their difference) would have smeared and smoothed all the differences in the results of all the projectile-target systems and put them in a featureless single curve (see, e.g., Fig. 3(b) of Ref. [36]). In the present comparison of the results, it appears that high energy behavior (above $2V_b$) for fusion excitation functions is similar (flattening) for ^{7}Li and ^{9}Be induced fusions with ^{27}Al and ^{28}Si, respectively, while that for ^{6}Li has slightly larger values and shows an increasing tendency.

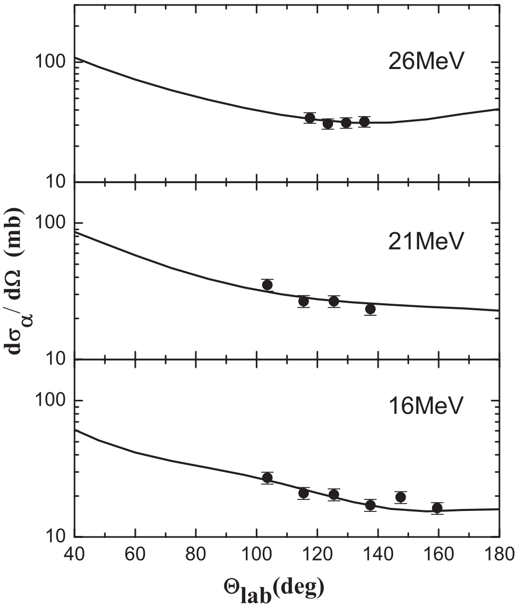

FIG. 3. α angular distributions at three projectile energies. Experimental values (solid circles) are compared with best fit PACE2 estimates (solid lines).

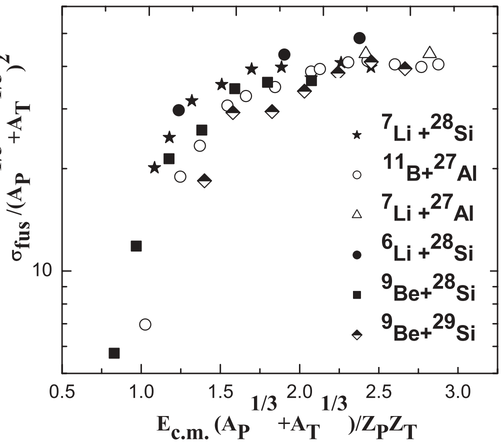

FIG. 4. Reduced fusion cross section of ^{7}Li+^{28}Si system and neighboring target-projectile combinations.

In summary, we have measured the total fusion cross section for ^{7}Li+^{28}Si at above-barrier energies for the first time with two different techniques yielding almost similar results. Most of the existing data with the neighboring target projectile combinations are reported to agree with the 1D BPM model [with widely varying optical model (OM) parameters] at near-barrier energies. Our data for the ^{7}Li+^{28}Si system also agree with 1D BPM predictions up to about twice the barrier energy, but at higher energies (above $2V_b$) these are lower than the theoretical estimates, similar to the results obtained by Figueira *et al.* [19] for the ^{9}Be+^{29}Si system. Though we could not identify any ICF events at our measured energies, one has to keep in mind that several of the residue channels that were populated could have been formed from incomplete fusion and direct processes as well. Though it is expected that breakup would be larger at energies above $2V_b$, but breakup followed by fusion (a second order effect) if present, would occur with a very small contribution. In fact, our experimental findings do corroborate this fact. Considering these conflicting arguments, it is not possible to comment on the quantitative estimate of ICF events and their energy dependence from this type of inclusive measurements. Explicit coincident measurements of ^{7}Li breakup fragments and tagging of residues with transfer components might provide more insight into the fusion behavior in this high energy region.

We thank Mr. P. Das of Saha Institute of Nuclear Physics for the preparation of the Si target. We acknowledge the Department of Atomic Energy (DAE) and the Board of Research in Nuclear Science (BRNS) for financial support through Grant No. 2002/37/38/BRNS.

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