Fusion barrier and spin distributions in $^{12}C+^{232}Th$ reaction via quasielastic scattering

R. Varma and Shrabani Sinha
Department of Physics, Indian Institute of Technology, Powai, Mumbai 400 076, India

B. K. Nayak, R. G. Thomas, A. Saxena, D. C. Biswas, L. M. Pant, D. M. Nadkarni, and R. K. Choudhury
Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai 400 085, India

P. Bhattacharya
Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Calcutta 00064, India

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Quasielastic (QE) excitation function measurements have been carried out for the $^{12}C+^{232}Th$ fissile system at $\theta_{lab}=170°$ in the energy range of E_{lab} = 51–79 MeV. The data has been analyzed to obtain a representation of the fusion barrier distribution, which has been compared with that obtained from fusion-fission excitation function measurements available from literature. The QE data have also been analyzed in the framework of generalized elastic scattering model to obtain the mean-square average compound nuclear spin ($\langle l^2 \rangle$) values, which has been compared with the prediction of standard fusion model (CCDEF) calculations and also with that obtained from fission fragment angular anisotropy measurements. The results show that the barrier distributions obtained from QE and fission excitation function measurement are consistent with each other. The $\langle l^2 \rangle$ values are also consistent with prediction of CCDEF calculations, but are in disagreement with the experimental $\langle l^2 \rangle$ values obtained from fission fragment anisotropy measurements. [S0556-2813(98)01406-X]

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The study of heavy-ion-induced fusion-fission reactions around the Coulomb barrier in systems with high fissility has assumed importance because of the failure of the standard saddle-point statistical model (SSPSM) [1–16] to reproduce the experimentally measured anisotropies in these systems. The measurement of fission-fragment angular distributions in ^{9}Be, ^{10}B, ^{12}C, ^{16}O, and ^{19}F induced reactions on ^{232}Th and ^{237}Np systems [3–5] and in the $^{12}C+^{232}Th$ system [15,16] at bombarding energies above the fusion barrier has revealed that the measured anisotropy is consistent with the predictions of SSPSM for projectiles ^{9}Be and ^{10}B. However, for heavier projectiles (like ^{12}C, ^{16}O, and ^{19}F) induced reactions, the measured anisotropies are much larger than the prediction of SSPSM and have therefore been termed anomalous. This observation of entrance channel dependence of measured anisotropy has been interpreted as evidence for a small admixture of pre-equilibrium/quasifission events, in addition to the fusion-fission events. On the other hand, at sub- and near-barrier energies, anomalous anisotropy has also been reported for a large number of systems such as $^{16}O+^{232}Th$ and $^{12}C+^{232}Th$ and $^{12}C+^{236}U$ by Vandenbosch *et al.* [2], for the system $^{16}O+^{238}U$ by Hinde *et al.* [7,8], for the $^{12}C+^{237}Np$ and $^{11}B+^{238}U$ systems by Zhang *et al.* [9,11], for the ^{11}B, ^{12}C, ^{16}O, and $^{19}F+^{232}Th$ systems by Majumdar *et al.* [12–14], and for the $^{12}C+^{232}Th$ system by Lestone *et al.* [15] and by Mein *et al.* [16] irrespective of entrance channel mass asymmetry. These measurements suggest that the anomalous fission anisotropy may either be due to the enhancement of mean-square average compound nuclear spin ($\langle l^2 \rangle$) [2,6,12] or narrowing of the **K** distribution at sub- and near-barrier energies [7,8,10,11].

The importance of coupling of various other degrees of freedom such as static deformation, inelastic excitation, transfer, etc., giving rise to the enhancement in fusion cross section and $\langle l^2 \rangle$ values in comparison to the one-dimensional barrier penetration model is well known. However, the experimentally observed anomalous fission fragment anisotropy in highly fissile systems cannot still be explained by including the above effects. Moreover, the determination of $\langle l^2 \rangle$ values from fission excitation function measurement does not show any anomalous values [17]. Recent measurement of fusion l distributions through γ-ray multiplicity measurements of fission fragments also does not show any such anomalous $\langle l \rangle_{CN}$ values around the Coulomb barrier [18].

One of the methods of investigating the effect of coupling on enhancement of fusion cross section and broadening of the **l** distribution is by measuring fusion barrier distribution. In fissile systems, the fusion barrier distribution is inferred through the study of fission excitation function measurements. Indirect methods are again adopted to obtain mean-square spin from the fission fragment anisotropies. These are model dependent and have therefore invariably turned out to be anomalous around the Coulomb barrier energies. Hence there is a clear need to investigate the fusion barrier and l distribution, if possible, through a complementary method.

In the past, the determination of the reaction cross section and partial wave distribution from the analysis of generalized elastic scattering (GES) data has been quite successful [19]. In this formalism, GES is defined as the sum of elastic and appropriate nonelastic channels (quasielastic) and the corresponding reaction cross section is called the reduced reaction cross section. Oeschler *et al.* [19] have shown that for heavy-ion collisions, the reduced reaction cross section and its partial wave distribution obtained by optical model fitting are consistent with the total reaction cross section for the remaining channels that are not added to the generalized elastic-scattering data. Recently [20] it has been shown that

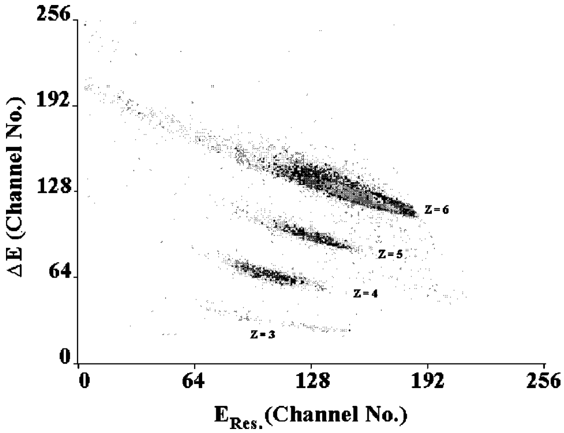

FIG. 1. The ΔE and E_{res} correlation plots at $E_{\mathrm{lab}} = 73$ MeV and $\theta_{\mathrm{lab}} = 170°$ for elastic and transfer channels.

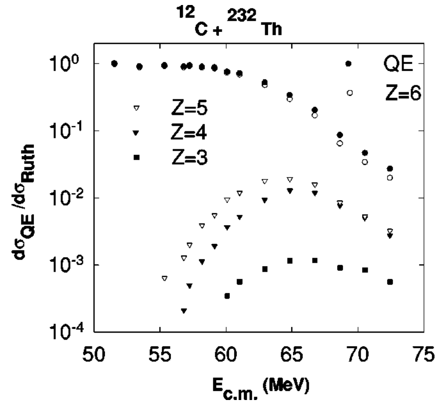

FIG. 2. The measured excitation functions of elastic and different transfer channels in the $^{12}C+^{232}Th$ reaction at $\theta_{\mathrm{lab}} = 170°$.

by an analysis of the quasielastic excitation function one can obtain a representation of fusion barrier distributions. Therefore, it is of interest to compare fusion barrier and spin distributions obtained by both quasielastic scattering and fission excitation function measurements, which may provide information on fusion-fission dynamics in these highly fissile systems.

In the present work we have carried out measurements on quasielastic excitation function at $\theta_{\mathrm{lab}} = 170°$ in the $^{12}C+^{232}Th$ reaction over a wide energy range around the Coulomb barrier. The results were analyzed to obtain the fusion barrier distribution and fusion spin distribution ($\langle l^2 \rangle$). These results have been compared with the fusion barrier distribution obtained from fission excitation function and the $\langle l^2 \rangle$ values obtained from fragment angular distribution measurements [16].

The measurements were carried out using ^{12}C beams from the 14UD pelletron accelerator at the BARC-TIFR pelletron facility, Mumbai. A self-supporting ^{232}Th target of 1.8 mg/cm^2 thickness was used in the experiment. The measurements were carried out in the beam energy range of $E_{\mathrm{lab}} = 51$–79 MeV in steps of 2.0 MeV. The bombarding energy has been corrected for the energy loss in half the target thickness which is ~0.75 MeV. A silicon surface barrier detector telescope [ΔE (17 μm)-E (1.0 mm)] was placed at an angle of 170° to the beam direction to detect the projectile-like fragments. Another silicon surface barrier detector at an angle of 20° with respect to the beam direction was used to measure Rutherford scattering events for normalization. Figure 1 shows one of the typical two-dimensional plots of $\Delta E - E_{\mathrm{res}}$ from the detector telescope, showing elastic and various transfer channels at $E_{\mathrm{lab}} = 73$ MeV. The various out going product charges are clearly identified in the experiment. However, with the present resolution it is not possible to separate the elastic peak from inelastic scattering from low-lying rotational target states. In the data analysis, quasielastic was defined as the sum of all the elastic, inelastic, and transfer events. The differential cross sections for the elastic and quasielastic and transfer events were determined relative to the Rutherford scattering at corresponding energy and laboratory angle. The ratios were normalized assuming that the elastic cross section was equal to the Rutherford cross section value at energies well below the Coulomb barrier. The measured excitation functions of elastic, quasielastic, and different transfer channels are shown in Fig. 2.

In a purely classical picture, the projectiles can either be elastically scattered or undergo fusion. There is a direct relationship between the fusion cross section and the elastic-scattering differential cross section, since any loss from elastic channel contributes directly to fusion. As the ratio of $d\sigma^{\mathrm{el}}/d\sigma^{\mathrm{R}}(E)$ at 180° is equal to the reflection coefficient R_0 for angular momentum $l\hbar = 0$, the transmission coefficient T_0 is related to the reflection coefficient R_0 as $T_0 = 1 - R_0$, and it follows [20] that

$$D^f(E) \equiv \frac{dT_0}{dE} = -\frac{dR_0}{dE} = -\frac{d}{dE}\left(\frac{d\sigma^{\mathrm{el}}}{d\sigma^R}\right) \equiv D^{\mathrm{el}}(E), \quad (1)$$

where $D^f(E)$ and $D^{\mathrm{el}}(E)$ are the barrier distributions derived from fusion and elastic excitation functions. In the presence of multiple barriers Eq. (1) becomes

$$D^{\mathrm{el}}(E) \equiv \sum_{\alpha} W_\alpha D^{\mathrm{el}}_\alpha, \quad (2)$$

so that $D^{\mathrm{el}}(E)$ reflects the distribution of barrier weights W_α for a given barrier α. Similarly the barrier distribution derived from the fusion data can be written as $D^f(E) \equiv \Sigma_\alpha W_\alpha D^f_\alpha$. The quasielastic (QE) excitation function for the $^{12}C+^{232}Th$ system measured at the angle of $\theta_{\mathrm{lab}} = 170°$ was used to determine the fusion barrier distribution $D^{\mathrm{qel}}(E)$ using a point difference formula with a step of 2 MeV in laboratory frame. In order to convert the results of $D^{\mathrm{qel}}(E,170°)$ to that of $D^{\mathrm{qel}}(E,180°)$, the energy scale of the former was reduced by centrifugal energy as

$$E_{\mathrm{cent}} = E_{\mathrm{c.m.}} \frac{\mathrm{cosec}(\theta_{\mathrm{c.m.}}/2) - 1}{\mathrm{cosec}(\theta_{\mathrm{c.m.}}/2) + 1}. \quad (3)$$

The results of the fusion barrier distribution $D^{\mathrm{qel}}(E)$ obtained from the present analysis are shown in Fig. 3, along with the results of $D^f(E)$ determined from fission excitation function measurements of Ref. [16]. Also plotted in the figure is the prediction of the coupled channel fusion model (CCDEF) [21] calculation which fits the experimental fission excitation function data [16]. One can see that the barrier distributions obtained from quasielastic and fission excitation measurement are quite similar as both the methods probe the

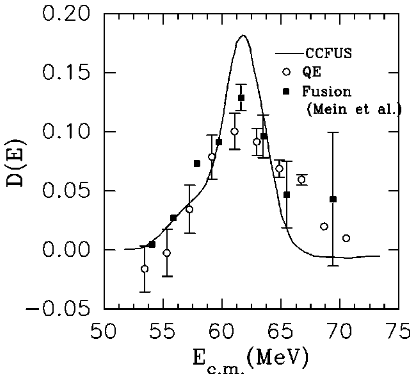

FIG. 3. The fusion barrier distribution obtained from present quasielastic scattering measurement along with the barrier distribution obtained from the fission excitation function of Ref. [16] for the $^{12}C+^{232}Th$ system.

entrance channel dynamics. The experimental barrier distribution is, however, somewhat broader than that calculated in the framework of CCDEF model which includes coupling of static deformation and inelastic excitation of the target ($\beta_2=0.22$ and $\beta_4=0.09$, 3^- state with excitation energy 0.774 MeV), which fits the excitation function of Ref. [16]. This may be due to the wider D_α^{el} [Eq. (2)] for the elastic channel as compared to the D_α^f in the fusion channel for a given barrier height α [22].

As seen earlier, the barrier distributions obtained from quasielastic scattering and fission reaction are similar. Thus it is of interest to compare the spin distributions ($\langle l^2 \rangle$ value) obtained from QE scattering and fission fragment angular distribution measurements. More so because the spin distribution obtained from fusion-fission measurements is crucially dependent on the dynamics of the fission process. Hence it probes the exit channel whereas the quasielastic measurements probe the entrance channel. To derive $\langle l^2 \rangle$ value from the QE scattering data, we have carried out analysis in terms of generalized elastic-scattering theory [19]. In the present analysis, we have taken the sum of elastic, inelastic, and transfer channels as QE. The QE excitation function at $\theta_{lab}=170°$ has been fitted with optical model code ECIS to obtain potential parameters for the best fit of the experimental data as shown in Fig. 4. The potential parameters so obtained are $V_0=40.0$ MeV, $R_0=10$ fm, $a=0.8$ fm, $W=10.0$ MeV, $R_{0i}=1.4$ fm, and $a_i=0.19$ fm, respectively. The corresponding reaction cross sections and partial wave distributions obtained for the above potential parameters are identified as for the fusion channel.

To derive the $\langle l^2 \rangle$ value in fusion fission reactions one has to work within the framework of SSPSM which relies on the assumption that fission fragments originate from fully equilibrated compound systems and that there are no other dynamical processes giving rise to fissionlike phenomena. It also assumes that the motion from saddle to scission is fast enough, so that **K** (the projection of total angular momentum on the nuclear symmetry axis) remains a good quantum number. The $\langle l^2 \rangle$ value is determined by measuring fission fragment anisotropy A through the approximate relation,

$$A=\frac{W(0°)}{W(90°)}\approx 1+\frac{\langle l^2 \rangle}{4K_0^2}. \quad (4)$$

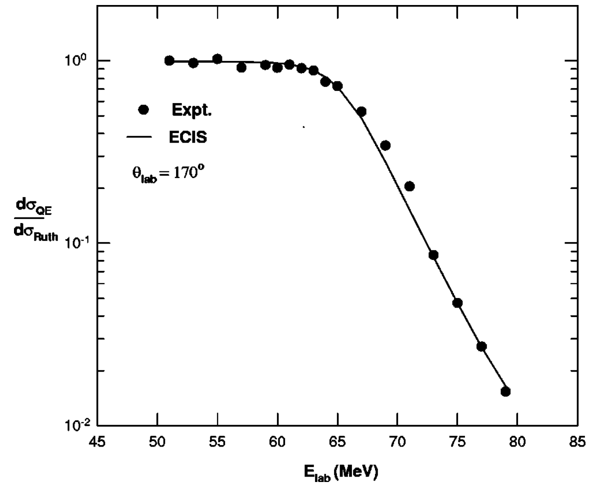

FIG. 4. The QE excitation function at $\theta_{lab}=170°$ has been fitted with optical model code ECIS to obtain potential parameters for the best fit of the experimental data in the $^{12}C+^{232}Th$ reaction.

Here K_0^2 is the variance of the Gaussian **K** distribution.

The dependence of $\langle l^2 \rangle$ values as a function of bombarding energy are shown in Fig. 5 as calculated from QE data along with that obtained from fission fragment anisotropy measurements of Refs. [6,14–16]. Also shown are the predictions of CCDEF including the coupling of static deformation and inelastic excitation of the target ($\beta_2=0.22$ and $\beta_4=0.09$, 3^- state with excitation energy 0.774 MeV), which fits the excitation function of Ref. [16]. It is seen that the $\langle l^2 \rangle$ values obtained from QE data and that from standard fusion model CCDEF are quite similar, whereas the experimental values of $\langle l^2 \rangle$ obtained from fission fragment anisotropy measurement are in large deviation from QE and CCDEF predictions around the Coulomb barrier. The slight deviation in $\langle l^2 \rangle$ values obtained from QE data from that of CCDEF around the barrier may be due to the energy-independent potential parameters used in the present calculations to de-

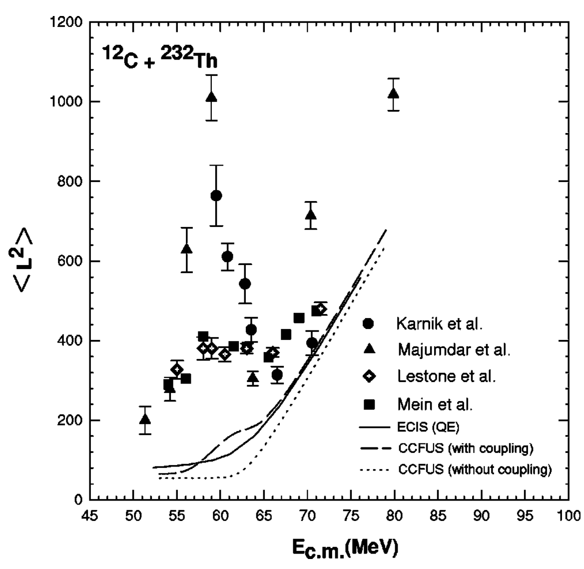

FIG. 5. The dependence of $\langle l^2 \rangle$ values as a function of bombarding energy calculated from QE data along with that obtained from the fission fragment anisotropy measurements of Refs. [6,14,15], and [16]. Also shown are the predictions of CCDEF.

rive $\langle l^2 \rangle$ values from QE data. It is known that potential parameters are energy dependent around the Coulomb barrier (threshold anomaly in elastic scattering). Thus, one can see, in general, the predictions of the $\langle l^2 \rangle$ values of QE data and standard fusion models are quite consistent.

Our measurements on QE data indicate that $\langle l^2 \rangle$ values are consistent with prediction of standard fusion models. Therefore, according to our results, it seems that in the observation of anomalous anisotropy $\langle l^2 \rangle$ may not be the culprit. Therefore, a closer look at the **K** distribution assumed in SSPSM [1] is required. In SSPSM the value of K_0^2 depends on the effective moment of inertia (J_{eff}) and the temperature (T) of the fused system at the saddle point. According to SSPSM the K distribution is decided by the K_0^2 value at the saddle point, with the assumption that K is a good quantum number in saddle-to-scission dynamics. This is because motion from saddle to scission is assumed to be very fast. However, recent measurements on prescission neutron multiplicities have shown that for systems with high fissility, the saddle-to-scission time is much larger than assumed by SSPSM [23] and these systems also show anomalous anisotropy. Hence for these systems **K** may not remain a good quantum number. In the past, to explain the anomalous anisotropy, **K** distribution has been altered either by invoking the admixture of pre-equilibrium fission [3] or orientation-dependent quasifission [24] with fully equilibrated fission and using the SSPSM to calculate the $\langle l^2 \rangle$ values. It is observed that for low fissility systems such as $^{16}O+^{208}Pb$, where saddle-to-scission time is small, the $\langle l^2 \rangle$ values derived from fusion-fission data agree with the SSPSM prediction [25]. However, for systems with large fissility, such as $^{12}C+^{232}Th$, where the saddle-to-scission time is large the deduced value of $\langle l^2 \rangle$ does not agree with fusion models. Hence it may not be correct to use the SSPSM model to deduce $\langle l^2 \rangle$ values for systems with high fissility. As our results show, one can take the $\langle l^2 \rangle$ derived from quasielastic scattering or fission excitation measurement to be a compound nuclear $\langle l^2 \rangle$ value for such fissile systems.

In summary, we have carried out measurements on fusion barrier and spin distributions in the $^{12}C+^{232}Th$ reaction via quasielastic scattering. The results on fusion barrier and spin distribution have been compared with those obtained from fission fragment excitation function and fission fragment angular distribution measurement [25]. It was observed that the barrier distributions obtained from both the methods are consistent, whereas the spin distributions are inconsistent. It is therefore suggested that in the systems having large saddle-to-scission times, the derivation of average compound nuclear spin from fusion-fission data may not be correct.

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