PHYSICAL REVIEW C **75**, 054615 (2007)

Evidence for Coulomb effects on the fusion barrier distribution for deformed projectile nuclei

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(Received 13 November 2006; published 22 May 2007)

Coulomb effects during the interaction of light deformed projectile nuclei with a heavy collision partner have been predicted to modify the fusion barrier distribution leading to a hindrance in the sub-barrier fusion cross section. In order to verify this experimentally, we have determined the fusion barrier distributions from the measurement of quasielastic excitation functions for ^{16}O(spherical)+^{115}In, ^{28}Si(oblate)+ ^{115}In, and ^{30}Si(prolate)+ ^{115}In systems. For ^{16}O+^{115}In system, the fusion barrier distribution is single peaked, whereas for ^{28}Si+^{115}In and ^{30}Si+^{115}In systems, one observes broadening and well defined structures in fusion barrier distribution, which could be explained by coupled-channel calculations performed using the CCFULL code after including deformation and Coulomb effects on the projectile in the field of target nucleus.

DOI: 10.1103/PhysRevC.75.054615 PACS number(s): 25.70.Bc, 25.70.Hi, 25.70.Jj

The dependence of fusion on the structure of the interacting nuclei manifests itself in strong enhancements of the sub-barrier cross sections as compared to that given by one-dimensional barrier penetration model. These effects are explained quantum mechanically to arise due to coupling between relative motion and internal degrees of freedom such as static deformation, collective excitation (rotation and/or vibration) of the colliding ions, nucleon transfer, projectile breakup, etc. [1]. The coupling can be described in terms of changes in the potential barrier between interacting bodies, leading sometimes to its splitting into several components around the one-dimensional barrier giving rise to a distribution of barriers, the lower ones being responsible for the enhancement of the fusion cross section at sub-barrier energies. Recently, it has been shown [2] that for systems involving light deformed projectile and heavy spherical collision partner the fusion barrier distribution gets affected due to Coulomb reorientation of the projectile nucleus in the field of target nucleus giving rise to fusion hindrance at sub-barrier energies. There has been so far no experimental evidence for this effect in the heavy ion reaction process. The aim of the present study is to test the Coulomb effects in heavy ion reactions by determining the fusion barrier distribution from quasielastic excitation function measurements using spherical and deformed projectiles.

It is now well known that the barrier distribution can be extracted experimentally from the fusion excitation function $\sigma_{\mathrm{fus}}(E)$ by taking the second derivative of the product $E\sigma_{\mathrm{fus}}(E)$ with respect to the center-of-mass energy E, that is, $d^2(E\sigma_{\mathrm{fus}})/dE^2$. The extracted fusion barrier distribution has been found to be very sensitive to the structure of the colliding nuclei. 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. Since the channel coupling also affects the scattering process, it was suggested in Refs. [3,4] that the barrier distribution can also be obtained from the excitation function of the quasielastic scattering (a sum of elastic, inelastic, and transfer cross sections) at backward angles. It was proposed to use the first derivative of the ratio of the quasielastic cross section σ_{qel} to the Rutherford cross section σ_{R} with respect to energy, $-d(d\sigma_{\mathrm{qel}}/d\sigma_{\mathrm{R}})/dE$, as an alternative representation of the barrier distribution [5]. These measurements are much simpler and can be applied to a large number of target-projectile nuclei for a systematic study of the barrier distributions [6,7]. In the present work, we have aimed to carry out experimental investigations of the fusion barrier distribution to study the Coulomb effect on the deformed projectile in the field of the target nucleus. The systems of ^{28}Si+^{115}In and ^{30}Si+ ^{115}In were chosen for the very large and opposite nature of quadrupole deformation of the projectile nuclei. While the ^{28}Si is oblate in shape, ^{30}Si is prolate, and the β_2 values of ^{28}Si and ^{30}Si are (-0.408) and (0.316), respectively. For comparison, we have also taken the spherical ^{16}O+^{115}In system. The excitation of high-lying octupole vibrational state of ^{16}O at 6.1 MeV renormalizes the static potential and does not give any structure effect on fusion barrier distribution [1]. Hence ^{16}O behaves as an inert nucleus in fusion reaction. A comparative study of fusion barrier distribution of ^{16}O+^{115}In, ^{28}Si+^{115}In, and ^{30}Si+^{115}In systems is ideal to investigate selectively the rotational coupling and Coulomb effects on the ^{28}Si and ^{30}Si projectiles.

The measurements were carried out using ^{16}O, ^{28}Si, and ^{30}Si beams from the 14UD pelletron accelerator at the BARC-TIFR pelletron facility, Mumbai. A self-supporting ^{115}In target of 400 μg/cm^2 thickness was used in the experiment. The measurements were carried out in the beam energy range of $E_{\mathrm{lab}} = 49$–69 MeV for ^{16}O+^{115}In and $E_{\mathrm{lab}} = 92$–114 MeV for ^{28}Si+^{115}In in steps of 2.0 MeV. Measurements for ^{30}Si+^{115}In system were carried out in the beam energy range $E_{\mathrm{lab}} = 92$–120 MeV in steps of 2.0 MeV using a self-supporting ^{115}In target of 250 μg/cm^2 thickness in a separate experiment. The bombarding energy has been corrected for the energy loss in half the target thickness which is $\sim$0.46 MeV to 0.54 MeV for ^{16}O, $\sim$1.18 MeV to 1.27 MeV for ^{28}Si and $\sim$0.60 MeV to 0.67 MeV for ^{30}Si beam. A silicon surface barrier detector telescope $\Delta E(15\,\mu\mathrm{m}) - E(1.0\,\mathrm{mm})$ was placed at an angle of 160° to the beam direction to detect the projectile-like fragments (PLF) in the ^{16}O+^{115}In reaction. 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. A single surface barrier detector of E(150.0 μm) was used for ^{28}Si+^{115}In and ^{30}Si+^{115}In systems to detect projectile-like fragments at an angle of 160° to the beam direction as for lower bombarding energies PLFs were stopping in the ΔE detector. In the data analysis, quasielastic events were defined as the sum of all the elastic, inelastic, and transfer events. The detector telescope used in ^{16}O+^{115}In reaction enabled us to check that the projectile-like fragments following elastic, inelastic, and transfer reactions were contained within the integration limits, while protons and α-particles (for example, evaporated from fusion products) were rejected. The possible products of n-transfer reaction, in our measurement were not distinguishable from the inelastic excitations as they were in the same energy range and were also necessarily included in the quasielastic events. In case of ^{28,30}Si+^{115}In systems, where a single detector was used, the evaporartion particles(proton and alpha) could be distinguished from quasielastic events in their energy distributions. The quasielastic excitation functions measured at the angle of 160° were used to determine the fusion barrier distribution $D_{\rm qe}(E_{\rm eff})$ using a point difference formula with a step of 2 MeV in laboratory frame. In order to convert the results of $D_{\rm qe}$(, 160°) to that of $D_{\rm qe}(E, 180°)$, an effective energy was introduced into the cross section such that $\sigma_{\rm qe}(E_{\rm eff}) \approx \sigma_{\rm qe}(E_{\rm c.m.}, 160°)$, where $E_{\rm eff} = 2E_{\rm c.m.}/(1+\mathrm{cosec}(\theta_{\rm c.m.}/2))$. This corrects for centrifugal effects [5].

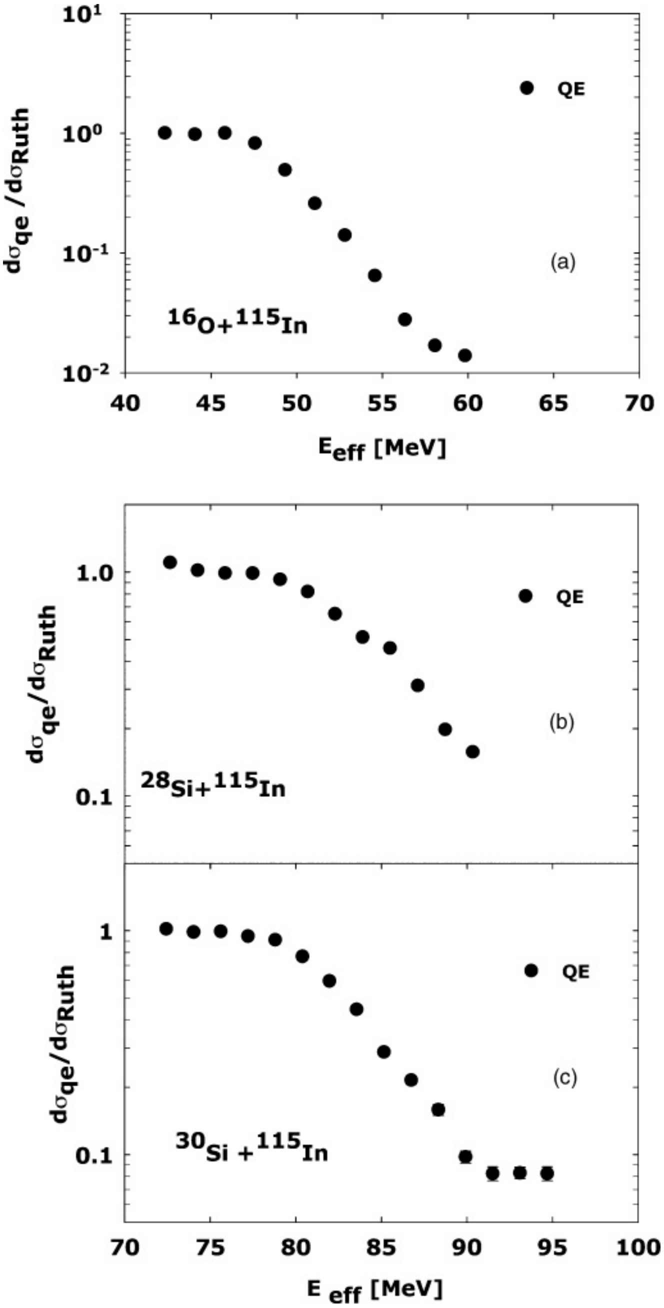

FIG. 1. (a) Experimental values of $\sigma_{\rm qe}/\sigma_{\rm R}$ as a function of $E_{\rm eff}$ (see text) for ^{16}O+^{115}In; (b) for ^{28}Si+^{115}In; and (c) for ^{30}Si+^{115}In systems, respectively.

The experimental results on $\sigma_{\rm qe}/\sigma_{\rm R}$ are shown for ^{16}O+^{115}In, ^{28}Si+^{115}In, and ^{30}Si+^{115}In systems in Fig. 1(a), 1(b), and 1(c), respectively. These data were converted to the $D_{\rm qe}$ distributions as described above, which are shown for all the three systems in Fig. 2(a), 2(b), and 2(c). We note that the $D_{\rm qe}$ distribution for ^{16}O+^{115}In system consists of a single peak, whereas for ^{28}Si+^{115}In and ^{30}Si+^{115}In systems, there is distinct broadening and multipeak structure in $D_{\rm qe}$ distributions. The Coupled channel (CC) calculations for fusion excitation function was performed using the program CCFULL [10] for ^{16}O+^{115}In system without including any couplings. The potential parameters for CCFULL were so adjusted to produce the experimental average fusion barrier to $V_{\rm B}$ = 49.40 MeV. In Fig. 2(a), the dotted line is the result of CCFULL calculation without coupling. The calculation is consistent with the experimental barrier distribution without any structure as expected for ^{16}O+^{115}In system as there are no dominant channels to couple to fusion. Of course, the experimental barrier distribution has slight tailing toward the higher energy side in comparison to the CC predictions. This tailing is more likely to be due to coupling to other weak inelastic channels which have not been taken into consideration in the present CCFULL calculations as suggested in Ref. [9]. In Figs. 2(b) and 2(c), the dotted lines are the results on fusion barrier distribution of CCFULL calculations without coupling for ^{28}Si+^{115}In and ^{30}Si+^{115}In systems. The potential parameters of CCFULL were adjusted to give the observed experimental average fusion barrier $V_{\rm B}$ = 83.15 MeV and $V_{\rm B}$ = 83.00 MeV for ^{28}Si+^{115}In and ^{30}Si+^{115}In systems. The CCFULL results without coupling do not reproduce the experimental barrier distributions for ^{28}Si+^{115}In and ^{30}Si+^{115}In systems. ^{28}Si and ^{30}Si being oblate and prolate deformed nuclei can affect the fusion process in two ways: (i) The fusion barrier height depends on the orientation of the deformation axis of the projectile with the collision axis, thereby giving rise to a distribution of barrier rather than a single barrier as in case of spherical target and projectile, (ii) The barrier distribution is also affected due to reorientation of the deformed ^{28}Si and ^{30}Si projectiles before fusion in the Coulomb field of the target nuclei similar to that predicted for ^{24}Mg+^{208}Pb system as reported in [2]. From the quantum

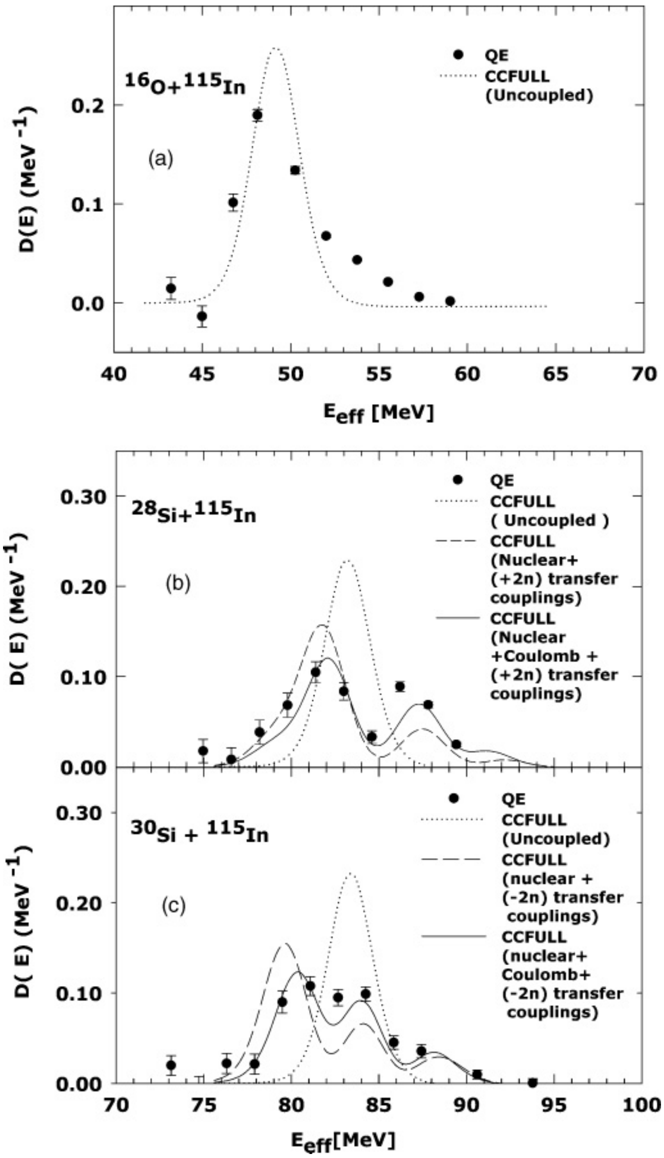

FIG. 2. (a) Experimental $D_{\rm qe}$ for ^{16}O+^{115}In compared with the CCFULL results without coupling (dotted line). (b) Experimental $D_{\rm qe}$ for ^{28}Si+^{115}In compared with the CCFULL results without coupling (dotted line), nuclear+(+2n) transfer coupling (dashed line), and nuclear+Coulomb+(+2n) transfer couplings (solid line). (c) Experimental $D_{\rm qe}$ for ^{30}Si+^{115}In compared with the CCFULL results without coupling (dotted line), nuclear+($-2n$) transfer coupling (dashed line), and nuclear+Coulomb+($-2n$) transfer couplings (solid line).

mechanical point of view, the reorientation is a consequence of the excitation of rotational states. In case of coupling of rotational states of the target/projectile to the fusion channel, the coupling matrix elements consist of both nuclear and Coulomb parts. The Coulomb part of the coupling matrix element gives rise to reorientation effect due to the change in the orientation of the projectile in the Coulomb field of the target nucleus. This effect has been incorporated by the use of long range Coulomb coupling in the CCFULL code [10]. In order to investigate the deformation and Coulomb effects of the projectile on fusion barrier distribution, calculations were carried out by taking into consideration coupling of rotational states of ^{28}Si and ^{30}Si projectiles in ^{28}Si+^{115}In and ^{30}Si+^{115}In fusion reactions with (nuclear+Coulomb) and without (only nuclear) coupling in the CCFULL code. The deformation parameters of ($\beta_2 = -0.408$, $E_{\rm x} = 1.72$ MeV, and $\beta_4 = 0.10$) for ^{28}Si and ($\beta_2 = 0.32$, $E_{\rm x} = 2.23$ MeV, and $\beta_4 = 0.10$) for ^{30}Si were taken in the CCFULL code for the rotational coupling calculations of the deformed projectiles. In case of ^{28}Si+^{115}In reaction two-neutron pickup (+2n) channel is having positive Q-value of 2.773 MeV and two-neutron stripping ($-2n$) channel is having negative Q-value of -14.939 MeV. So in the present calculation, we have considered only (+2n) transfer coupling for ^{28}Si+^{115}In reaction along with rotational coupling. The (+2n) and ($-2n$) transfer channel Q-values are (-0.519 MeV) and (-3.531 MeV), respectively for ^{30}Si+^{115}In reaction. The CCFULL calculations were carried out by including either (+2n) or ($-2n$) transfer coupling along with the coupling of the rotational states of ^{30}Si projectile for ^{30}Si+^{115}In systems. It is observed that CCFULL results on fusion barrier distribution for ($-2n$) transfer channel coupling compare better with the experimental data in the case of the ^{30}Si+^{115}In reaction. Hence we have considered ($-2n$) transfer channel coupling in CCFULL for ^{30}Si+^{115}In reaction along with rotational coupling. Figures 2(b) and 2(c) show CCFULL results including rotational(only nuclear)+two-neutron transfer (dashed lines) and rotational(nuclear+Coulomb)+two-neutron transfer (solid lines) couplings to the rotational states 0+, 2+, 4+, 6+ in the ^{28}Si and ^{30}Si ground state rotational band with a long range (100 fm). The results converge rapidly as the number of states is increased. It was verified that truncation of calculations at the 6+ level is entirely sufficient for the present purpose. It may be noted that taking the matching radius around 100 fm provides sufficiently accurate results for the present systems. We see that the coupled channels calculations result in a $D_{\rm fus}$ which possesses two distinct peaks for ^{28}Si+^{115}In and three peak structure for ^{30}Si+^{115}In systems in broad agreement with the experimental D$_{\rm qe}$. Predictions of CCFULL calculations with rotational(only nuclear)+neutron-pair-transfer couplings overpredicts the strength of low energy component and under predicts high energy component of the barrier distributions. After considering rotational(nuclear+Coulomb)+neutron-pair-transfer couplings a reasonably good agreement between experiment and the prediction of CCFULL calculations is observed on barrier distributions in both ^{28}Si+^{115}In and ^{30}Si+^{115}In systems. Above observations suggest that the fusion barrier is redistributed due to the Coulomb effect of the deformed projectile in the field of the spherical target nucleus before fusion. This phenomenon is implicitly taken into account in CCFULL due to long-range Coulomb coupling.

In summary, we have obtained the fusion barrier distributions ($D_{\rm qe}$) for ^{16}O+^{115}In, ^{28}Si+^{115}In, and ^{30}Si+^{115}In systems via quasielastic excitation function measurements. It is observed that $D_{\rm qe}$ consists of a single peak for ^{16}O+^{115}In system, whereas there is distinct broadening and multiple peak structure for ^{28}Si+^{115}In and ^{30}Si+^{115}In systems. The experimental fusion barrier distributions have been compared with the CCFULL predictions with and without rotational Coulomb coupling along with the two-neutron transfer (pickup/stripping) couplings for ^{28}Si+^{115}In and ^{30}Si+^{115}In systems. The agreement between experiment and prediction of CCFULL improves after inclusion of Coulomb effects of the ^{28}Si and ^{30}Si projectiles in the field of target nucleus in the fusion process within the framework of rotational Coulomb coupling of projectile states to fusion.

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