MEASUREMENT OF QUASI-ELASTIC SCATTERING: TO PROBE ^{28}Si+^{154}Sm REACTION*

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We discuss the role of channel coupling of ^{28}Si on fusion mechanism with permanently deformed target ^{154}Sm. To this end, we analyze the experimental quasi-elastic cross sections at a large backward angle and quasi-elastic barrier distribution for ^{28}Si+^{154}Sm system using the coupled-channels approach. While earlier studies have reported the rotational excitation of ^{28}Si playing role on fusion with spherical and near spherical target nuclei, we find its vibrational excitation as origin of observed barrier distribution for ^{28}Si+^{154}Sm system. Our study also reveals significant influence of channel couplings on the surface diffuseness parameter of an inter-nuclear potential supporting the earlier observations.

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1. Introduction

The heavy-ion fusion reaction is sensitive to coupling of inter-nuclear distance to nuclear intrinsic degrees of freedom. Due to this coupling, distinctive signatures of the nuclear properties are present in the fusion excitation function and barrier distribution (BD) [1]. It has been suggested that channel couplings also affect the scattering process and the same information can also be obtained from quasi-elastic (QE) scattering cross sections at large backward angles [2] and QE BD [3].

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Indeed, the QE measurement even allows the study of very heavy systems leading to the creation of super-heavy compound nuclei [4] where fission and quasi-fission dominate, and the "fusion" BD becomes meaningless. Moreover, from the experimental point of view, the detection method is simpler for the QE events at backward angles close to 180° than that for the fusion residual at forward angles close to beam direction. Therefore, in literature the backward QE measurements have been employed in experiment to probe the surface diffuseness parameter [5] and the BD [6], *etc.*

Depending upon the energy of various excited states, the nuclei have been categorized as a vibrator and rotor. However, there are few dynamical nuclei such as ^{28}Si where nature of states and even the existence of some of them is far less clear. In the present work, our keen interest is to study the excitation of projectile ^{28}Si through BD in conjunction to the permanent deformation of target. The fusion BD for the system ^{28}Si+^{154}Sm has been studied [7] in our previous work but unfortunately, the precision of the experimental data impeded us from deep understanding of the nuclear structure responsible for the fusion process.

In this work, a precise QE cross section has been measured for the system ^{28}Si+^{154}Sm at a large backward angle and experimental BD has been extracted using the method proposed by Timmers *et al.* [3]. Coupled channel calculations, with various coupling schemes for target and projectile, have been performed to probe the effects of coupling on BD. To study the effect of coupling on a surface diffuseness parameter of an inter-nuclear potential, the QE excitation function below the Coulomb barrier has been analyzed. Furthermore, the reaction ^{28}Si+^{154}Sm has positive Q values for neutron transfer channels whose influence may be reflected in BD.

2. Experimental details

The QE measurements are performed for the ^{28}Si+^{154}Sm system using a detector array, as HYTAR (HYbrid Telescope ARray) [8], developed at IUAC, New Delhi. Here, four telescope detectors, two of them in plane and other two out of plane, each at an angle of 170° are arranged in a symmetrical cone geometry to minimize the uncertainty due to beam misalignment. To check the consistency of the measured QE scattering events, one more telescope is placed at an angle of 140°. The array is placed in the General Purpose Scattering Chamber (GPSC) at IUAC, New Delhi. A beam of ^{28}Si, delivered from 15UD Pelletron is put on sandwiched target of ^{154}Sm (typical thickness $\approx 180\ \mu g/cm^2$). The beam energy is varied in steps of 2 MeV ranging from 90.0 MeV (25% below barrier) to 135.0 MeV (11% above barrier). The bombarding energies are corrected for the energy loss in half the target

thickness, ranging from 0.42 to 0.49 MeV for ^{28}Si. Two 300 μm thick silicon detectors are placed at $\pm 10°$ with respect to the beam direction for beam monitoring and normalization purpose.

3. Analysis and calculations

The QE events are defined as the sum of elastic, inelastic, transfer and other peripheral processes. The detector telescopes give identification of such events from other reaction events. Figure 1 (left) shows a typical two-dimensional correlation plot of dE–E (energy loss *versus* residual energy) obtained with $E_{\rm lab} = 118$ MeV at $\theta_{\rm lab} = 170°$ for the ^{28}Si+^{154}Sm system. The counts from all the lobes have been summed to obtain the total QE events. The results of QE events at 170° and 140° are converted to that of 180° by introducing an effective energy, $E_{\rm eff} = \frac{2E_{\rm cm}}{1+{\rm cosec}(\frac{\theta_{\rm cm}}{2})}$, where $E_{\rm cm}$ and $\theta_{\rm cm}$ are energy and scattering angle in center-of-mass frame, respectively. This corrects for "angle-dependent" centrifugal effects. The obtained QE cross sections, $\sigma_{\rm qe}(E,\theta)$, normalized to Rutherford cross section, *i.e.*, $d\sigma_{\rm qe}/d\sigma_{\rm R}(E)$ for $\theta_{\rm lab} = 170°$ and 140°, are shown in figure 1 (right). The statistical error is found to be less than 1% at lower energies and around 2% at higher energies. The BD extracted from QE excitation function [3], using $D_{\rm qe}(E,\theta) = -\frac{d}{dE}(\frac{d\sigma_{\rm qe}(E,\theta)}{d\sigma_{\rm R}(E,\theta)})$, is shown in figure 2. The BDs extracted from two different scattering angles are compared in figure 2. The identical BD structure for two scattering angles gives a check on the consistency of the experimental data.

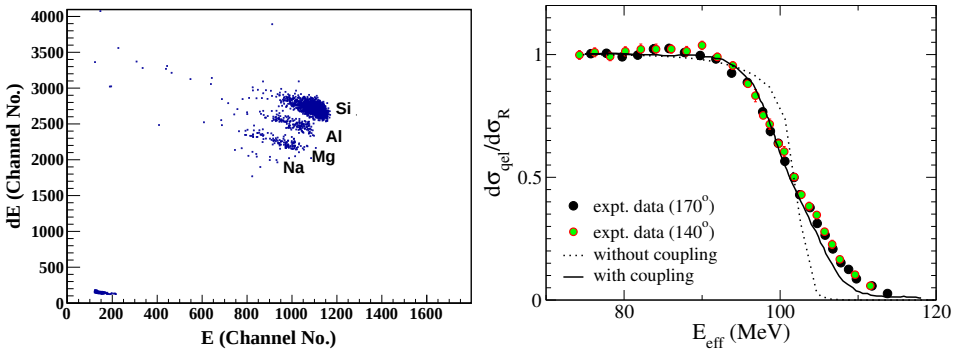


Fig. 1. (Color online) (Left) Two-dimensional correlation plot of dE–E energy signals from hybrid telescope detector at 170° w.r.t. beam direction in ^{28}Si+^{154}Sm reaction at $E_{\rm lab} = 118$ MeV. Projectile-like fragments of different atomic numbers are identified. (Right) Quasi-elastic excitation function obtained from two backward scattering angles, *i.e.*, $\theta_{\rm lab} = 170°$ and 140° for the system ^{28}Si+^{154}Sm.

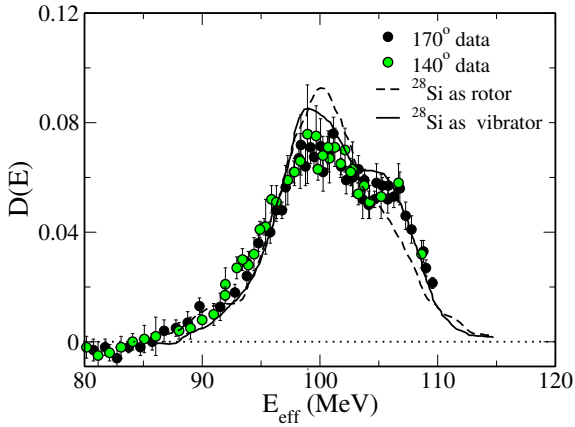


Fig. 2. (Color online) Experimental barrier distribution (dots) for the ^{28}Si+^{154}Sm system. Solid lines are results of coupled channel calculation (with rotational excitation of ^{154}Sm + excitation of ^{28}Si as mentioned inside figure).

To interpret the experimental data, single-channel and coupled-channel calculations have been performed using a scattering version of the CCFULL program [9]. The nuclear potential used in the calculations has a real and an imaginary components, both of which are assumed to have a Woods–Saxon form. The imaginary part simulates a compound nucleus formation. In the calculations, we have used an imaginary potential with the depth parameter of 30 MeV, the radius parameter of 1.0 fm, and the diffuseness parameter of 0.3 fm. For the real part of the nuclear potential, the potential depth V_0 is fixed to be 185 MeV. The value of radius parameter r_0 is then adjusted for a particular value of the diffuseness parameter such that the Coulomb barrier height V_B for the ^{28}Si+^{154}Sm system becomes the same as that for the Bass potential [10]. For the coupled-channels calculations, we have included the rotational excitations in the permanently deformed ^{154}Sm target nucleus in the harmonic oscillator limit. The various excitations of projectile are considered to see its effect on the BD. The deformation parameter and the excitation energy for both the nuclei are taken from Ref. [7].

4. Results and disscusion

To numerically extract the surface diffuseness parameter for ^{28}Si+^{154}Sm system from the experimental QE data, we have first performed the single-channel calculations without including the inelastic excitations of the target and projectile nuclei. Following the procedure explained in Ref. [11], the optimum value of the surface diffuseness parameter as 0.75 ± 0.07 fm is obtained. The comparison of the single-channel calculations with several values of a_0 with the experimental data is shown in figure 3. We notice

that this value is significantly larger than the "standard value" of around 0.6 fm (obtained from elastic scattering cross sections), which is in a similar situation as in systems with a deformed target [5].

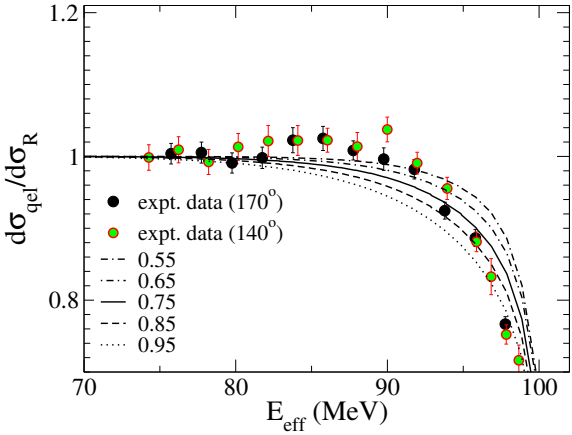


Fig. 3. (Color online) Comparisons of the single-channel calculations for the quasi-elastic excitation function obtained with several values of the surface diffuseness parameter, a_0, in the nuclear potential for the system ^{28}Si+^{154}Sm.

In order to investigate whether the large value of surface diffuseness parameter obtained with the single-channel calculations are due to the neglect of channel coupling effects, we have next performed the coupled-channels calculations including the rotational and vibrational excitations in the target and projectile nuclei, respectively. The best fitted value of a_0 for ^{28}Si+^{154}Sm system as 0.67 ± 0.06 fm is obtained. Hence, the diffuseness parameter decreases in the coupled-channels calculation as compared to the single-channel calculation. This observation is similar to that reported in literature for rotational coupling [5]. Now, considering the diffuseness parameter as 0.67 fm in the real part of nuclear potential, further calculations are performed to explain the QE excitation function and its BD. It is observed that the calculation involving only the rotational coupling of ^{154}Sm is not able to reproduce the experimental data. In other words, coupling to excited states of ^{28}Si could not be ignored. As the mode of excitation of ^{28}Si is not well-established, both the vibrational and rotational excitation of ^{28}Si are studied individually along with rotational excitation of permanently deformed target ^{154}Sm. The comparison of experimental QE excitation function and BD with theoretical predictions from coupled channel calculations, for the ^{28}Si+^{154}Sm system, is shown in figure 1 (left) and figure 2, respectively. It is observed that both types of excitation of ^{28}Si are fairly reproducing the QE excitation function which reflects that it is not possible to distinguish

between two modes of excitation. However, if we look at the comparison of BD shape, it seems that high energy side of BD is better explained by its vibrational coupling instead of rotational coupling. This, in turn, shows that the mode of excitation of ^{28}Si is more like a vibrational excitation. Moreover, the inelastic excitations of target and projectile well explained the shape of BD without need of any further coupling. Hence, it appears that the influence of transfer coupling on fusion is very weak for this system even though it has positive Q-values for neutron transfer channels.

5. Summary and conclusion

Firstly, surface diffuseness parameter from coupled-channels calculation revealed the reduction in its value in comparison with that from single-channel calculations, supporting the earlier observations for deformed systems. Secondly, significant difference in the QE BD is observed due to different coupling of ^{28}Si. Due to this difference, the vibrational excitation of ^{28}Si seems to give better representation of the experimental BD as compared to its rotational excitation. Hence, it appears that the ^{28}Si nucleus exhibits excitation like a vibrational mode. Furthermore, our result implies very weak influence of transfer coupling on fusion of ^{28}Si+^{154}Sm system, even though the positive Q-value neutron transfer channels are present.

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