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QUASI-ELASTIC SCATTERING IN THE ^{48}Ti+^{232}Th REACTION*

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The barrier distribution (BD) for a system ^{48}Ti+^{232}Th, leading to the super-heavy nucleus ^{280}Cn$_{112}$ (copernicium) is obtained by measuring the flux reflected from the Coulomb barrier at large backward angles. The coupled-channel calculations are performed to study the effect of target and projectile excitation on the BD structure. Furthermore, from the BD study, the information on the fusion barrier is extracted.

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1. Introduction

The cold [1] and hot fusion reactions [2] are utilized to synthesize the super-heavy elements (SHEs) with $Z = 108$–118. Classically, for the fusion to occur, the incident particle has to overcome the fusion barrier and in order to maximize the fusion probability, the bombarding energy needs to be chosen accordingly. Moreover, in heavier systems, due to coupling to nuclear intrinsic degrees of freedom, the fusion barrier splits into a fusion barrier distribution (BD). The average of the energy distribution may be different from the classical fusion barrier depending on the target–projectile combination. The quantitative information on the fusion barrier is essential for planning the synthesis experiments. The conventional method to measure the fusion barrier experimentally is through a measure of the fusion excitation function

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or the fusion BD. For SHEs, such a method is experimentally difficult due to very small values of the fusion cross section (of the order of picobarns or even lower). In such cases, quasi-elastic (QE) scattering method for extracting BD becomes important.

For Pb-based cold fusion reactions populating SHEs, the fusion BDs have been systematically measured using the QE method [3, 4] and theoretically studied [5] for the ^{48}Ti, ^{54}Cr, ^{56}Fe, ^{64}Ni, ^{70}Zn, ^{76}Ge and ^{86}Kr + ^{208}Pb reactions, with a spherical target nucleus. It was observed that the centroids of the BDs show a deviation from the predicted barrier heights [6–8] toward the low-energy side due to the coupling effects of projectile and target excitation.

Recently, the production of the $Z = 120$ element has been attempted through ^{64}Ni + ^{238}U hot fusion reaction at GSI [9]. However, it was unsuccessful because of the very small production cross section. Since ^{238}U is prolate deformed, the most probable barrier may depend on its orientation and may significantly influence the probability of fusion which, in turn, may affect the production of SHEs. To study the effect of target orientation, we measured the BD in the ^{48}Ti+^{232}Th reaction leading to SHE ^{280}Cn$_{112}$. The target of ^{232}Th was chosen as it has collective states similar to ^{238}U. To extract the BD, the technique of QE scattering at large backward angles was used.

2. Experimental details

The experiment was performed using the Pelletron + LINAC accelerator system of the IUAC, New Delhi. A ^{48}Ti beam was impinged on a ^{232}Th target of $\sim$150 μg/cm^2 thickness (with a carbon backing of $\sim$30 μg/cm^2) at incident energies varying from 220 MeV to 285 MeV in 5 MeV steps. The reaction products, mainly projectile-like particles, were detected in the hybrid telescope array (HYTAR) [10] mounted in the 1 m diameter spherical scattering chamber of the National Array of Neutron Detectors (NAND). The active length of dE detectors was 18 mm and the thickness of E detectors was 300 μm, which was sufficient to fully stop the heavy projectile-like particles. Four telescopes, two in plane and two out of plane, each at 173° relative to the beam direction, were placed in a ring arrangement. Five more telescopes were placed at angles from 160° to 120° with an angular pitch of 10°. Each scattering angle corresponds to scattering at a certain angular momentum, and the cross section can be scaled in energy by taking into account the centrifugal correction: $E_{\mathrm{eff}} = 2\ E_{\mathrm{cm}}/(1 + \mathrm{cosec}(\theta_{\mathrm{cm}}/2))$. Consequently, by combining the data from all detectors, we obtained the QE excitation function with energy step less than 2 MeV. Two silicon PIPS detectors of 300 μm thickness were positioned at $\pm 13°$ relative to the beam direction to monitor the beam and for normalization purpose.

A two-dimensional spectrum of the differential energy loss in the dE detector *versus* the residual energy in the E detector provided the Z identification of the incoming particles. A typical particle identification spectrum obtained at $\theta_{\rm lab} = 120^\circ$ and $E_{\rm lab} = 260$ MeV for the ^{48}Ti+^{232}Th system is shown in Fig. 1.

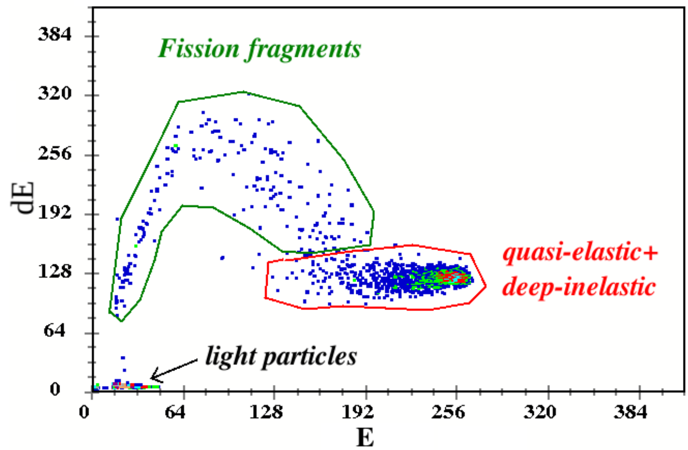

Fig. 1. Online 2D spectra (energy loss *versus* residual energy) of the ^{48}Ti+^{232}Th system for $E_{\rm lab} = 260$ MeV and $\theta_{\rm lab} = 120^\circ$ relative to the beam direction.

3. Separation of pure QE events

For a heavy system, like ^{48}Ti+^{232}Th, the probability of fission is very high at energies around and above the Coulomb barrier. Hence, a gate was applied on the two-dimensional E–dE spectra in order to supress the fission events and the light particles. The two-dimensional spectra of the remaining events, which are peripheral events, were transformed to energy spectra. At energies below the Coulomb barrier, the calibrated energy spectrum has a form of a pure Gaussian, however, with increase of the incident beam energy, a tail starts appearing at the lower energy side. At energies above the Coulomb barrier, the elastic peak diminishes and the contribution of the tail starts to dominate. Figure 2 shows the energy spectra measured at $\theta_{\rm lab} = 120^\circ$ for $E_{\rm lab} = 255$ MeV and 270 MeV along with the reaction Q value for the inelastic exit channel. The component with a large negative Q value, corresponding to deep-inelastic events, becomes dominant at higher incident energies.

A simple method to extract the pure QE events is to set an energy borderline between the QE and the deep-inelastic components at Q value around -20 MeV. This choice of an energy cut is applicable for ^{48}Ti + ^{208}Pb, how-

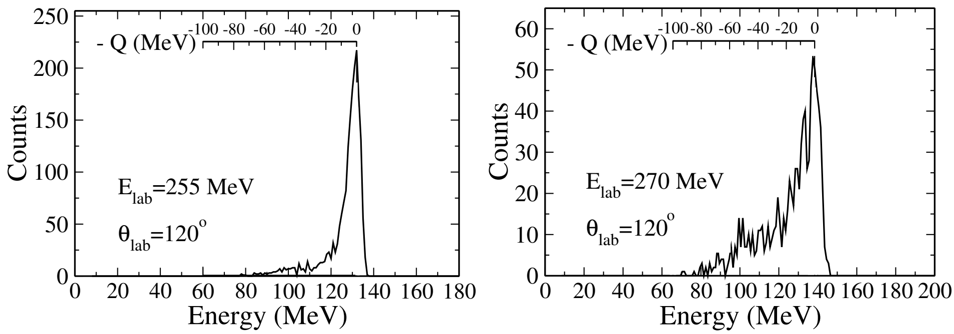

Fig. 2. Measured energy spectra for the ^{48}Ti+^{232}Th system at $E_{\rm lab} = 255$ MeV and 270 MeV (left and right panel, respectively) along with the reaction Q value scale for the inelastic exit channel.

ever, in the present case, the target is the deformed ^{232}Th nucleus, instead of the spherical ^{208}Pb. For the deformed target, the transfer probability may be enhanced, so the borderline between the QE and the deep-inelastic components may be shifted towards slightly more negative Q value for the ^{48}Ti+^{232}Th system. Hence, we considered a second gate extending to a slightly more negative Q value, *i.e.*, equal to -23 MeV. The results obtained with these two gates are similar, with only a small variation in the BD width (around 0.5 MeV more in the latter case). Then the BD is extracted by taking the first derivative of QE cross sections, that is $-{\rm d}(\sigma_{\rm QE}(E)/\sigma_{\rm R}(E))/{\rm d}E$. The measured QE excitation function and the BD are shown in Fig. 3.

4. Coupled-channel calculations

The coupled-channel calculations were performed using the scattering version of the CCFULL code. The nuclear potential used in the calculations has a real component and an imaginary one, both of which are assumed to have a Woods–Saxon form. For the imaginary potential, we used a depth parameter of 30 MeV, a radius parameter of 1.3 fm, and a diffuseness parameter of 0.30 fm. For the real part of the nuclear potential, the potential depth V_0 was fixed to be 240 MeV. The value of the radius parameter R_0 was then adjusted for a specific value of the diffuseness parameter A_0 so that the Coulomb barrier height $V_{\rm B}$ for the present system becomes the same as that for the Bass potential [11]. Without any coupling, the excitation function and BD were not reproduced. Hence, the rotational excitation to the 2^+ state of Th has been considered as it has a very low excitation energy and large deformation ($\beta_2 = 0.2608$, $E^* = 0.049$ MeV). A significant influence of the Th excitation was observed on the excitation function as well as the BD. However, it was not sufficient to reproduce the data completely. Hence, the vibrational excitation of Ti ($\beta_2 = 0.26$, $E^* = 0.9835$ MeV) has also been considered in the calculations. It also seems to have a significant influence, providing an improved fit to the data. The calculated excitation function and BD are compared to their experimental values in Fig. 3. It should be noted that a large numerical instability was observed for the present super-heavy system. This limits the inclusion of higher excited states of the projectile and the target in the calculations.

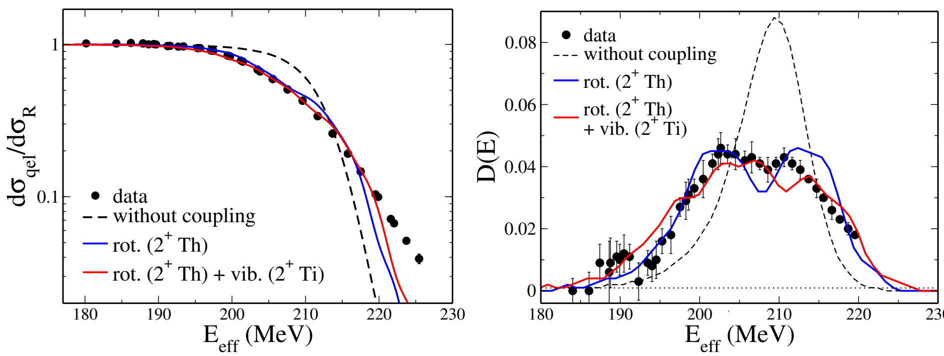

Fig. 3. Left panel: Experimental QE excitation function and its fit from the coupled-channel calculation. Right panel: Experimental barrier distribution and its fit from the coupled-channel calculation for the ^{48}Ti+^{232}Th system.

5. Result and discussion

From the extracted BD, it can be observed that the most probable barrier for the ^{48}Ti+^{232}Th system is around 209 MeV (with an uncertainty of 2 MeV). The extracted value is close to the Bass barrier value for this system equal to 210.9 MeV. According to Ref. [12], in heavier systems, the most probable barrier gives the reaction threshold. As the fusion barrier will be higher with respect to the reaction threshold, it means that for the ^{48}Ti+^{232}Th system it will be above the Bass barrier.

Including the first excited state of the projectile ^{48}Ti and the target ^{232}Th in the coupled-channels calculations improves the agreement between the theoretical and experimental BDs, and taking into account higher excited levels would result in its further improvement. Unfortunately, this could not be studied in detail due to numerical instabilities. One should add that in such heavy systems the transfer channels will also smooth out the shape of BD.

6. Summary and conclusion

The QE scattering measurements were performed for the ^{48}Ti+^{232}Th system at large backward angles to study the BD. From this study, we may conclude that the fusion barrier for ^{48}Ti+^{232}Th is higher than the Bass barrier value. Such a shift in the fusion (or most probable) barrier, influencing the probability of SHE formation, may occur due to the deformation of the target.

The coupled-channel calculations reveal that including the effect of the rotational excitation of the target and vibrational excitation of the projectile significantly improves the fit to the measured data. The role of higher states could not be studied due to numerical instabilities.

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