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Barrier distributions for $^{16}O+^{152}Sm$ quasielastic and elastic scattering

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Excitation functions have been measured for quasielastic and elastic scattering of $^{16}O+^{152}Sm$ around the Coulomb barrier at three backward angles with high precision in small energy steps. The barrier distributions have been extracted from the quasielastic and elastic scattering excitation functions and compared with experimental barrier distributions obtained from the existing fusion excitation function and spin distributions for the same reaction system, and from the quasielastic and elastic scattering excitation functions for the neighboring isotope ^{154}Sm. The agreement is rather good. The results show clearly that the asymmetric barrier distributions are due to the effects of static deformations on the target nucleus. This is the first attempt to compare quantitatively the experimental barrier distributions with the fusion barrier distributions extracted from the spin distributions for the same system. [S0556-2813(98)50903-X]

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Recently, the exploration of the fusion process in terms of the barrier distributions has attracted much attention in heavy ion collisions at near- and sub-barrier energies. It is well known that the observed sub-barrier fusion enhancement [1] is due to the coupling between the relative motion and the internal degrees of freedom of the colliding nuclei, such as static deformation, collective vibration, inelastic excitation, and nucleon transfer. The coupling gives rise to a distribution of fusion barriers rather than a single barrier and passage over the lower barriers is responsible for the fusion enhancement at lower energies. Information on the nature and strengths of the couplings thus lies in the distribution of fusion barriers. The experimental determination of this distribution will provide a stringent test for sub-barrier fusion models.

It has recently been shown theoretically [2] that the barrier distribution can be extracted directly from a fusion excitation function which is measured with high precision in small energy steps, using the second derivative of the product of the energy E and the experimental fusion cross section $\sigma^{\mathrm{fus}}(E)$

$$D^{\mathrm{fus}}(E)=\frac{1}{\pi R_f^2}\frac{d^2}{dE^2}[E\sigma^{\mathrm{fus}}(E)], \tag{1}$$

where R_f is the fusion radius. In the case of fusion of deformed nuclei, one expects an asymmetric barrier distribution [2].

The fusion excitation function was first measured to a precision of $\sim 1\%$ with 0.5 MeV energy steps for the $^{16}O+^{154}Sm$ reaction [3]. The extracted distribution of fusion barriers was consistent with that for the deformed target nucleus. However, the quadrupole deformation parameter β_2 determined from the best fit to the data was significantly lower than that from Coulomb excitation. According to the modified theory [4], both quadrupole and hexadecapole deformations for the optimal fit of ^{154}Sm fusion data were required. The deformation parameters β_2 and β_4 extracted are in good agreement with those obtained from nonfusion reactions. In contrast, with the same theory the deformation parameters extracted from $^{16}O+^{186}W$ data [5,6] were significantly different from the accepted values. The situation was similar for the $^{16}O+^{184}W$ system [7].

Although the barrier distributions were extracted from the fusion excitation functions successfully, the barrier distributions became less defined at higher energies, because the experimental error increases in proportion to the cross section. The barrier distribution data cannot be used to distinguish different model calculations at energies above the average barrier. Therefore, an alternative method of defining the distribution at high energies is required.

It has been proposed [8,9] that some information on the barrier distribution for a reaction might be contained in the scattering excitation function at backward angles. In the semiclassical derivation for a single barrier, the reflection coefficient $R_0(E)$ for angular momentum $l=0$ is given by the ratio of the quasielastic differential cross section and the Rutherford differential cross section at 180°. The corresponding transmission coefficient $T_0(E)$ can be expressed in terms of the fusion cross section σ^{fus}. The derivative of $T_0(E)$, with respect to E, represents the fusion barrier distribution $D^{\mathrm{fus}}(E)$. Since $T_0=1-R_0$ it follows that $D^{\mathrm{fus}}(E)\equiv dT_0/dE=-dR_0/dE=-d/dE(d\sigma^{\mathrm{el}}/d\sigma^{\mathrm{R}})$. Therefore, in the classical picture a representation of the barrier distribution $D^{\mathrm{el}}(E)$ can be obtained from the derivative of $d\sigma^{\mathrm{el}}/d\sigma^{\mathrm{R}}$ with respect to E. Under the adiabatic and isocentrifugal approximation, for the multiple barriers the quasielastic differential cross section is a weighted sum of the eigenchannel elastic differential cross sections. The barrier distribution can be deduced from the quasielastic scattering excitation function [10] as follows:

$$D^{\mathrm{qel}}(E)\equiv-\frac{d}{dE}\left(\frac{d\sigma^{\mathrm{qel}}}{d\sigma^{\mathrm{R}}}(E)\right)=-\sum_{k=0}^{n}W_k\frac{d}{dE}\left(\frac{d\sigma_k}{d\sigma^{\mathrm{R}}}\right), \tag{2}$$

where W_k is k channel's weight; $d\sigma_k$ is the k channel's quasielastic scattering differential cross section; the $d\sigma^{\mathrm{qel}}$ and $d\sigma^{\mathrm{R}}$ are the quasielastic scattering and the Rutherford scattering differential cross sections, respectively. In addition, Rowley *et al.* [11] further proposed that, if the phases

ϕ_k did not depend too strongly on the eigenchannels k, the barrier distribution can be extracted from the elastic scattering excitation function.

$$D^{\mathrm{el}}(E)\equiv-\frac{d}{dE}\left(\frac{d\sigma^{\mathrm{el}}}{d\sigma^{\mathrm{R}}}(E)\right)^{1/2}=-\frac{d}{dE}\sum_{k=0}^{n}W_k\left|\frac{f_k^{\mathrm{el}}}{f^{\mathrm{R}}}e^{i\phi_k}\right|$$

$$\approx\sum_{k=0}^{n}W_kG^{\mathrm{el}}(E,B_k), \tag{3}$$

where $d\sigma^{\mathrm{el}}$ is the elastic scattering differential cross section; f_k^{el} and f^{R} are the elastic scattering and the Rutherford amplitudes, respectively; B_k is the k eigenchannel's barrier height; $G^{\mathrm{el}}(E,B_k)$ defines a sharply peaked test function at energy barrier B_k. Due to the difficulty of detecting scattered particles at $\theta_{\mathrm{lab}}=180°$, the detectors were setup at angle as close to 180° as possible. In order to compare the $D^{\mathrm{qel}}(E,\theta)$ or $D^{\mathrm{el}}(E,\theta)$ with the barrier distribution at 180°, the energy scale of the former was reduced by the centrifugal energy E_{cent},

$$E_{\mathrm{cent}}=E_{\mathrm{c.m.}}\frac{\mathrm{cosec}(\theta_{\mathrm{c.m.}}/2)-1}{\mathrm{cosec}(\theta_{\mathrm{c.m.}}/2)+1}, \tag{4}$$

where $\theta_{\mathrm{c.m.}}$ is the detection angle in the center-of-mass system.

It may be interesting to compare the $D^{\mathrm{qel}}(E)$ or $D^{\mathrm{el}}(E)$ with the fusion barrier distribution extracted from the existing experimental spin distribution. The analytic expression [12] of the relation between the fusion barrier distribution and the spin distribution is as follows:

$$D^{\mathrm{mom}}(E)\equiv-\frac{4\mu^2R_f^2E_0}{\pi\hbar^4(2l+1)^2}\frac{d\sigma_l^{\mathrm{fus}}(E_0)}{dl}, \tag{5}$$

where E_0 is the incident energy in the center-of-mass system and μ is the reduced mass of the entrance channel.

At present, although for many systems quasielastic and elastic angular distributions are well documented in the literature, excitation functions have rarely been measured. So far quasielastic [10] and elastic [11] barrier distributions have only been measured for the ^{16}O+^{144,154}Sm and ^{186}W systems with these two methods. In order to examine these methods, we have extracted the barrier distributions from the measured quasielastic and elastic scattering excitation functions for the ^{16}O+^{152}Sm reaction around the Coulomb barrier with high precision in 1 MeV energy steps and compared them with barrier distributions extracted from the existing fusion excitation function [13,14] and spin distributions [14] for the same reaction system and from the quasielastic and elastic scattering excitation functions for the neighboring isotope ^{154}Sm [10,11]. This is the first work to compare quantitatively the barrier distributions with the fusion barrier distributions deduced from the spin distributions for the same system.

The experiment was carried out with collimated ^{16}O beam from the HI-13 tandem accelerator at CIAE, Beijing in the energy range 53.0–75.1 MeV. The isotopically enriched ^{152}Sm (98.4%) target 100 μg/cm^2 in thickness was 3 mm in diameter to define the beam profile. Two collimators were mounted in the entrance and exit tubes 120 cm apart from each other. Two Si(Au) detectors, located at +36.0° and −24.0° with respect to the beam direction, were used to monitor the Rutherford scattering. The defining apertures of the two detectors were 3 mm and 2.5 mm in diameter, respectively, and were both positioned 226 mm from the target. The number of the Rutherford events detected by the two monitors was used to normalize the cross-section measurements. The ratio of the rates from the two monitors allowed any horizontal offset of the beam position on target to be determined. Three gas-ionization chambers positioned at 156°, 160°, and 164°, respectively, were used to measure the energy loss of the scattered particles. Each chamber was backed by a Si (Au) detector, which measured the residual energy. The combined information from these $\Delta E-E$ detectors, with energy resolution less than 1.3%, allowed the identification of the atomic number of the detected nuclei. The energy resolution of the detectors allows to distinguish the ground state from excitation states with $E_x\geqslant 0.8102$ MeV, while the inelastic scattering from the three lowest rotational states (0.1218, 0.3665, and 0.7069 MeV) of the target nucleus ^{152}Sm could not be resolved from the measured elastic scattering.

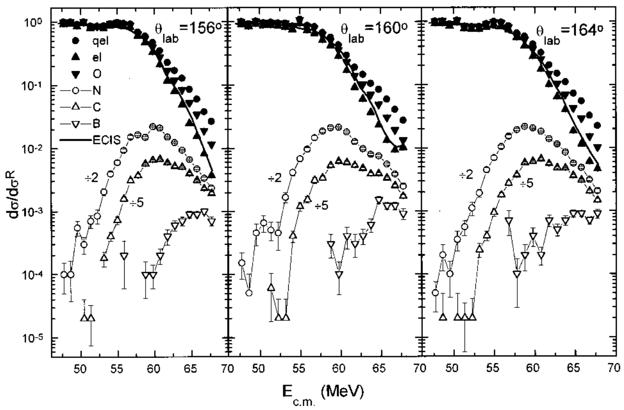

FIG. 1. The ratio of the differential quasielastic scattering (qel), elastic scattering (el) and $Z=8$ (O), $Z=7$ (N), $Z=6$ (C) and $Z=5$ (B) reaction cross sections relative to the Rutherford scattering cross sections. The solid curves are the ECIS79 calculation values including the inelastic scattering from the three lowest rotational states of ^{152}Sm.

The CAMAC-MBD-MVAXR system was used for online data acquisition event-by-event. The cross sections were obtained by projecting the two-dimensional spectra with gates on O, N, C, and B products. The experimental excitation functions of the quasielastic and elastic scatterings and the transfer reactions for the ^{16}O+^{152}Sm system at 156°, 160°, and 164° are shown in Fig. 1. The incident energies have been corrected for the target thickness. In general, the relative errors of all cross sections are less than 1%, except for transfer data. In order to compare with experimental results, the theoretical elastic scattering excitation functions were calculated in terms of the coupled-channels theory with code ECIS79. In the calculations, the Woods-Saxon parameters $V=22$ MeV, $r_V=1.34$ fm, $a_V=0.57$ fm, $W=22$ MeV, $r_V=1.34$ fm and $a_V=0.36$ fm were used. The ^{152}Sm deformation parameters $\beta_2=0.280$, $\beta_4=0.092$, and $\beta_6=0.010$ were taken from Ref. [15]. Also, the calculations

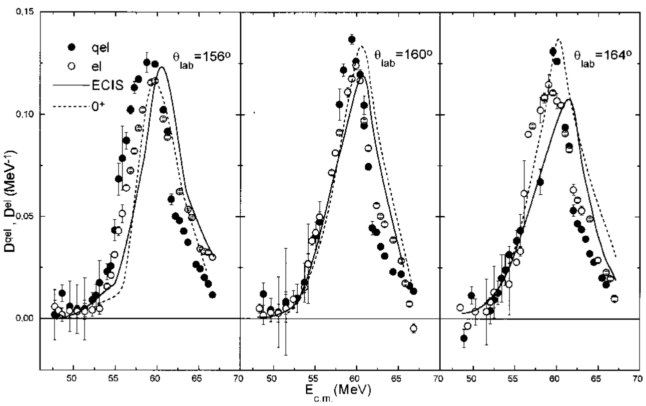

FIG. 2. The representations $D^{\mathrm{qel}}(E)$ and $D^{\mathrm{el}}(E)$ of the barrier distribution compared with the ECIS79 calculations. The dash and solid curves are theoretical calculation values for the 0^+ ground elastic scattering and elastic scattering including inelastic scattering from the three lowest rotational states of ^{152}Sm, respectively. The energy scales are reduced by the centrifugal energy E_{cent}.

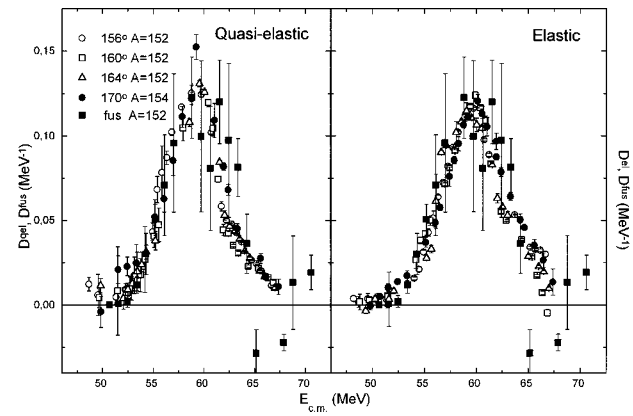

FIG. 3. The comparison of the quasielastic, elastic, and fusion barrier distributions $D^{\mathrm{qel}}(E)$, $D^{\mathrm{el}}(E)$, and $D^{\mathrm{fus}}(E)$ for $^{16}O+^{A}Sm$. The energy scales are reduced by the centrifugal energy E_{cent}.

of the elastic scattering cross sections included inelastic scattering from the three lowest rotational states of the target nucleus ^{152}Sm. It can be seen from Fig. 1 that the agreement between the experimental and theoretical excitation functions is quite satisfactory for all the three angles. The figure also shows that the quasielastic and elastic scattering excitation functions monotonically decrease with energy, but there are small oscillations due to diffraction effect in the low-energy range. It should be pointed out that the elastic scattering differential cross sections are much larger than that for the other channels at near- and sub-barrier energies, but transfer differential cross sections are comparable with elastic scattering or even larger above the average barrier energy. This has a great influence on the extraction of the barrier distributions from excitation functions.

According to Eqs. (2) and (3), the barrier distributions $D^{\mathrm{qel}}(E)$ and $D^{\mathrm{el}}(E)$ have been extracted by a point-difference formula applied directly to the experimental quasielastic and elastic scattering excitation functions. The results are shown in Fig. 2. The energy scales were reduced by the centrifugal energy given in Eq. (4). It can be seen from Fig. 2 that the shape and magnitude of barrier distributions $D^{\mathrm{qel}}(E)$ and $D^{\mathrm{el}}(E)$ are very similar for all three angles. The barrier distributions are asymmetric, increasing slowly from 50 to 60 MeV, and then decreasing relatively quickly due to the effect of static deformations of the target nucleus. The barrier distributions $D^{\mathrm{el}}(E)$ extracted from elastic scattering excitation functions using the code ECIS79 are also shown in Fig. 2. The solid and dashed curves in Fig. 2 represent the theoretical $D^{\mathrm{el}}(E)$ including inelastic scatterings from the three lowest rotational states of the target nucleus and only considering the 0^+ ground state scattering, respectively. The coupled-channels calculations basically agree with the experimental barrier distributions $D^{\mathrm{el}}(E)$, especially for the 0^+ ground state scattering calculations. It can be seen from Fig. 2 that there are some differences between the ECIS79 calculations and the experimental results. Perhaps, an energy dependent optical potential should be used in the calculations.

In order to compare the measured barrier distributions with other experimental results, Fig. 3 shows the barrier distributions $D^{\mathrm{qel}}(E)$ and $D^{\mathrm{el}}(E)$ extracted from the measured quasielastic [10] and elastic [11] scattering excitation functions of $^{16}O+^{154}Sm$ at 170°, respectively. In addition, the fusion excitation function has been obtained from the experimental fusion cross sections [13,14] at seven energies reproduced by coupled-channels theory for the $^{16}O+^{152}Sm$ fusion reaction. According to Eq. (1), the barrier distribution $D^{\mathrm{fus}}(E)$ was deduced from the fusion excitation function with $\pi R_f^2 = 3420$ mb and relative errors of cross sections $\sim 1\%$. These data are also presented in Fig. 3. In fact, this measurement was not with high precision and not in small energy steps, however, the fusion data still reflect the effect of the static deformation of the target nucleus. The results indicate that, the peak position, weight, and shape of the measured barrier distributions $D^{\mathrm{qel}}(E)$ and $D^{\mathrm{el}}(E)$ at three angles for the $^{16}O+^{152}Sm$ system are consistent with each other. There are small phase shifts at different angles. The shifts were also found in theoretical calculations [11]. Secondly, the peak positions, weights, and shapes of barrier distributions D^{qel}, D^{el} and D^{fus} for $^{16}O+^{152}Sm$ are consistent

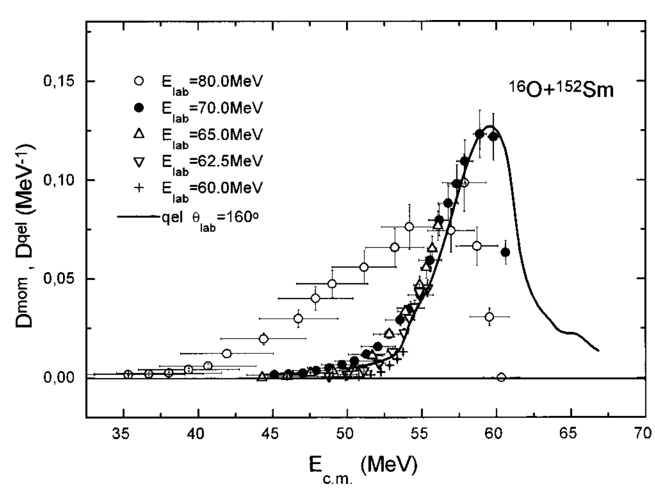

FIG. 4. The comparison of the measured barrier distribution $D^{\mathrm{qel}}(E)$ at $\theta_{\mathrm{lab}} = 160°$ with $D^{\mathrm{mom}}(E)$ extracted from spin distributions taken from Ref. [14].

with each other. Thirdly, the measured barrier distributions D^{qel} and D^{el} for the $^{16}\mathrm{O}+^{152}\mathrm{Sm}$ system are in agreement with the $^{16}\mathrm{O}+^{154}\mathrm{Sm}$ system. These facts indicate that information about the fusion barrier distribution for the $^{16}\mathrm{O}+^{152}\mathrm{Sm}$ reaction could be probed from the quasielastic and elastic scattering excitation functions.

Figure 4 shows the barrier distributions $D^{\mathrm{mom}}(E)$ extracted from the experimental fusion spin distributions [14] at five incident energies using Eq. (4). For the sake of comparison, the measured barrier distribution $D^{\mathrm{qel}}(E)$ at $\theta_{\mathrm{lab}}=160°$ is also shown in Fig. 4 by the solid curve. This is the first time that such kind of quantitative comparison is made for the same reaction system. It is seen from Fig. 4 that the agreement between D^{mom} and D^{qel} is quite satisfactory for all incident energies except the 80 MeV data. As Wuosmaa *et al.* [14] pointed out, at $E_{\mathrm{lab}}=80$ MeV, the discrepancy between the theory and the experiment in the spin distribution is not yet understood. At energies well above the Coulomb barrier, however, other reaction mechanisms not contained in the coupled-channels calculations, such as neutron transfer, deep inelastic scattering, and incomplete fusion could begin to affect the spin distribution.

In summary, we have measured the quasielastic and elastic scattering excitation functions for the $^{16}\mathrm{O}+^{152}\mathrm{Sm}$ reaction around the Coulomb barrier at three backward angles with high precision in 1 MeV energy steps. The elastic scattering excitation functions were calculated using the coupled-channels theory with the code ECIS79. The barrier distributions D^{qel} and D^{el} have been extracted from the measured excitation functions and compared with barrier distributions extracted from the existing fusion excitation function, spin distributions, and from the quasielastic and elastic scattering excitation functions for the neighboring isotope $^{154}\mathrm{Sm}$. The agreement is quite good, except for the $E_{\mathrm{lab}}=80$ MeV spin distribution data. Asymmetric barrier distributions (as theoretically predicted) are obtained. These facts indicate that the information about the fusion barrier distribution for a reaction can be probed by quasielastic and elastic scattering excitation functions.

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