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BARRIER DISTRIBUTIONS IN ^{16}O + ^{116,119}Sn*

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Using the Warsaw Cyclotron beam we determined fusion barrier distributions by quasi-elastic scattering of ^{16}O on ^{116,119}Sn targets. They turned out to be similar in both systems but some differences apparently do exist. Experimental results were compared to the coupled channels calculations performed by means of the Fresco code. Fair agreement between experiment and theory was obtained but some disagreements remain.

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1. Introduction

Since few years one can observe a revival of the fusion barrier studies. This is caused by breakthrough in the experimental methods and theoretical interpretations (*cf.* review paper [1]). Dependence of fusion on the structure of interacting nuclei manifests itself in dramatic differences between fusion excitation functions for different isotopes and in the strong enhancements of the subbarrier cross sections observed in some cases.

In classical terms, these effects are caused by static deformation of reaction partners, giving rise to the barrier height dependence on the relative orientation of deformed nuclei. In the language of quantum mechanics it is the coupling of different reaction channels (fusion, inelastic scattering via excitation of rotations and/or vibrations, mono- and multi-nucleon transfer, projectile break-up *etc.*) which generates distribution of fusion barriers, the shape of which, sometimes surprisingly rich in structure, can be considered as "fingerprint" of these couplings.

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The main motivations of these studies are the following:

- Testing nuclear reaction models (in particular Coupled Channels and Optical Model).
- Determination of the reaction channel coupling strengths and its connection to nuclear structure.
- Determination of the nuclear deformation parameters.
- Expected application in the superheavy elements production and in the radioactive beam studies.

The usual, direct method of determination of fusion barrier distribution $D_{\rm fus}$, as proposed by Rowley *et al.* [2], relies on measurements of the fusion excitation function $\sigma_{\rm fus}(E)$ and subsequent numerical differentiation of experimental data:

$$D_{\rm fus}(E) = \frac{d^2[E * \sigma_{\rm fus}(E)]}{dE^2}\,. \tag{1}$$

In spite of great experimental efforts, the double differentiation results in large statistical errors, especially in the high energy part of the barrier distribution because the fusion cross section saturates there. However, as it was shown recently [3], one can obtain similar results using a much simpler technique, namely measuring excitation function for the quasi-elastic scattering to backward angles. Then, the barrier distribution is obtained as:

$$D_{\rm qel}(E) = -\frac{d}{dE}\left[\frac{\sigma_{\rm qel}}{\sigma_{\rm Ruth}}(E)\right]\,. \tag{2}$$

The term "quasi-elastic scattering" is used here in the very wide meaning as the sum of elastic, inelastic and transfer processes, without necessity of individual component identification. This experimental simplicity is of course very attractive.

According to this formula, the Rutherford scattering should be measured at the same angle as the backward scattering, however it differs from the easily experimentally accessible $\sigma_{\rm Ruth}$ measured at forward angle only by a multiplicative constant (for Θ clearly less than $\Theta_{\rm graz}$ elastic scattering is dominated by Rutherford scattering). Thus, finally, the method consists in measurement of the backward/forward counting ratio in function of the projectile energy. The ratio is independent of the beam intensity instabilities, that is another attractive feature.

Then, according to the above formula, the excitation function should be differentiated with respect to energy. Single differentiation results in much smaller statistical errors in comparison with formula (1). Moreover, in difference to $\sigma_{\rm fus}$, the $\sigma_{\rm qel}$ changes above the barrier very rapidly, so the derivative is large and, consequently, relative errors are much smaller. Finally, the quasi-elastic method is technically simpler, as we do not need to separate fusion products from the beam, as it is necessary in the first approach.

On the other hand the first method is more precise in deep sub-barrier region since $\sigma_{\rm fus}$ increases there by orders of magnitude, while $\sigma_{\rm qel}/\sigma_{\rm Ruth}(E)$ is there quite flat. Moreover, there are known some cases when the first method is more sensitive in comparison to the second one, in determination of the distribution structure [3].

2. Experiment

The aims of our measurements were fourfold:

- Previous investigations on this subject were done by means of Tandem accelerators, which in principle are more suitable for this kind of experiments because of their inherent beam qualities and in particular facility of beam energy changing, what should be done precisely and in small steps. However, not all beams can be provided by Tandems, so we wanted to check whether this kind of measurements is feasible using cyclotron beams.
- To test new data analysis methods, utilizing data filtering to improve the signal/noise ratio. This will be described in the forthcoming paper [4].
- To compare barrier distributions for even–even and even–odd targets and check influence of neutron number on fusion process.
- To compare experimental results with coupled-channels calculations.

Considering the advantages and attracted by its simplicity, we used in our experiment the second method to extract barrier height distributions in ^{16}O + ^{116,119}Sn systems. The experiment was set at Warsaw Cyclotron. The 3–5 MeV/u ^{16}O beam of intensity 1–500 enA (depending on energy) impinged the ^{116,119}Sn targets of about 0.5 mg/cm^2 thickness, produced in the Heavy Ions Laboratory. To facilitate beam energy changes, the Al degraders of 0.5–2.0 mg/cm^2 thickness were used.

For detection we used the small CUDAC reaction chamber with 32 PIN-diodes (see Fig. 1): thirty at backward angles $\pm130°$, $140°$, $150°$ and two placed at $\pm50°$, for registering the Rutherford scattering (in our case, for the highest projectile energy $\Theta_{\rm graz} = 63°$). Registering scattered ions at three backward angles gives us additional bonus: as the "effective" cms energy (see [5]) depends on angle, this is equivalent to performing measurements at three energies simultaneously.

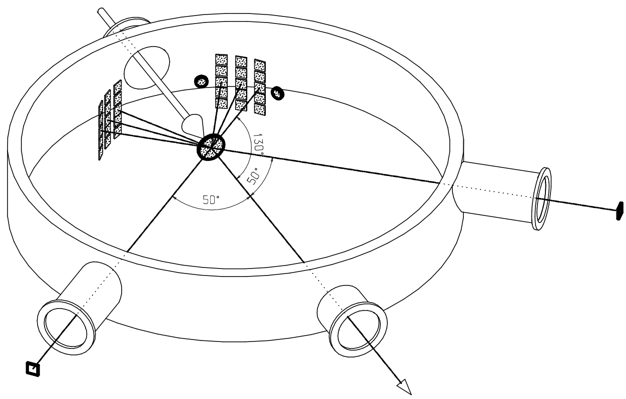

Fig. 1. Geometry of detector set-up inside the CUDAC reaction chamber. Thirty PIN-diodes at backward angles, two forward detectors and two telescopes are shown.

As we show in the figure, to increase the counting rate we placed ten 10x10 mm detectors at (almost) the same angle. The target–detector distance was equal to 92 mm for backward detectors and 370 mm for the forward ones. The forward detectors were used also for the beam energy determination.

In addition, two $E-\Delta E$ telescopes at 110° and 170° were used to learn about intensity of the light charged particle transfer and of the $Z = 1,2$ particle background coming from projectile and fusion product evaporation.

The standard electronics was set up in a very simple way, as no coincidences between detectors were necessary. The energy spectra of scattered ions were recorded event wise using the PC-based acquisition system, working in conjunction with an ADC and a multiplexer.

3. Results

Results for both investigated systems are compared in Fig. 2.

Barrier distributions for both systems are similar, although some unexplained differences in lowest energies seem to exist. This implies that in this case parity effects (giving rise to differences in neutron transfer Q-values and differences in target energy levels) do not influence fusion process significantly.

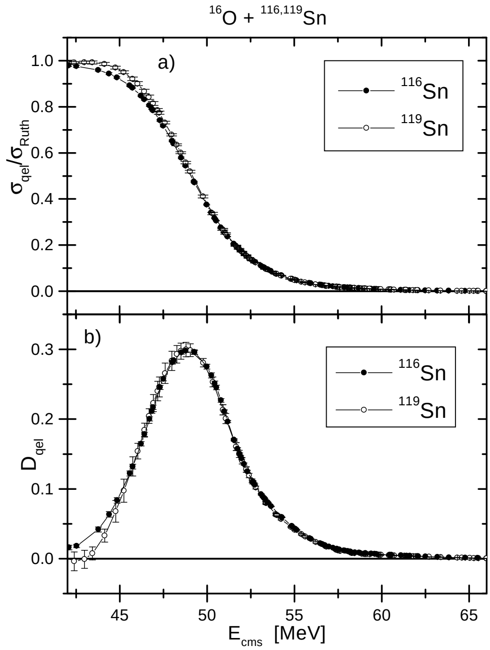

Fig. 2. (a) Quasi-elastic excitation functions measured for ^{16}O+^{A}Sn systems. Solid circles represent ^{116}Sn, empty — ^{119}Sn. (b) The experimental fusion barrier distributions for the same systems.

We compared experimental data to calculations performed "to all-orders" [6] using coupled-channels code FRESCO [7]. The complex interaction potential consisted in a real part evaluated within double-folding model JLM, while for imaginary one we assumed the Woods–Saxon potential with W_0 = 50 MeV, r_0 = 1.0 fm and diffuseness parameter a = 0.4 fm. Energy levels, spins, parities and deformation parameters were taken from Refs. [8,9].

We took into account couplings to 2^+ and 3^- states as the most important in target and 3^- state in projectile. Experimental results for ^{16}O + ^{16}Sn compared to the coupled-channels calculations are presented in Fig. 3.

One can observe a shift between experimental and calculated distributions. We consider this effect as not significant as being within the estimated energy calibration uncertainty. Moreover, one should remember that an error of only 0.07 fm in the interaction radius would give rise to disagreement of 0.5 MeV in peak positions. More important is the fact that the experimental distribution is somewhat broader and more symmetric than the results of our calculations. The reason of this discrepancy is still unknown. One

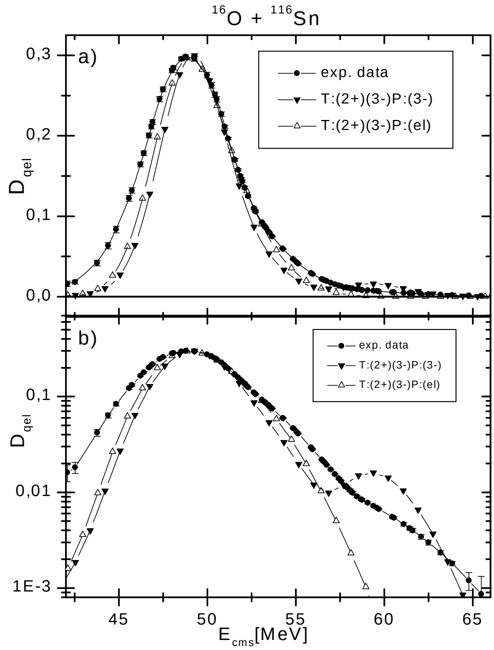

Fig. 3. Fusion barrier distributions for ^{16}O+^{116}Sn arbitrarily normalized at the peaks. Comparison between experimental results (solid circles) and calculations. Experimental resolution was taken into account.

can see in logarithmic scale (Fig. 3(b)) a tail of distribution measured at high-energy region. It has never been observed before since experiments were not previously investigating this energy range. Our calculations indicate that this might be a trace of coupling to 3^- state in ^{16}O having very large excitation energy (6.13 MeV). We would like to stress, however, that these are only preliminary results, which can be revised in the forthcoming paper [4].

4. Conclusions

We proved the feasibility of performing measurements of fusion barrier distributions using cyclotron beams. This is important, as some heavy ions cannot be accelerated using tandem accelerators, while being easily accessible by means of cyclotrons.

The barrier distributions for ^{16}O + ^{116,119}Sn are very similar. There is a general agreement between model calculations and experimental results (including lack of any clear structure). This is the more encouraging as the essentially parameter-free double-folded real potential was used, however some differences between theory and experiment, concerning details of barrier height distribution, are observed.

After receiving such encouraging results we plan to study other beam and target combinations, starting from the ^{20}Ne + ^{116}Sn system. This projectile seems to us particularly interesting as it differs only slightly from the "inert" ^{16}O projectile and still, due to the presence of the collective 2^+ level, the predicted barrier distribution is much more structured than that determined in the present work.

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