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INFLUENCE OF SINGLE PARTICLE EXCITATIONS ON BARRIER DISTRIBUTIONS: ^{24}Mg+^{90,92}Zr*

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We present preliminary results of barrier height distribution measurements for ^{24}Mg+^{90,92}Zr systems. The experiment was performed at LNS INFN in Catania with the CHIMERA detector system and a ^{24}Mg beam accelerated by Tandem MP. The measurements were done at the near-barrier beam energies of 68–88.5 MeV. A discrepancy between experimental results and the predictions of Coupled Channels (CC) calculations was observed. We suggest that this discrepancy may be due to a cumulative effect of many individual weak channels such as non-collective excitations of the target, which cannot be fully implemented in practical CC calculations of a standard form.

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1. Introduction

One of the most interesting near-barrier reactions is fusion. The basic reaction mechanism can be described in terms of a central potential, which depends on the distance between the centers of mass of the target and the

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projectile. At some distance, the potential reaches its maximum value, which is referred to as the Coulomb barrier. It arises from the competition between the long-range repulsive Coulomb force and the short-range attractive nuclear interaction. A fusion event requires that the two reaction partners overcome the barrier or penetrate through it.

It is known that there is a connection between the reaction mechanism and internal degrees of freedom of the interacting nuclei. This frequently manifests itself as a strong enhancement of the fusion cross section at sub-barrier energies in comparison with the simple quantal model of the Coulomb barrier transmission. In the frame of the Coupled Channels (CC) method, this fact is commonly understood as a result of the interplay between various reaction channels. As a result of the couplings, a single interaction barrier is replaced by many barriers of different heights. Indeed, a barrier height distribution, D_{fus}, is generated. This phenomenon was experimentally confirmed in many systems [1, 2]. In some cases, one observes a significant structure in the distribution, a "fingerprint" of the couplings involved [1, 3].

The barrier distribution, D_{fus}, can be determined both experimentally as well as theoretically by studying the products of barrier penetration, namely directly from the fusion excitation function [4] through the relation

$$D_{\mathrm{fus}} = \frac{\mathrm{d}^2(E\sigma_{\mathrm{f}})}{\mathrm{d}E^2}\,, \tag{1}$$

where σ_{f} is the fusion cross section and E is the incident energy in the center-of-mass (c.m.) system. However, fusion measurements are difficult and require complicated experimental set-ups. There exists also an alternative method that can be used to measure the barrier height distribution. This approach [5] achieves it by measuring the flux of ions which did not penetrate the barrier, but were back-scattered. Namely, one should register at backward angles all products of quasi-elastic (qe) processes: heavy ions resulting from elastic and inelastic scattering, transfers and break-up products, without the need of identifying particular reaction channels. The cross section for quasi-elastic scattering, σ_{qe}, measured at backward angles, normalized to the cross section for Rutherford scattering, σ_{Ruth}, gives the barrier distribution via the following formula [6]:

$$D_{\mathrm{qe}} = -\frac{\mathrm{d}}{\mathrm{d}E}\left(\frac{\sigma_{\mathrm{qe}}}{\sigma_{\mathrm{Ruth}}}\right)\,. \tag{2}$$

2. Motivation

Measurements of barrier distributions are a long-lasting project of our group. In previous experiments, we focused on the ^{20}Ne projectile, as this nucleus has extremely large deformation parameters. It was hence expected, in agreement with the CC calculations, that a barrier distribution for ^{20}Ne and any target nucleus would be determined by the Ne excitations. Usually in CC calculations, only strong reaction channels, *i.e.* collective excitations, are taken into account. Weak reaction channels, such as transfers or single particle excitations, are difficult or practically impossible to implement in such calculations. Moreover, according to Ref. [7], such excitations mean that we enter the field of "open quantum systems", where the Schrödinger equation, used in the CC method, is not adequate anymore.

We performed a series of barrier distribution measurements for several targets. The results of the studies of the $^{20}\mathrm{Ne}+^{90,92}\mathrm{Zr}$ and $^{20}\mathrm{Ne}+^{58,60,61}\mathrm{Ni}$ systems brought us to the conclusion that the shape of the barrier height distribution is significantly influenced by weak but numerous non-collective (mainly single-particle) excitations of the system [8–12].

A question arises if the observations from experiments using the ^{20}Ne projectile are specific for this nucleus, or rather more general. In this work, we look at the barrier distributions for the $^{24}\mathrm{Mg}+^{90,92}\mathrm{Zr}$ systems. The ^{24}Mg nucleus is also strongly deformed, which makes it a proper choice for studies addressing the above question.

3. Experiment

The measurements were performed at INFN-LNS Catania with the CHIMERA detector system [13]. Back-scattered ions were registered by rings of Si detectors placed at 6 backward angles: 122, 130, 138, 146, 159.5 and 169.5 degrees. Four detectors placed at forward angles (29 degrees), where the Rutherford scattering dominates, measured σ_{Ruth} and were also used to monitor the beam energy.

The ^{24}Mg beam of intensity of $\sim 50\ e$nA, accelerated to energies spanning the 68–88.5 MeV range (in 0.5 MeV steps), was delivered by the Tandem. We used Zr targets of 100 μg/cm^2 thickness prepared from $\mathrm{ZrO_2}$ on a C backing $\sim 30\ \mu$g/cm^2 thick.

The method of data analysis is described in Refs. [8, 14]. The energy spectra for registered ions were transformed to the Q-value spectra assuming two-body kinematics, see formula (5) in Ref. [14]. The number of counts was determined by integrating the Q-value spectra between -3.5 and 4.0 MeV. After binning over 0.3 MeV intervals, the excitation function $\sigma_{\mathrm{qe}}/\sigma_{\mathrm{Ruth}}$ was constructed. The data were normalized by imposing $\sigma_{\mathrm{qe}}/\sigma_{\mathrm{Ruth}}$ at the lowest energy equal to 1.0. In this way, precise knowledge of the detector solid angles, the target thickness and absolute beam current was not necessary, and related systematic errors were avoided.

The preliminary results of barrier height distributions measured at 130 degrees are presented in Fig. 1.

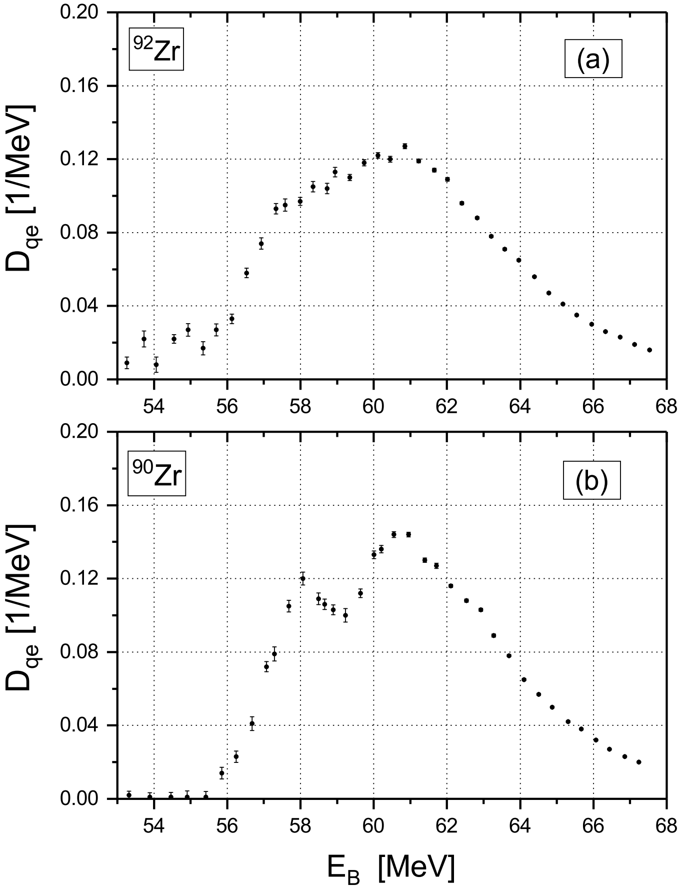

Fig. 1. Barrier height (E_{B}) distributions for the ^{24}Mg+^{92}Zr (a) and ^{24}Mg+^{90}Zr (b) measured at 130 degrees (laboratory system) — preliminary results.

The experimental results are in agreement with our expectations: for the semi-magic ^{90}Zr target, where the level density is low, the barrier height distribution is structured (has two maxima). For the ^{92}Zr target, where the level density at a comparable excitation energy is higher, the structure at 58–60 MeV is almost completely washed out.

4. Discussion and conclusions

According to our hypothesis, the observed effect *i.e.* smoothing of the barrier height distribution structure is due to the influence of weak but numerous couplings to non-collective excitations. The effect is much stronger in the case of the ^{92}Zr nucleus, which has a level density higher by an order of magnitude than that of ^{90}Zr. Excitation of a multitude of non-collective levels means a partial dissipation of the projectile kinetic energy. Taking this into account would require to go beyond the standard Coupled Channels approach. One of the proposed solutions is to replace the Schrödinger equation by the Lindblad equation, taking into account dissipation and decoherence [7]. Another possible approach merges Statistical Physics with Quantum Mechanics by extending the CC method using very general Random Matrix Theory. The method was successfully applied to the ^{20}Ne+^{90,92}Zr case [15] and proved that coupling to many non-collective levels in the ^{20}Ne+^{92}Zr system visibly smooths the D_{qe}. The calculations for ^{24}Mg+^{90,92}Zr are in progress. Preliminary results confirm the hypothesis.

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