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Role of dissipation on the quasielastic barrier distributions of the ^{20}Ne+^{92,94,95}Mo systems

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ABSTRACT

The quasielastic barrier distributions of the ^{20}Ne + ^{92,94,95}Mo systems were measured at the Heavy Ion Laboratory (HIL) of the University of Warsaw. The measurement aimed at studying the influence of dissipation due to single-particle excitations on the structure of the barrier distribution. The comparison of the three systems indicates the larger number of single-particle excitations for the heaviest Mo isotopes as a leading cause of the smoothing of the barrier distribution, which loses the structure foreseen by the coupling to only collective excitations. The theoretical calculations performed including the coupling to the non-collective excitation are in good agreement with the experimental barrier distributions for the ^{20}Ne + ^{92,94,95}Mo systems.

1. Introduction

Fusion reactions at energies near and below the Coulomb barrier are strongly related to the coupling between the relative motion of the colliding nuclei and their intrinsic nuclear motions. In the frame of the Coupled Channels (CC) model [1,2], the couplings of the relative motion to intrinsic degrees of freedom, such as collective inelastic excitations of the colliding nuclei, split the barrier into several distributed barriers, whose weighted sum generates the barrier distributions. As a result, the barrier distributions present

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significant differences among different systems, and their extractions from careful and detailed measurements proved to be useful in identifying the nature of the coupling and, consequently, the dynamics of the reaction [3].

The CC model successfully explained the structures observed in the barrier distributions for many systems. However, the influence on the fusion of several mechanisms remains unclear, that is the role of weak (non-collective) reaction channels on barrier height distributions and, consequently, on fusion dynamics.

The experimental quasielastic barrier distributions (D_{qe}) of some systems appeared smooth (without any structure), in contradiction to theoretical CC predictions. This was first observed for the ^{20}Ne+^{90,92}Zr systems [4] where the experimental quasielastic barrier distribution of the ^{20}Ne+^{92}Zr shows a much smoother structure than that for the ^{20}Ne+^{90}Zr. The results were in contrast with the CC calculations, which foresaw very similar barrier distributions for the two systems because of the dominant role of the rotational excitations of the strongly deformed ^{20}Ne nucleus with respect to the collective vibrational excitations in the Zr isotopes. The cause of the difference with respect to the CC expectations was found in a dissipative mechanism, where part of the kinetic energy is dissipated into the excitation of a multitude of internal non-collective levels of the system. The ^{92}Zr has two neutrons outside the N = 50 closed shell in ^{90}Zr, thus a much higher density of single-particle (s.p.) excited states is present. Although the coupling of these levels is generally much weaker than that of the collective ones, the non-collective excitations are so numerous that they can influence the barrier penetrability and, therefore the shape of barrier distribution. The hypothesis was strengthened by the experiments with Ni isotopes [5] and ^{24}Mg + ^{90,92}Zr [6] systems.

Such experimental evidence led to the development of a new model capable of including the non-collective excitations in the fusion reactions [7], where a statistical approach is merged with quantum mechanics by extending the CC method using the random matrix theory (RMT). The CC+RMT method was successfully applied to some studied systems [8].

Following the same investigations, the quasielastic barrier distributions of the ^{20}Ne + ^{92,94,95}Mo systems were measured at the Heavy Ion Laboratory (HIL) of the University of Warsaw. To study the influence of dissipation on fusion under well-controlled conditions, isotopes of the same element which differ by single particle level densities were chosen. According to the standard CC method, the shapes of the barrier distributions for all three systems should be similar and determined mainly by the ^{20}Ne projectile's strongly deformed structure. However, the influence of the larger number of s.p. excitations for heavier Mo isotopes should manifest in the smoothing of the barrier distributions.

2. Experimental procedure

The ^{20}Ne beam at an average current of 25 enA and energies of 65, 70 and 73 MeV was provided by the U200-P Cyclotron of HIL. Smaller energy step measurements (∼ 0.5 MeV) were achieved by employing degraders consisting of thin ^{nat}Ni and ^{nat}Au foils. Thin targets were prepared from MoO_3 on a C backing of 40 μg/cm^2 thickness. The ^{92}Mo (enriched to 98.27%), ^{94}Mo (92.03%) and ^{95}Mo (96.47%) targets had a thickness of ∼ 180, 160 and 160 μg/cm^2, respectively.

The barrier distributions were measured with the back-scattering method by employing the compact CUDAC3 scattering chamber. An array of 30 silicon detectors (PIN diodes) placed at the backward angles of 145, 135, and 125 degrees provides the energy and number of the backscattered projectiles. Four PIN diodes at forward angles of 35 degrees are used for beam energy determination and normalization by Rutherford scattering. These detectors also constantly monitor the energy resolution, which was equal to ∼1.5 MeV, 2.2 MeV and 1.3 MeV for ^{92,94,95}Mo, respectively, in the center-of-mass system and was determined mainly by beam properties.

The energy spectra of the detected ions were converted into Q-value spectra [4,9]. Subsequently, the number of quasielastic backscattered and Rutherford scattered events was estimated by integrating the Q-value spectra in the range of -5 MeV and 11 MeV. The ratio of the quasielastic backscattered and Rutherford scattered events ($\sigma_{qe}/\sigma_{Ruth}$) for each measured energy was normalized to the $\sigma_{qe}/\sigma_{Ruth}$ at the lowest measured energy. Such a procedure allows us to neglect precise information on the detectors' solid angles, target thickness and absolute beam current, along with associated systematic errors. The overall data were binned over 0.5 MeV intervals.

3. Results

The comparison of the obtained quasielastic excitation functions (preliminary results) is shown in Fig. 1 (a). Small differences among the systems are observable, that is, a steeper trend of the ^{92}Mo with respect to the neighbour isotopes at energies above the Coulomb barrier. Significant differences are highlighted by comparing the barrier distributions. This is shown in Fig. 1 (b), where the ^{92}Mo presents a clear two-peak structure that is smoothed out for the heavier ^{94,95}Mo isotopes.

Fig. 2 shows the experimental barrier distributions compared with the theoretical predictions. The CC calculations (blue dashed lines) included the rotational coupling to the first three excited states of ^{20}Ne and the vibrational couplings up to the two-phonons excitations of the first quadrupole and octupole excited states of ^{92,94}Mo isotopes. Being the ^{95}Mo an odd nucleus, the couplings to the $3/2^+$ and $5/2^+$ excited states were included by treating them as quadrupole and octupole excitations, respectively. In particular, the one-phonon excitation of the $3/2^+$ and the two-phonon excitations of the $5/2^+$ excited states were included.

In the case of the ^{92}Mo target, where the level density is low, the barrier distribution is structured as predicted by the CC model. On the other hand, the experimental barrier distributions for the ^{94}Mo and ^{95}Mo are almost structureless, in contrast with the CC expectation.

The couplings to 150 single-particle levels of the target nuclei were included within the CC+RMT model (blue solid lines). By considering the couplings to non-collective excitations, the predicted barrier distributions nicely reproduce the experimental barrier distributions of the ^{20}Ne+^{92,94}Mo systems. In the case of the ^{95}Mo, the coupling to the s.p. excitations significantly improves the

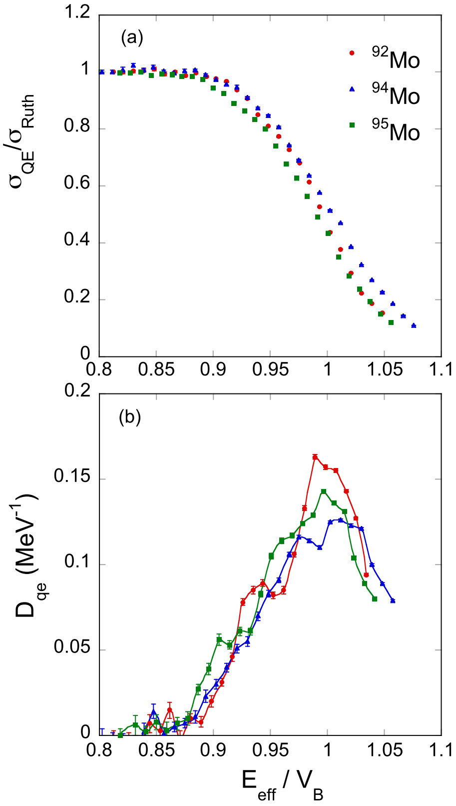

Fig. 1. Comparison of the excitation functions (a) and barrier distributions (b) of the ^{20}Ne + ^{92,94,95}Mo systems (preliminary results). The energy scale is normalized to the height of the Coulomb barriers V_B estimated according to Akyüz-Winther parametrization.

agreement with the experimental data, but not as well as for the ^{92,94}Mo isotopes. Furthermore, for the intermediate case of the ^{94}Mo isotope, the structure of the experimental barrier distribution is smoother with respect to the one of ^{95}Mo, despite the higher level density of the latter.

4. Role of transfer reactions

Besides the non-collective level excitations, there is another mechanism of dissipation: the projectile - target transfers of light particles. In this regard, the measurement of the transfer cross-sections for different transfer channels, as well as the following comparison between the neighbour isotopes, is crucial to comprehend the role that transfer couplings might play in the dynamic of the reaction [4,10,11].

Recently the measurement of the differential transfer cross-sections of the ^{20}Ne + ^{92,94,95}Mo systems was performed at HIL. An array of 19 silicon detectors combined with a Microchannel Plate (MCP) detector placed at the backward angle of 142 degrees allow the identification in mass by exploiting the different energy and Time of Flight (ToF) of the products; an E-ΔE telescope, placed at the same angle, provides their charge identification. At energies near the Coulomb barrier the transfer angular distribution has a flat maximum at backward angles, thus, the measurement performed at one backward angle should give good information about the contributions of the different transfer channels. Three silicon detectors at forward angles are used for precise beam energy measurement and monitoring. The measurements were performed at four beam energies to investigate the presence of significant variation in the strength of transfer channels at energies around the Coulomb barrier that might be related to the structure of the barrier distributions [12].

Preliminary results indicate the transfer leading to the mass A = 19 and 16 as the dominant transfer channels in all three systems. However, in the case of the ^{95}Mo also one neutron pick-up transfer (A = 21) occurs. This is shown in Fig. 3, where the E-ToF matrices for the three systems are reported. Further analysis should allow us to clarify the influence that such transfer channels might have on the different structures of the barrier distributions of the ^{20}Ne + ^{92,94,95}Mo systems. The analysis is ongoing.

5. Summary and conclusions

A comparative study of the ^{20}Ne+^{92,94,95}Mo systems indicates the influence of the dissipation due to non-collective excitations on the shape of the barrier distributions, which manifests in the smoothing out of the barrier distribution with respect to the CC prediction. Such an effect is more evident for the heavier Mo isotopes, where the level density is higher. The theoretical calculations

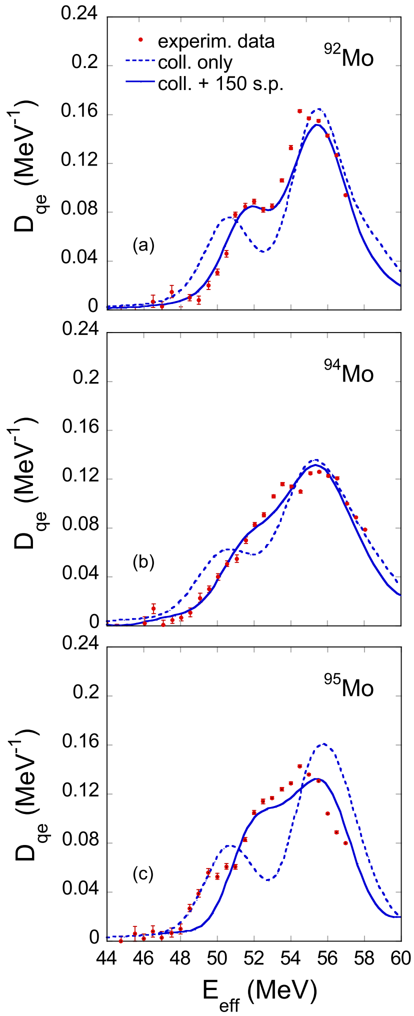

Fig. 2. Experimental quasielastic barrier distributions of the $^{20}Ne + ^{92,94,95}Mo$ systems compared with the predicted barrier distributions obtained with (blue solid lines) and without including the dissipation due to non-collective excitations (blue dashed lines). The energy resolutions for the three systems were taken into account by folding the calculated distributions with a Gaussian function with a correspondent FWHM. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

performed within the CC+RMT model nicely agree with the experimental data, supporting the hypothesis that s.p. excitations can smear the structure of the barrier distributions. Interesting is the case of the ^{94}Mo, whose structure is smoother with respect to the ^{95}Mo, despite its highest level density. The more recent measurement of differential transfer cross-sections of the three systems suggests the presence of differences in the transfer channels in the ^{95}Mo with respect to the $^{92,94}Mo$ isotopes. Additional investigations are mandatory to understand the influence of transfer channels on the considered systems.

CRediT authorship contribution statement

G. Colucci: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **A. Trzcińska:** Writing – review & editing, Supervision, Project administration, Investigation, Data curation. **E. Piasecki:** Writing – review & editing, Investigation, Data curation, Conceptualization. **M. Wolińska-Cichocka:** Data curation. **A. Barbon:** Data curation. **Z.K. Czerski:** Data curation. **G. D'Agata:** Data curation. **E. De Filippo:** Data curation. **R. Dubey:** Data curation. **E. Geraci:** Data curation. **B. Gnoffo:** Data curation. **K. Hadyńska-Klęk:** Data curation. **G. Jaworski:** Data curation. **M. Kisieliński:** Data curation. **P. Koczoń:** Resources. **M. Kondzielska:** Data curation. **M. Kowalczyk:** Software. **Y. Leifels:** Resources. **B. Lommel:** Resources. **M. Matuszewski:** Resources. **N.S. Martorana:** Data curation. **E.V. Pagano:** Data curation. **L. Quattrocchi:** Data curation. **F. Risitano:** Data curation. **P. Russotto:** Data curation. **J. Samorajczyk-Pyśk:** Data curation. **A. Stolarz:** Resources. **G. Tiurin:** Data curation. **M. Trimarchi:** Data curation. **W.H. Trzaska:** Resources, Data curation. **A. Tucholski:** Data curation. **C. Zagami:** Data curation. **B. Zalewski:** Data curation.

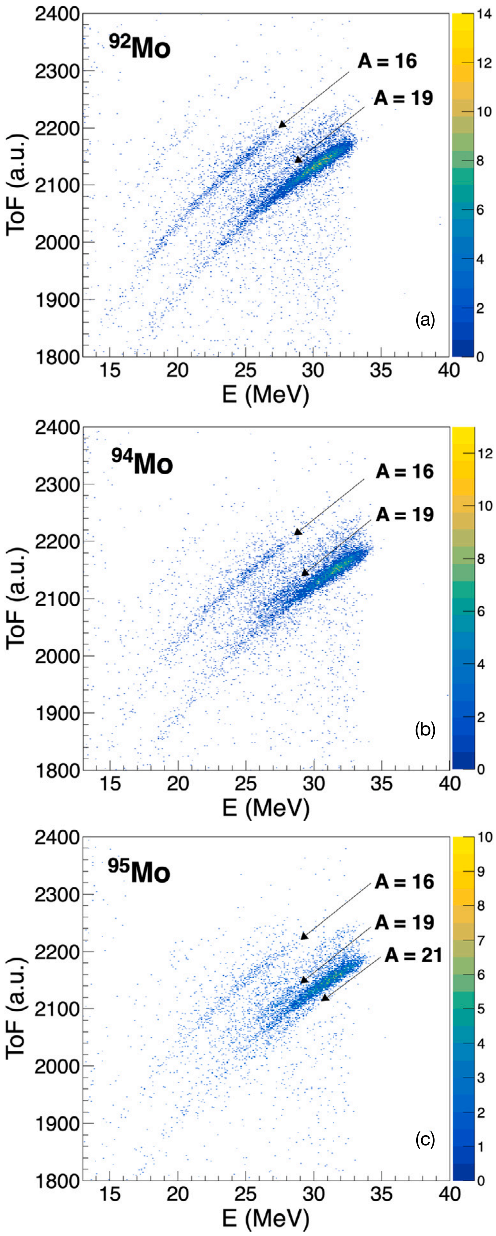

Fig. 3. E-ToF matrices for $^{20}Ne+^{92,94,95}Mo$ systems at the beam energy of 73 MeV (in the laboratory system).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data are preliminary.

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