

Dissipation on the quasielastic barrier distributions of $^{20}\text{Ne}+^{92,94,95}\text{Mo}$: the role of transfer channels

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Abstract. The influence of the dissipation due to transfer processes on the quasielastic barrier distributions of the $^{20}\text{Ne}+^{92,94,95}\text{Mo}$ systems was investigated at the Heavy Ion Laboratory, University of Warsaw. Differential transfer cross sections were measured at four beam energies (66–73 MeV) around the Coulomb barrier. For the ^{92}Mo target, the measurements indicate no significant variation in the transfer channels across the beam energy range. In contrast, for the $^{94,95}\text{Mo}$ isotopes, additional one- and two-neutron pickup reactions appear at lower energies. These preliminary results suggest that transfer reactions may influence to the shape of quasielastic barrier distributions in heavier Mo isotopes. Further analysis and theoretical developments, including an upgrade of the CCFUL-sc code to explicitly include the energy dependence of transfer couplings, are underway to better quantify this effect.

1 Introduction

Barrier distributions are an useful tool for identifying subtle variations in the energy dependence of fusion cross-sections at energies around the Coulomb barrier [1]. Within the Coupled Channels (CC) model [2, 3], the coupling between the relative motion and intrinsic excitations – such as collective inelastic excitations of the interacting nuclei – causes the nominal barrier to split into multiple barriers. Consequently, the shape of the barrier distribution depends strongly on the structure and dynamics of the colliding nuclei. The CC model successfully explained the large increase in sub-barrier fusion cross sections, as well as the observed structures in barrier distributions for a variety of systems. However, the role of other processes remains unclear, particularly the contribution of weak channels such as transfer and

non-collective excitations to the shape of the barrier height distribution and fusion dynamics.

The experimental quasielastic barrier distributions (D_{qe}) for some systems appeared unexpectedly smooth, in contrast with CC predictions. This effect was first observed in the $^{20}\text{Ne}+^{90,92}\text{Zr}$ systems [4], where the $^{20}\text{Ne}+^{92}\text{Zr}$ showed a much smoother distribution than $^{20}\text{Ne}+^{90}\text{Zr}$, despite CC calculations predicting similar results due to the dominant role of ^{20}Ne rotational excitations. The discrepancy was attributed to a dissipative mechanism where part of the kinetic energy is transferred into numerous non-collective excitations. Indeed, because of the two neutrons outside the $N=50$ closed shell, the ^{92}Zr exhibits a much higher density of single-particle (s.p.) states with respect to the ^{90}Zr . Further evidence from $^{20}\text{Ne}+^{58,60,61}\text{Ni}$ and $^{24}\text{Mg}+^{90,92}\text{Zr}$ systems [5, 6] supported this hypothesis, leading to a new model that incorporates the coupling to non-collective excitations in the fusion reactions. By

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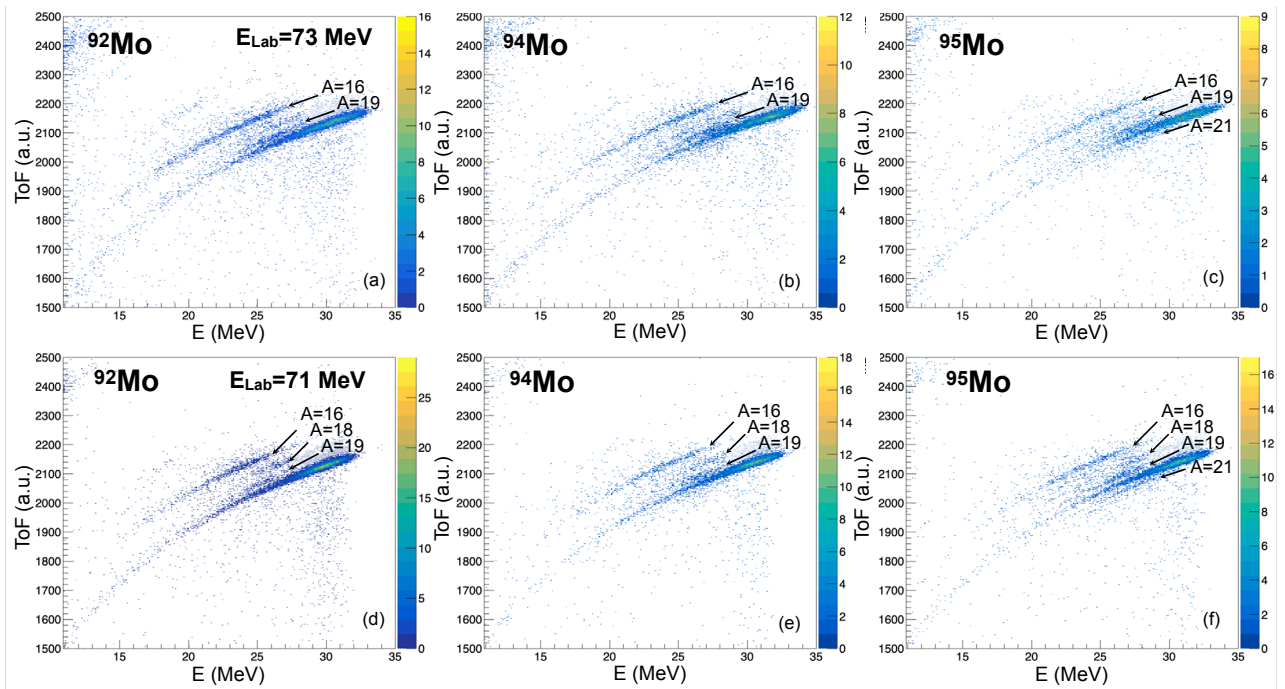


Figure 1. Transfer products' identification in mass for $^{20}\text{Ne}+^{92,94,95}\text{Mo}$ systems at the beam energy of 73 MeV (upper panels) and 71 MeV (bottom panels).

combining the CC method with the random matrix theory (RMT) [7], the model successfully reproduced several experimental results [8].

The quasielastic barrier distribution of the $^{20}\text{Ne}+^{92,94,95}\text{Mo}$ systems was measured at the Heavy Ion Laboratory (HIL) of the University of Warsaw [9]. The comparative study indicates that for the ^{92}Mo target, which has a relatively low level density, the experimental barrier distribution exhibits a well-defined structure consistent with CC model predictions. In contrast, the distributions for ^{94}Mo and ^{95}Mo are almost structureless, deviating significantly from the CC expectations. By including couplings to non-collective excitations, the predicted barrier distributions reproduce well the experimental data for the $^{20}\text{Ne}+^{92,94}\text{Mo}$ systems. For ^{95}Mo , the inclusion of single-particle excitations improves the agreement, though not as effectively as for the lighter Mo isotopes. Interestingly, the ^{94}Mo distribution is smoother and broader than that of ^{95}Mo , despite the latter's higher level density.

In addition to non-collective excitations, dissipation may also arise from the transfer of light particles between the projectile and the target. Coupling to nucleon transfer channels plays a key role in near- and sub-barrier fusion processes, although its quantitative impact on fusion dynamics is still under discussion [10–14].

Recently, the CCFULL-sc code [15] has been upgraded to improve the treatment of transfer couplings

in both fusion and quasielastic backscattering calculations [16, 17]. The updated version includes a larger number of transfer channels and introduces a dependence of the coupling strength on the type of transferred particle as well as on the experimental Q-value distributions. The code was employed to investigate the influence of transfer processes on the smoothing of the measured D_{qe} for the $^{24}\text{Mg}+^{92}\text{Zr}$ and $^{20}\text{Ne}+^{208}\text{Pb}$ systems, where for the latter the Q-value distributions were obtained at two different projectile energies. The study showed that the transfer channels which mainly contribute to the observed smoothing of D_{qe} vary with the beam energy, emphasizing the importance of including an explicit dependence of the transfer coupling strength on the projectile kinetic energy in theoretical descriptions of fusion dynamics.

In this framework, the measurement of transfer cross sections offers an effective way to investigate how the dissipation arising from transfer channels affects the D_{qe} . By comparing the transfer cross sections of different reaction channels among neighboring isotopes, one can evaluate whether transfer couplings have a significant impact on the reaction dynamics [18–20].

An experiment of this kind was recently carried out at HIL for the $^{20}\text{Ne}+^{92,94,95}\text{Mo}$ systems. The aim was to investigate whether transfer processes contribute to the experimentally observed different shapes of the

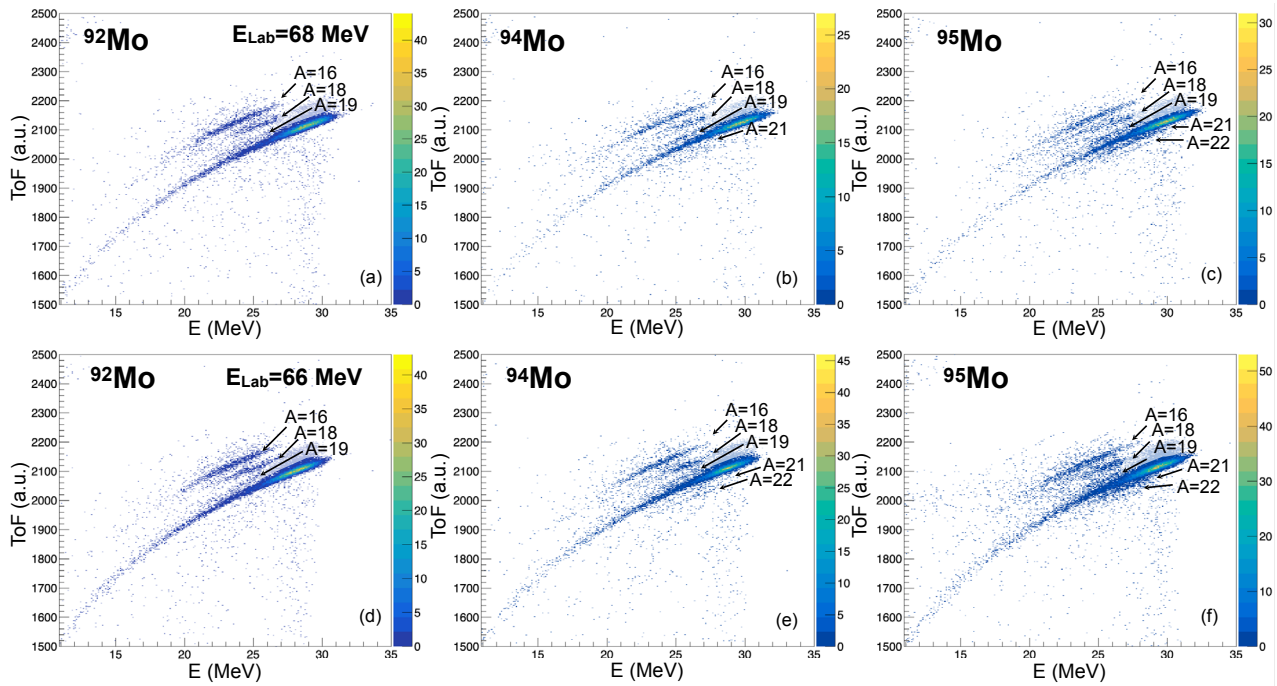


Figure 2. Transfer products' identification in mass for $^{20}\text{Ne}+^{92,94,95}\text{Mo}$ systems at the beam energy of 68 MeV (upper panels) and 66 MeV (bottom panels).

D_{qe} , and whether variations in the transfer channels appear at different projectile kinetic energies.

2 Experimental procedure and preliminary results

A ^{20}Ne beam with an average intensity of 25 enA was accelerated by the U200-P cyclotron at the HIL to the laboratory energies of 71, and 73 MeV, and lower energies of 68 and 66 MeV were obtained by using degraders made of thin ^{nat}Ni and ^{nat}Au foils. In particular, since the experimental Coulomb barriers for the $^{20}\text{Ne}+\text{Mo}$ systems are around 68 MeV in the laboratory frame [9], the four beam energies were selected to cover the range of the measured D_{qe} and to related the structure of the barrier distribution to possible variations in the strength of transfer channels [16].

The experiment was performed in the ICARE scattering chamber. Mass identification of the reaction products was achieved with a Microchannel Plate (MCP) detector and an array of 13 silicon detectors, which provided the residual energy and time-of-flight (ToF) of the products and were placed at the backward angle of 142° . Near-barrier transfer angular distributions are nearly flat at backward angles, thus measurements at this single angle provide insight into the relative contributions of the various transfer channels. Charge identification was provided by an E- ΔE gas telescope placed at the same angle as the MCP and silicon detectors array. The combined use of the

E-ToF and E- ΔE information provides mass (A) and charge (Z) identification, allowing an unambiguous assignment of the different transfer channels beyond Q-value considerations. Three additional silicon detectors at forward angles were used for precise beam energy measurement.

The E-ToF matrices for the three systems at the four beam energies are shown in Figs. 1 and 2. At the highest energy of 73 MeV (Fig. 1, upper panels), the dominant transfer channels in all three systems are the one leading to masses $A = 19$ and 16 , which correspond to one-proton and one-alpha stripping, respectively. In addition, for the $^{20}\text{Ne} + ^{95}\text{Mo}$ system, a one-neutron pick-up channel ($A = 21$) is also observed. As the beam energy decreases to 71 MeV (Fig. 1, lower panels), an additional channel leading to $A = 18$ becomes significant for all Mo isotopes.

At the lower energies of 68 and 66 MeV, more pronounced differences emerge between the $^{20}\text{Ne} + ^{92}\text{Mo}$ and $^{20}\text{Ne} + ^{94,95}\text{Mo}$ systems. As shown in Fig. 2 ((a) and (d)), the main transfer channels for ^{92}Mo remain essentially the same as those observed at 71 MeV (see Fig. 1 (d)). In contrast, at 68 MeV (Fig. 2, (b) and (c)), additional transfer channels leading to $A = 21$ and $A = 22$ – thus, two-neutrons pick-up – appear for ^{94}Mo and ^{95}Mo , respectively. Furthermore, at the lowest beam energy of 66 MeV (Fig. 2, (e) and (f)), the $A = 22$ channel also becomes visible for the ^{94}Mo case, while the set of transfer channels for ^{95}Mo remains unchanged. The emergence of neutron pickup channels

may partly reflect angular distributions. This does not affect 71 MeV and below, but may slightly impact the 73 MeV measurement. A dedicated analysis with the updated CCFULL-sc code will provide a quantitative estimate of this effect.

These preliminary results indicate notable differences in the transfer channels among the three systems, and these differences evolve with the projectile kinetic energy. In particular, for the ^{92}Mo target the transfer pattern remains almost unchanged as the beam energy decreases, whereas for $^{94,95}\text{Mo}$ clear variations are observed, with the onset of one- and two-neutron pick-up channels. This suggests that transfer processes may influence the shape of the barrier distributions in the $^{20}\text{Ne}+^{94,95}\text{Mo}$ systems. However, to better assess the impact of these transfer channels on the observed structures of the barrier distributions, further analysis is required, including an upgrade of the CCFULL-sc code to account for the explicit energy dependence of the transfer couplings.

3 Summary

A systematic study of the $^{20}\text{Ne}+^{92,94,95}\text{Mo}$ systems was conducted to explore the influence of transfer channels on quasielastic barrier distributions. The preliminary results show that for the ^{92}Mo target the dominant transfer channels remain constant across the measured energies. In contrast, the $^{94,95}\text{Mo}$ systems exhibit additional one- and two-neutron pick-up channels at lower energies, suggesting an energy dependence of the transfer strength. These differences may contribute to the different and smoother experimental barrier distributions observed for the heavier isotopes. Future work will focus on detailed cross-section analyses and on improving the CCFULL-sc model by introducing an explicit dependence of the transfer coupling strength on projectile kinetic energy.

Acknowledgements

This work was partly funded by the SHENG1 project of the National Science Centre, Poland, under contract No. 2018/30/Q/ST2/00163 and the IDUB project under the contract No. PSP 501-D355-20-0002220. This project has received funding from the European Union's Horizon Europe Research and Innovation program under Grant Agreement No 101057511 (EURO-LABS) and by NextGeneration EU project, through MUR-PNRR ecosystem SAMOTHRACE (ECS00000022). The work was also partially supported by the Polish National Science Centre (Grant No. 2020/39/D/ST2/00466). The authors acknowledge funding from the National Science Centre, Poland, through the SONATA 20 programme, Grant No. 2024/55/D/ST2/02423.

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