Investigation of quasi-elastic scattering in $^{24}Mg + ^{92,94,95}Mo$ reactions

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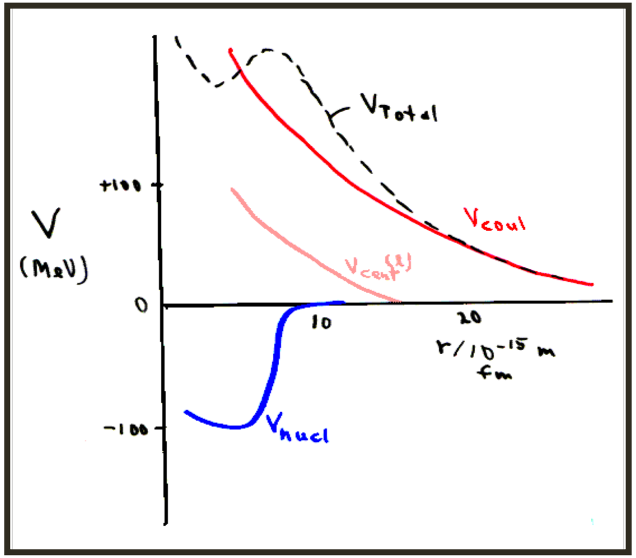
Near-Barrier Heavy-Ion Reactions



Three forces:

1. Coulomb force

2.Centrifugal force

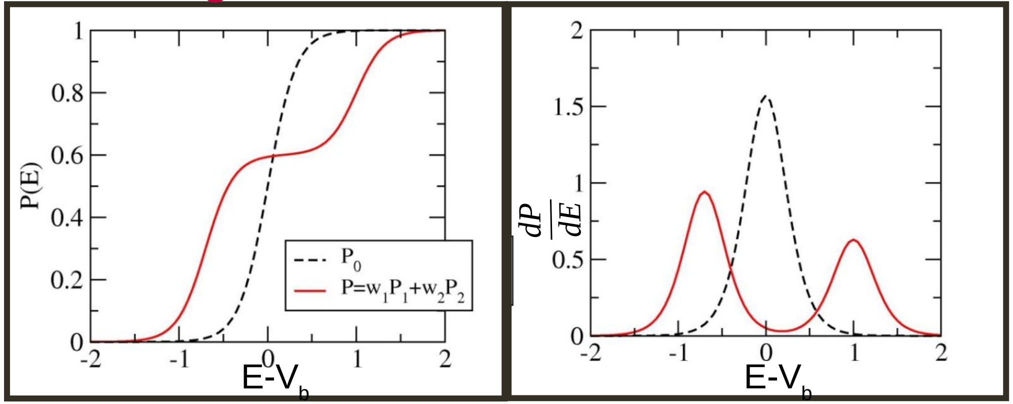
Long range, repulsive

3. Nuclear force

Short range, attractive

$$V_{total} = V_c + V_n + V_{cent}$$

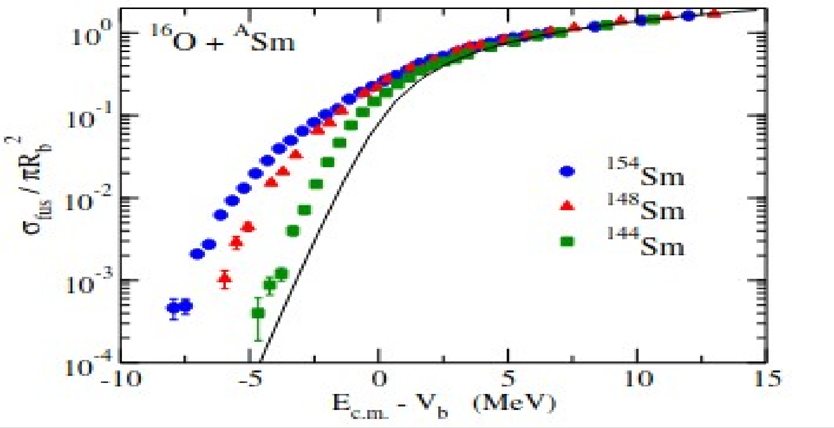
Tunneling Effect: Near and Sub-barrier Fusion

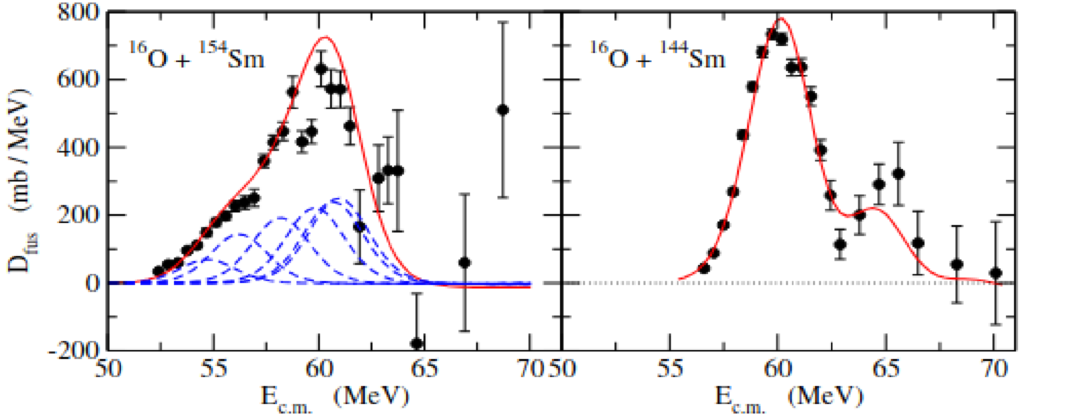


Many Explanations--Coupling effects:

- **Nuclear structure (collective excitations)**
- **Reaction dynamics (transfer/breakup reactions)**

K. Hagino, Progress of Theoretical Physics, Vol. 128, No. 6, (2012)





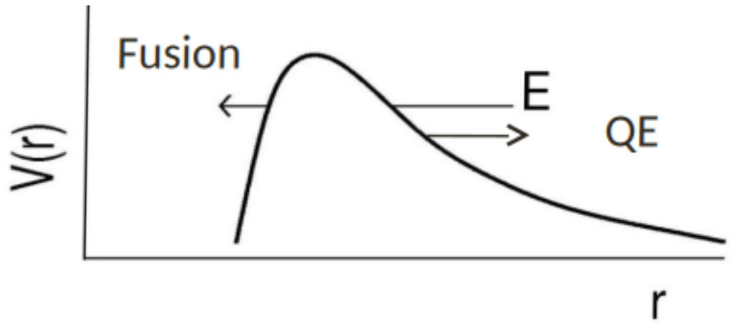
Barrier Distributions: Fusion vs Quasi-elastic

Barrier distribution is tagged as a fingerprint of any nuclear reaction.

Fusion Barrier Distribution can be experimentally obtained:

$$D_{\text{fus}}(E) \equiv \frac{d^2(E\sigma_{\text{fus}})}{dE^2}$$

In quantum mechanics, reflection occurs even at $E > Vb$
i.e. Quantum Reflection



$$P(E) + R(E) = 1$$

Reflection prob. carries the same information as penetrability, and barrier distribution can be defined in terms of reflection prob.

Related to reflection and Complementary to fusion

$$D_{\text{qel}}(E) = -\frac{d}{dE}\left(\frac{\sigma_{\text{qel}}(E,\pi)}{\sigma_R(E,\pi)}\right)$$

H. Timmers et al., NPA584("95)190
M.V.Andres et al.,Phys. Lett. B,1988

Advantages for D_{qel}

- **Less statistical error in QE (1st vs. 2nd derivative)**
  - **Much easier to be measured**

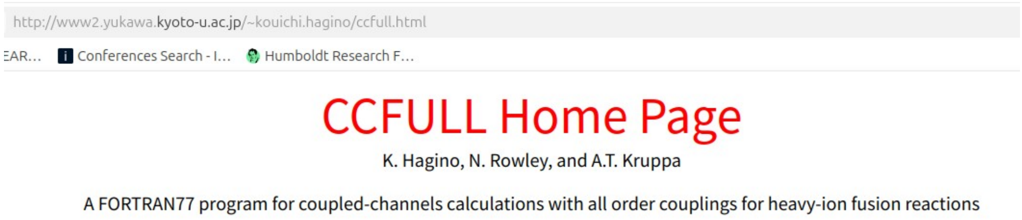
Qel： a sum of everything
a very simple charged-particle detector
Fusion： requires a specialized recoil separator to separate ER
ER + fission for heavy systems

- **Several effective energies can be measured at a single-beam energy**

$$E_{\text{eff}} = 2E\ \sin(\theta/2)/[1 + \sin(\theta/2)]$$

Coupled-Channels Framework

- Theoretically, the coupled channels calculations are performed to obtain the fusion/QE cross-section and then using the point difference formula to find the second derivative for obtaining the BD.
- Various codes are available to perform these calculations. These codes include CCDEF, CCFUS, CCFULL.
- Presently, CCFULL is employed for the study of fusion. This code takes into consideration the vibrational, rotational nature of the target and projectile into consideration and to a few extent, this code includes only pair transfer.
- For Quasi-elastic scattering, the scattering version of CCFULL i.e CCQUEL is employed. This code gives us the QE excitation function and taking its first derivative w.r.t energy gives us the barrier distribution.


http://www2.yukawa.kyoto-u.ac.jp/~kouichi.hagino/ccfull.html

EAR... Conferences Search - I... Humboldt Research F...

CCFULL Home Page

K. Hagino, N. Rowley, and A.T. Kruppa

A FORTRAN77 program for coupled-channels calculations with all order couplings for heavy-ion fusion reactions

C.H. Dasso et al Computer Phys. Commun. 46, 187 (1987).
J. Fernandez-Niello et al Computer Phys. Commun. 54, 409 (1989).
K. Hagino, et al, Comput. Phys. Commun. 123, 143 (1999)
K. Hagino, yet to published..

Experimental Puzzle: Smooth Barrier Distributions

^{20}Ne+X Reactions

^{20}Ne projectile - strongly deformed nucleus: β_2=0.46, β_3=0.39, β_4= 0.27

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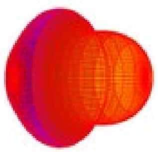
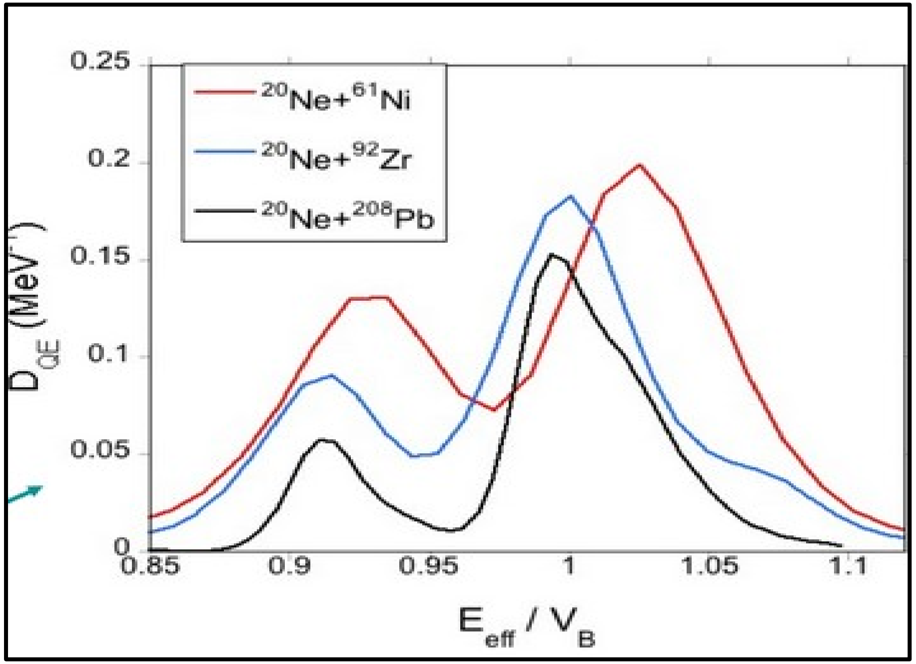


Calculations carried out by the Coupled Channels (CC) method predict the distribution of barriers with a strong "structure" for all ^{20}Ne + X systems



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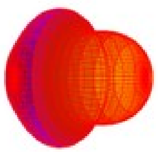

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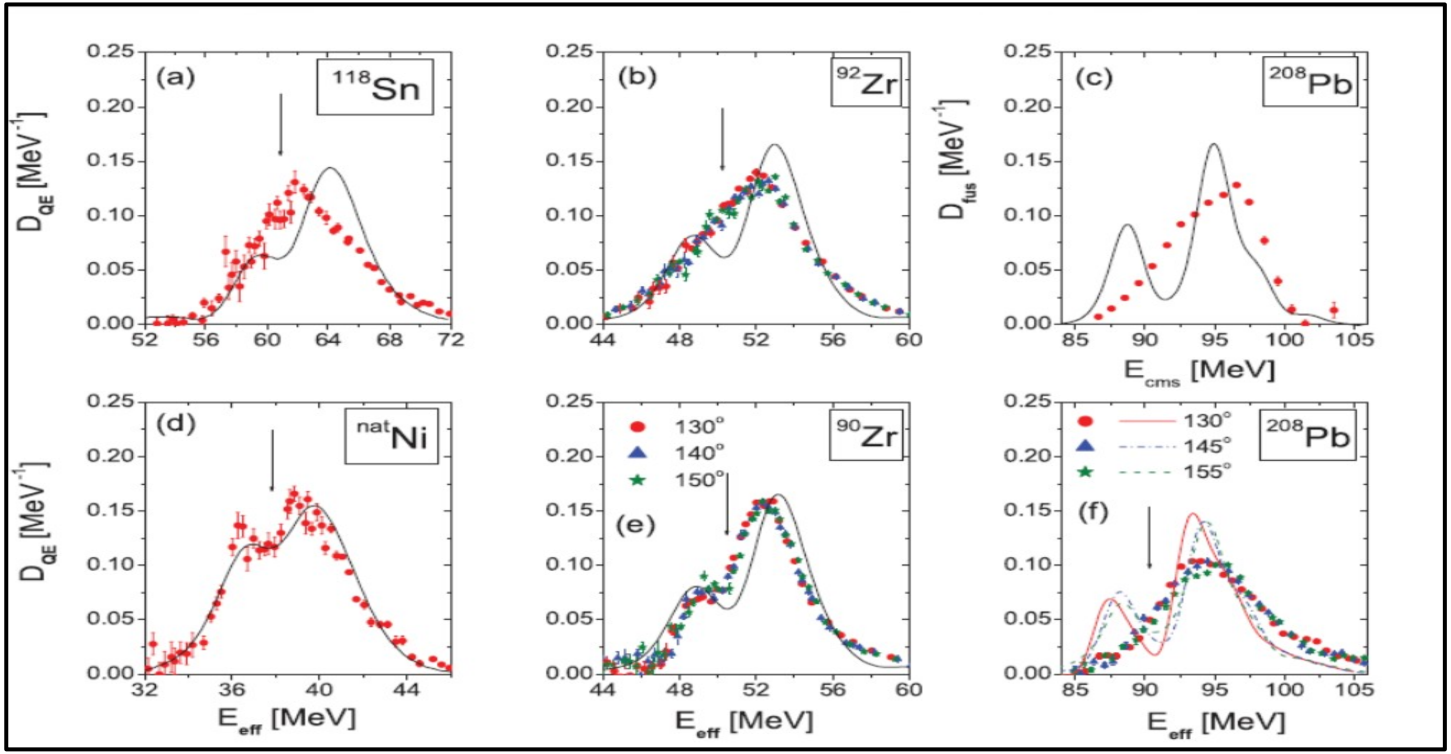

E. Piasecki et al., Phys. Rev. C 85, 054604 (2012)

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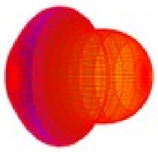
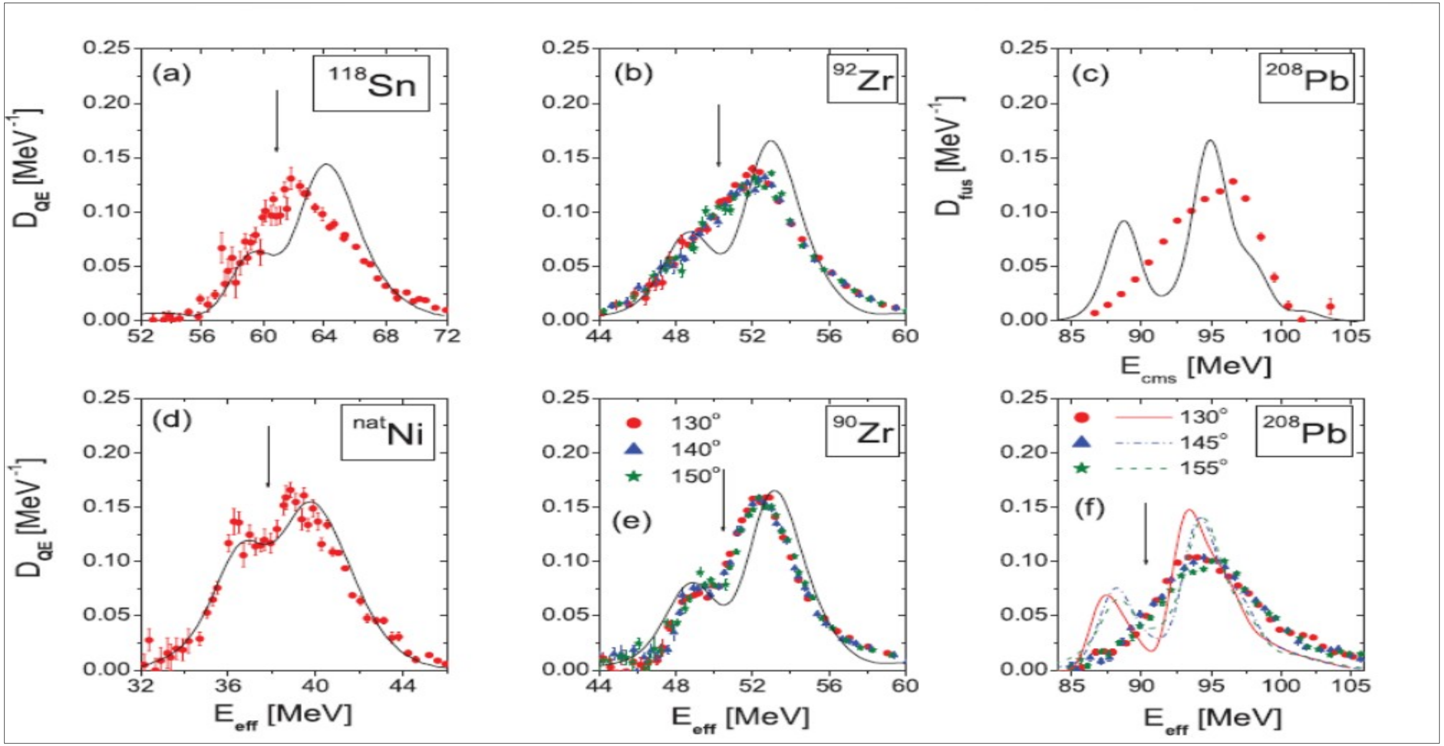


Calculations carried out by the Coupled Channels (CC) method predict the distribution of barriers with a strong "structure" for all ^{20}Ne + X systems

One possible origin of this smoothing is dissipation due to weak channel coupling : non-collective states or transfer of nucleons.



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Coupled-Channels Code – MODIFIED

Coupled Channels (CC) model takes into account strong collective excitations of the participating nuclei. However, not all excitations are collective in nature.

Much less is known about the dissipation due to weak couplings like non collective excitations or transfer channels.

To explore these effects theoretically, the existing **CCFULL code has been modified to CC-RMT** using the Random Matrix theory to include the single particle excitations along with the collective excitations.

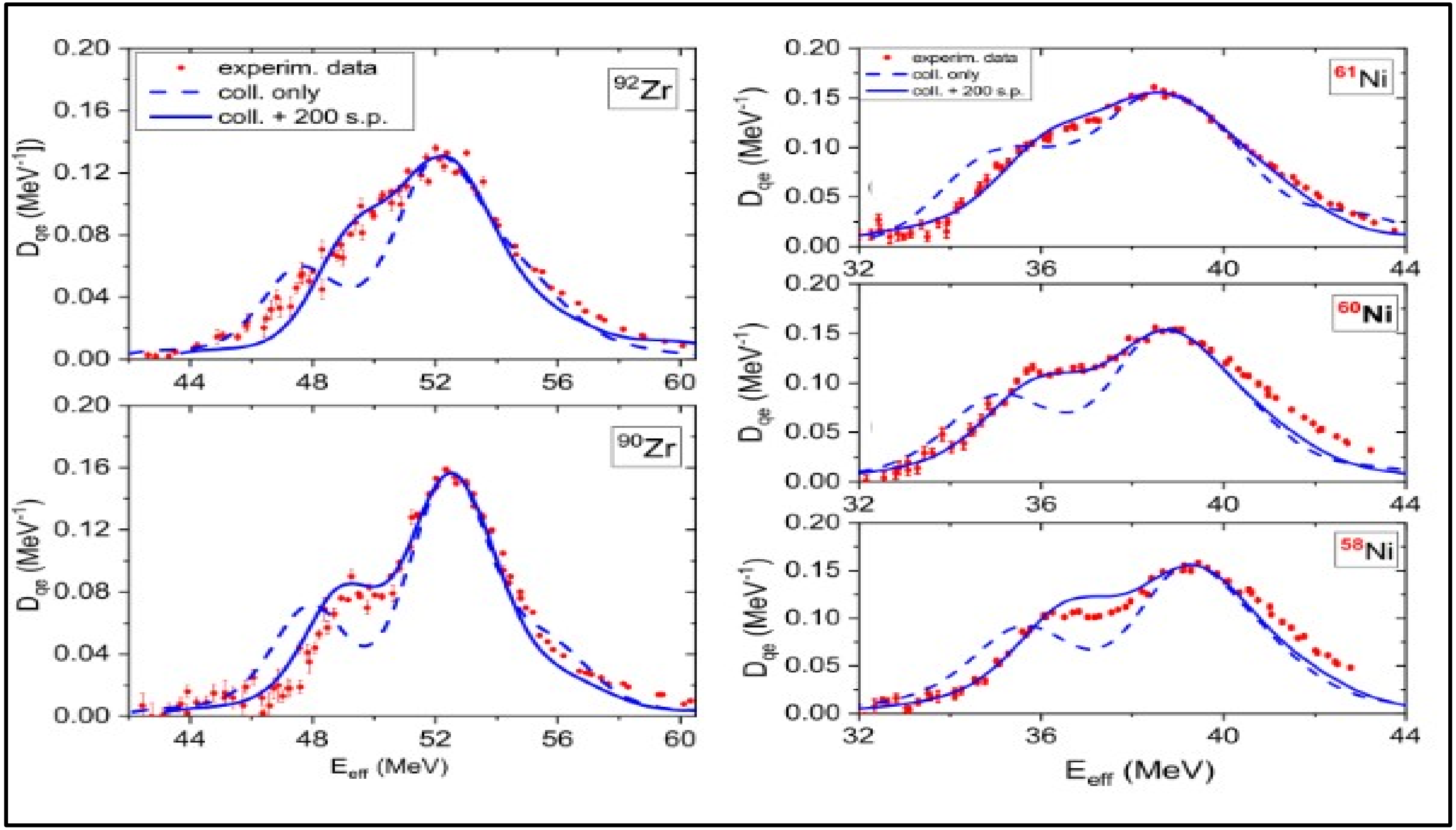
Also, the transfer part of CCFULL-SC (CCQEL) were upgraded to include all the possible transfer channels.

Weak Couplings: Non Collective excitations & Transfer Channels

^{20}Ne +X reactions

Influence of single particle excitations on the smoothing of the barrier distribution.

Coupling to non-collective included within CC+RMT model.



E. Piasecki et al., Phys. Rev. C 80, 054613 (2009)
A. Trzcinska et al., Phys. Rev. C 92, 034619 (2015)
E. Piasecki, et al., Phys. Rev. C 100, 014616 (2019)

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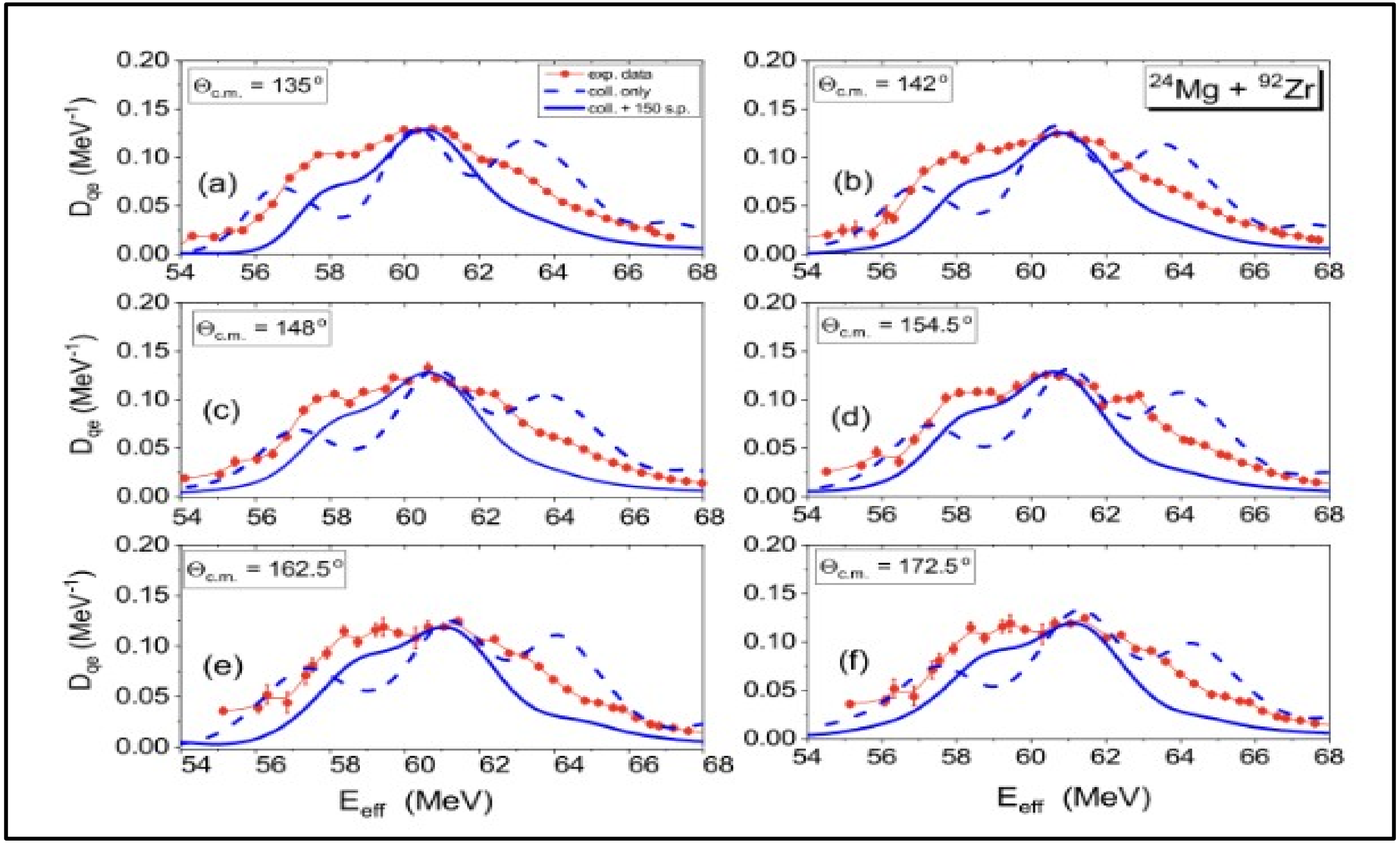
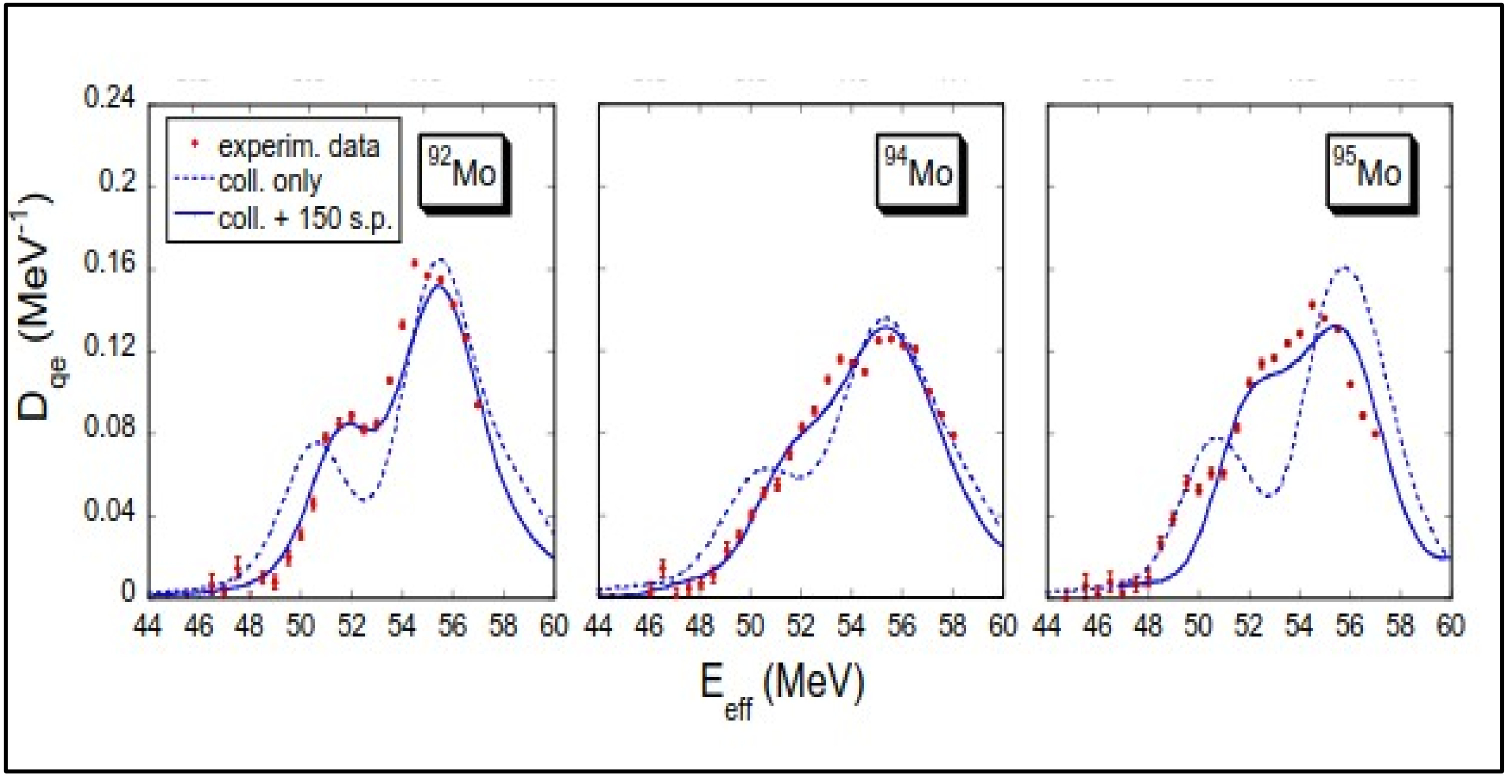


Weak Couplings: Non Collective excitations & Transfer Channels

- Experimental D_{QE} of $^{20}Ne+^{92}Mo$ preserves two-peaks structure.
- Experimental D_{QE} of $^{20}Ne+^{95}Mo$ has much smoothed structure respect to CC calculations, as predicted by CC+RMT model.
- D_{QE} of $^{20}Ne+$ ^{94}Mo is smoother and wider with respect to the one of ^{95}Mo.



Possible significant differences in transfer channels between the isotopes.

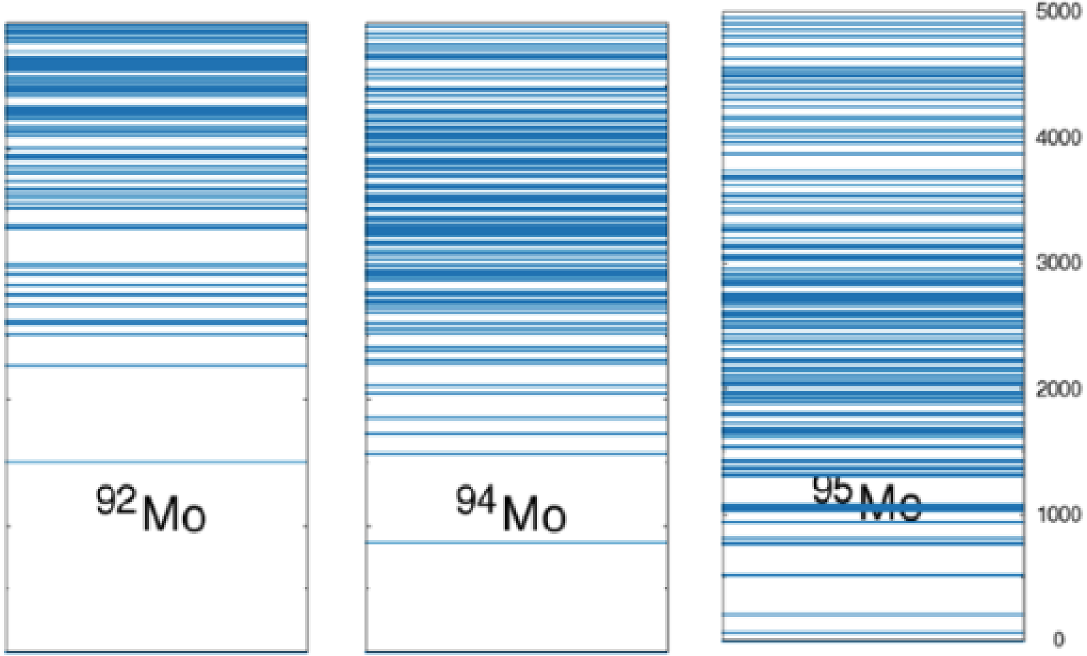
G. Colucci et al., Acta Phys.Pol. B 17, 3-A23 (2024)

Motivation for ^{24}Mg + ^{92,94,95}Mo Systems

To further validate this hypothesis, a quasi-elastic measurement experiment was carried out for the ^{24}Mg + Mo reaction.

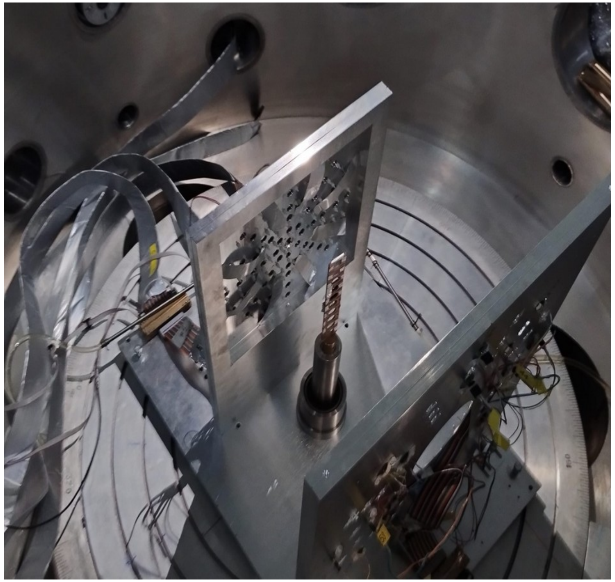
^{24}Mg projectile - strongly deformed nucleus:
β_2=0.59, β_3=0.27, β_4= −0.03

Observing the influence of increasing level density on barrier distribution



Experimental Setup

- The experiment was carried out at CIAE using a ^{24}Mg beam delivered by the HI-13 tandem accelerator.
- Thin Mo targets with an areal density of approximately 100 μg/cm^2 were employed for the measurements.
- Quasi-elastic particles were detected using an array of Si detectors positioned at backward angles between 139∘ to 169∘.
- Beam monitoring was performed with PIN detectors placed at forward angles of 30∘ and 40∘.
- The calibration of the detectors was performed using alpha source and pulse generator after the experiment.



Pictorial view of inside of the chamber

Data Analysis Method

The quasi-elastic excitation function has been calculated using formula

$$\frac{d\sigma_{qel}}{d\sigma_{Ruth}} = \frac{N_{tel}(E,\theta_{tel})}{N_{mon}(E,\theta_{mon})} \times \frac{\Delta\Omega_{mon}}{\Delta\Omega_{tel}} \times \frac{(d\sigma_{Ruth}/d\Omega)(E,\theta_{mon})}{(d\sigma_{Ruth}/d\Omega)(E,\theta_{tel})}$$

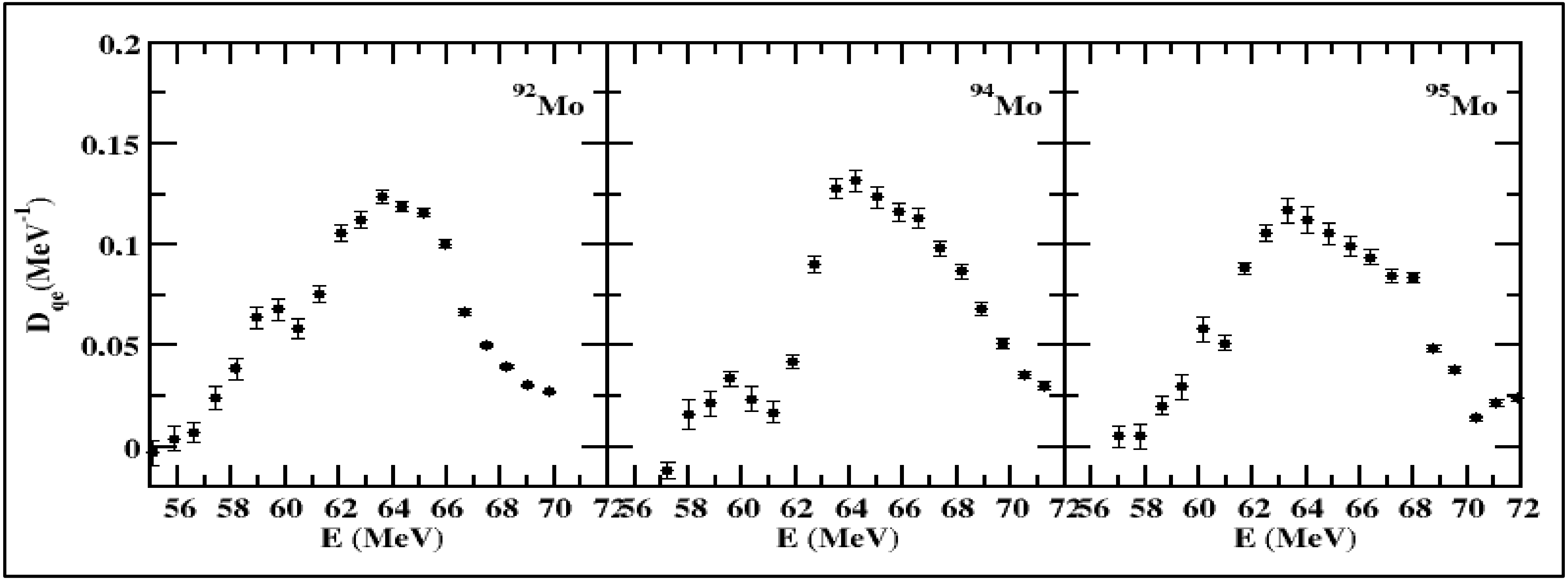
- Energy spectra of registered ions → converted to Q-value spectra assuming two-body kinematics
- Counts obtained by integrating Q-values
- Excitation function $\sigma_{QE}/\sigma_{Ruth}$ constructed from the counts
- Normalized $\sigma_{QE}/\sigma_{Ruth}$ to 1 at lowest energy
- Avoided need for precise detector angles, target thickness, or beam current → minimized systematic errors

Then, the barrier distributions were determined using the finite-difference method

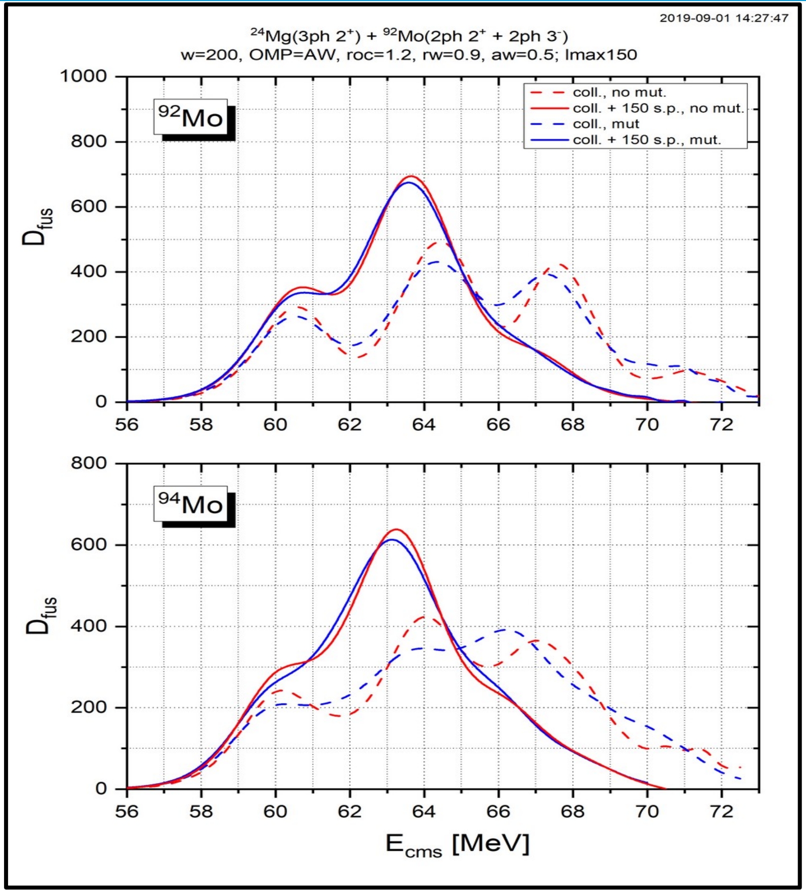
$$D_{qel}(E_{\mathrm{eff}}) = -\frac{d}{dE_{\mathrm{eff}}}\left[\frac{d\sigma_{\mathrm{qel}}(E_{\mathrm{eff}})}{d\sigma_{\mathrm{R}}(E_{\mathrm{eff}})}\right],$$

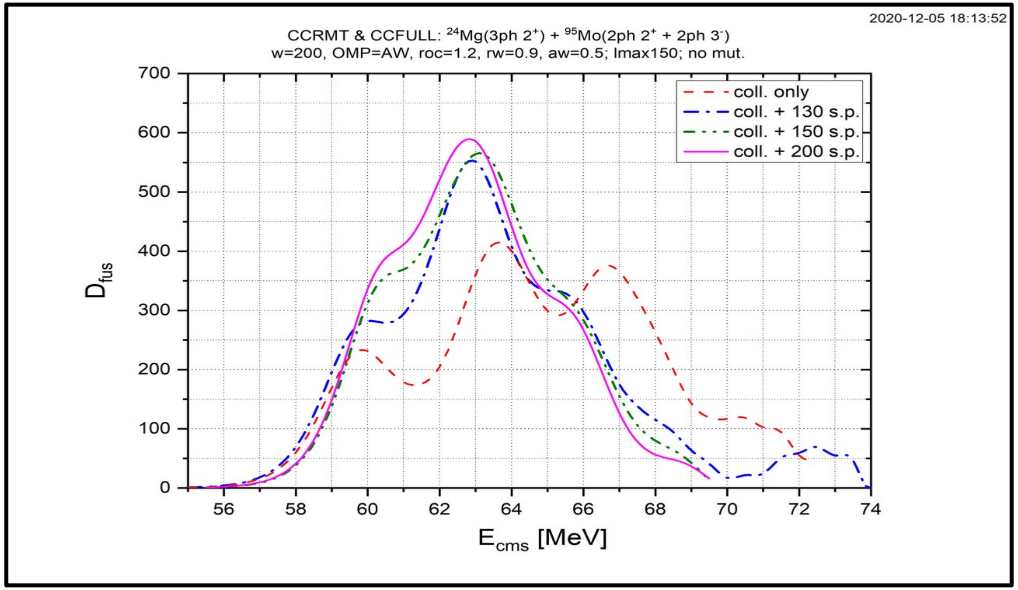
Status of Results

The **PRELIMINARY** results of barrier height distributions measured at 153 degrees are:



CC-RMT calculations done for Fusion BD





D_{fus} results change due to the dissipation by non-collective excitations.

The results for D_{qe} are expected to be similar (although with somewhat weaker structure)

Summary and Outlook

SUMMARY

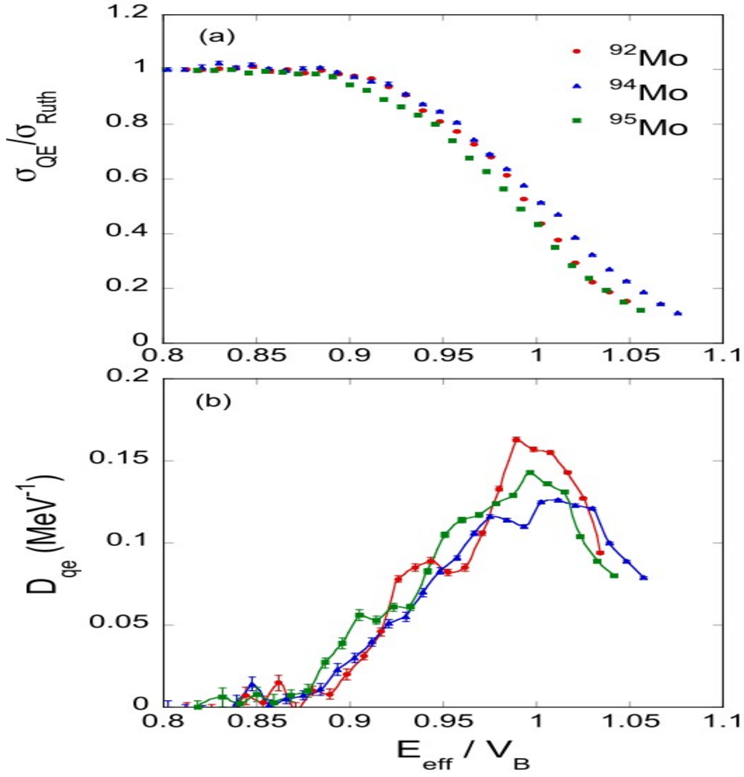
- Quasi-elastic scattering measurements were performed for the ^{24}Mg + ^{92,94,95}Mo systems near the Coulomb barrier
- Barrier distributions were extracted from quasi-elastic excitation functions at backward angle
- A systematic smoothing of the barrier distributions is observed with increasing target level density
- The preliminary results suggests a significant role of weak couplings (dissipation due to non-collective excitationsor transfer channels)

FUTURE OUTLOOK

- Extract experimental QE-BD at various other backward angles.
- To perform detailed coupled-channels calculations for QE including non-collective excitations using CC-RMT.
- An experiment to measure fusion barrier distribution for the same reactions is approved to be performed at INFN-LNS (Catania).
- Compare quasi-elastic and fusion barrier distributions for the same systems.

THANK YOU

BACK UPS



$$E_{\mathrm{exc}} = \left(1 + \frac{A_{\mathrm{PLF}}}{A_{\mathrm{TLF}}}\right) E_{\mathrm{PLF}} - \left(1 - \frac{A_{\mathrm{proj}}}{A_{\mathrm{TLF}}}\right) E_{\mathrm{proj}} - \frac{2\sqrt{A_{\mathrm{proj}} A_{\mathrm{PLF}} E_{\mathrm{proj}} E_{\mathrm{PLF}}}}{A_{\mathrm{TLF}}} \cos\Theta,$$