Barrier distributions studies at HIL: recent results and future plans

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on behalf of HIL Barrier Group

Near barrier fusion reactions

Fusion and quasielastic barrier distributions

D_{QE} measurements performed at HIL and LNS

Transfer cross section measurements at HIL

New CCQEL code: the cases of $^{24}Mg + ^{92}Zr$ and $^{20}Ne + ^{208}Pb$

D_{QE} of $^{20}Ne + ^{92,94,95}Mo$

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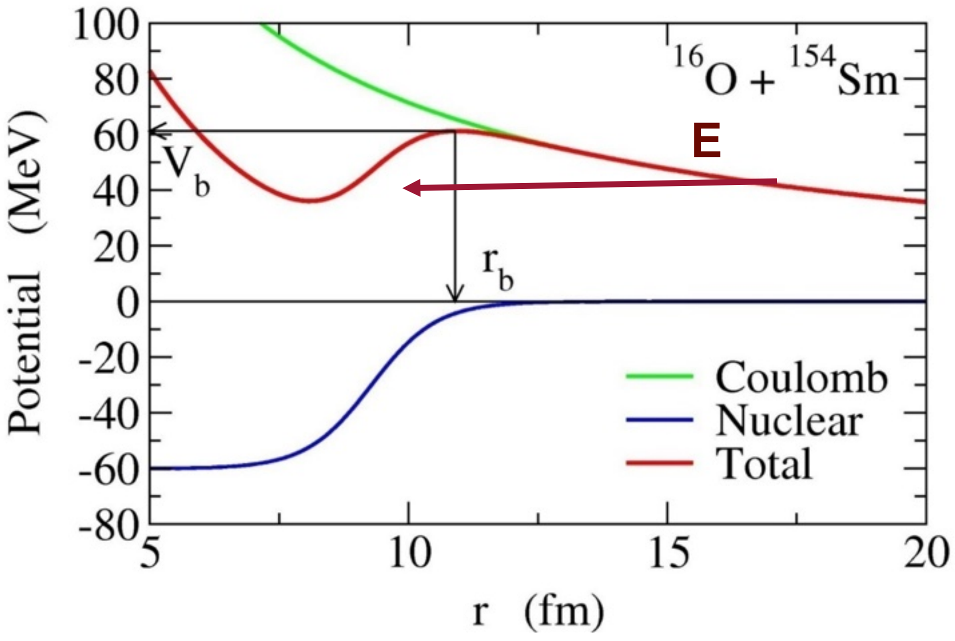
Two interactions: long range repulsive **Coulomb force** and short range attractive **nuclear force**. Cancellation between the two forces generates **Coulomb barrier**.



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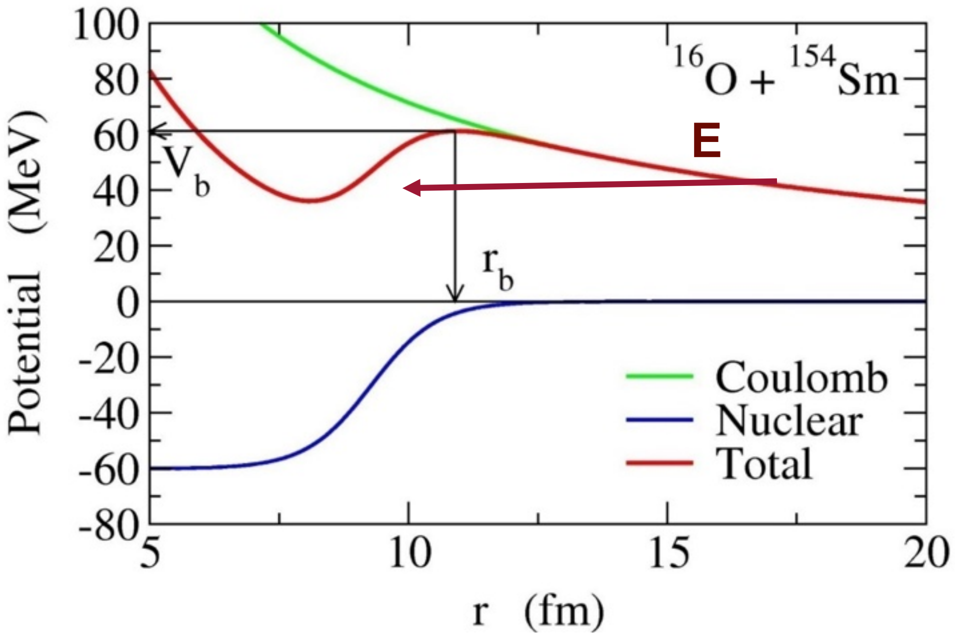

Why sub-barrier fusion?

- Many-particle tunnelling effect
  - → Many types of intrinsic degrees of freedom (collective vibrational, rotational states..)
  - → Energy dependence of tunnelling probability
- Strong interplay between reaction and structure

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$$H(r) = -\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + V(r)$$

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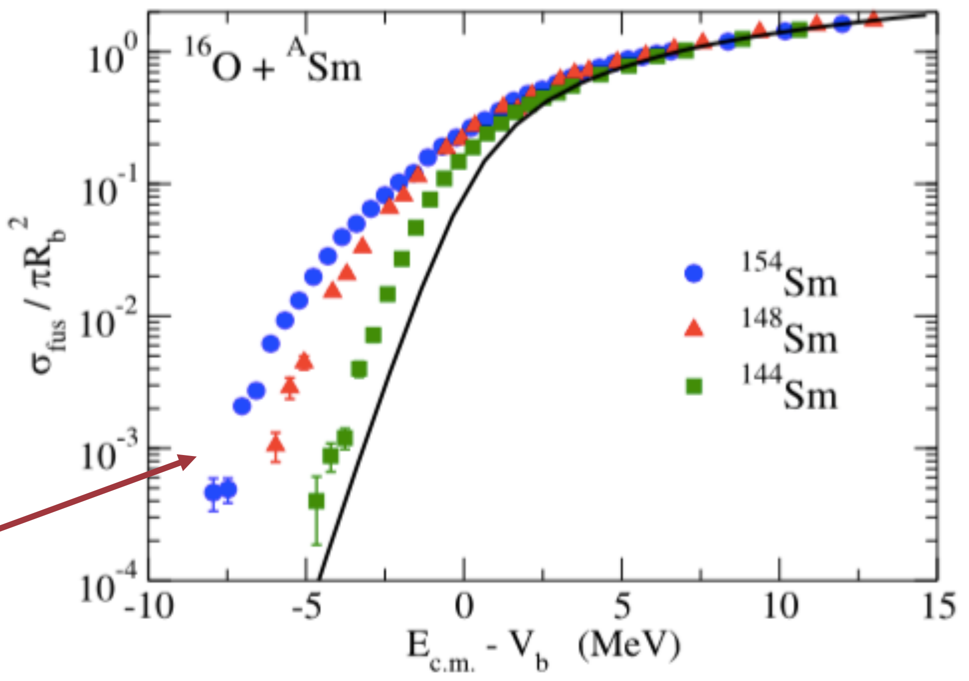

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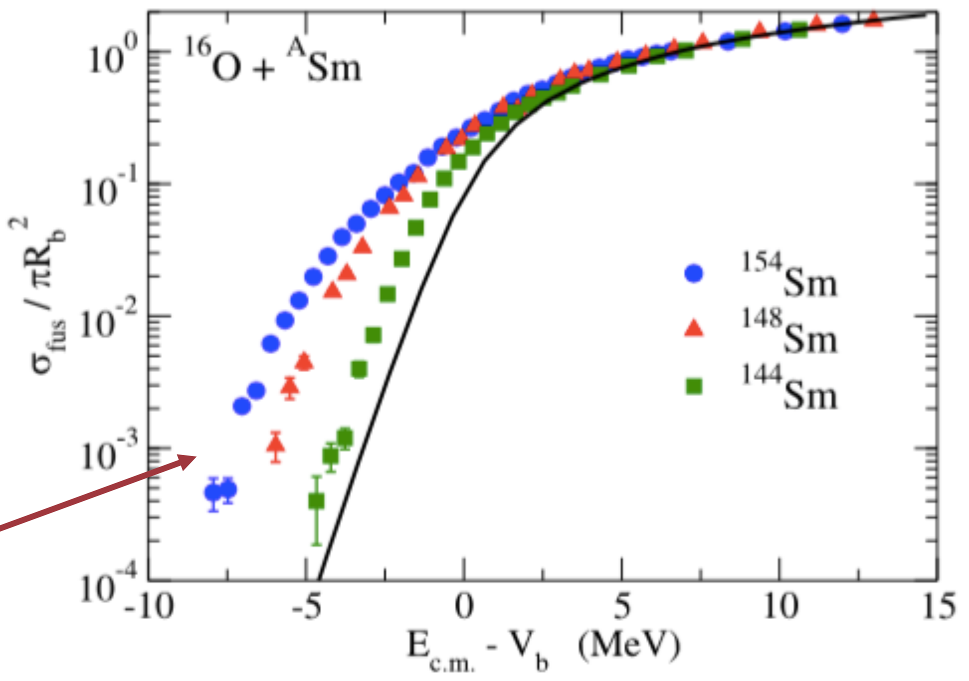

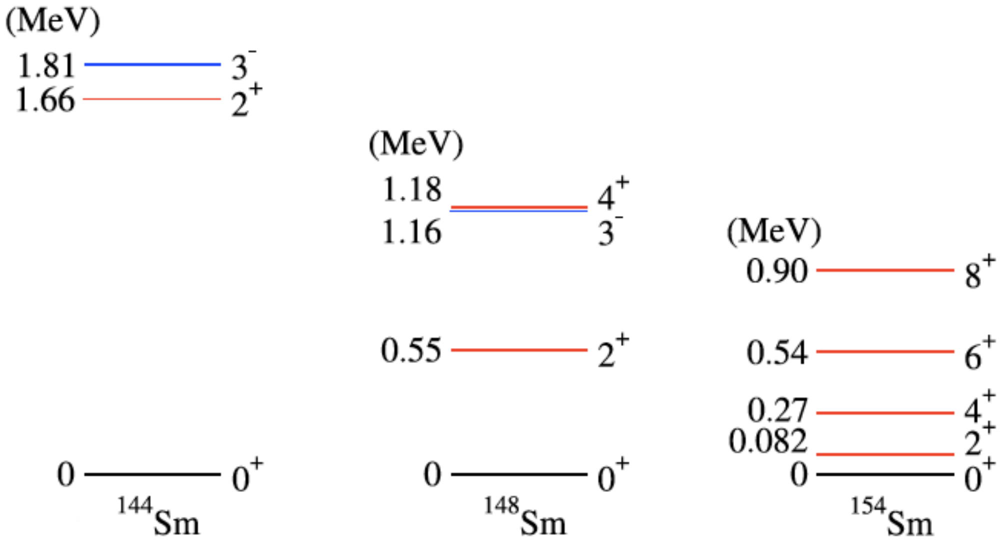

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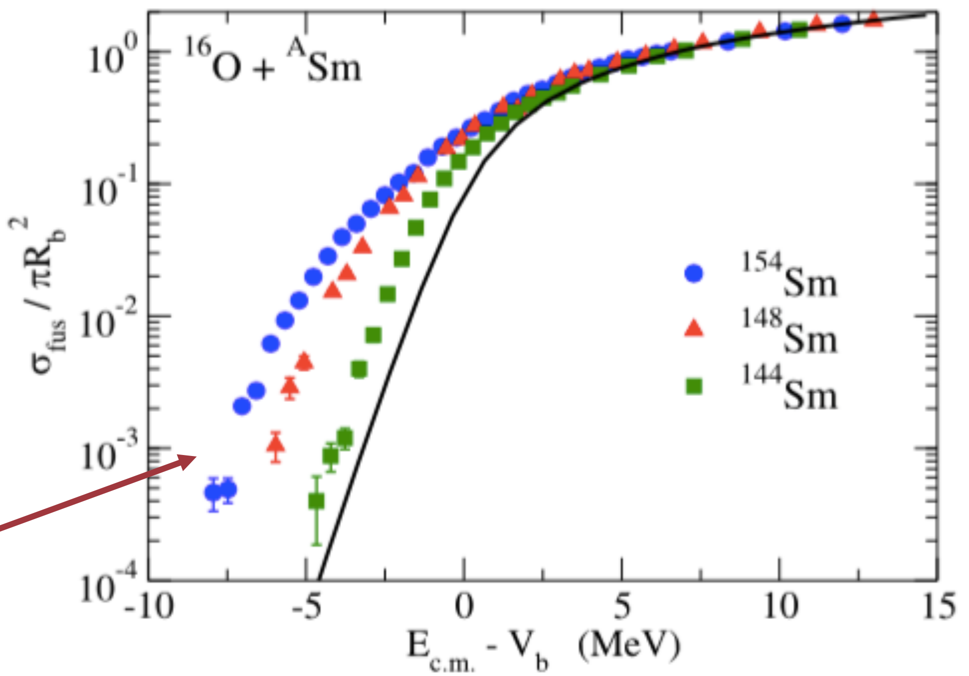

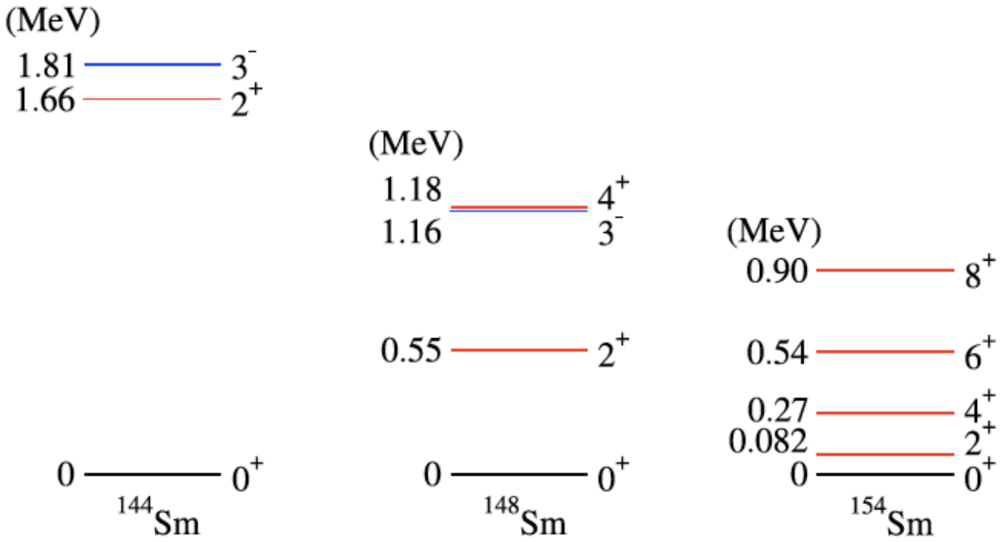

Correlation between the degree of enhancement of the fusion cross sections and the energy of the first 2^+ state

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$$H(r,\xi) = -\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + V(r) + H_0(\xi) + V_{Coup}(r,\xi)$$

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Intrinsic Hamiltonian

Coupling Hamiltonian

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Sudden tunnelling limit

$$H(r,\xi) = -\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + V(r) + H_0(\xi) + V_{Coup}(r,\xi) \implies \sigma_{FUS}(E) = \sum_k w_k \sigma_{FUS}(E;V_k)$$

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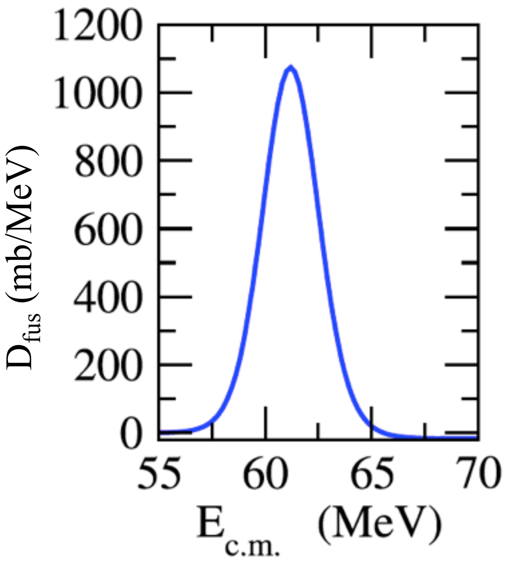

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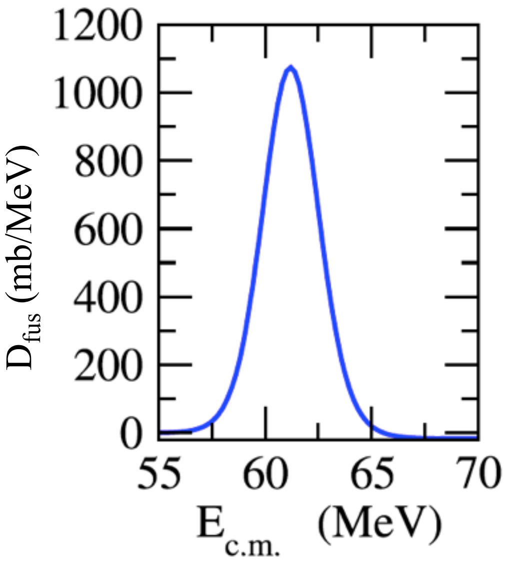
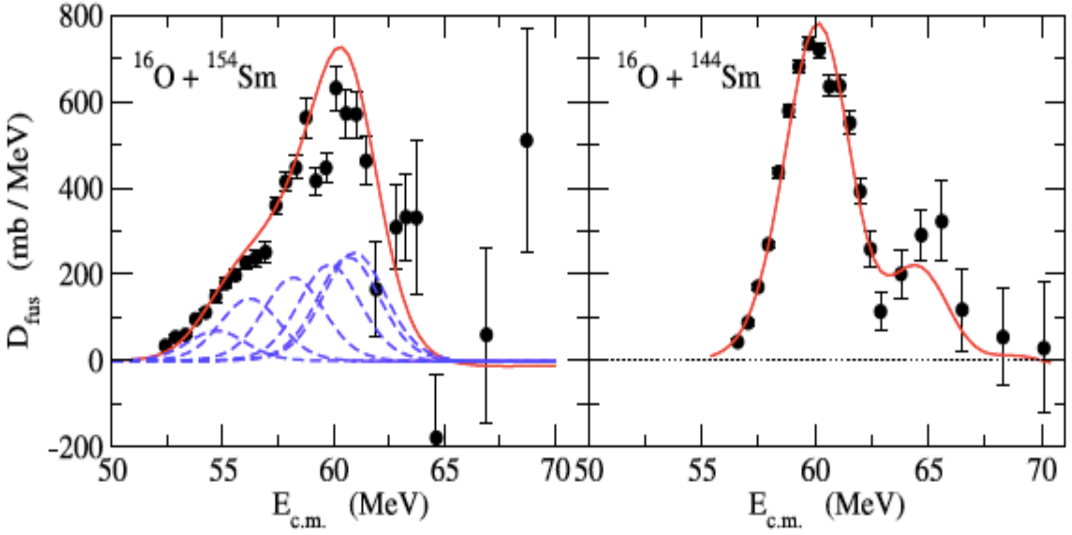


Distribution of barriers due to the channel coupling effects



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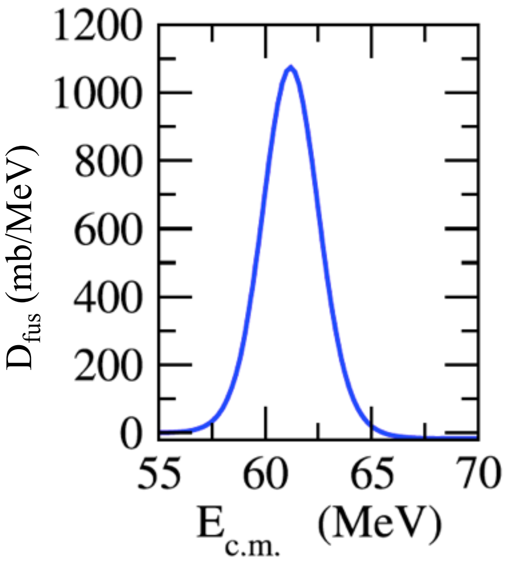

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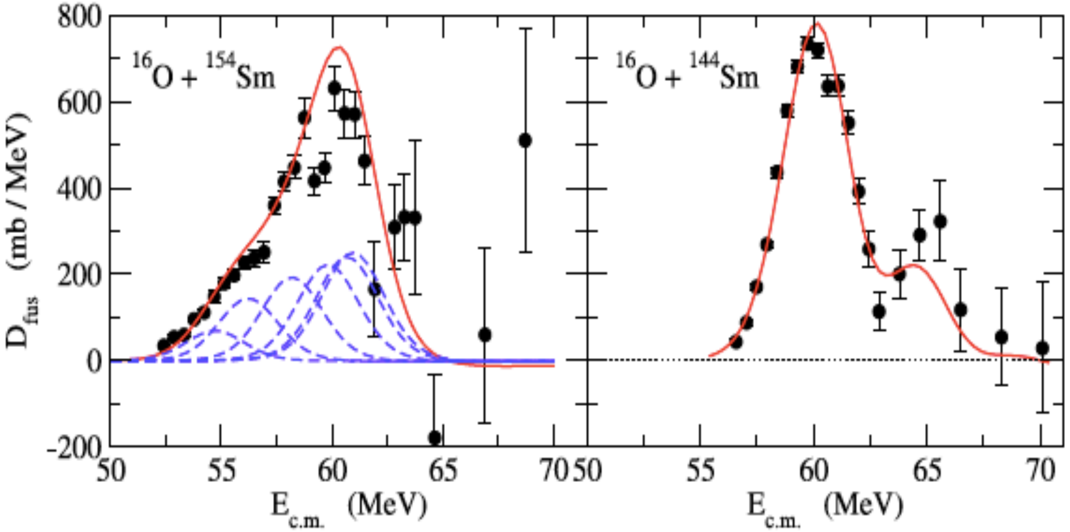

Fingerprint of the structure of the interacting nuclei and the dynamics of the reaction

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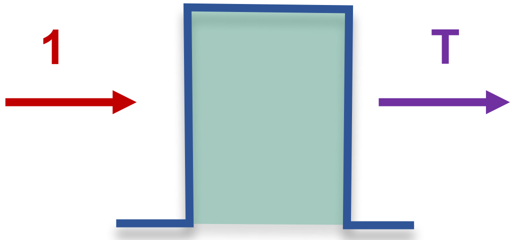
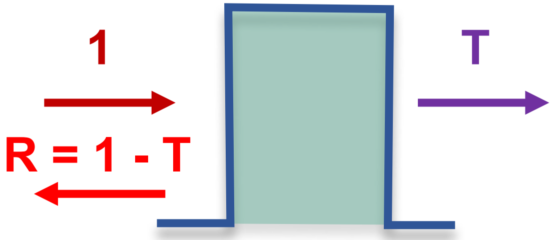


FUSION

$$D_{FUS}(E) = \frac{d^2}{dE^2}(E\sigma_{FUS})$$



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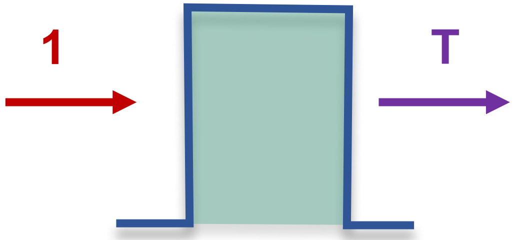

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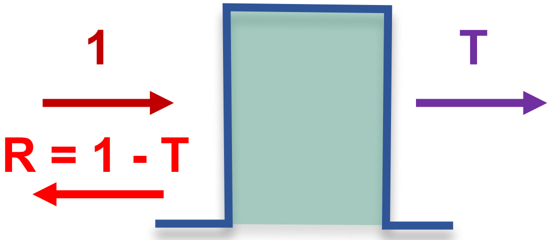

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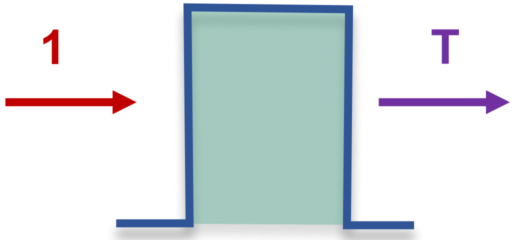

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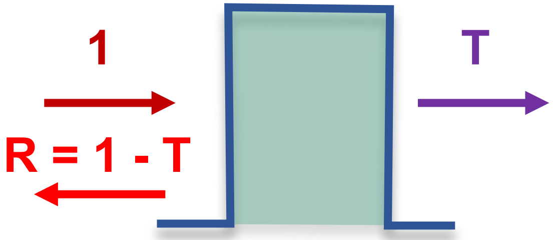

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- $D_{FUS}(E)$: Detection of evaporation residues (ER) at forward angles (**ER separation from residual beam**)
- $D_{QE}(E)$: Detection of quasi-elastic channels at backward angles (**charge-particle detectors**)

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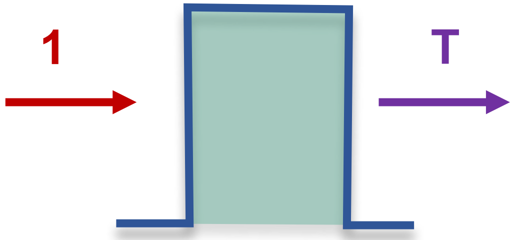

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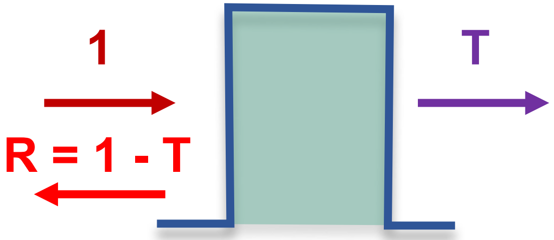

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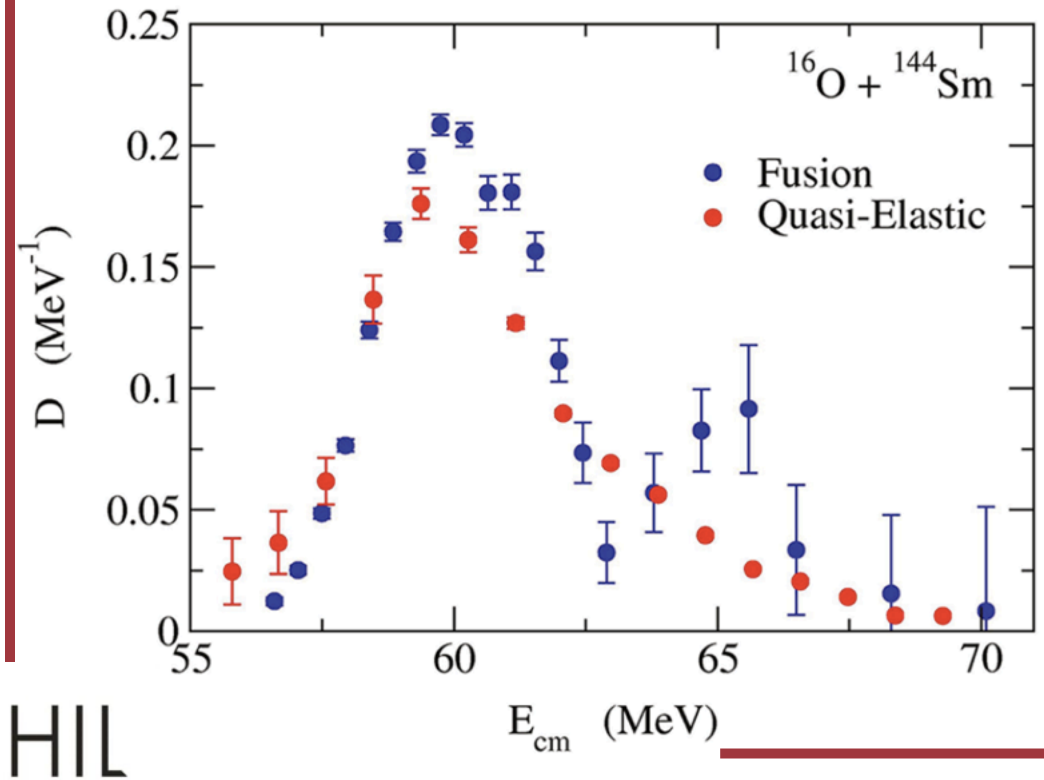

- $D_{FUS}(E)$: Detection of evaporation residues (ER) at forward angles (**ER separation from residual beam**)
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- $D_{QE}(E)$ smaller experimental uncertainties above the Coulomb barrier
- $D_{FUS}(E)$ smaller experimental uncertainties below the Coulomb barrier
- $D_{FUS}(E)$ better resolution

A. Stefanini and G. Montagnoli, Eur. Phys. J. A (2017) **53**

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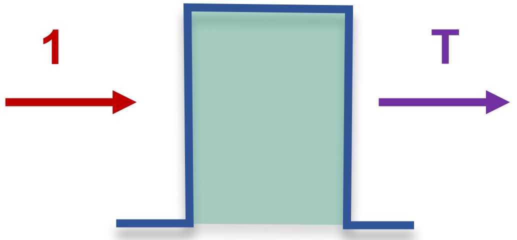

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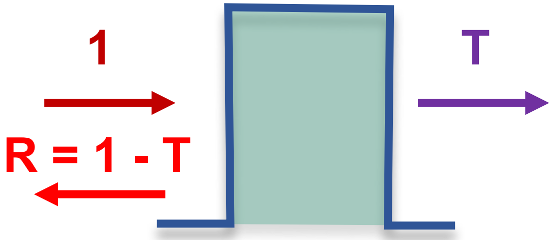

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Theoretically the two approaches are approximatelly **complementary**

Coupled Channels (CC) model takes into account strong collective excitations of the participating nuclei

The role of dissipation by a multitude of **non-collective excitations** and different **transfer channels** is much less understood

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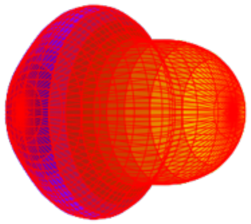
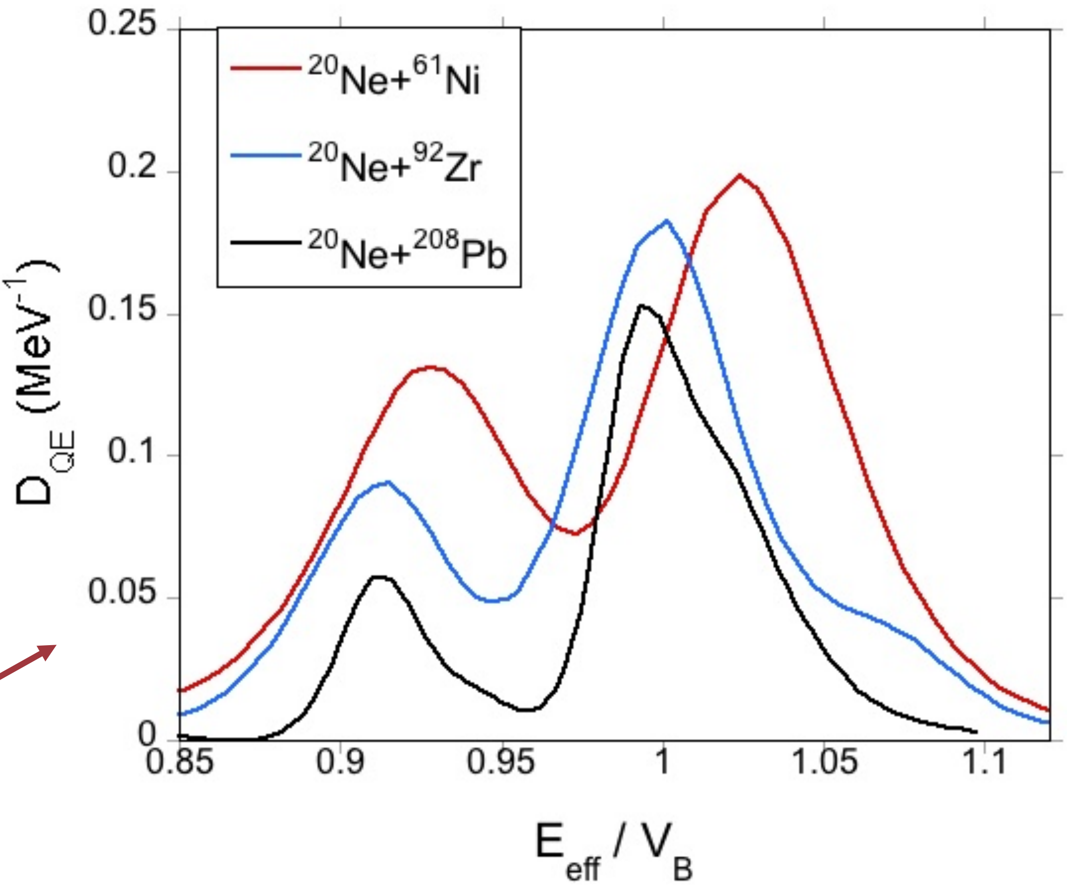
^{20}Ne projectile - strongly deformed nucleus: $\beta_2 = 0.46$, $\beta_3 = 0.39$, $\beta_4 = 0.27$



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



Two peaks structure

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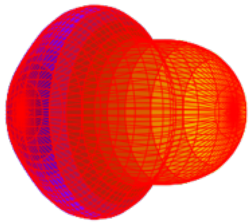
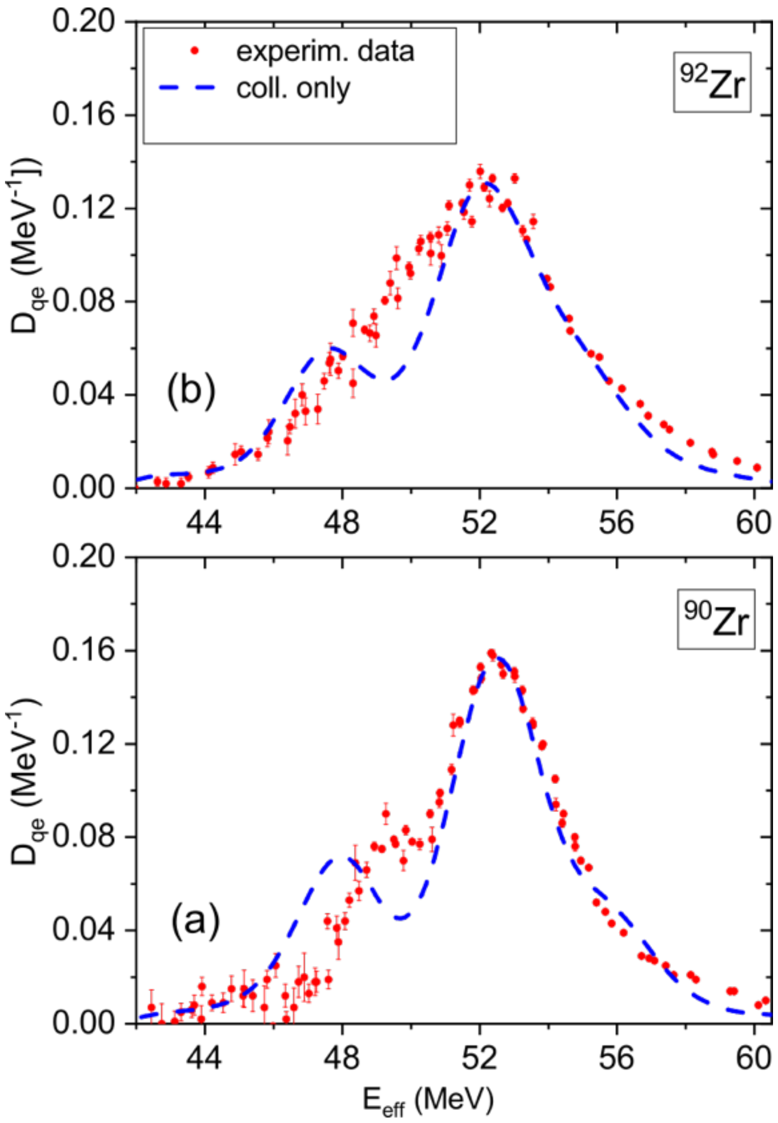


Experimental D_{QE} have much smoother structure in comparison to coupled channels (CC) calculation predictions

Structure disappears for $^{20}Ne + ^{92}Zr$



E. Piasecki et al., Phys. Rev. C 80 (2009) 054613

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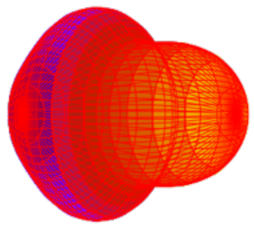

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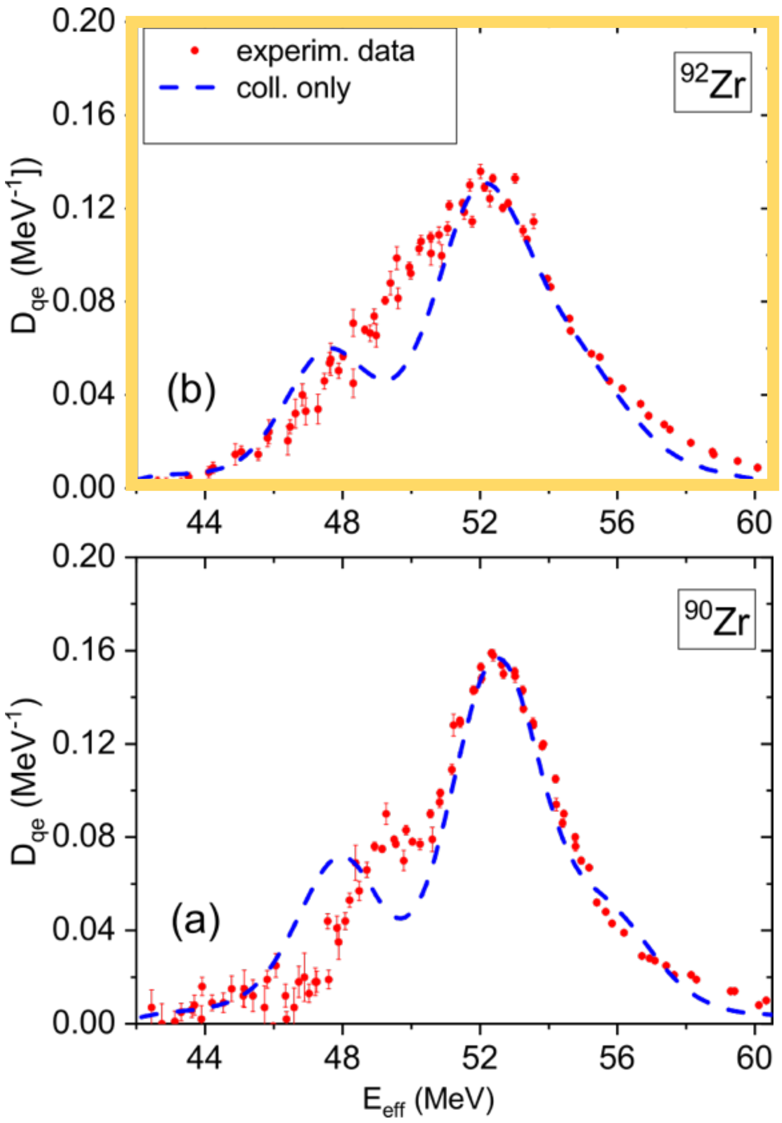

E. Piasecki et al., Phys. Rev. C 80 (2009) 054613

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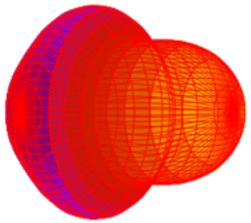
Future plans: fusion

Summary

^{20}Ne projectile - strongly deformed nucleus: $\beta_2 = 0.46$, $\beta_3 = 0.39$, $\beta_4 = 0.27$



Experimental D_{QE} have much smoother structure in comparison to coupled channels (CC) calculation predictions

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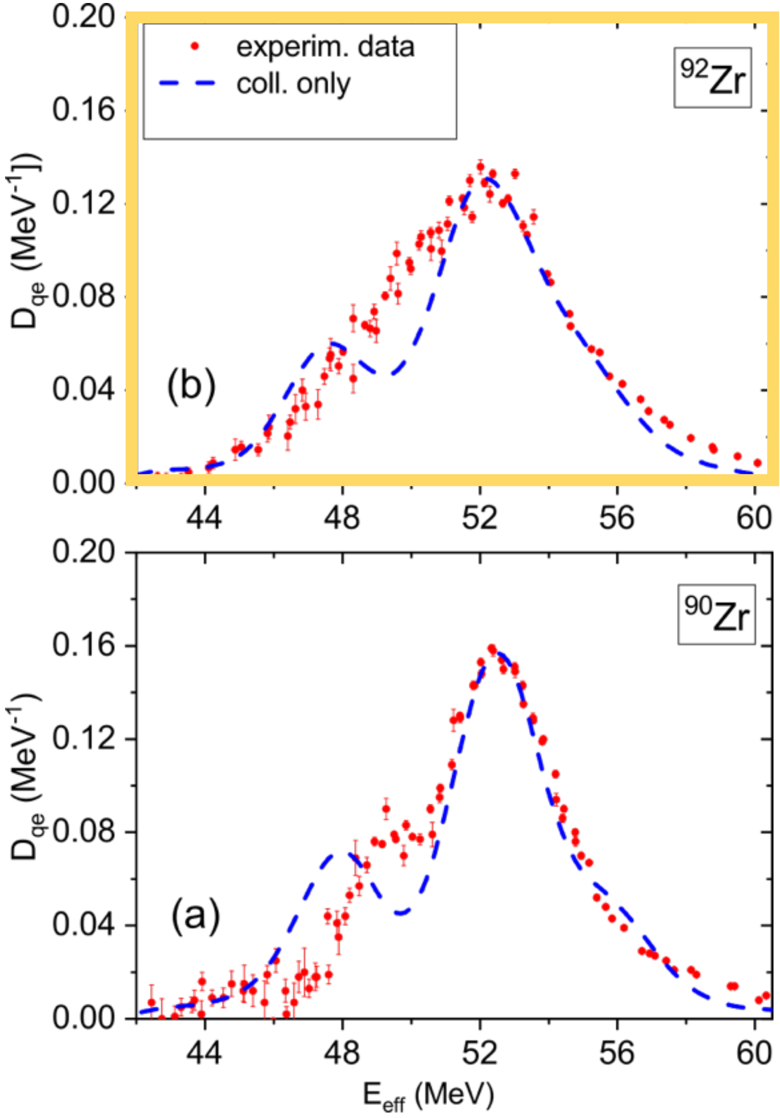
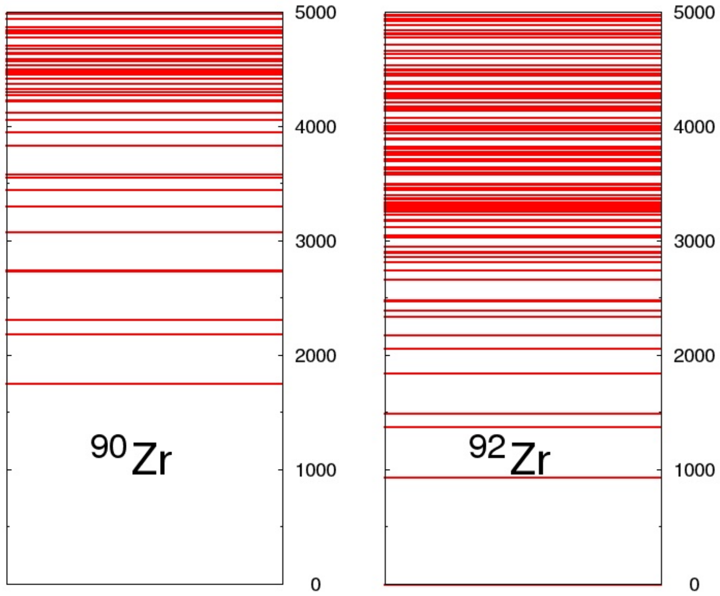


Influence of single particle excitations on the smoothing of the barrier distribution



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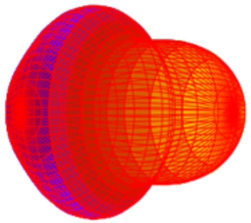

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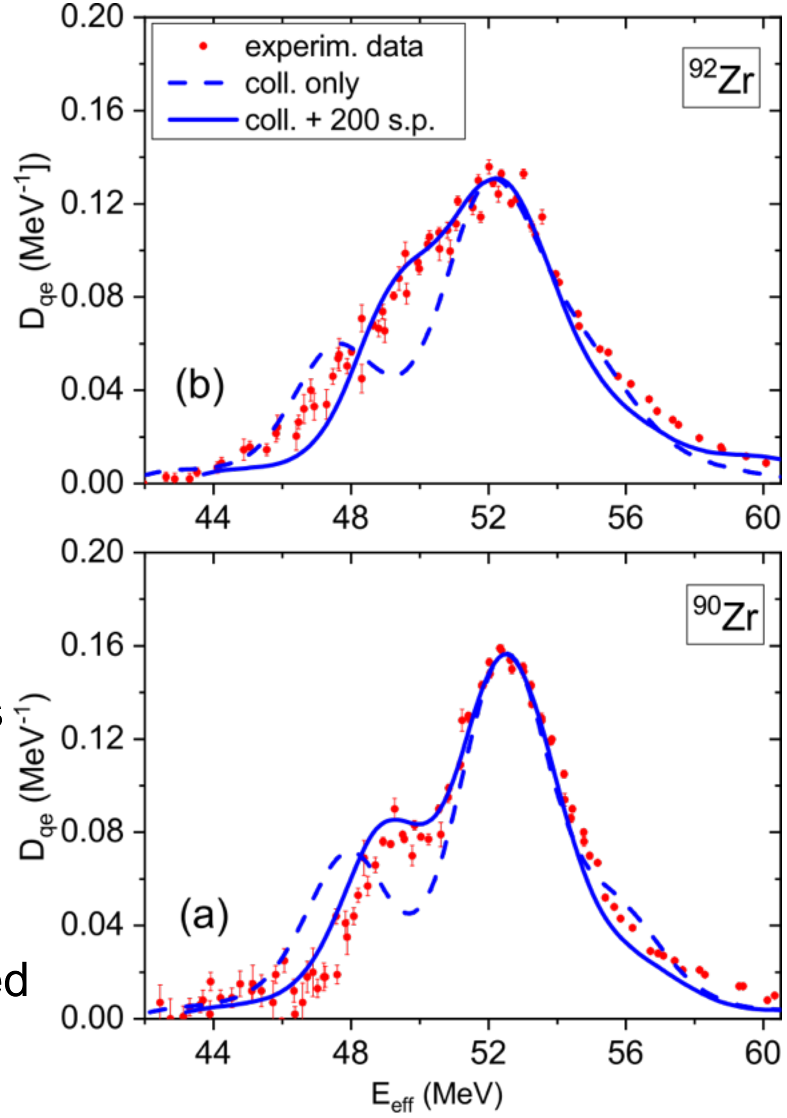
Coupling to noncollective included within CC+RMT model



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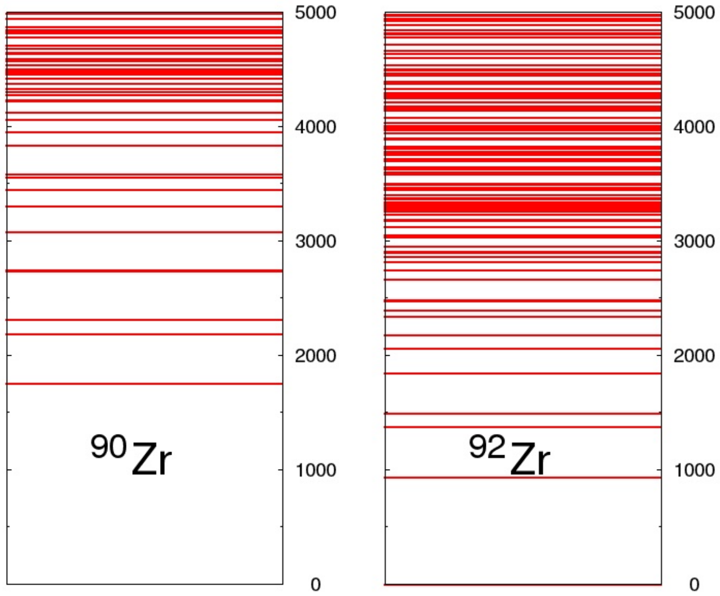

Dissipation due to the coupling of a multitude of noncollective levels

E. Piasecki et al., Phys. Rev. C 100 (2019) 014616 S. Yusa et al., Phys. Rev. C 82 (2010) 024606 E. Piasecki et al., Phys. Rev. C 80 (2009) 054613

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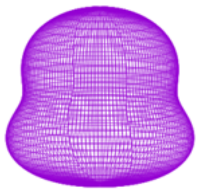
Future plans: fusion

Summary

^{24}Mg projectile - also deformed nucleus (6 α particles) β_2 = 0.59, β_3 = 0.23, β_4 = -0.03



A. Trzcińska et al., Phys. Rev. , C 102 (2020) 034617

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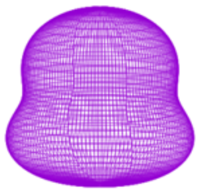

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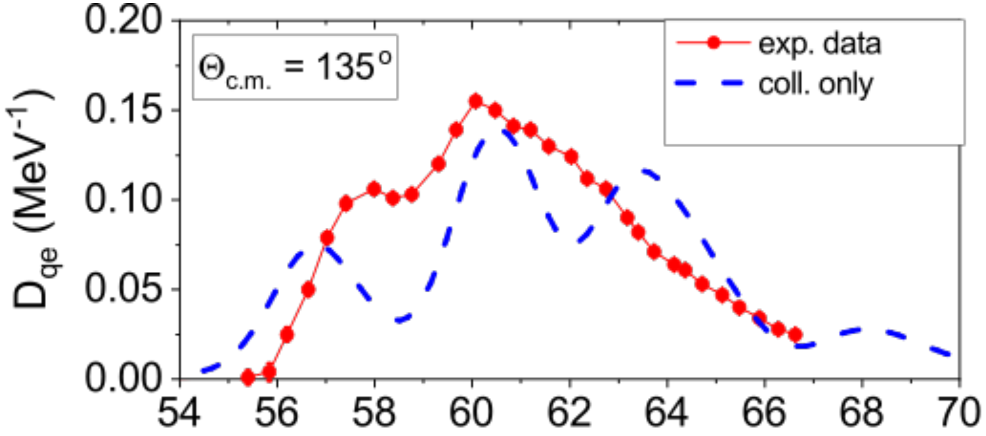
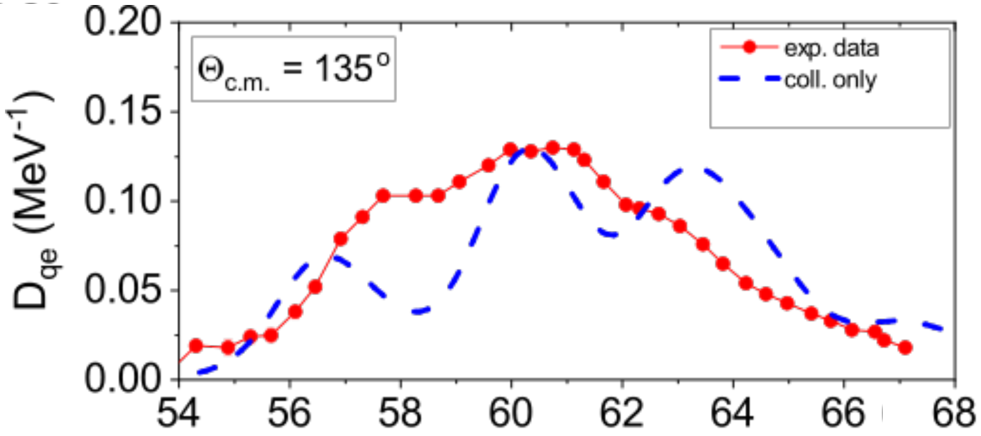
$^{24}Mg+^{90}Zr$



$^{24}Mg+^{92}Zr$



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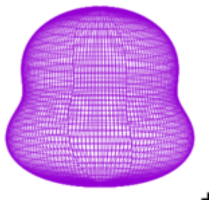
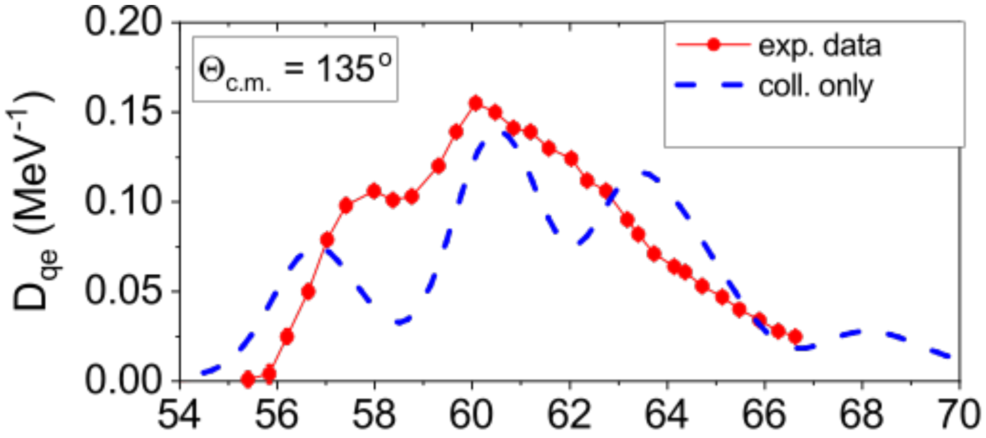


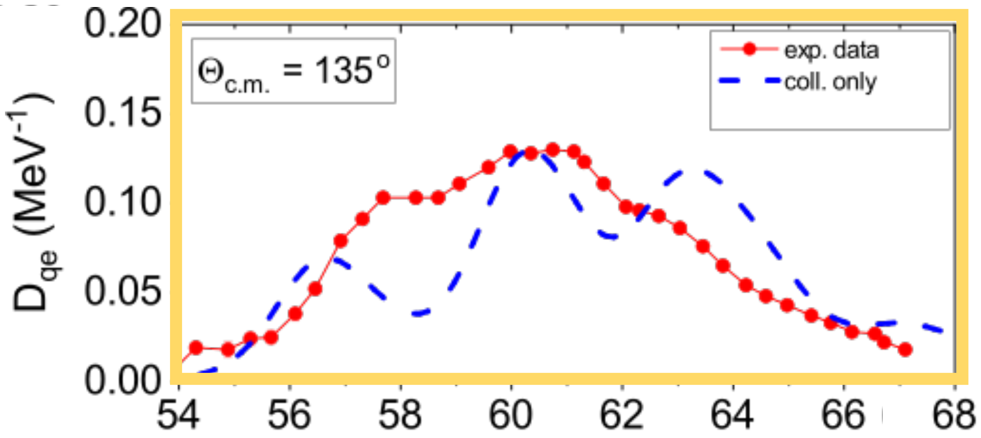
Experimental D_{QE} have much smoothed structure in comparison to CC calculations predictions

Structure almost disappears for $^{24}Mg + ^{92}Zr$

$^{24}Mg+^{90}Zr$



$^{24}Mg+^{92}Zr$



A. Trzcińska et al., Phys. Rev. , C 102 (2020) 034617

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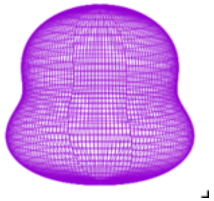

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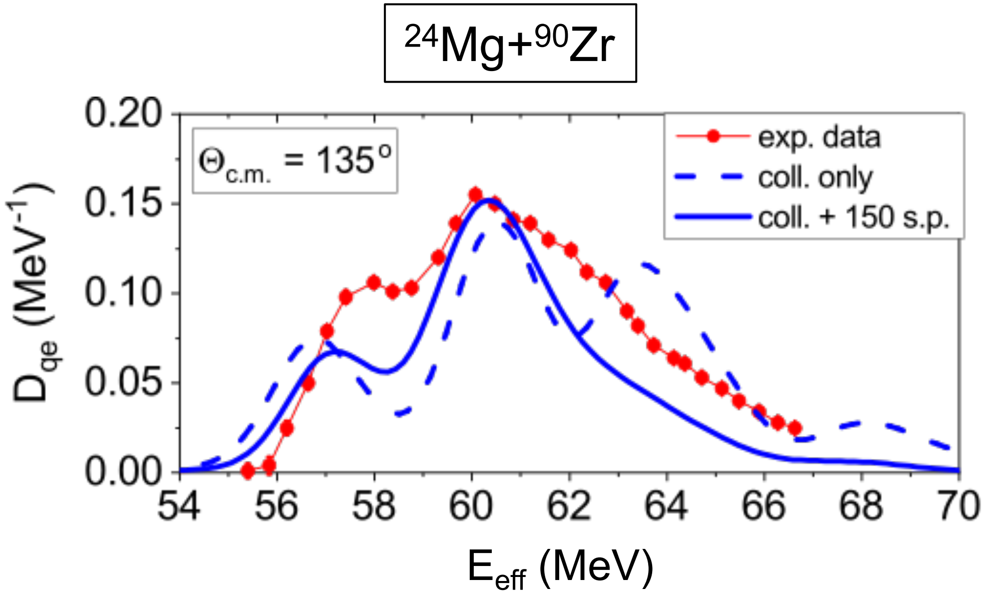

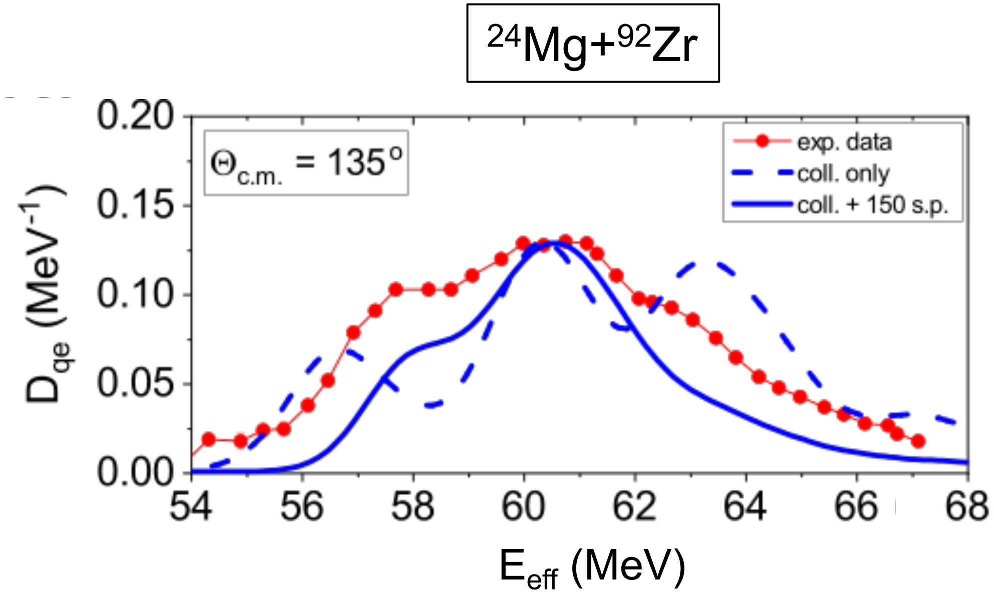

Effects of dissipation due to the coupling of a multitude of noncollective levels

A. Trzcińska et al., Phys. Rev. , C 102 (2020) 034617

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Future plans: fusion

Summary

Influence of transfer channels

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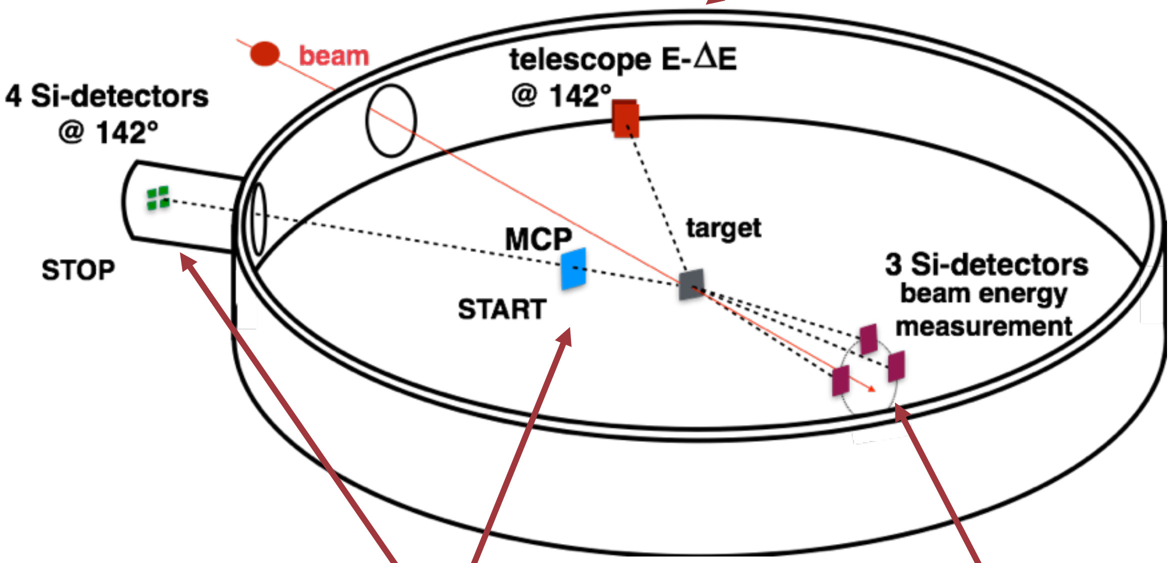
Future plans: fusion
Summary

Influence of transfer channels

ICARE scattering chamber at HIL

Product identification in **Z**
E – ΔE



Product identification in **mass**
E – ToF

Beam energy and cross-section normalization

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Future plans: fusion

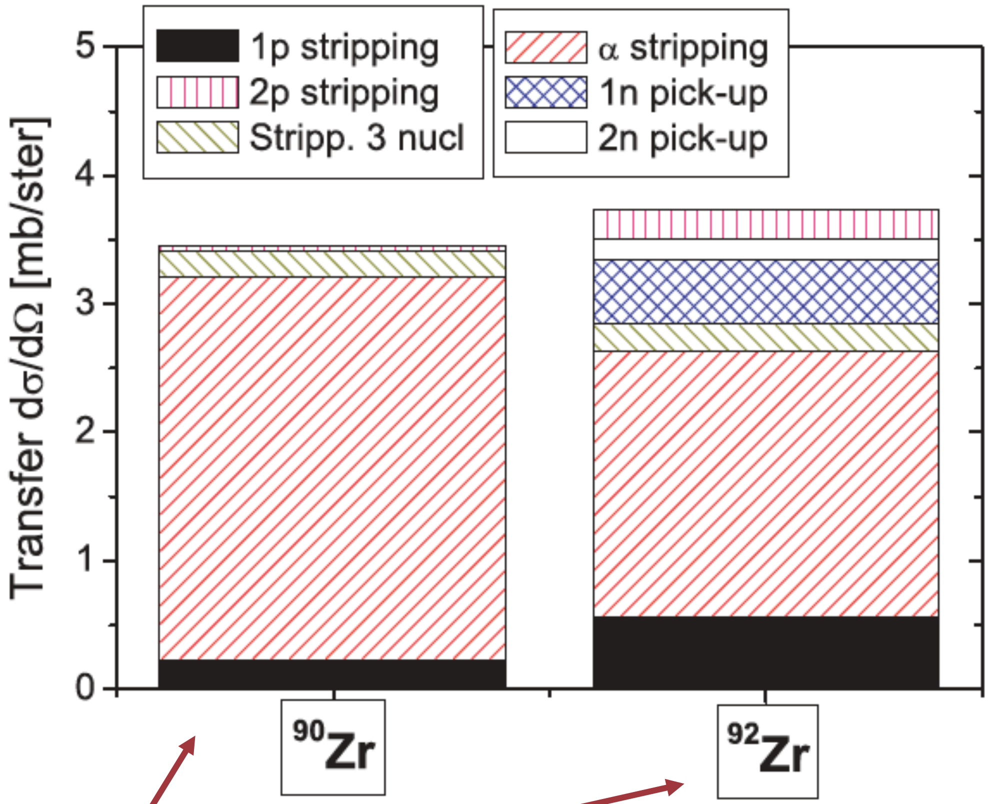
Summary

Influence of transfer channels →

Transfer cross-sections measurements of ^{20}Ne+^{90,92}Zr

ICARE scattering chamber at HIL

Transfers can play a significant role in the shape of barrier distributions, **but** in this case probably other mechanism is responsible for the very marked difference between the barrier distributions for the ^{90,92}Zr



Total transfer cross sections for the ^{90}Zr and ^{92}Zr targets are essentially the same (6% of the total quasielastic scattering)

E. Piasecki et al., Phys. Rev. , C 80 (2009) 054613

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Transfer measurement of ^{20}Ne + ^{92,94,95}Mo

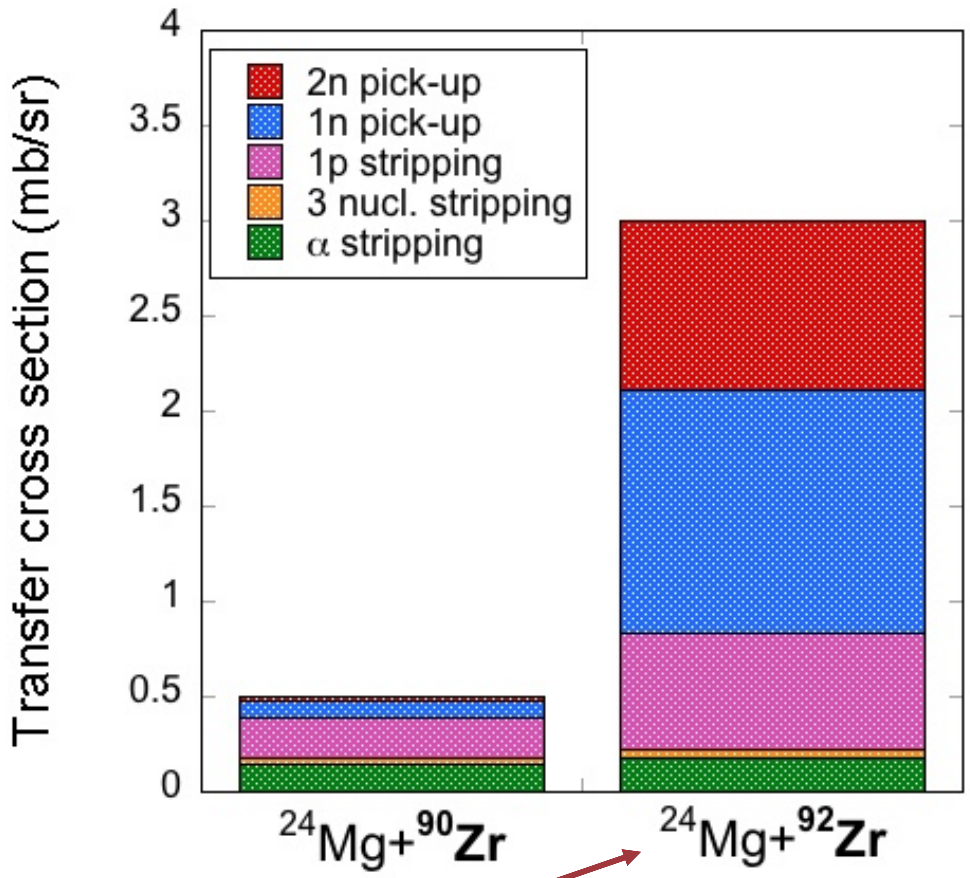
Future plans: fusion

Summary

Influence of transfer channels → **Transfer cross-sections measurements of ^{24}Mg+^{90,92}Zr**

ICARE scattering chamber at HIL

The smoothing of the D_{QE} shape in the ^{24}Mg+^{92}Zr might be caused by transfer reaction channels



Higher total transfer cross section for ^{24}Mg+^{92}Zr system

D. Wójcik et al., Acta Phys. Pol. , B 49 (2018), 387

Near barrier fusion reactions

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Future plans: fusion

Summary

Dissipation due to projectile - target transfers of light particles.

Standard CCQEL and CCFULL codes	Upgraded CCQEL and CCFULL codes
• Transfer coupling form factor F_{tr} * dV/dr, where F_{tr} is fixed for a single Q_{gg} value	• Transfer coupling form factor F_{tr} * dV/dr, where $F_{tr}(Q)$ is extracted from experimental Q-distributions
• Only one transfer reaction included → Two neutrons transfer is the dominant channel	• Several transfer reactions included

Near barrier fusion reactions

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Future plans: fusion

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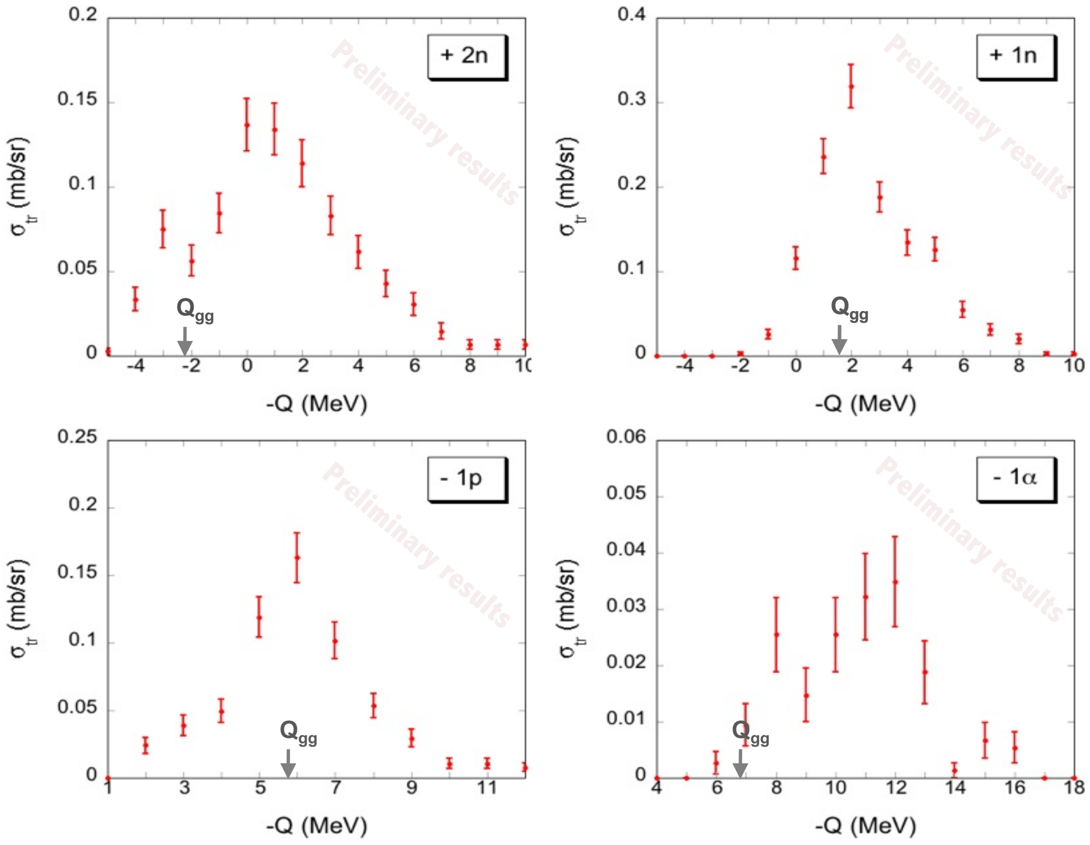
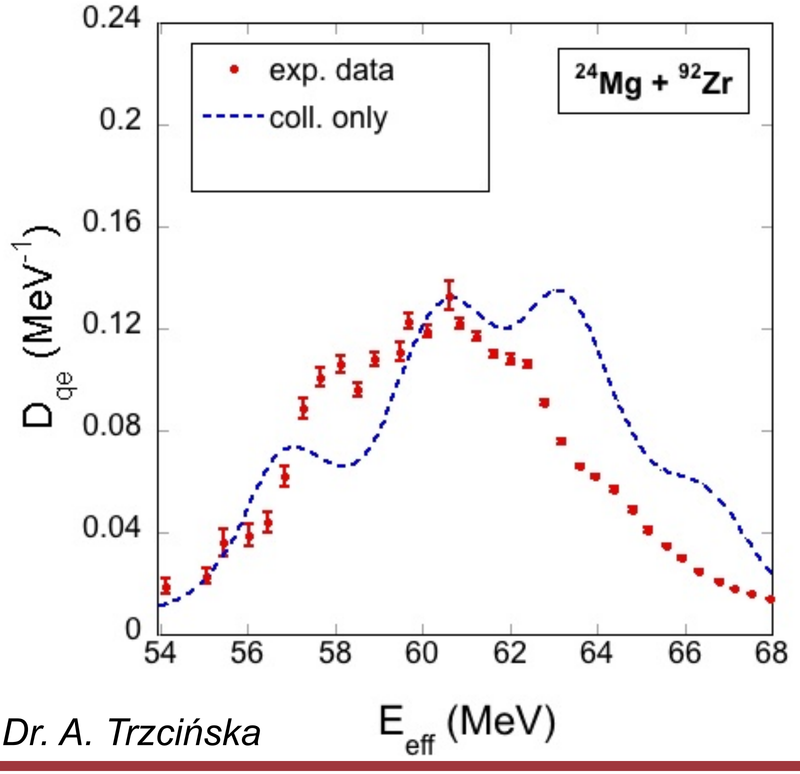
Dissipation due to projectile - target transfers of light particles.

Upgraded CCQEL and CCFULL codes

Upgraded code applied to the $^{24}Mg+^{92}Zr$ system



- Transfer coupling form factor F_{tr} * dV/dr, where $F_{tr}(Q)$ is extracted from experimental Q-distributions
- Several transfer reactions included



Courtesy of Dr. A. Trzcińska

Near barrier fusion reactions

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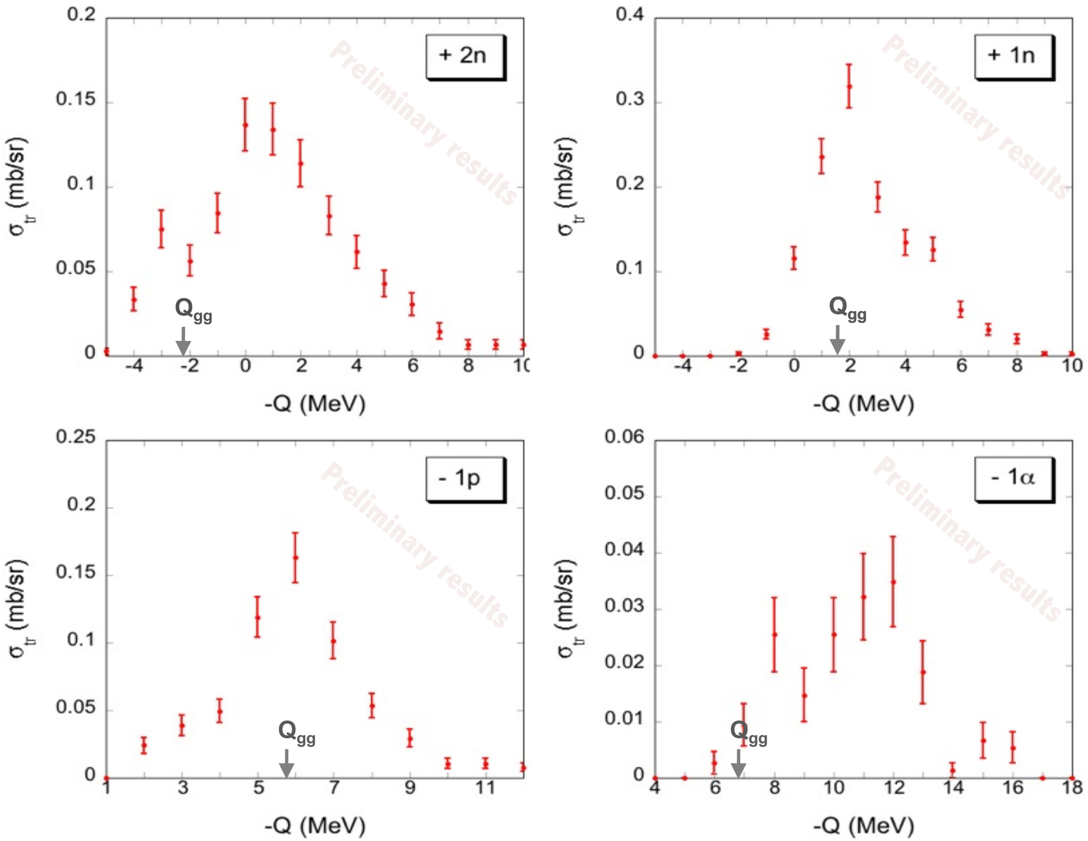

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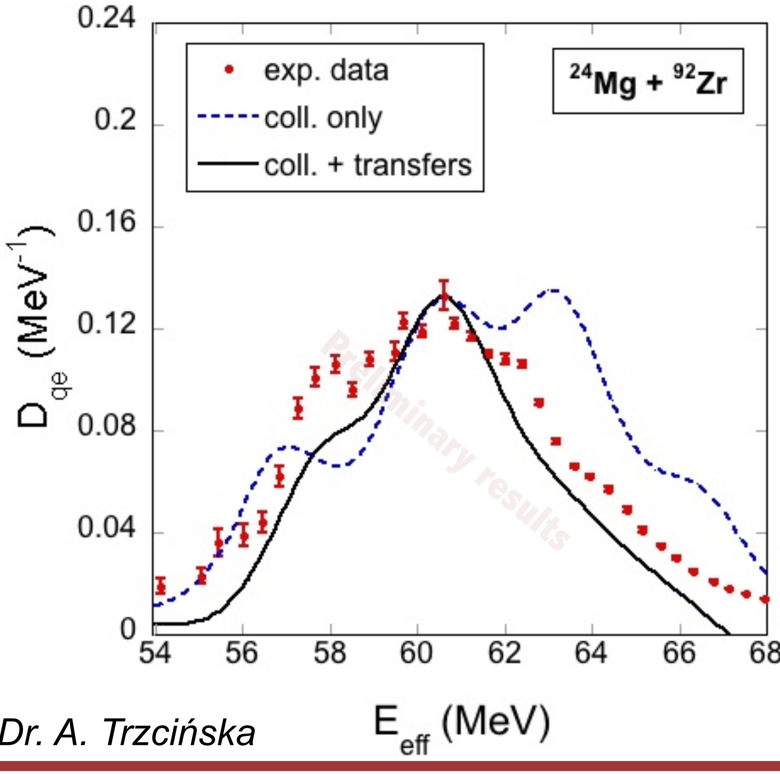

Courtesy of Dr. A. Trzcińska

HIL Heavy Ion Laboratory

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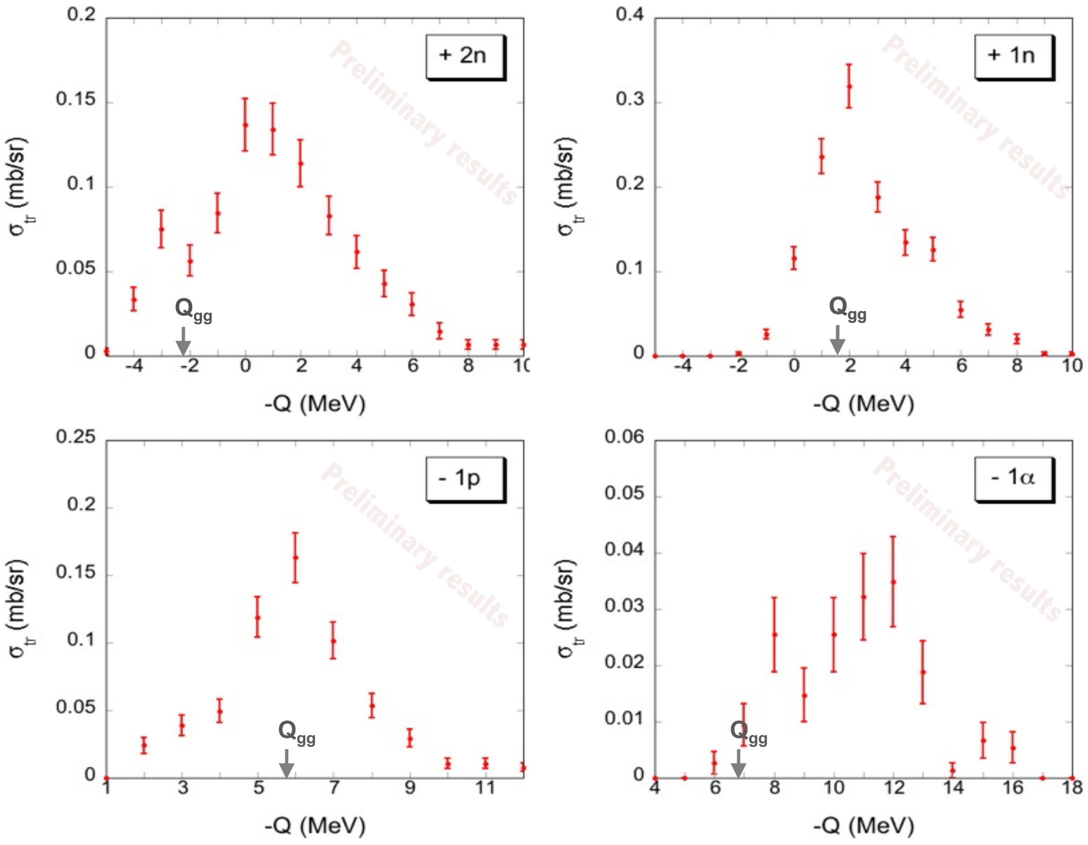
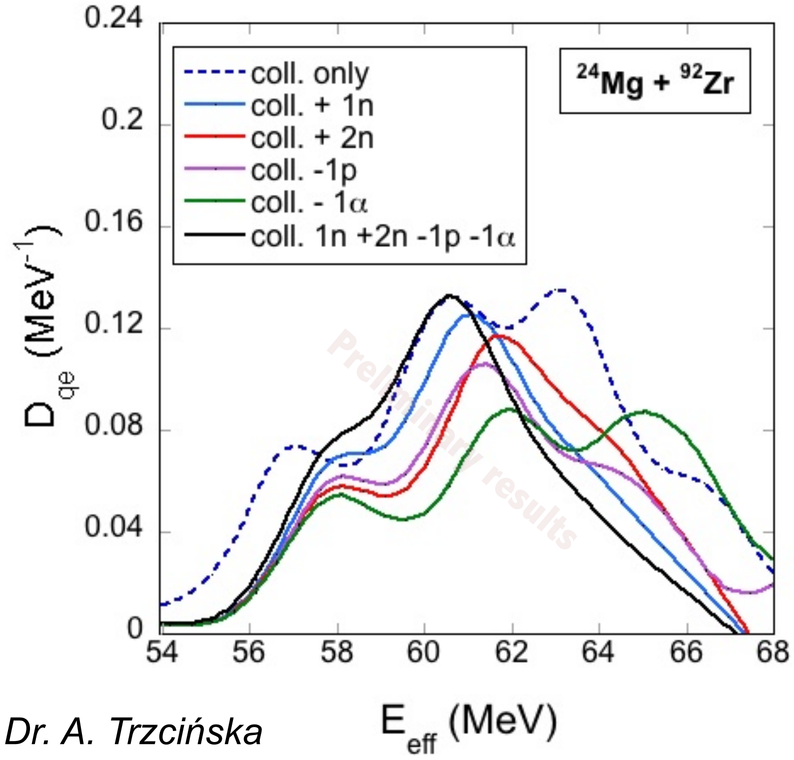


Smoothing dominated by **1n** transfer

- Transfer coupling form factor F_{tr} * dV/dr, where $F_{tr}(Q)$ is extracted from experimental Q-distributions
- Several transfer reactions included



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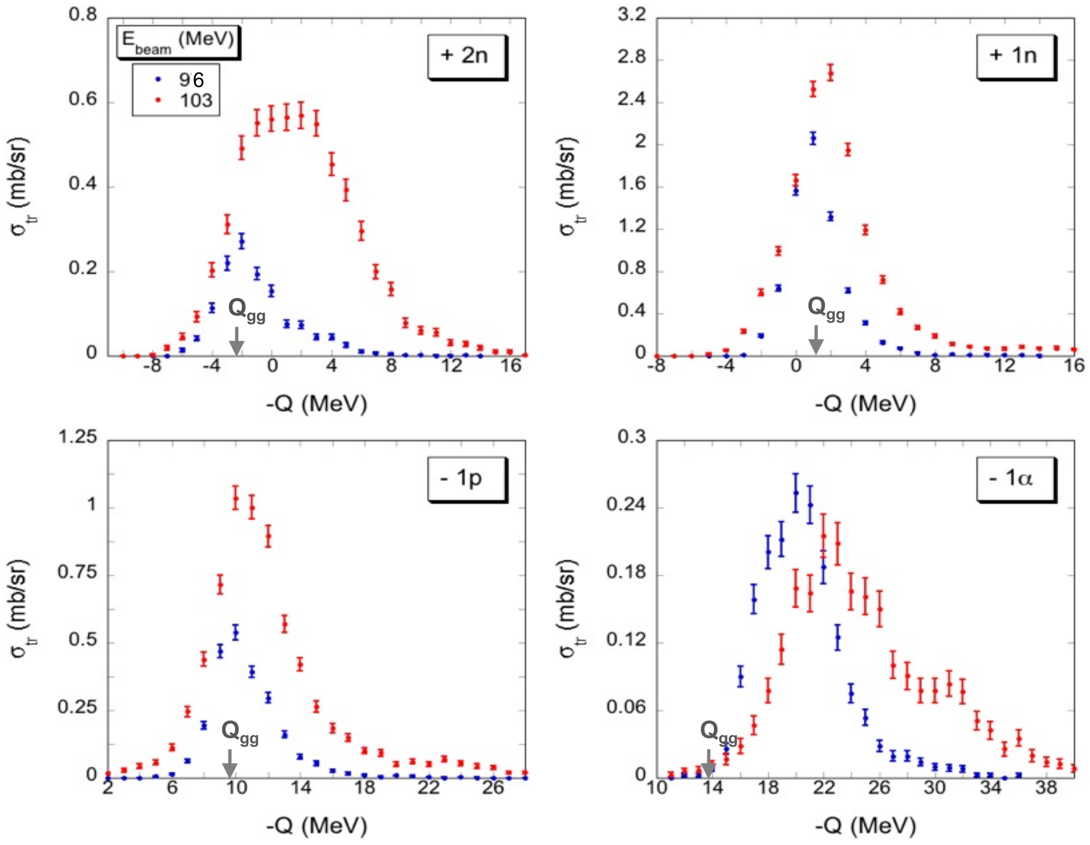
Future plans: fusion

Summary

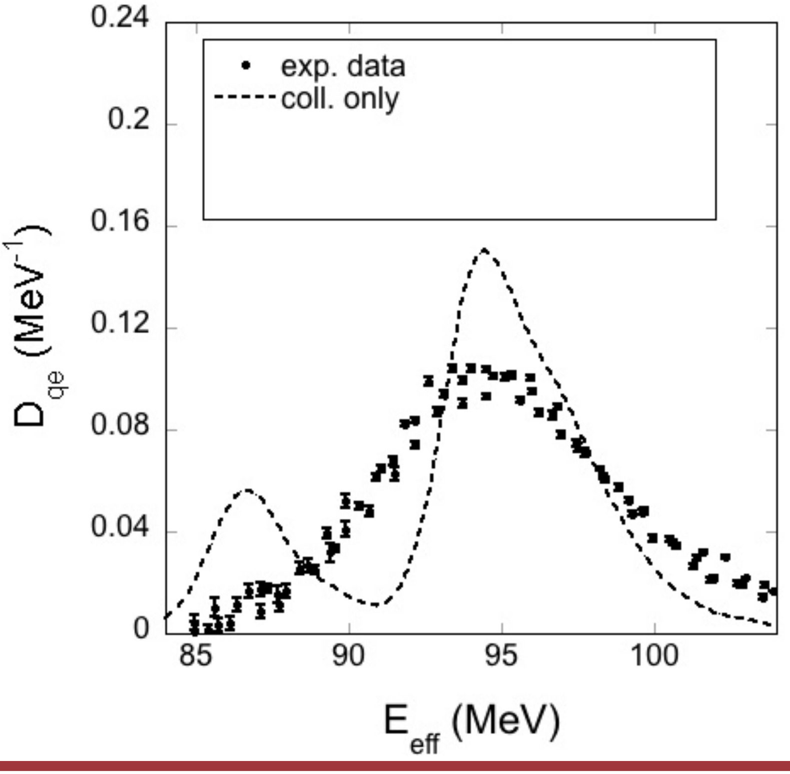
Dissipation due to projectile - target transfers of light particles.

Upgraded CCQEL and CCFULL codes

Upgraded code applied to the $^{20}Ne+^{208}Pb$ system



- Transfer coupling form factor F_{tr} * dV/dr, where $F_{tr}(Q)$ is extracted from experimental Q-distributions
- Several transfer reactions included



Dissipation due to projectile - target transfers of light particles.

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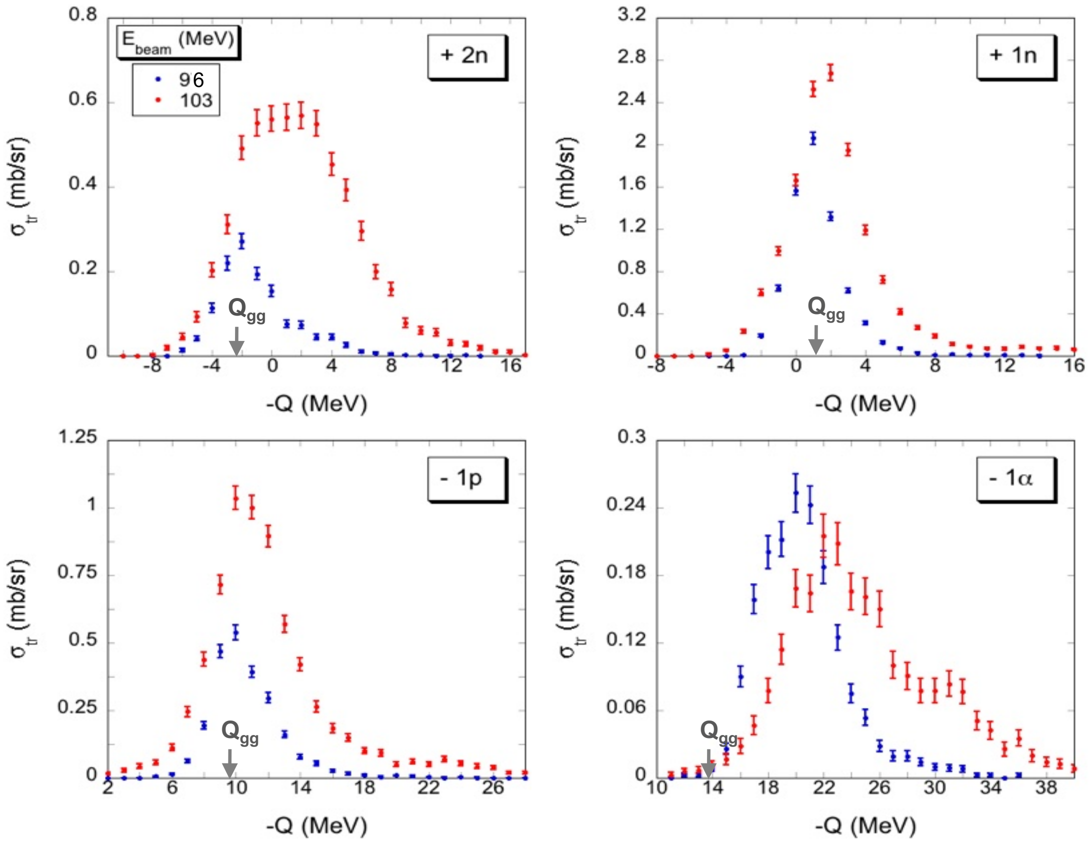

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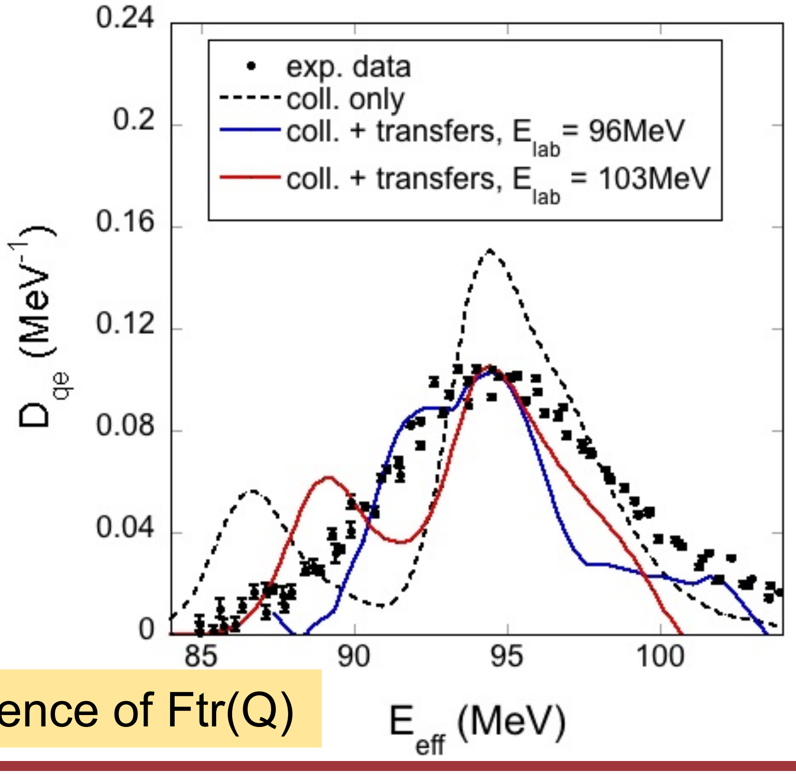

Q-distributions depend on energy → Beam energy dependence of Ftr(Q)

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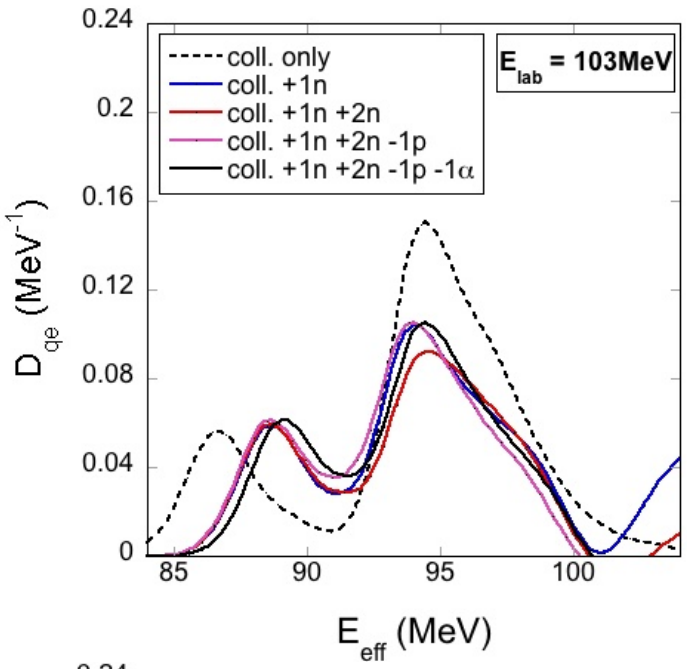

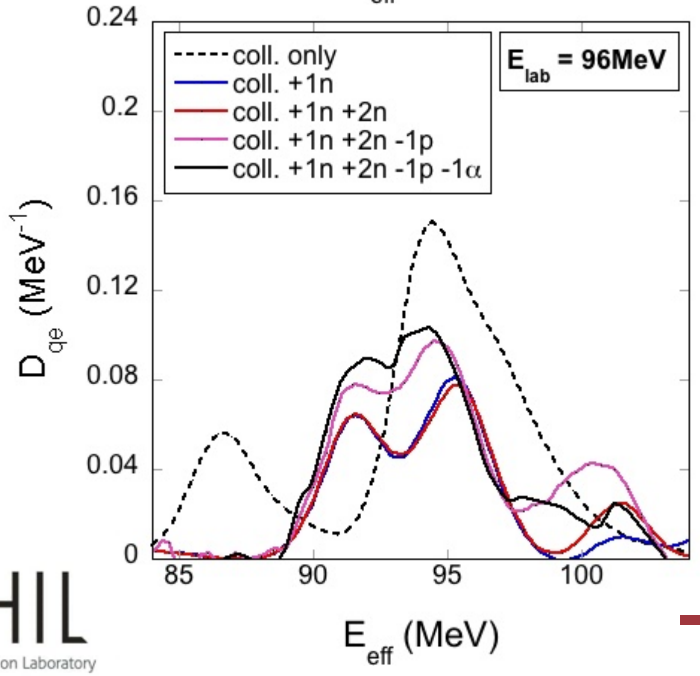

Smoothing dominated by 1n transfer

Smoothing dominated by 1n and 1p transfers

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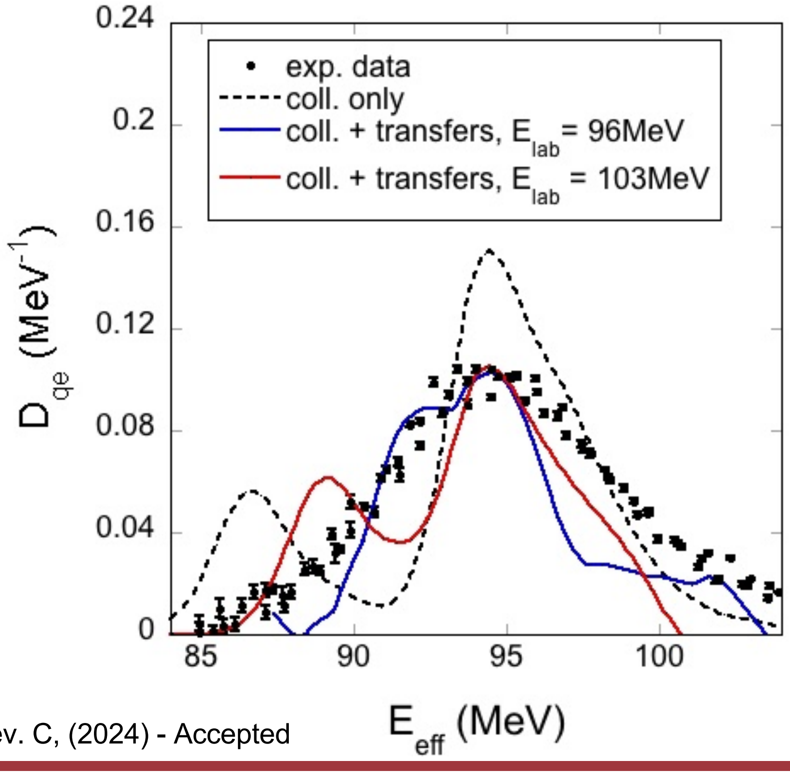

G. Colucci et al., Phys. Rev. C, (2024) - Accepted

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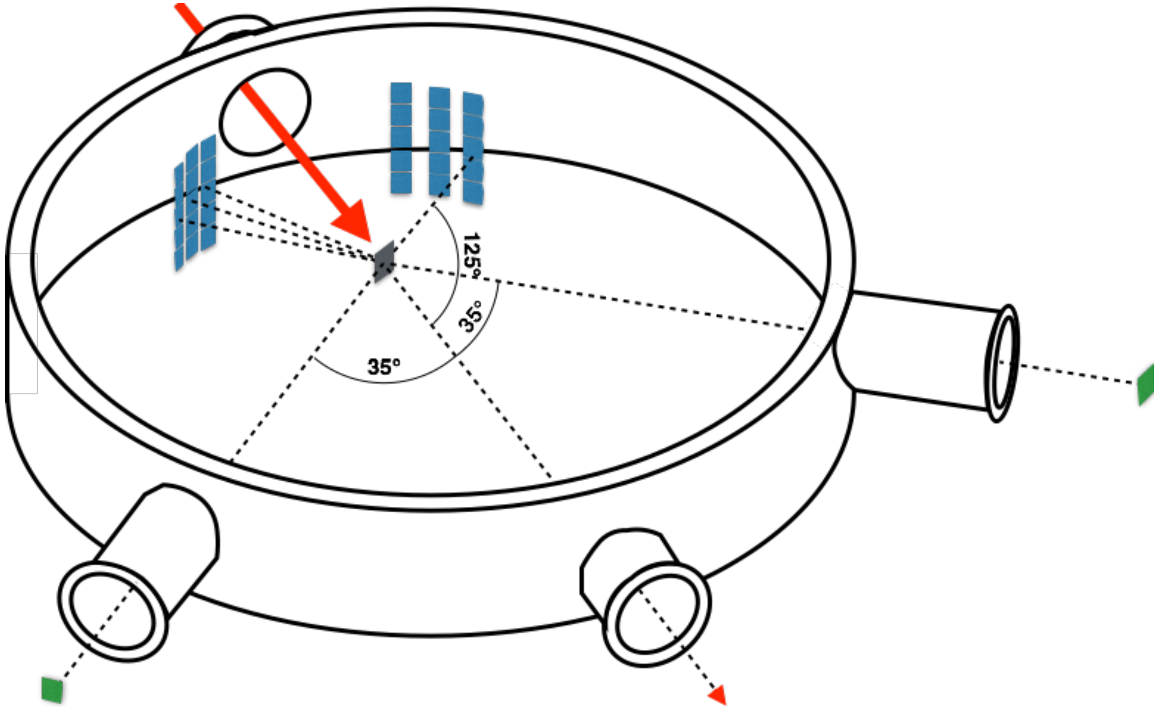
Future plans: fusion

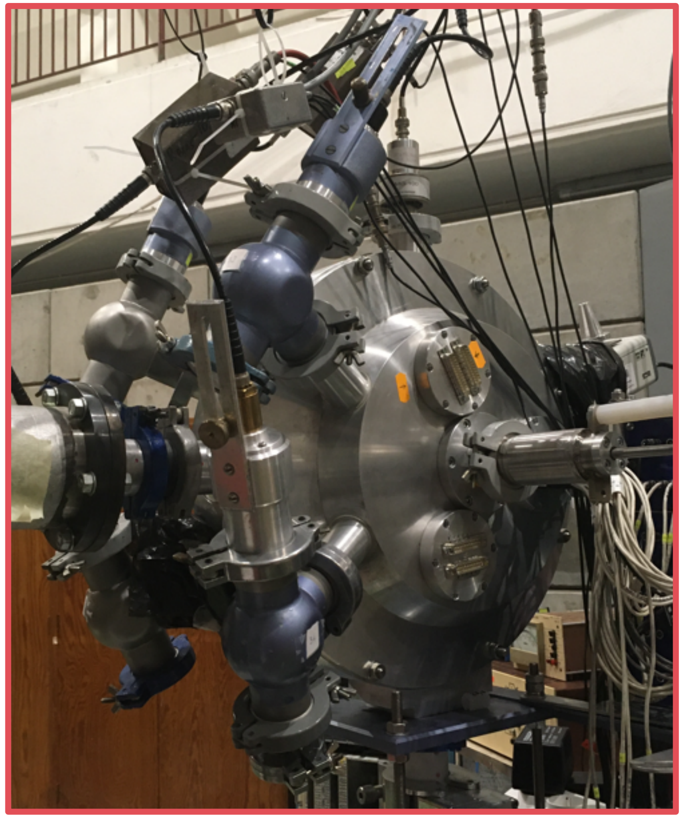
Summary

Quasielastic barrier distribution of $^{20}Ne+^{92,94,95}Mo$

CUDAC (Coulomb Universal Detector Array Chamber) at HIL

- 30 PIN diodes (1cmx1cm) at the backward angles of 125°, 135°, 145°
- 4 PIN diodes the forward angles of 35°





- $^{92,94,95}MoO_3$ targets of ~150 μg/cm² thickness (40 μg/cm² C backing);
- E_{lab} = 65 MeV, 70 MeV and 73 MeV;
- Ni and Au degraders for smaller energy steps.

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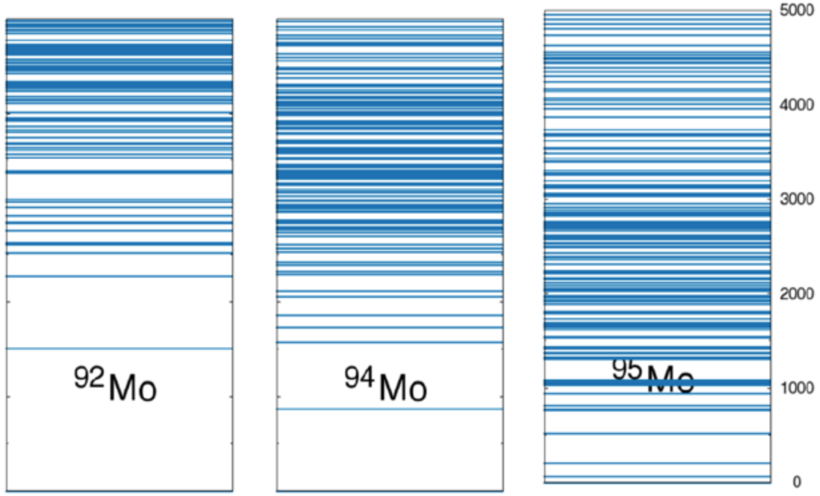

Increasing of dissipation in a "controlled" way: observing the influence of increasing level density on D_{QE}

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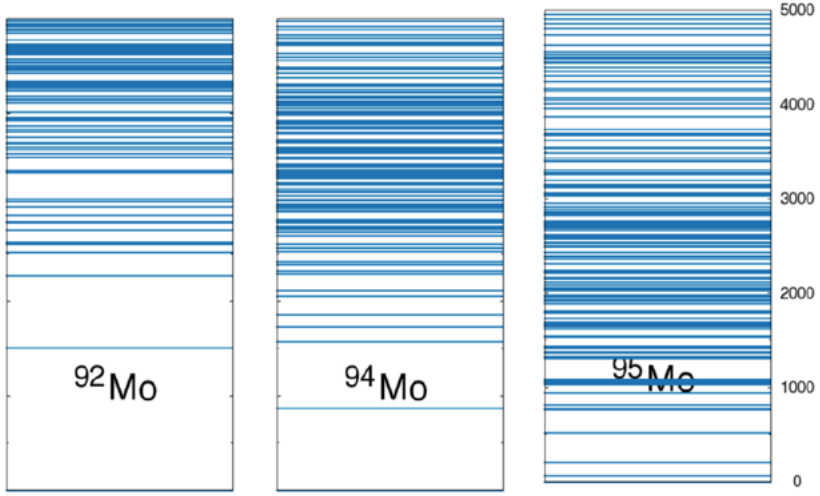
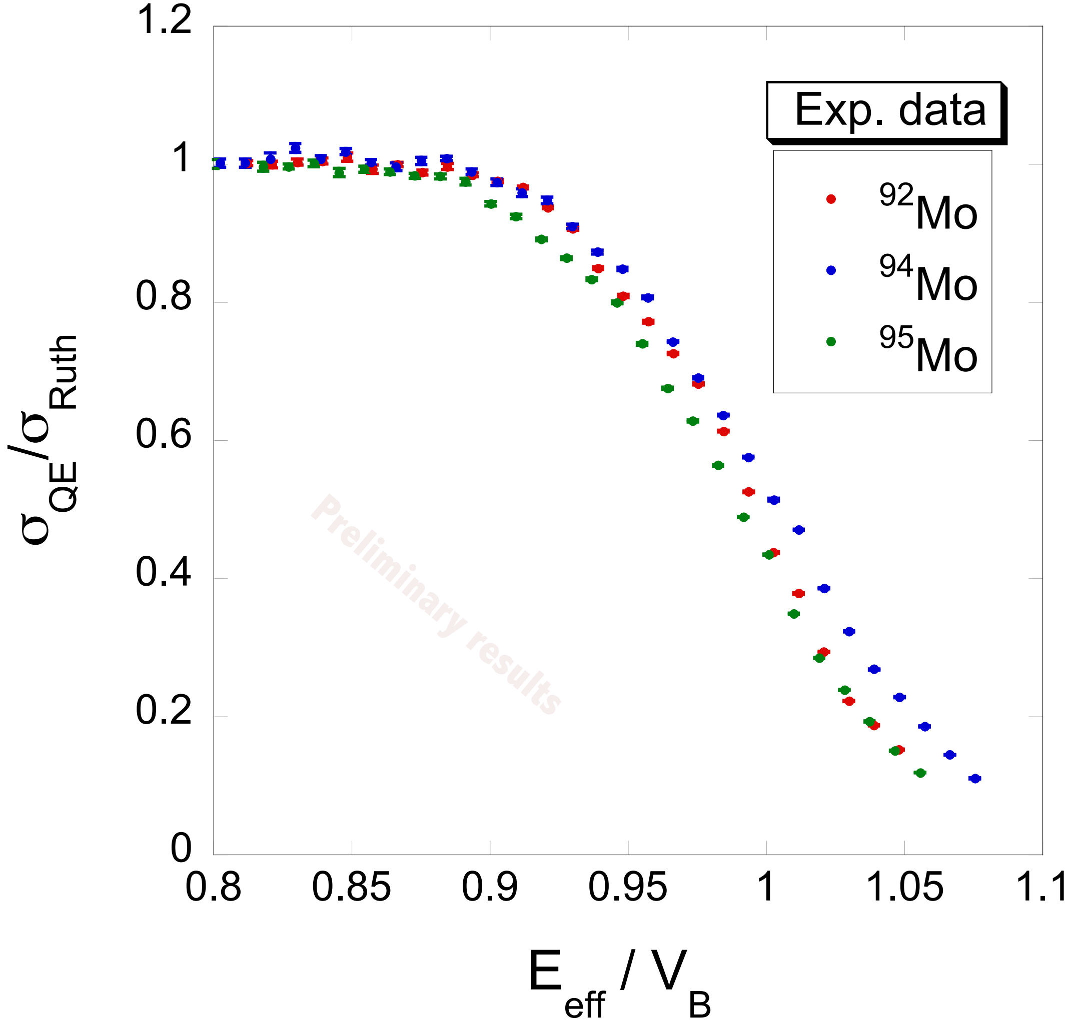
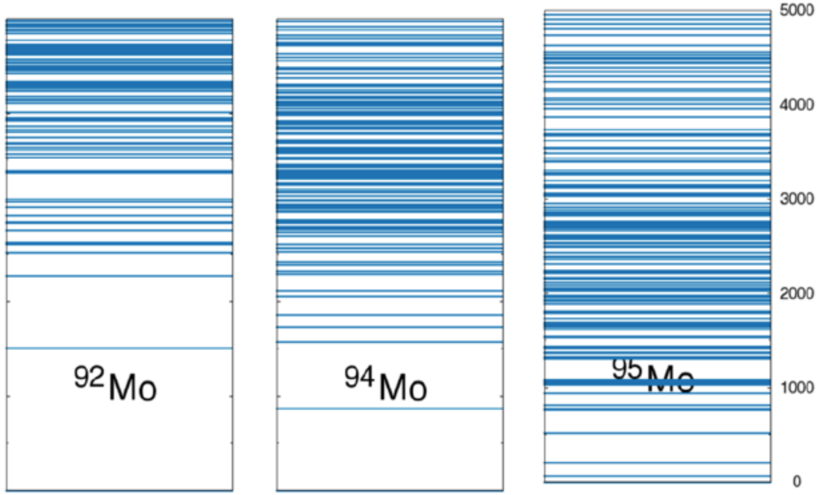


Increasing of dissipation in a "controlled" way: observing the influence of increasing level density on D_{QE}



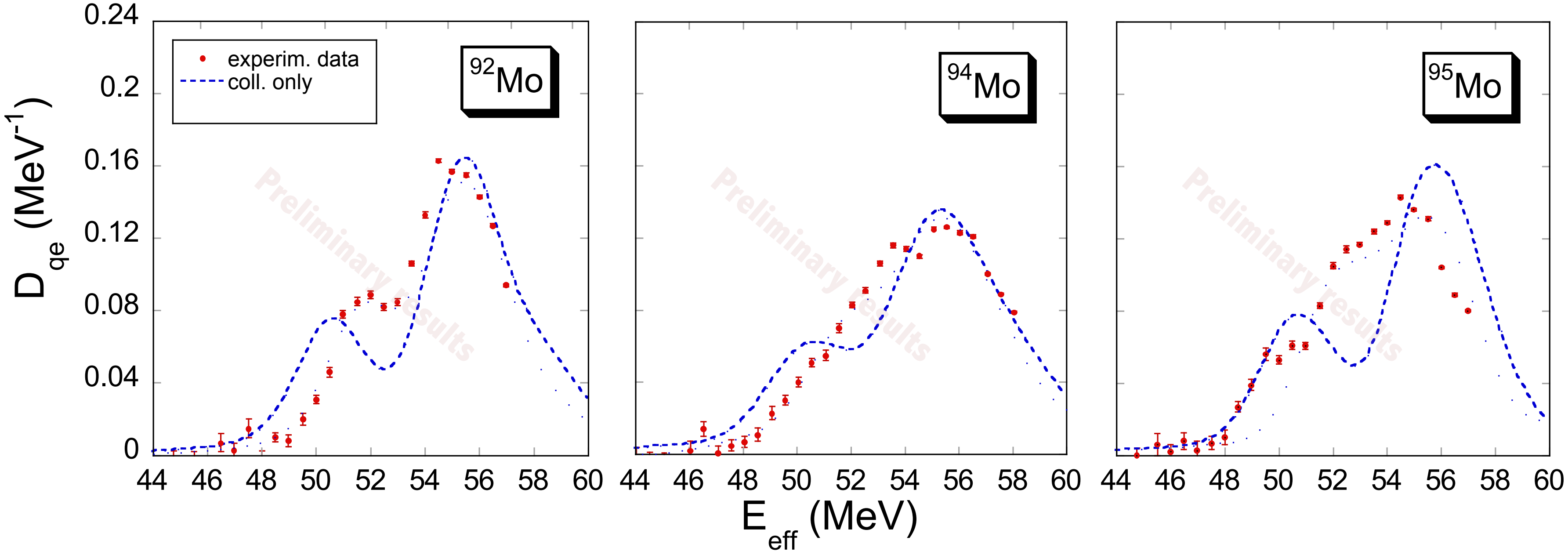
Different trend of the excitation functions for the three Mo isotopes

Quasielastic barrier distribution of ^{20}Ne+^{92,94,95}Mo



Increasing of dissipation in a “controlled” way: observing the influence of increasing level density on D_{QE}

- Experimental D_{QE} of ^{92}Mo preserves two-peaks structure



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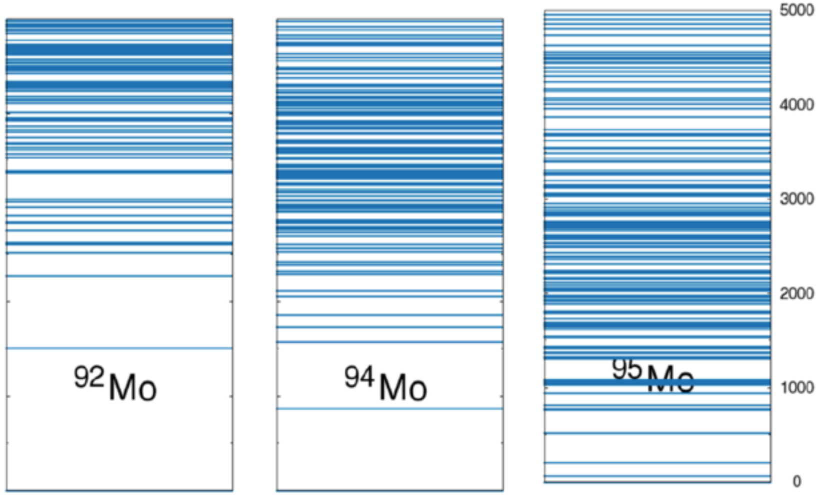
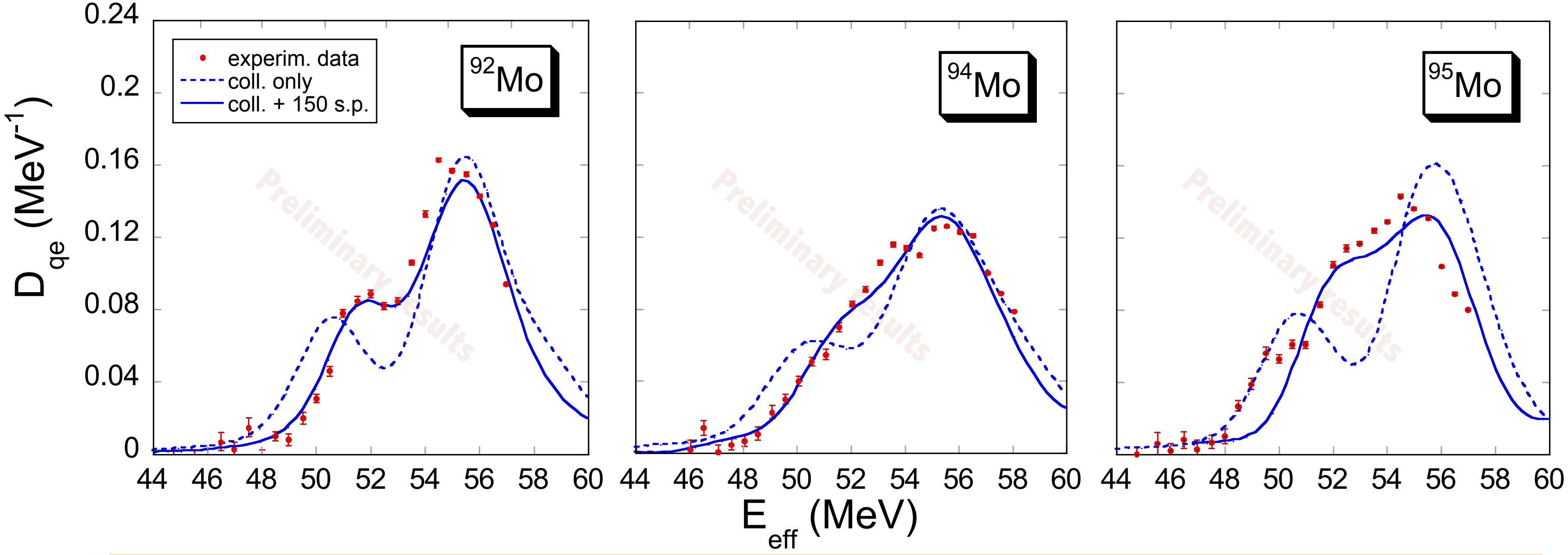


Increasing of dissipation in a "controlled" way: observing the influence of increasing level density on D_{QE}

- Experimental D_{QE} of ^{92}Mo preserves two-peaks structure
- Experimental D_{QE} of ^{95}Mo and ^{94}Mo have much smoothed structure respect to CC calculations, as predicted by CC+RMT model;



Possible significant differences in transfer channels between the isotopes.

Near barrier fusion reactions

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Direct transfer cross-section measurements of the $^{20}Ne+^{92,94,95}Mo$

- Comparison of the transfer cross sections for different transfer reaction of the neighbour isotopes
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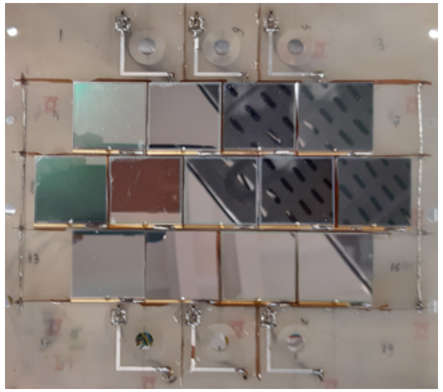

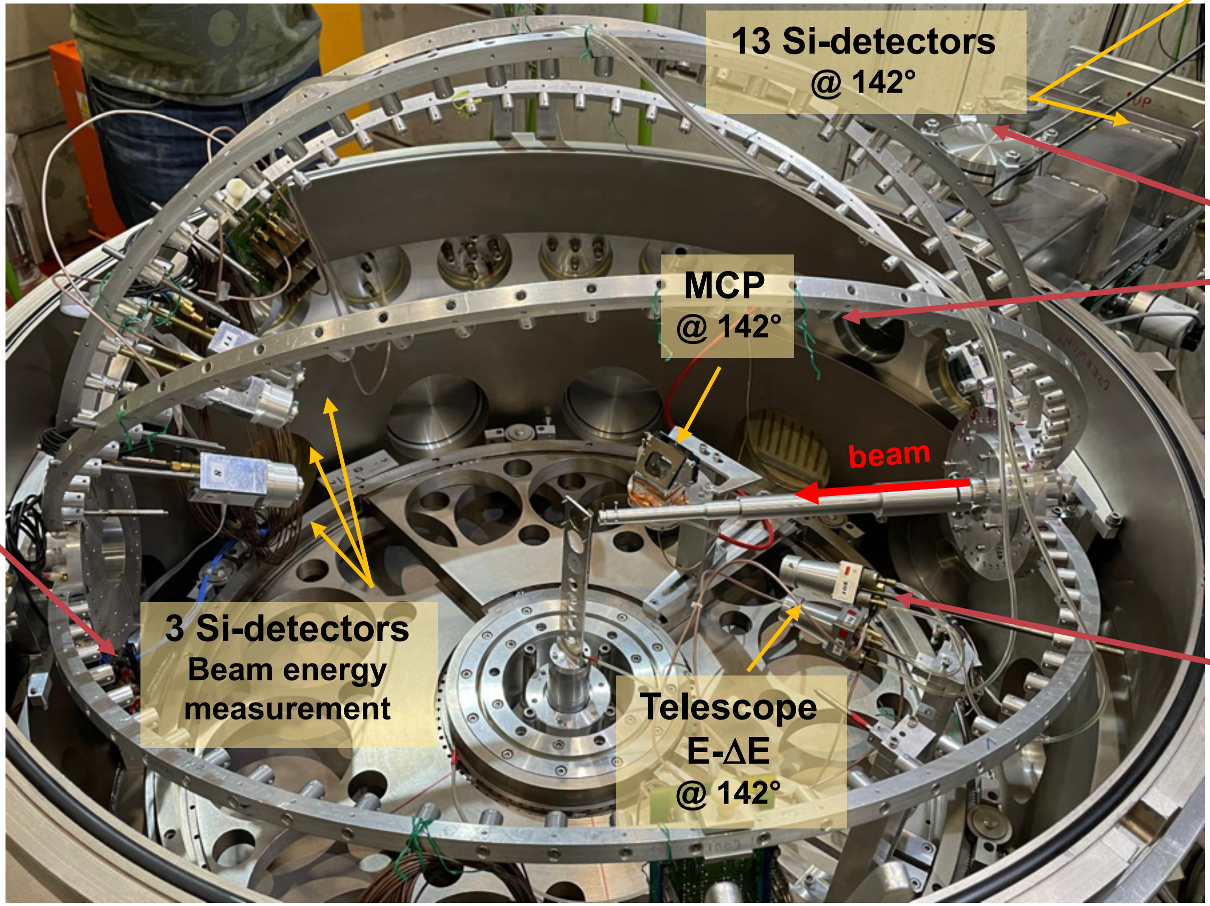

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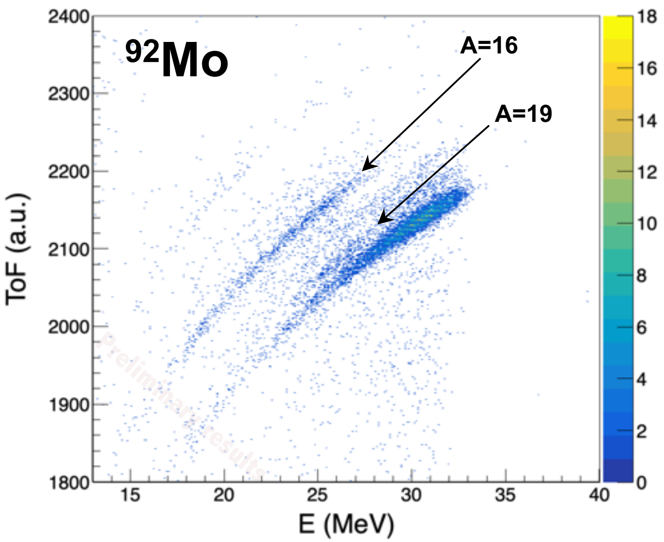
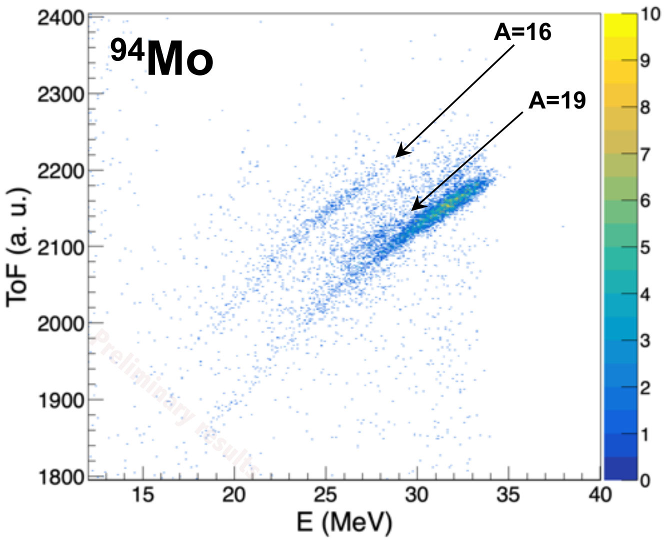
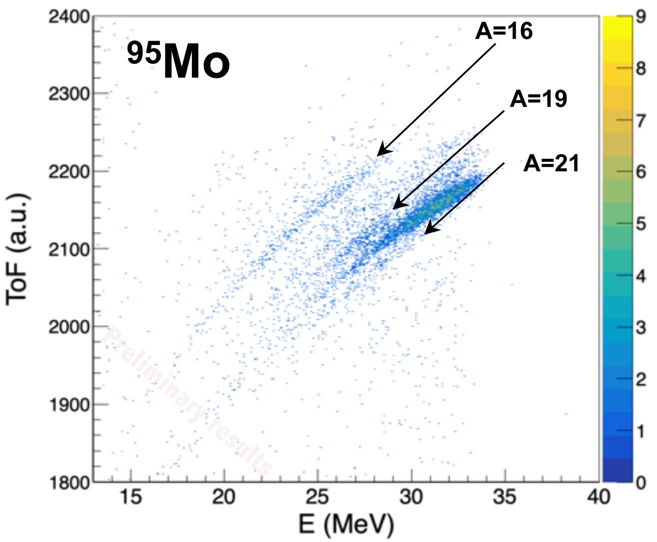
Product identification in mass at the beam energy of 73 MeV







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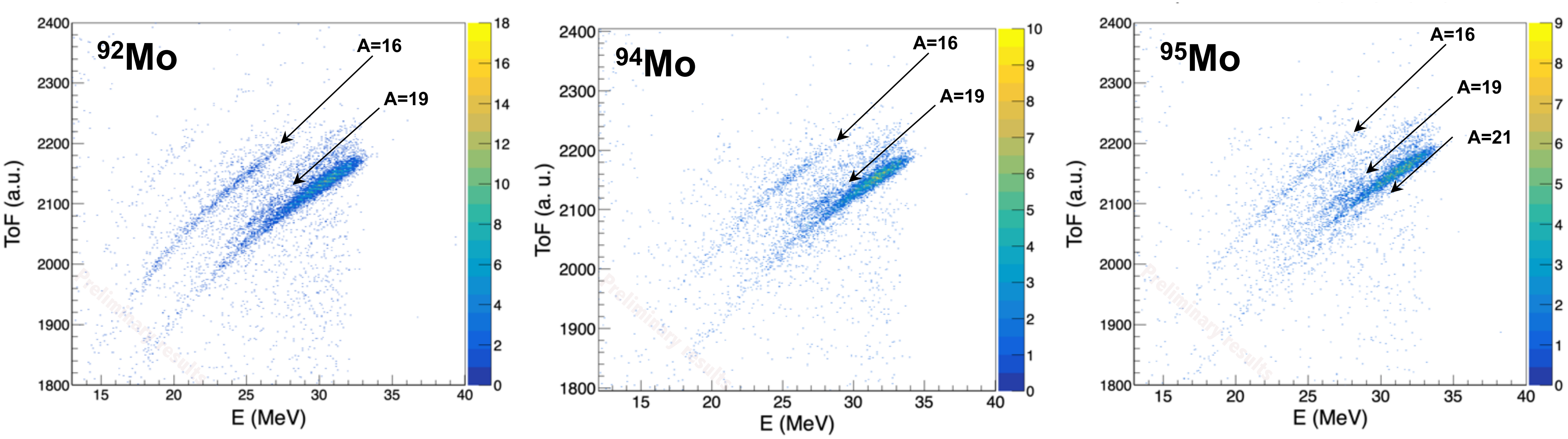

One neutron pick-up observed for $^{20}Ne+^{95}Mo$ system

Analysis in progress . . .

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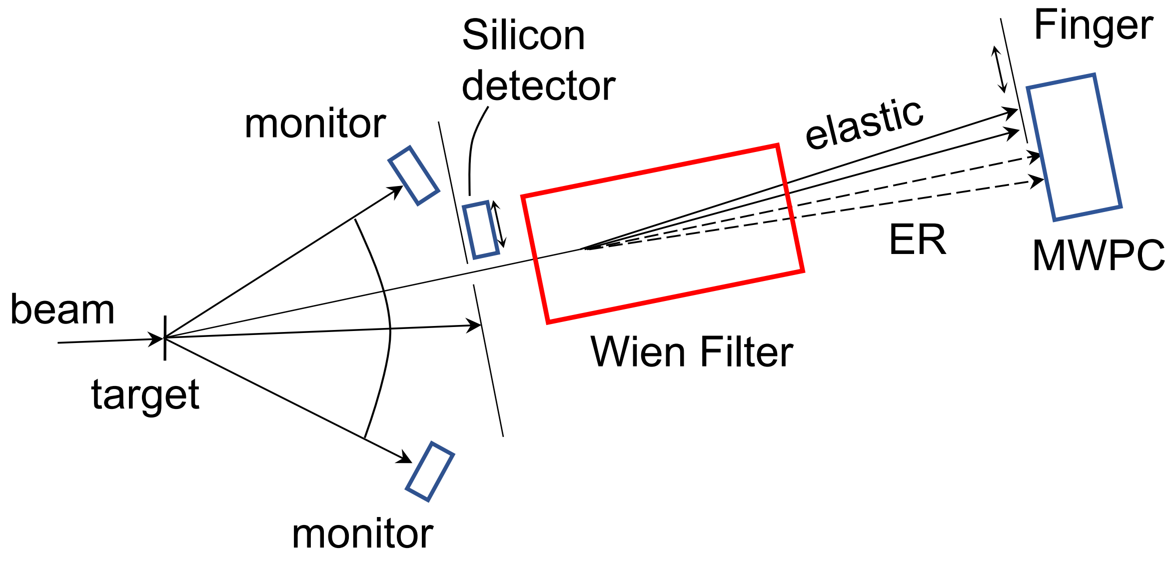

Based on set-up in use at ANU (Australia)

J. X. Wei et al., NIM., A 306, (1991)

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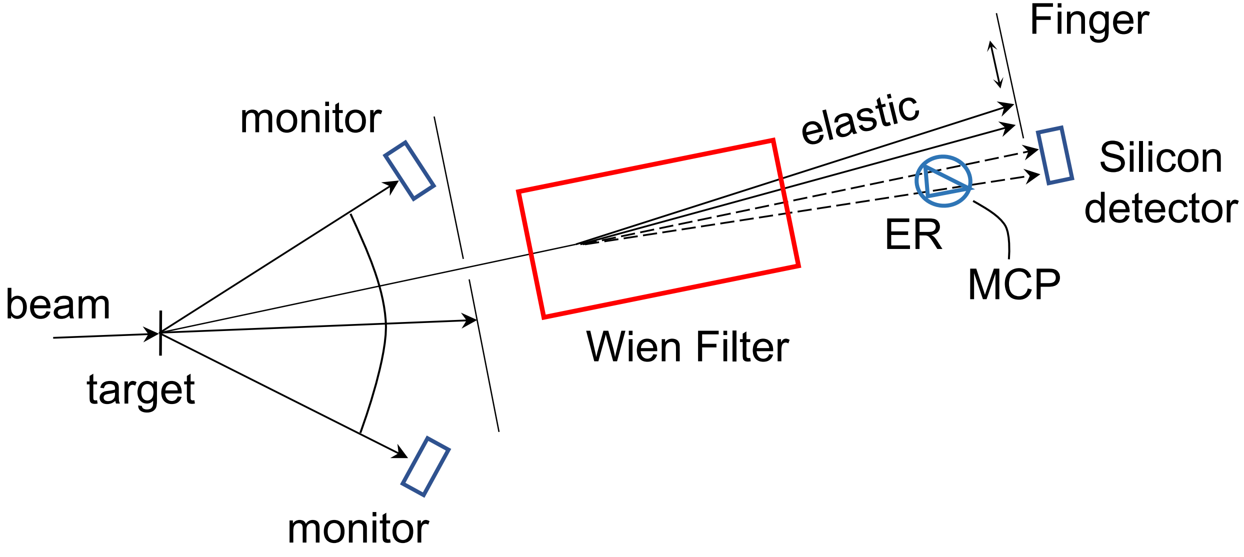

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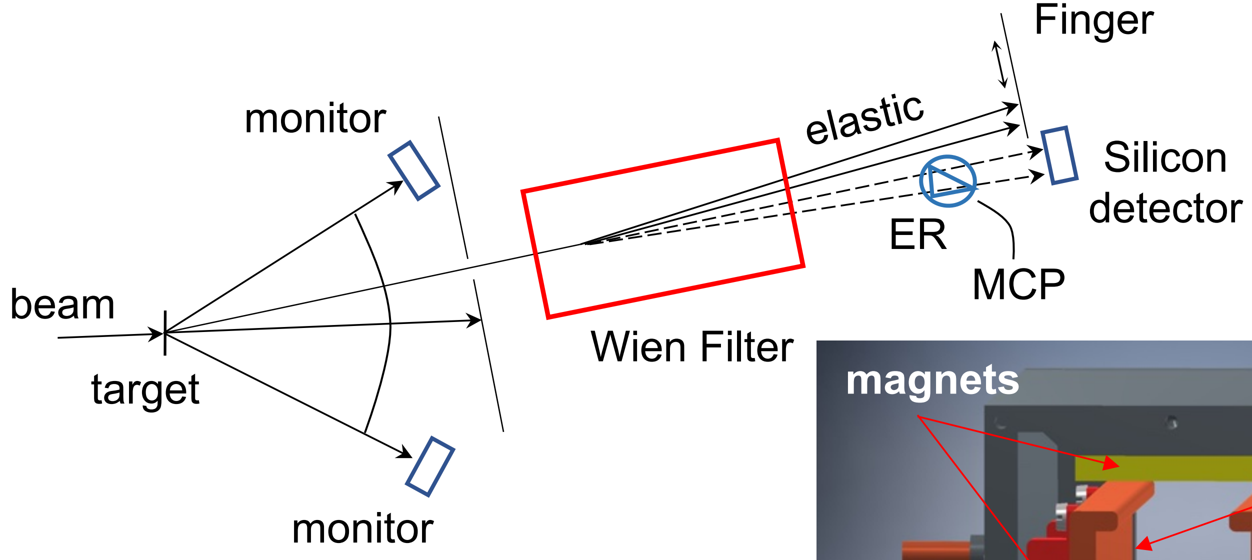

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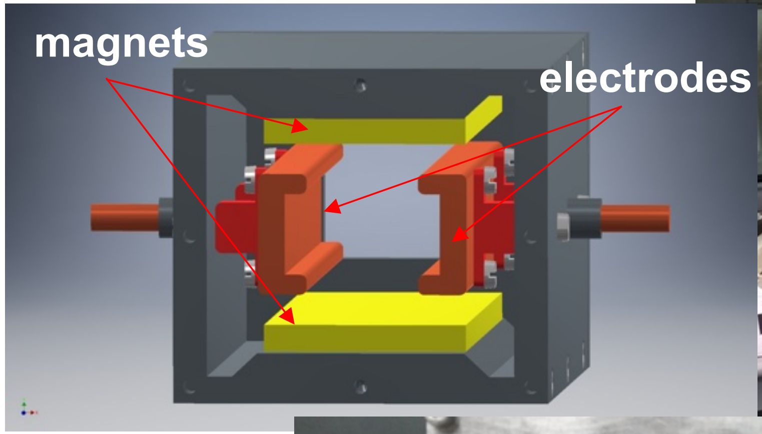
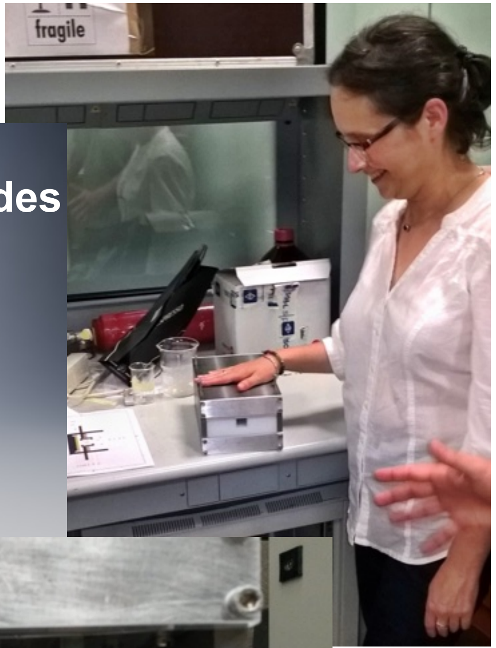
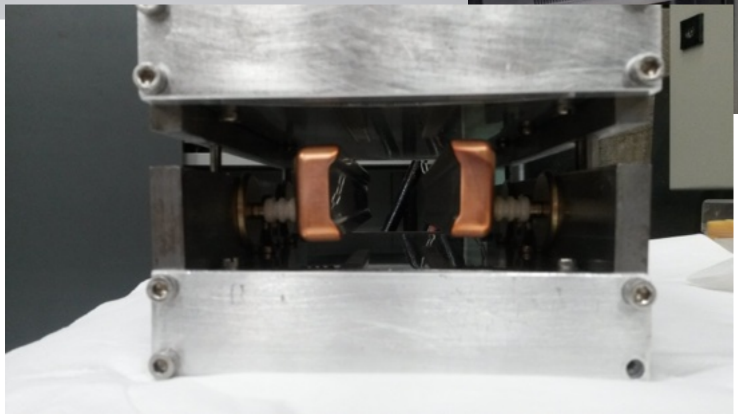
Using a MCP and a Silicon detector

The Wien Filter at LNS

- Dimensions of 106 x 150 x 250 mm^3
- 20 permanent magnets (Sm_2Co_{17}) 41 x 41 x 11 mm^3 (Vacuumshmalze)
- Magnets distance 60 mm
- Magnetic field 1.7 kG
- Electrodes at distance of 44 mm
- Maximum high voltage for each electrode ±20 kV







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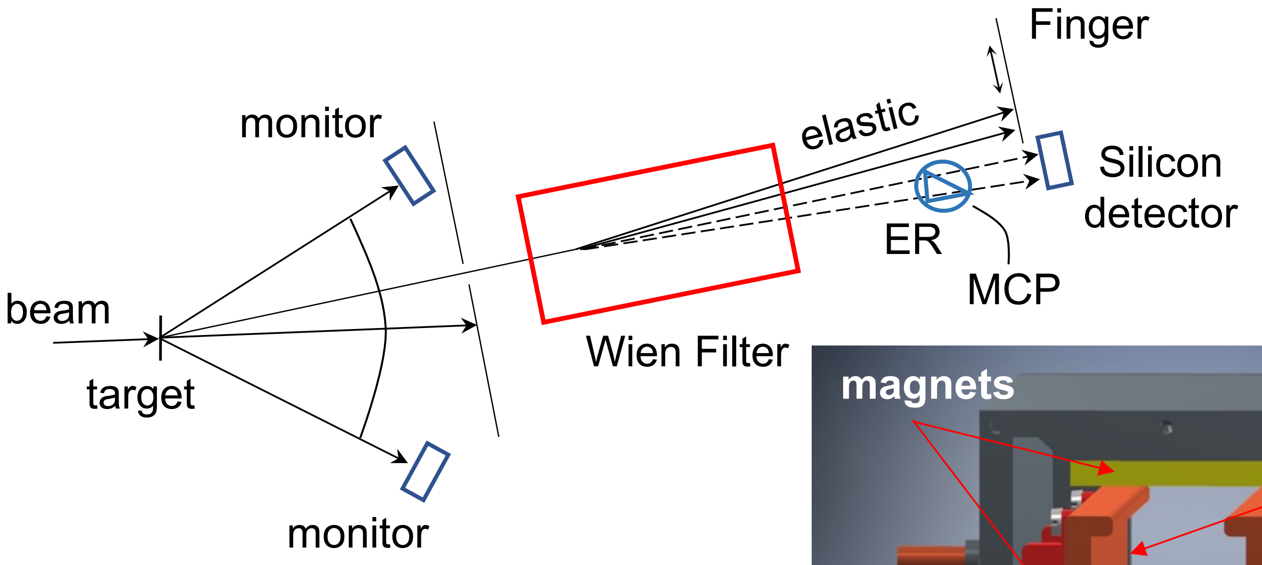

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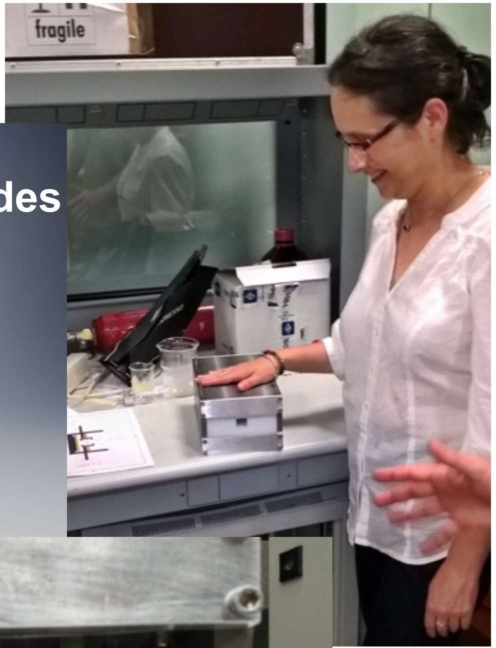

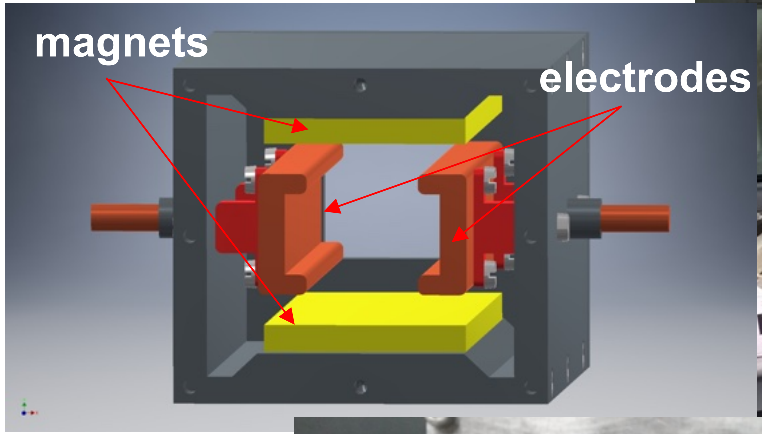

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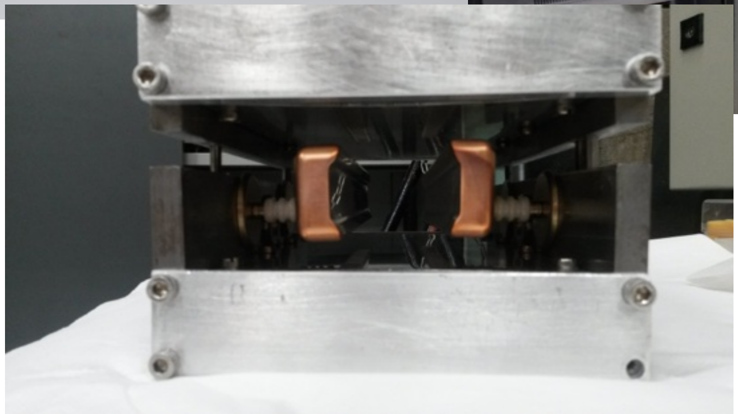

Two in-beam tests have been performed at LNS

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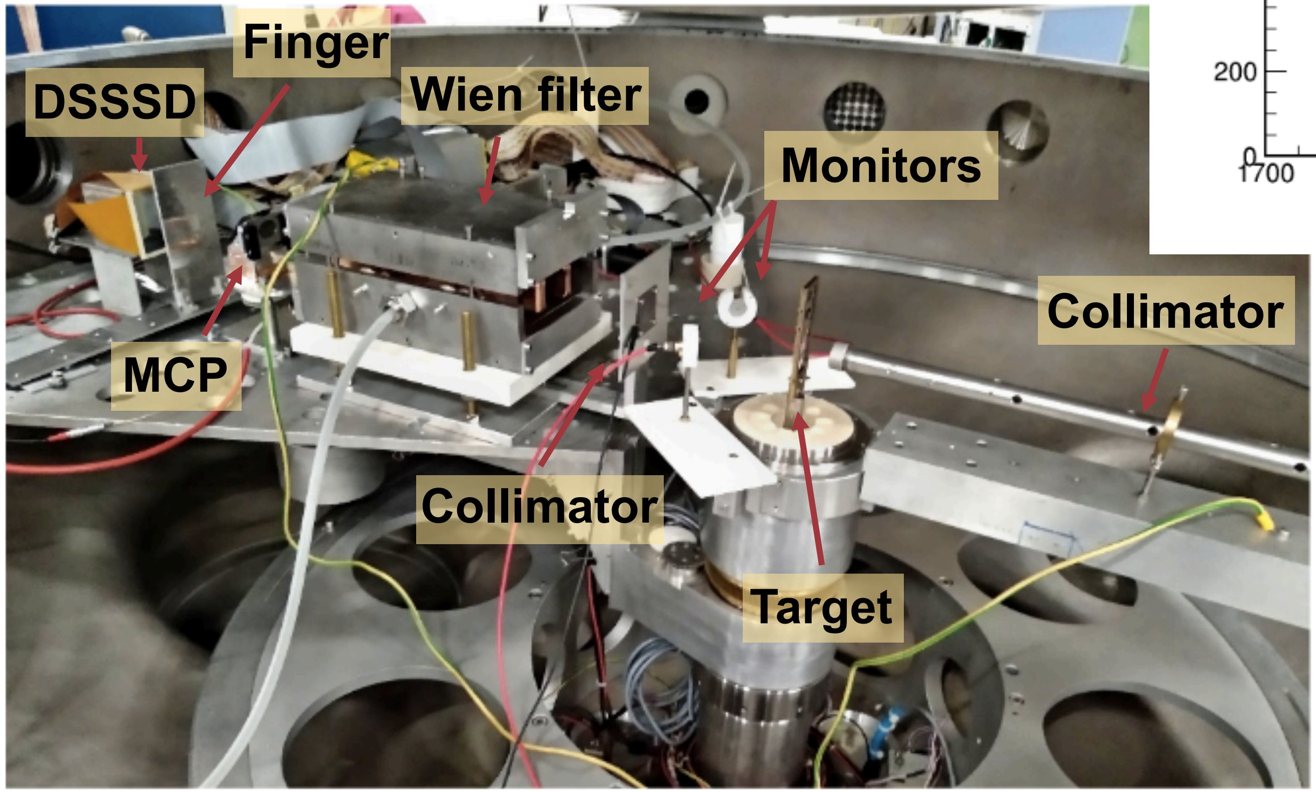
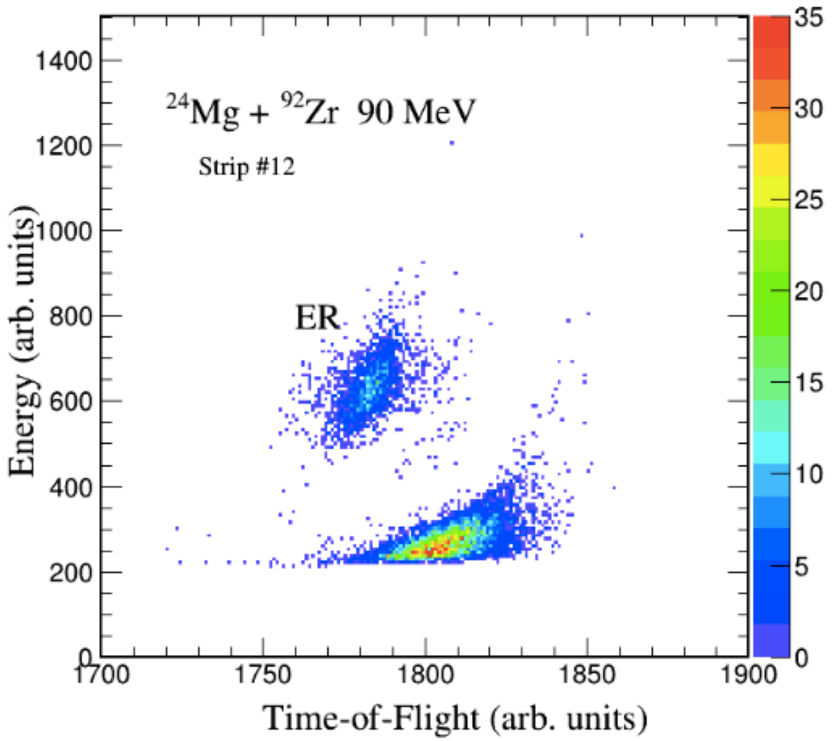
Future plans: fusion

Summary

Tests performed in the following condition:

- ^{24}Mg in the energy range 67-90 MeV on a ^{92}Zr target
- Silicon strip detector DSSSD 64x64 mm^2
- MCP detector
- Collimator before Wien Filter





- Measurement of ER angular distribution
- ER identification for $^{24}Mg+^{92}Zr$ at energies above and below the barrier
- Operational with voltage for each electrode ±20 kV

E. V. Pagano et al., LNS Activity Report 2018/2019 E. V. Pagano et al., LNS Activity Report 2020

Heavy Ion Laboratory

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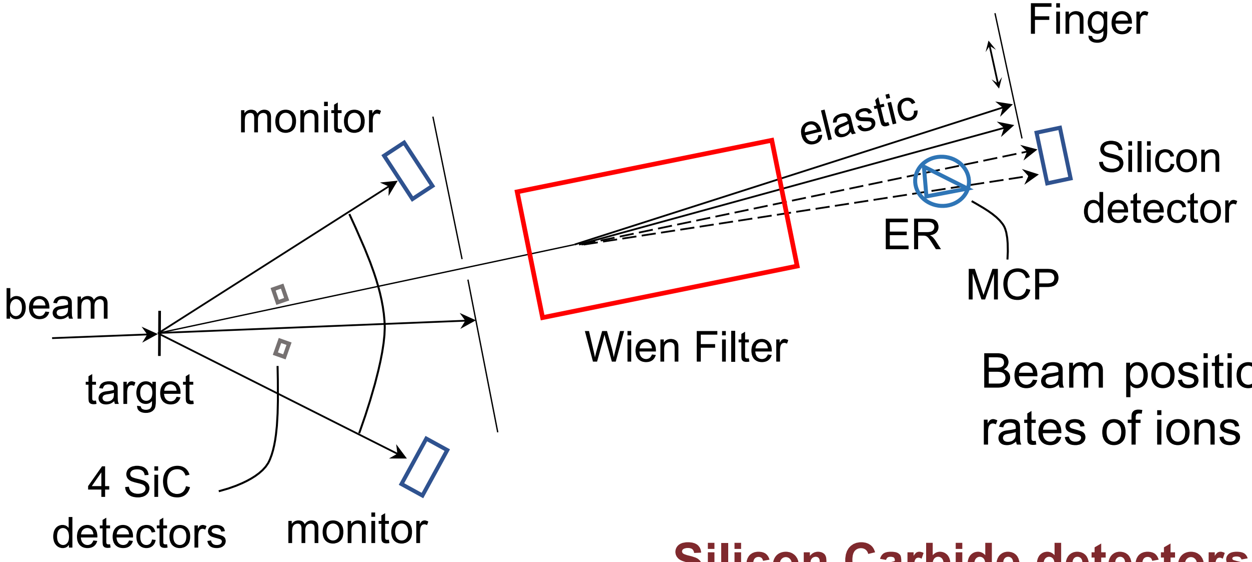
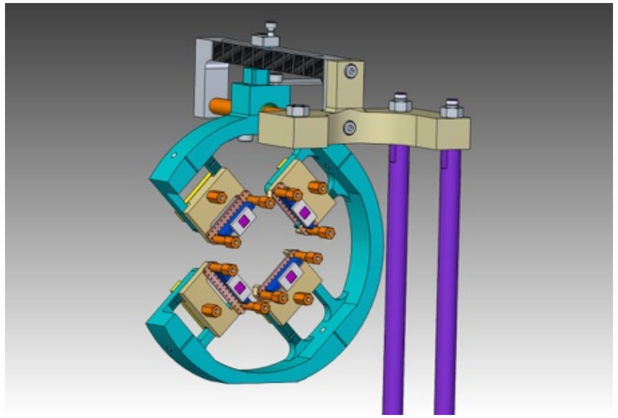


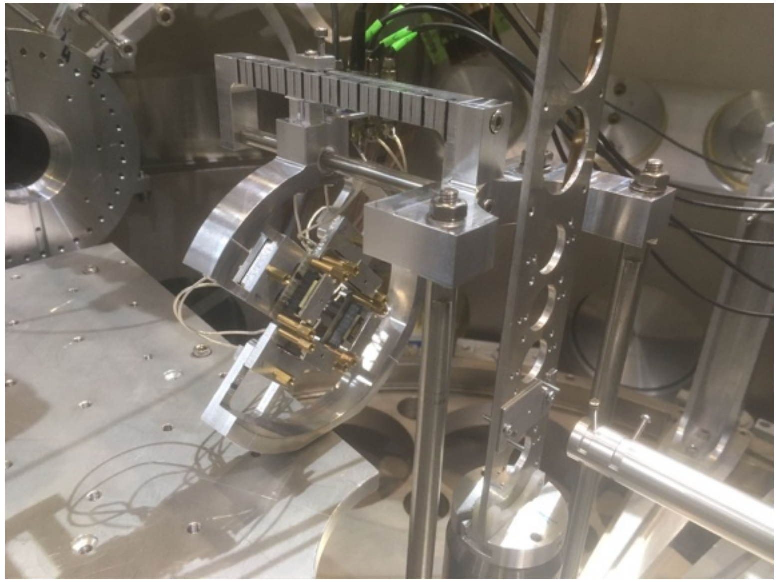
Slight change in the beam spot position on the target influences the detected angle and cross-section

Beam position from the ratios of the counting rates of ions hitting the detectors.

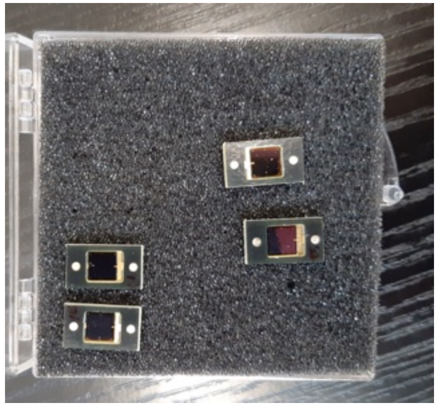
Silicon Carbide detectors (SiC)



SiC position can be set in the angular range of 8° – 15° and distance range 10 cm -15 cm



Beam monitoring system tested at HIL



- Active area 5x5 mm, thickness 80 μm (www.techjw.com)
- Radiation hardness around ~5 times larger than Si detector

E. Piasecki et al., HIL Aannual Report, A (2021) 25-27

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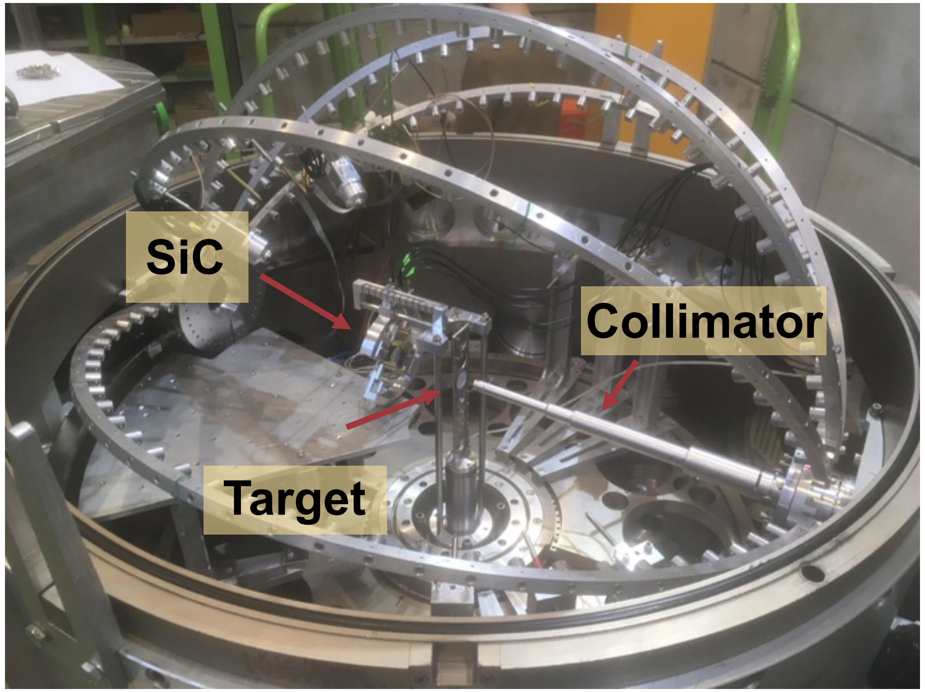
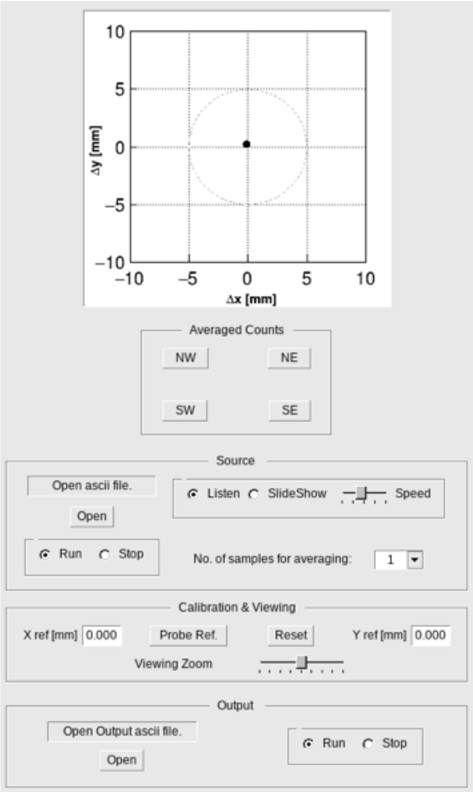
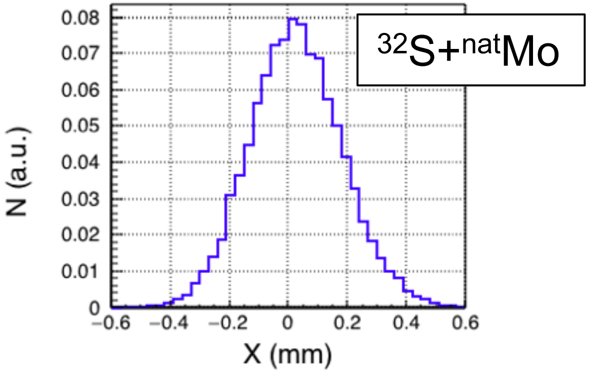


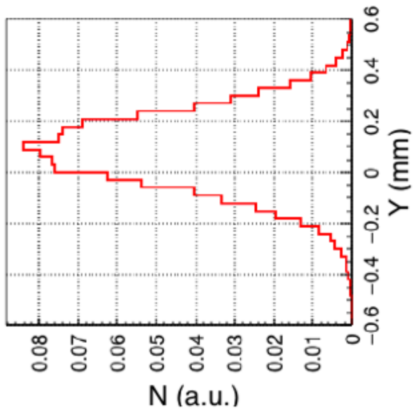


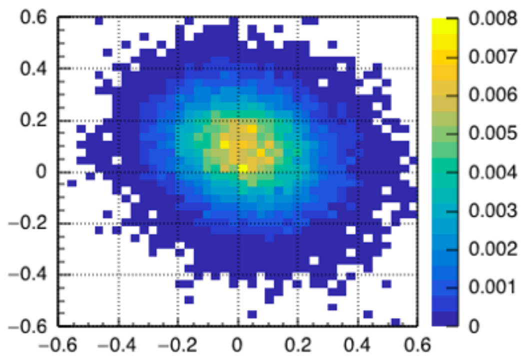
GUI application "BeamMon" visualizes online beam center's position (*by K. Piasecki*)



- ^{32}S beam of 85 MeV (2 pnA)
- Targets ^{nat}Au (0.1 mg/cm^2), ^{nat}Sn (0.1 mg/cm^2) and ^{nat}Mo (0.6 mg/cm^2)

Beam position stable in 7 h run with uncertainty of 0.15 mm (0.1°)





E. Piasecki et al., HIL Aannual Report, A (2021) 25-27

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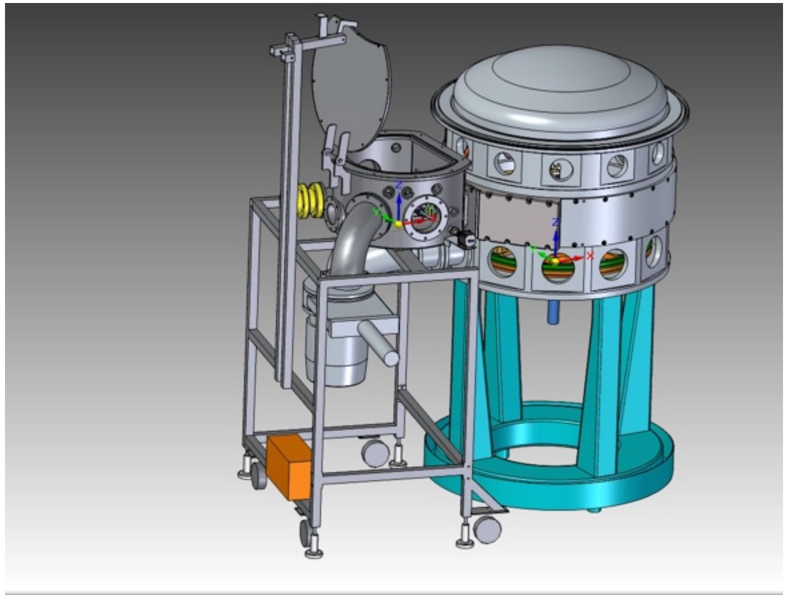
Extend the study of dissipation to the direct fusion barrier distribution.

- Verify the degree of agreement between the direct and non-direct methods of the barrier distribution determination;
- Verify the agreement between experimental and calculated fusion excitation functions and barrier distributions when the non-collective excitations are included within the CC+RMT model;



- Verify the existence of Dissipative Fusion Enhancement (DFE), a phenomenon predicted by the CC+RMT model.

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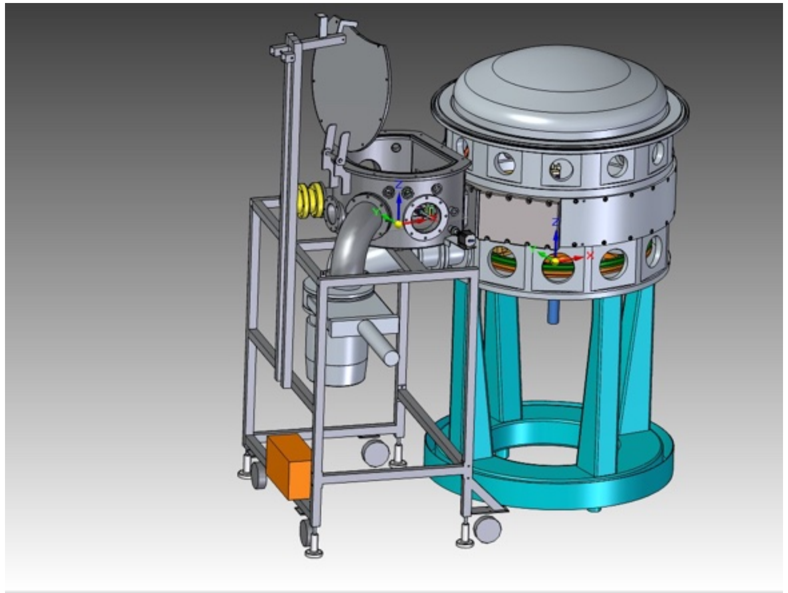

- Verify the existence of Dissipative Fusion Enhancement (DFE), a phenomenon predicted by the CC+RMT model.

Fusion reaction experiment:

- at **LNS** of $^{24}Mg+^{90,92}Zr$ or $+^{92,94,95}Mo$ or other systems of interest;

- at **HIL** of $^{20}Ne+^{90,92}Zr$, $+^{58,60,61}Ni$ and $+^{92,94,95}Mo$ or other systems of interest.

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Summary

- Barrier distribution studies performed at HIL and LNS focus on the study of influence of dissipation due to weak but numerous non-collective excitations and transfer reactions on quasielastic barrier distribution D_{QE}
- This observation triggered a new theoretical approaches to describe the fusion (CC+RMT)
- An upgraded CCQEL/CCFULL codes able to include dissipation of kinetic energy due to several transfer reactions was developped
- Measurement $^{20}Ne+^{92,94,95}Mo$ clearly shows the influence of non-collective excitations on smoothing of D_{QE}
- Transfer cross section measurement of $^{20}Ne+^{92,94,95}Mo$ to clairify the role of transfer and upgrade the CCQEL code
- Future plans:
  - studies of dissipation effect on $\sigma_{fus}(E)$ and D_{fus}
  - direct fusion measurements with velocity filter in LNS
  - employing the filter at HIL using the extension of ICARE chamber
  - further CC+RMT improvement

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