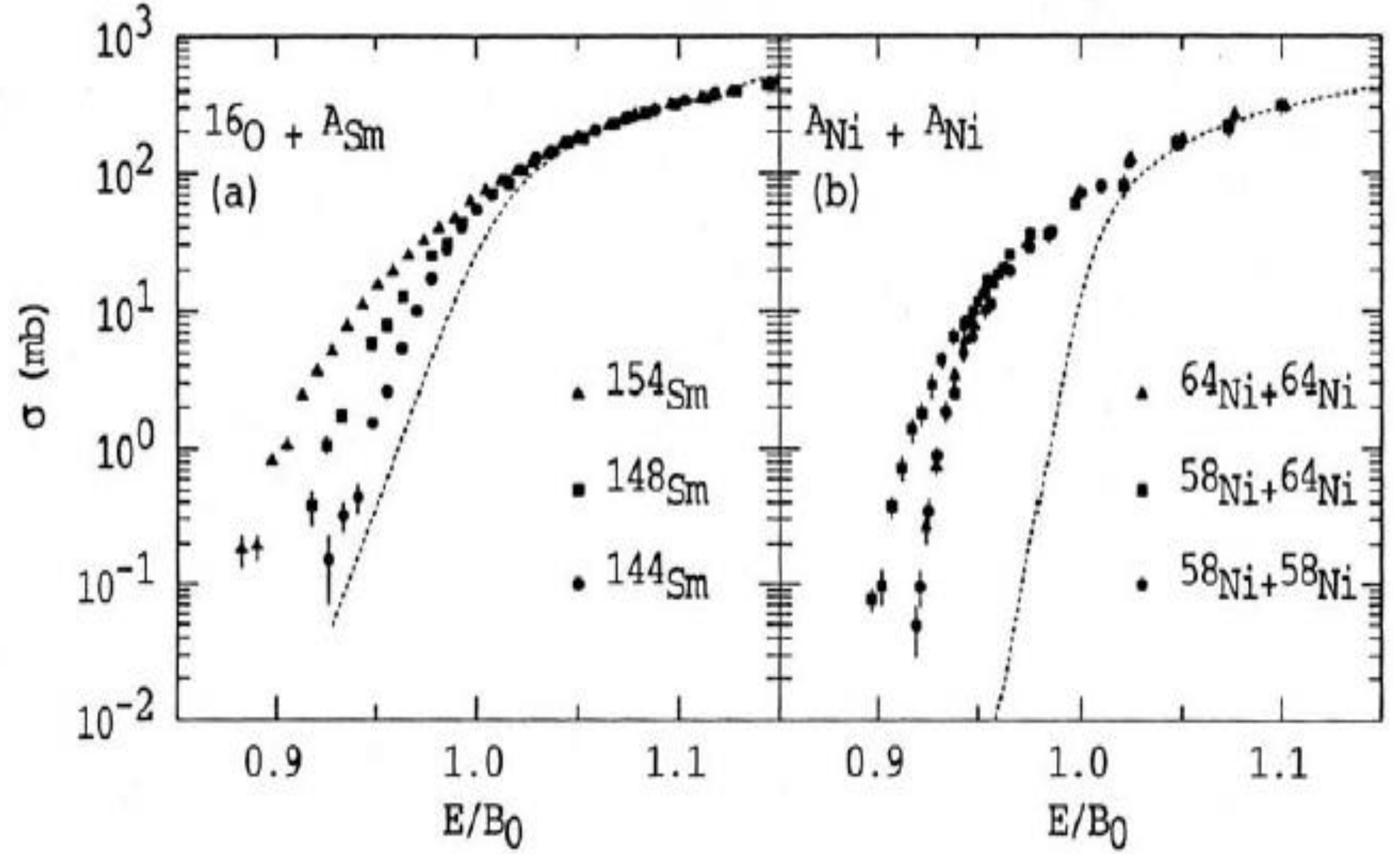
Dissipation and

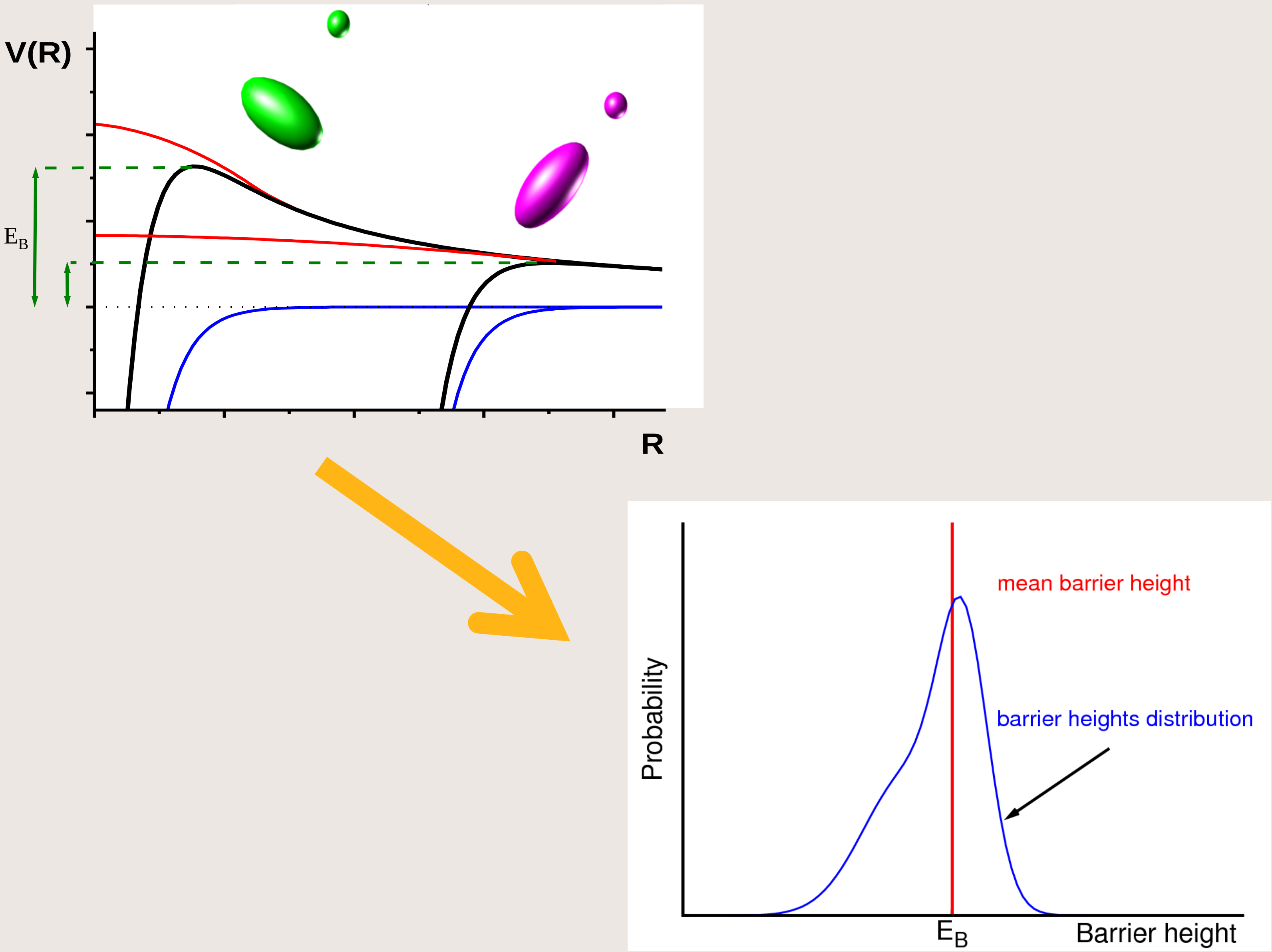
Coulomb barriers

Eryk Piasecki & the „Barrier" collaboration

Warszawa, 5.X.2017



J.Leigh et al., PR C52(1995); M.Beckerman et al., PR C23(1981)1581

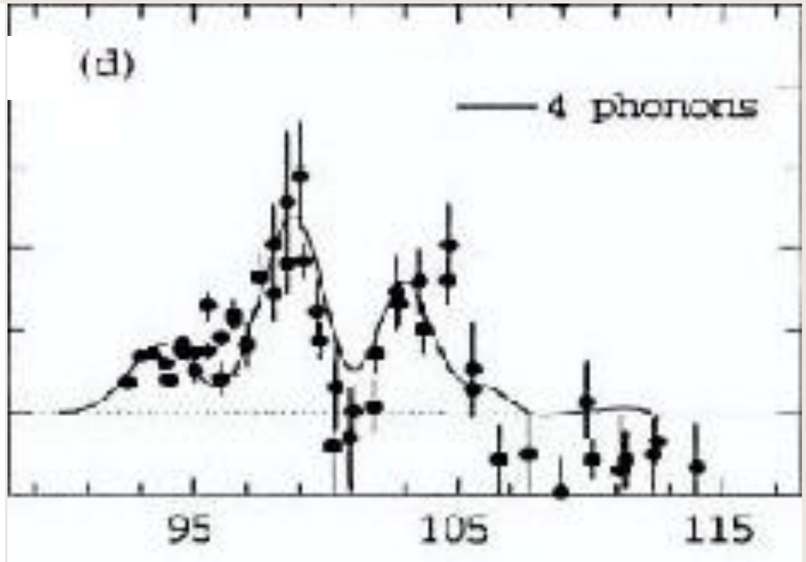

V(R)
E_B
R
mean barrier height
barrier heights distribution
Probability
E_B
Barrier height

Proof of the quantal nature of the phenomenon:

even for undeformed nuclei...

$^{58}Ni + ^{60}Ni$

d²(Eσ)/dE² [mb/MeV]



E_B [MeV]

A.M.Stefanini et al.., PRL 74(1995)865

TUNNELING

In many branches of science tunneling through the barrier is influenced by environment (in nuclear phys. environment = nuclear structure)

The nuclear structure influences reaction channels and couplings between them → **potential barrier splits into many barriers (lower and higher)**

Usually this can be calculated by Coupled Channels method

According to the Coupled Channels Method (improved Optical Model),

collision partners emerge in a superposition of

a limited number of discrete (collective) quantum states,

explicitely taken into account in calculations

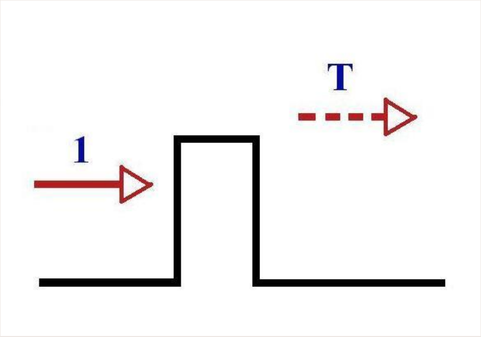
Presently the best model in nuclear reaction studies but there are some problems:

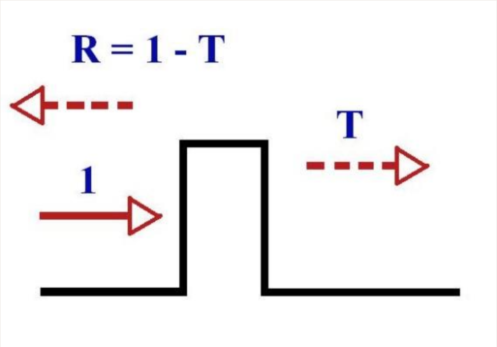
- **parameters fitted (limited predictive power)**
- **different values of a_v for fusion and scattering**
- **problems with simultaneous description of σ_{fus} below and above the barrier**

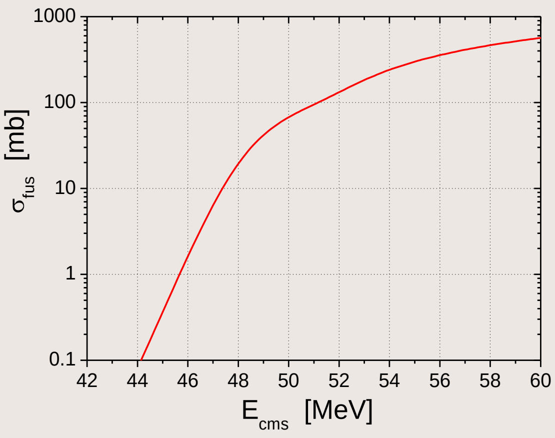
Our present motivation

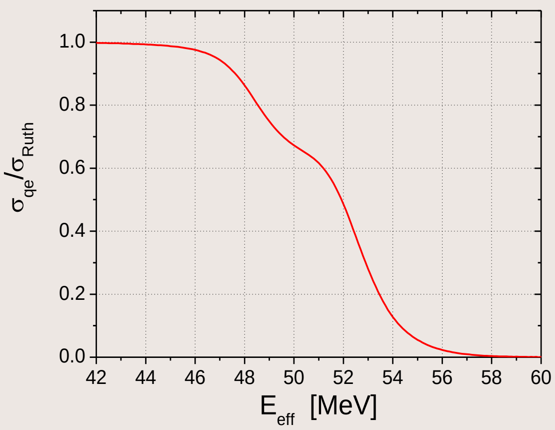
Testing the limits of the standard (coherent) Coupled Channels method and in particular the influence of **dissipation on barier distribution**

Two experimental methods:









$$D_{fus}(E) = \frac{d^2}{dE^2}\left(E\sigma_{fus}\right)$$

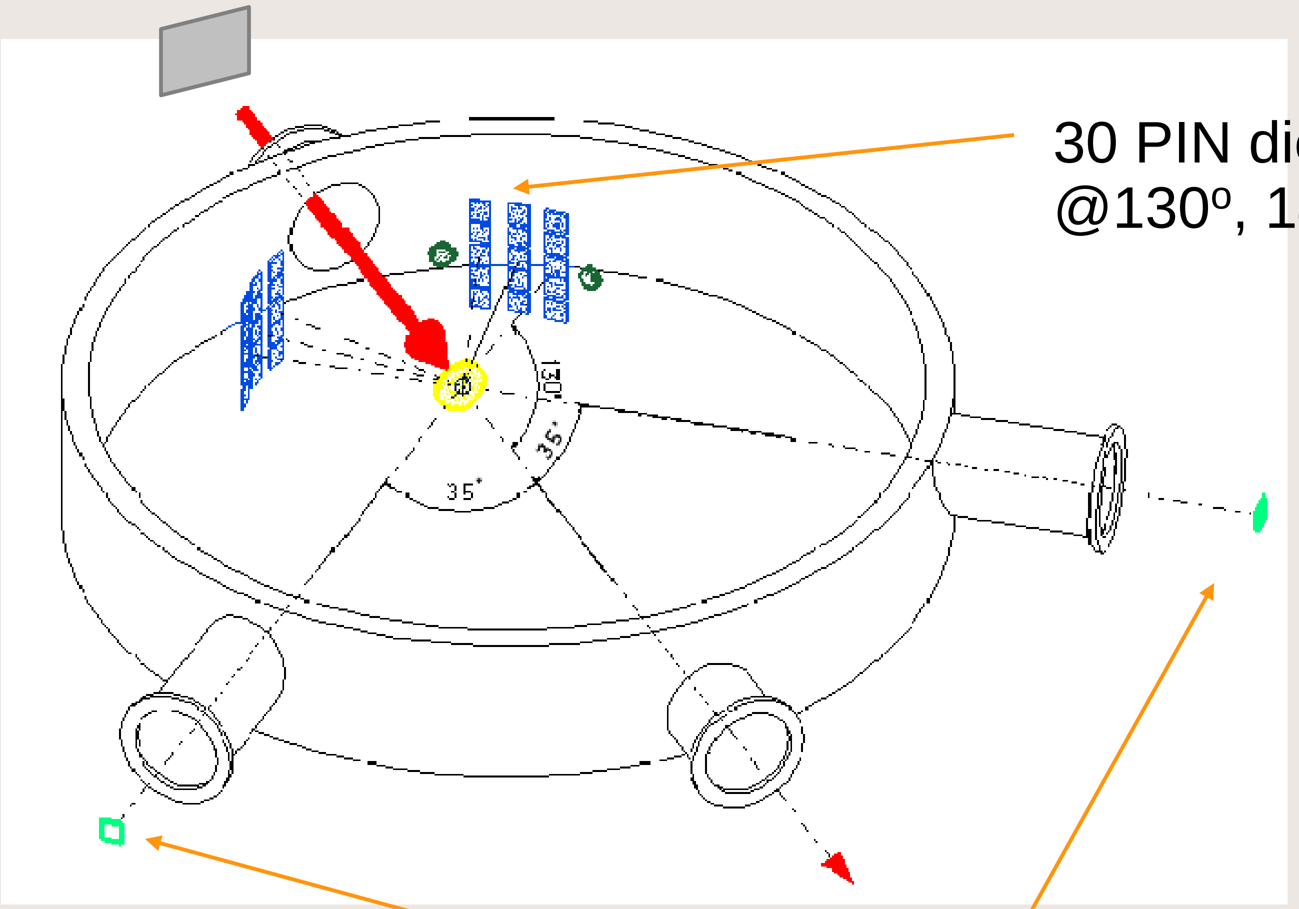
$$D_{qe}(E) = -\frac{d}{dE}\left(\frac{\sigma_{qe}}{\sigma_{Ruth}}\right)$$

$$E_{eff} = \frac{2E}{1 + cosec(\theta/2)}$$

Experimental set-up

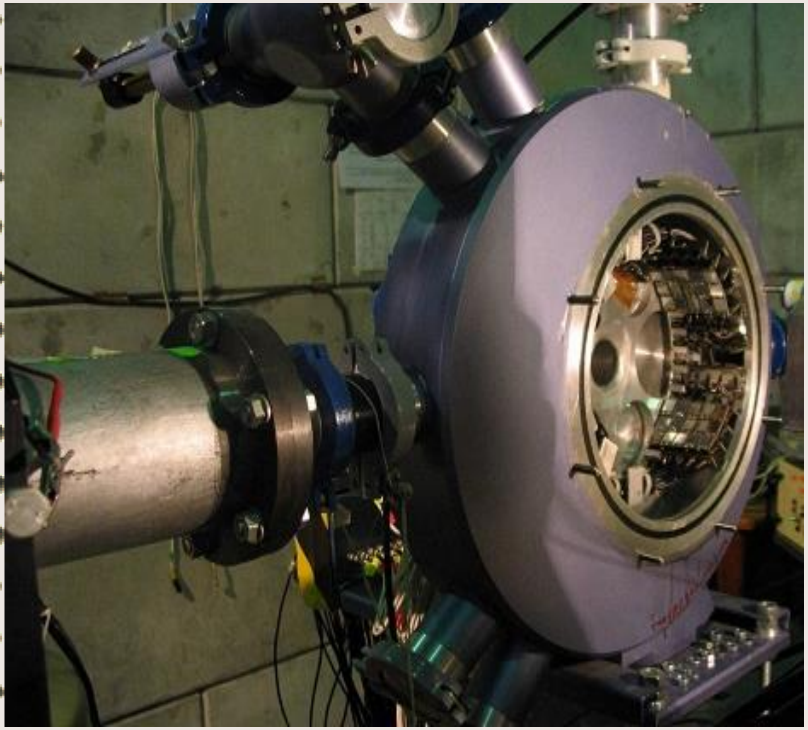
degrader

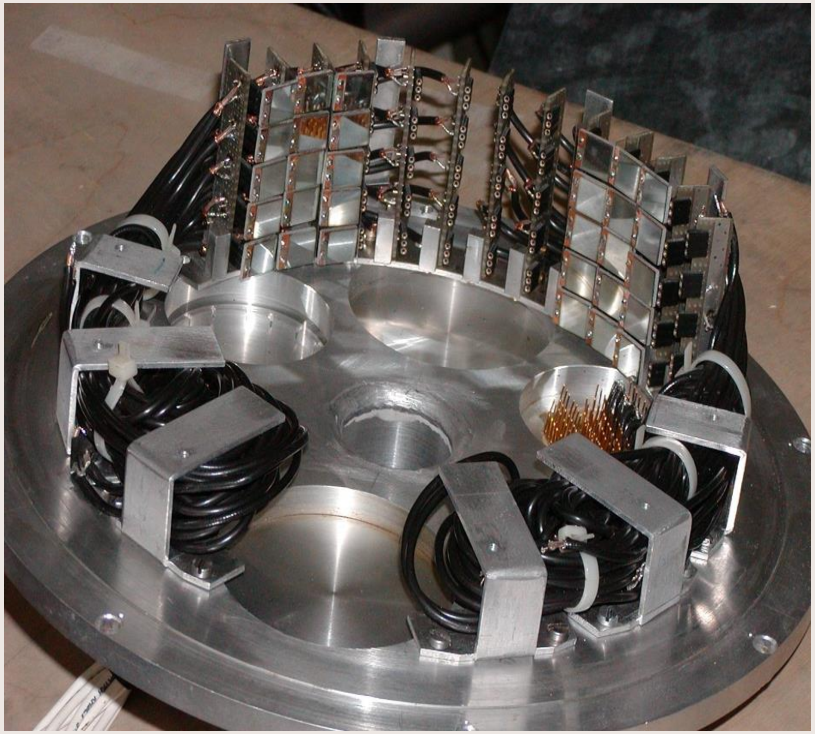
30 PIN diods 1x1cm
@130^o, 140^o, 150^o



2 PIN diods @ 35^o

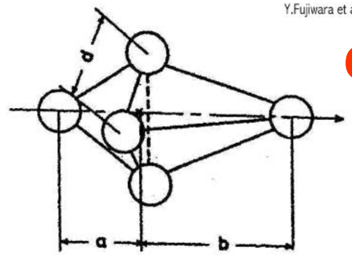
CUDAC 2





Predictions of Coupled Channels Model for ^{20}Ne + ^{118}Sn (CCFULL code)

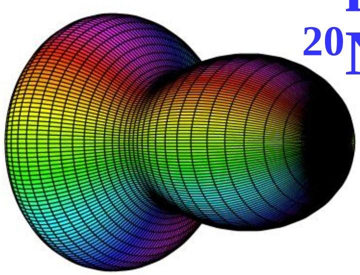
Y.Fujiwara et al., Suppl.Progr.Th.Phys. 68(1980)111



5α configuration of the basis intrinsic wave function in the α-^{12}C-α GCM; *d* is the distance between two α in ^{12}C-like core, and *a* and *b* are treated as the generator coordinates.

Cluster model

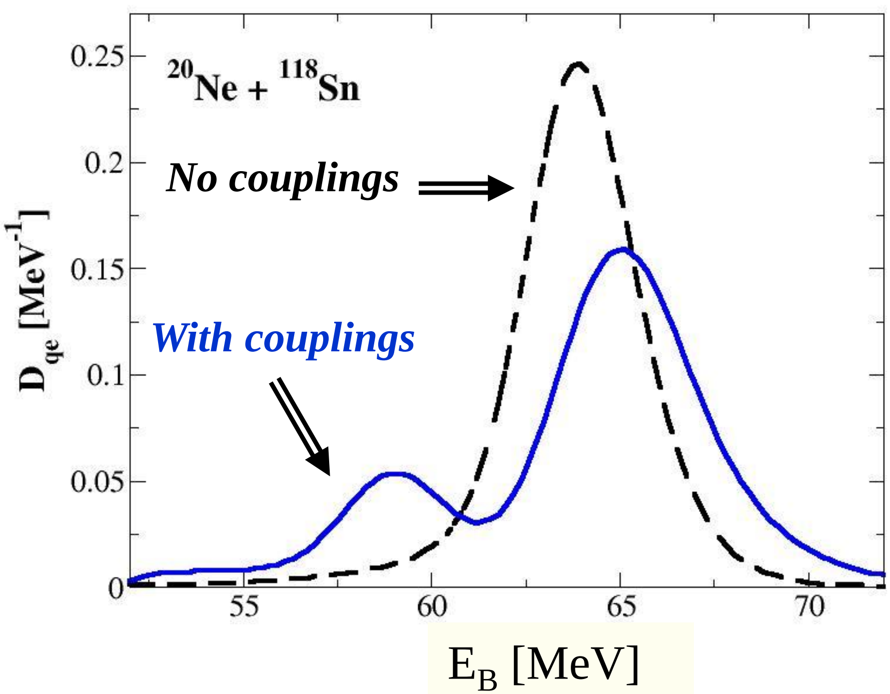
Shape of ^{20}Ne

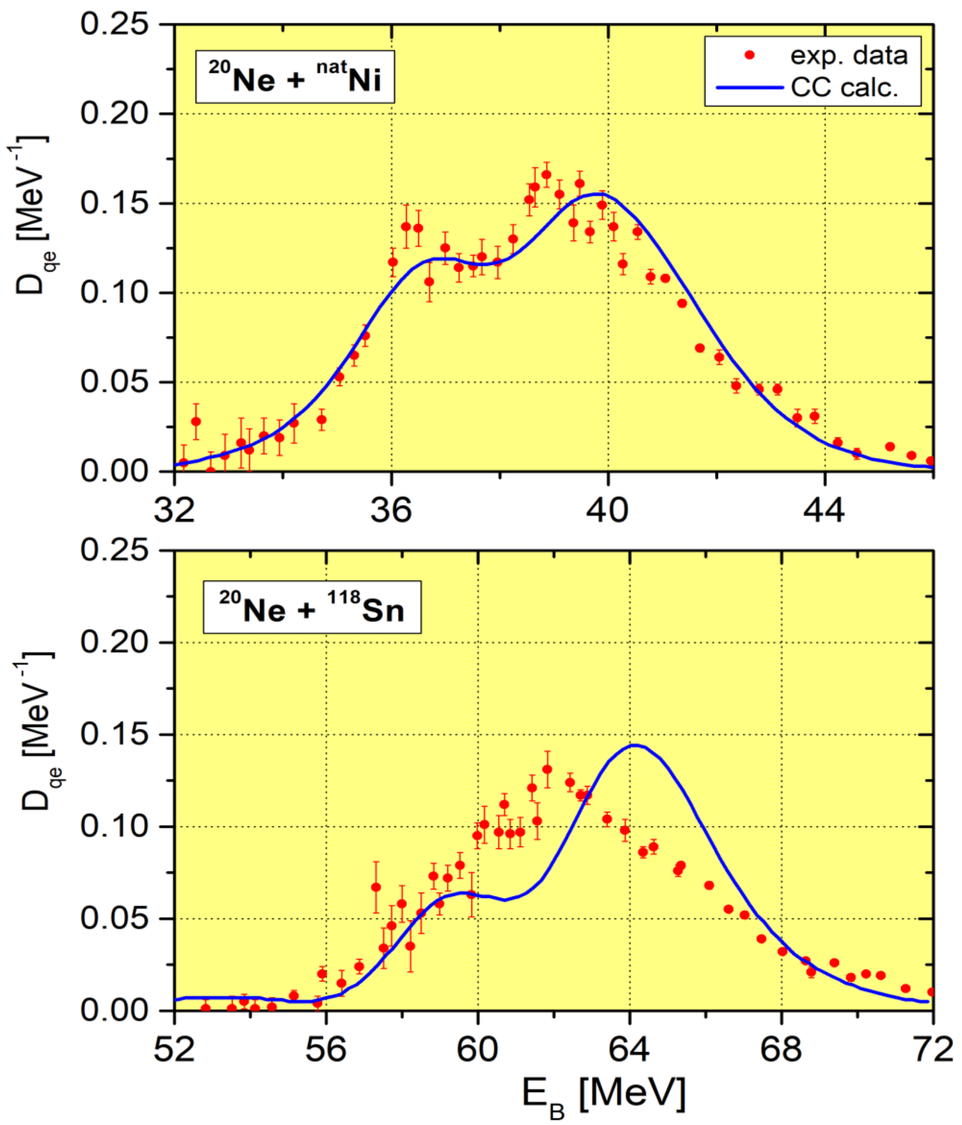


$\beta_2 = 0.46$

$\beta_3 = 0.39$

$\beta_4 = 0.27$





0.25
0.20
0.15
0.10
0.05
0.00
D_{qe} [MeV^{-1}]
^{20}Ne + ^{nat}Ni
exp. data
CC calc.
32
36
40
44
0.25
0.20
0.15
0.10
0.05
0.00
D_{qe} [MeV^{-1}]
^{20}Ne + ^{118}Sn
52
56
60
64
68
72
E_B [MeV]

What causes smoothing of structure in the case of the Sn targets?

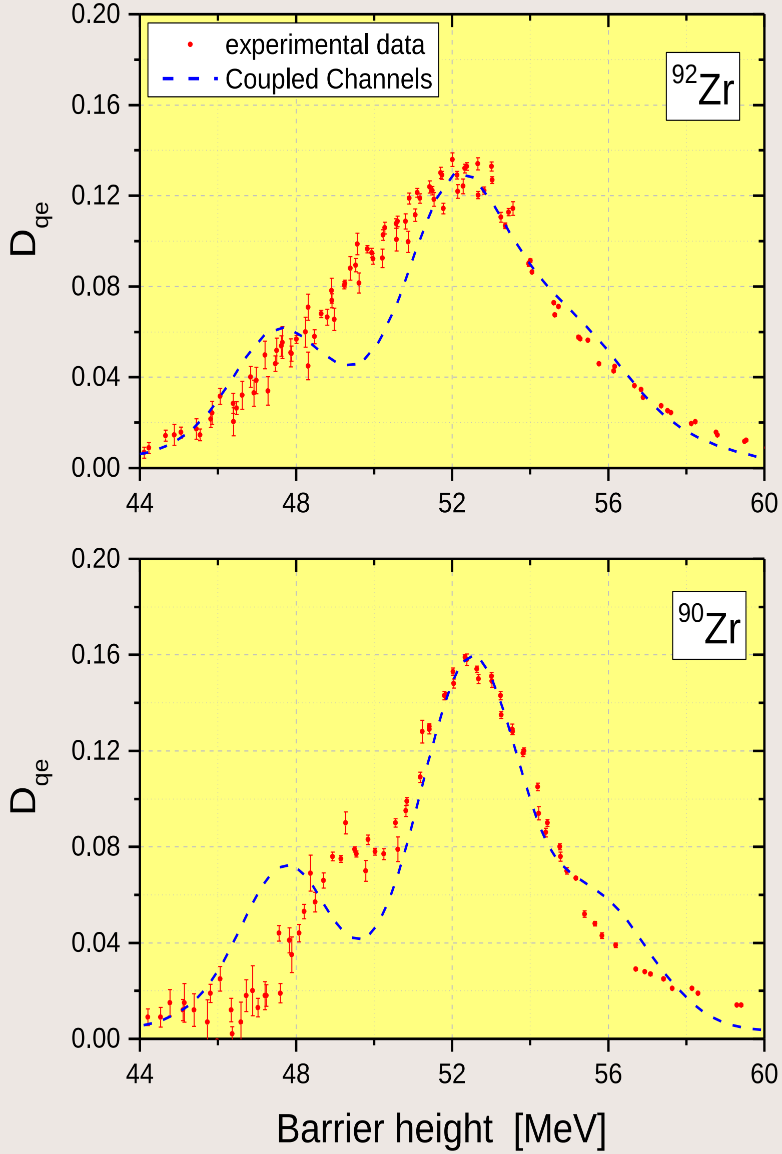
Why in the case of Ni target the structure is clearly seen, being in agreement with theory?

Hypothesis: disregarded in the CC calculations

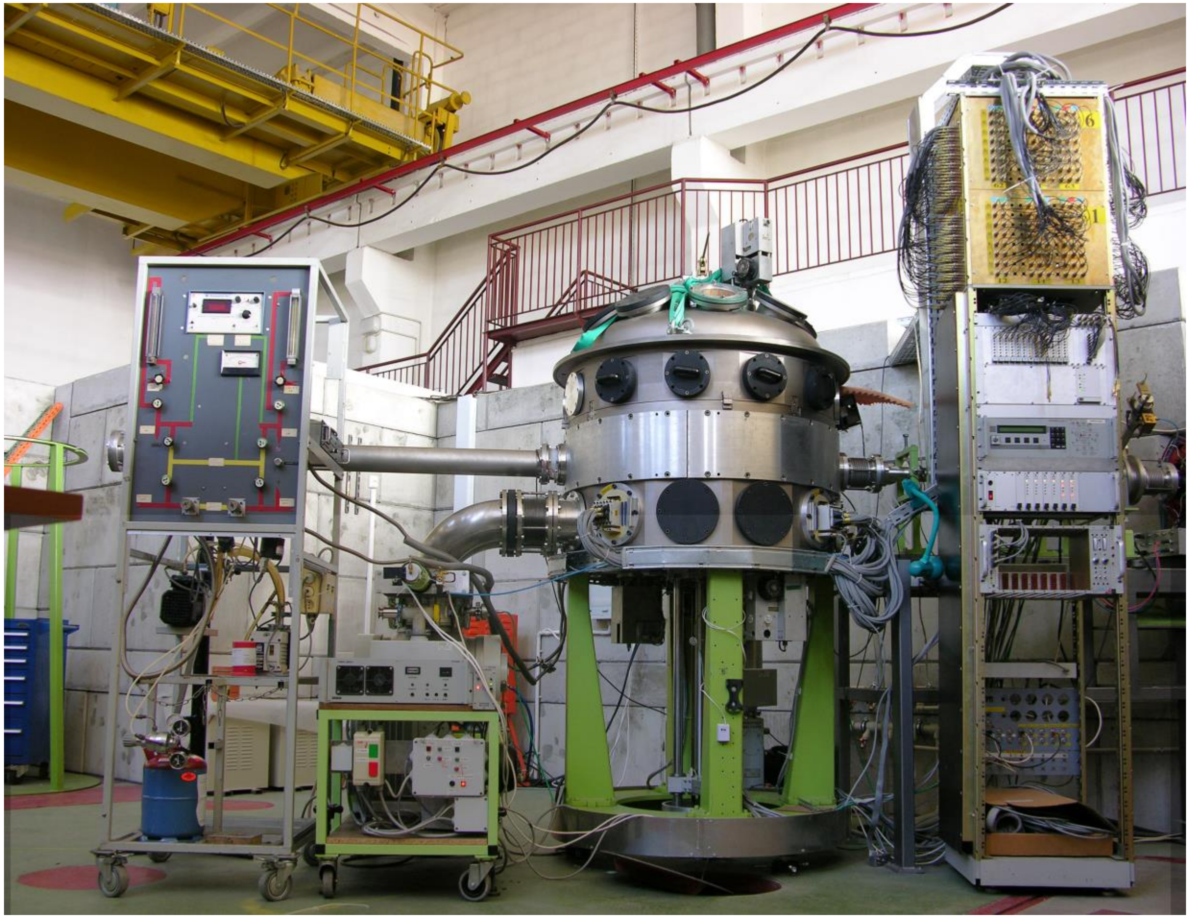
p, n, α **TRANSFERS** during ^{20}Ne scattering

(stronger in the Sn than in the Ni case)

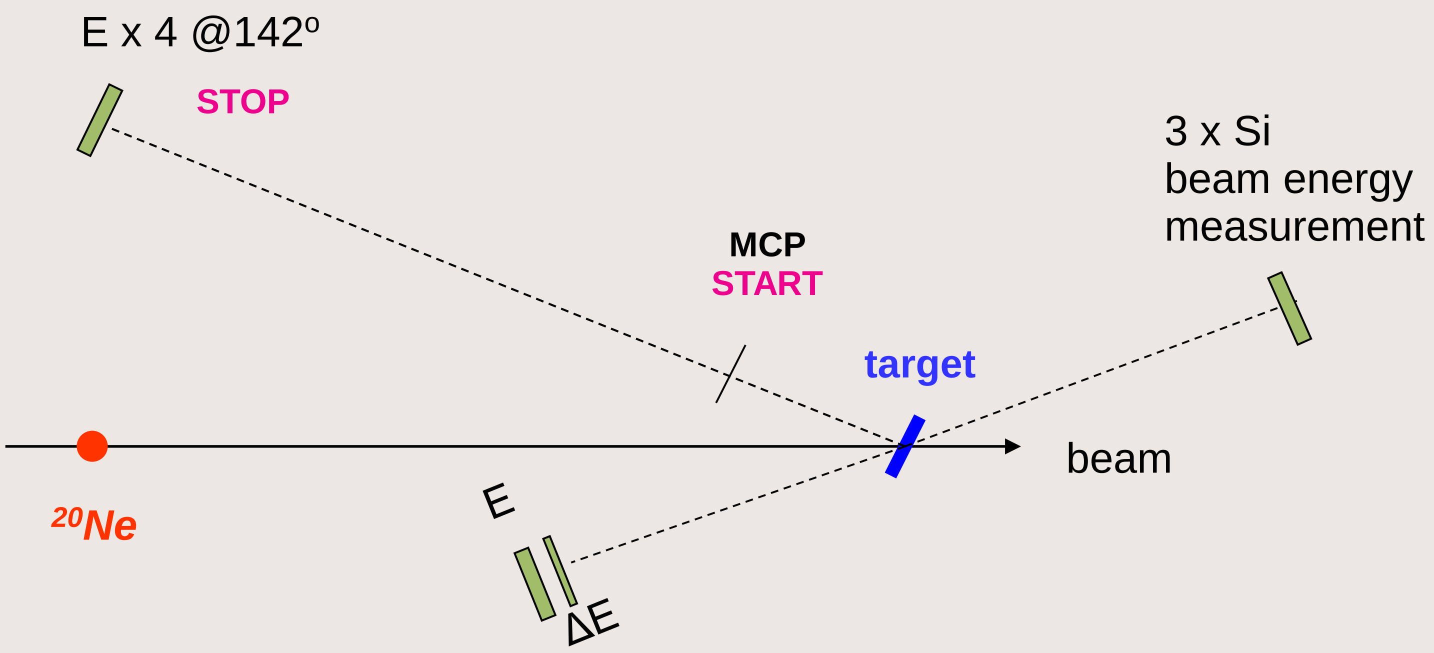
$^{20}Ne + ^{90,92}Zr$


experimental data
Coupled Channels
92Zr
90Zr
Dqe
0.20
0.16
0.12
0.08
0.04
0.00
44
48
52
56
60
Barrier height [MeV]

Transfer probablity measurements: ICARE @ HIL

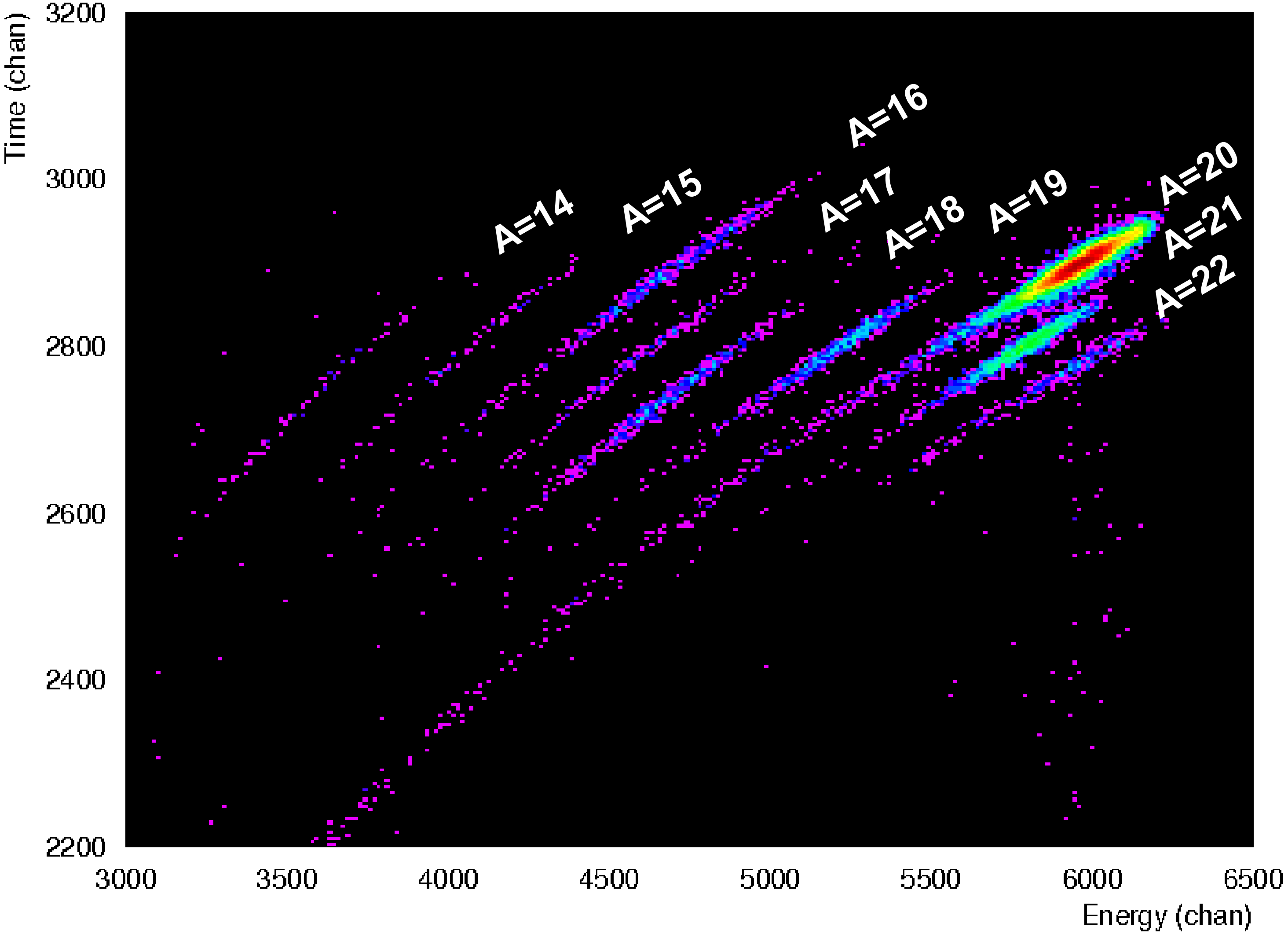


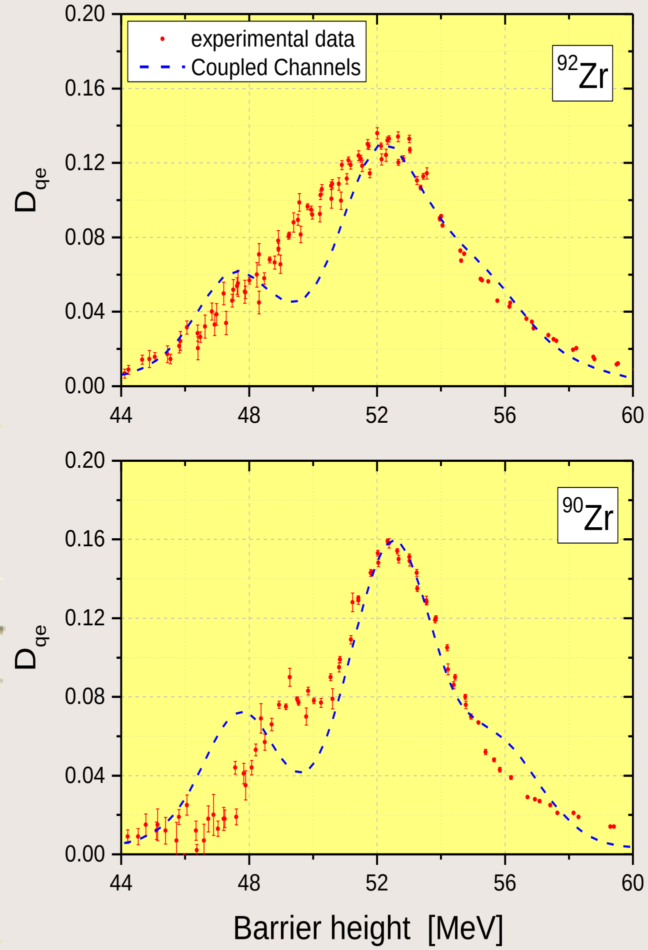
ToF @ ICARE

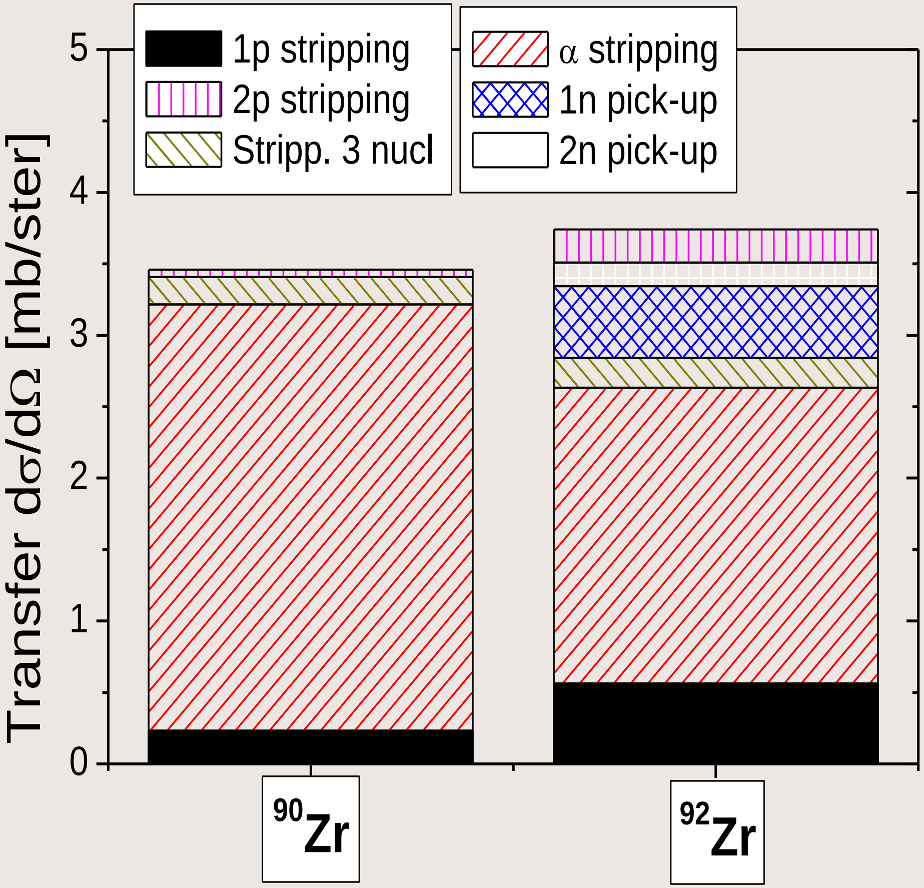

E x 4 @142°
STOP
3 x Si
beam energy
measurement
MCP
START
target
beam
20Ne
E
ΔE

Example of ToF vs energy spectrum

$^{20}Ne + ^{208}Pb$







E. Piasecki et al., Phys.Rev. C80 (2009) 054613

Our hypothesis: we see here the effect of

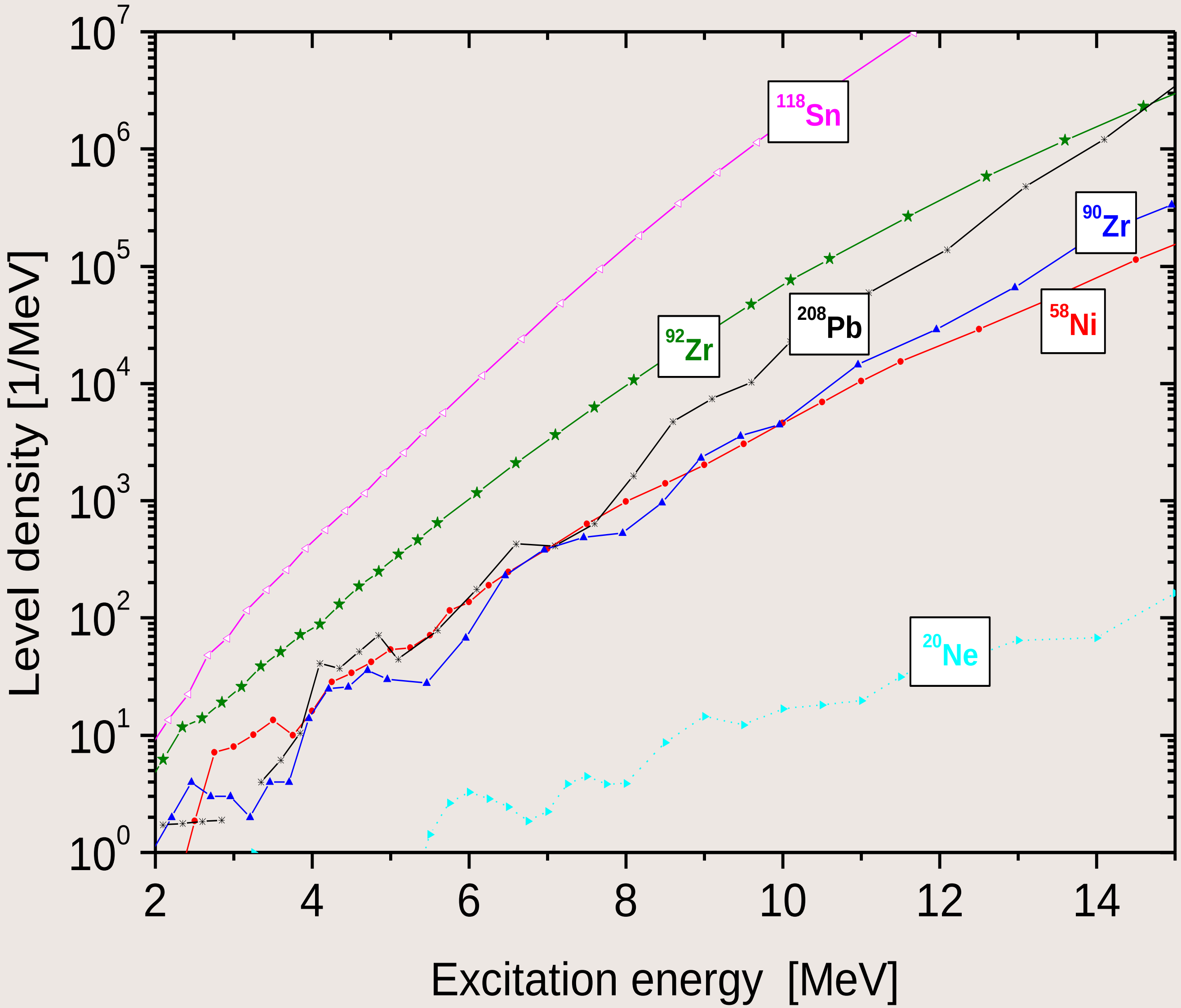
DISSIPATION

i.e.

excitation of many non-collective states

One can FIT imaginary potentials to describe both distributions, but what is the physics? (fusion + transfers + coll. & non-coll. excitations)

HFB calculations of s.p. level density



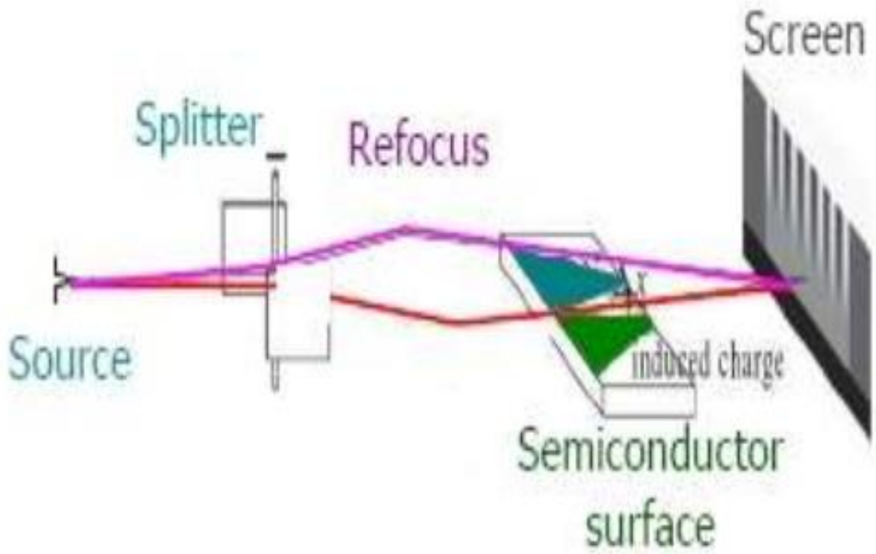
A. Diaz-Torres et al. (2007):

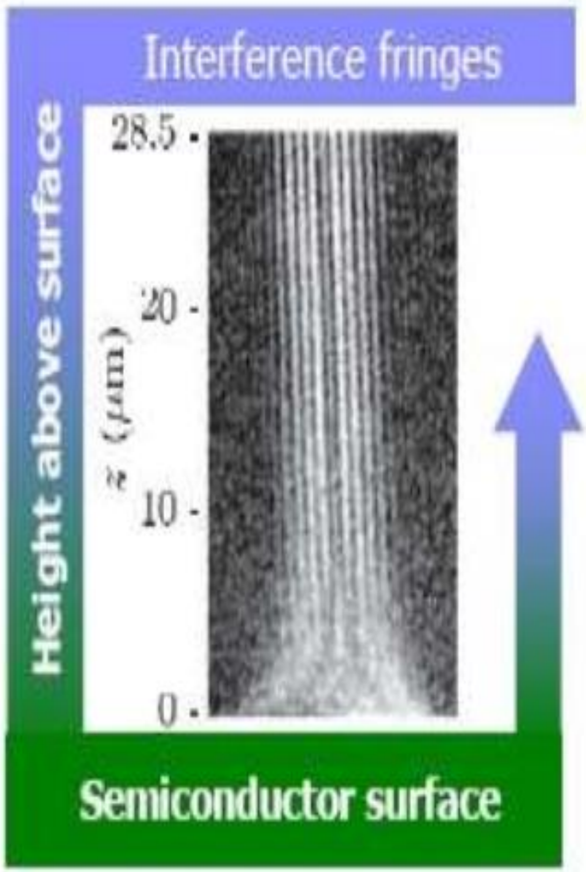
The Coupled Channels Model using Schrodinger equation describes reversible processes (coherent superposition of a few intrinsic states)

In reality we have irreversible damping of relative motion into many internal (collective and non-collective) degrees of freedom → dissipation

One can show that in quantum systems dissipation results in destruction of the coherent superposition (decoherence)

Double-slit type experiment with single electrons

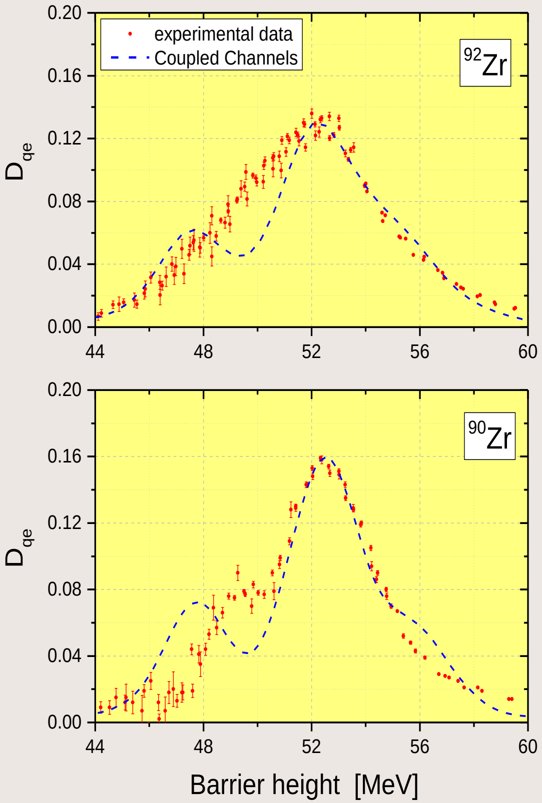




Sonnentag & Hasselbach, PRL **98** (2007) 200402

According to A. Diaz-Torres we see here: → the case of decoherence in nuclear physics

Proposed model of dissipative dynamics of open quantum systems: time dependent Coupled Channels Density-Matrix method which quantifies the role of quantum decoherence



One can prove that imaginary potential does not generate decoherence

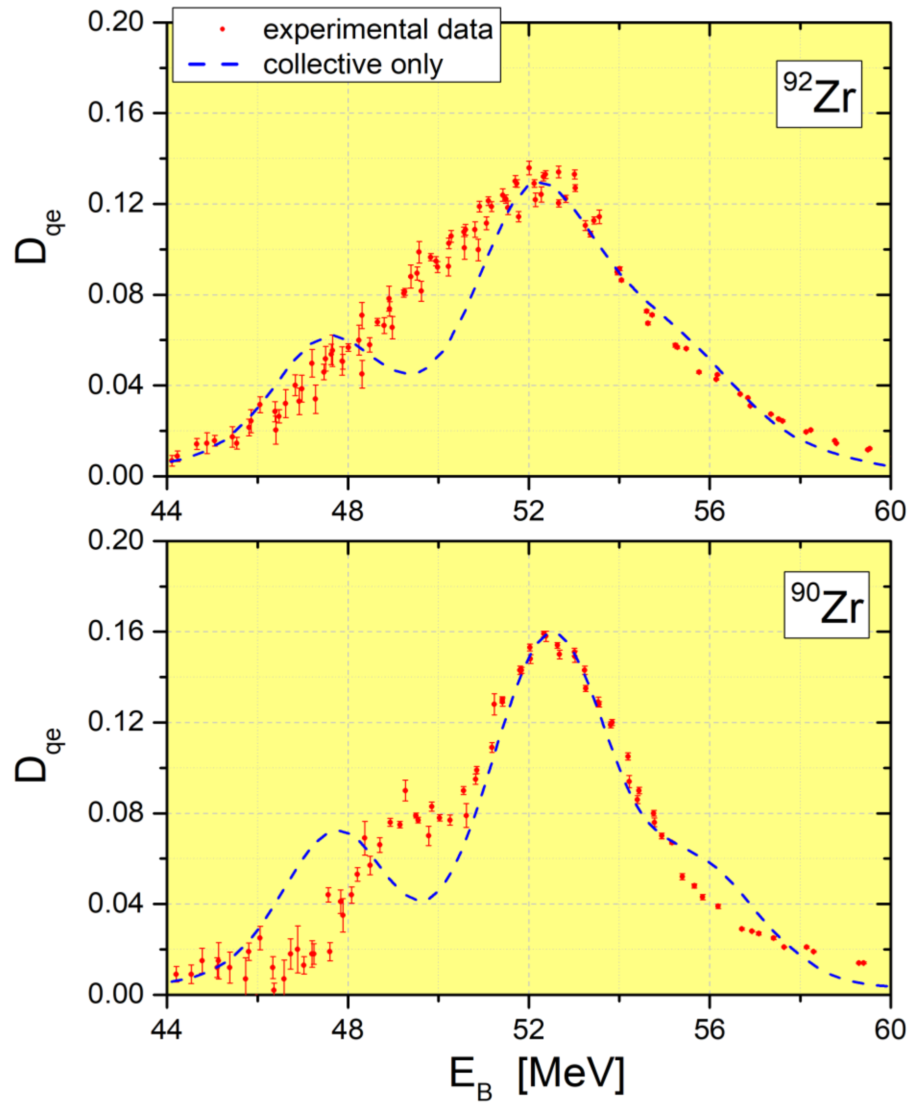
Beyond the standard (coherent) CC model:

Schrodinger equation → Lindblad equation, taking into account dissipation and decoherence

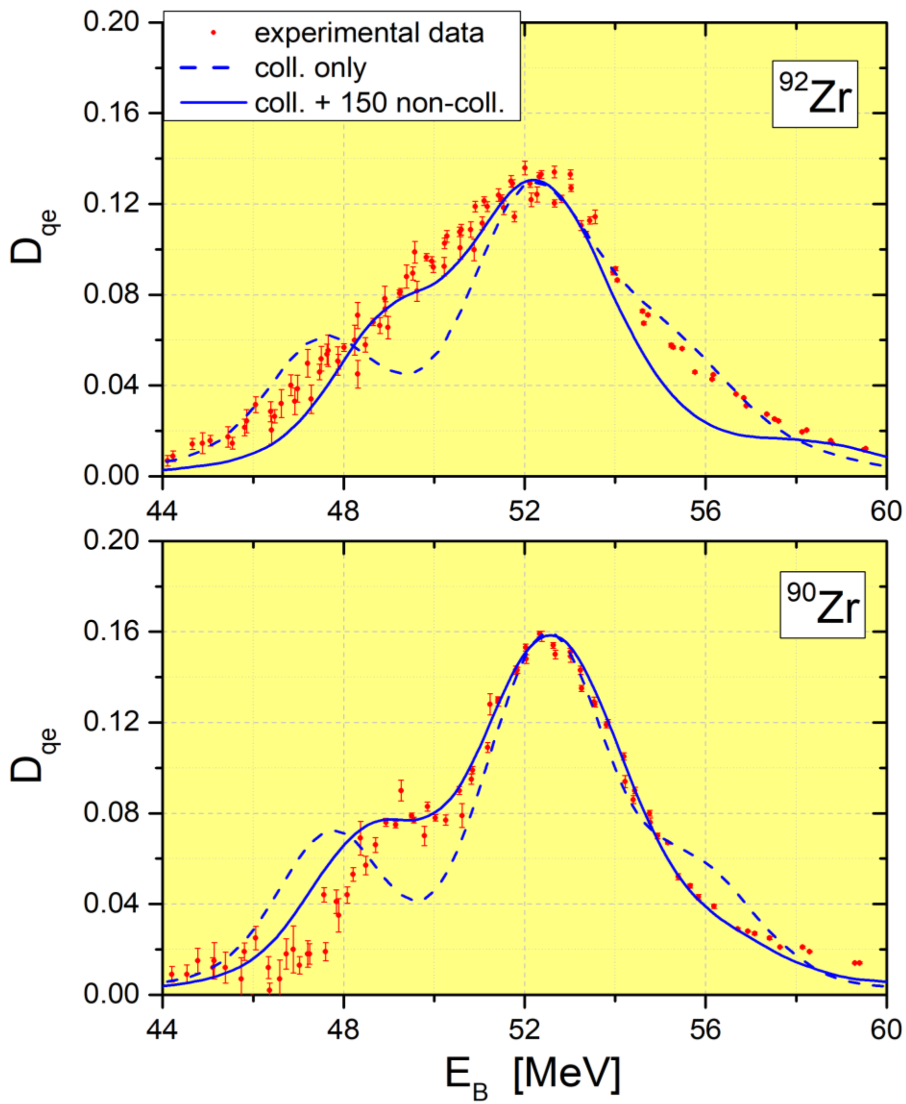
Coupled Channels +
Random Matrix Theory

S.Yusa, K.Hagino, N.Rowley
Phys. Rev. C88(2013)054621
(improved)

1 parameter fitted for all cases

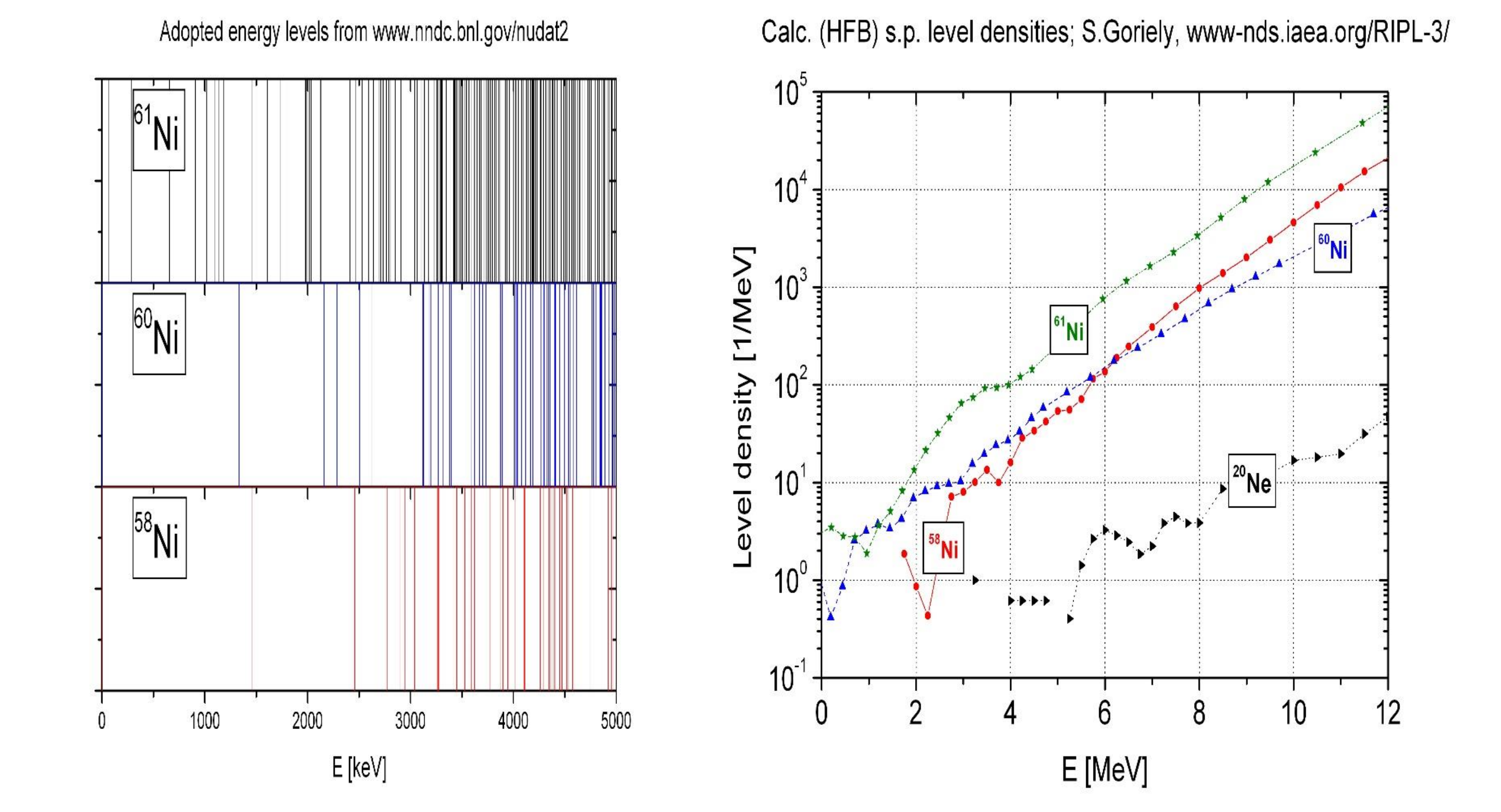


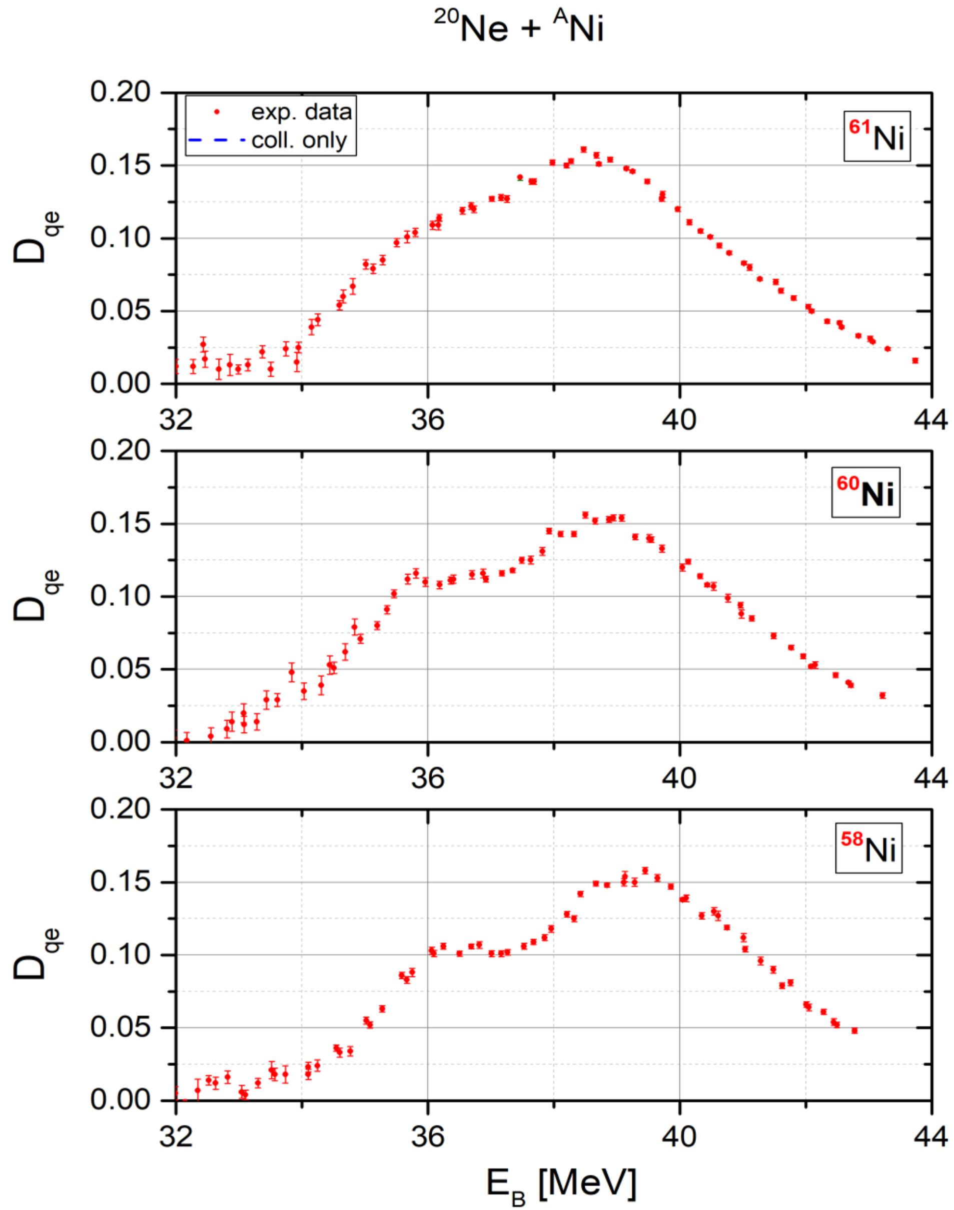
experimental data
collective only
^{92}Zr
^{90}Zr
D_{qe}
0.00
0.04
0.08
0.12
0.16
0.20
44
48
52
56
60
E_B [MeV]



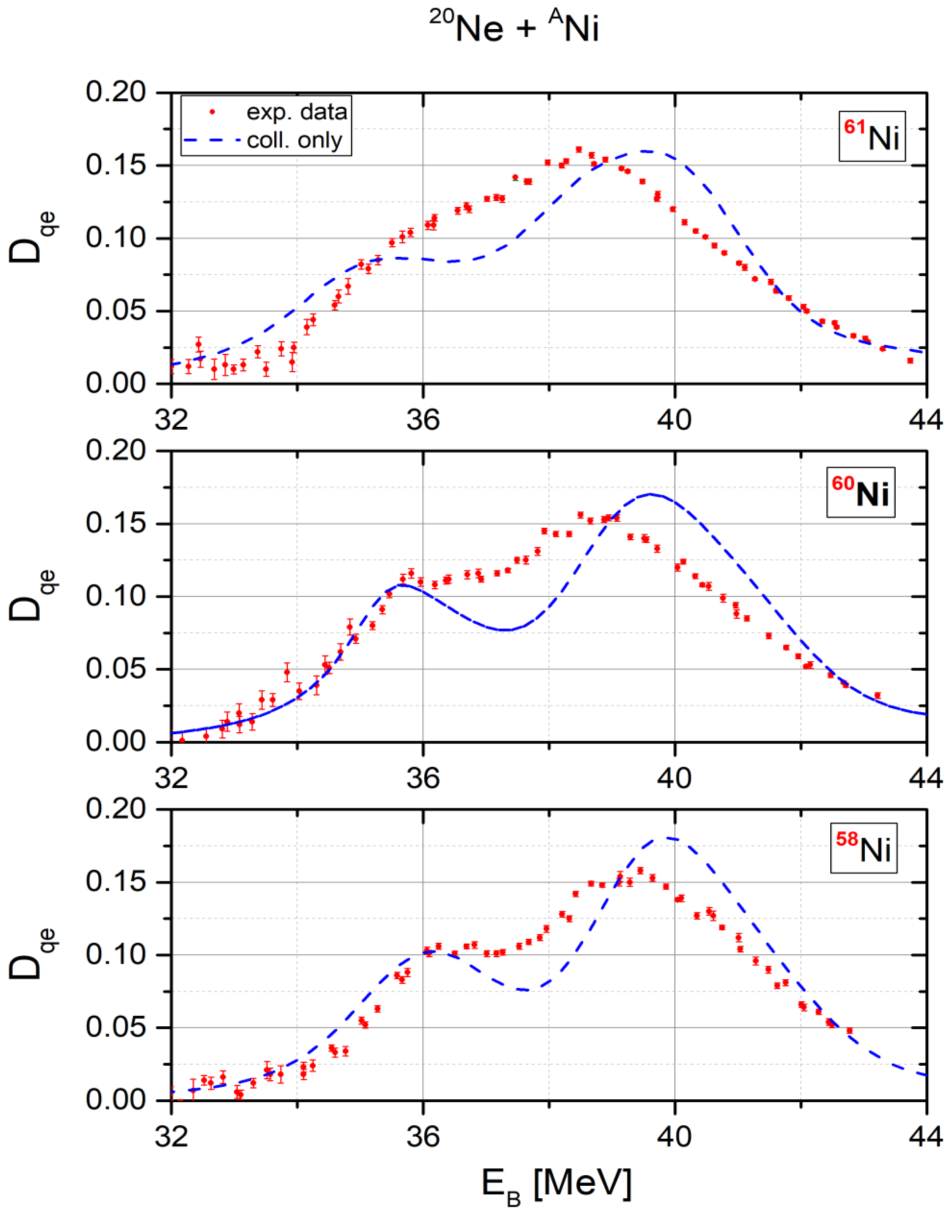
experimental data
coll. only
coll. + 150 non-coll.
92Zr
90Zr
Dqe
EB [MeV]
0.00
0.04
0.08
0.12
0.16
0.20
44
48
52
56
60

Test: $^{20}Ne + ^{58,60,61}Ni$



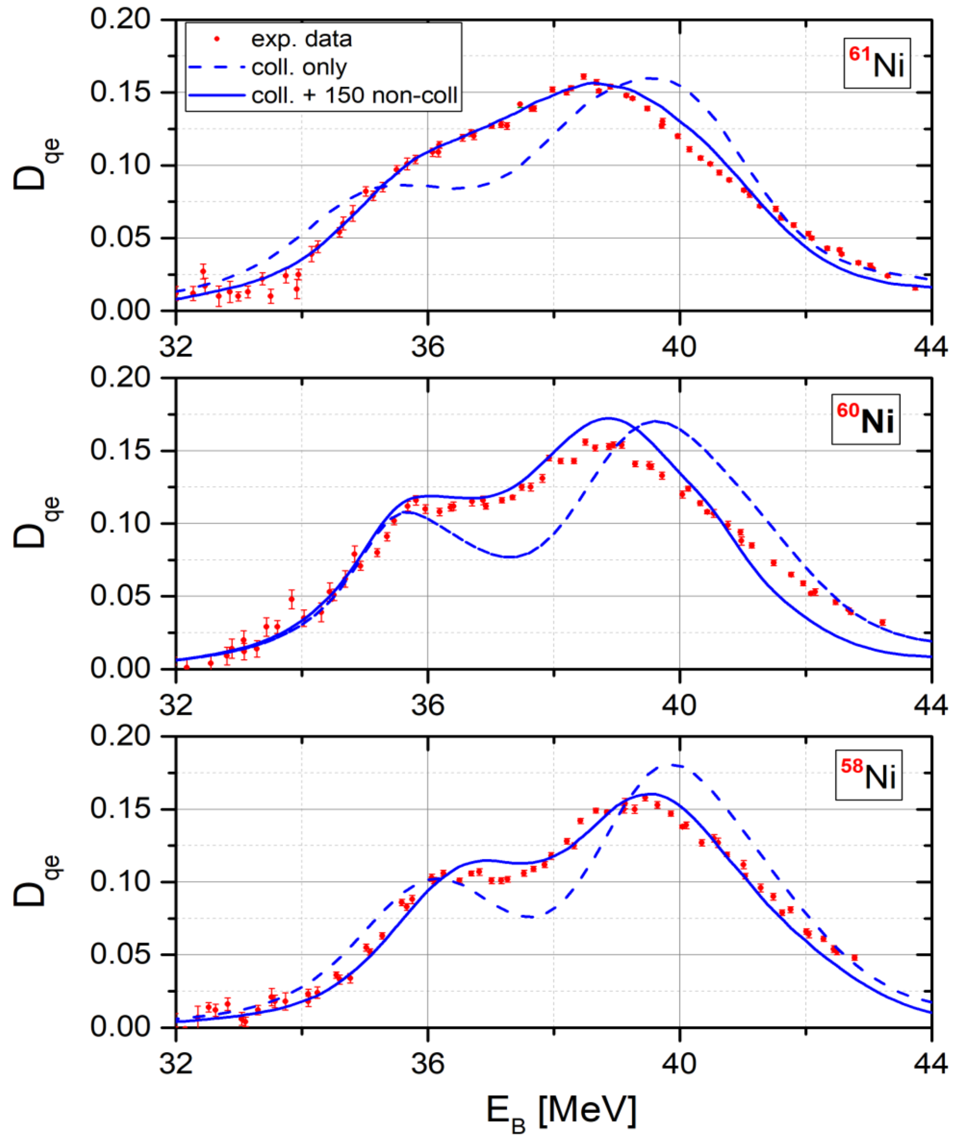


^{20}Ne + ^{A}Ni
exp. data
coll. only
^{61}Ni
^{60}Ni
^{58}Ni
D_{qe}
0.00
0.05
0.10
0.15
0.20
32
36
40
44
E_B [MeV]



20Ne + ANi
exp. data
coll. only
61Ni
60Ni
58Ni
Dqe
0.20
0.15
0.10
0.05
0.00
32
36
40
44
EB [MeV]

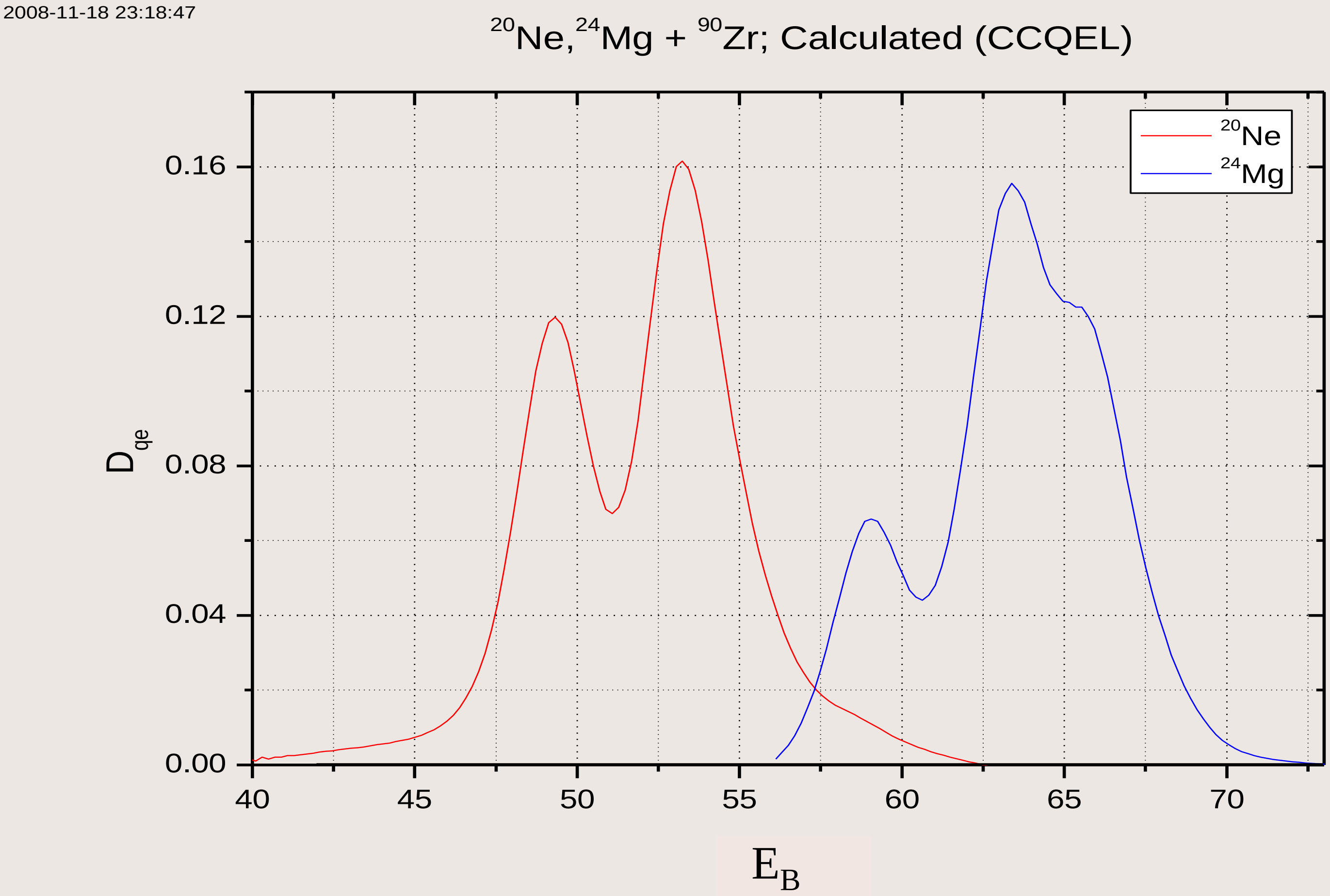
$^{20}Ne + {}^{A}Ni$



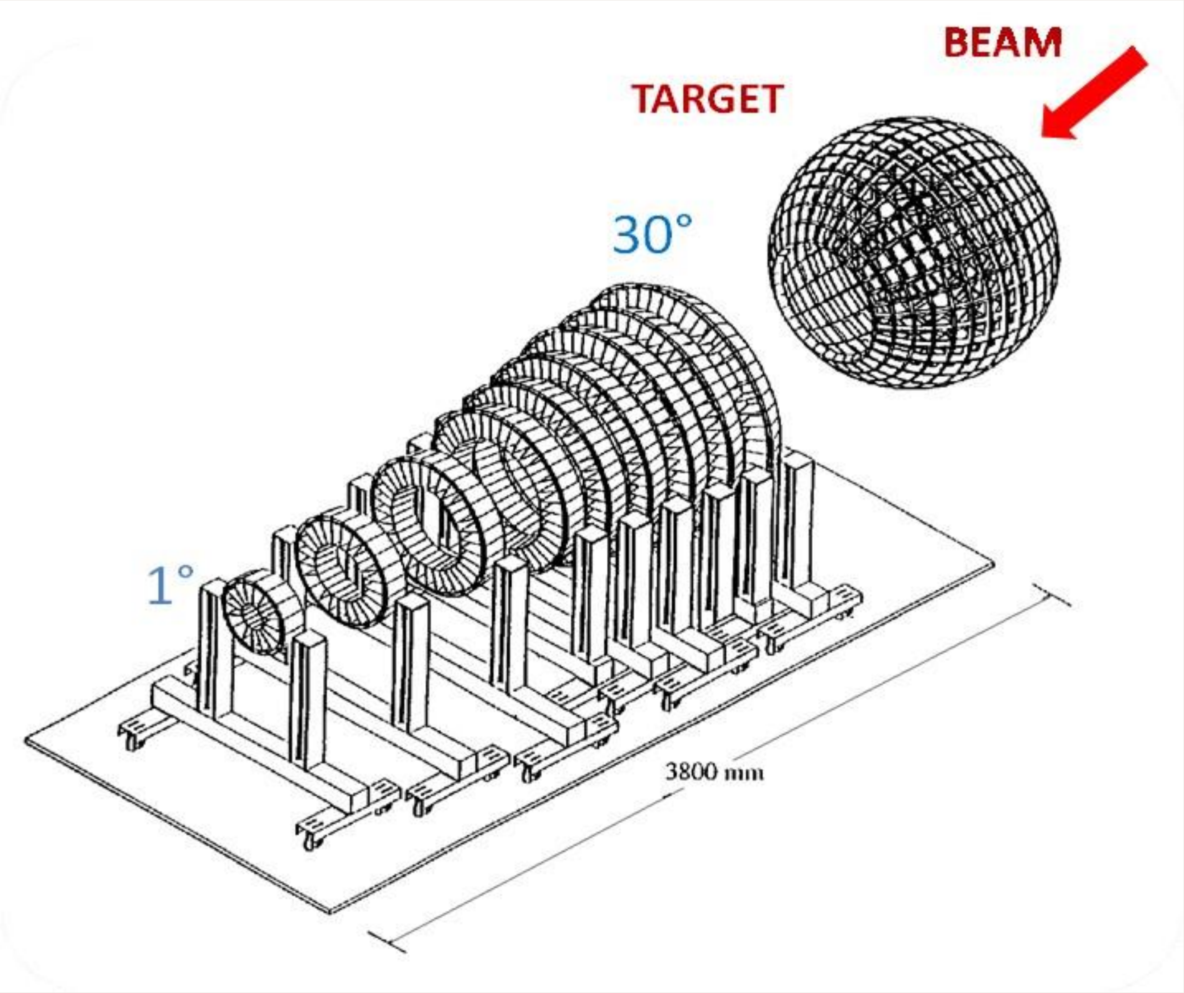
exp. data
coll. only
coll. + 150 non-coll
61Ni
60Ni
58Ni
Dqe
EB [MeV]
0.20
0.15
0.10
0.05
0.00
32
36
40
44

Is ^{20}Ne unique?
^{24}Mg consists of 6 α – clusters & is strongly deformed

To increase experimental information we would like to measure D_{qe} for ^{24}Mg + ^{90,92}Zr

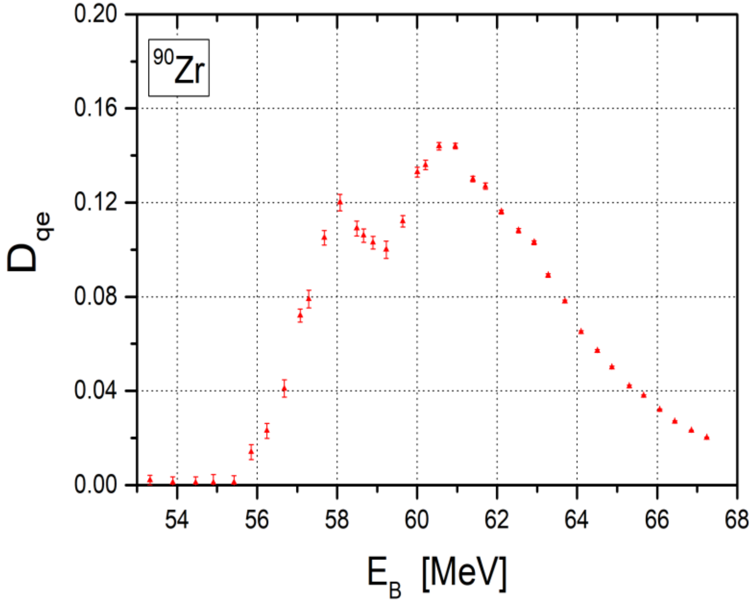


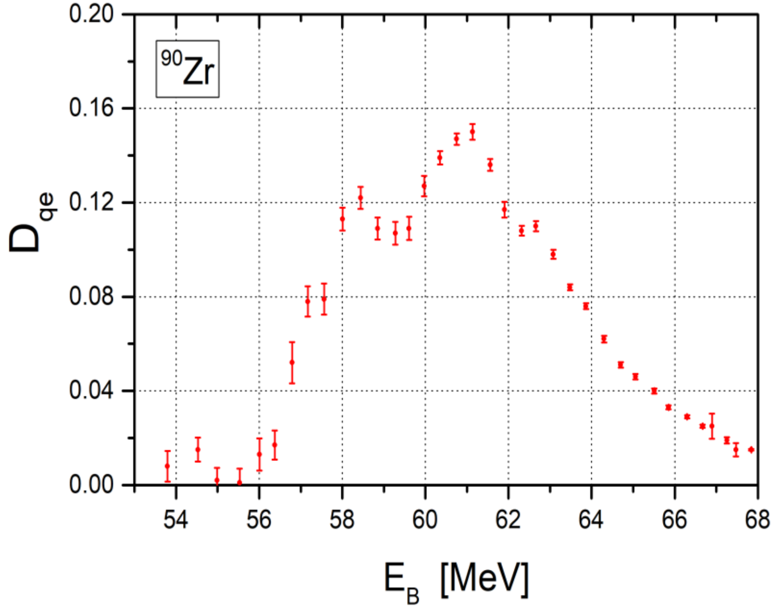
CHIMERA (LNS – Catania)

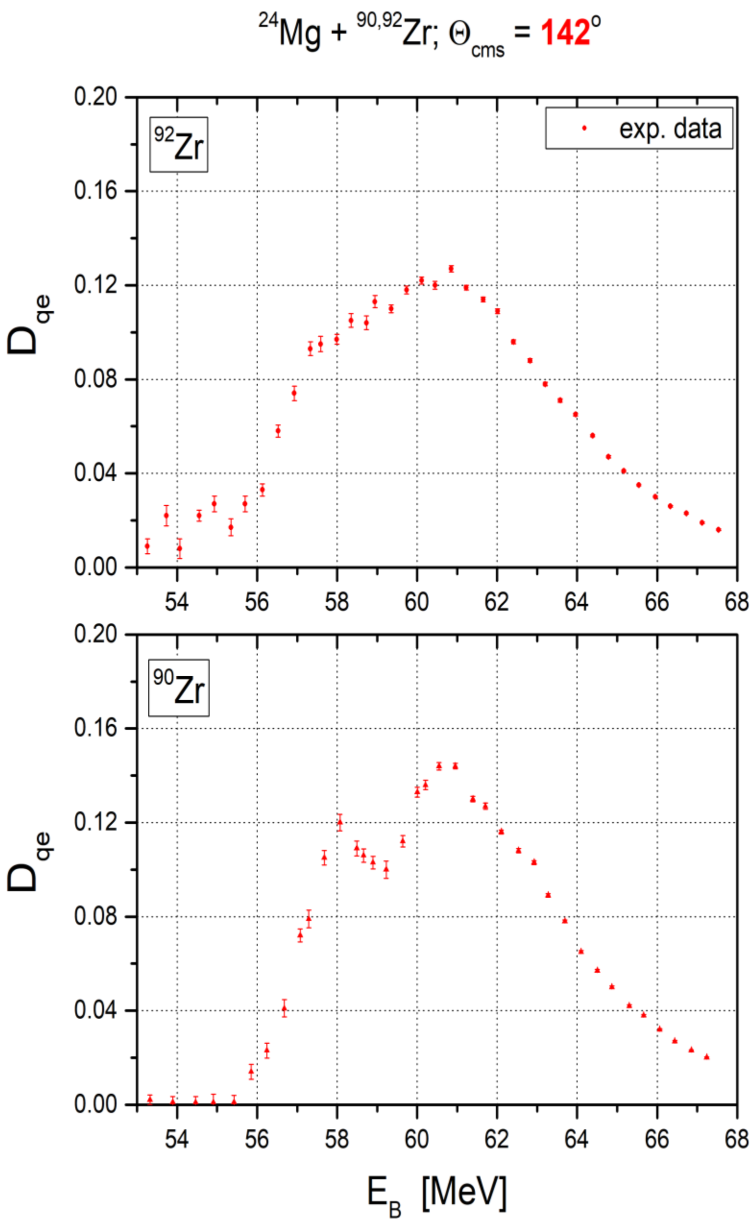


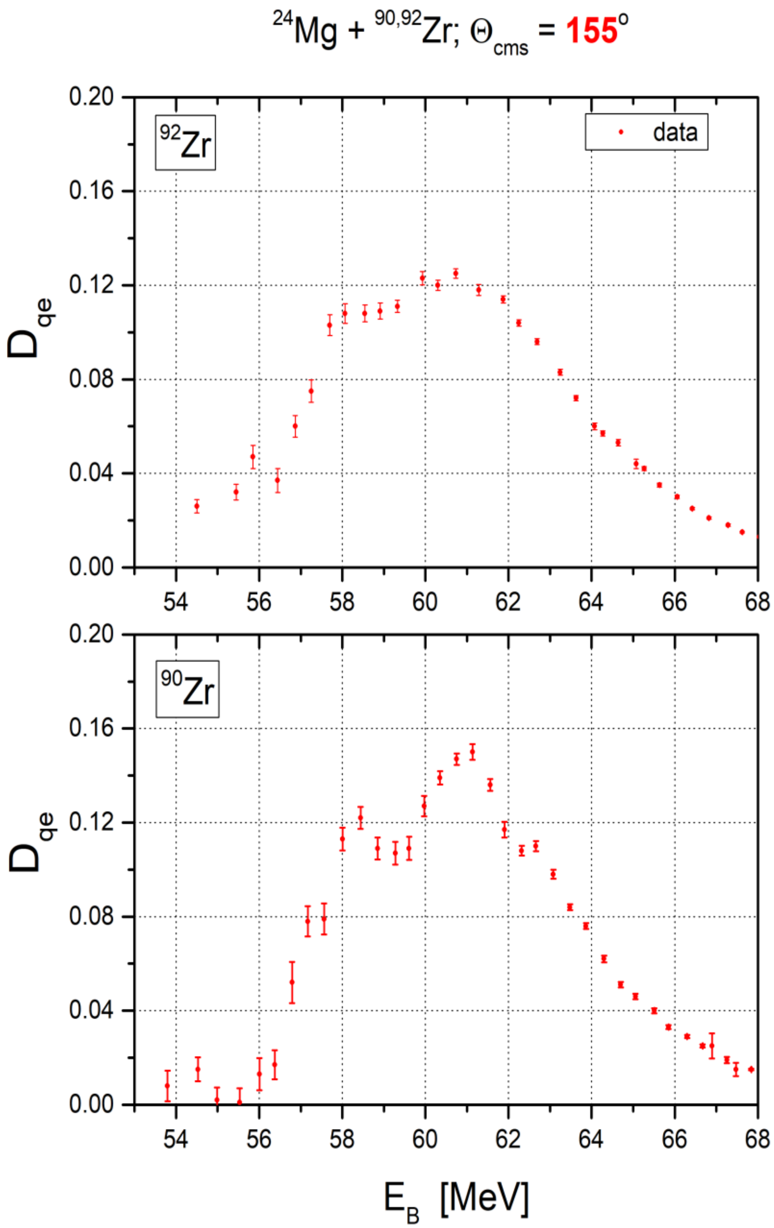
$^{24}Mg + {}^{90,92}Zr$; Θ_{cms} = **142°**

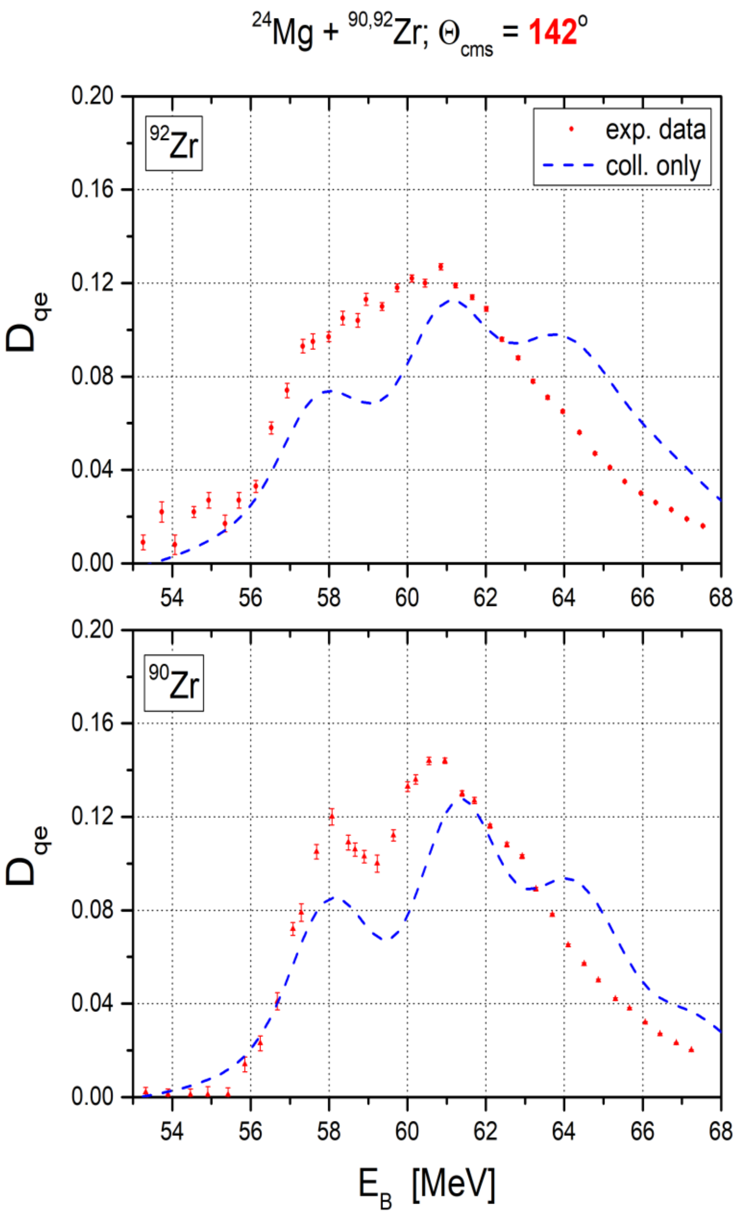
$^{24}Mg + {}^{90,92}Zr$; Θ_{cms} = **155°**

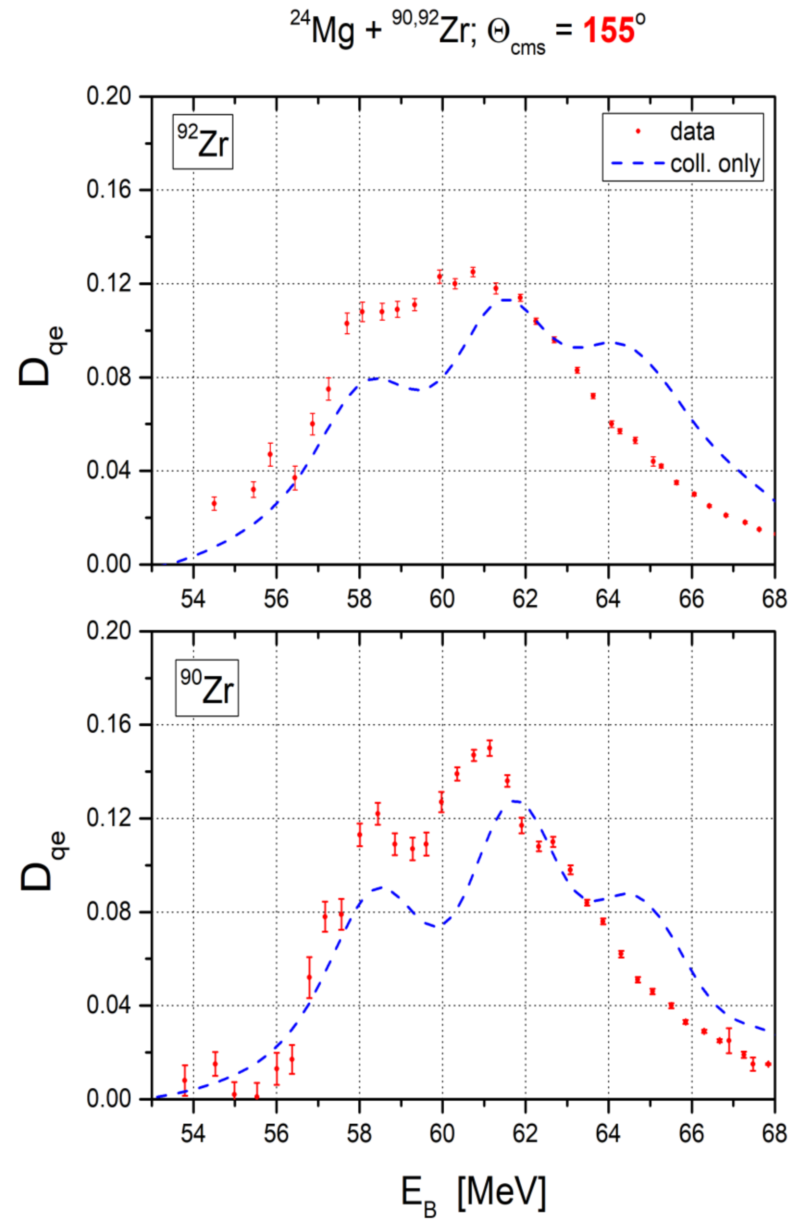




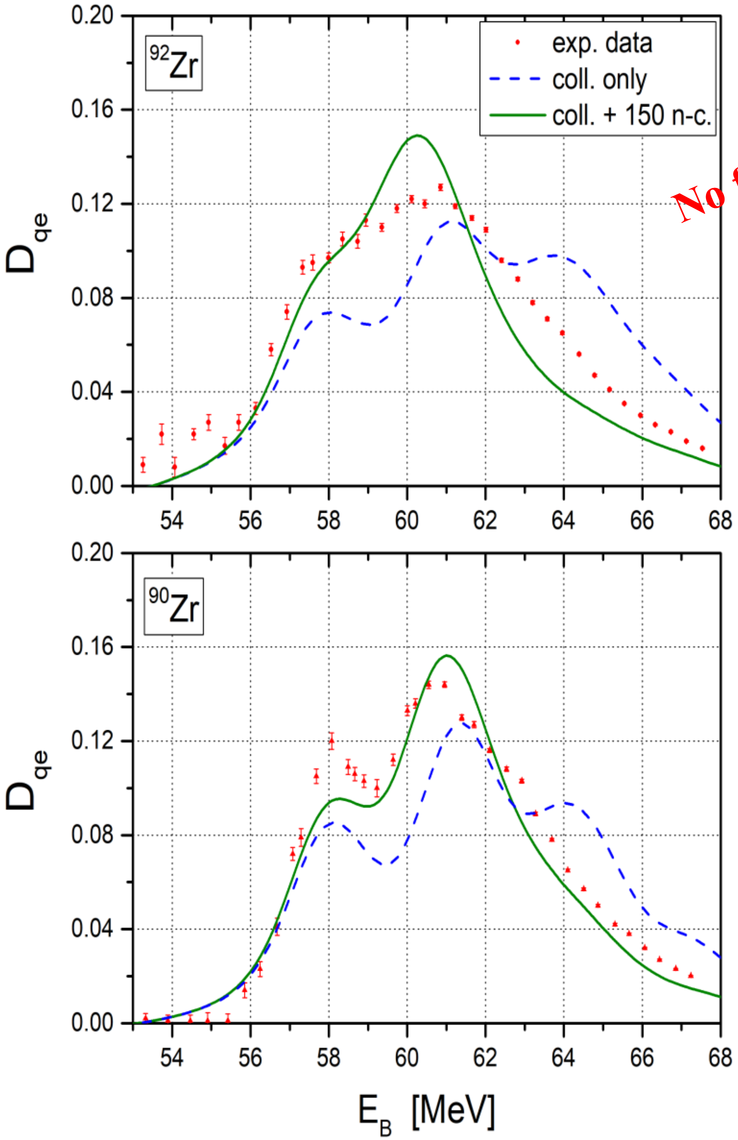

$^{24}Mg + ^{90,92}Zr; \Theta_{cms}$ = 142°
^{92}Zr
exp. data
^{90}Zr
D_{qe}
E_B [MeV]
0.00
0.04
0.08
0.12
0.16
0.20
54
56
58
60
62
64
66
68


$^{24}Mg + ^{90,92}Zr; \Theta_{cms}$ = 155°
^{92}Zr
data
^{90}Zr
D_{qe}
E_B [MeV]
0.00
0.04
0.08
0.12
0.16
0.20
54
56
58
60
62
64
66
68


$^{24}Mg + ^{90,92}Zr; \Theta_{cms} = 142^o$
^{92}Zr
exp. data
coll. only
^{90}Zr
D_{qe}
E_B [MeV]

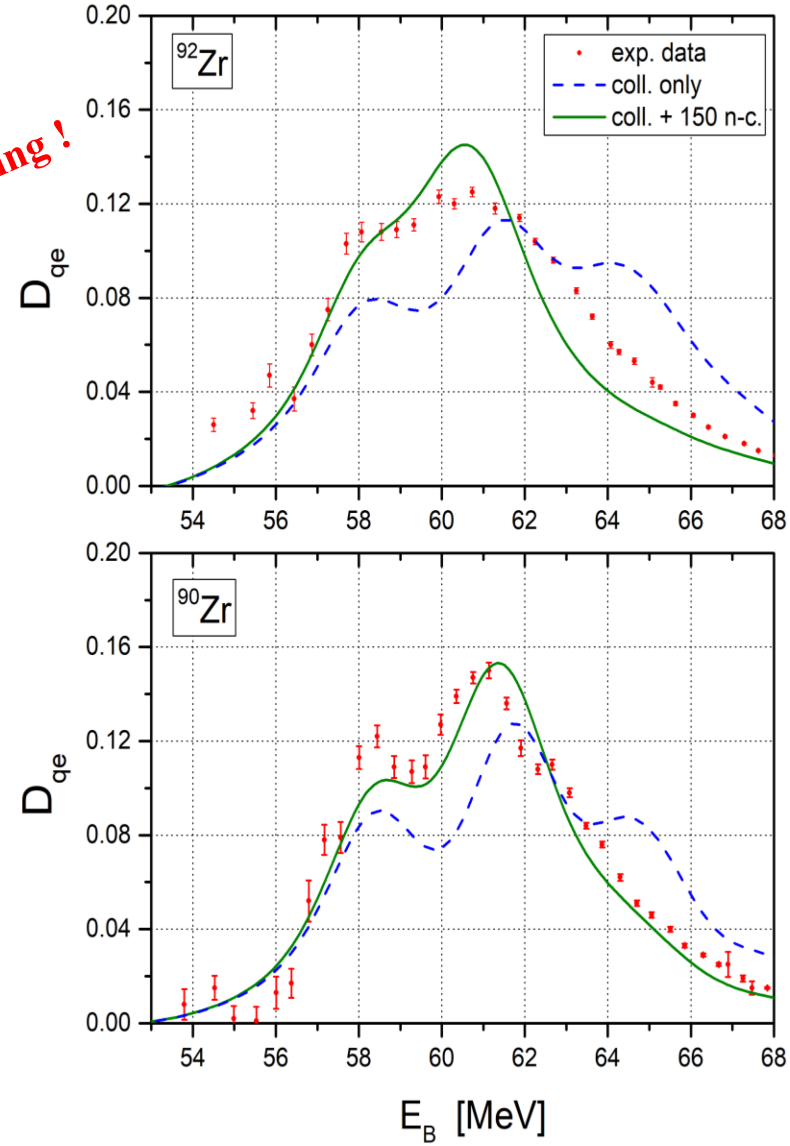

$^{24}Mg + ^{90,92}Zr; \Theta_{cms} = 155^o$
^{92}Zr
data
coll. only
^{90}Zr
D_{qe}
E_B [MeV]

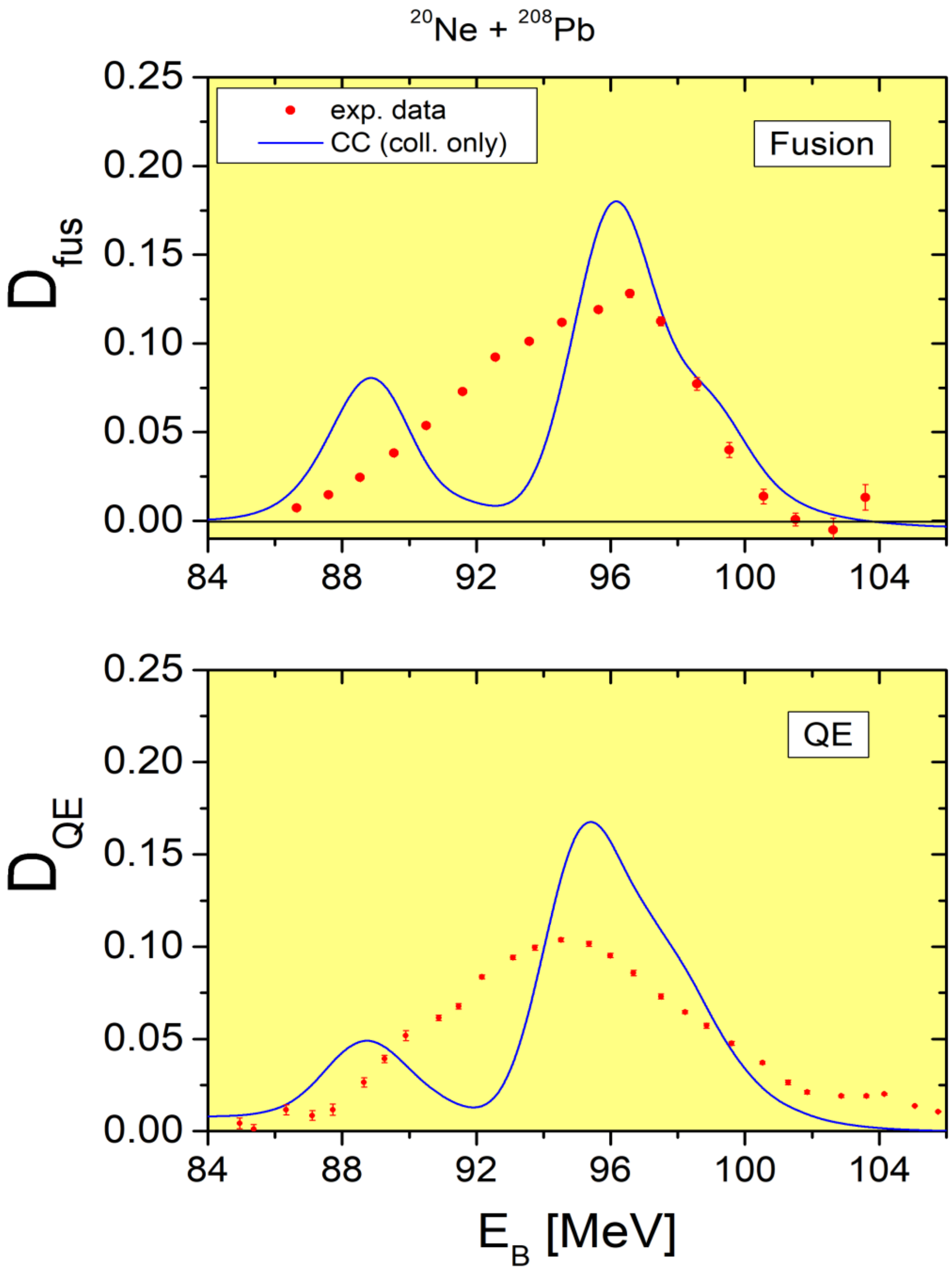
^{24}Mg + ^{90,92}Zr; Θ_{cms} = **142^{o}**



No fitting !

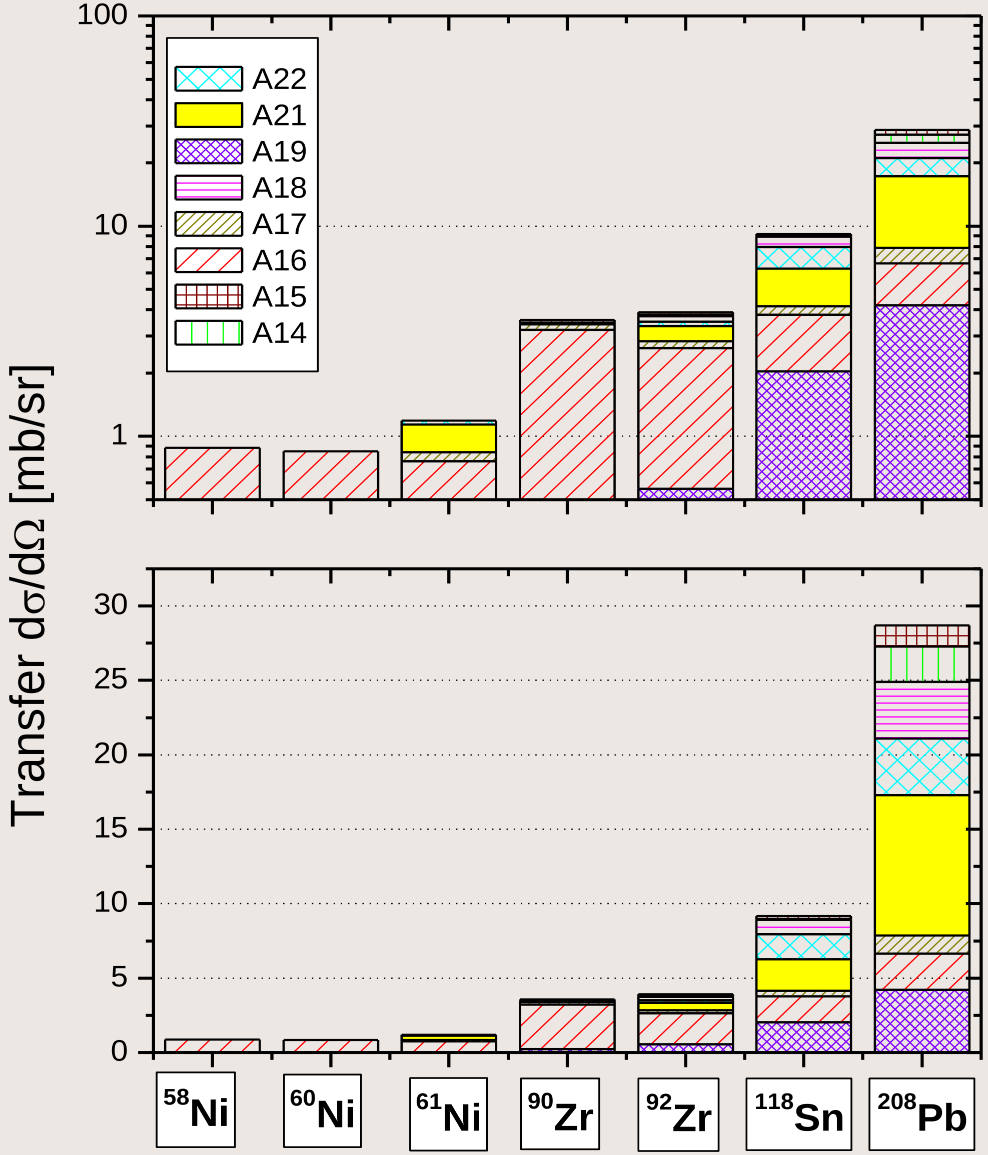
^{24}Mg + ^{90,92}Zr; Θ_{cms} = **155^{o}**





$^{20}Ne + ^{208}Pb$
exp. data
CC (coll. only)
Fusion
D_{fus}
0.25
0.20
0.15
0.10
0.05
0.00
84
88
92
96
100
104
QE
D_{QE}
E_B [MeV]

$^{20}Ne + X$



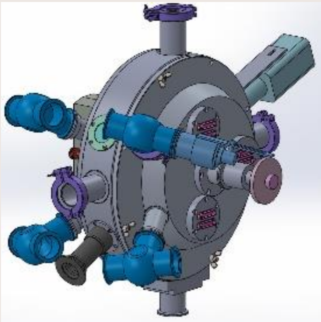
Transfer dσ/dΩ [mb/sr]
100
10
1
A22
A21
A19
A18
A17
A16
A15
A14
30
25
20
15
10
5
0
58Ni
60Ni
61Ni
90Zr
92Zr
118Sn
208Pb

What next?

1. Barrier distribution in backscattering $^{58}Ni + ^{60}Ni$
2. Influence of transfer on barrier distribution (Gurpreet's proposal) :

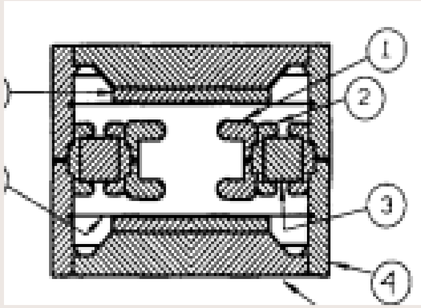
   $^{40}Ar + ^{142}Ce, ^{142}Nd$

   $^{20}Ne + ^{142}Ce, ^{142}Nd$



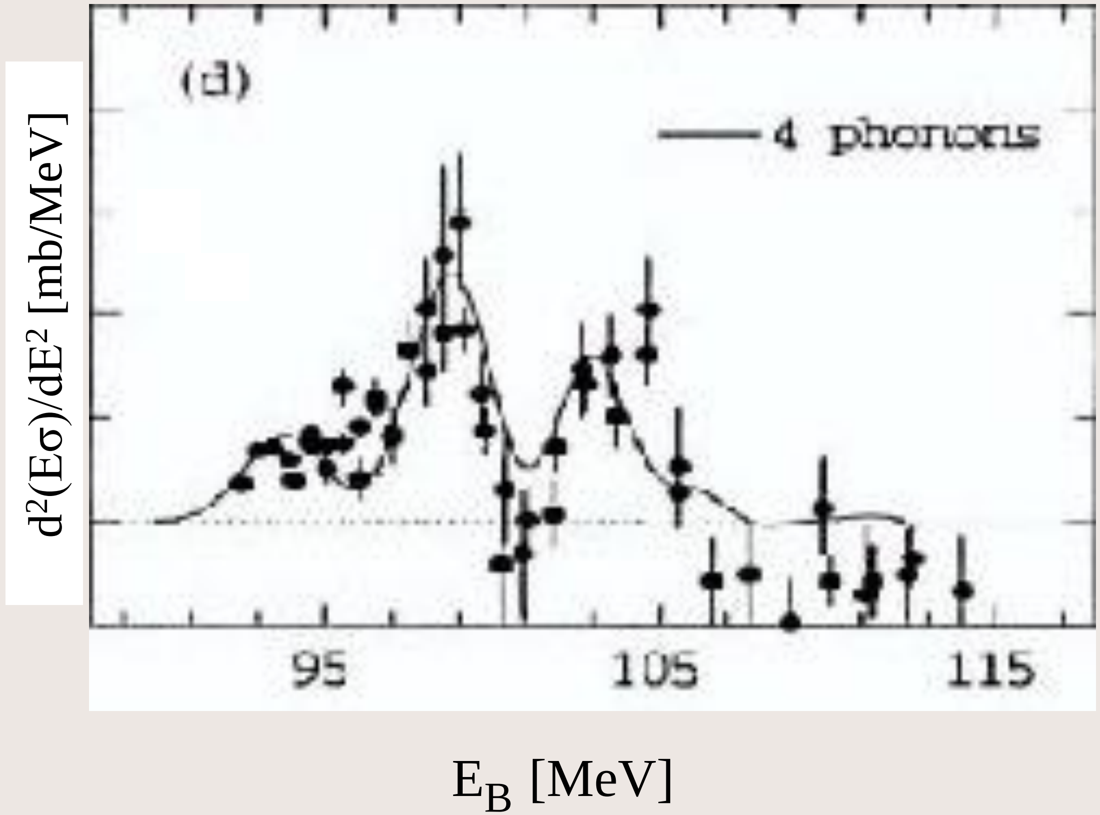
3. Fusion barrier distribution in $^{24}Mg + ^{90,92}Zr$

   Velocity Filter, Catania



4. CC-RMT calculations

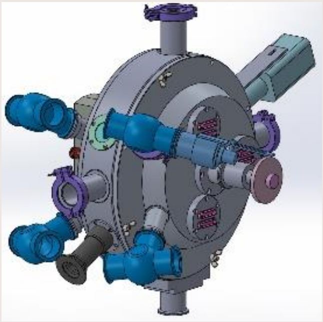
$^{58}Ni + ^{60}Ni$



A.M.Stefanini et al.., PRL 74(1995)865

What next?

1. Barrier distribution in backscattering $^{58}Ni + ^{60}Ni$
2. Influence of transfer on barrier distribution (Gurpreet's proposal) :

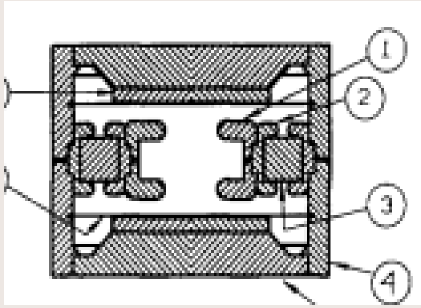


   $^{40}Ar + ^{142}Ce, ^{142}Nd$

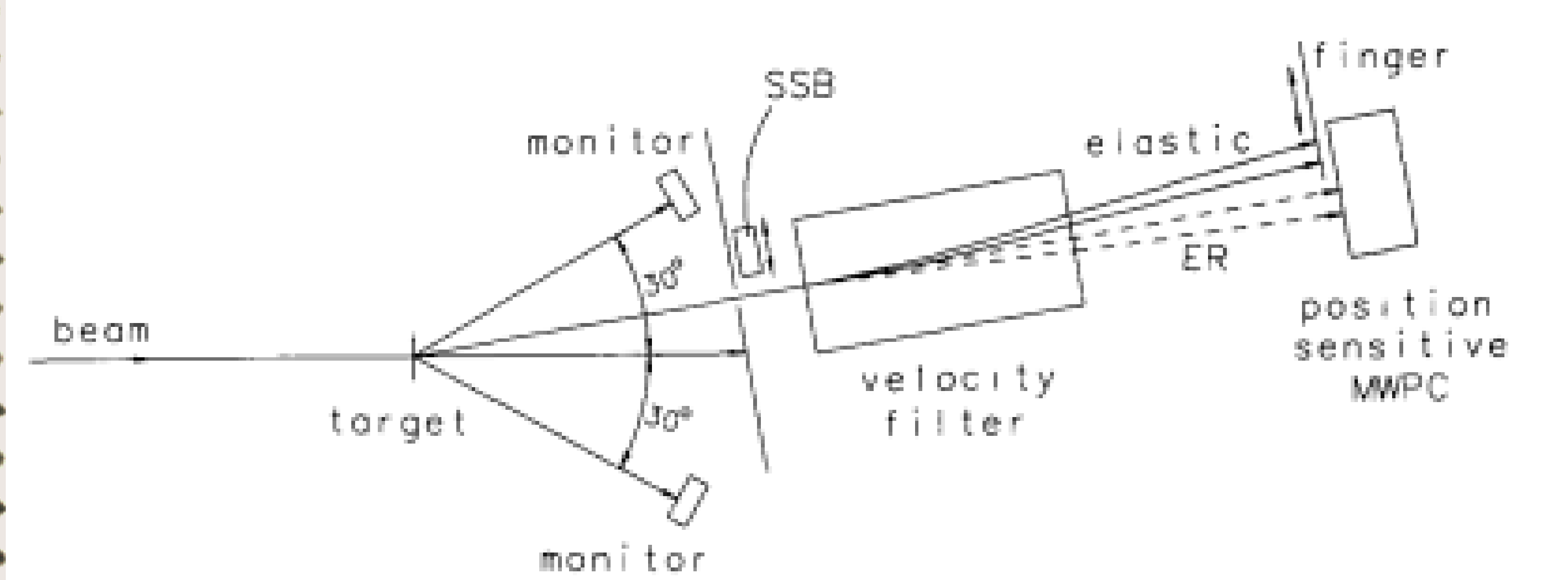
   $^{20}Ne + ^{142}Ce, ^{142}Nd$

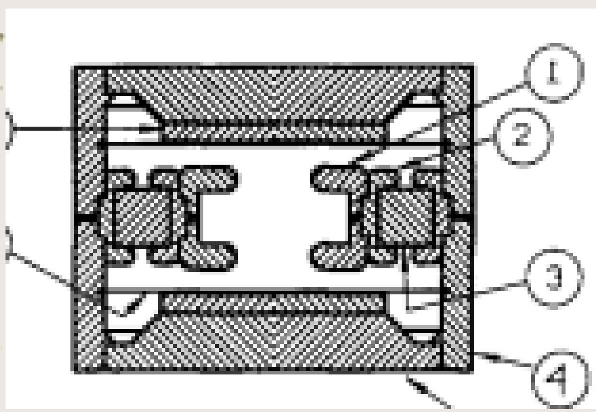
3. Fusion barrier distribution in $^{24}Mg + ^{90,92}Zr$

Velocity Filter, Catania

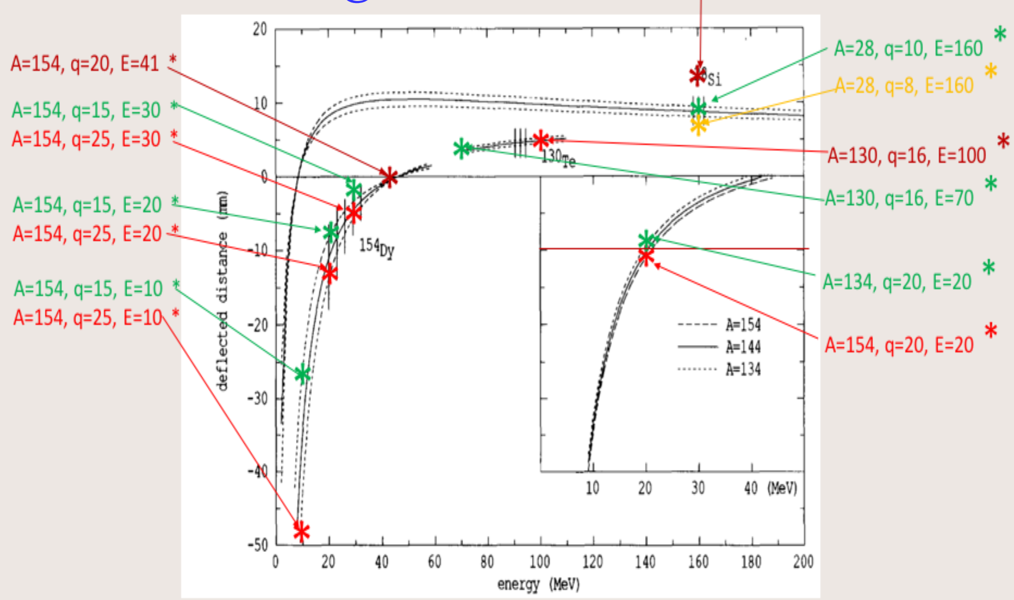


4. CC-RMT calculations





$^{28}Si + ^{130}Te$ @ 160 MeV




fragile

Conclusions:

- *The weak (non-collective) couplings can considerably influence the barrier height distributions*
- *We can predict when the effect is dominated by transfers or s.p. excitations*
- *These couplings can also influence σ_{fus} and scattering angular distributions*

•*Open question: do we observe decoherence phenomenon?*

- *Theory:*

- *necessity of improved taking into account dissipation (s.p. excitations) via coupling of Statistical Physics with Quantum Mechanics and/or*
- *taking into account also decoherence (time dependent dissipative dynamics of open systems)*

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