# *Barrier Height Distribution Studies at HIL*


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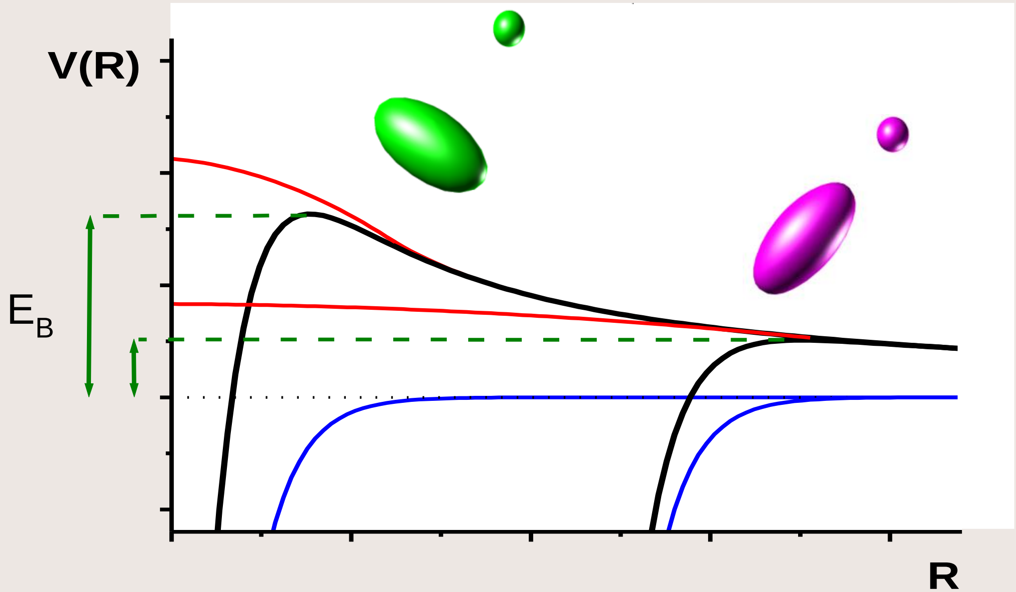
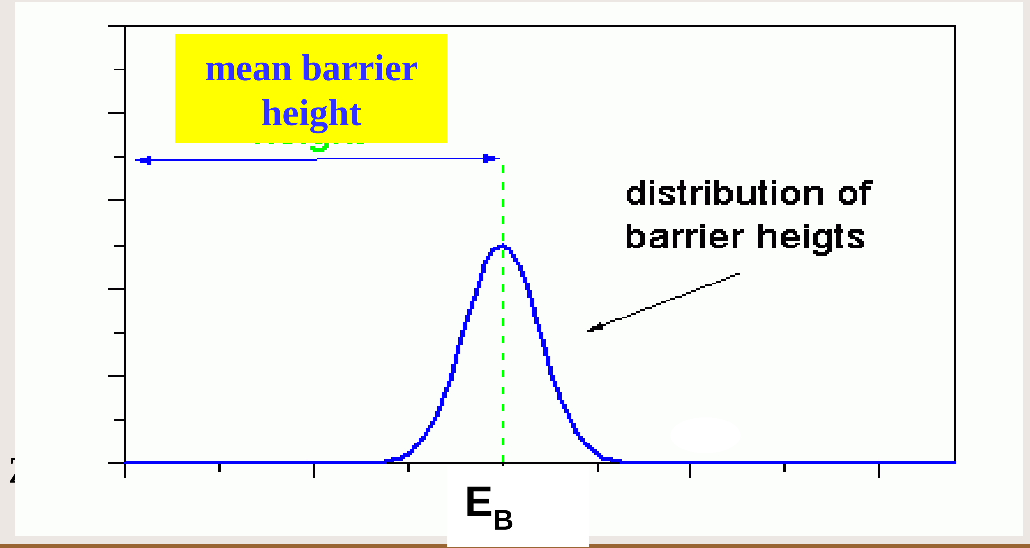
# Classical explanation of barrier distribution



**COUPLED CHANNELS MODEL:**
**coupling between relative motion and a few, usually collective states**

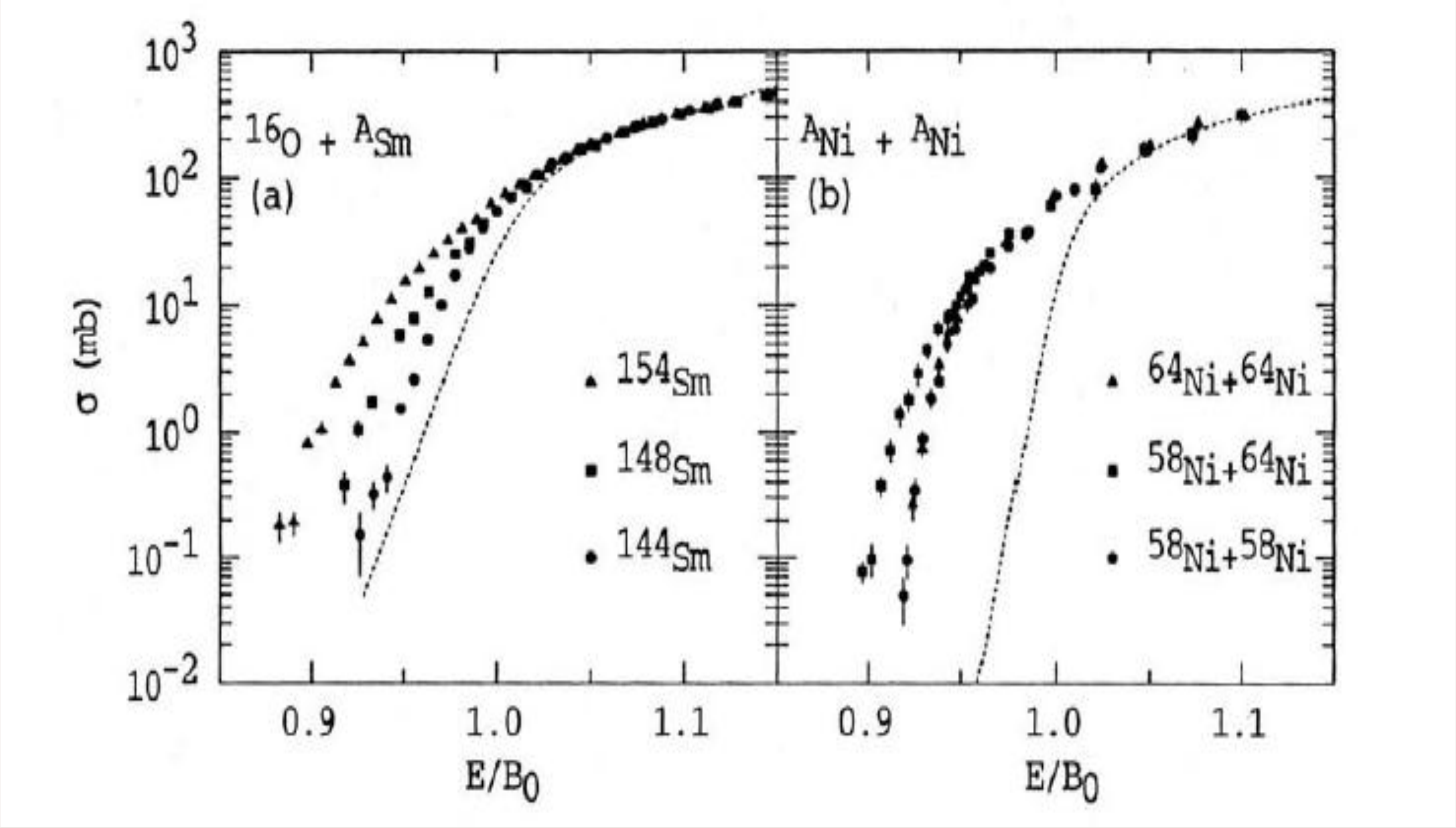
**coherent superposition of collective states**

$\Downarrow$

**potential barrier splits into many barriers**

$\Downarrow$

**fusion ENHANCEMENT**




**Main review: M. Dasgupta et al., Annu.Rev.Nucl.Sci. 48 (1998) 41**

# The proof of quantal nature of the phenomenon: even for undeformed nuclei...

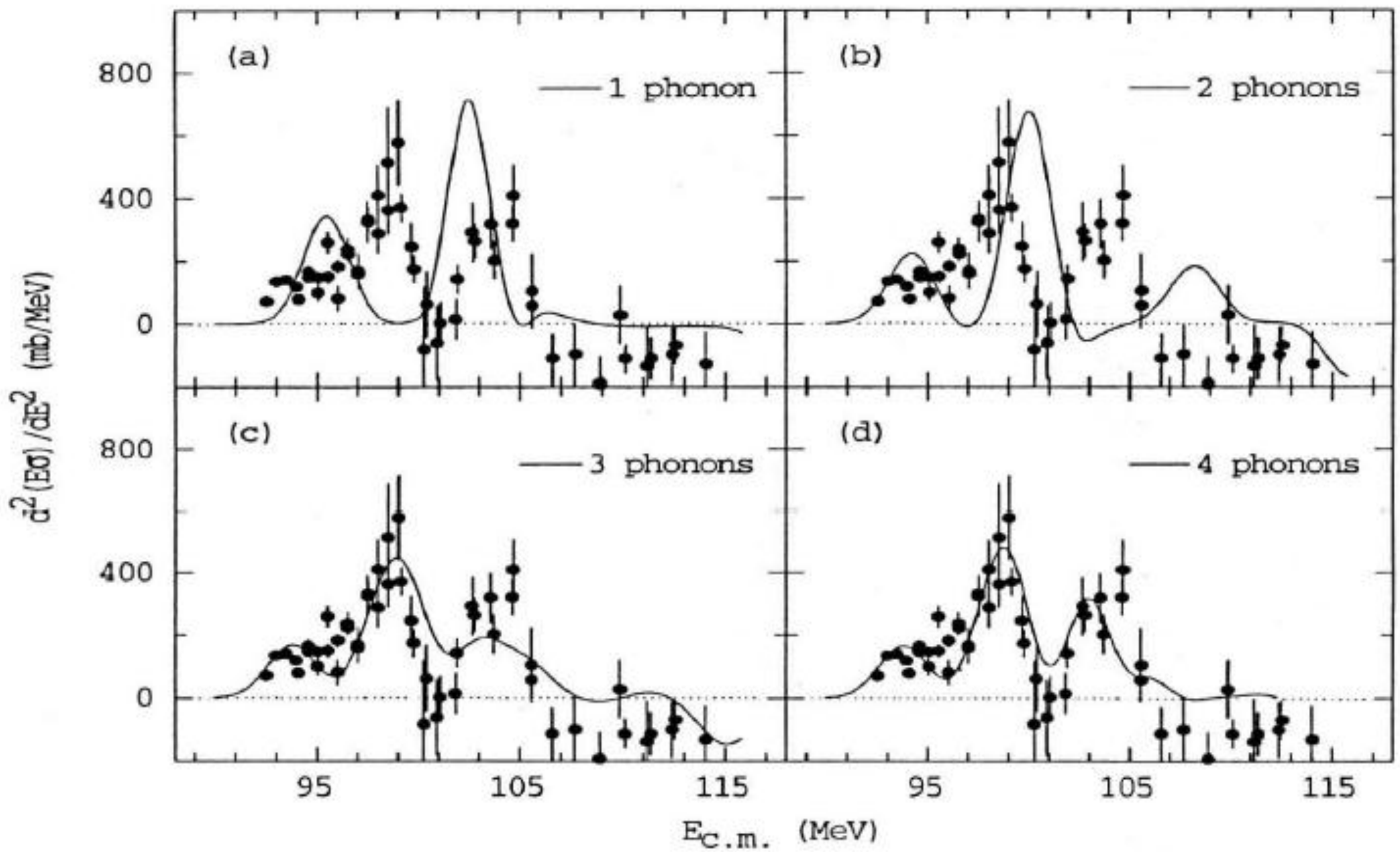



Fig. 2. The fusion barrier distributions of $^{58}Ni + ^{60}Ni$, compared with the results of coupled-channels calculations in the one-, two-, three-, and four-phonon spaces.

**A.M.Stefanini et al., Phys.Rev.Lett., 74, 864(1995)**

# Motivation

- Tunneling is influenced by environment

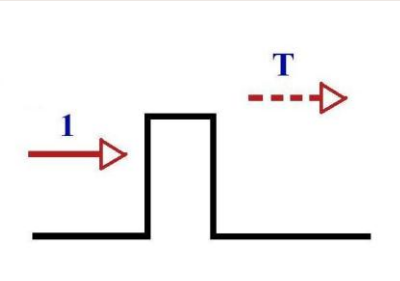
(in nuclear phys. environment = nuclear structure)

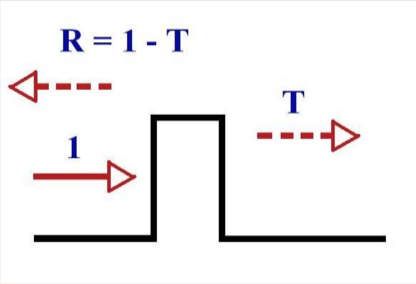
- **Barrier distribution** is a fingerprint of the couplings between reaction channels

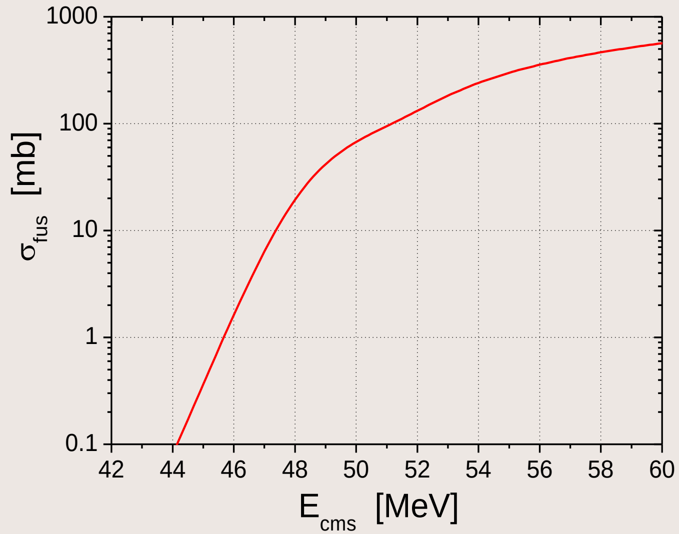
- Testing of Coupled Channels Method with strong channels(*) explicitly taken into account

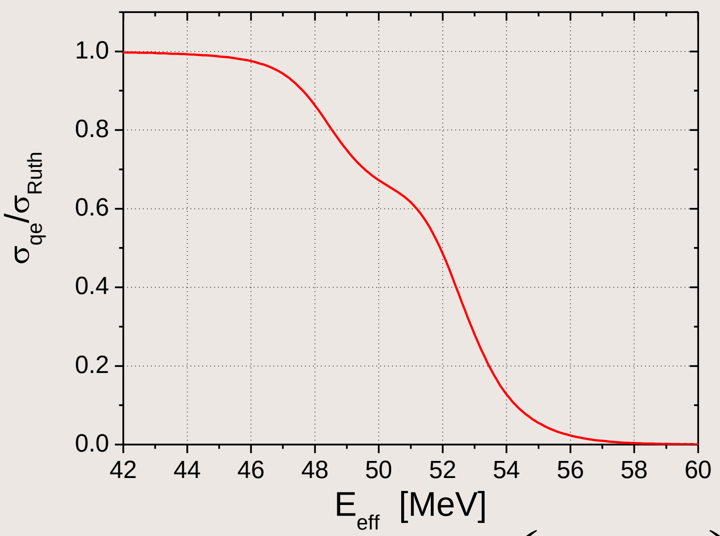
(*) *strong channels = connected with collective state excitations*

# Two experimental methods:




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

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

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

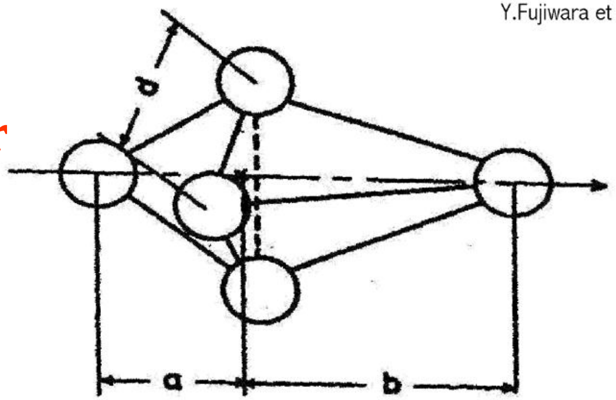
# Are the methods equivalent?

## Usually YES

**See e.g. H.Timmers et al., NP A 633(1998)421**

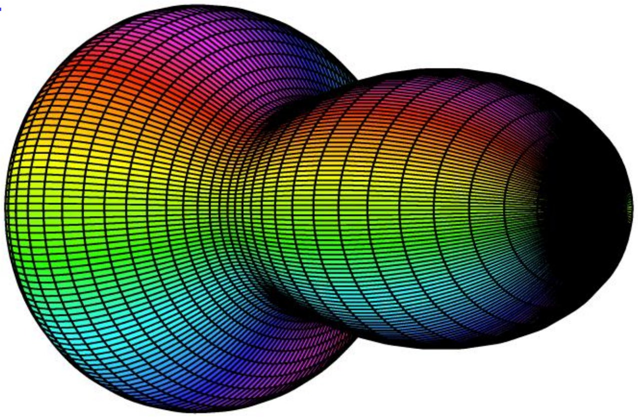
Y.Fujiwara et al., Suppl.Progr.Th.Phys. 68(1980)111

**Cluster model**




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

**Shape of $^{20}$Ne**



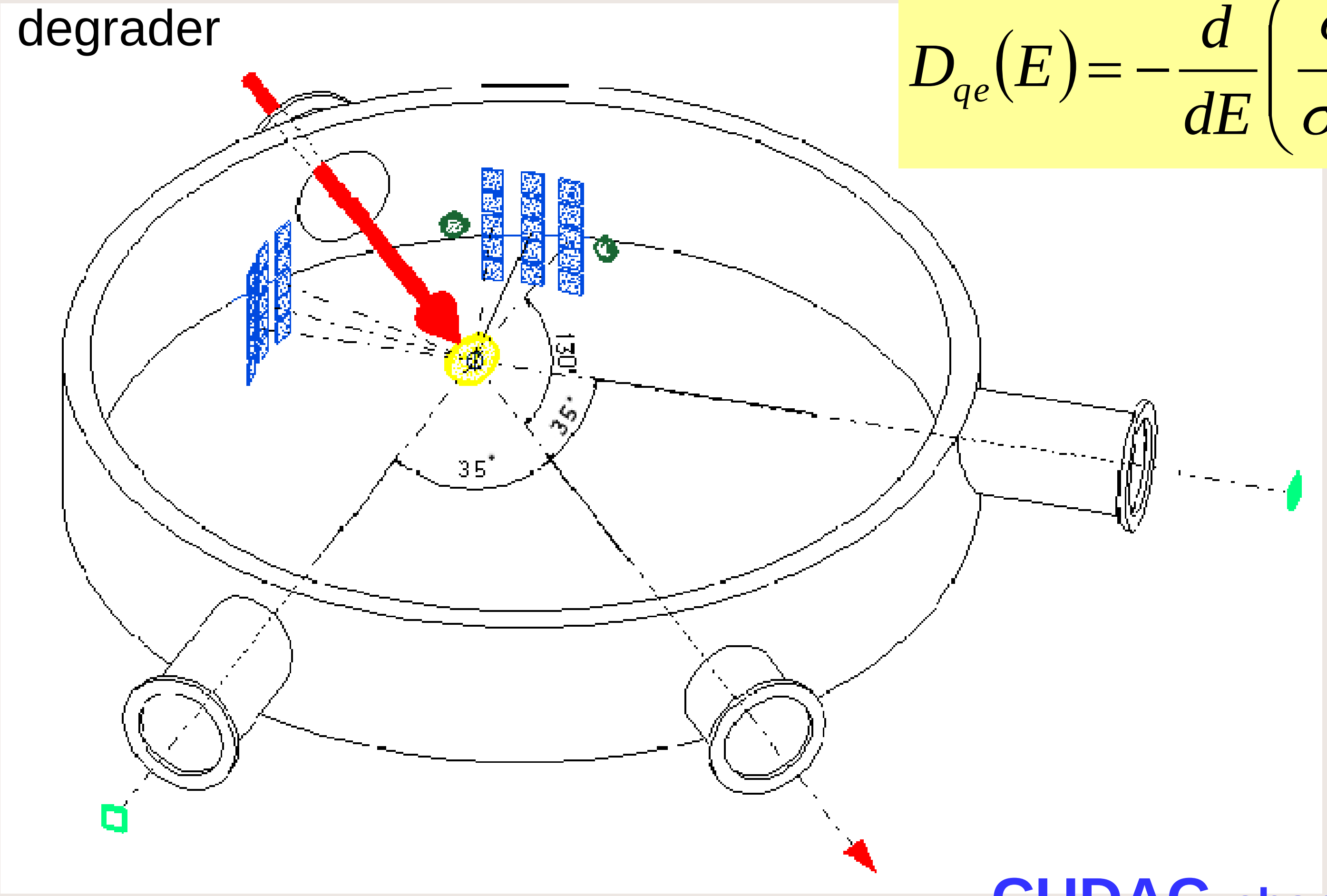
$\beta_2 = 0.46$

$\beta_3 = 0.39$

$\beta_4 = 0.27$

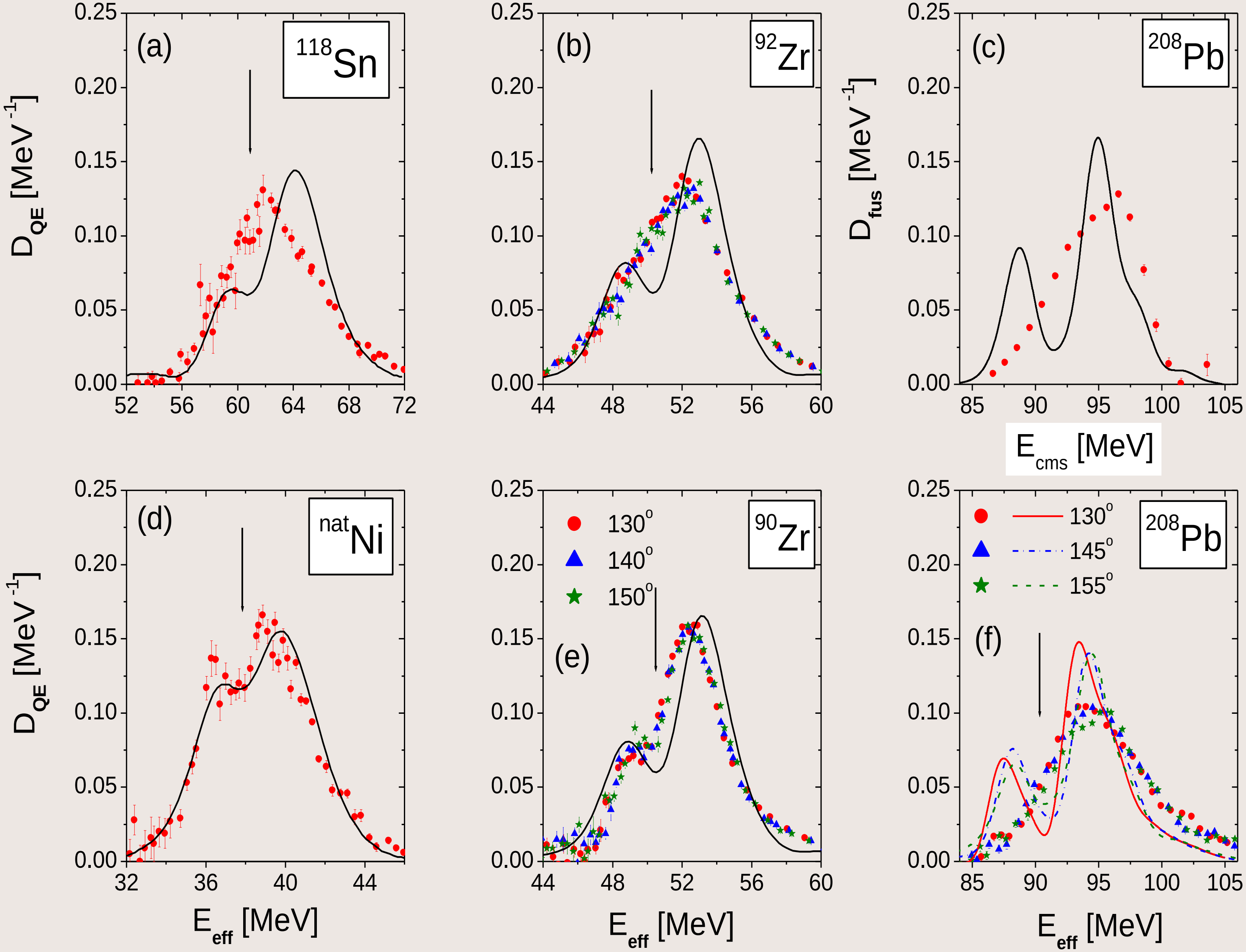
# *Measurements of QE barrier distributions at HIL*

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

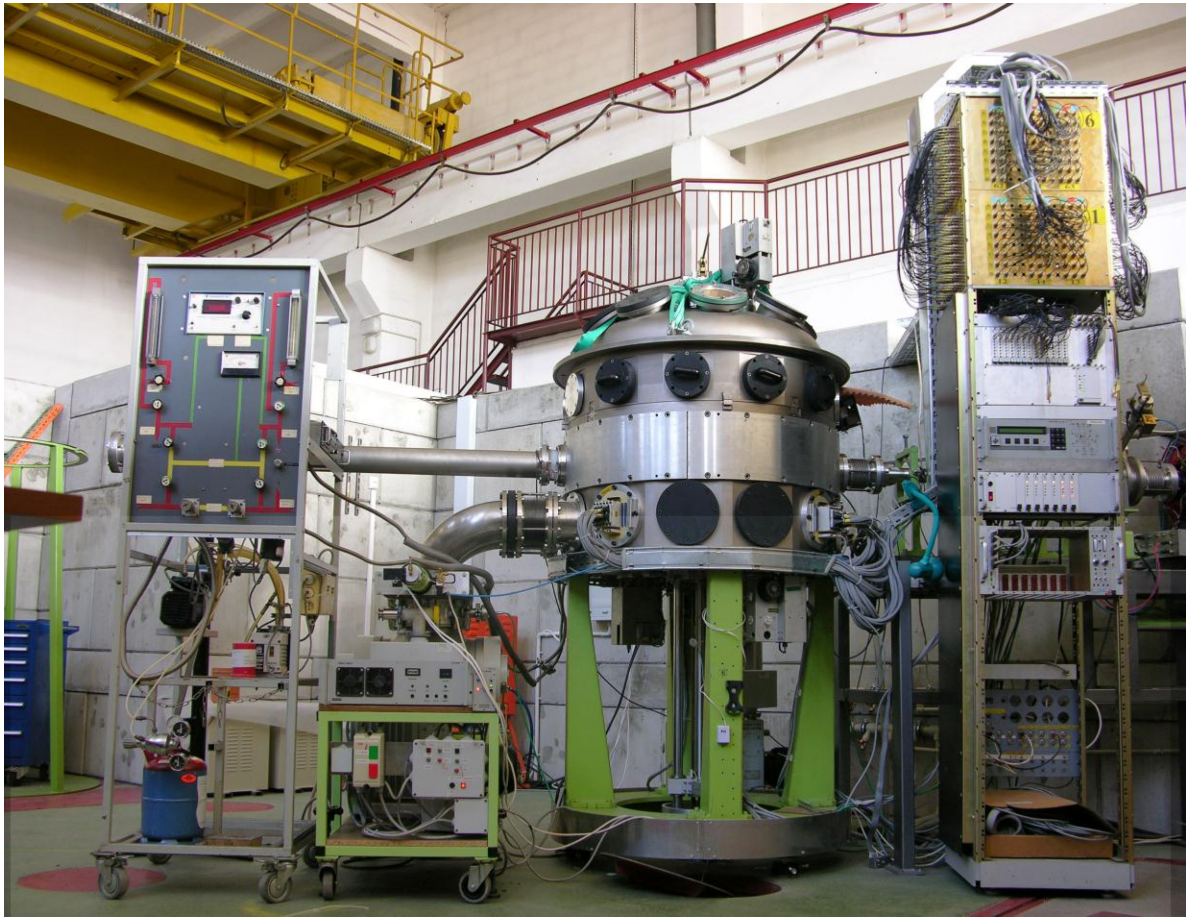



**CUDAC chamber**

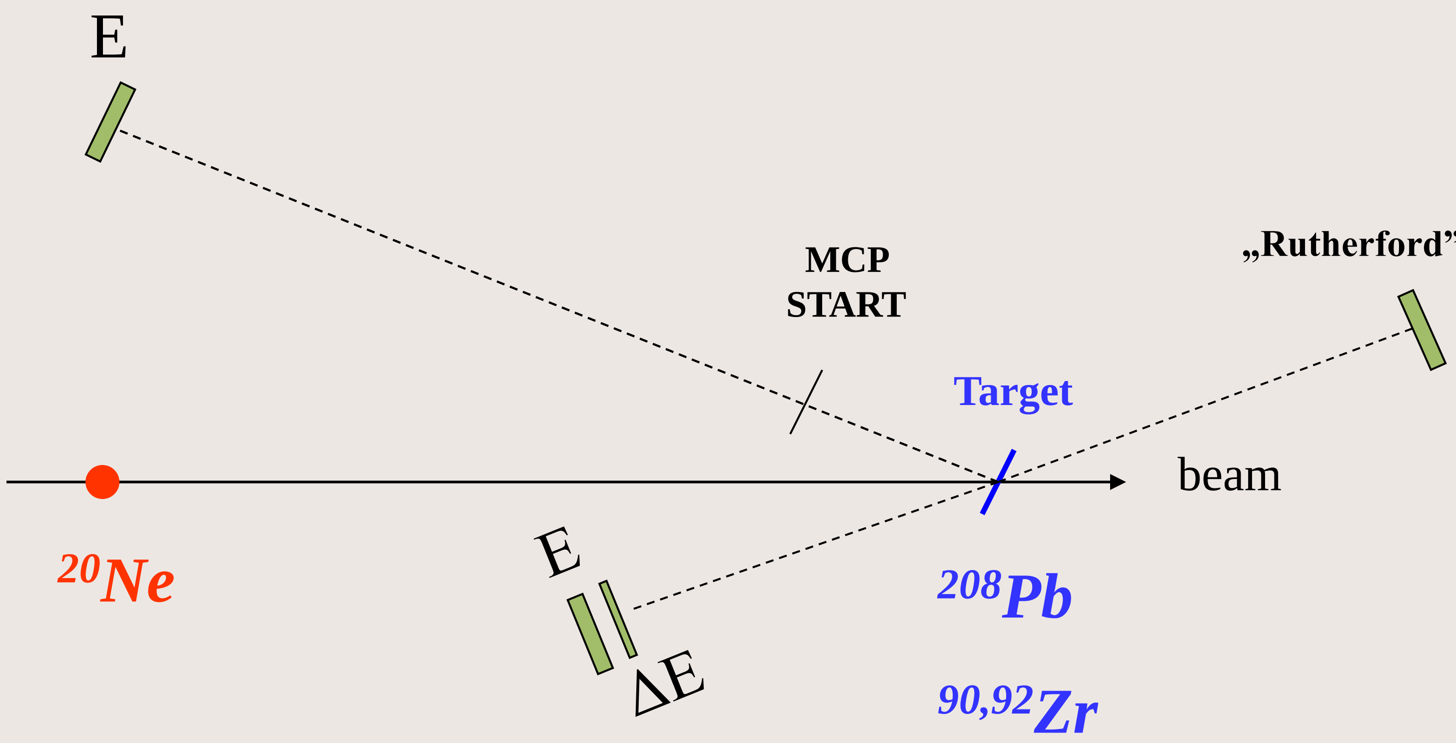
# Compilation of our $^{20}Ne + X$ results: barrier distributions



# *Transfer probablity measurements: ICARE @ HIL*



# *Experimental set-up*

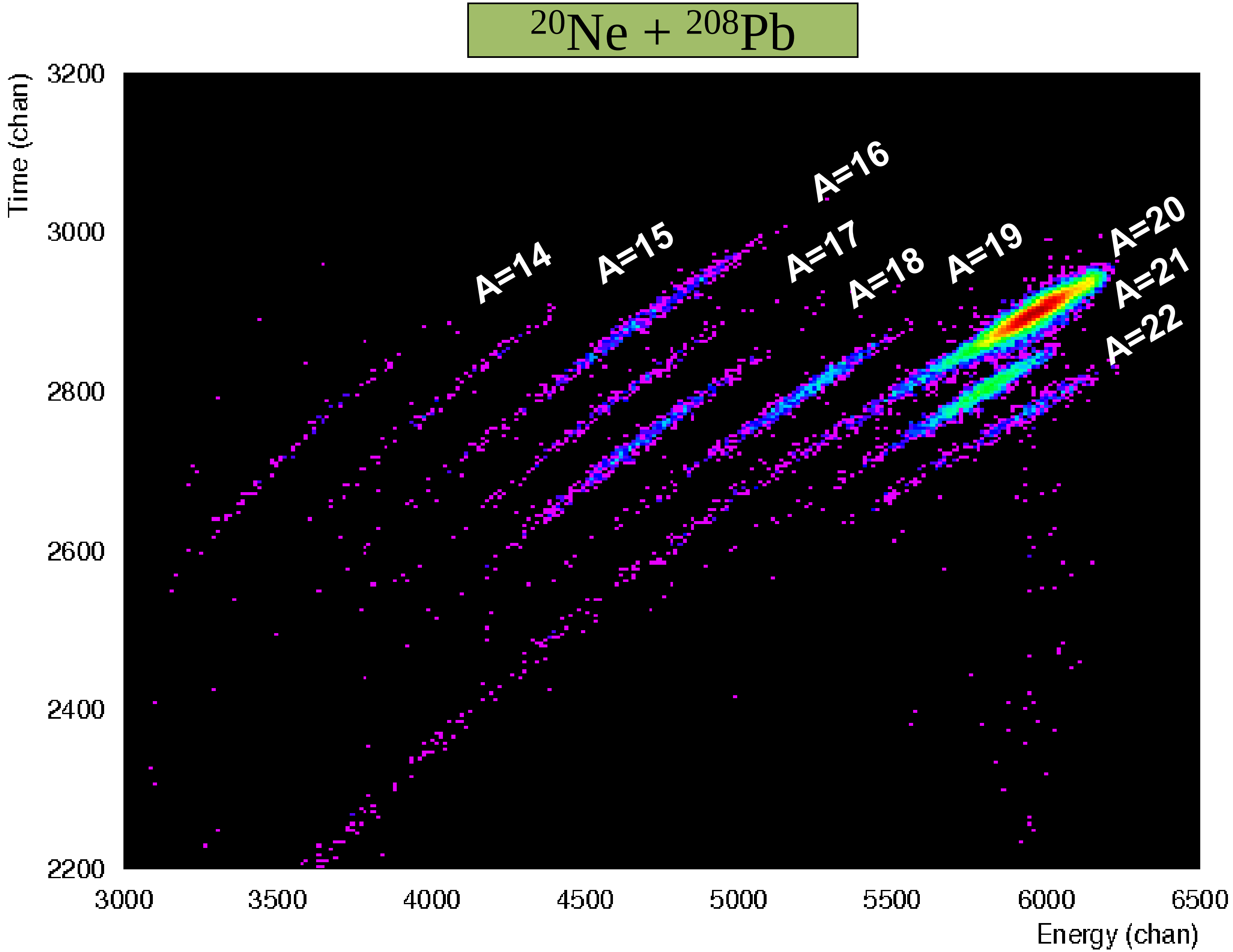



**(E,ToF) · A**

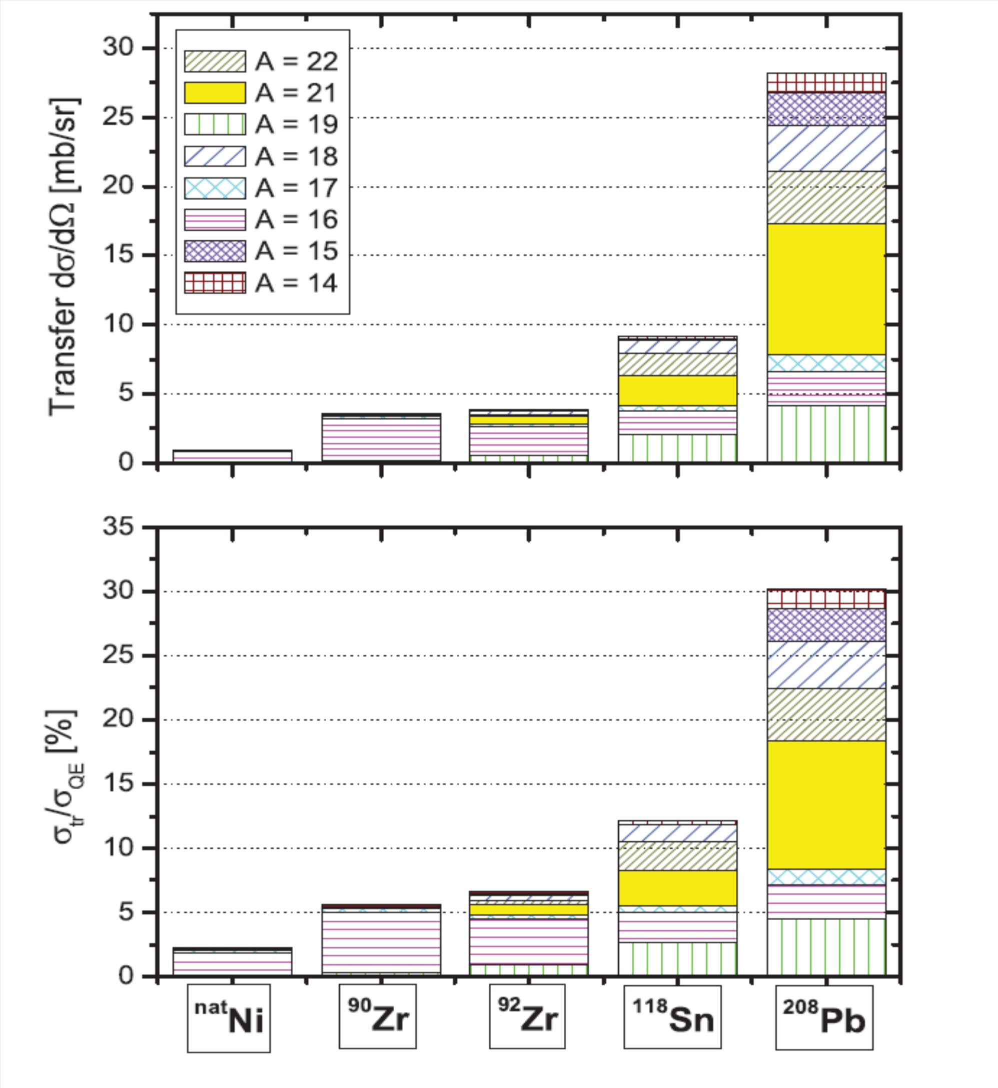
$L_{ToF}$ = 82 cm

$FWHM_{ToF} \approx 120$ ps

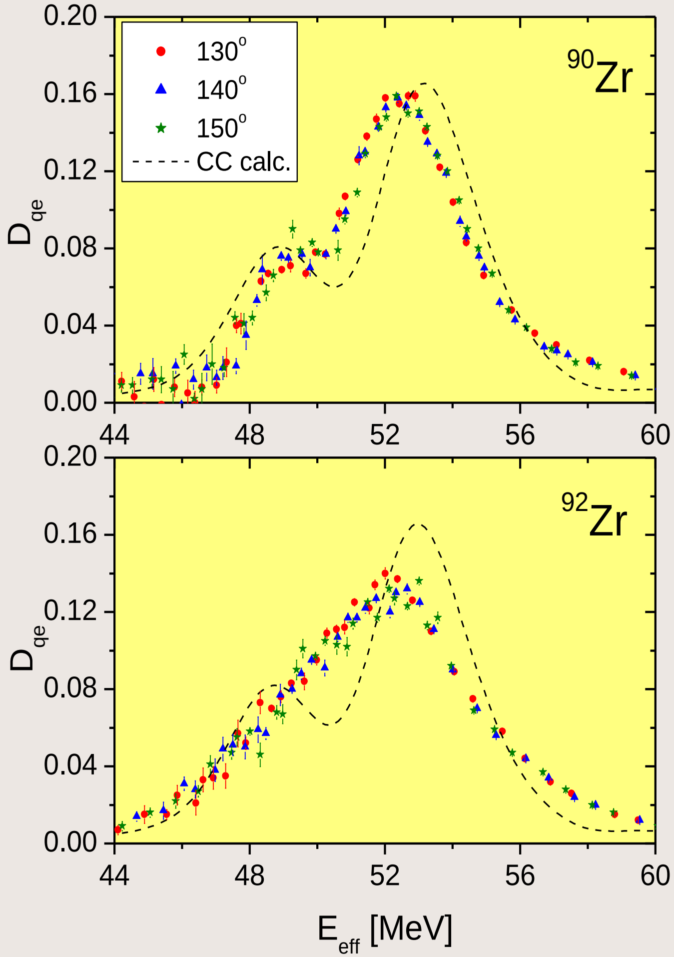
# Example of ToF vs energy spectrum

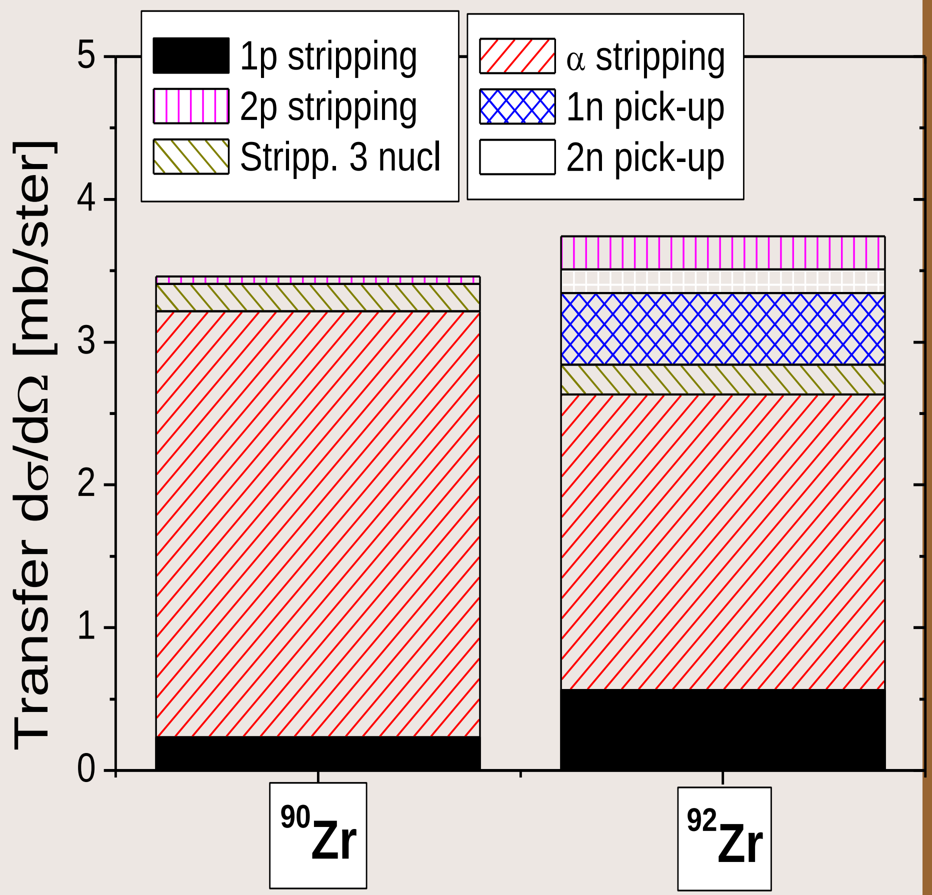


# Compilation of our $^{20}$Ne + X results: transfer cross sections in backscattering at near-barrier energies



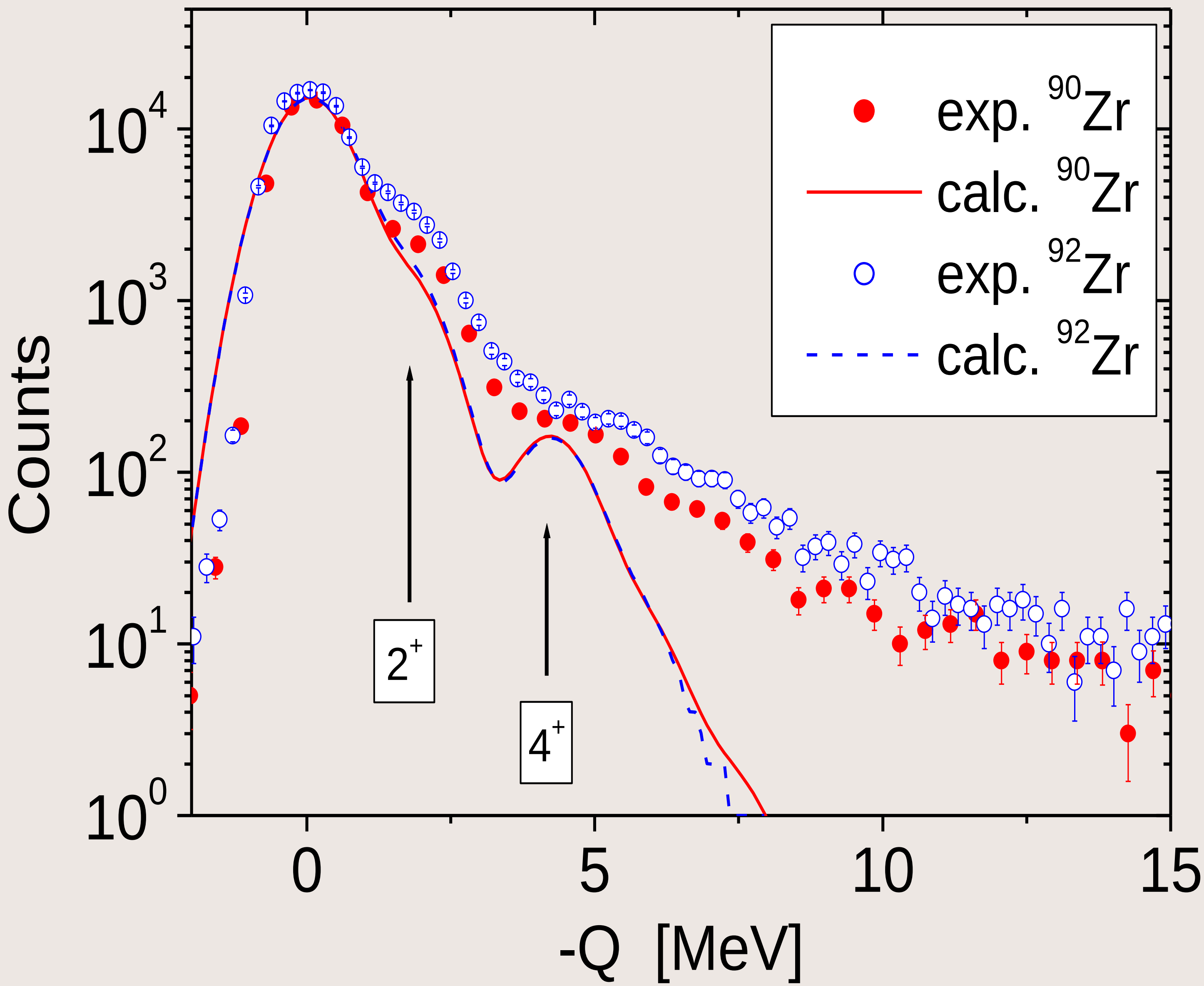

E. Piasecki *et al.*,
PRC 85 (2012) 054604



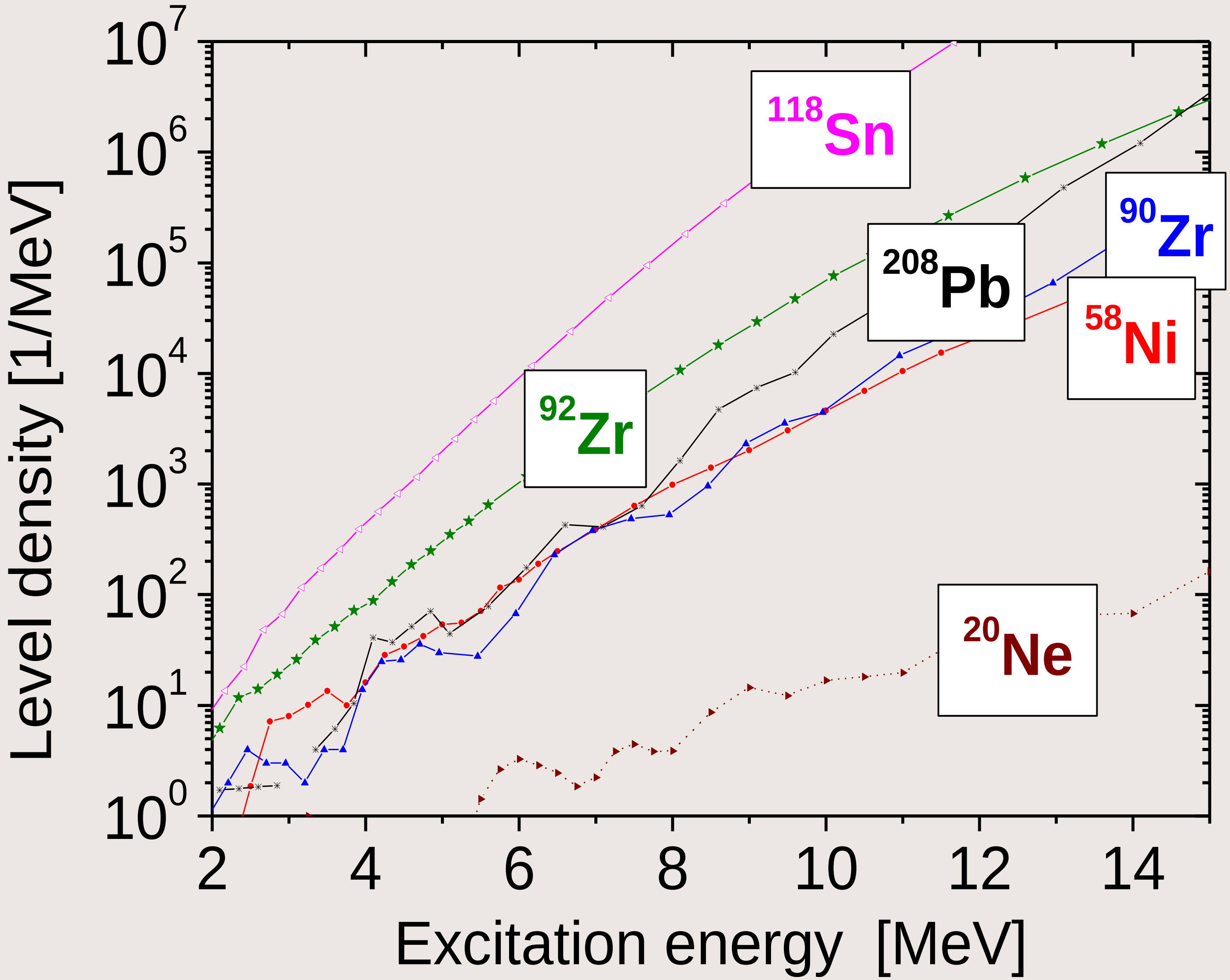




E. Piasecki et al., Phys.Rev. C80 (2009) 054613

# Non-transfer backscattering $^{20}Ne + ^{90,92}Zr$

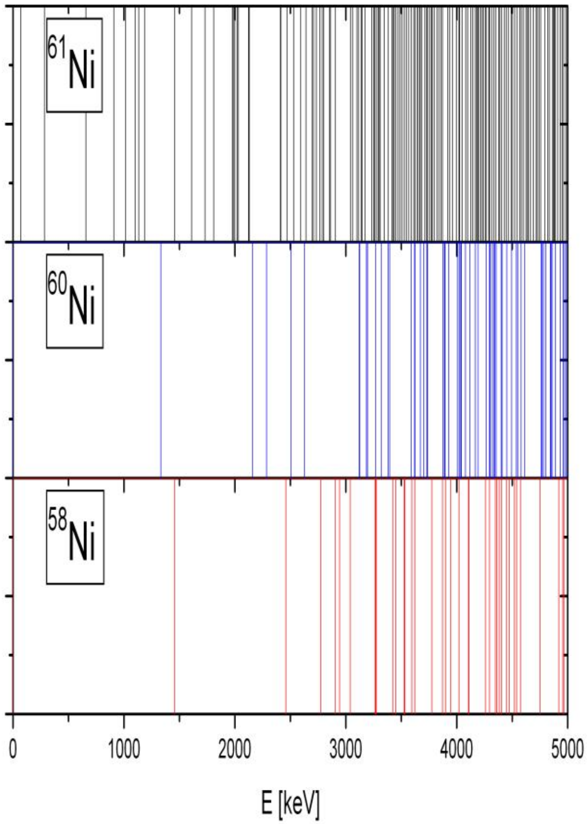


# HFB calculations of s.p. level density

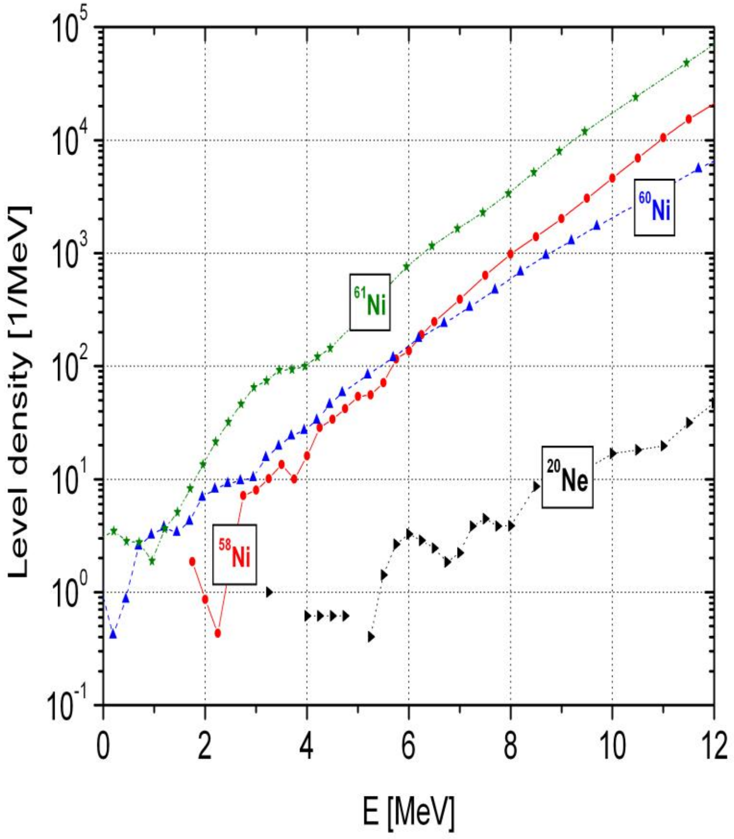


# *Impact of non-collective excitations? Testing with $^{58,60,61}Ni$*

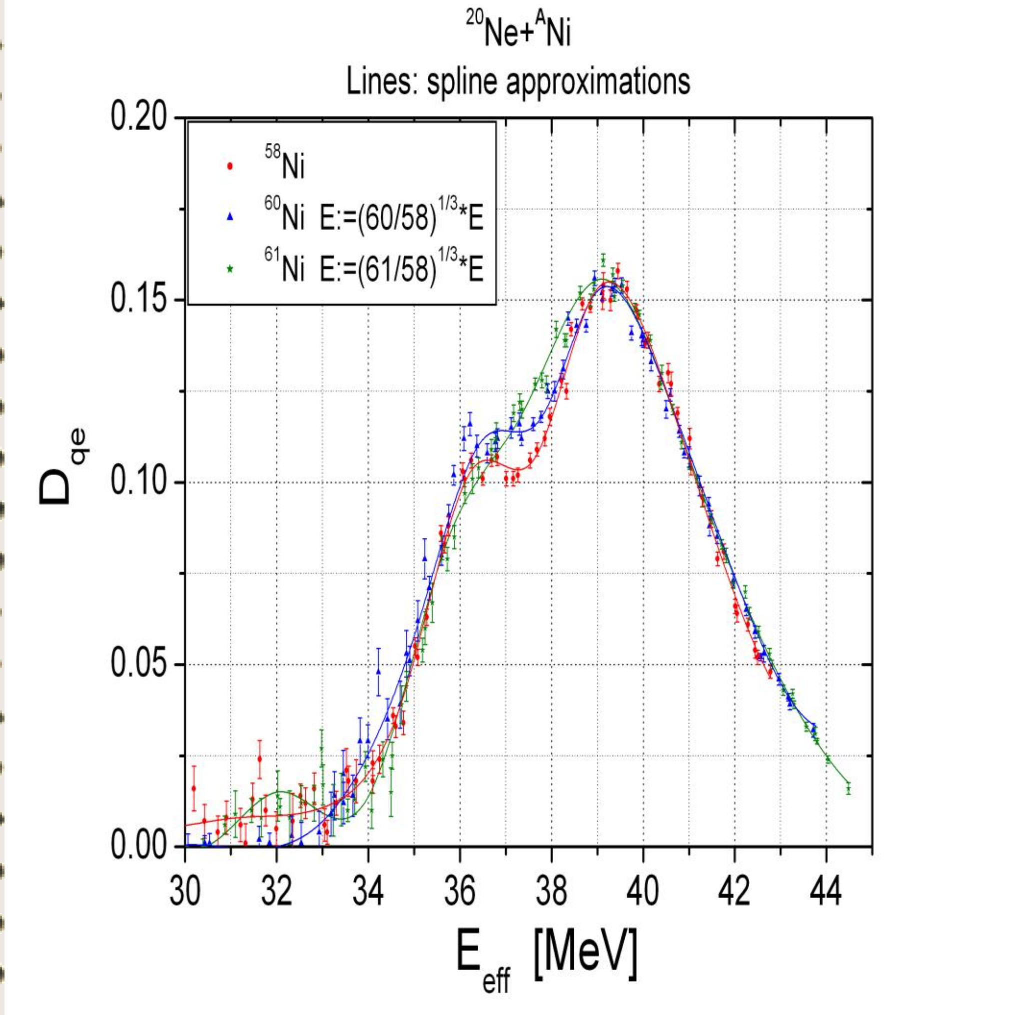
Adopted energy levels from www.nndc.bnl.gov/nudat2

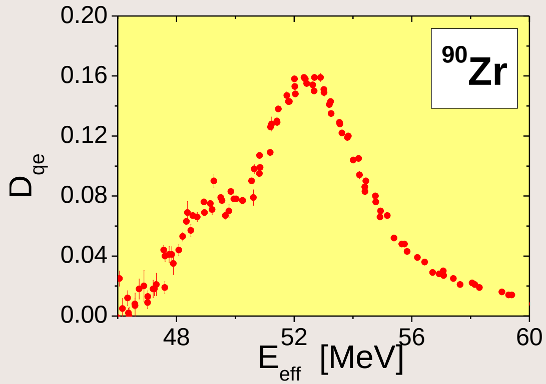


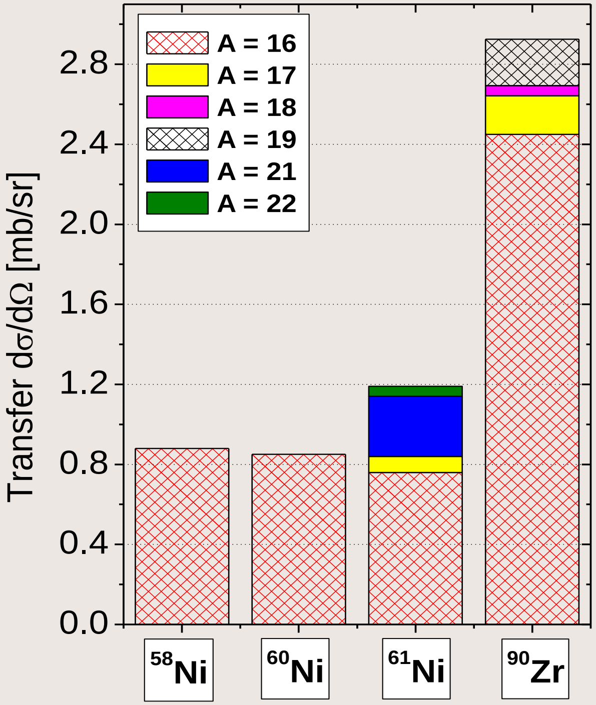

Calc. (HFB) s.p. level densities; S.Goriely, www-nds.iaea.org/RIPL-3/



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



According to the Coupled Channels Method,

collision partners emerge in a superposition of

a limited number of discrete (usually collective) quantum states

The method usually works fine.

However we see here a manifestation of the influence of

transfers and many non-collective states

## How to include to the CC many non-collective states?

- By brute force (K.Hagino et al., PRC 85, 054601 (2012))
- Random matrix theory (PRC 82, 024606 (2010)?
- Irreversible dynamic? (A.Diaz-Torres et al., PRC 82, 054617 (2010))

**The Coupled Channels Model using Schrodinger equation describes reversible processes (coherent superposition of a few intrinsic states), which is OK for isolated systems**

**Excitation of many non-collective levels means irreversible damping of relative motion into internal degrees of freedom (open system)**

**Moreover, interaction of quantum system with a complex environment results in partial destruction of the coherent superposition (decoherence)**

- **This goes beyond the standard CC method**

# *Summary*

- **For some systems the theoretically expected barrier distribution structure is smoothed out.**

- **We suspect that responsible for this are weakly coupled channels:**
  **- for the $^{92}$Zr and $^{61}$Ni targets s.p. excitations,**
  **- for $^{208}$Pb transfers,**
  **- for $^{118}$Sn – both**

- **The barrier distribution structure can be observed for the systems, for which the $\sigma_{tr}$ and s.p. level densities are small simultaneously**

- **Some theoreticians think that the observed by us $D_{QE}$ smoothing by s.p. excitations is a manifestation of decoherence in nuclear physics. They try to go beyond the standard CC, developing methods including the *dissipation* and *decoherence* effects.**

# Our plans

- ***Measuremens of the beam energy and angular dependence of Q-spectra for $^{20}$Ne + X systems (Warsaw)***

- ***Measurements of $D_{fus}$ for $^{20}$Ne + $^{92}$Zr, $^{58}$Ni + $^{61}$Ni (Legnaro?)***

- ***Measurements of $D_{QE}$ with various Mg beams (Warsaw, Ganil)***

# The BARRIER Collaboration:

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