Fission hindrance from GDR γ-rays emission - Overview

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- GDR clock -

* based on the emission of high energy γ rays from giant dipole resonance excited in the hot fissioning nucleus prior to scission.

* its speed depends only on the level density parameter and the GDR strength function.

✓ in principle no free parameters.

✓ no transmission factors.

✓ strength function follows the evolving deformation of nucleus.

✓ sensitivity of the γ rays - fission angular correlation to the deformation of the nucleus at the time of γ ray emission.

✗ fissioning nucleus γ rays and fission fragments γ rays can not be distinguished experimentally.

- Fission time scales -

* approach of Grangé and Weidenmüller

1. inside the saddle:

$$\Gamma_f(t) = \Gamma_f^{KRAMERS}\left[1 - \exp\left(-\frac{t}{\tau_f}\right)\right]$$

2. at the saddle:

$$\Gamma_f^{KRAMERS} = \Gamma_f^{BW}\left(\sqrt{1+\gamma^2} - \gamma\right); \quad \Gamma_f^{BW} = \frac{\hbar\omega_{gs}}{2\pi}\exp\left(-\frac{B_f}{T}\right)$$

3. from saddle to scission

$$\tau_{ssc} = \tau_{ssc}^0\left(\sqrt{1+\gamma_0^2} + \gamma_0\right), \quad \tau_{ssc}^0 = 3 \cdot 10^{-21}\,s$$

$$\gamma\ (\text{nuclear friction coeff.}) = \frac{\beta}{2\omega}$$

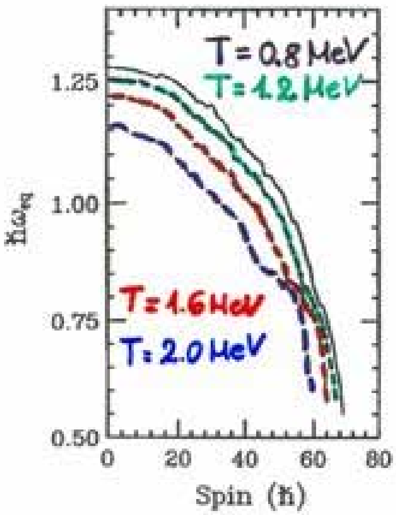
$$\beta\ (\text{reduced dissipation coeff.}) = \frac{\eta}{m}$$

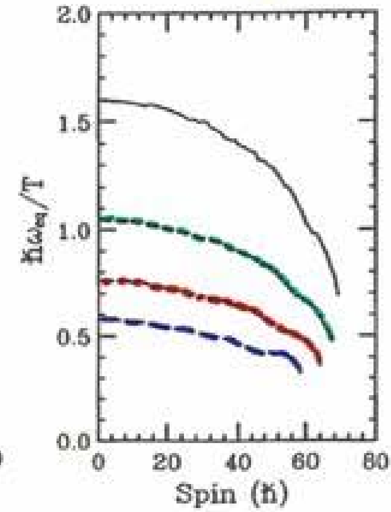
$$\tau_f = \begin{cases} \dfrac{\beta}{2\omega_1^2}\ln\dfrac{10B_f}{T}, & \text{overdamped motion} \\[2ex] \dfrac{1}{\beta}\ln\dfrac{10B_f}{T}, & \text{underdamped motion} \end{cases}$$

$$(\gamma_{inside}, \gamma_{outside}) \Rightarrow \tau_{Fis}^{TOTAL} = \tau_f + \tau_{ssc}$$

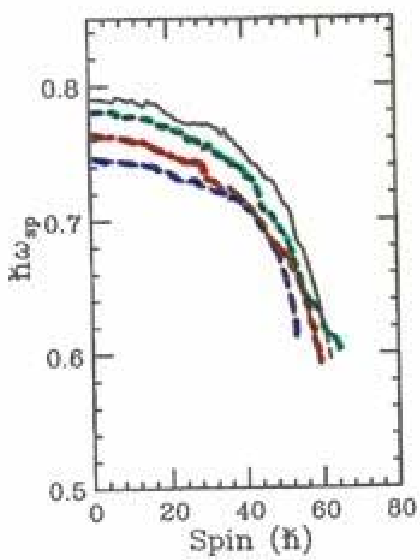
- Cascade -

$$\Gamma^{(\gamma=0)}_{\mathrm{CASCADE}} = \frac{T}{2\hbar}\exp\left(-\frac{B_f}{T}\right) = \frac{T}{\hbar\omega_{eq}}\Gamma_f^{BW} \quad : \quad \hbar\omega_{eq} = T$$





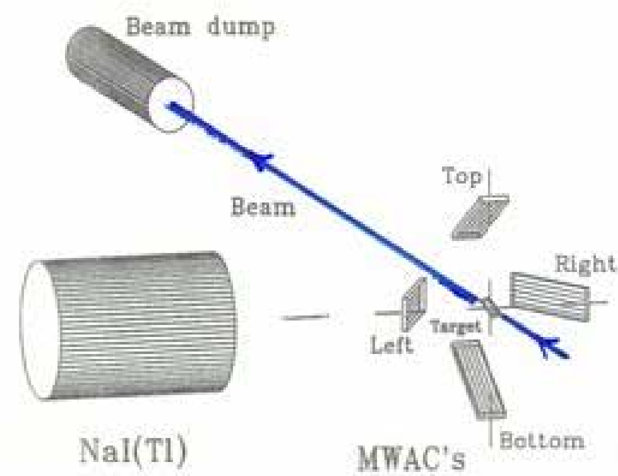
$$\gamma \leftrightarrow \beta \leftrightarrow \tau \quad : \quad \omega_{sp} = 1\cdot 10^{21}\, s^{-1}$$



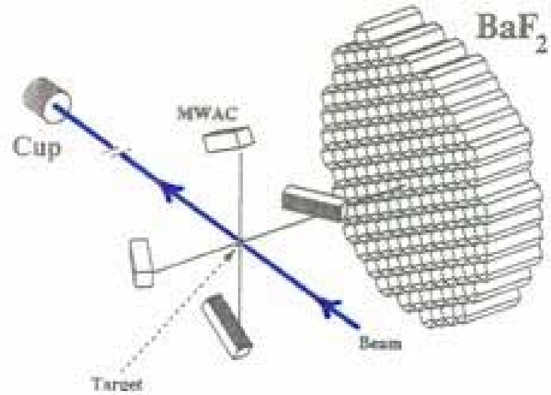
M. Thoennessen,
Proceed. 3rd Intern. Conf.
Dynam. Aspects of Nucl.
Fission, Častá-Papiernika,
Slovak Republik.

-Experimental methods-

* Diószegi I. et al., Phys. Rev. C46 (1992) 627

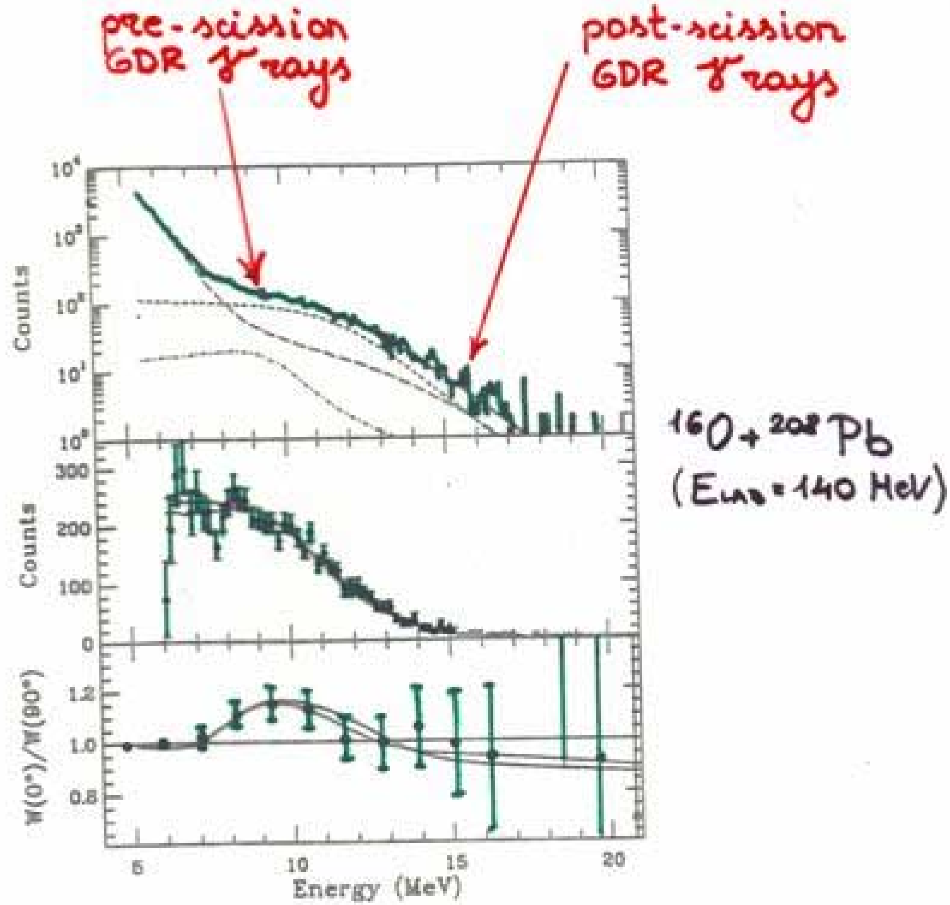


* Shaw N.P. et al., Phys. Rev. C61 (2000) 044612



– Experimental methods –

* medium and heavy nuclei : $E_{GDR} \approx 80 \cdot A^{-1/3}$ (MeV).
* simultaneous fit to the γ ray spectrum and the angular correlation can determine the strengths of the pre- and post-scission GDR decays separately.



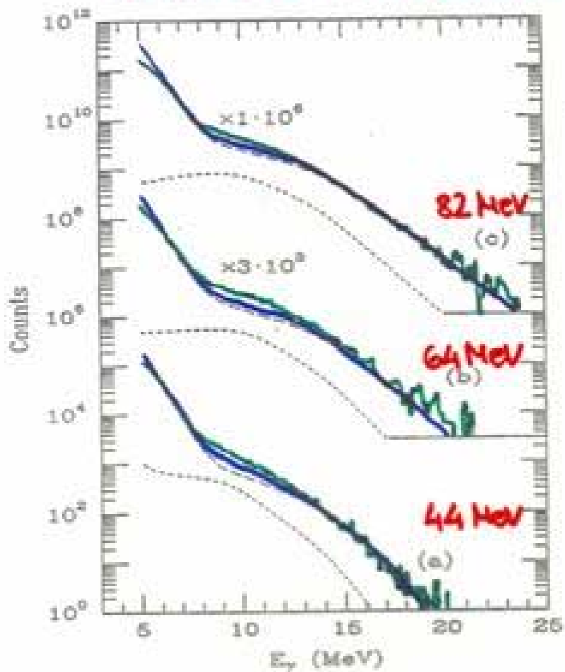
Diószegi I. et al., Phys. Rev. C46 (1992) 627.

– Experimental results[1] –

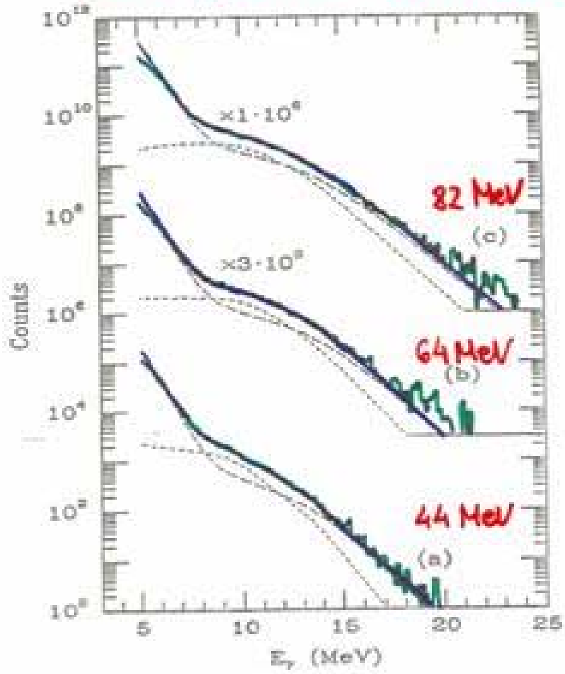
* Thoennessen M. et al., Phys. Rev. Lett. 59 (1987) 2861.

$^{16}O + ^{208}Pb \rightarrow Th$ at $E^* = 44, 64, 82$ MeV

no fission hindrance



with fission hindrance



* the best agreement with experimental data:

$$\beta = 5 \cdot 10^{21}\ s^{-1}$$

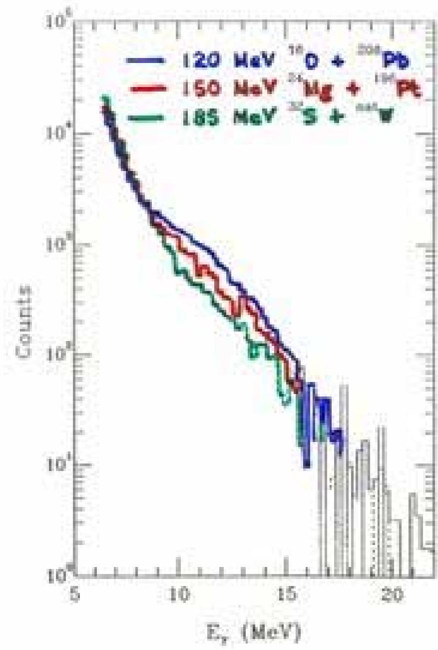
– Experimental results –

* Butsch R. et al., Phys. Rev. C44 (1991) 1515

  $^{16}O + ^{208}Pb$ ($E^* = 44, 64, 90$ MeV)

  $^{24}Mg + ^{196}Pt$ ($E^* = 70$ MeV)

  $^{32}S + ^{nat}W$ ($E^* = 72$ MeV)



* fusion-fission: $\beta = (10-20)\cdot 10^{21} s^{-1} \rightarrow \tau_{fiss}^{TOTAL} \approx 2.9\cdot 10^{-19} s$

  GDR γ rays are mostly emitted before the system passes over the saddle point.

* quasifission: $\beta = 20\cdot 10^{21} s^{-1} \rightarrow \tau_{qf} = (2-9)\cdot 10^{-20} s$;

  $\tau_{qf} = (2-4)\cdot 10^{-20} s$ in Diószegi I. et al. Phys. Rev C 46 (1992) 627 for $^{32}S + ^{nat}W$ at $E^* = 72, 97, 110$ MeV

- Experimental results -

* Hofman D.J. et al, Phys. Rev. Lett. 72 (1994) 470.

$^{32}S + ^{208}Pb \rightarrow ^{240}Cf$, $E^* = 67$ and 93 MeV

* at $E^* = 67$ MeV no fission hindrance
* at $E^* = 93$ MeV $\tau_{ssc} \simeq 30 \cdot 10^{-21}$ s ($\beta_o = 10 \cdot 10^{21} s^{-1}$) with taking $\beta_i = (10-20) \cdot 10^{21} s^{-1}$

* Shaw N.P. et al, Phys. Rev. C 61 (2000) 044612

same system extended to higher excitation energies ($E^*_{MAX} = 138$ MeV)

* best agreement with data by taking $\beta_i = 4 \cdot 10^{21} s^{-1}$ and $\beta_o = 20 \cdot 10^{21} s^{-1}$

* the extracted nuclear dissipation coefficient is found to be independent of temperature.

– Temperature/deformation dependence of dissipation –

* Hofman D.J. et al, Phys. Rev. C51 (1995) 2597.

$^{16}O + ^{208}Pb$ at $E^* = 47, 65$ and 84 MeV

simultanious fit of γ ray spectra, neutrons multiplicities and evaporation residue cross sections → $\gamma = 16.49 \cdot T_{saddle} - 18.57$

$\gamma = 5.71 \cdot T^2_{saddle} - 6.91$

* Diószegi I. et al, Phys. Rev. C61 (2000) 024613

same system at two more E^* (102, 118 MeV)

1. new level density approach (Ignatyuk – Reisdorf)
2. $\gamma(T)$ during the deexcitation process

→ $\gamma = 0.2 + 5T$ and $\gamma = 0.2 + 3T^2$

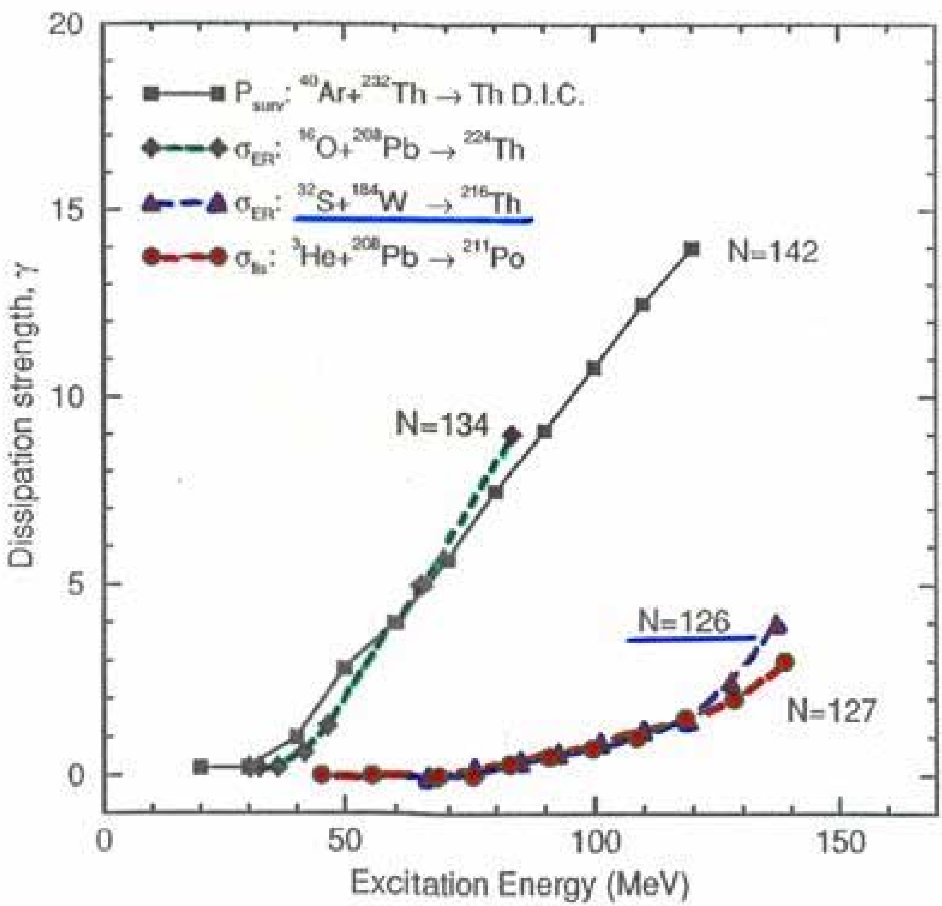
3. additional temperature dependent factor in level density

→ $\gamma = 0.2 + 1.7T^2$

4. data also fitted with constant $\gamma_i = 2$ inside the saddle and constant $\gamma_o = 10$ outside the saddle.

No definite conclusion!

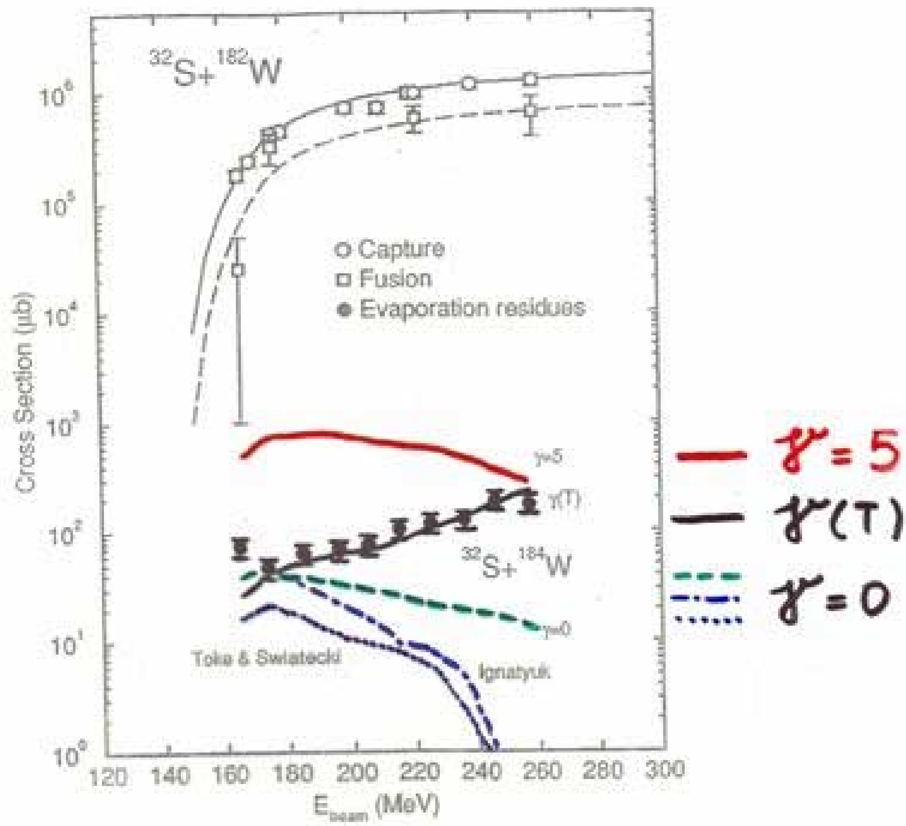
Back B.B. et al, Phys. Rev. C 60 (1999) 044602



- Evaporation residue measurements -

* Back B.B. et al, Phys. Rev. C 60 (1999) 044602

$^{32}S + ^{184}W$ at $E_{beam} = 165-257$ MeV



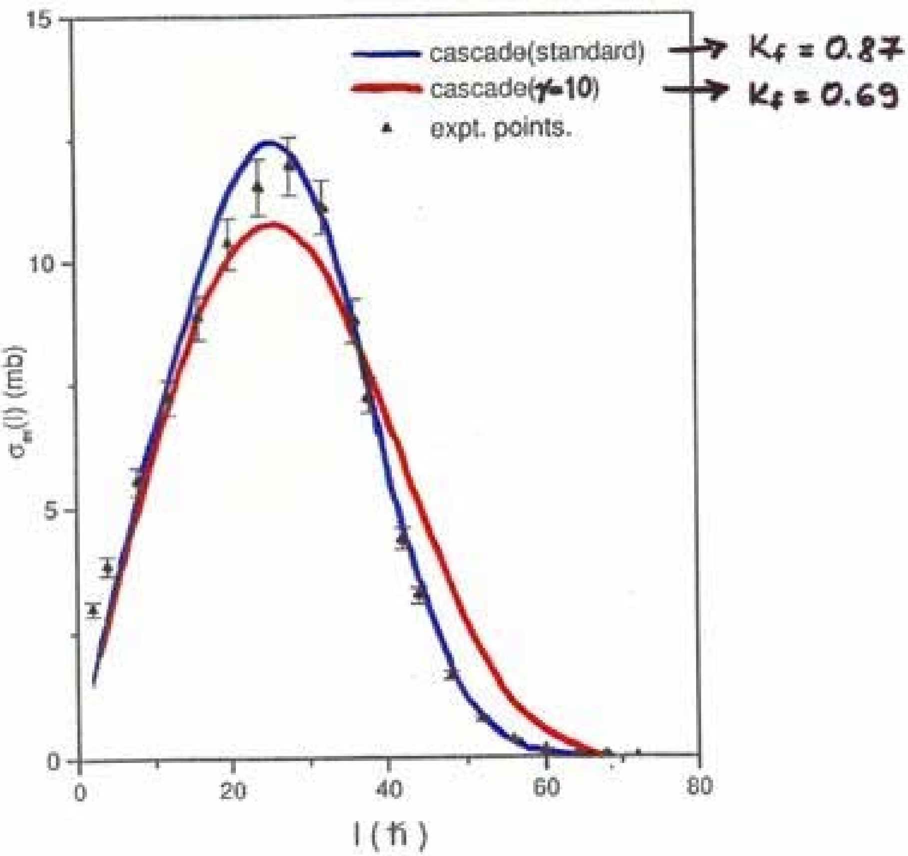
* the dissipation strength is NOT allowed to vary as the system cools down during the particle evaporation cascade.

– Evaporation residue measurements –

* Hui S.K. et al, Phys. Rev. C 62 (2000) 054604

  $^{19}F + ^{175}Lu$ at $E_{beam} = 90 - 125$ MeV

* measured ER cross section is not sensitive enough, but the spin dependence is.

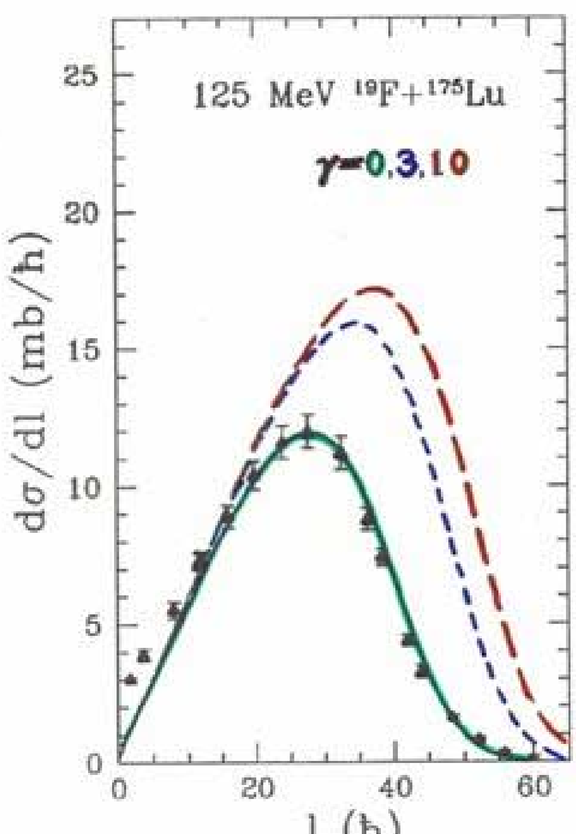


BUT! ⇒

* Diószegi I., Phys. Rev. C 64(2001) 019801

* ER cross section is a very sensitive measure of the nuclear viscosity, if the calculations are done without scaling the fission barrier using the appropriate level density method:

Ignatyk - Reisdorf approach →



– Level density calculations –

* original version of CASCADE:

$E^* < 10$ MeV → parametrization of Dilg W. et al, Nucl. Phys. A217 (1973) 269.

$E^* > 20$ MeV → nucleus ⇔ liquid drop

* improved excitation energy dependent description:

- Ignatyk A.V. et al, Sov. J. Phys. 21 (1975) 255

$$a(U) = \tilde{a}(A)\left[1 + \frac{\delta W}{U}\left(1 - e^{-U/E_d}\right)\right]$$

- Reisdorf W., Z. Phys. A300 (1981) 227.

$$\tilde{a}(A) = 0.04543 r_0^3 + 0.1355 r_0^2 A^{-1/3} B_s + 0.1426 r_0 A^{-2/3} B_k$$

* additional temperature dependence:

$$a(T) = a(U) \cdot \left[1 - k \cdot f(T)\right]$$

$$f(T) = 1 - \exp\left[-\left(T A^{1/3}/21\right)^2\right]$$

$$k = 0.4$$

(Shlomo S. and Natowitz J.B., Phys. Rev. 44 (1991) 2878)

– 1-exp versus step –

$\Gamma_f^{KRAMERS}$ $\qquad$ Γ_f^{BW}

System	1-exp	step
$^{32}S + W$	$\tau_f \propto 10 \cdot 10^{-21} s$ (1) $\tau_{QF} = (20\text{-}40) 10^{-21} s$ (2)	$\tau_{PRE} \sim 10 \cdot 10^{-21} s$ (3) $\tau_{POST} \sim 20 \cdot 10^{-21} s$
$^{32}S + {}^{208}Pb$	$\tau_{SSC} = 30 \cdot 10^{-21} s$ (4) $\tau_{SSC} = 54 \cdot 10^{-21} s$ (5)	$\tau_{PRE} \sim 10 \cdot 10^{-21} s$ (3) $\tau_{POST} \sim 20 \cdot 10^{-21} s$

(1) Back B.B. et al, Phys. Rev. C (1999) 044602
$^{32}S + {}^{184}W$, ER

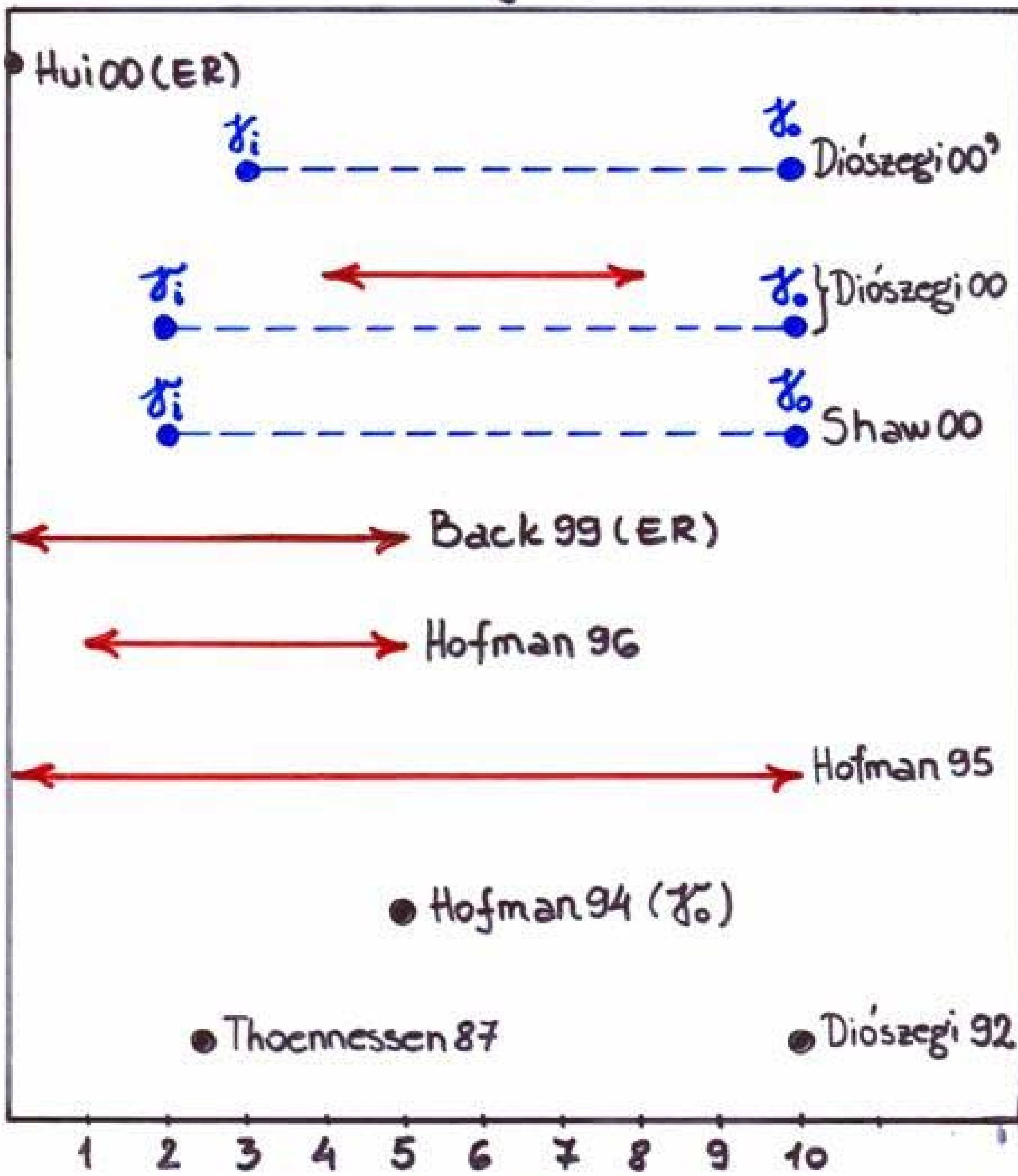
(2) Diószegi I. et al, Phys. Rev. C 46 (1992) 627
$^{32}S + {}^{nat}W$, GDR clock

(3) Morton C.R. et al, J. Phys. G 23 (1997) 1383.
$^{32}S + {}^{nat}W$, GDR clock

(4) Hofman D.J. et al, Phys. Rev. Lett. 72 (1994) 470.

(5) Shaw N.P. et al, Phys. Rev. C 61 (2000) 024613.

– Summary –



$$\gamma = \frac{\beta}{2\omega} = \frac{\eta}{2M\omega}$$

——— temperature dependence

- - - - - - deformation dependence

1. Thoennessen M. et al, Phys. Rev. Lett. 59 (1987)
$^{16}O + ^{208}Pb$, $E^* = 44, 64, 82$ MeV

2. Diószegi I. et al, Phys. Rev. C46 (1992) 627
$^{16}O + ^{208}Pb$, $E^* = 82$ MeV
$^{32}S + ^{nat}W$, $E^* = 72 - 110$ MeV

3. Hofman D.J. et al, Phys. Rev. Lett. 72 (1994) 470
$^{32}S + ^{208}Pb$ $E^* = 67 - 93$ MeV

4. Hofman D.J. et al, Phys. Rev. C 51 (1995) 2597
$^{16}O + ^{208}Pb$ $E_{LAB} = 80 - 140$ MeV

5. Hofman D.J. et al, Nucl. Phys. A599 (1996) 23c
$^{32}S + ^{nat}W$ $E^* = 50 - 140$ MeV

6. Back B.B. et al, Phys. Rev. C60 (1999) 044602
$^{32}S + ^{184}W \rightarrow ER$, $E_{LAB} = 165 - 257$ MeV

7. Shaw N.P. et al, Phys. Rev C 64 (2000) 044612
$^{32}S + ^{208}Pb$ $E^* = 46 - 138$ MeV

8. Diószegi I. et al, Phys. Rev. C61 (2000) 024613
$^{16}O + ^{208}Pb$ $E^* = 46 - 118$ MeV

9. Diószegi I. et al, Phys. Rev. C 63 (2000) 014611
$^{19}F + ^{181}Ta$ $E^* = 121, 139$ MeV

10. Hui S.K. et al, Phys. Rev. C62 (2000) 054604
$^{19}F + ^{175}Lu \rightarrow ER$ $E^* = 90 - 125$ MeV