Probing Dynamics of Fusion-Fission Process in Heavy to Very Heavy Nuclei

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India-JINR Workshop on Elementary Particle and Nuclear Physics, and Condensed Matter

Oct. 16 - 19, JINR, Dubna

raison d' étre of the current program

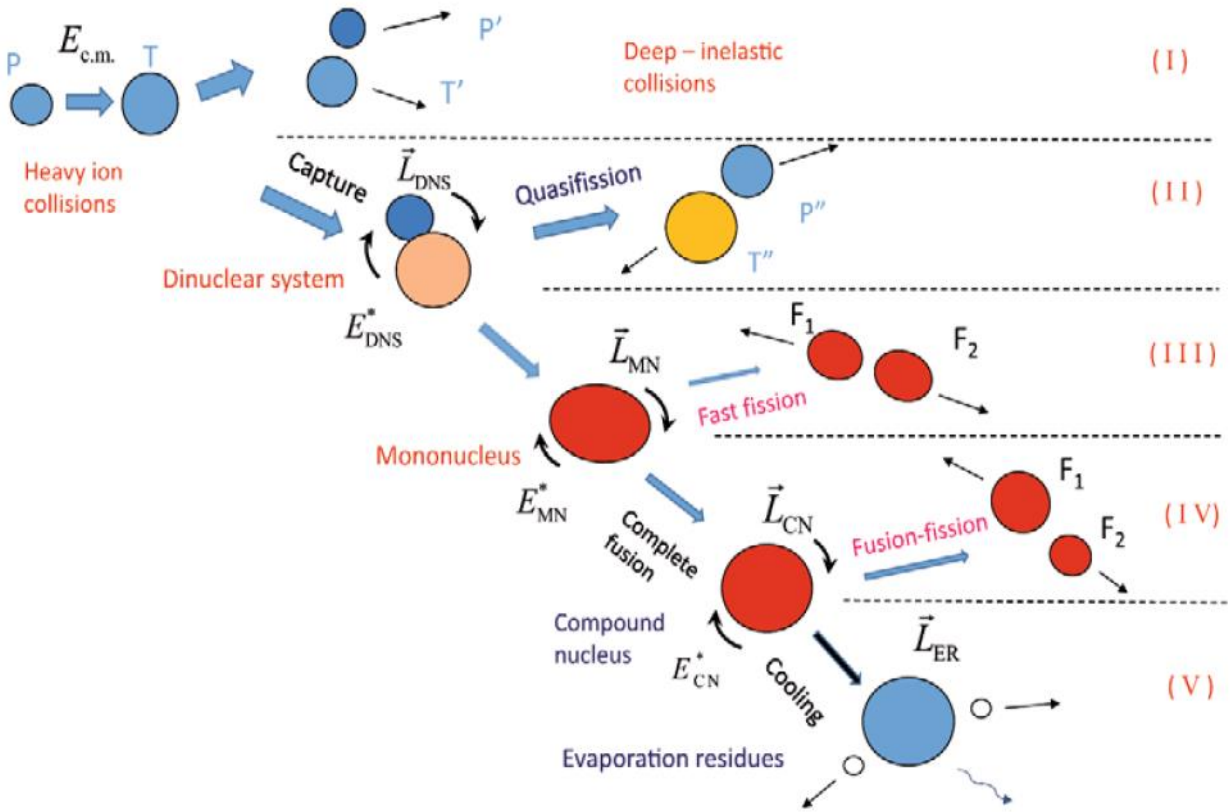
Heavy-Ion Physics at low and medium energy in a nutshell

HI induced fusion brings in T & J and opens up new vistas.

It helps in probing real time response of the nuclear many-body system to external trigger

The universal goal 1) Nuclear structure and structural evolution with T, J

2) Reaction dynamics



Nasirov et al. (2013)

Nuclear Fission is an example of large scale mass transfer across a barrier in a dissipative medium. The transport problem gets even more difficult considering the fact that nucleus is a quantum mechanical object.

The Primary Motivation is Two-Fold:

- To understand the dynamics of the fusion and subsequent fission or survival against fission
- The quest towards formation of the SHE

Experimentally, this is achieved by measuring the

1) Fission fragments 2) Evaporation residues 3) particles and GDR gamma rays

The measured cross sections demand understanding the dynamical and statistical observables,

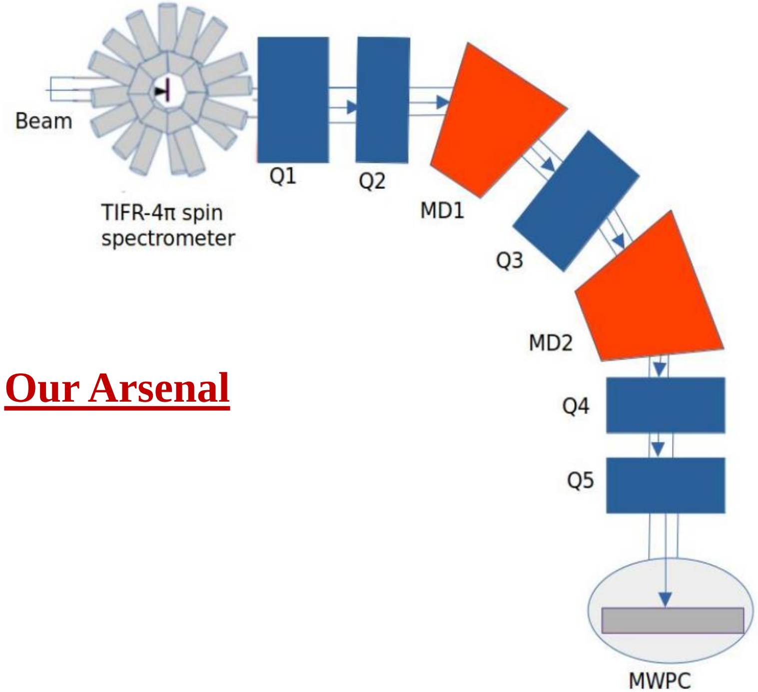
Nuclear Level Density, Nuclear Viscosity, Shell effects, entrance channel masses,
Target – projectile deformations, Barrier heights etc. and their dependence upon

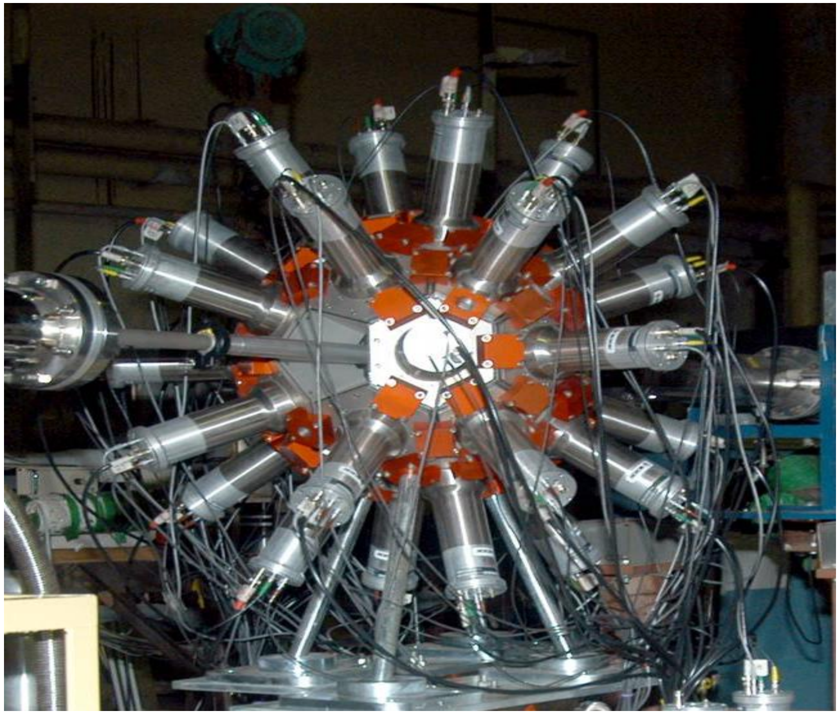
Temperature and angular momentum

Theoretical approaches: Macroscopic (phenomenological)

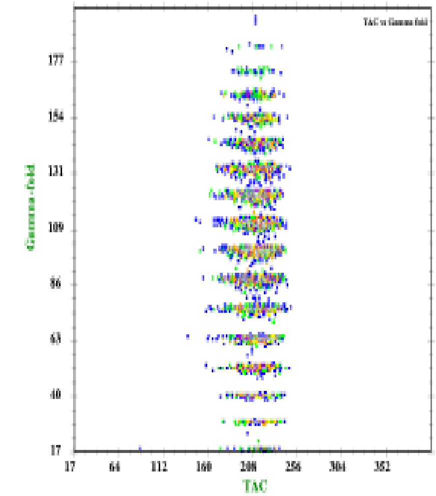
Microscopic

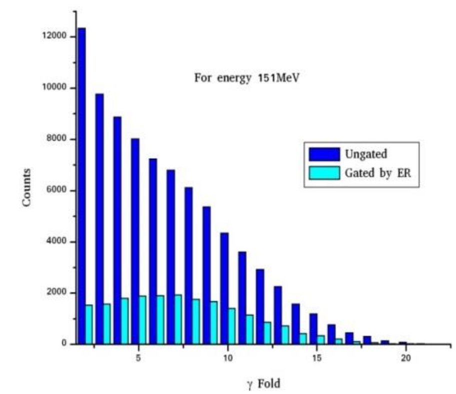
Our Arsenal

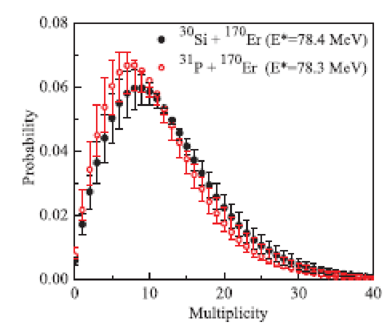




Hybrid Recoil Analyzer (HYRA) at Inter University Accelerator Centre, Delhi Coupled with the TIFR 4π Sum-Spin Spectrometer





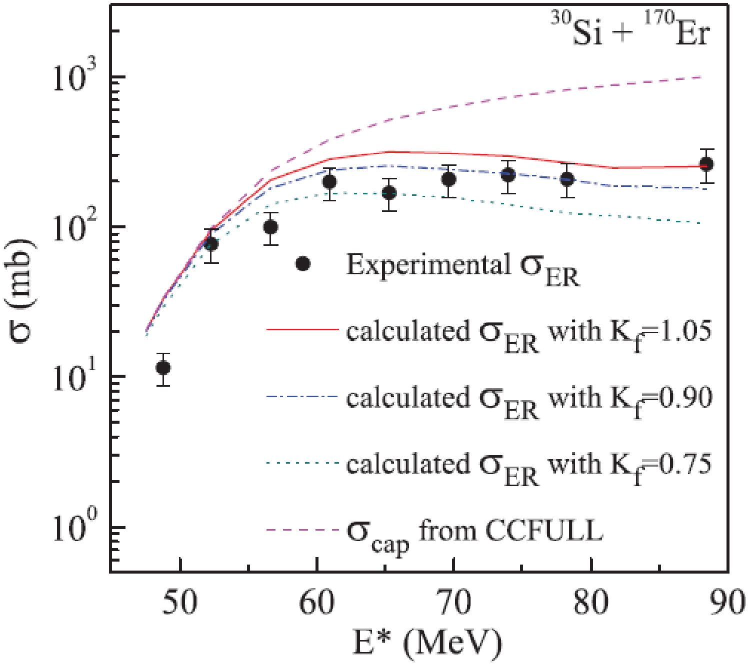


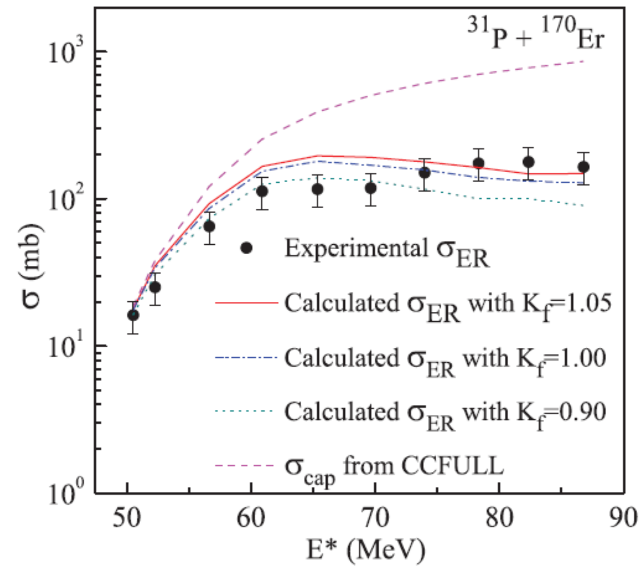
- <u>ER cross section, spin distribution for</u>
  ($^{31}P+^{170}Er$), ($^{30}Si + ^{170}Er$), ($^{28}Si + ^{176}Yb$) ($^{48}Ti+^{150}Nd$), ($^{19}F,^{16}O + ^{197}Au$), ($^{16}O+^{208}Pb$), ($^{18}O+^{206}Pb$) $^{48}Ti + ^{142, 144}Sm$

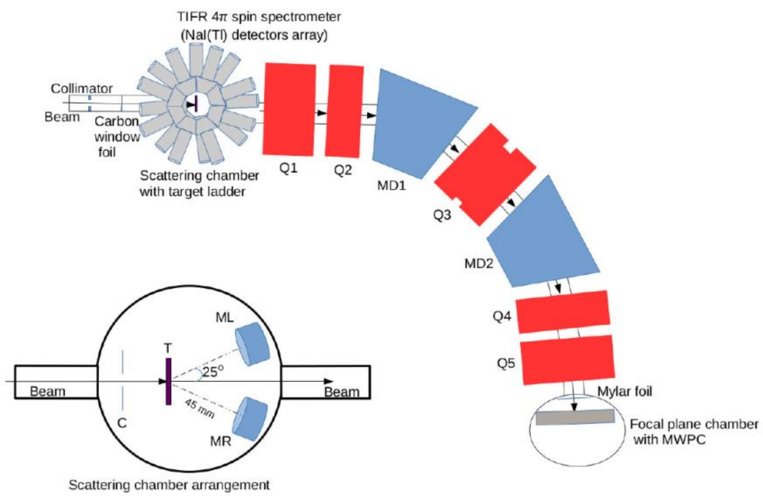
***The European Physical Journal A* volume 58, (2022)**

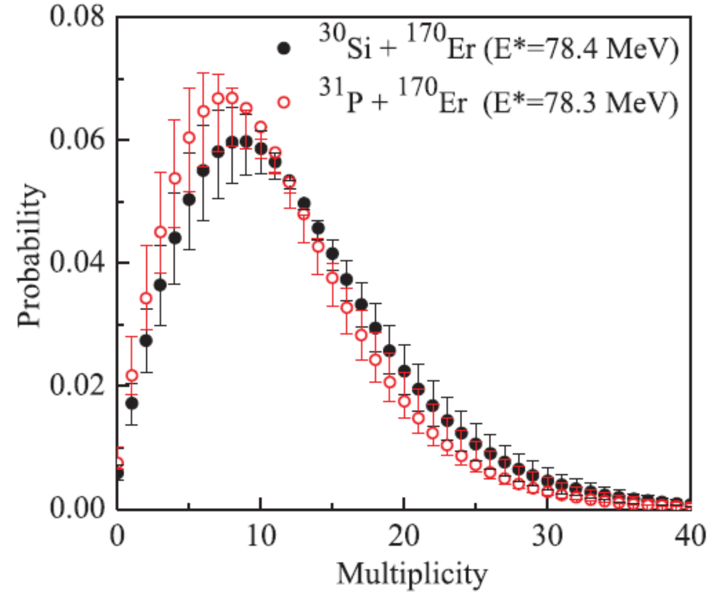
- *Phys Rev. C 88 024312 (2013)*
- *Phys Rev C 88 034606 (2013)*
- *Nucl. Phys. A 890, 62 (2012)*
- *Jour. Phys. G 41 (2014)*
- *EPJ Web of Sc.(2011,2013)*
- *Phys. Rev. C 95 (2017)*
- *Phys. Rev. C 96 (2017)*
- *Phys. Rev. C 99 (2019)*
- *Phys Rev C. 101 ,(2020)*

Probing role of proton shell closure

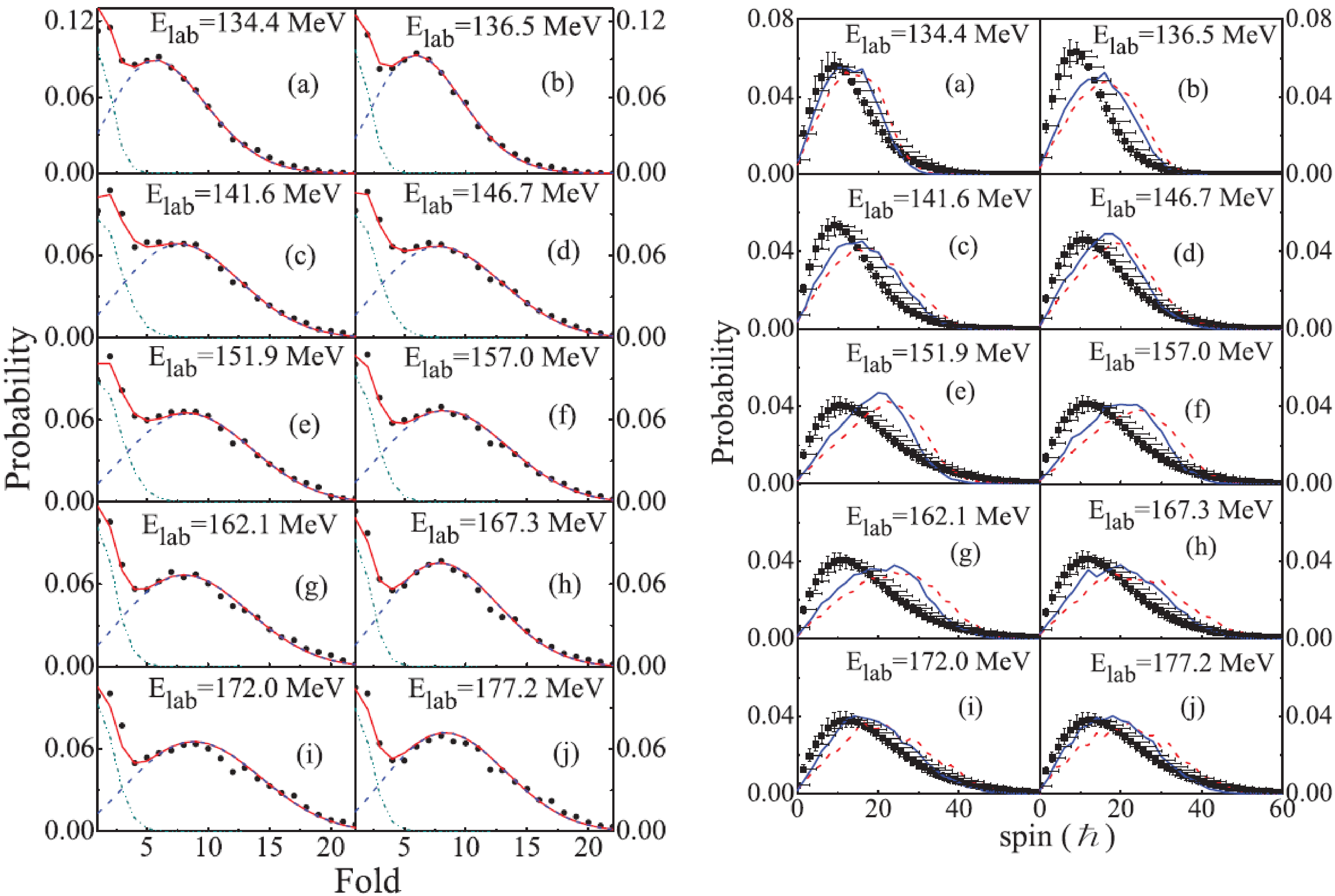








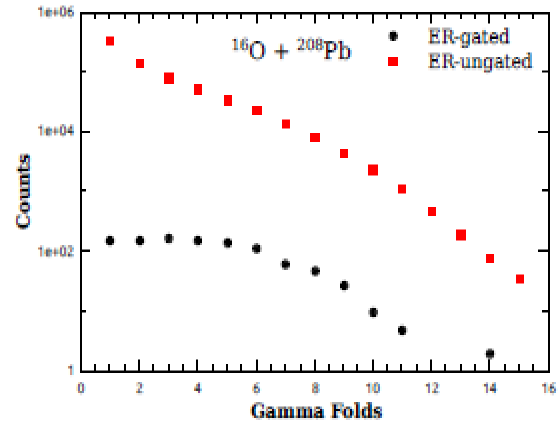
G. Mohanto et al.
Phys. Rev. C 88 (2013)

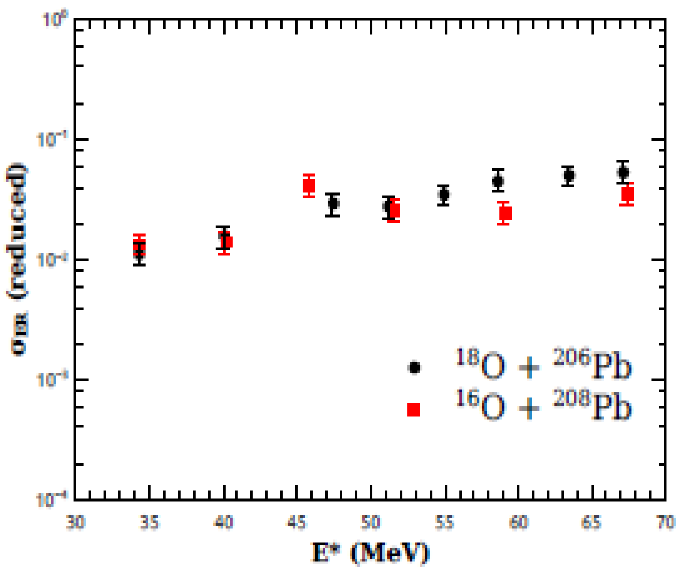


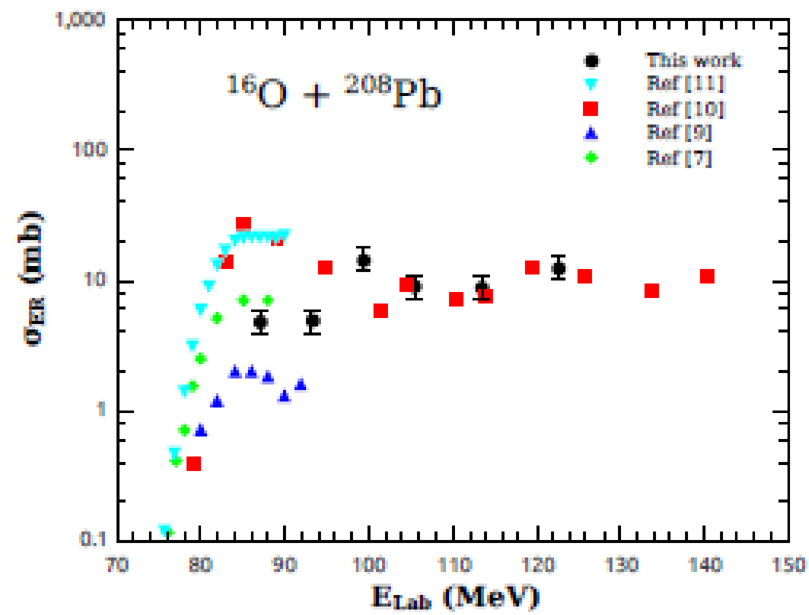
Phys. Rev. C 88 (2013)

TABLE V. The fitted Fermi-function free parameters for ^{16}O + ^{208}Pb and ^{18}O + ^{206}Pb.

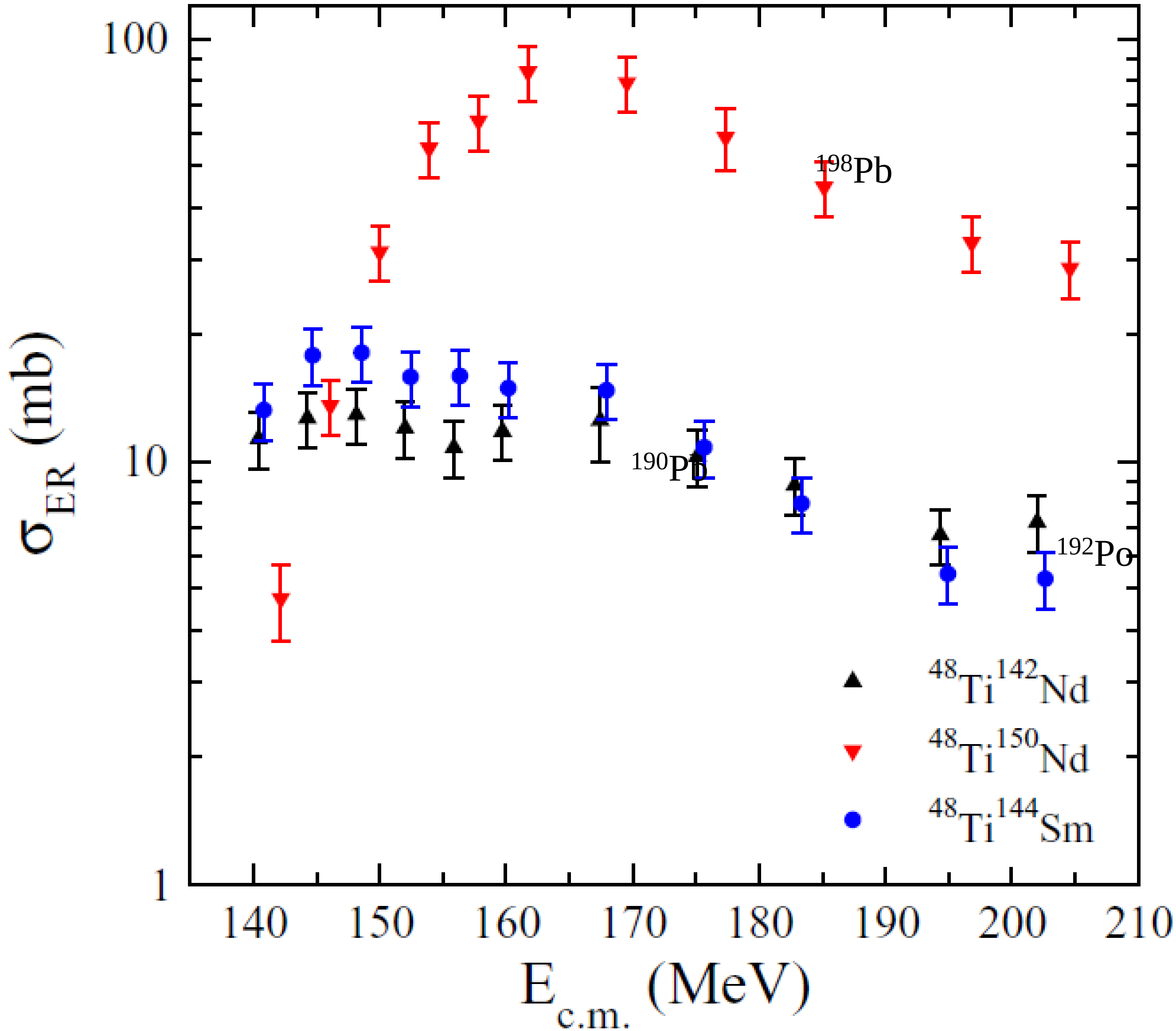
Reaction system	E_{cm} (MeV)	E^* (MeV)	Fermi-function free parameters	
			M_0	ΔM
^{16}O + ^{208}Pb	80.7	34.3	11	1.0
	86.5	40.1	11	1.0
	92.2	45.8	11	0.75
	97.9	51.5	12	0.25
	105.3	59.0	17	1.0
	113.8	67.3	16	1.0
^{18}O + ^{206}Pb	78.8	34.3	8	0.5
	84.5	40.0	9	0.25
	111.6	67.0	10	1.0







Hosamani et al. Phys Rev. C 101, (2020)



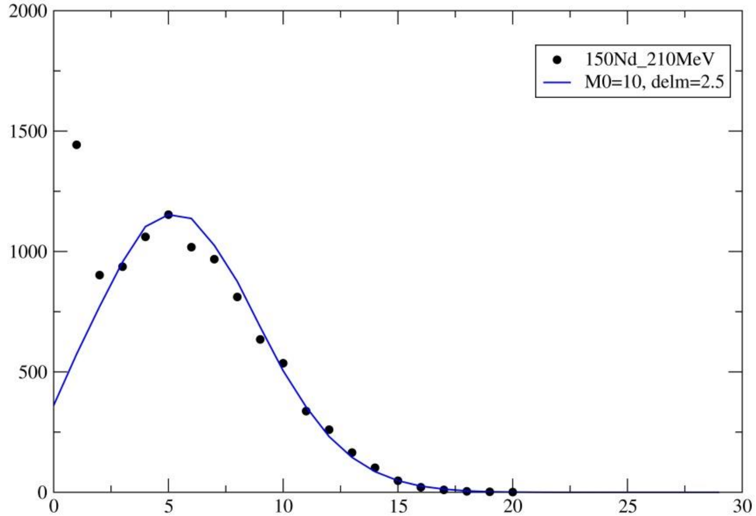
Significantly larger ER survival for ^{198}Pb.

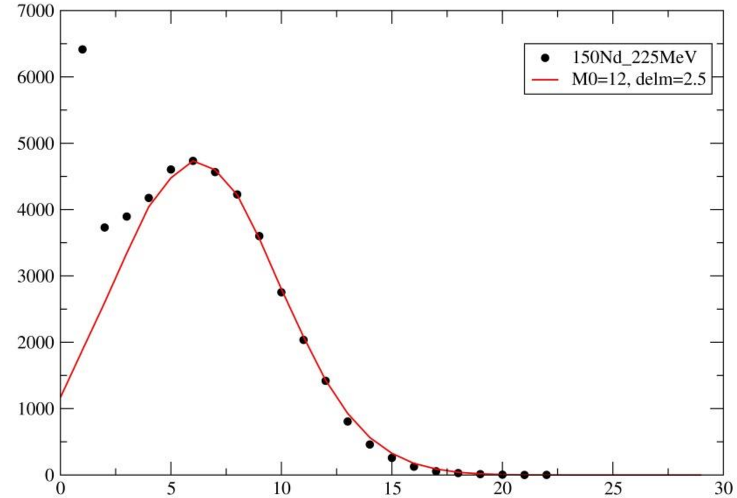
May be due to higher LDM Barrier and shell correction energy.

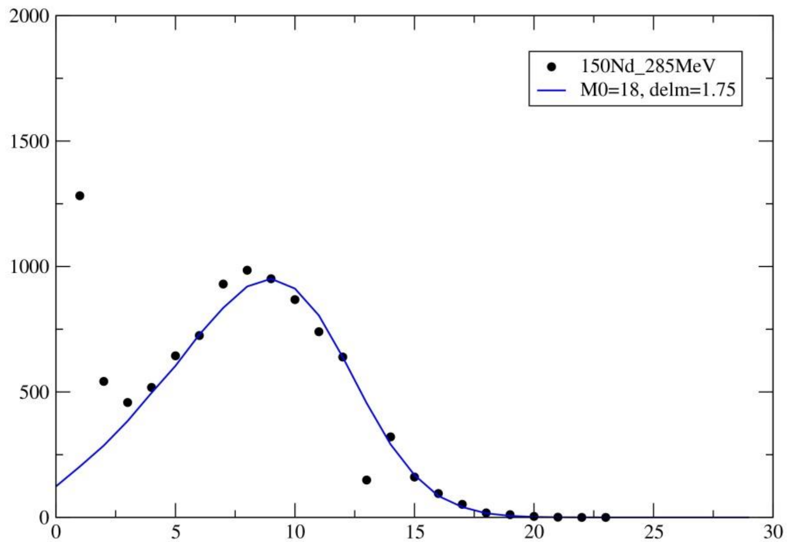
Possible role of NCN is also discussed

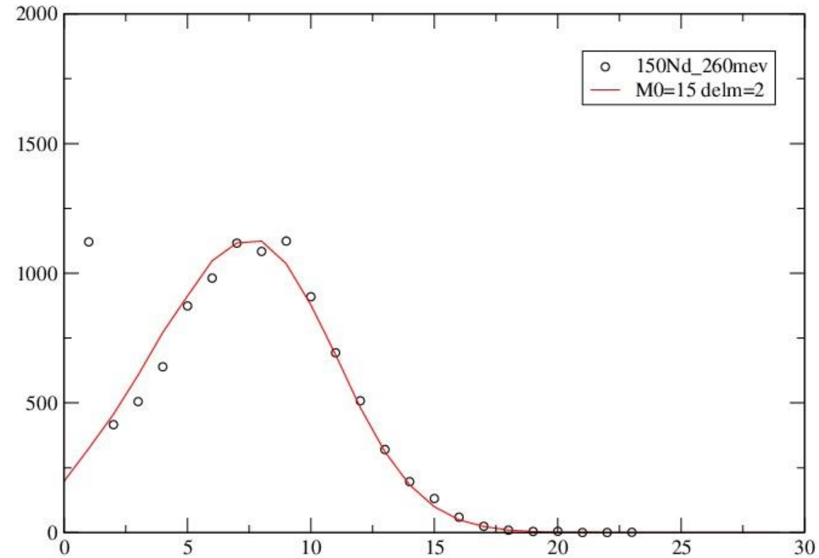
P. Sharma et al.
PRC 96 (2017)

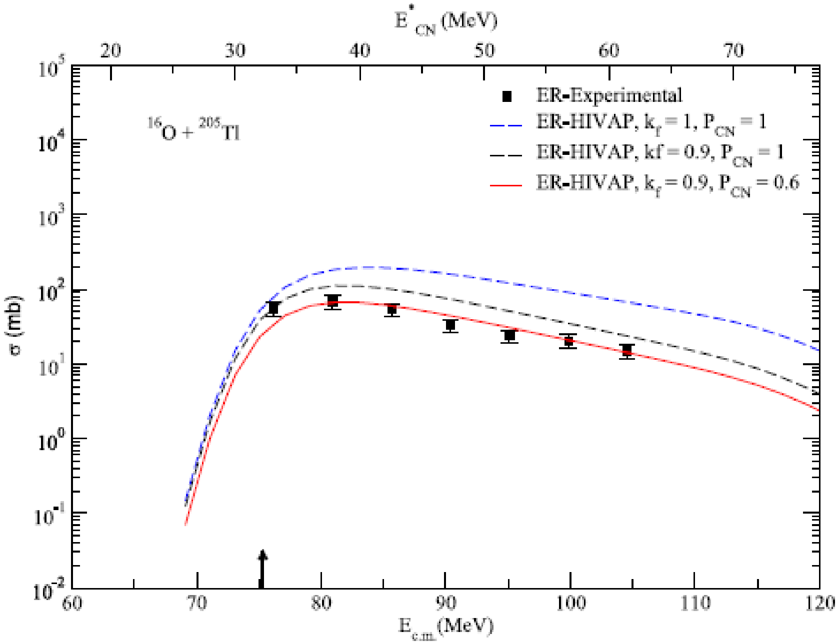
Spin Distributions from $^{48}Ti+^{150}Nd$ system

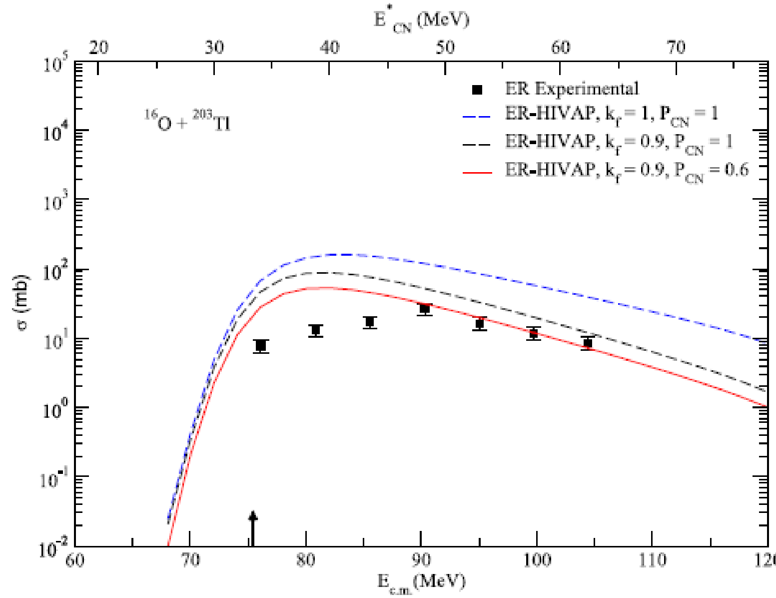










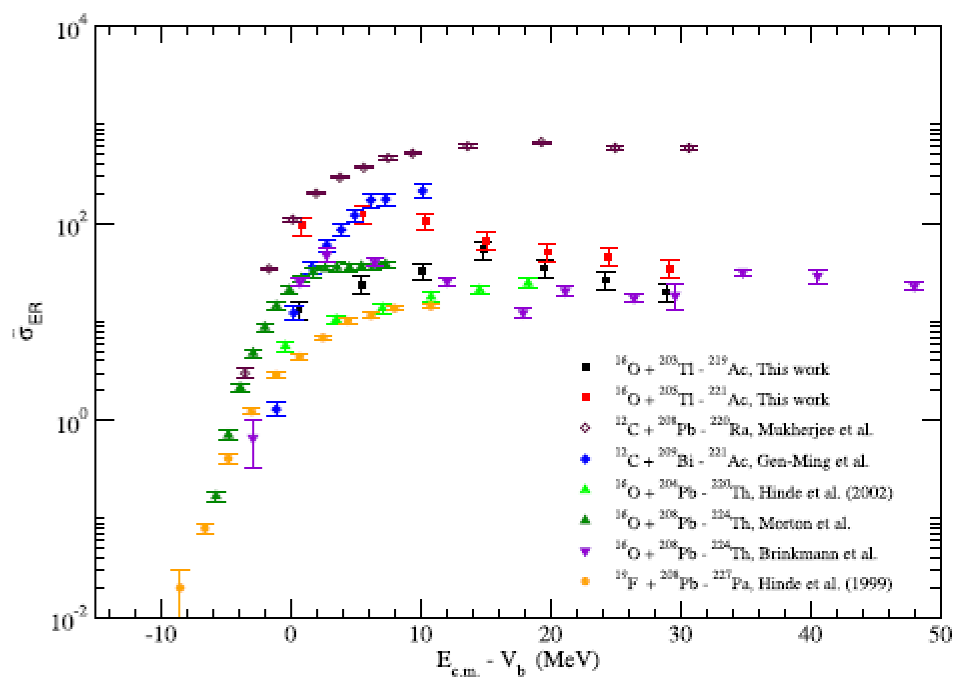


^{16}O+^{203}Tl & ^{16}O + ^{205}Tl Systems:

ERs are reproduced by tuning the barrier..

Possibility of NCN process suggested
(*in comparison with HIVAP output*)

J. Gehlot et al.,
Phys. ReV C 99, (2019)



The Heavy System

$^{32}S + ^{154}Sm \rightarrow ^{186}Pt$

- We have measured the cross sections of ER from ^{186}Pt Compound Nucleus above barrier for the first time at five beam energies.
- We have also measured for the first time the spin distributions at all the beam energies.

The Very Heavy System

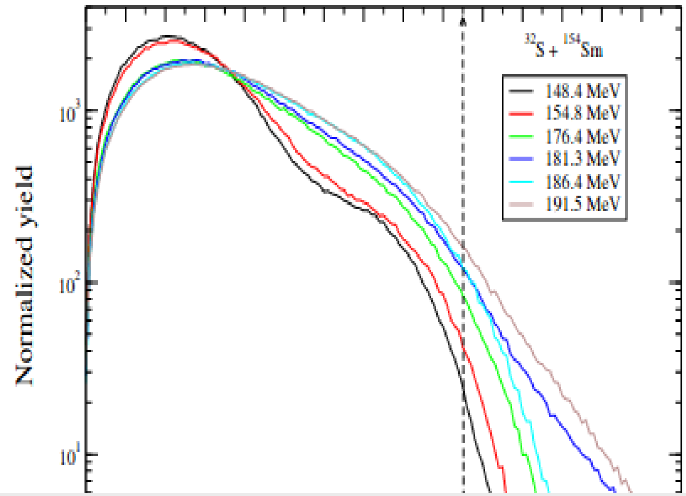
$^{32}S + ^{208}Pb \rightarrow ^{240}Cf$

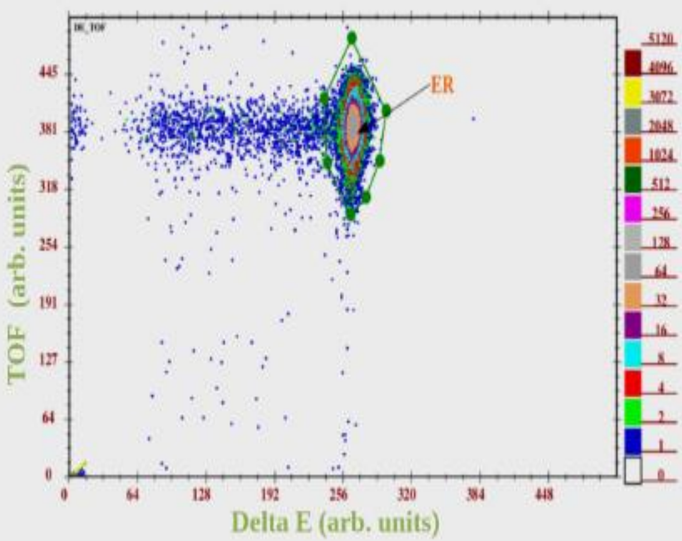
^{240}Cf, being very heavy is predominantly fissioning system. Till date, there exists no data for ER for this nucleus.

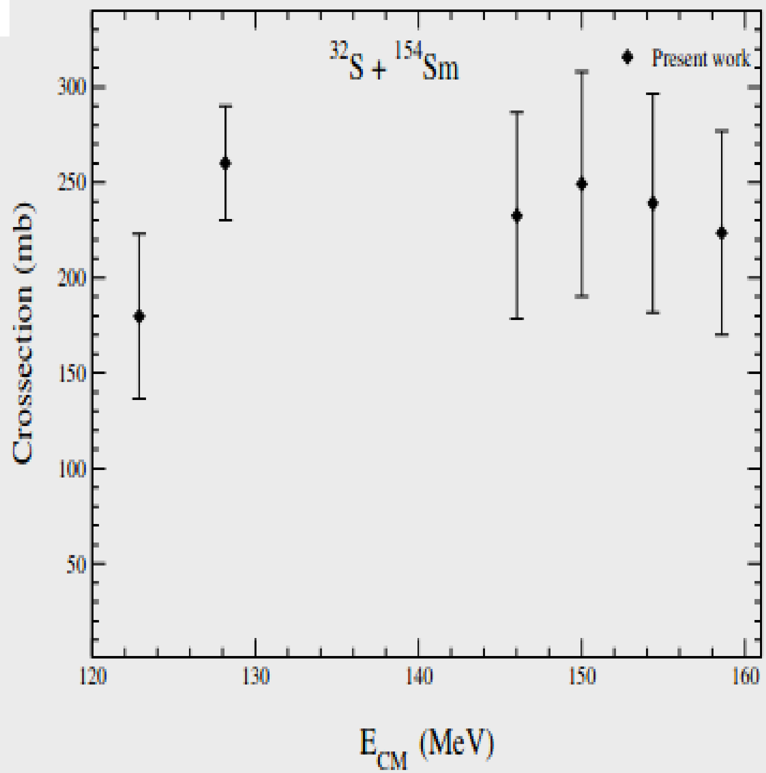
This is the first measurement of ER cross sections from this CN

Any excess cross section of ER over what is predicted by Statistical Model is likely to hint towards mechanisms, like viscosity hindering the fission process.

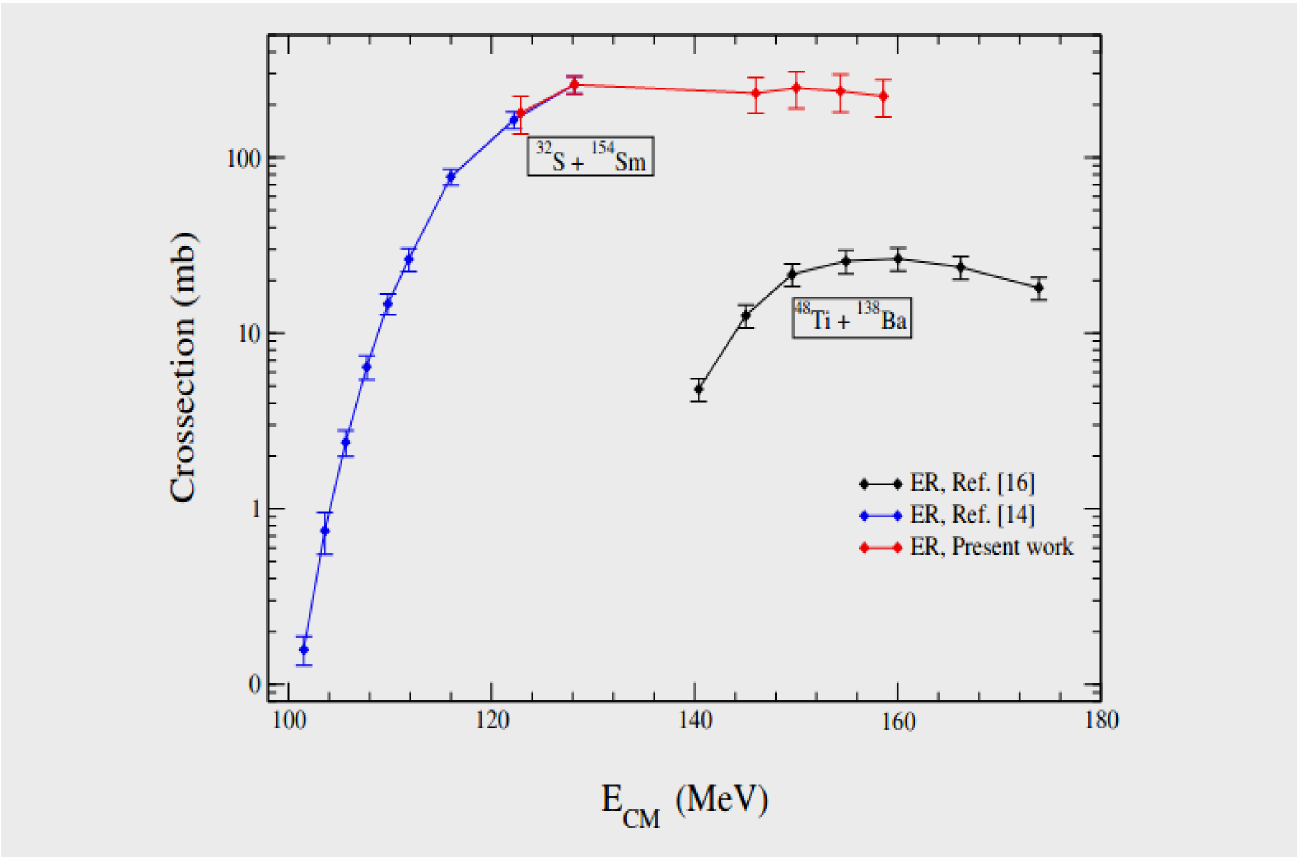
E_{lab} (MeV)	E_{cm} (MeV)	E^*_{CN} (MeV)	$\sigma_{ER}\pm$ error (MB)
148.4	122.9	62.3	180 ± 43
154.8	128.2	67.6	260 ± 30
176.4	146.0	85.4	232 ± 54
181.3	150.1	89.5	249 ± 59
186.4	154.4	93.8	239 ± 58
191.5	158.6	98.0	223 ± 53







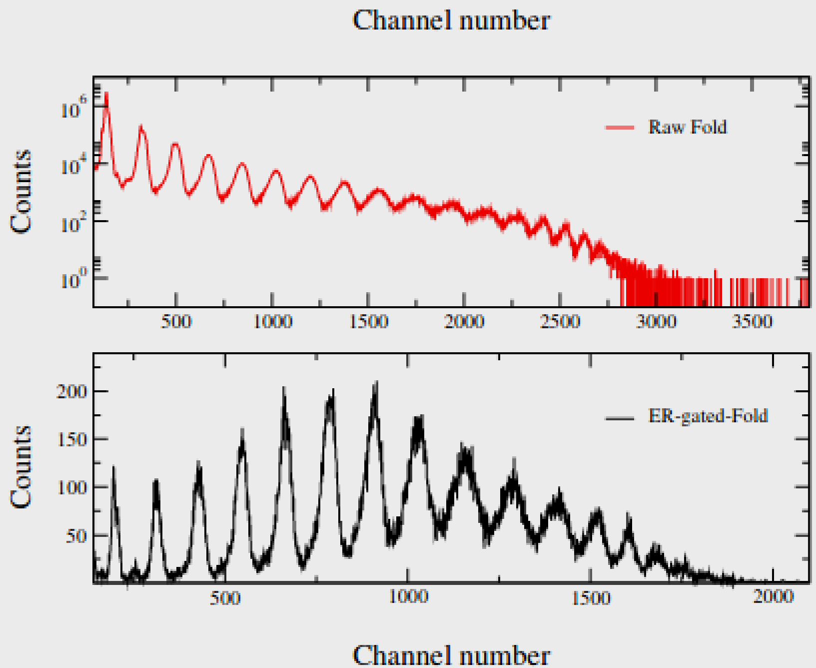
First Important Observation from the Data Analysis

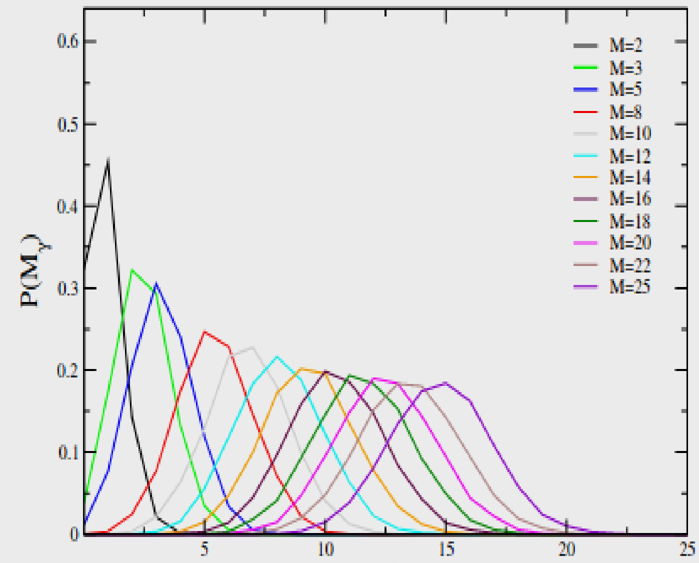


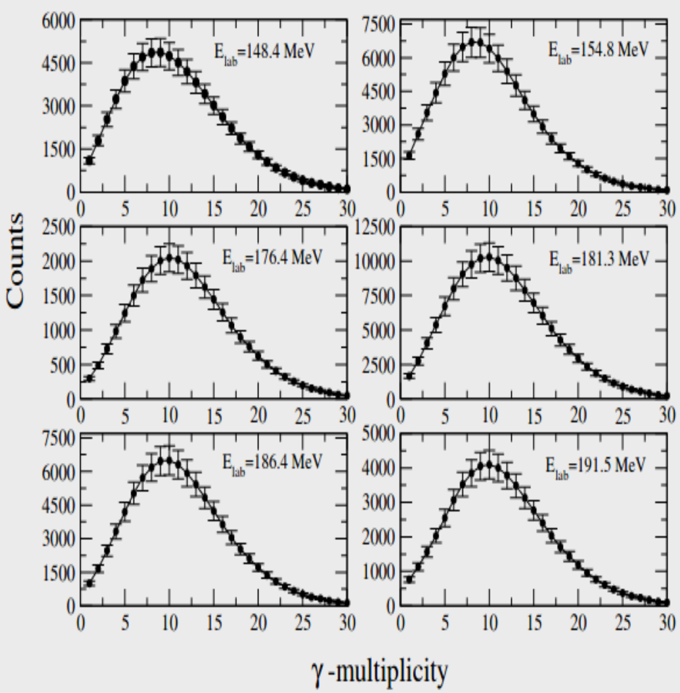
P R S Gomes et al PRC 49 (1994) 245
R. Sariyal et al Present work:
K K Rajesh et al PRC 100 (2019) 044611

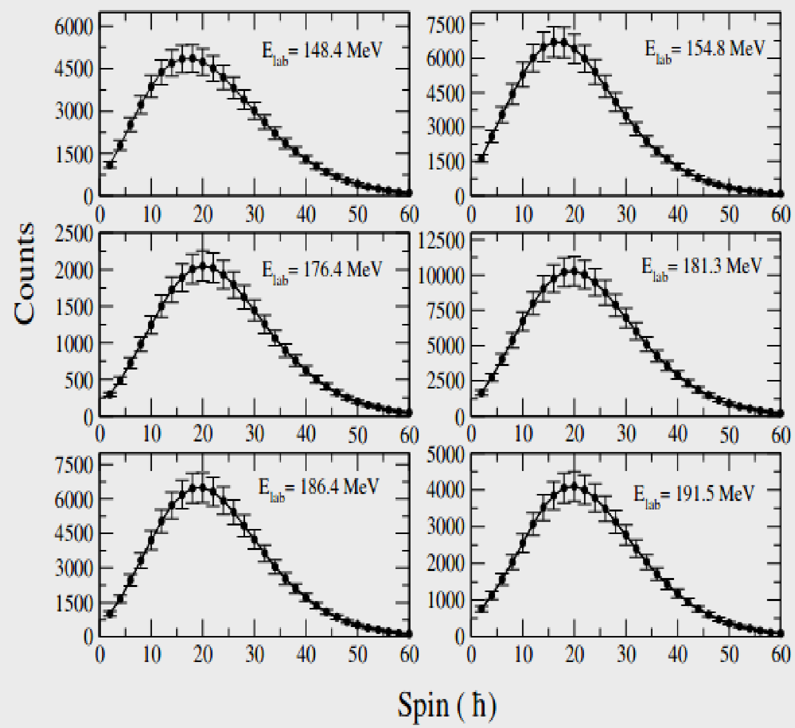
Clear demonstration of role of entrance channel mass asymmetry

Figure 5: (Color online) Raw and ER-gated γ-ray fold distribution at E_{lab} = 191.4 MeV.









Theoretical Analysis: I Statistical Model Analysis

Experimental Spin Distribution and Fusion Cross sections are Fed in the Calculations

- Fission Channel Calculation

Saddle point transition state model: Bohr & Wheeler, Phys. Rev. 56 426 (1939)

The fission rate is determined by integrating over all available states at the saddle point

$$R_{\mathrm{fiss}} = \frac{1}{2\pi\hbar\rho_1(E_i, J_i)} \int_0^{E_i - E_b} \rho_2(E_i - E_b - E, J_i)\, dE,$$

$$\Gamma_f^{\mathrm{BW}} = \frac{T}{2\pi} \exp(-E_f/T).$$ Vandenbosch & Huizenga (1974)

Note: we compute this exact integral and not any other simpler form

Analysis:

Stage I. No viscosity, No temperature dependent NLD parameter *a*

Stage II Includes viscosity & temperature dependent NLD *a*
[Ignatyuk-Reisdorf & Ignatyuk-Reisdorf + Shlomo-Natowitz]

$$a(U)=\tilde{a}\left(1+\frac{f(U)}{U}\delta W\right)$$

where

$$f(U)=1-\exp(-U/E_D)\,;$$

$$(\delta W = M_{\mathrm{exp}} - M_{\mathrm{LDM}})$$

A.V. Ignatyuk et al., Yad. Fiz, 21 , 485 (1975), [Soviet Journal of Nucl. Phys. 21, 255 (1975)]

$$\tilde{a}=0.04543r_0^3A+0.1355r_0^2A^{2/3}B_s+0.1426r_0A^{1/3}B_k$$

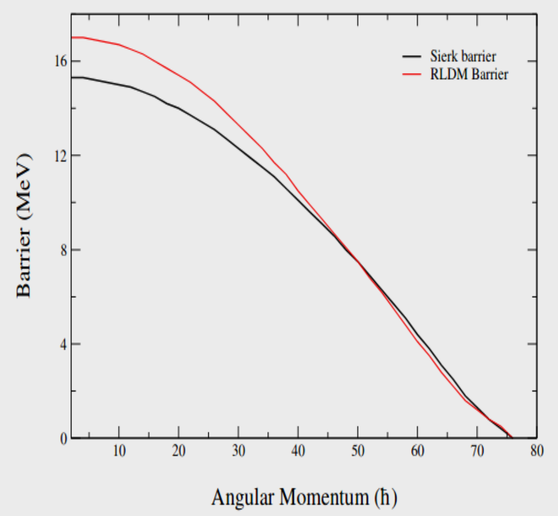
W. Reisdorf, Z. Phys. A 300, 227 (1981)

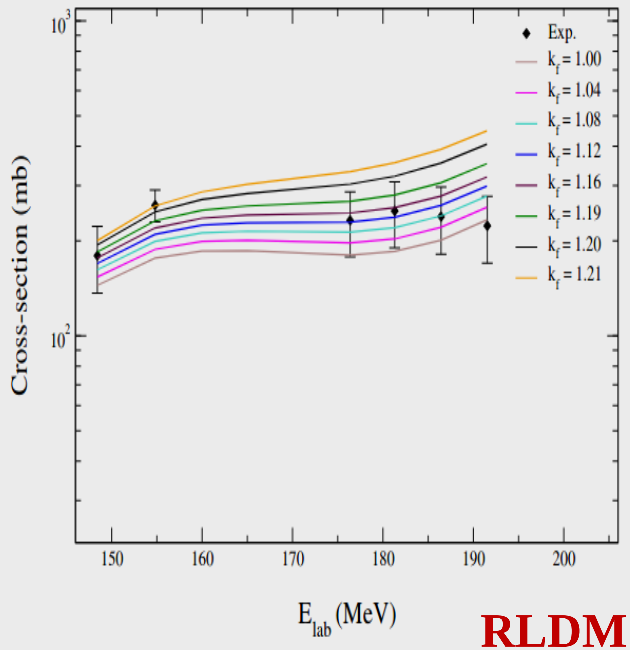
$$a(T)=a(U)[1-\kappa f(T)],$$

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

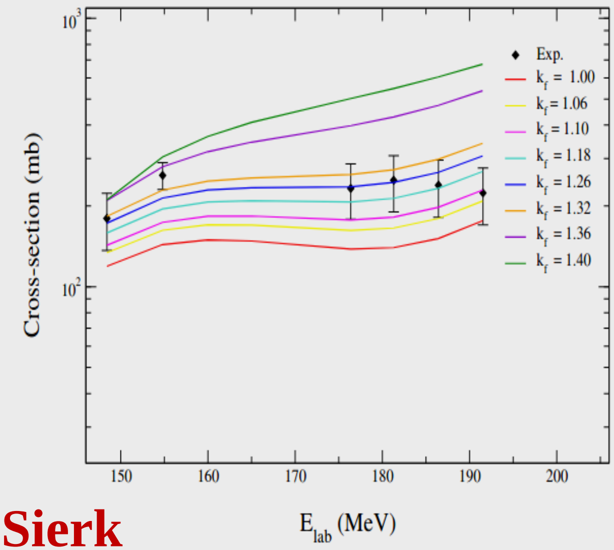
Shlomo and Natowicz, Phys. Rev C 44, 2878 (1991)
Lestone, Phys. Rev C52 118 (1995)

Variation of the Fission Barrier



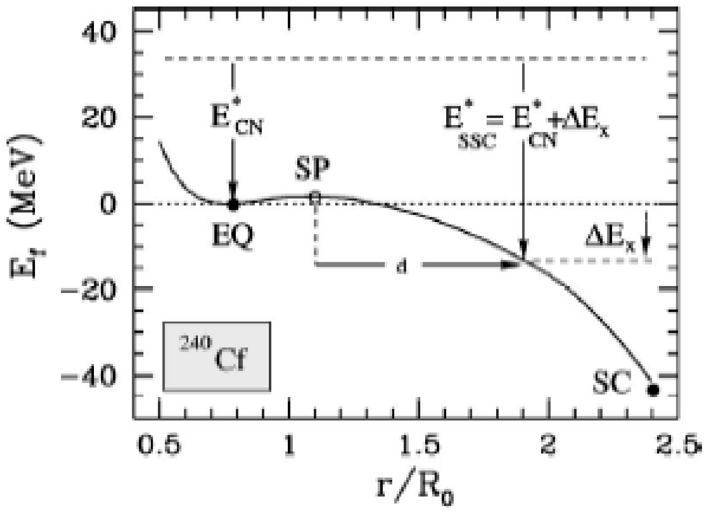


RLDM



Sierk

Introducing Dissipative Mechanism



$$\Gamma_{\text{fiss}}^{\text{BW}} = \frac{1}{2\pi\rho_1(E_i, J_i)} \int_0^{E_i - E_b} \rho_2(E_i - E_b - E, J_i)\, dE,$$

Saddle point transition state model: Bohr & Wheeler, Phys. Rev. 56 426 (1939)

H.A. Kramers, Physica, 4 284 (1940)

$$\Gamma_f^{\text{Kramers}} = \Gamma_f^{\text{BW}}[(1+\gamma^2)^{1/2} - \gamma]$$

$$\tau_{\text{ssc}} = \tau_{\text{ssc}}^0[(1+\gamma^2)^{1/2} + \gamma].$$

$\gamma = \beta/2\omega_0$

$\omega_0 = 10^{21}\ s^{-1}$

$$\tau_{\text{ssc}}^0 = \frac{2}{\omega_0} R[(\Delta V/T)^{1/2}]$$

$$R(z) = \int_0^z \exp(y^2)\, dy \int_y^\infty \exp(-x^2)\, dx.$$

Additional buildup time

Grange, Jun-Qing, Weidenmuller (1983)

$$\tau_f = \beta/2\omega_1^2[\ln(10B_f / T)]$$

Need for decoupling the effects of temperature and angular momentum

Separation of contributions from pre-saddle and saddle to scission regions

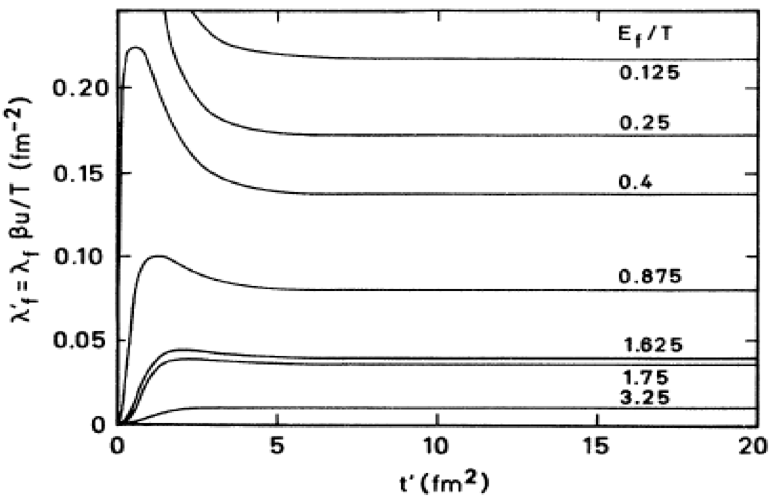


FIG. 2. The scaled rate $\lambda_f'(t')$ versus t' for various choices of a or, equivalently, E_f/T, as indicated.

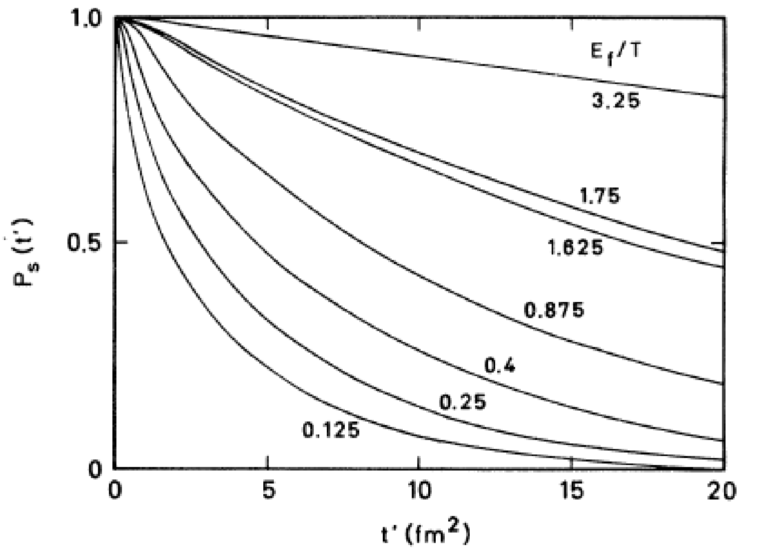
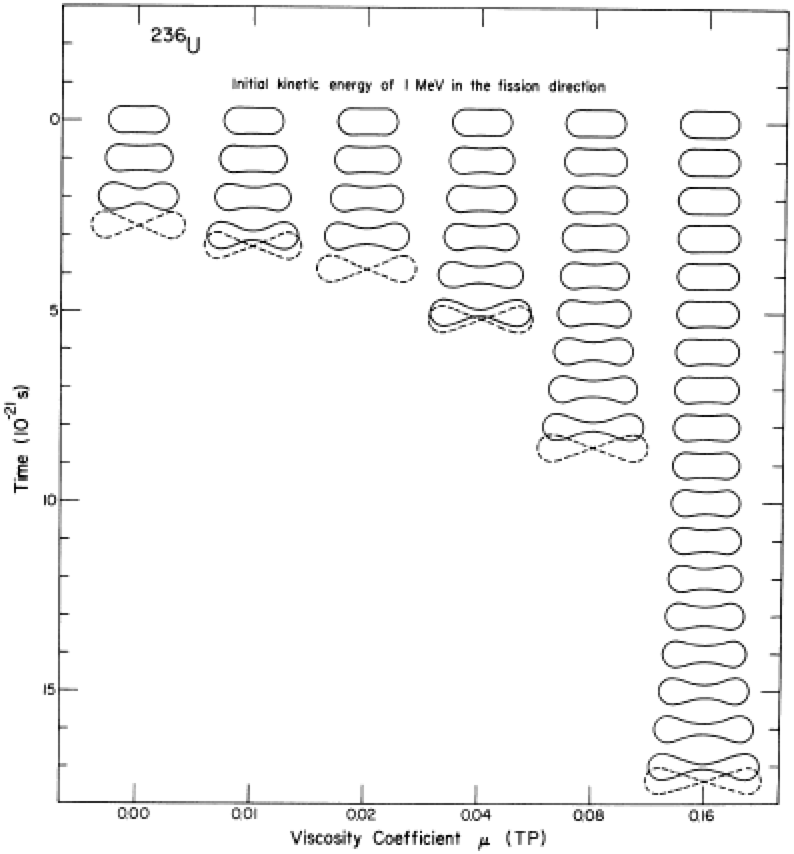


FIG. 3. The probability $P_s(t')$ of finding the system to the left of the saddle point versus t' for various choices of a or, equivalently, of E_f/T, as indicated.

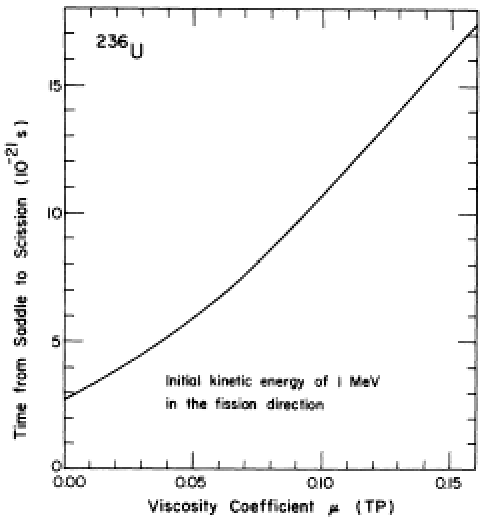
Weidenmuller and Jing-Shang (1984)

Strong temperature dependence demands two-body mechanism:

KTR Davies, AJ Sierk, JR Nix, Phys Rev C 13, (1976) 2385



Calculated shapes with time for different viscosity coefficient.



Time required for ^{236}U to travel saddle to scission

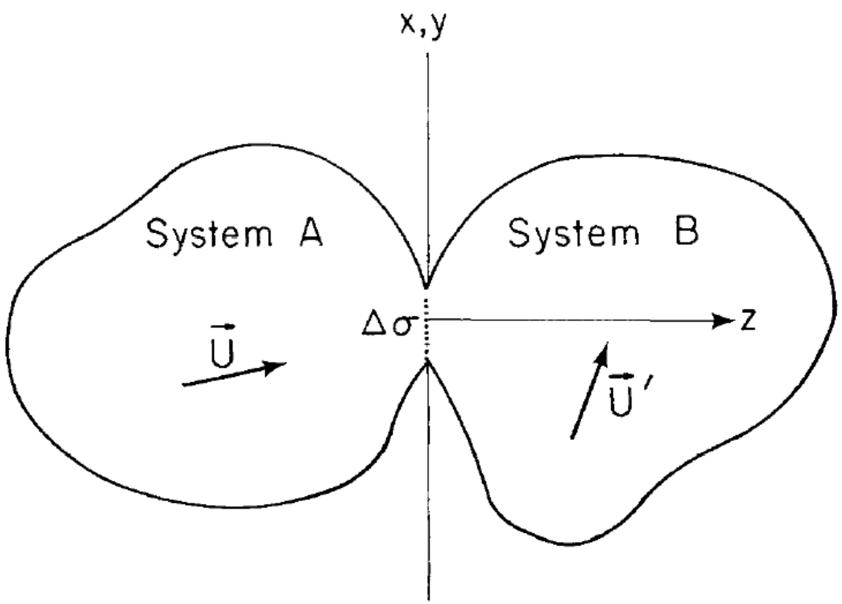
Two-body viscosity hinders the formation of the neck

Strong Temperature dependence

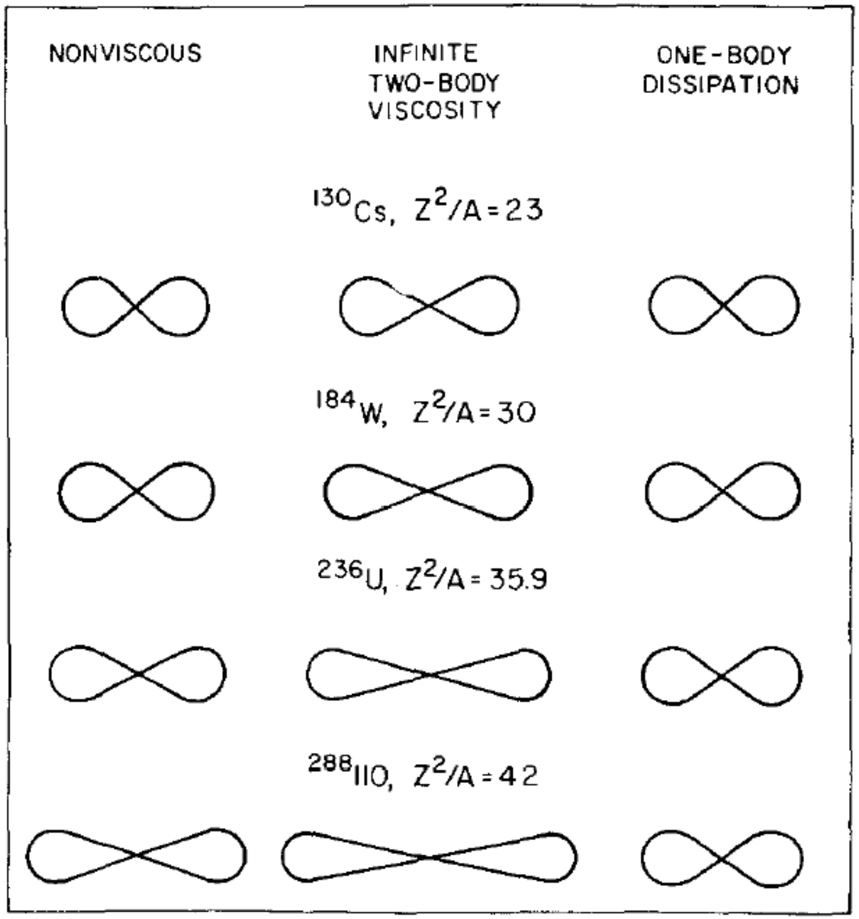
However, the authors admit, large mean free path can result in one-body viscosity, collision of nucleon with moving wall.

Favours neck formation

Little or no temperature dependence of viscosity parameter.



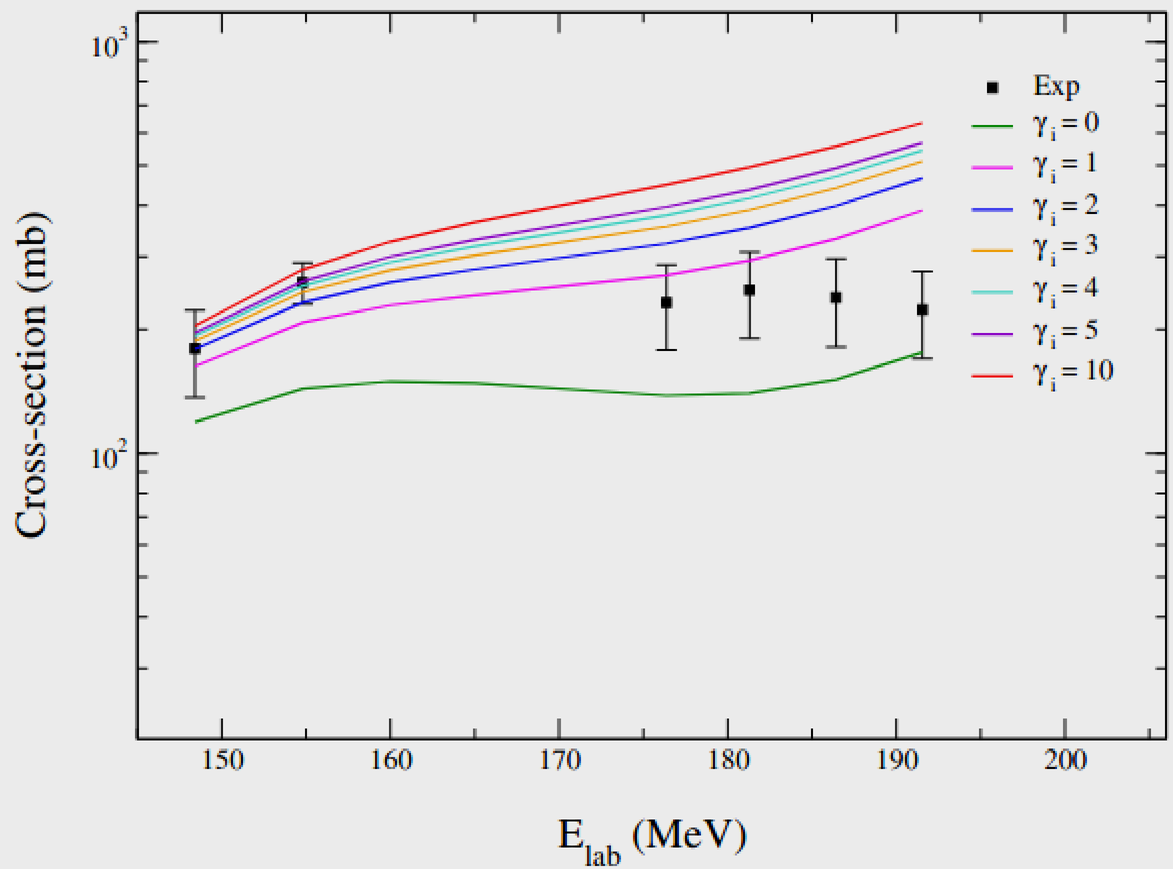
One-body mechanism



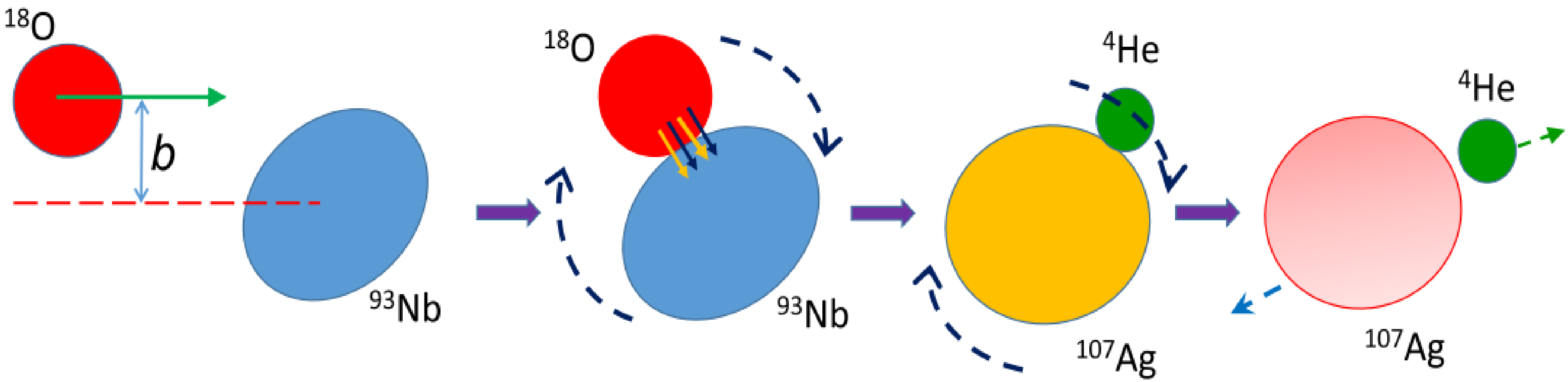
J. Blocki *et al*,

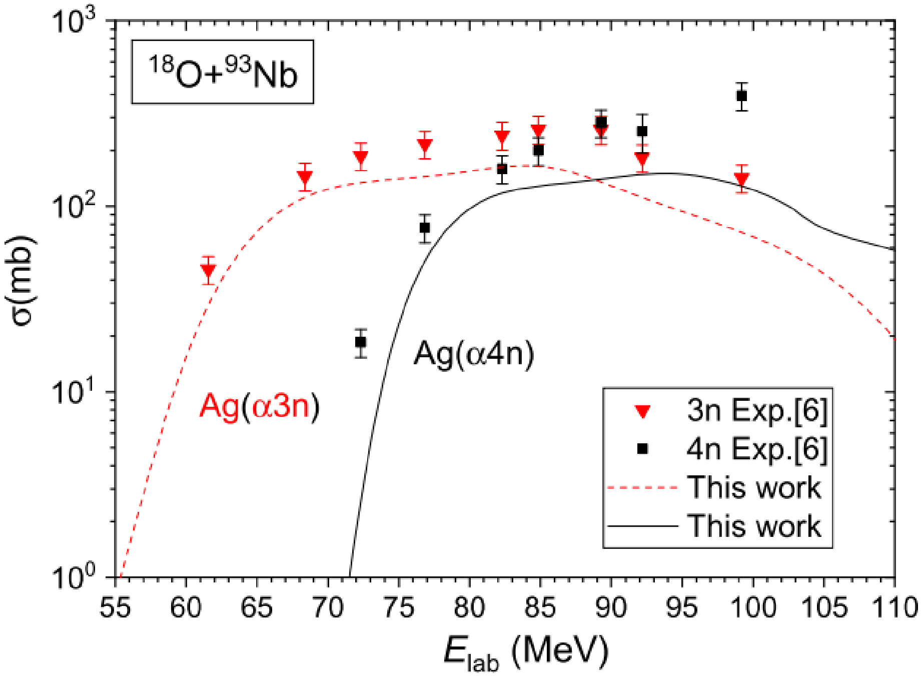
Annals of Physics, 113, 330 (1978)

ER from $^{32}S + ^{154}Sm \rightarrow ^{186}Pt$ system



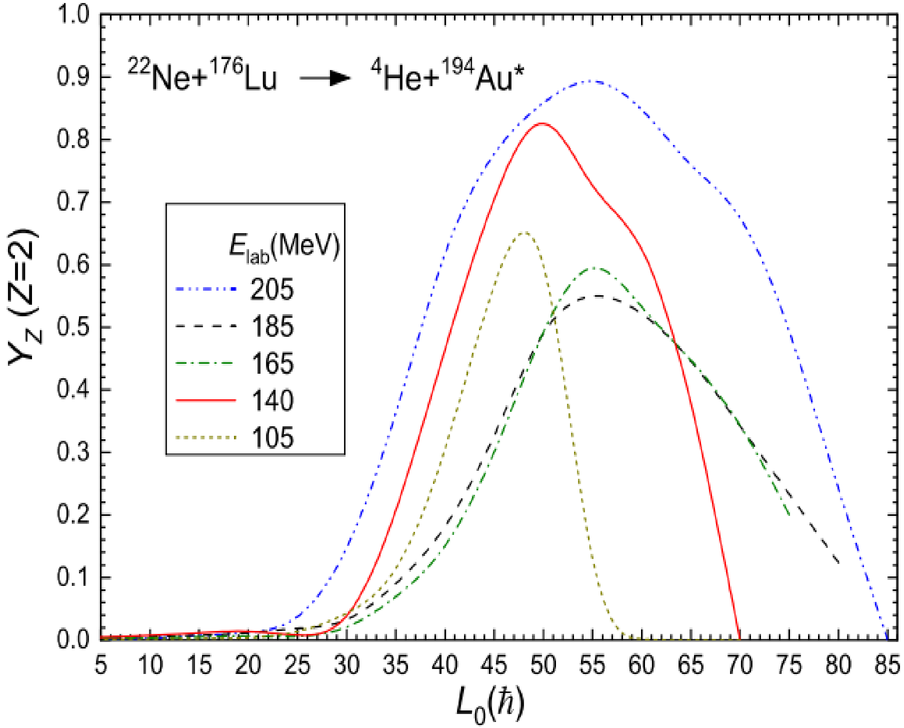
Dynamical Calculations: The DNS Model



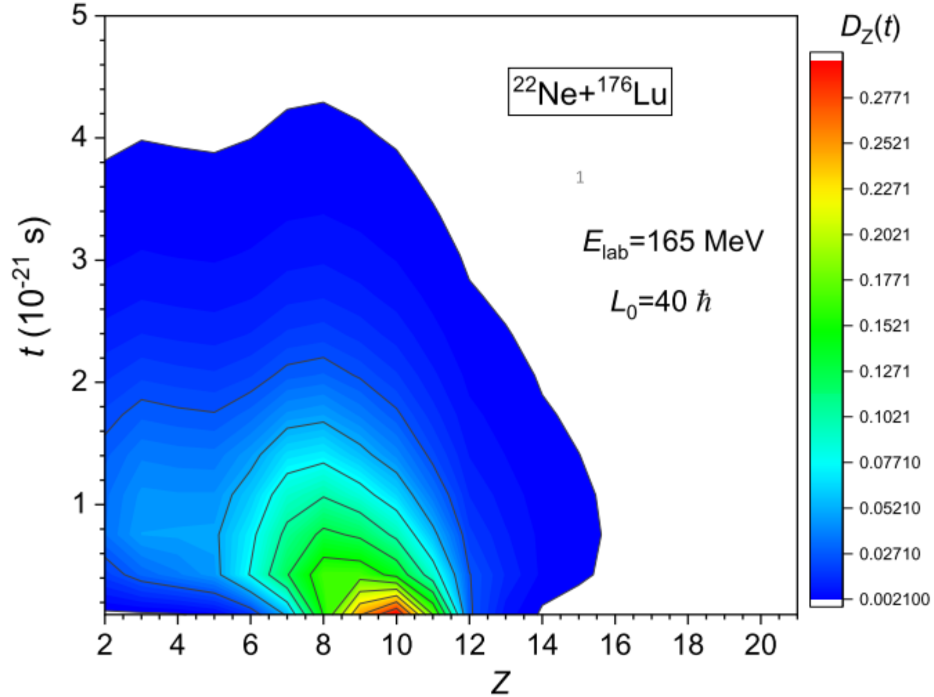


A. Nasirov et al

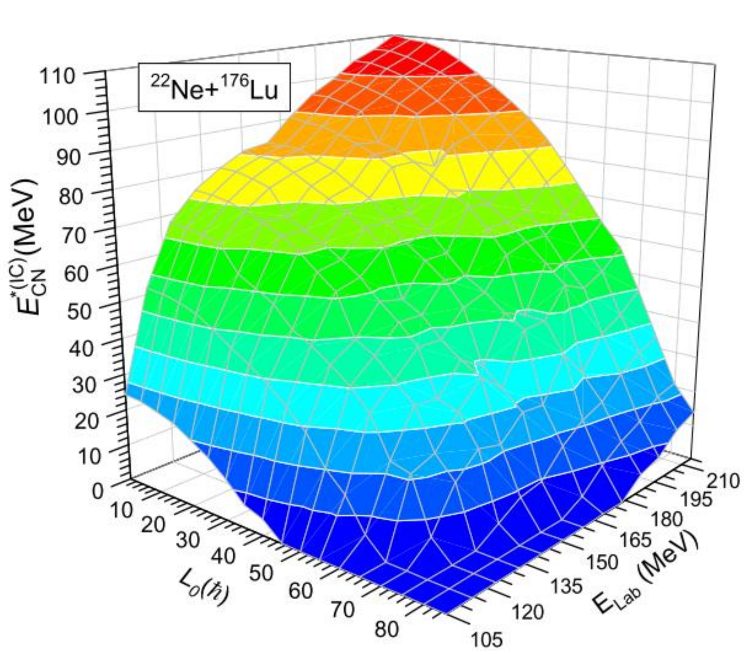
- Phys. Lett B842 (2023)
- Nucl. Phys A 946 (2016)
- PRC 105 (2022)
- EPJ A 49 (2013)
- Nucl. Phys. A 759 (2005



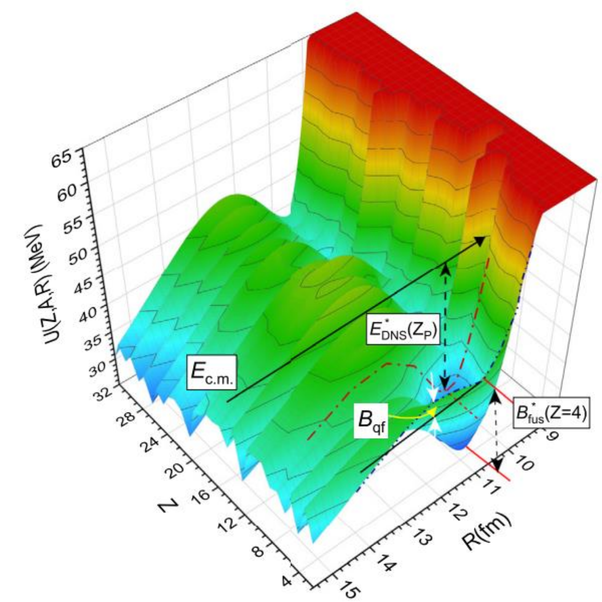
^{22}Ne+^{176}Lu → ^{4}He+^{194}Au*
E_{lab}(MeV)
205
185
165
140
105
Y_Z (Z=2)
$L_0(\hbar)$



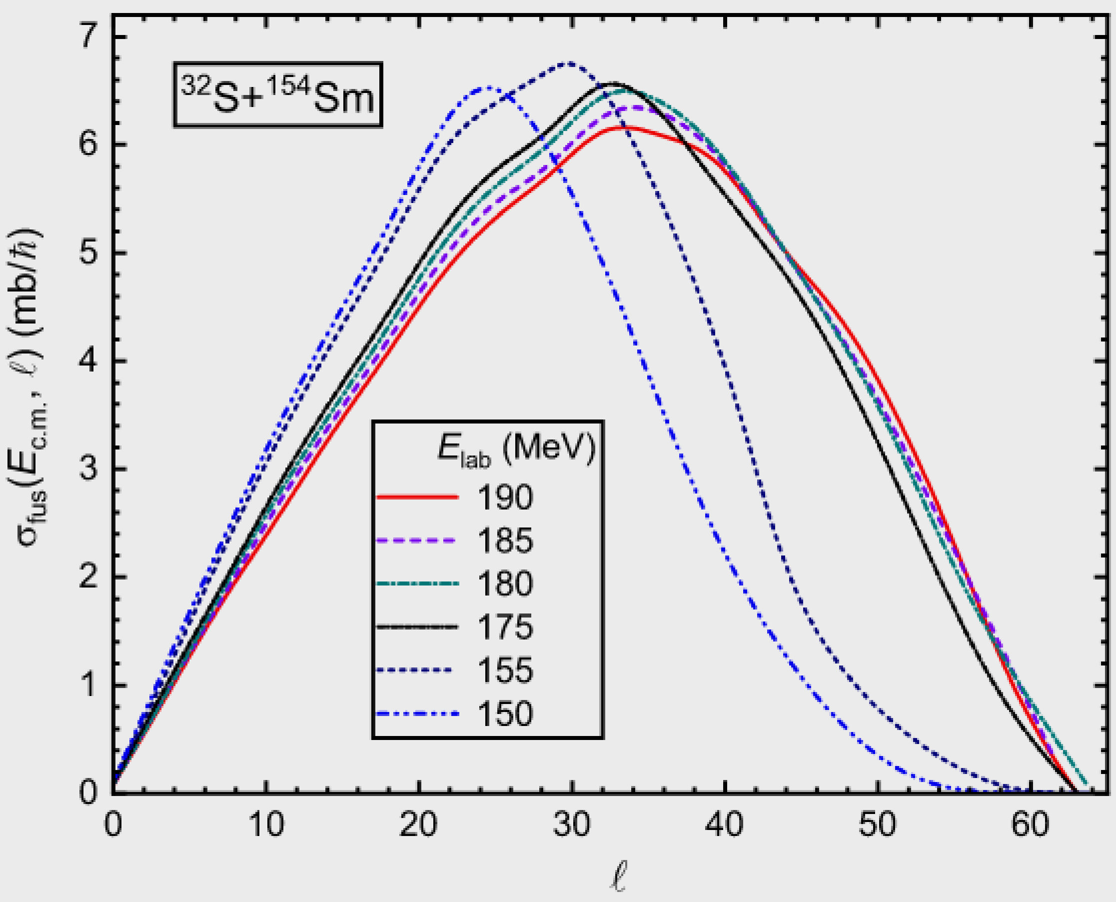
^{22}Ne+^{176}Lu
E_{lab}=165 MeV
L_0=40 $\hbar$
$D_Z(t)$
t (10^{-21} s)
Z



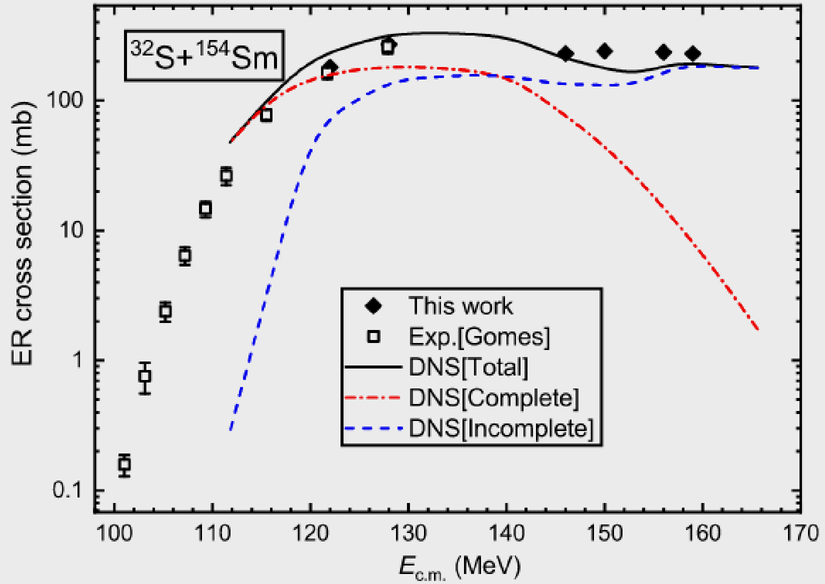
^{22}Ne+^{176}Lu
$E^{*(IC)}_{CN}$(MeV)
$L_0(\hbar)$
E_{Lab} (MeV)



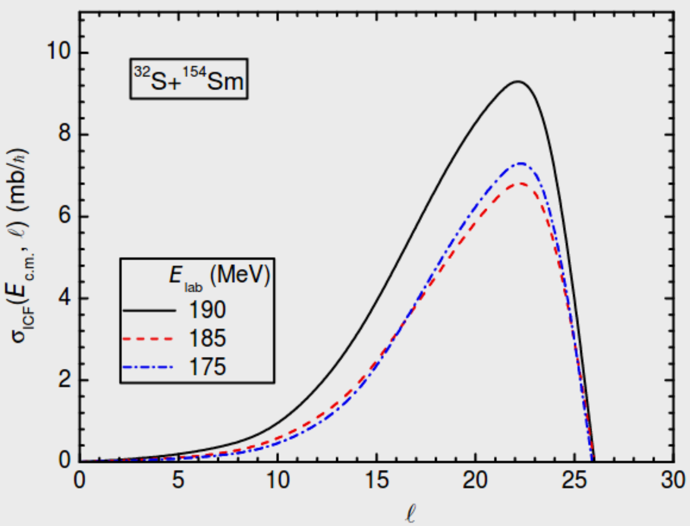
U(Z,A,R) (MeV)
$E_{c.m.}$
$E^*_{DNS}(Z_P)$
B_{qf}
B^*_{fus}(Z=4)
Z
R(fm)



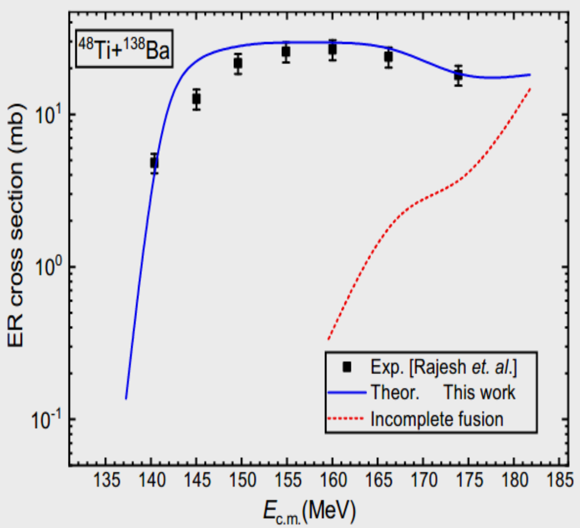
$^{32}S+^{154}Sm$
$\sigma_{fus}(E_{c.m.}, \ell)$ (mb/ħ)
ℓ
E_{lab} (MeV)
190
185
180
175
155
150
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60



^{32}S+^{154}Sm
This work
Exp.[Gomes]
DNS[Total]
DNS[Complete]
DNS[Incomplete]
ER cross section (mb)
$E_{c.m.}$ (MeV)



^{32}S+^{154}Sm
E_{lab} (MeV)
190
185
175
$\sigma_{ICF}(E_{c.m.}, \ell)$ (mb/ħ)
ℓ



^{48}Ti+^{138}Ba
Exp. [Rajesh et. al.]
Theor. This work
Incomplete fusion
ER cross section (mb)
$E_{c.m.}$(MeV)

$^{32}S + {}^{208}Pb \rightarrow {}^{240}Cf$

This system has been studied by several groups for *Fission fragments, GDR γ-rays,*

1) M.B. Tsang *et al.*, Phys. Rev. C 28,747(1983)
2) B.B. Back *et al.*, Phys. Rev C 32, 195(1985)

Fission Fragment measurements

3) R. Butsch *et al.*, Phys. Rev. C 44, 1515(1991)
4) N.P. Shaw *et al.*, Phys. Rev. C 61, 044612(2000)

GDR gamma rays measurements

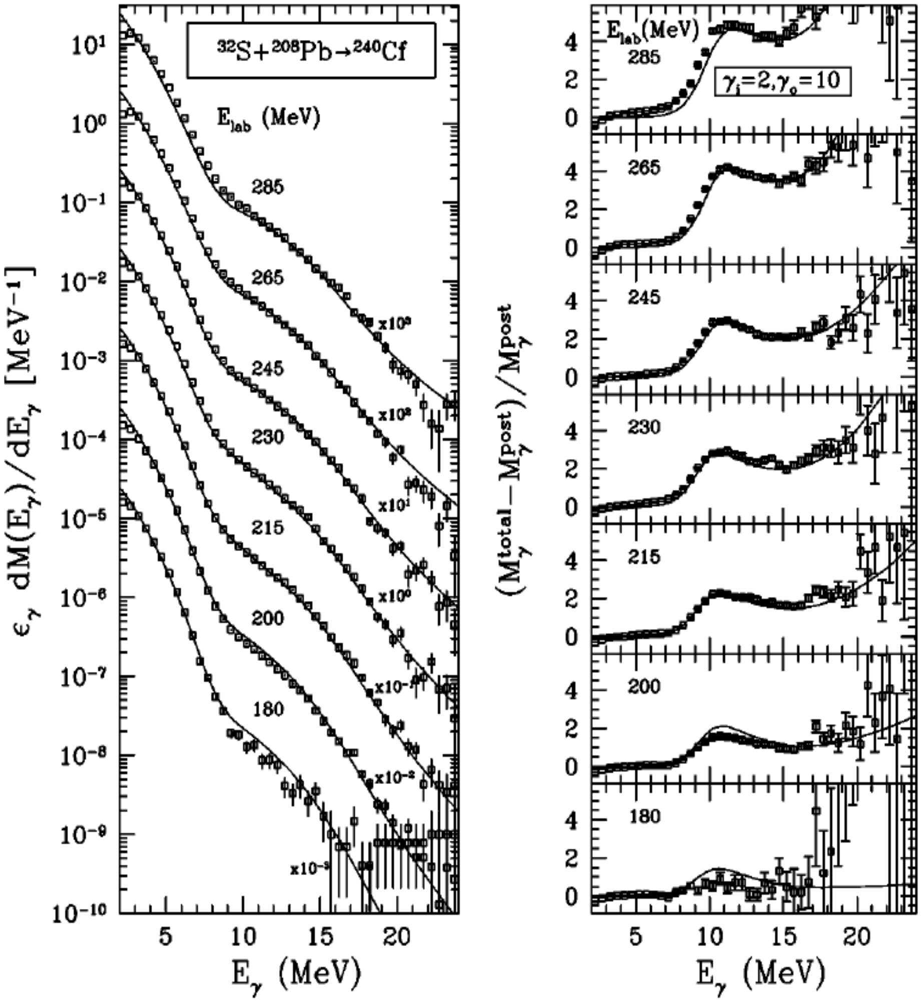
5) W. Loveland *et al.*, Phys. Rev C 74, 044607 (2006)
6) D.J. Hinde *et al.*, Phys. Rev. C 75, 054603 (2007)

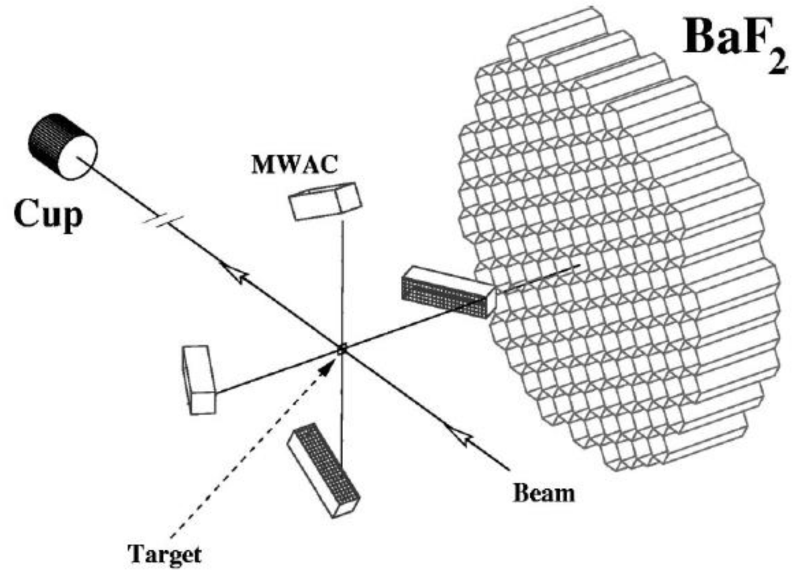
Dependence of fusion barrier energies on neutron rich projectiles

6) R. Yanez *et al.*, Phys. Rev. C 82, 054615 (2010)
8) J. Khuyagbaatar *et al.*, Phys. Rev. C 86, 064602 (2012)
9) J. Khuyagbaatar *et al.*, Phys. Rev C 91, 054608 (2015)
10) A.K. Nasirov *et al.*, Eur. Phys. J A 55, 29 (2019)

Entrance channel effect

Fission Delay in ^{240}Cf: $^{32}S + ^{208}Pb$





Phys. Rev C61, 044612
Phys. Rev. C61, 024613
Phys. Rev. C63, 047601
Phys. Rev. C63, 014611
Pramana 85, No.2 (2015)

$\gamma_i = 2$; $\gamma_o = 10$ fit all the spectra

No apparent temperature dependence of γ
It may be spin(deformation) dependent

With increasing T γ-yield is almost entirely from Saddle to scission

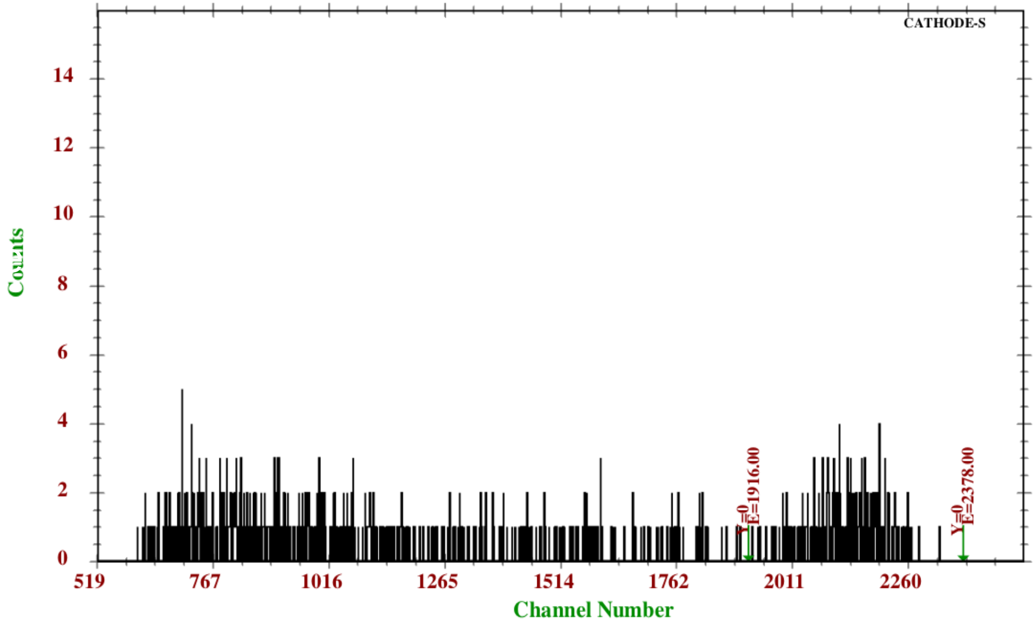
η/s Ratio in Finite Nuclei at low temperature

- *Auerbach & Shlomo PRL 103, 172501 (2009)*
- *N. Dinh Dang, PRC 85, 064323 (2012)*
- *Hung & Dang PRC86, 024302 (2012)*

Extracted from GR widths

The HYRA Measurements at IUAC

$^{32}S + ^{208}Pb$



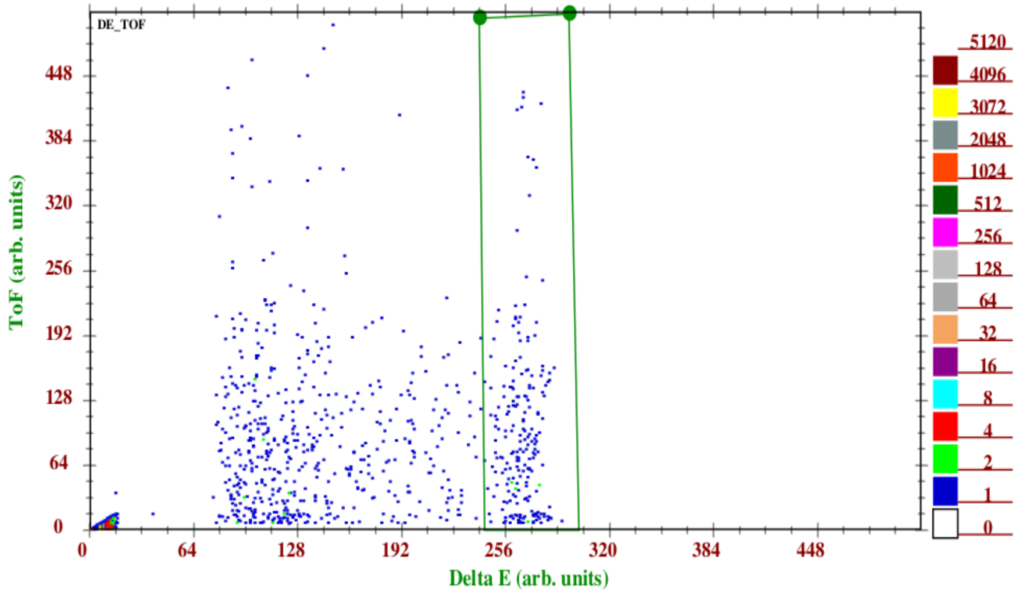


Table 5.1: Total ER cross-section of $^{32}S + ^{208}Pb$ at different energies.

E_{lab}(MeV)	E_{cm}(MeV)	E^*_{CN}(MeV)	Hyra efficiency (ϵ_H)(%)	σ_{ER}(μb)
			1	448
			2	224
176.4	146.0	40.3	3	149
			4	112
			5	89
			1	334
			2	167
181.3	150.1	44.4	3	111
			4	84
			5	66
			1	155
			2	77
186.4	154.4	48.7	3	52
			4	39
			5	30
			1	151
			2	75
191.5	158.6	52.9	3	50
			4	37
			5	30

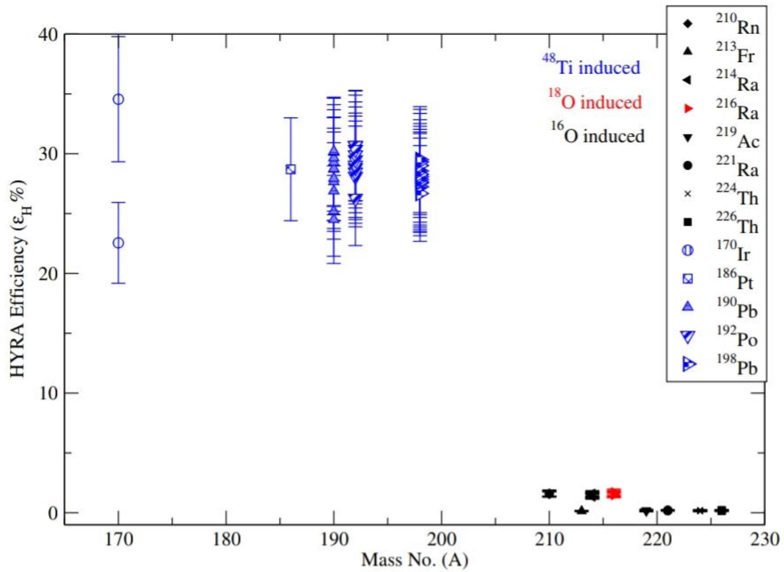
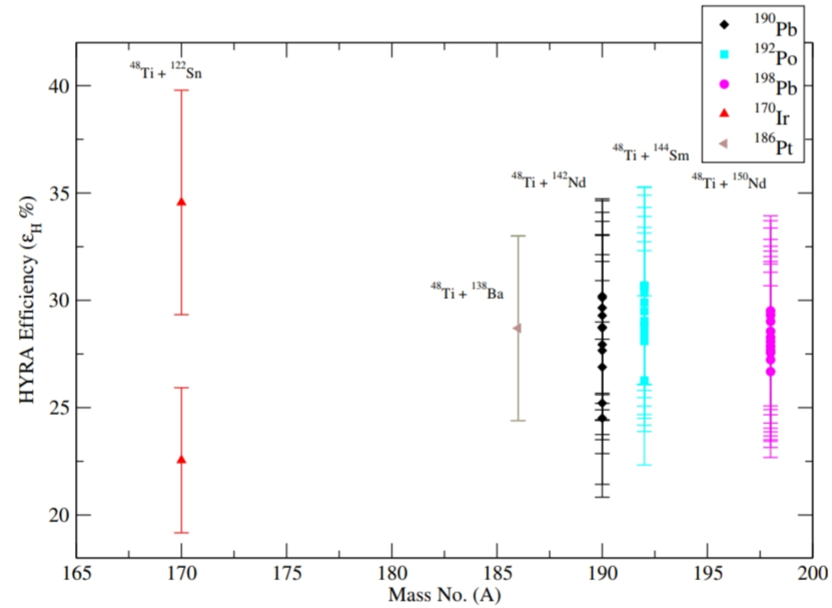
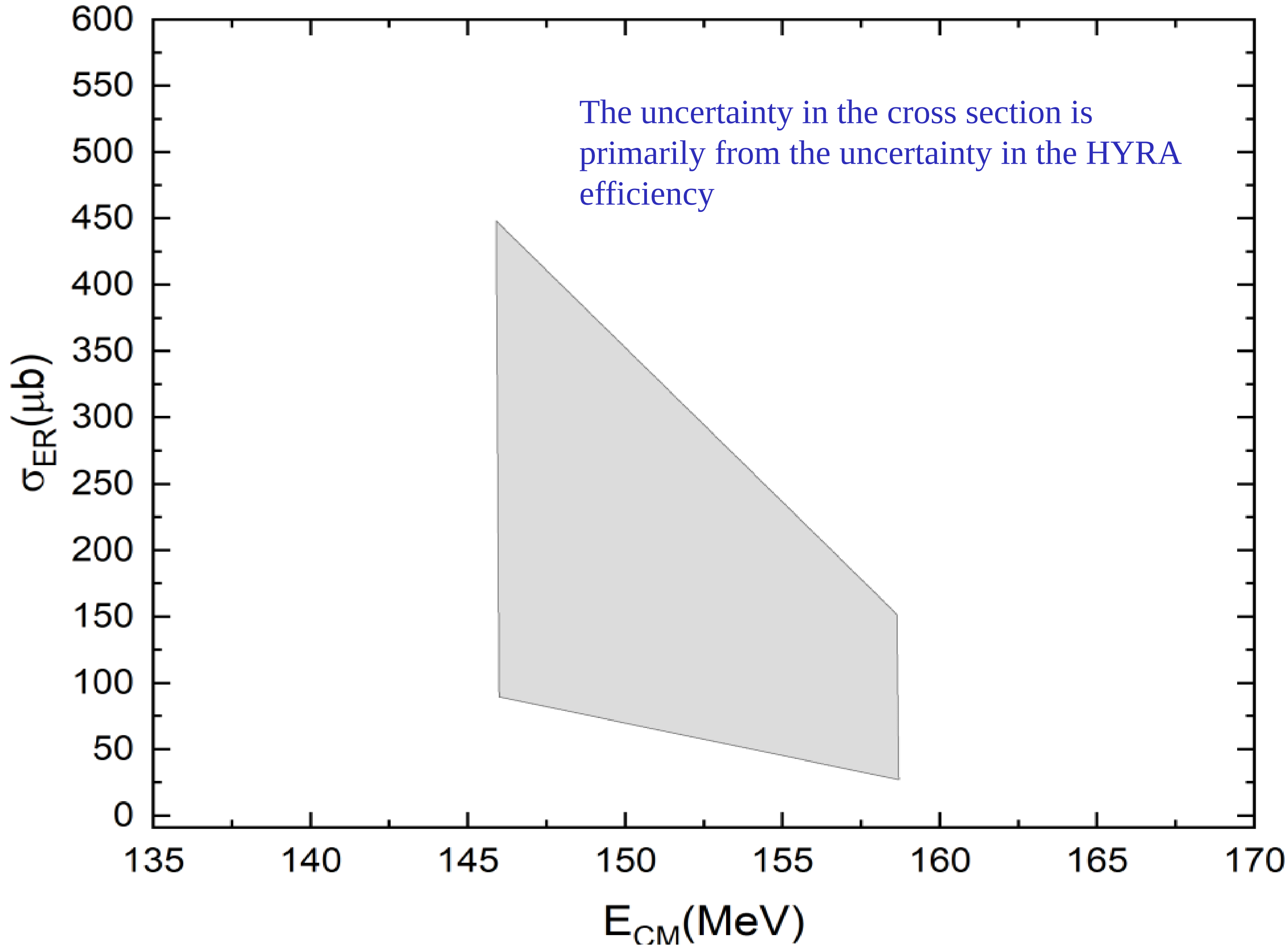


Figure 5.8: The efficiency of HYRA (ϵ_H) for ^{48}Ti and ^{16,18}O induced reaction as a function of mass number A at different lab energies.





The uncertainty in the cross section is primarily from the uncertainty in the HYRA efficiency
600
550
500
450
400
350
300
250
200
150
100
50
0
135
140
145
150
155
160
165
170
σER(μb)
ECM(MeV)

Summary:

ER cross sections for ^{186}Pt measured at five new energies above barrier

Spin distributions measured for the first time for ^{186}Pt

Clear observation of QF when compared with 48Ti+138Ba system

Range of parameter spaces for barrier and viscosity determined

DNS calculations show role of inclusion of ICF

First measurements of ER of 240Cf

Future Plans

The wish list as inspired by the measurements so far:

I Heavy Systems:
Spin and ER gated charged particle Spectra

II Very Heavy Systems:

Further measurements of ER cross sections from mass 240 and heavier systems

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A. K. Nasirov,	BLTP, JINR, Dubna &
B. M. Kayumov	

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Thank You