To Fuse or Not to Fuse:

A tale of two Nuclei

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A.N. Mitra Memorial Meeting and Lecture

14th – 15th April, 2025

A.N. Mitra, 2010 TIFR, Mumbai

N-N Interaction & Nuclear Many-Body Problem

<u>This Talk is Dedicated to the Hallowed Memory of Prof. A.N. Mitra</u>

The Selection of the Topic of This Talk

The Raison détre

INDIA IN THE WORLD OF NUCLEAR PHYSICS: THEN AND NOW

A. N. MITRA

https://doi.org/10.1142/S0218301309013397

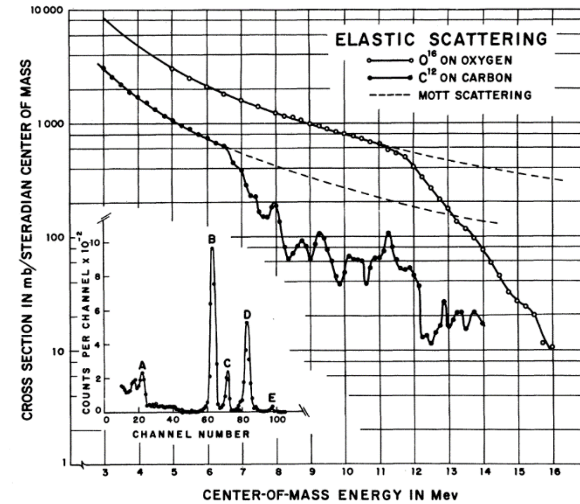
Organisation of the Talk

- *Prefatory Comments or Raison détre for this program*
- *The experimental arsenal*
- *Brief Summary of a decade long Studies (From TIFR-IUAC experiments)*
- *Two Specific Case Studies : very recent measurements*
  (heavy and very heavy systems)
  (The measurements & Phenomenological Analysis)
- *Summary, conclusion and proposition for future measurements*

I
Prefatory Comments

1. Resonant Elastic Scattering of ^{12}C by Carbon,
D. A. Bromley, J. A. Kuehner, and E. Almqvist, PRL 4, 365 (1960)

2. Resonances in ^{12}C on Carbon reactions,
E. Almqvist, D. A. Bromley, and J. A. Kuehner, PRL 4, 515 (1960)

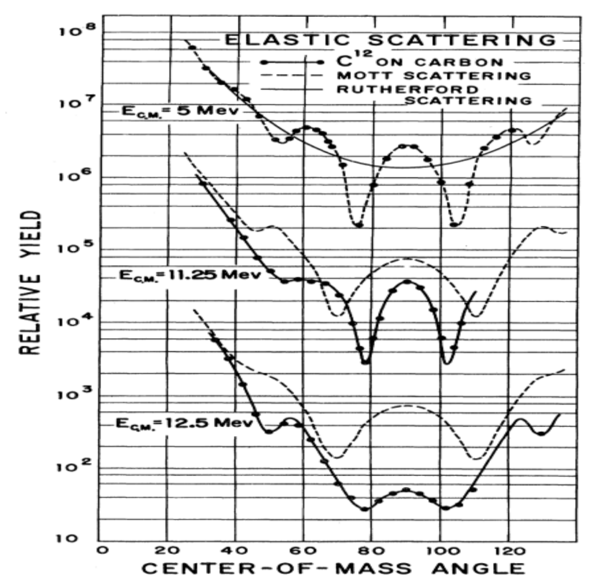


Experimental results were contrary to expectations

Excitation functions for a variety of reaction products (α, γ, n etc.) around the Coulomb barrier were measured. Pronounced resonant phenomena in all channels seen around the barrier.

Formation of nuclear molecule and more normal states of ^{24}Mg (Theoretical input from Erich Vogt, Hugh McManus)

Further experiments from Yale, Munster and Theory from Group of Walter Greiner at Frankfurt



The experimental discovery and theoretical description of nuclear molecule led to the development of modern heavy ion physics

1) *Greiner, Park, Scheid, Nuclear Molecules, 1995*
2) *Treatise on Heavy Ion Physics, Ed D A Bromley Compound Nuclear Phenomena Vol III, 1985*

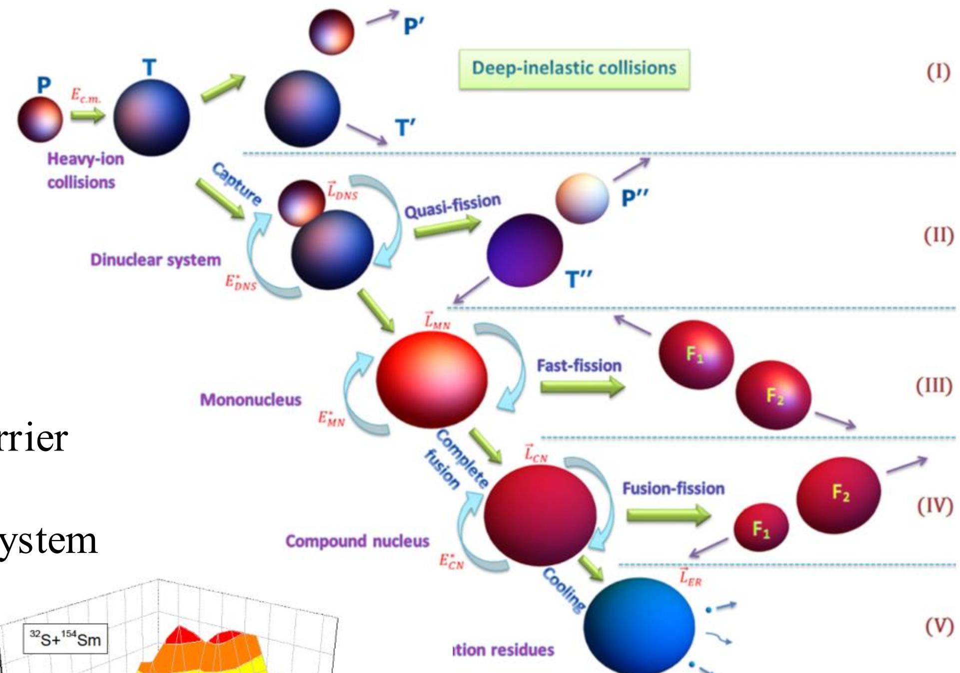
The World of Heavy-Ion Induced Fusion-Evaporation, Fusion-Fission Reactions

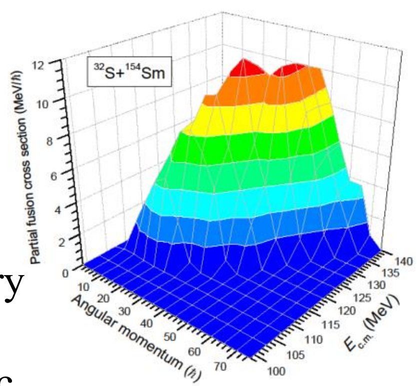
- Dynamics of Formation
- Dynamics of Decay of the System
- Statistical Theory
- Dynamical Theory

N. Bohr , J.A. Wheeler, Phys. Rev. C 56 (1939) 426
H.A. Kramers, Physica 7 (1940) 284
V.M. Strutinsky, Phys. Lett. B 47 (1973) 121

Major Features & Challenges:

- Fusion above, below and much below the barrier
- Equilibration and stability of the compound system
- Role of Shell effect
- Complete & Incomplete Fusion
- Role of Entrance Channel mass asymmetry
- Roles of NLD, barrier height, viscosity etc.





Pictorial Description of the Evolution of the Target-Projectile System

Courtesy: A. Nasirov

The Amazing World of Heavy-Ion Induced Fusion & Fission

What We know and what we don't

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) charged particles 4) neutrons 5) GDR γ–rays

The measured cross sections are reproduced by Statistical or/and Dynamical calculations

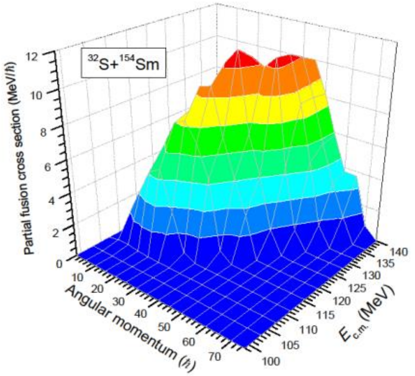
The crucial physical observables are,

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

Temperature and Angular Momentum

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

Theoretical approaches:



Macroscopic (phenomenological) (Based upon LDM)

Microscopic

Microscopic+Macroscpic Approach (A middle Path)

- *Schunck & Robledo, Rep. Prog. Physics (2016) (Microscopic Theory of Fission)*
- *Schunck & Reginer, Prog. Part. Nucl. Physics (2022)*
- *M. Bender et al., J. Phys G 47, (2020) (Fission Theory)*
- *Smits et. al., (Limits of Periodic Table)*
- *Nazarewicz, Nature Physics 14 (2018) (Limit of nuclear mass and charge)*
- *Giuliani et al., Rev. Mod. Physics (2019) (SHE, Oganesson and Beyond)*
- *D. Ackermann, APP B50, 517 (2019) (Basic Structure Features of SHN and S^3)*

II
The Experimental Arsenal

The Experimental Scenario:
Saga of Last four decades

Detection Facilities: *International & National Perspectives*

Fission Fragment detectors

Charged particle detectors

Neutron detectors

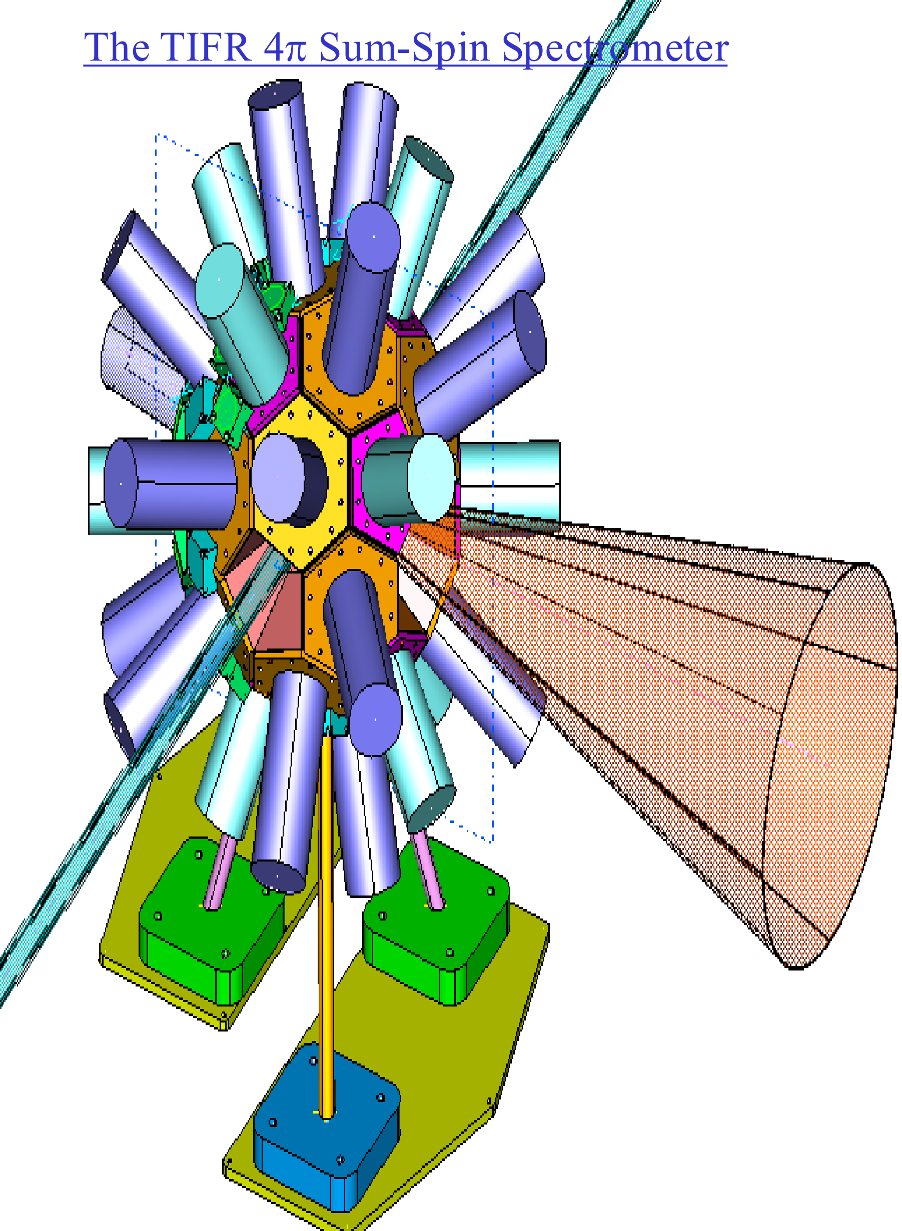
High Energy gamma ray detectors

Evaporation residue detection system

Low energy gamma-ray multiplicity detectors

I shall be drawing from our efforts to measure ER cross sections using Gas filled magnetic separator HYRA and ER gated spin distributions using TIFR 4π Sum-Spin Spectrometer.

The TIFR 4π Sum-Spin Spectrometer

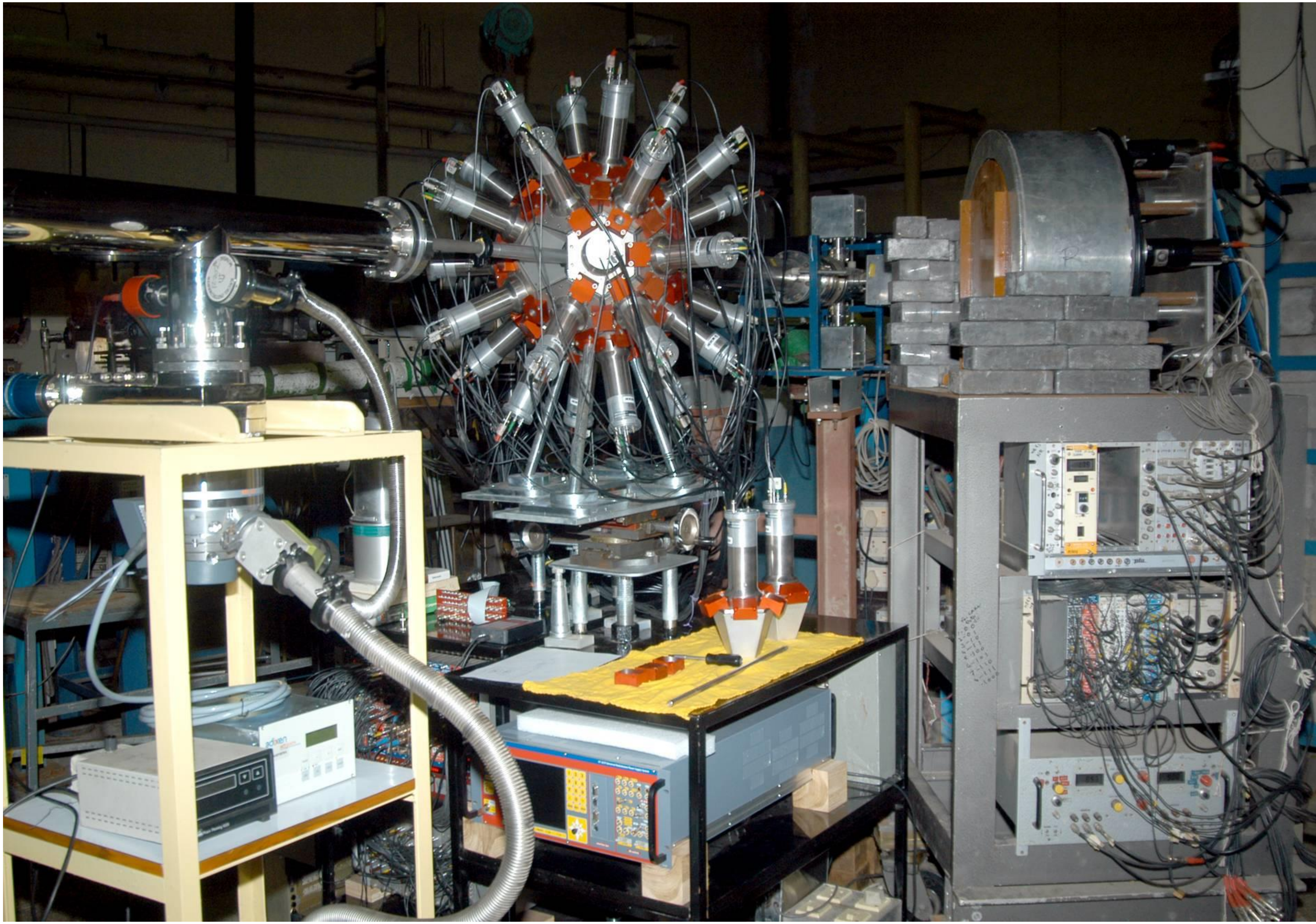


Kumar , Mazumdar, Gothe, Srivastava

Nucl. Instr. Meth. A 611 (2009)

Nucl. Instr. Meth. A 609 (2009)

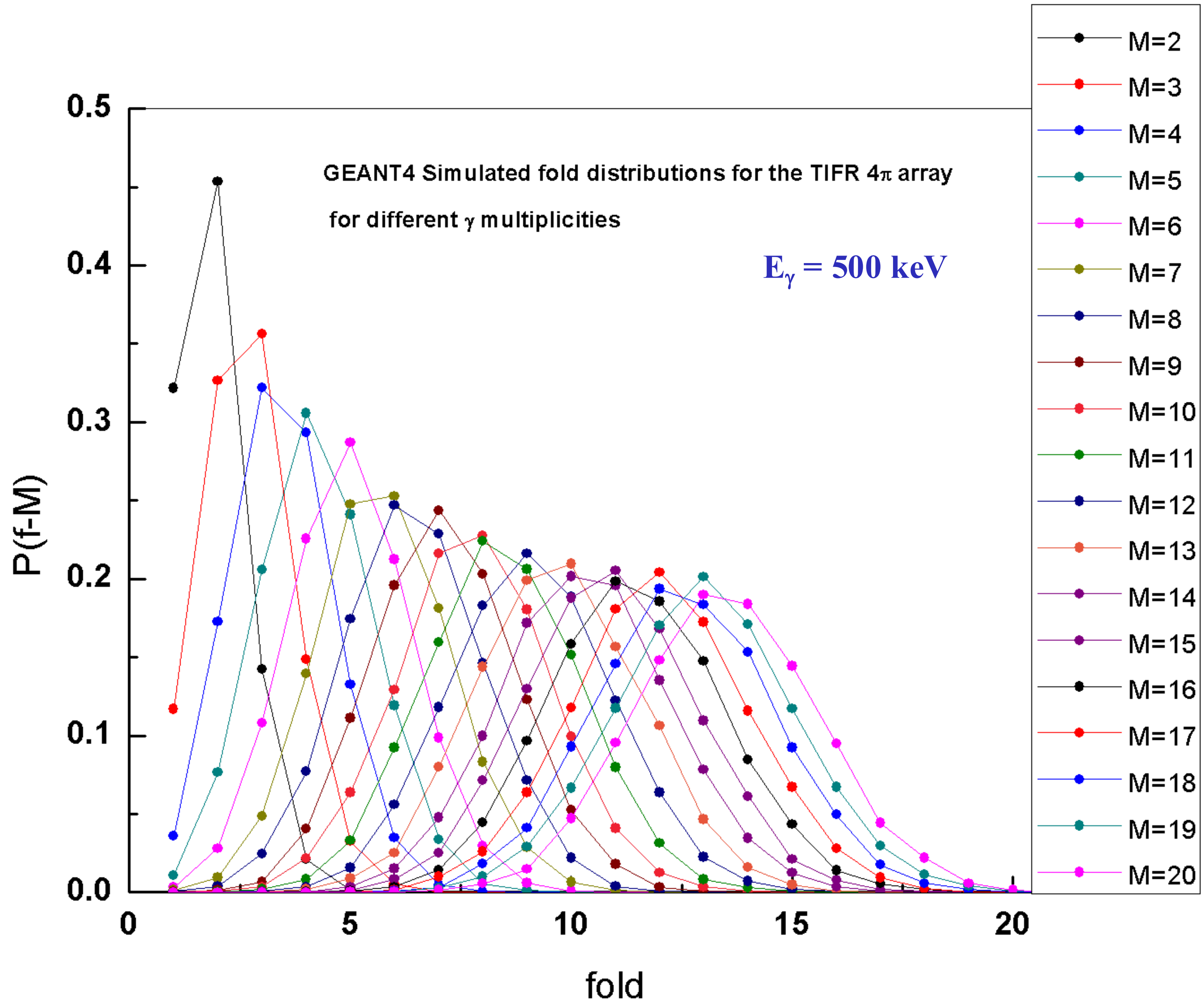
Nucl. Instr. Meth. A (2023)



The 4π Sum-Spin Spectrometer at TIFR

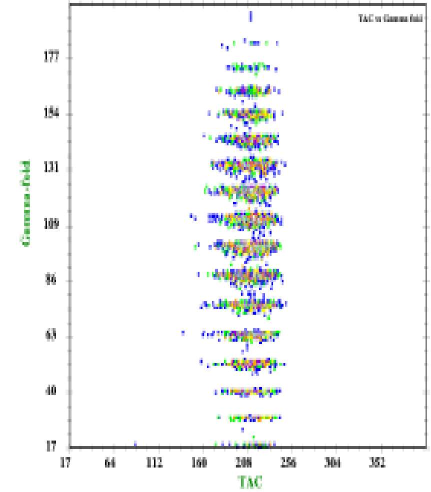
Kumar, Mazumdar, Gothe, NIM-A 611 (76) (2009);

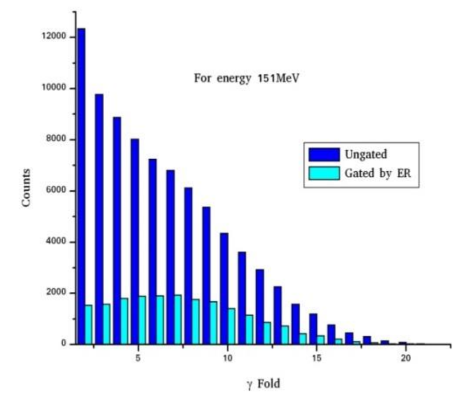
32 Conical NaI(Tl) detectors.
12 Pentagonal & 20 Hexagonal.

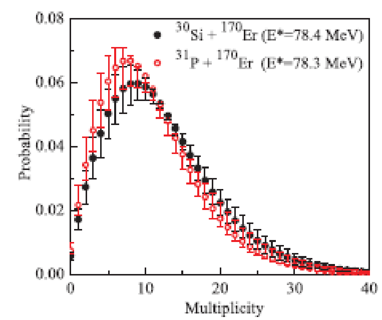


GEANT4 Simulated fold distributions for the TIFR 4π array
for different γ multiplicities
E_γ = 500 keV
P(f-M)
fold
0.0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
20
M=2
M=3
M=4
M=5
M=6
M=7
M=8
M=9
M=10
M=11
M=12
M=13
M=14
M=15
M=16
M=17
M=18
M=19
M=20

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

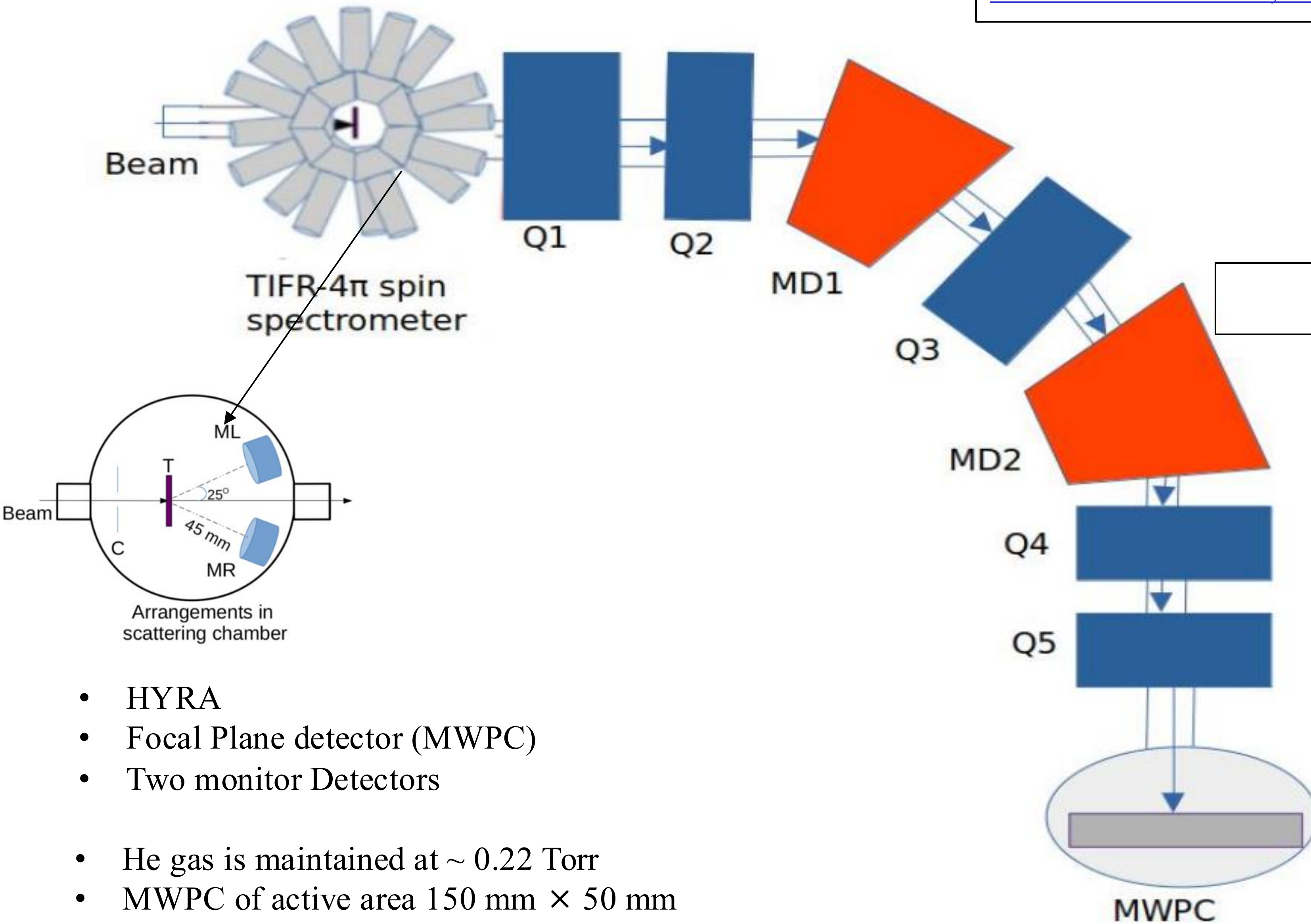






The detection facility :

The HYRA at IUAC, Delhi



- HYRA
- Focal Plane detector (MWPC)
- Two monitor Detectors

- He gas is maintained at ~ 0.22 Torr
- MWPC of active area 150 mm × 50 mm

Measurements of ER cross sections & Spin Distributions (Above barrier)

Primary Objectives:

To study,

1. *Role of Shell Effects (closure)*
2. *Role of entrance Channel mass asymmetry*
3. *Role of Barrier Heights*
4. *Role of Fusion/fission hindrance (quantum viscosity)*

ER cross section, spin distribution for

($^{31}P+^{170}Er$), ($^{30}Si+^{170}Er$), ($^{28}Si+^{176}Yb$),
($^{48}Ti+^{150}Nd$), ($^{19}F,^{16}O+^{197}Au$), ($^{16}O+^{208}Pb$), ($^{18}O+^{206}Pb$),
($^{48}Ti+^{142,144}Sm$), ($^{32}S+^{154}Sm$), ($^{32}S+^{208}Pb$), ($^{30}Si+^{178}Hf$), ($^{48}Ti+^{160}Gd$)

- *Nucl. Phys. A 890, 62 (2012)*
- *Phys Rev. C 88 024312 (2013)*
- *Phys Rev C 88 034606 (2013)*
- *EPJ Web of Sc.(2011,2013)*
- *Jour. Phys. G 41 (2014)*
- *Phys. Rev. C 95 (2017)*
- *Phys. Rev. C 96 (2017)*
- *Phys. Rev. C 99 (2019)*
- *Phys Rev C. 101 ,(2020)*
- *Phys Rev C 110 (2024)*

What have we learnt from these measurements?

Summary

A large number of systems have been studied and a large body of new data especially, spin distribution data have been generated

what do these measurements and the results tell us (beyond the obvious interpretations) ?

1) A definite need for reducing the parameter space to realistic limits in statistical model calculations *(barrier height, Nuclear Level density, viscosity etc.)*

1) To carry out systematic analysis of global data (FF, ER, neutron, charged particles, γ-rays)

3) To arrive at the similar conclusions while using different phenomenological approaches

4) To reproduce the data with same set of parametrs irrespective of the analysis package used

III

Two Specific Case Studies

Two very recent measurements

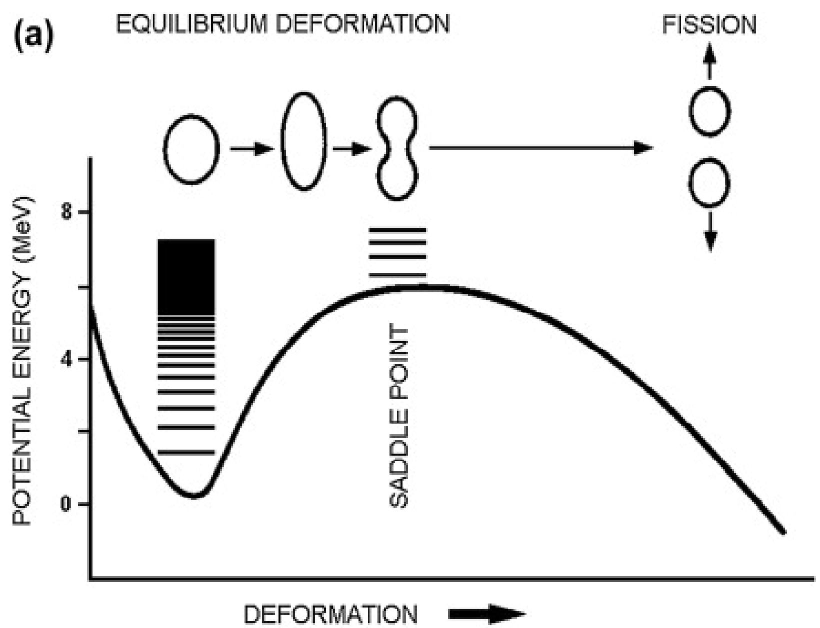
$^{32}S + ^{154}Sm \rightarrow ^{186}Pt$

A Heavy CN

- We have measured the cross sections of ER from ^{186}Pt Compound Nucleus a
- We have also measure

Both ER & Fission channels are open

both inside & Outside the saddle



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

Very Heavy CN

^{240}Cf, being very h system. Till date, nucleus.

ission channel is predominant

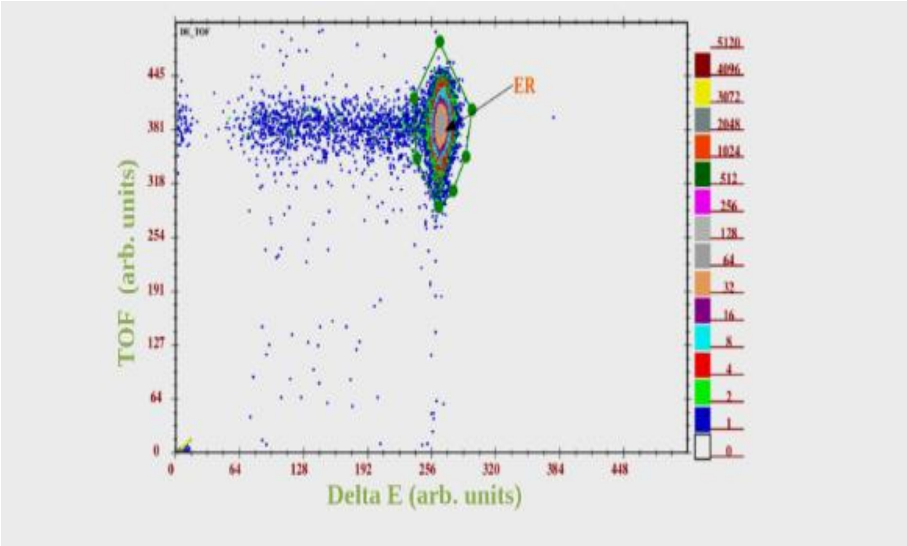
R formation is rare

Probing mainly outside the saddle

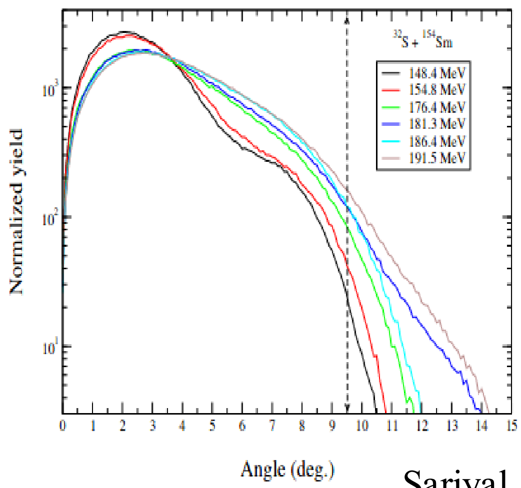
Any excess cross section of ER over what is predicted by Statistical Model is likely to hint towards mechanisms, (like viscosity) hindering the fission process.

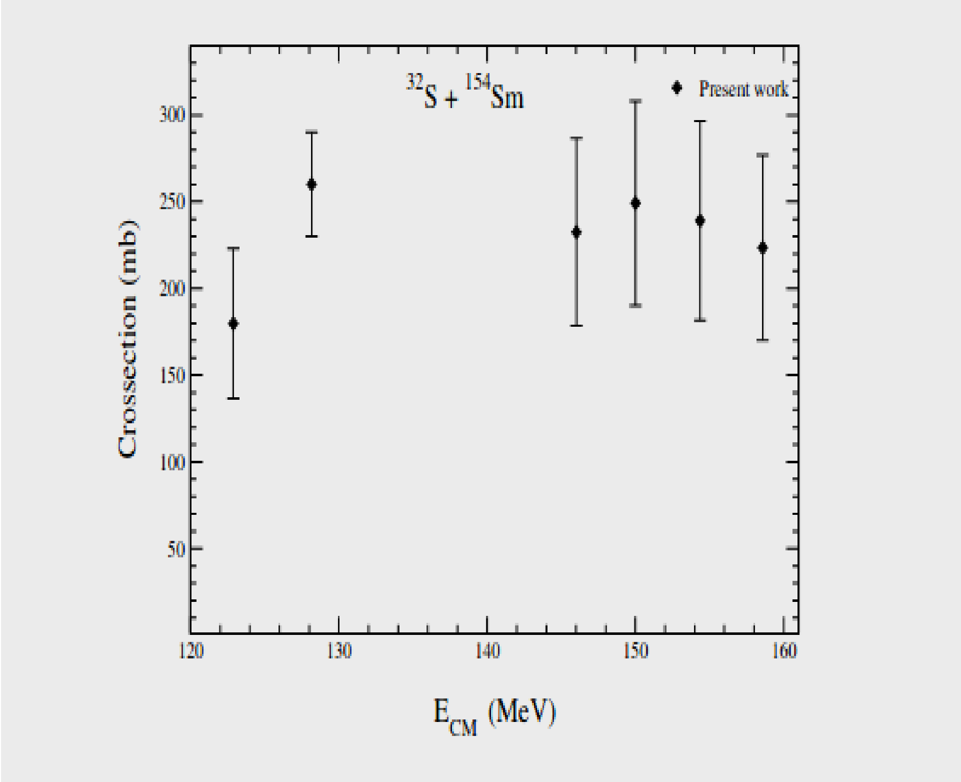
$^{32}S + ^{154}Sm \rightarrow ^{186}Pt$

- We have measured the cross sections of ER from ^{186}Pt Compound Nucleus above barrier for the first time.
- We have also measured for the first time the spin distribution



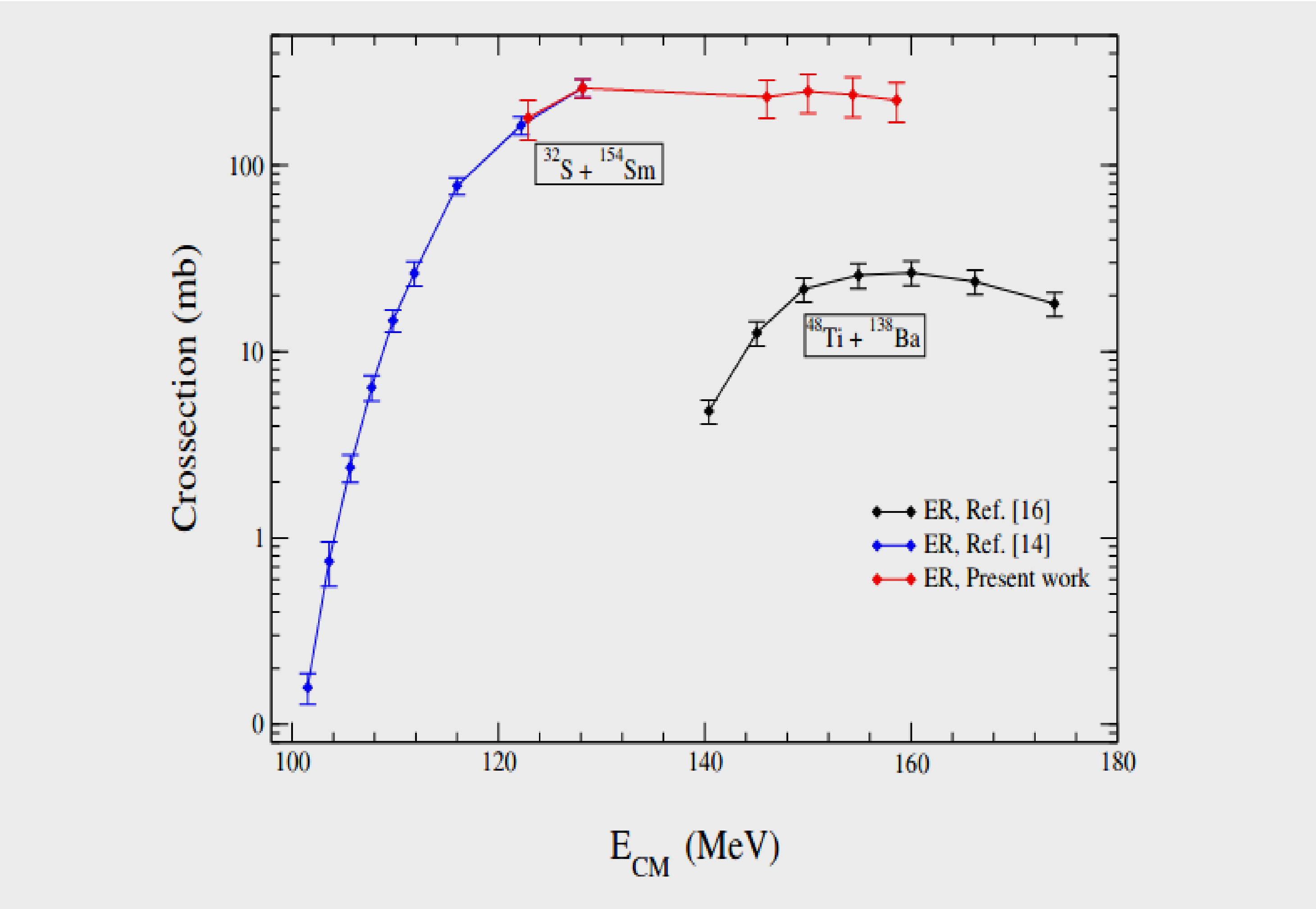
E_{lab} (MeV)	E_{cm} (MeV)	E^*_{CN} (MeV)	$\sigma_{ER} \pm$ error (MB)
148.4	122.9	62.3	180 ± 43
154.8	128.2	67.6	260 ± 30
176.4	146.0	85.4	232 ± 54
181.3	150.1	89.5	249 ± 59
186.4	154.4	93.8	239 ± 58
191.5	158.6	98.0	223 ± 53





Sariyal, Mazumdar *et al*
PRC In Press

First Major Experimental Observation (Model Independent Conclusion



P R S Gomes et al PRC 49 (1994) 245
R. Sariyal et al Present work: PRC 110 (2024)
K K Rajesh et al PRC 100 (2019) 044611

Clear demonstration of role of entrance channel mass asymmetry

Theoretical Analysis: I Statistical Model Analysis (Salient Features)

Experimental Spin Distribution & Fusion Cross sections are Fed in the Calculation

Temperature dependent Nuclear Level Density

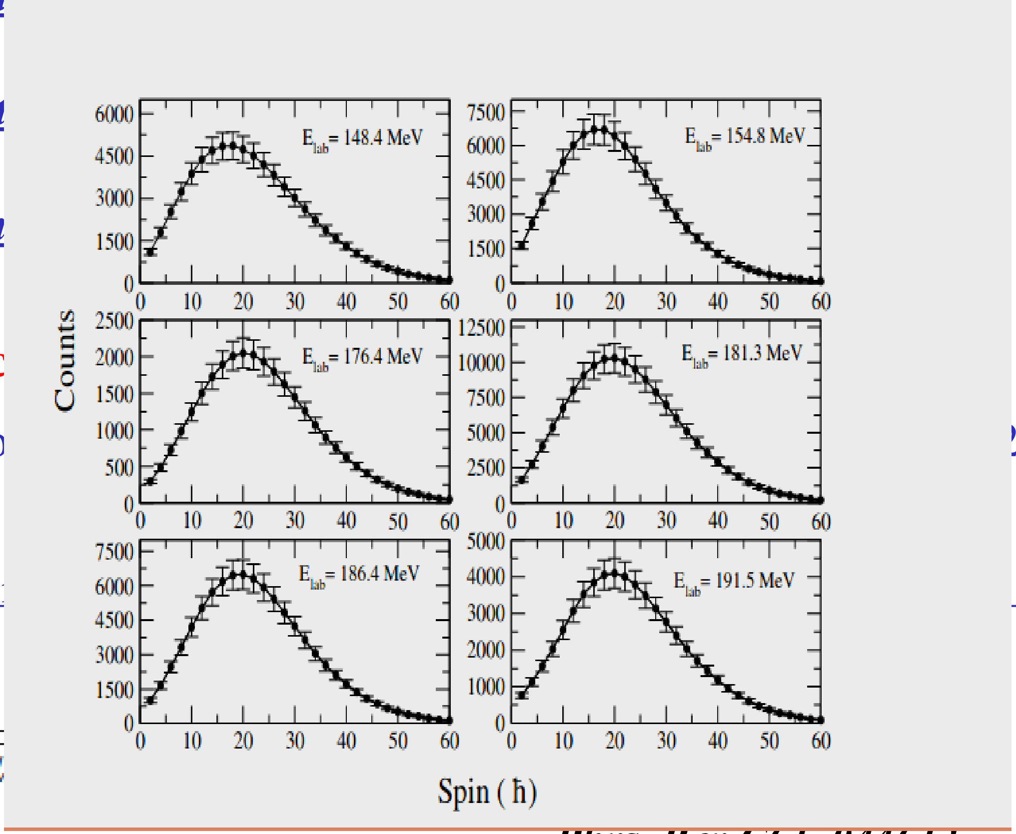
Inclusion of viscosit

Temperature & Spin

Fission Channel Calc

Saddle point transitio ... 26 (1939)

The fission rate is deter ... point



$$R_{\rm fiss} = \frac{1}{2\pi\hbar\rho_1(E}$$

Phys. Rev C61, 044612
Phys. Rev. C61, 024613
Phys. Rev. C63, 047601
Phys. Rev. C63, 014611
Pramana 85, (2015)

→ Nuclear level density

A combinatorial game: number of ways in which a given energy E of an A-particle system can be distributed over single particle states

$$\rho(E,J) = \frac{2J+1}{12\theta^{3/2}}\sqrt{a}\frac{\exp(2\sqrt{aU})}{U^2}.$$

$$U = E - \Delta - J(J+1)\hbar^2/2\theta'$$

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

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

Level density parameter, a

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

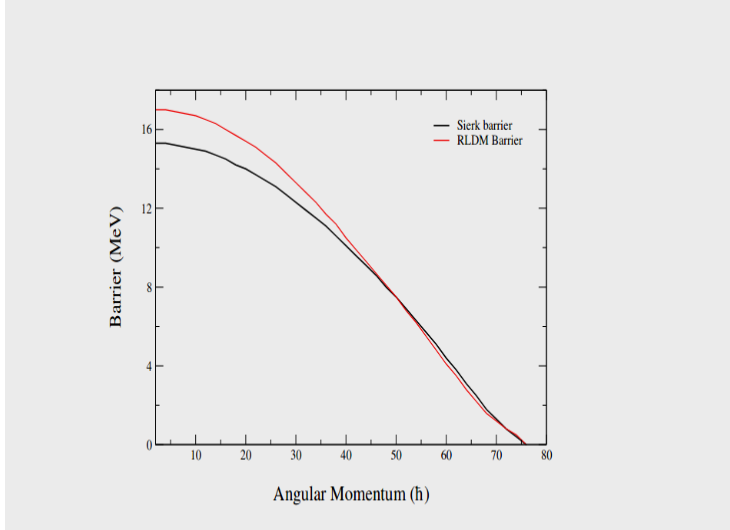
$$f(U) = 1 - \exp(-U/E_D).$$

Shlomo & Natowicz

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

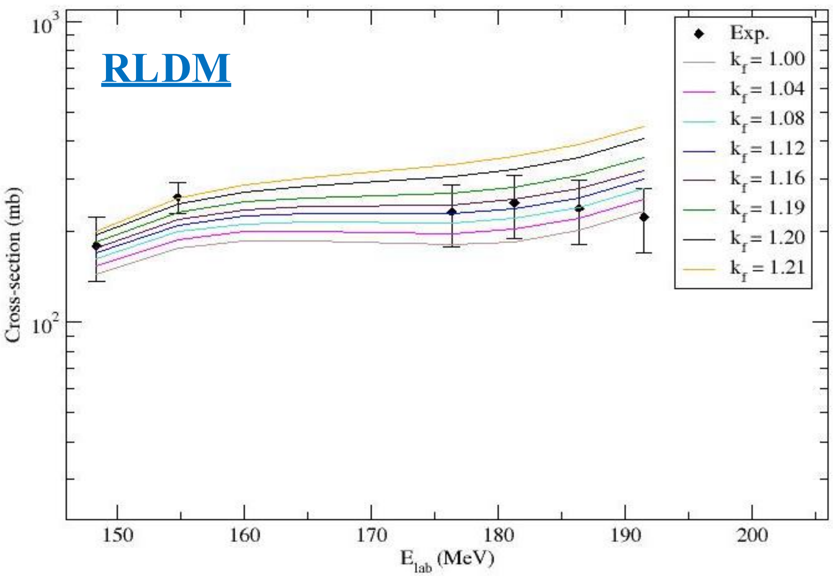
$$\tilde{a} = 0.04543 r_0^3 A + 0.1355 r_0^2 A^{2/3} B_s + 0.1426 r_0 A^{1/3} B_k$$

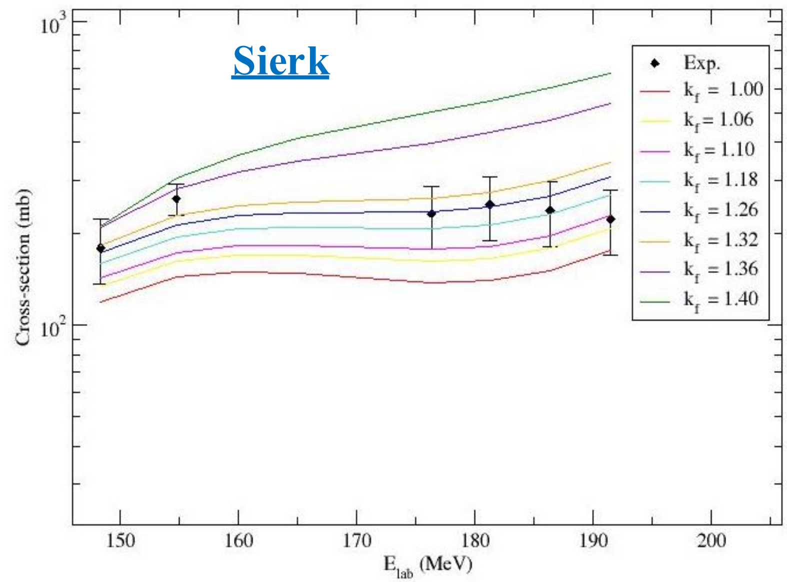
W. Reisdorf, Z. Phys. A 300, 227 (1981)



$^{32}S + ^{154}Sm$

Reproducing ER cross section by varying Barrier at zero viscosity





ER cross-section with RLDM fission barrier variation at different E_{lab}

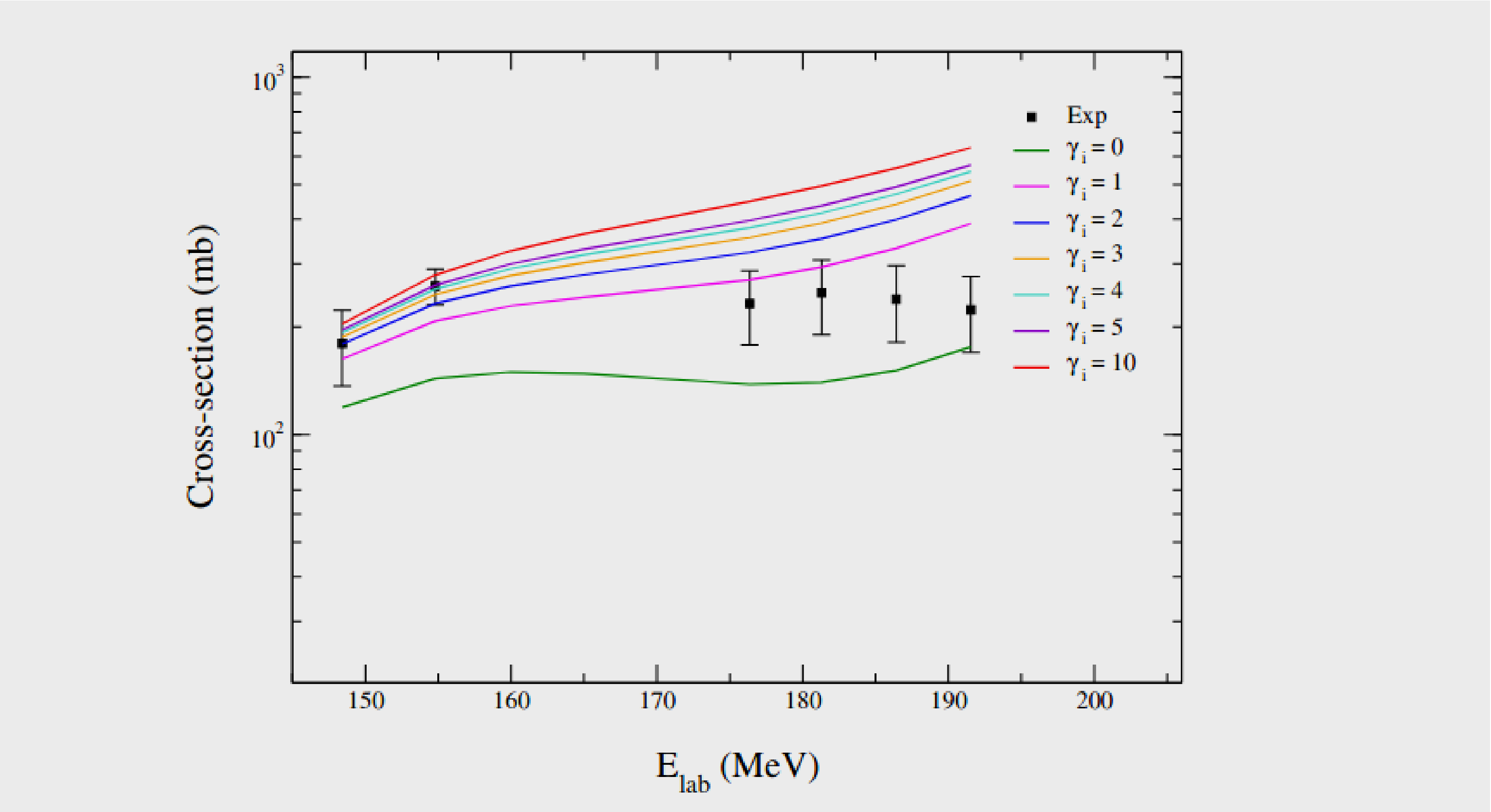
ER cross-section with Sierk fission barrier variation at different E_{lab}

- ➔ In case RLDM, fission barrier has to be scaled from:
  K_f = 1.00 to 1.21

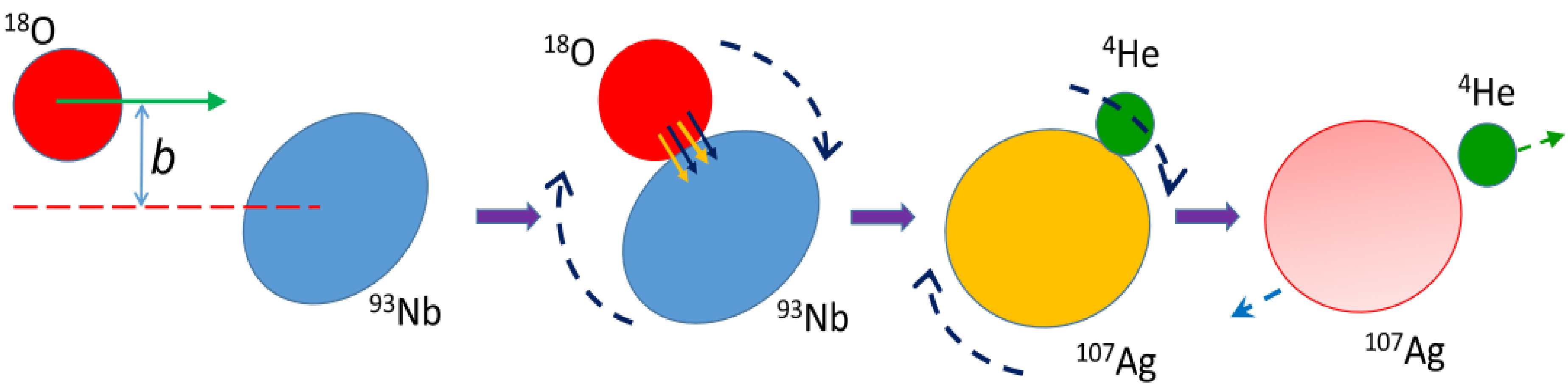
- ➔ In case Sierk model, fission barrier has to be scaled from:
  K_f = 1.00 to 1.40

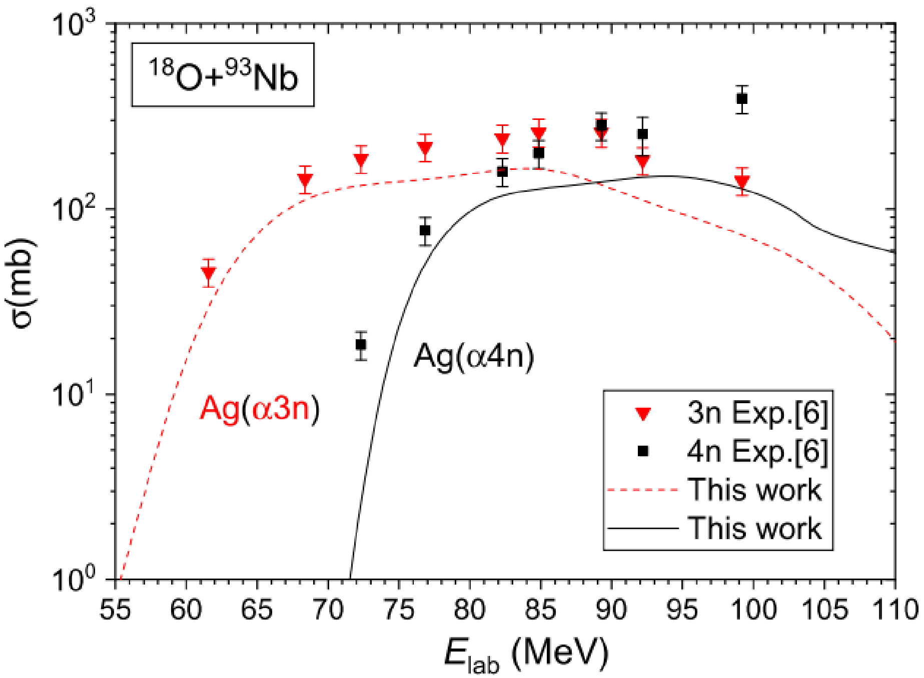
ER from $^{32}S + ^{154}Sm \rightarrow ^{186}Pt$ system

Reproducing ER cross section by varying viscosity at a fixed barrier



Dynamical Calculations: The DNS Model

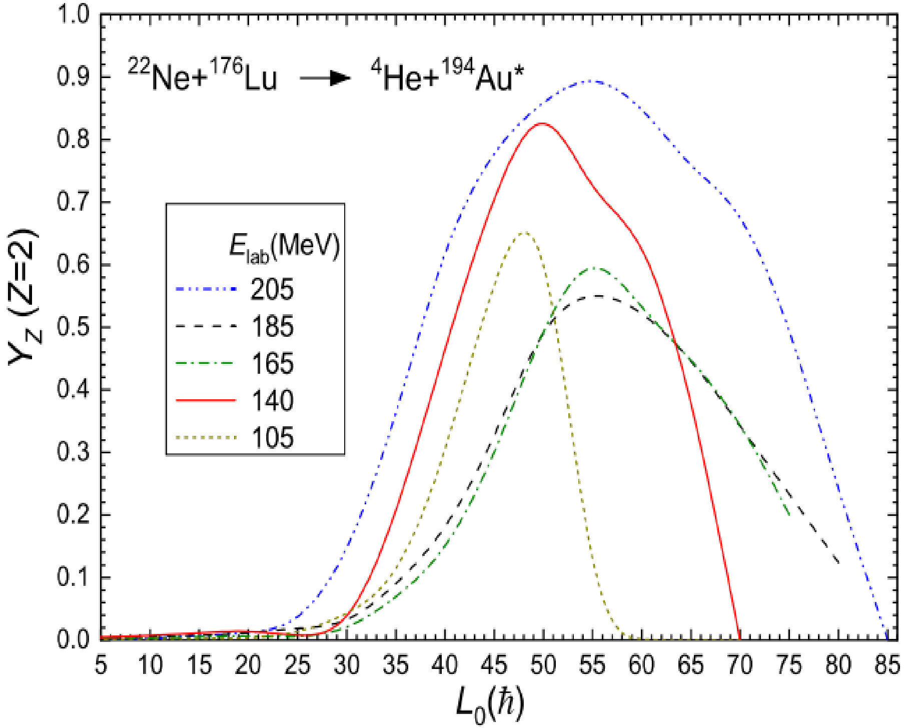




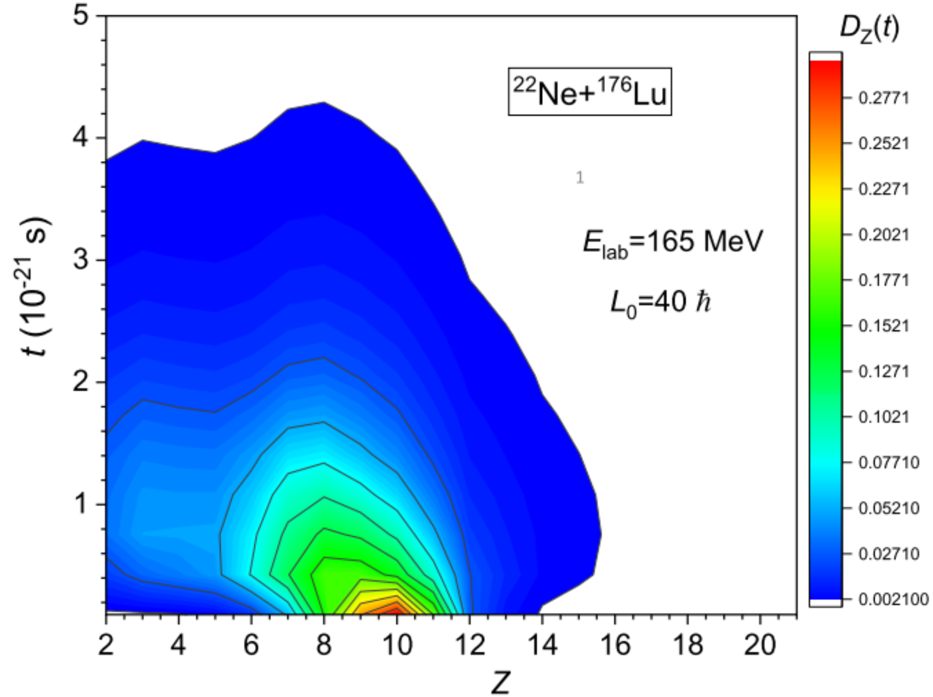
Role of Incomplete Fusion

A. Nasirov et al

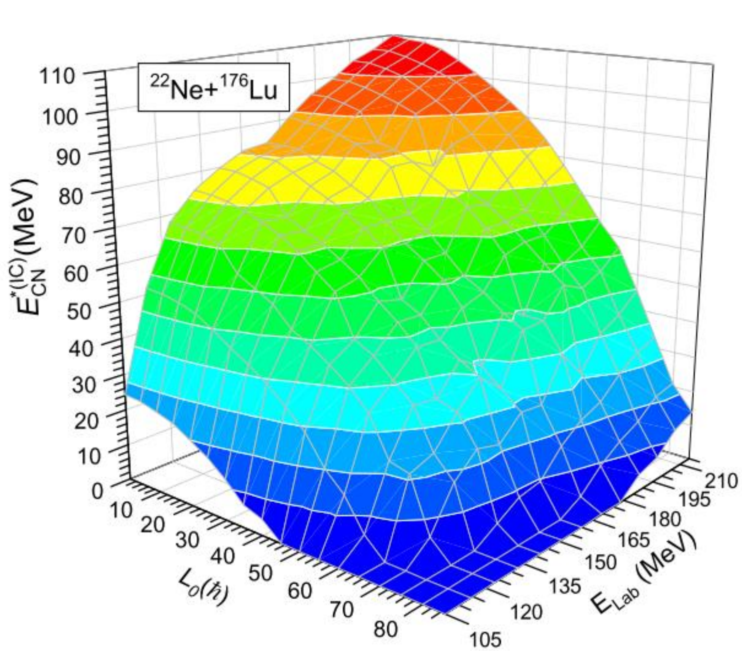
- Phys. Lett B842 (2023)
- Nucl. Phys A 946 (2016)
- PRC 105 (2022)
- EPJ A 49 (2013)
- Nucl. Phys. A 759 (2005



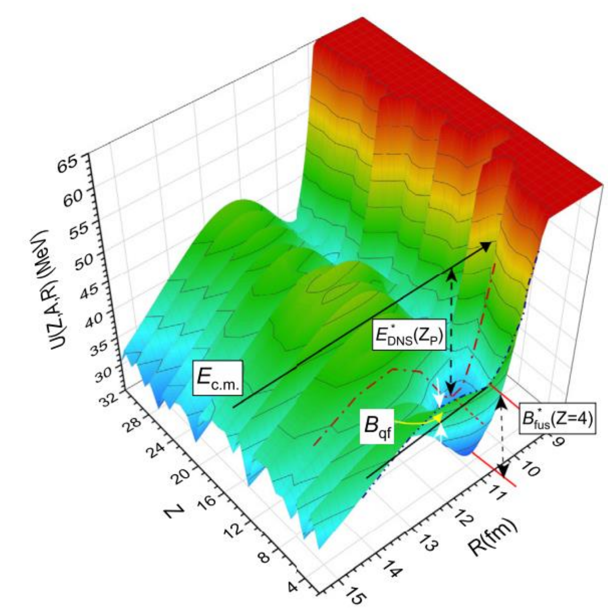
^{22}Ne+^{176}Lu → ^{4}He+^{194}Au*
E_{lab}(MeV)
205
185
165
140
105
Y_Z (Z=2)
$L_0(\hbar)$



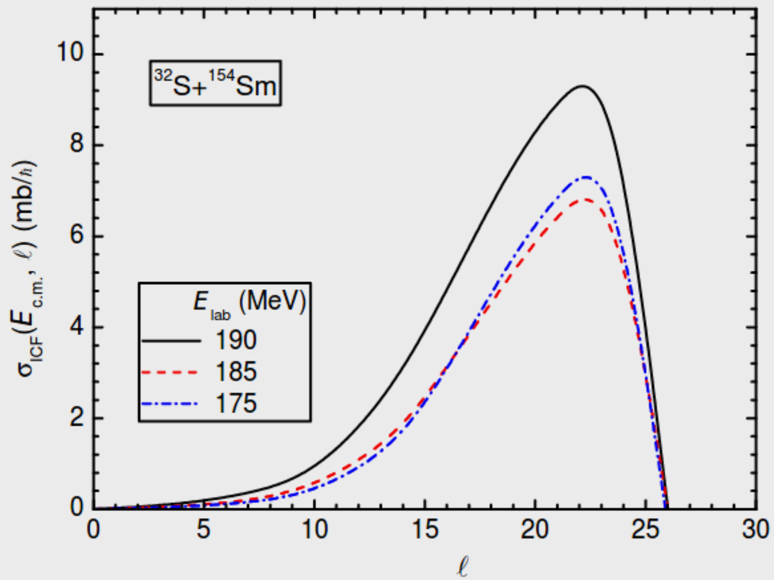
^{22}Ne+^{176}Lu
E_{lab}=165 MeV
L_0=40 ħ
$D_Z(t)$
t (10^{-21} s)
Z



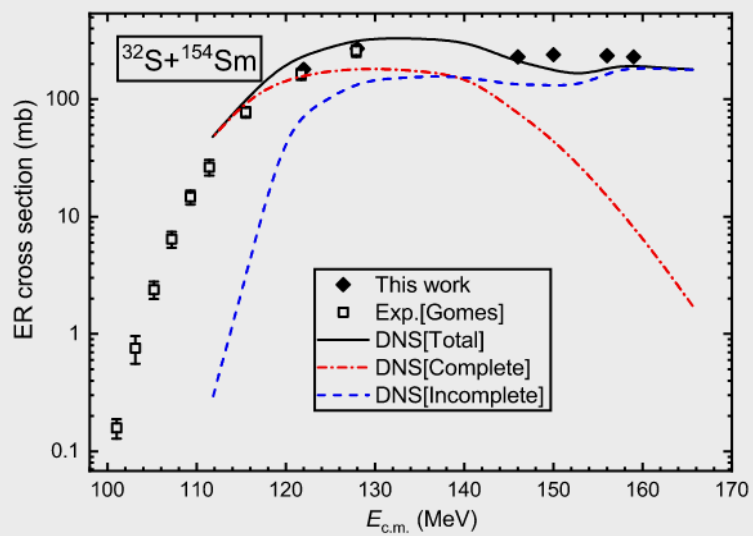
^{22}Ne+^{176}Lu
$E^{*(IC)}_{CN}$(MeV)
$L_0(\hbar)$
E_{Lab} (MeV)



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
E_{lab} (MeV)
190
185
175
$\sigma_{ICF}(E_{c.m.}, \ell)$ (mb/ħ)
ℓ



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

Summary, Conclusion, Future Scope:

ER cross sections above barrier measured for six beam energies

Spin distributions of ERs measured

Statistical model analysis and restraining the parameter space

Dynamical (DNS) model analysis done

Role of Incomplete Fusion in the formation of ER

Exclusive measurements of Charged particle spectra

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

A very Heavy predominantly Fissioning Compound Nucleus

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

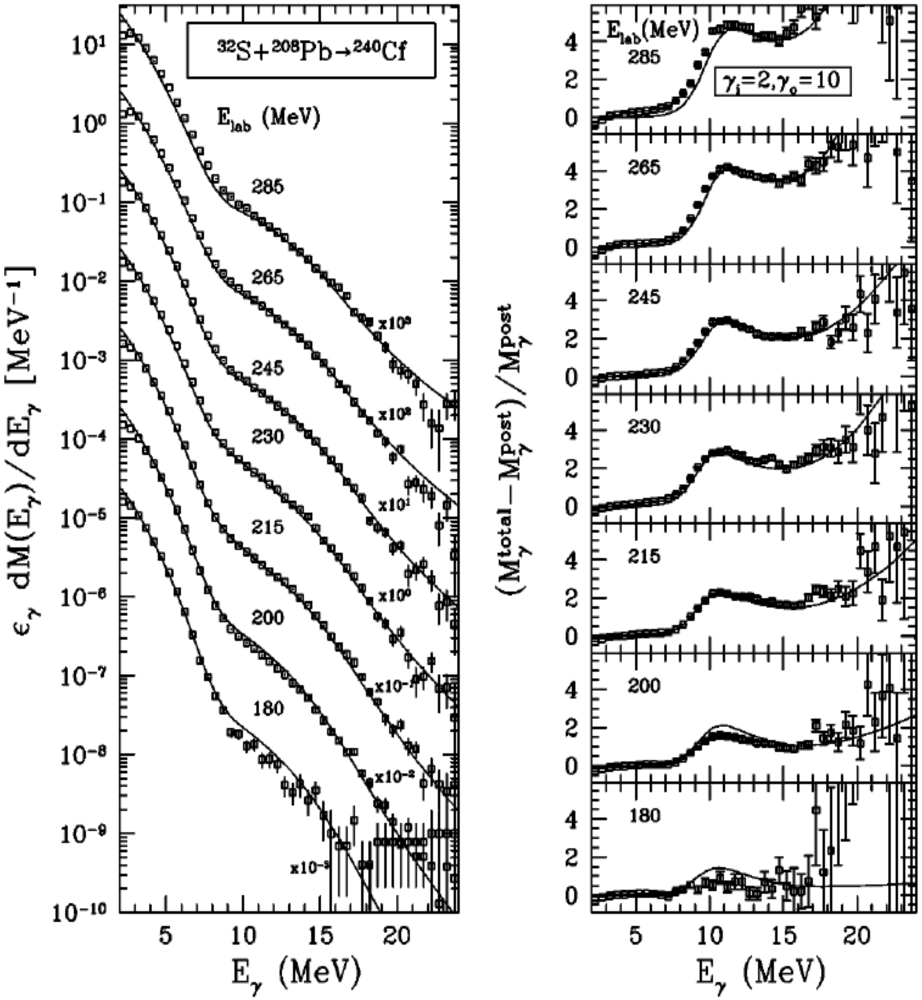
5) W. Loveland *et al*., Phys. Rev C 74, 044607 (2006)
6) D.J. Hinde *et al*., Phys. Rev. C 75, 054603 (2007)

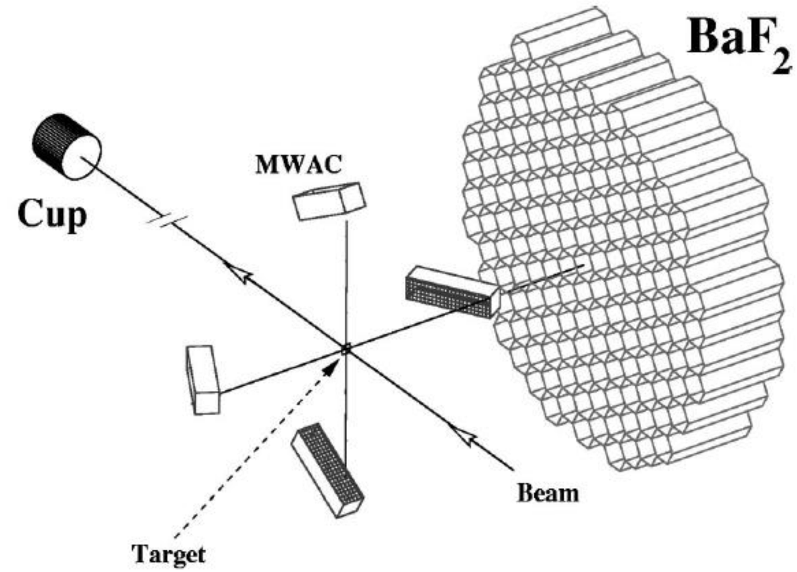
Dependence of fusion barrier energies on neutron rich projectiles

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

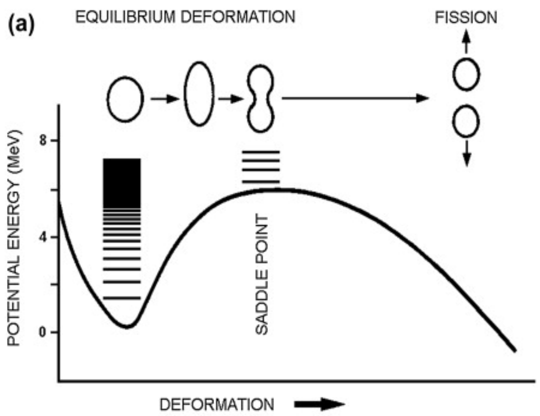
With increasing T γ-yield is almost entirely from Saddle to scission

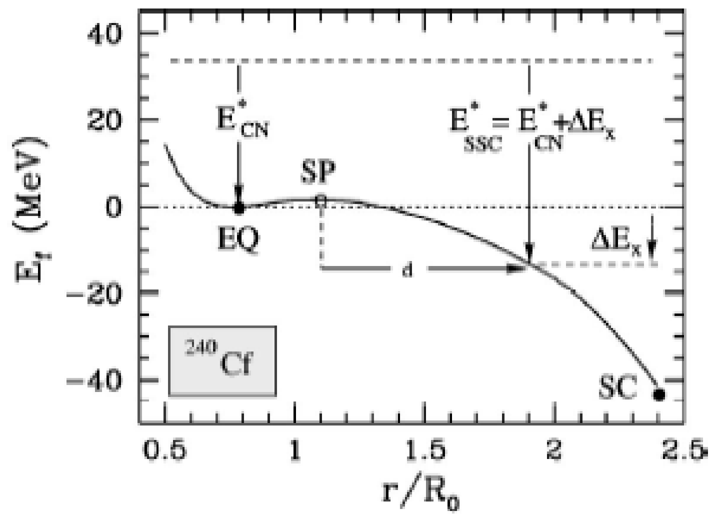
η/s Ratio in Finite Nuclei at low temperature

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

Extracted from GR widths

Introducing Dissipative Mechanism





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

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

$\gamma = \beta/2\omega_0$

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

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

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

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

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

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

Additional buildup time

Grange, Jun-Qing, Weidenmuller (1983)

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

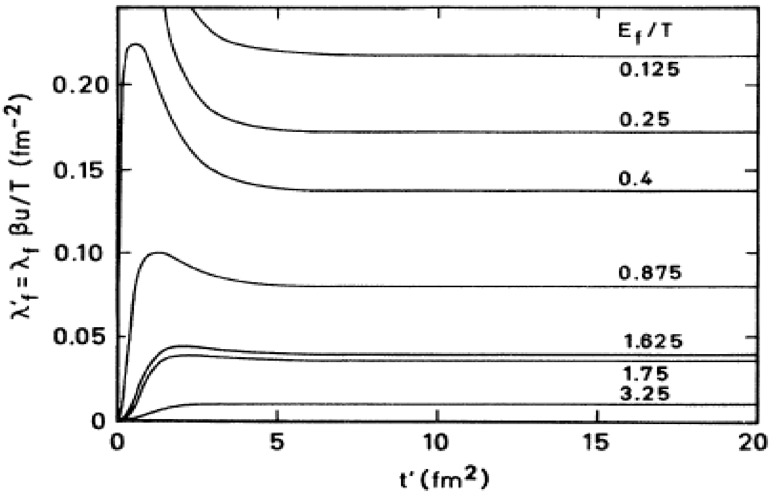


FIG. 2. The scaled rate $\lambda'_f(t')$ versus t' for various choices of a or, equivalently, E_f/T, as indicated.

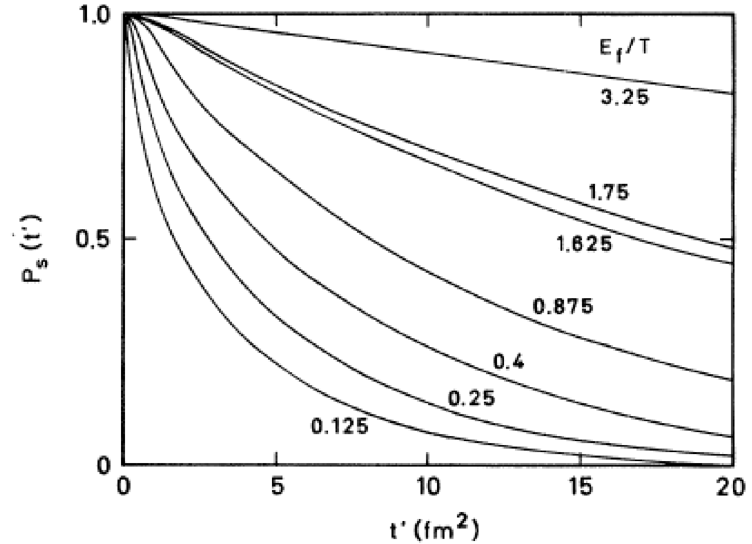


FIG. 3. The probability $P_s(t')$ of finding the system to the left of the saddle point versus t' for various choices of a or, equivalently, of E_f/T, as indicated.

The Transient Effect

Weidenmuller and Jing-Shang (1984)

Understanding the dependence of γ on Temperature and/or Angular Momentum

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

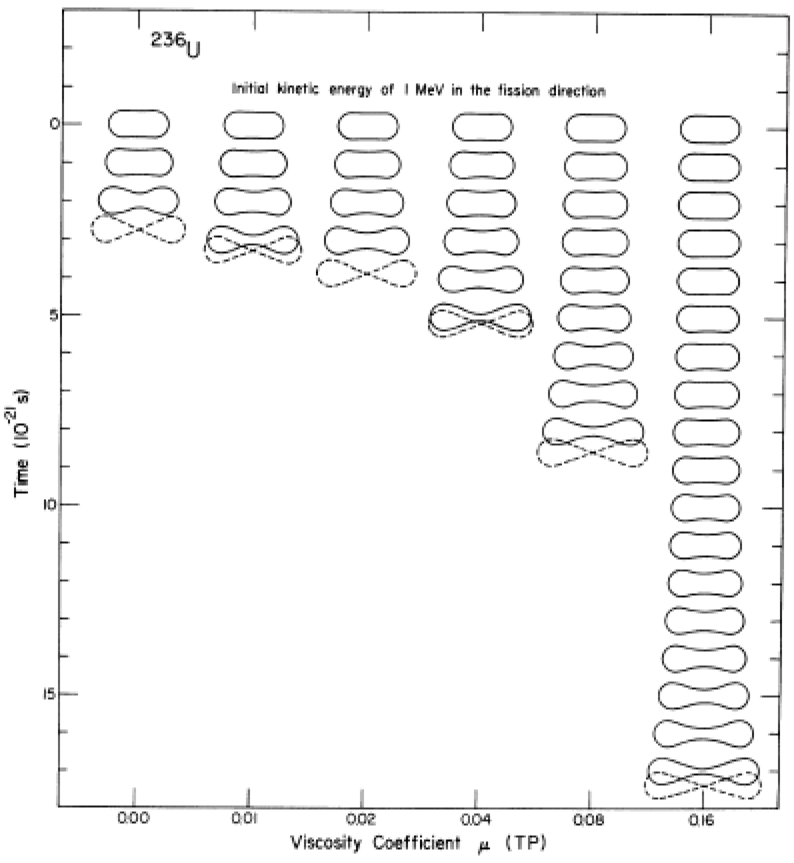
Need for decoupling the effects of temperature and angular momentum

Microscopic picture of nuclear viscosity

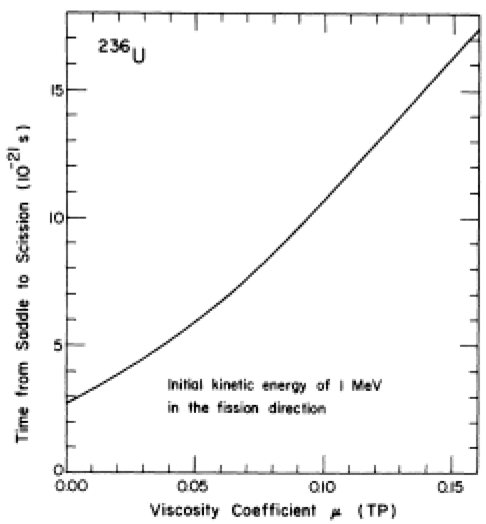
One- body or two – body mechanism

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

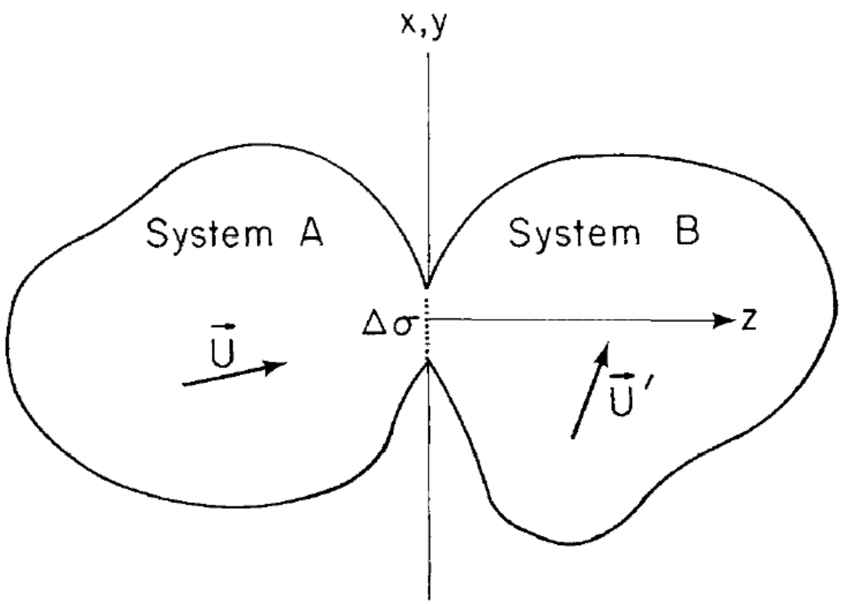
Strong Temperature dependence

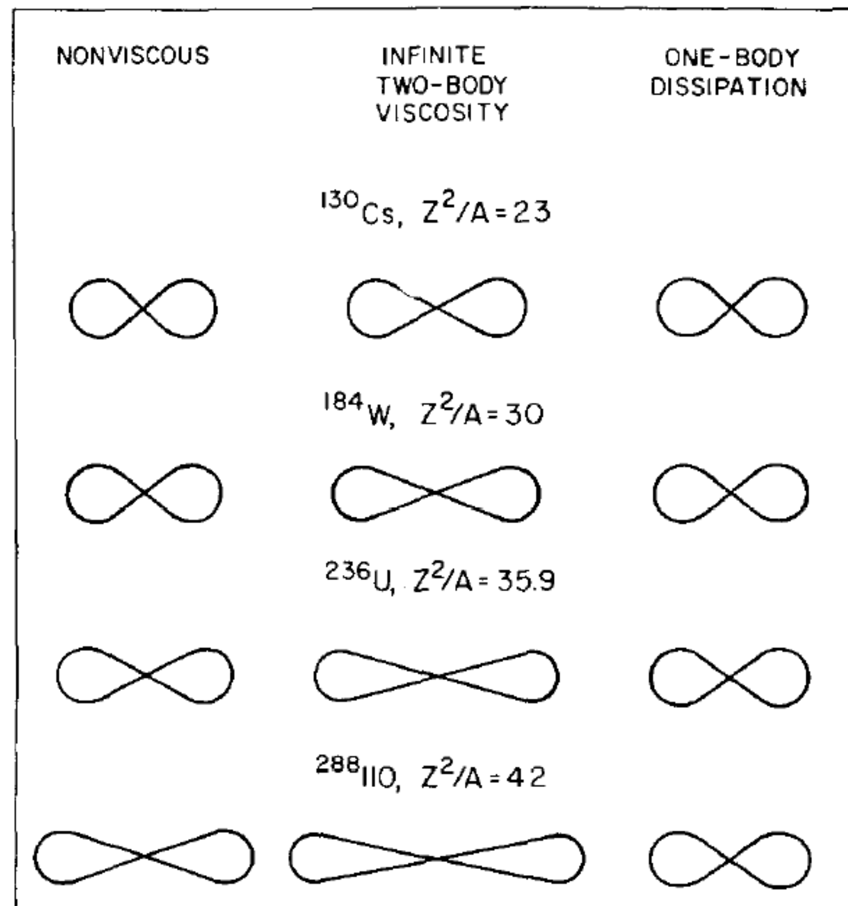
However, the authors admit, large mean free path can result in one-body viscosity, collision of nucleon with moving wall.

Favours neck formation

Little or no temperature dependence of viscosity parameter.

One-body mechanism





J. Blocki *et al,*

Annals of Physics, 113, 330 (1978)

Measurements:

Pulsed Beam
IUAC Pelletron-LINAC facility,

➔ $^{32}S + ^{208}Pb = ^{240}Cf$

E_{lab}= 176. , 181.3, 186.4, 191.5 MeV

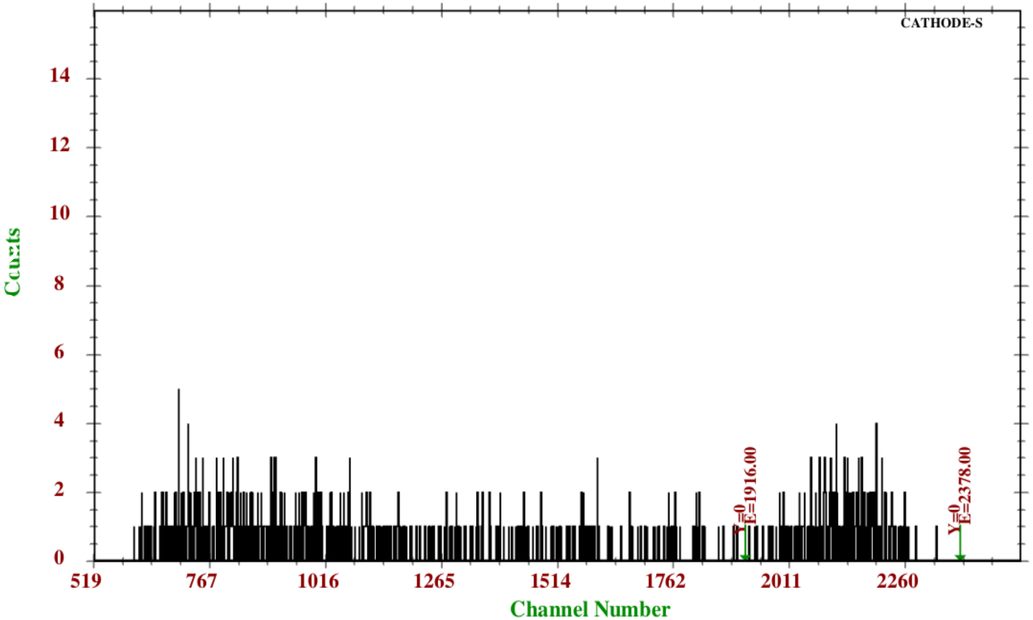
Target Specification :

Materia l	Thickness (μg/cm²)	Backing Material	Backing Thickness (μg/cm²)
^{208}Pb	227	Carbon	~ 20

Measurements using HYRA + TIFR 4π spin spectrometer.
ER cross sections.
&
Spin distributions

The HYRA Measurements at IUAC

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



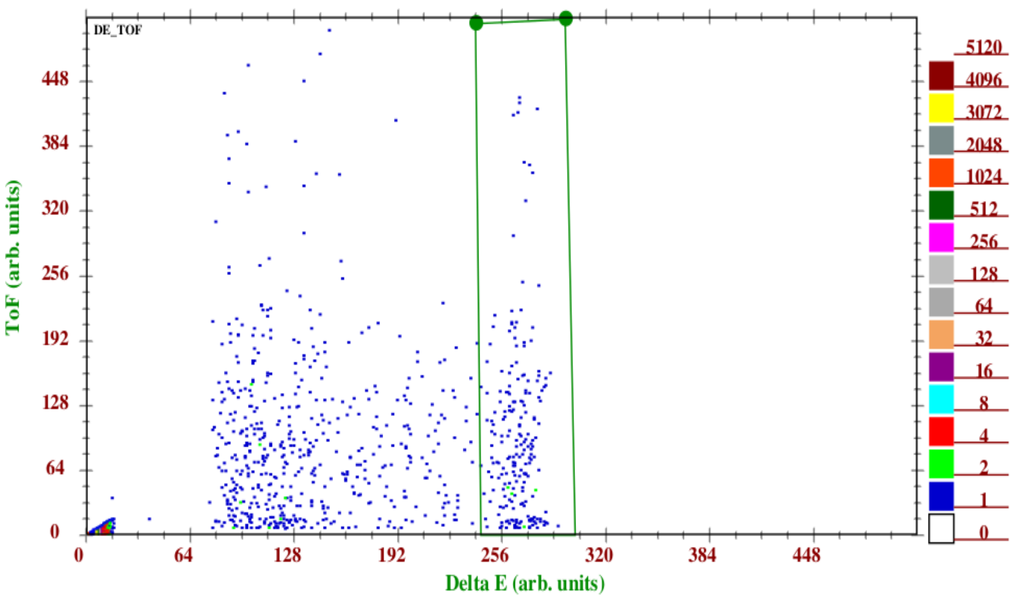
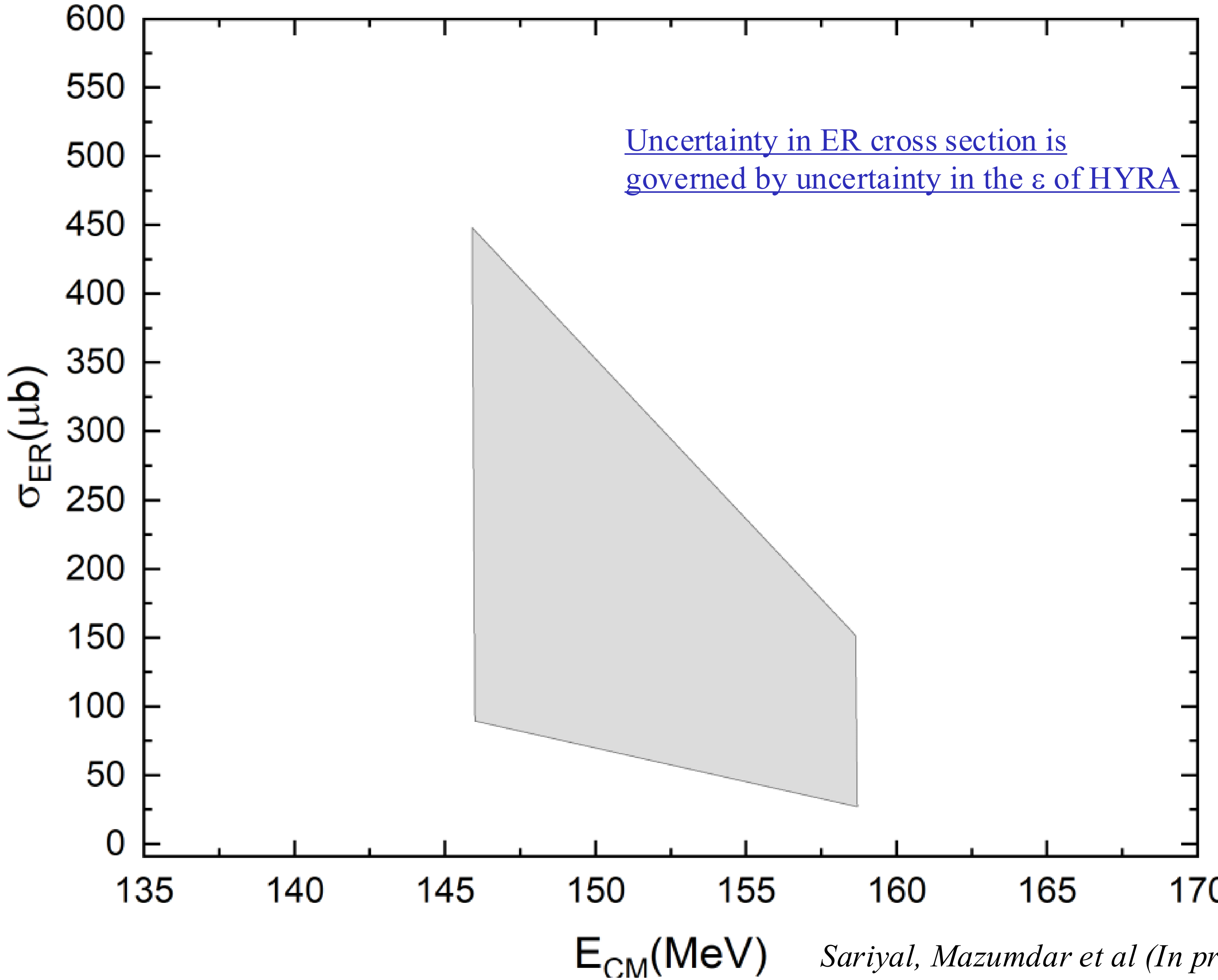


Table 5.1: Total ER cross-section of ^{32}S + ^{208}Pb at different energies.

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



Sariyal, Mazumdar et al (In preparation)

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- IUAC, Delhi
- Panjab University
- JINR, Dubna, Russia (A.V. Nasirov)


Thank You

Backup Slides

DNS → di nuclear system

Formed during the collision of projectile and target in heavy-ion induced reaction.

➔It can be formed either in a deep-inelastic collision or capture process.

➔While in the deep-inelastic collision, full momentum transfer does not take place.

➔In the case of capture, full momentum transfer takes place.

➔For DNS to undergo capture, it needs to be trapped in the potential well of the nucleus-nucleus interaction. Without the presence of a potential well, only a deep-inelastic collision can occur.

➔The DNS formed in the capture process can end with a mononucleus, or it can prefer to break down into two fragments without reaching the CN state, a process called quasifission.

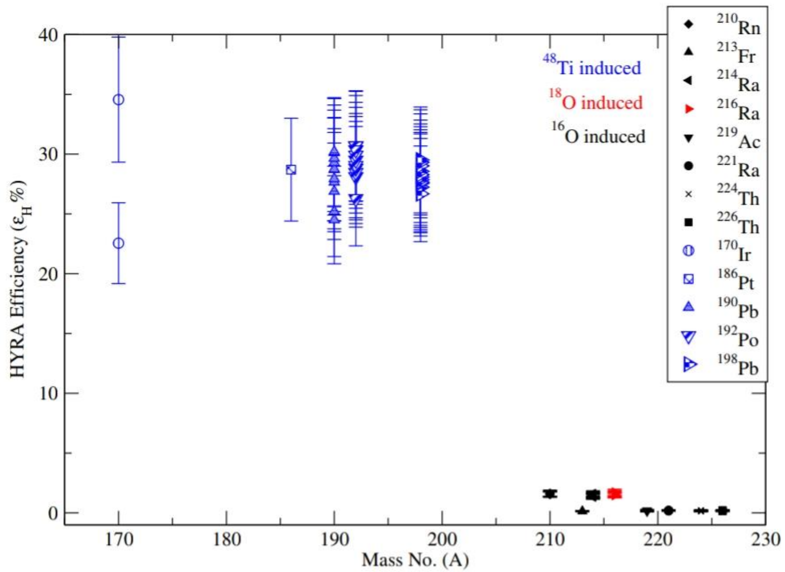
- ➔ There can be an overlap in the mass distributions of the products (quasifission) from deep-inelastic collisions and capture reactions.

- ➔ Typically, in such cases, the contribution of quasifission is attributed to the deep-inelastic collision.

- ➔ The quasifission can be the main hindrance to CN formation in reactions with massive nuclei.

- ➔ Competition between fusion and the quasifission process starts after initial DNS formation. Also to form a compound nucleus, the system has to overcome the fusion barrier (B_{fus}) and quasifission barrier (B_{QF}).

- ➔ This model considers the competition between different channels, for example, it takes quasi-fission into account, which makes it different from other models such as the optical model and surface friction model that don't incorporate this competition. The final step in the reaction mechanism during heavy-ion collisions at energies close to the Coulomb barrier is the formation of the ER.



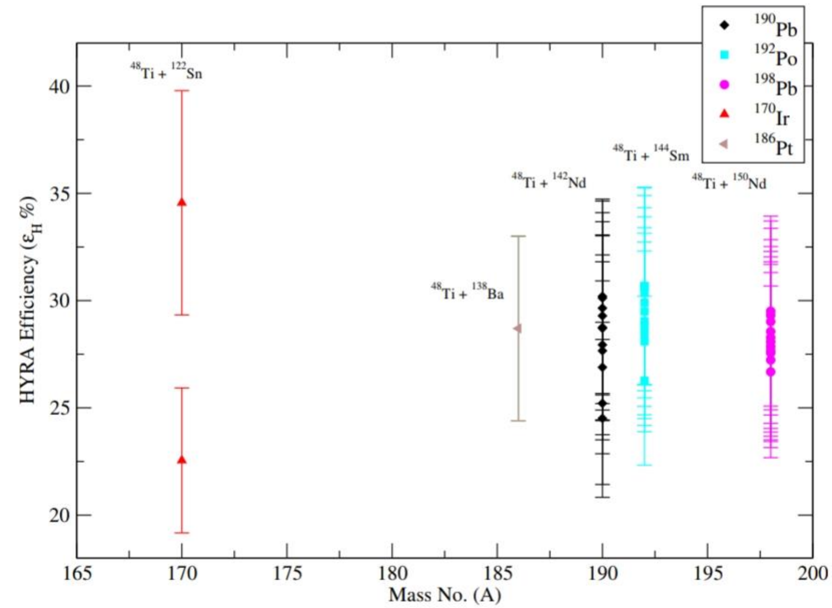
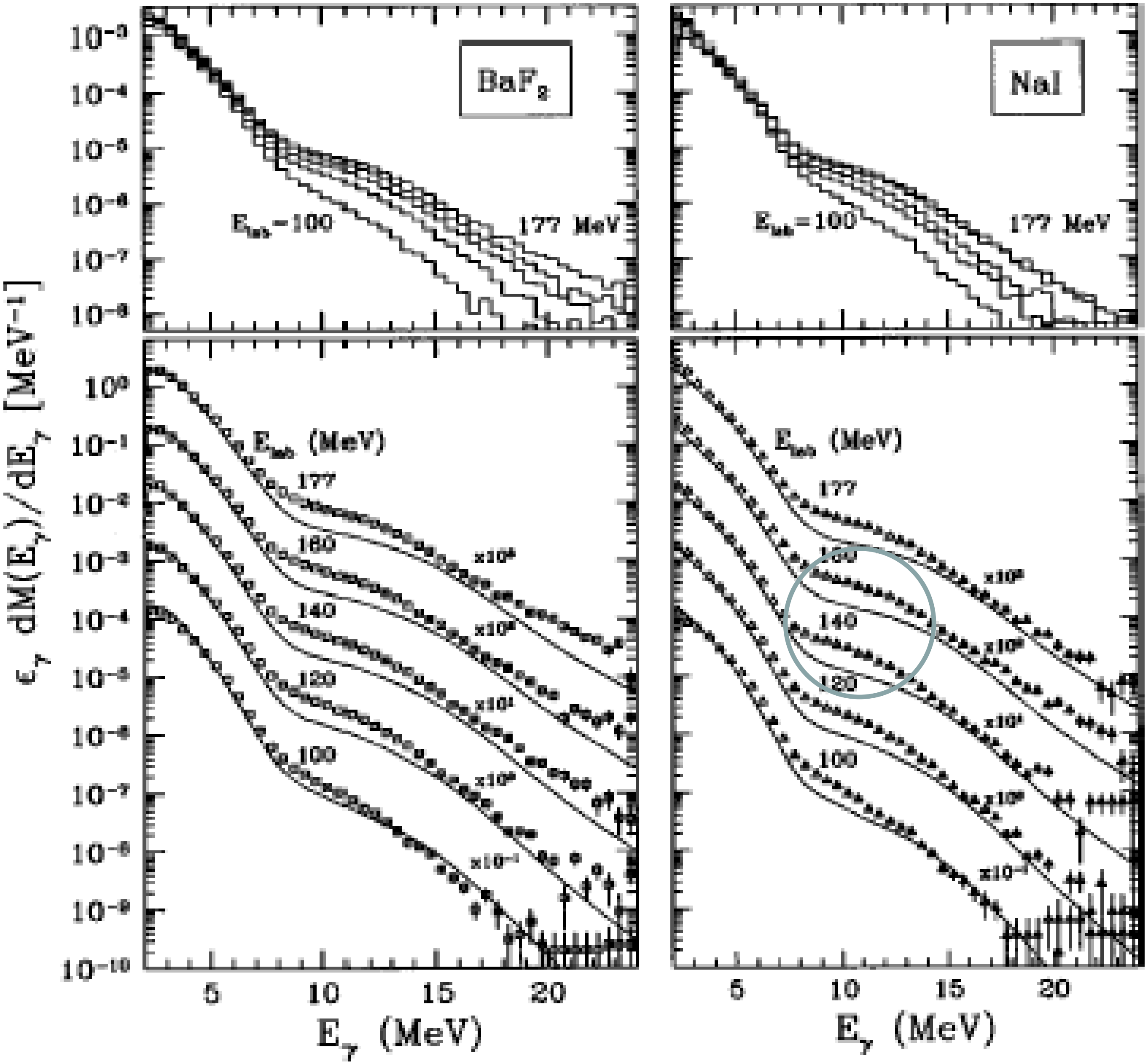
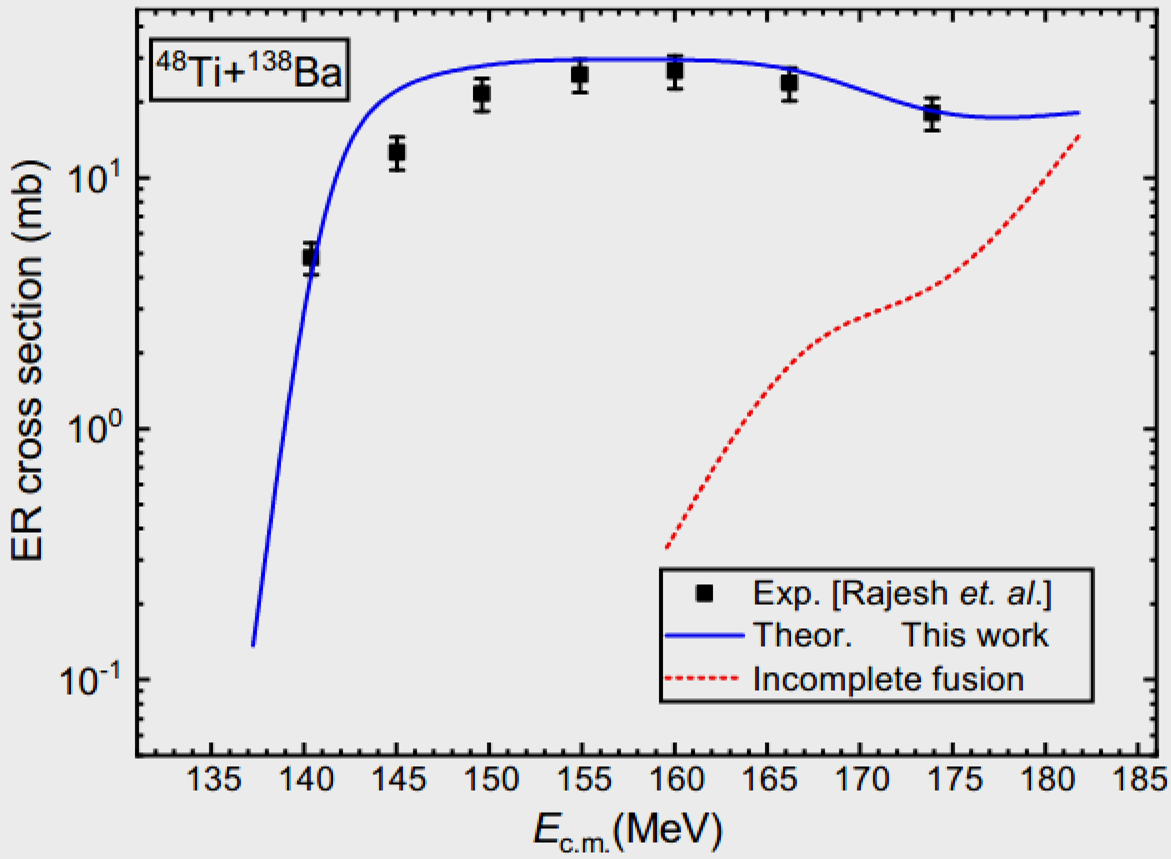


Figure 5.8: The efficiency of HYRA (ϵ_H) for ^{48}Ti and ^{16,18}O induced reaction as a function of mass number A at different lab energies.



GDR centroids

of CN ~ 11 MeV
of ff ~ 15.5 MeV



48Ti+138Ba
ER cross section (mb)
10^1
10^0
10^-1
135 140 145 150 155 160 165 170 175 180 185
Ec.m.(MeV)
Exp. [Rajesh et. al.]
Theor. This work
Incomplete fusion