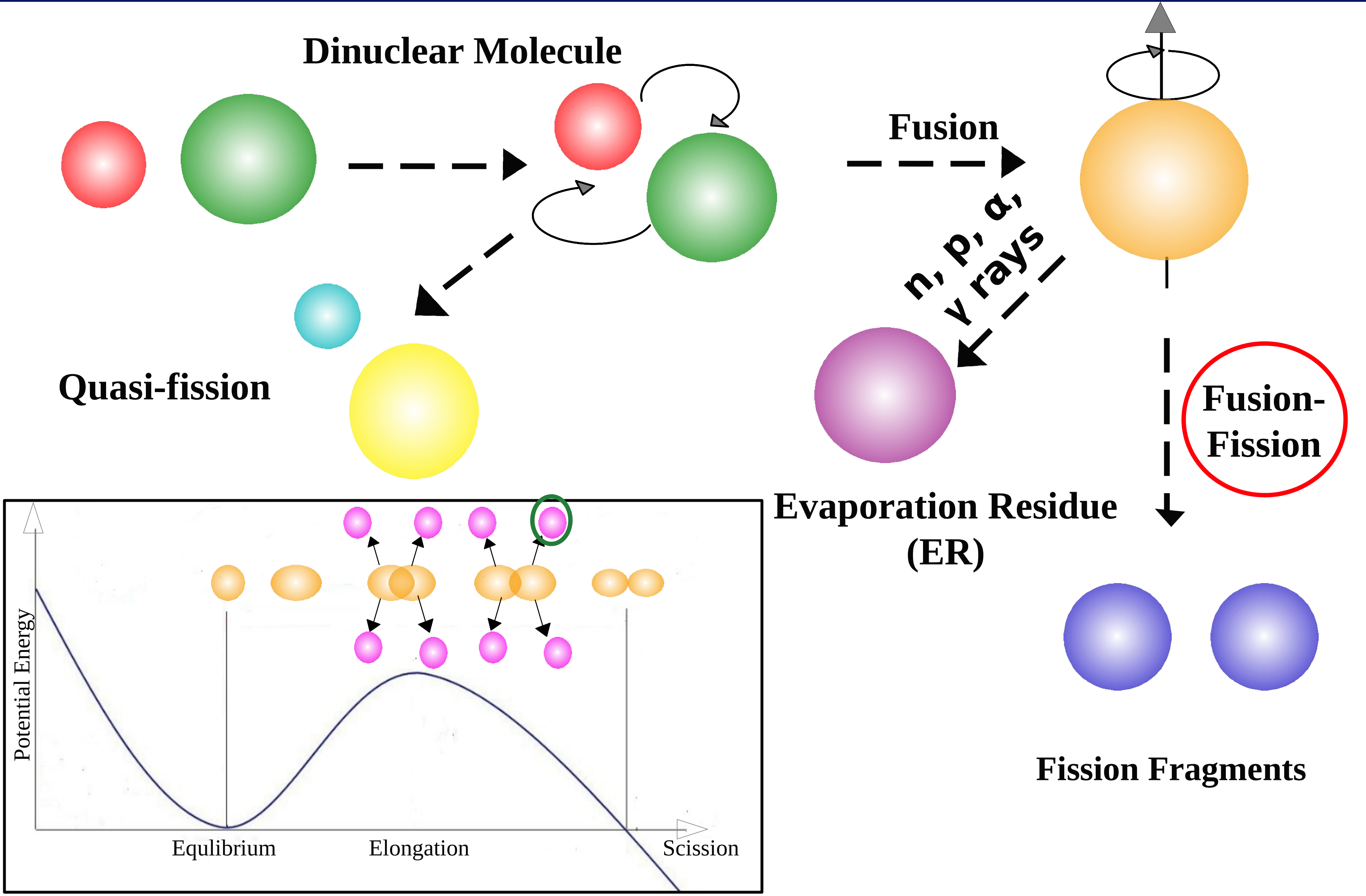
Influence of entrance channel shell closure on dissipative nature of nuclear fission

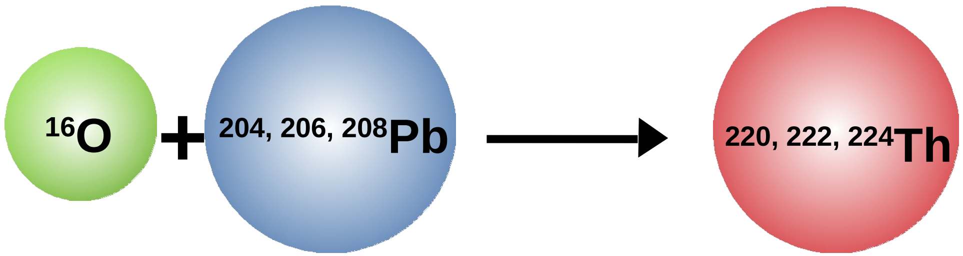
Kajol Chakraborty
Ph.D. Research Scholar
Department of Physics and Astrophysics
University of Delhi, New Delhi, India

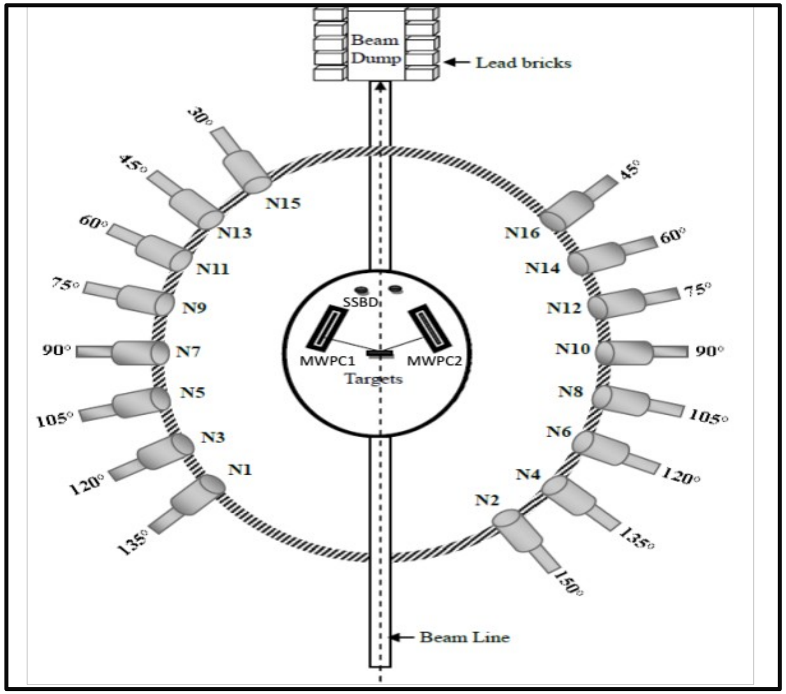
Co-authors : M.T. Senthil Kannan (VECC), Jhilam Sadhukhan (VECC), S. Mandal (University of Delhi)

India-JINR workshop on elementary particle and nuclear physics, and condensed matter research

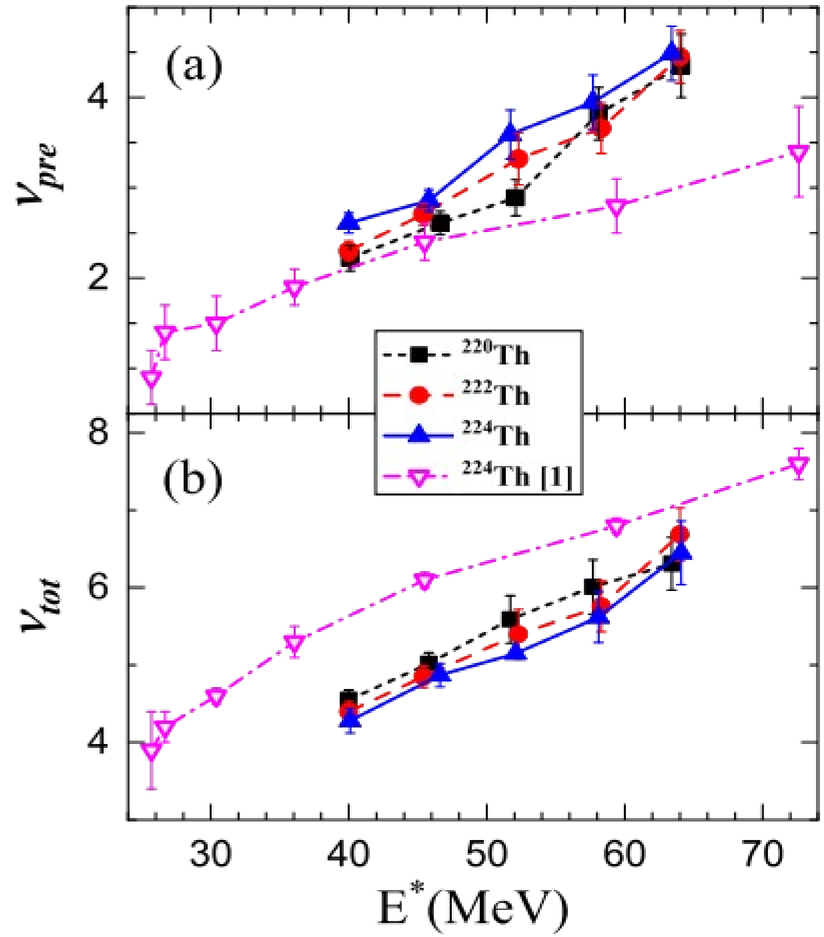

Dinuclear Molecule
Fusion
Quasi-fission
n, p, α,
γ rays
Evaporation Residue
(ER)
Fusion-
Fission
Fission Fragments
Potential Energy
Equlibrium
Elongation
Scission

Neutron Multiplicity Results : ^{220,222,224}Th





16 scintillators in reaction plane for pre- and post-scission neutron multiplicity through neutron-TOF measurements. Experiment done @ National Array of Neutron Detectors (OLD NAND) at IUAC, New Delhi.



(a) Variation of pre-scission (ν_{pre}) and (b) total (ν_{tot}) multiplicities with excitation energy (E*) for the present measurement (filled symbols) and from [1] (open symbols).

[1] Rossner *et al.*, Phys. Rev. C 45 (1992) 719.

Systematics of pre-scission neutron multiplicities

S.No	CN	Reaction
1	^{197}Tl	^{16}O+^{181}Ta
2	^{197}Tl	^{19}F+^{178}Hf
3	^{200}Pb	^{19}F+^{181}Ta
4	^{203}Bi	^{19}F+^{184}W
5	^{204}Pb	^{18}O+^{186}W
6	^{206}Po	^{12}C+^{194}Pt
7	^{210}Po	^{12}C+^{198}Pt
8	^{210}Po	^{18}O+^{192}Os
9	^{210}Rn	^{16}O+^{194}Pt
10	^{212}Rn	^{18}O+^{194}Pt
11	^{213}Fr	^{19}F+^{194}Pt
12	^{213}Fr	^{16}O+^{197}Au
13	^{214}Rn	^{16}O+^{198}Pt
14	^{215}Fr	^{19}F+^{196}Pt

28 reactions

$197 \leq A_{CN} \leq 251$

$A_P \leq 20$

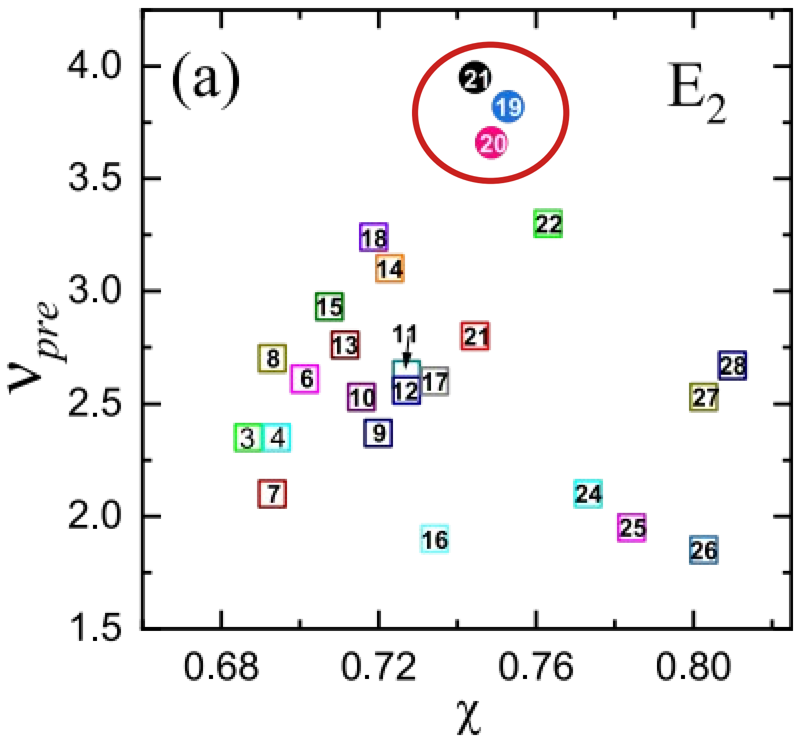
S.No	CN	Reaction
15	^{216}Rn	^{18}O+^{198}Pt
16	^{216}Ra	^{12}C+^{204}Pb
17	^{216}Ra	^{19}F+^{197}Au
18	^{217}Fr	^{19}F+^{198}Pt
19	^{220}Th	^{16}O+^{204}Pb
20	^{222}Th	^{16}O+^{206}Pb
21	^{224}Th	^{16}O+^{208}Pb
22	^{228}U	^{19}F+^{209}Bi
23	^{229}Np	^{20}Ne+^{209}Bi
24	^{243}Am	^{11}B+^{232}Th
25	^{244}Cm	^{12}C+^{232}Th
26	^{248}Cf	^{11}B+^{237}Np
27	^{248}Cf	^{16}O+^{232}Th
28	^{251}Es	^{19}F+^{232}Th

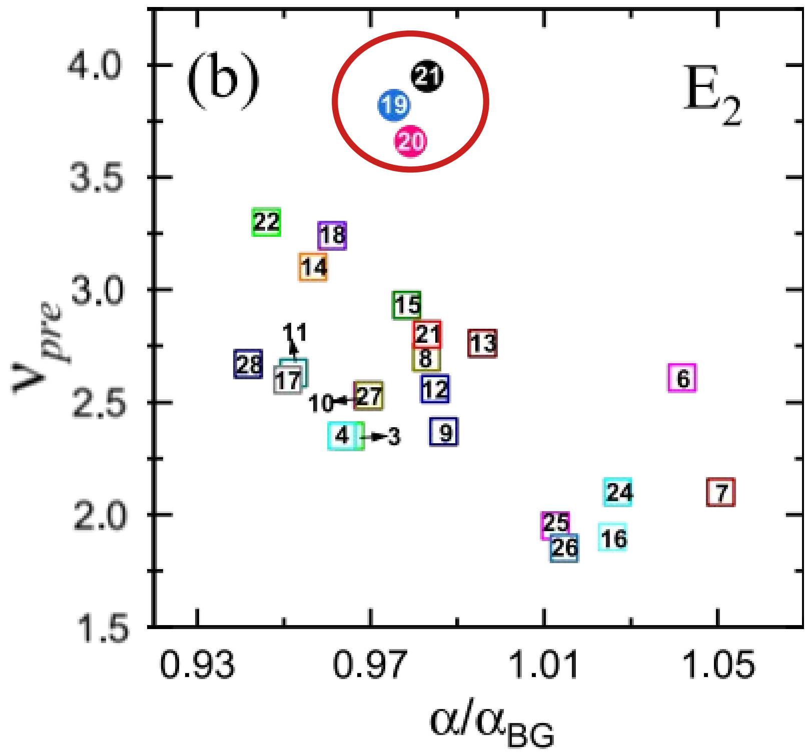
E1 bin
45 MeV ≤ E* ≤ 55 MeV

E2 bin
55 MeV ≤ E* ≤ 65 MeV

E3 bin
65 MeV ≤ E* ≤ 75 MeV

Systematics of pre-scission neutron multiplicities





Variation of ν_{pre} in the energy group E_2 along (a) the fissility parameter χ and (b) the ratio of entrance channel mass -asymmetry to Businaro-Gallone mass asymmetry parameter (α/α_{BG}).

$$X = \left(\frac{Z^2}{A}\right) \Big/ \left(\frac{Z^2}{A}\right)_{crit}$$

$$\alpha = (A_T - A_P)/(A_T + A_P)$$

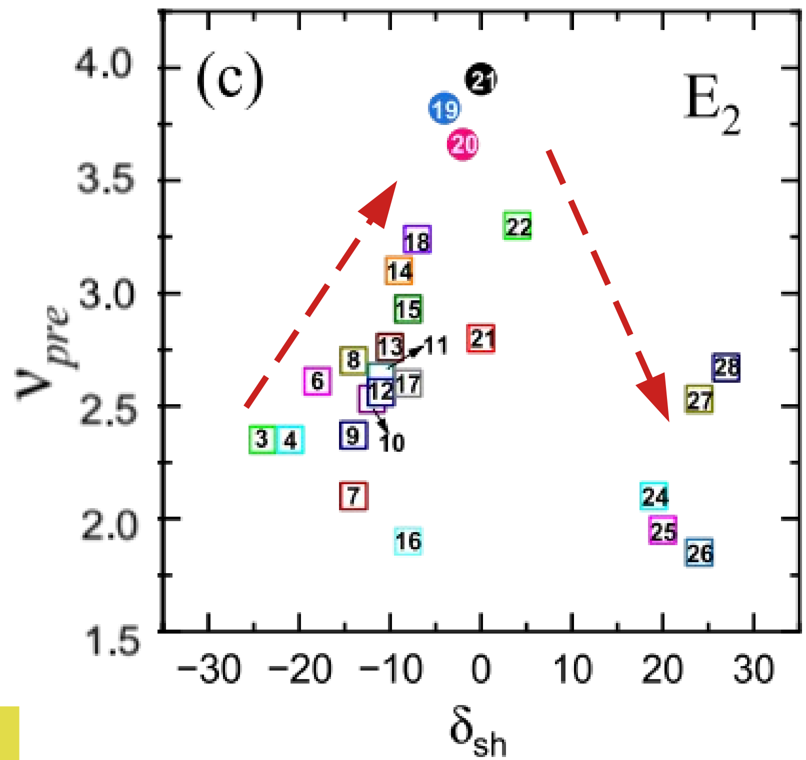
$$(Z^2/A)_{crit} = 50.883 * \left(1 - 1.7826 * \left(\frac{A-2Z}{A}\right)^2\right)$$

U. Businaro, S. Gallone, Nuovo Cimento 5 (1957) 315–317.

Systematics of pre-scission neutron multiplicities

Reaction	δ_{sh}
$^{16}O+^{181}Ta$	-27
$^{19}F+^{178}Hf$	-27
$^{19}F+^{181}Ta$	-24
$^{19}F+^{184}W$	-21
$^{18}O+^{186}W$	-20
$^{12}C+^{194}Pt$	-18
$^{12}C+^{198}Pt$	-14
$^{18}O+^{192}Os$	-14
$^{16}O+^{194}Pt$	-14
$^{18}O+^{194}Pt$	-12
$^{19}F+^{194}Pt$	-11
$^{16}O+^{197}Au$	-11
$^{16}O+^{198}Pt$	-10
$^{19}F+^{196}Pt$	-9

Reaction	δ_{sh}
$^{18}O+^{198}Pt$	-8
$^{12}C+^{204}Pb$	-8
$^{19}F+^{197}Au$	-8
$^{19}F+^{198}Pt$	-7
$^{16}O+^{204}Pb$	-4
$^{16}O+^{206}Pb$	-2
$^{16}O+^{208}Pb$	0
$^{19}F+^{209}Bi$	+4
$^{20}Ne+^{209}Bi$	+5
$^{11}B+^{232}Th$	+19
$^{12}C+^{232}Th$	+20
$^{11}B+^{237}Np$	+24
$^{16}O+^{232}Th$	+24
$^{19}F+^{232}Th$	+27



Deviation δ_{sh} of the neutron and proton numbers in the target and projectile from the respective nearest magic numbers

Variation of ν_{pre} in the energy group E_2 with δ_{sh}.

$(\delta_{sh})_{proj,prot} = Z_{12C} - Z_{16O} = -2$

$(\delta_{sh})_{proj,neut} = N_{12C} - N_{16O} = -2$

$\delta_{sh} = -8$

$(\delta_{sh})_{tar,prot} = Z_{204Pb} - Z_{208Pb} = 0$

$(\delta_{sh})_{tar,neut} = N_{204Pb} - N_{208Pb} = -4$

Bohr Wheeler fission width

$$\Gamma_f^{BW}(E^*, \ell, K=0) = \frac{1}{2\pi\,\rho_g(E^*)}\int_0^{E^*-B_f(\ell)} \rho_s(E^* - B_f(\ell) - \epsilon)\,d\epsilon,$$

collective enhancement in the level density

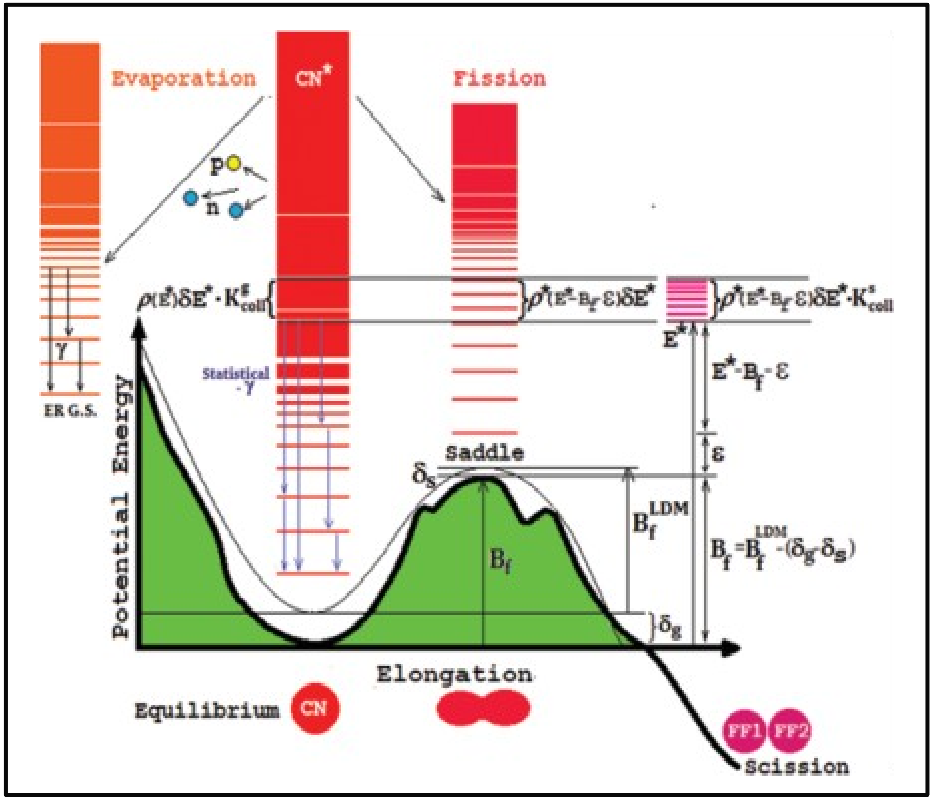
$$\rho(E^*) = K_{coll}(E^*)\rho_{intr}(E^*),$$

nuclear orientation along the symmetry axis

$$\Gamma_f^{BW}(E^*, \ell, K) = \Gamma_f^{BW}(E^*, \ell, K=0)\frac{(K_0\sqrt{2\pi})}{2\ell+1}\,\mathrm{erf}\left(\frac{\ell+1/2}{K_0\sqrt{2}}\right)$$

Kramers' fission width

$$\Gamma_f^{Kram}(E^*, \ell, K) = \Gamma_f^{BW}(E^*, \ell, K)\left\{\sqrt{1+\left(\frac{\beta}{2\omega_s}\right)^2} - \frac{\beta}{2\omega_s}\right\},$$



Potential energy as a function of elongation.

Reduced dissipation strength, β tuned to reproduce ν_{pre}

Figure is courtesy of T. Banerjee et al., Phys. Rev. C 99, 024610 (2019)

Statistical Model Analysis

$$\delta = M_{\mathrm{exp}} - M_{\mathrm{LDM}}.$$

FRLDM fission barrier

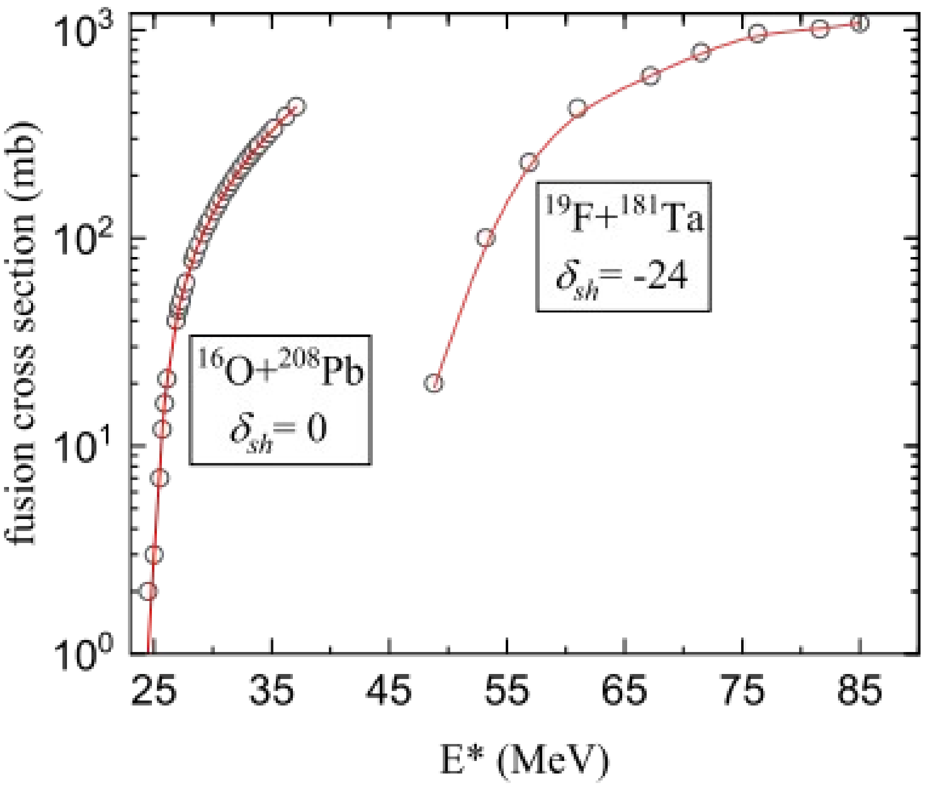
A.J. Sierk, Phys. Rev. C 33 (1986) 2039–2053.

$$B_{\mathrm{f}}(\ell) = B_{\mathrm{f}}^{\mathrm{LDM}}(\ell) - (\delta_{\mathrm{g}} - \delta_{\mathrm{s}}),$$

Ignatyuk's level density

Ignatyuk *et al*., Yad. Fiz. 21 (1975) 485–490.

$$a(E^*) = \tilde{a}\left[1 + \frac{1 - \exp\left(-\frac{E^*}{E_{\mathrm{D}}}\right)}{E^*}\delta\right].$$



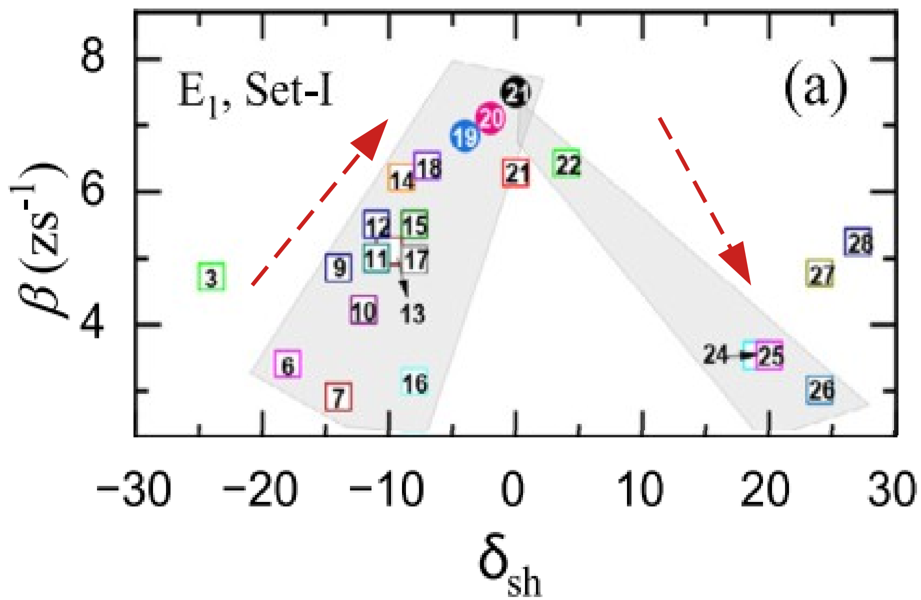
Shell Corrections in Fission Barrier and Level Density Parmeter

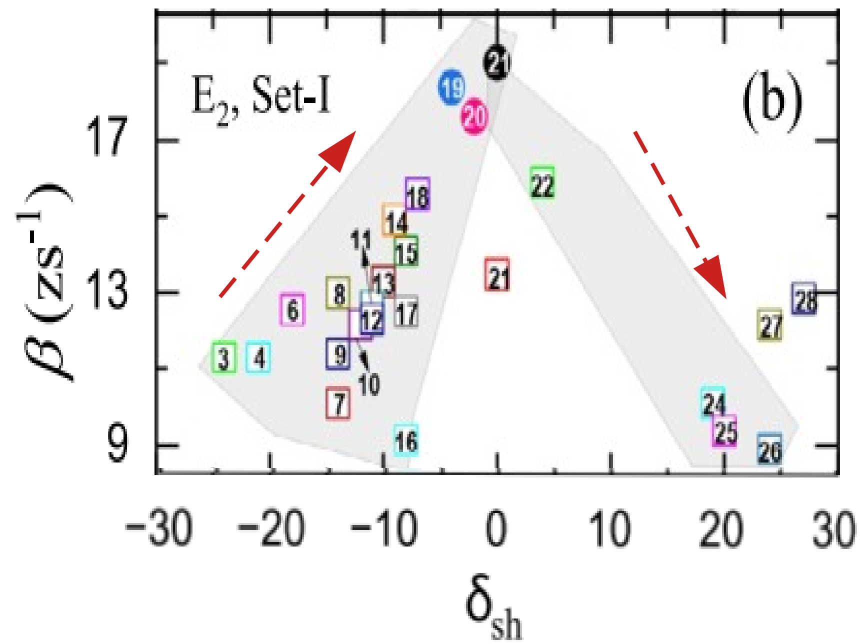
Calculated fusion cross sections (solid lines) compared with experimental values (symbols) for ^{16}O + ^{208}Pb [1] and ^{19}F + ^{181}Ta [2]

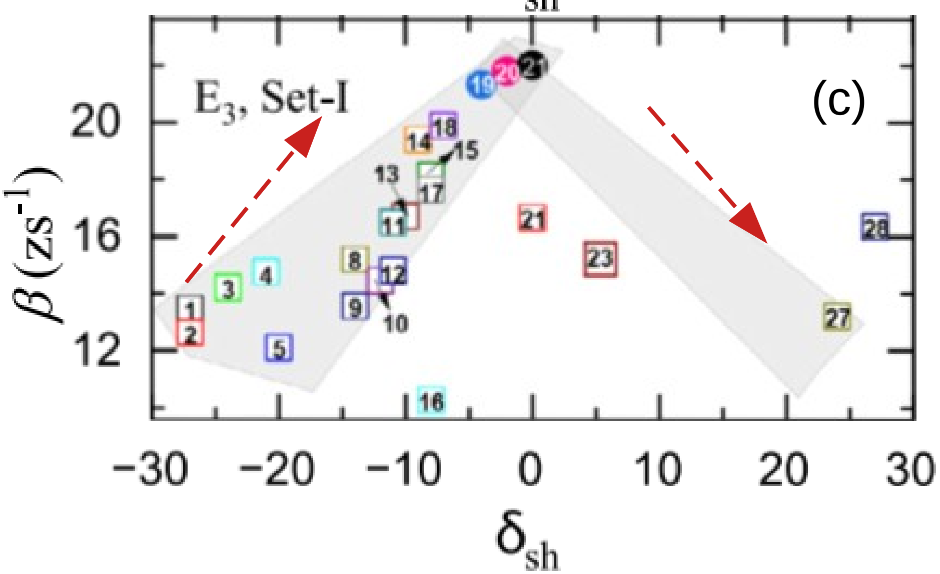
Two Set of Calculations : Set I (without) and Set II (with) shell corrections.

1. Morton *et al.*, Phys. Rev. C 52 (1995) 243–251.
2. Charity *et al,*, Nucl. Phys. A 457 (1986) 441–460.

Set-I Results : Impact of Entrance Channel Shell Closure







Variation of the reduced dissipation coefficient β with δ_{sh} obtained for Set-I in the excitation energy bin (a) E1, (b) E2, and (c) E3

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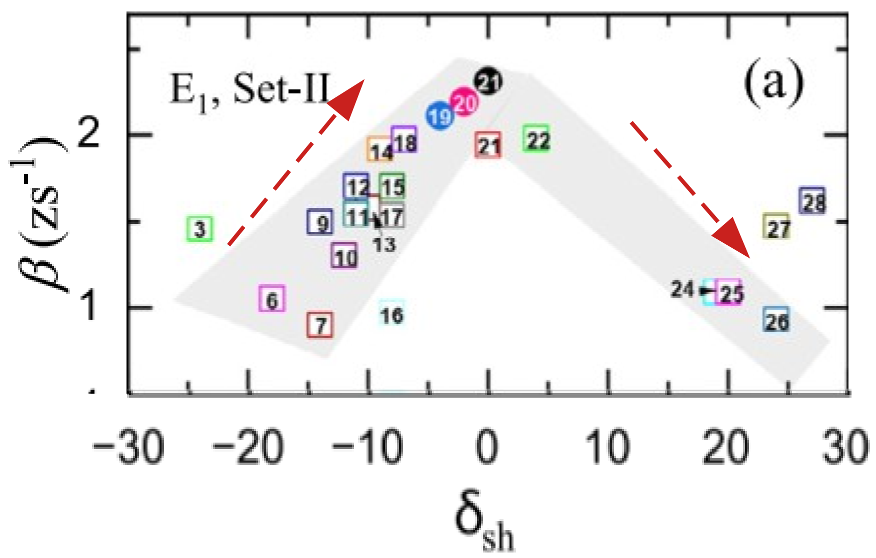

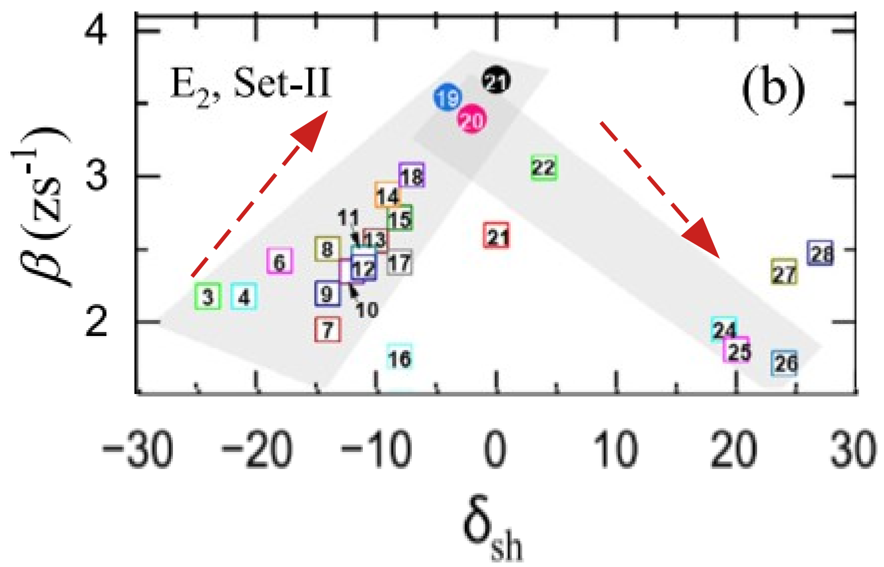

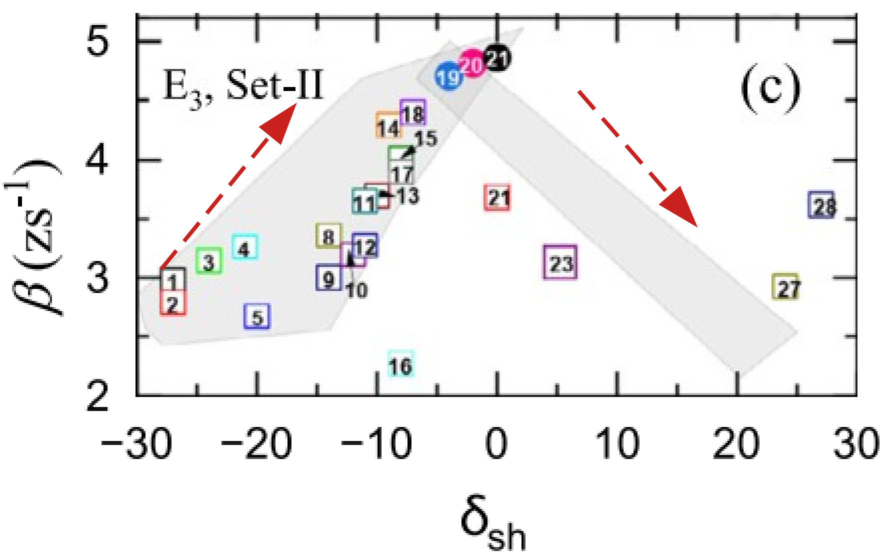

Variation of the reduced dissipation coefficient β with δ_{sh} obtained for Set-II in the excitation energy bin (a) E1, (b) E2, and (c) E3

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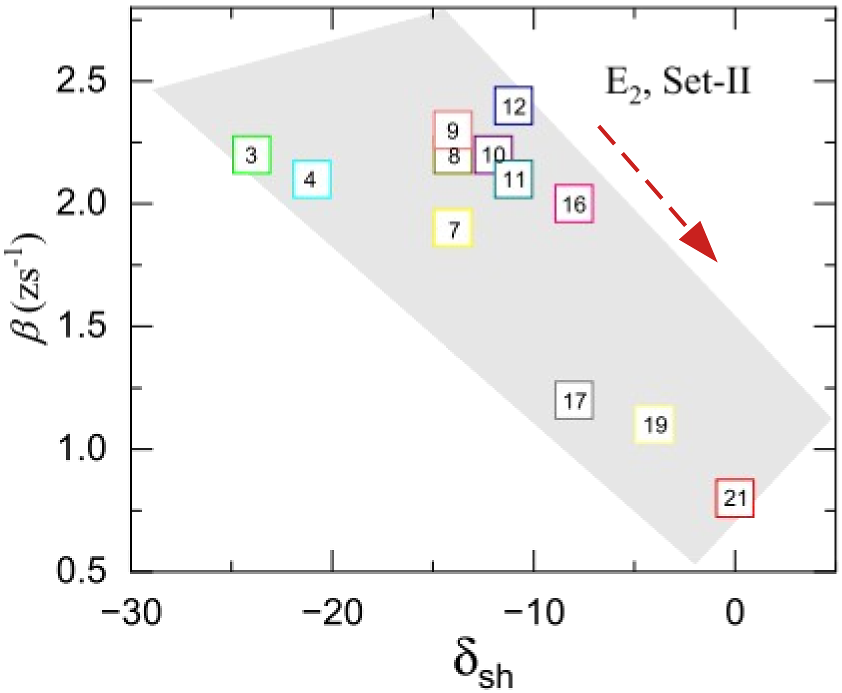
Results : Impact of Entrance Channel Shell Closure



Variation of β with δ_{sh} obtained by fitting the ER cross-section data

Hypothesis of complete equilibrium invalid!!

Detailed statistical model calculations for 28 reactions predominated by complete fusion-fission channel reveal a higher dissipation strength, β to reproduce ν_{pre} and a lower β to reproduce ER cross-sections for systems having a closed shell structure in the incoming channel. The investigations highlight the fact that the pathway to fission is more hindered for systems with closed shell nuclei as reaction partners.

K. Chakraborty, M.T. Senthil Kannan, Jhilam Sadhukhan, S. Mandal, Physics Letters B 843 (2023) 138021


Thank
You