Probing role of deformed target on the mass-energy distributions of ^{224}Th at above Coulomb barrier

Aniruddha Dey[1*,#], E. M. Kozulin[1], Moumita Maiti[2], A. A. Bogachev[1], G. N. Knyazheva[1], I. M. Itkis[1], K. A. Kulkov[1], Y. Mukhamejanov[1], K. V. Novikov[1], I. V. Pchelintsev[1], R. S. Tikhomirov[1], I. V. Vorobiev[1]

[1]Flerov Laboratory of Nuclear Reactions, JINR, 141 980 Dubna, Russia

[2]Department of Physics Indian Institute of Technology Roorkee, Roorkee-247 667, Uttarakhand, India

(*Email: deyaniruddha07@gmail.com)

JOINT INSTITUTE FOR NUCLEAR RESEARCH

India-JINR workshop

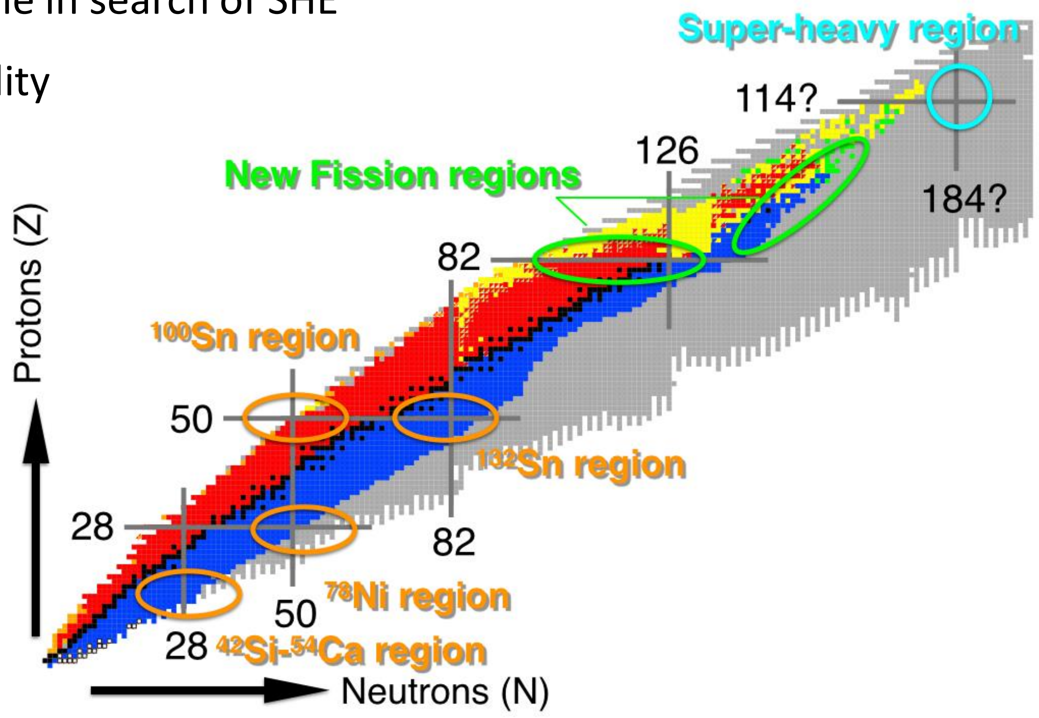
Joint Institute for Nuclear Research (JINR)

Dubna, Moscow Region, Russia

JINR FLNR 114 Flerovium Dubna

Introduction: Way Towards Super Heavy Nuclei

- JINR – One of the prime laboratories exploring the limits of the periodic table in search of SHE
- Several experimental evidences indicates the existence of an island of stability
- Theoretical models have predicted a range of possibilities with Z, N
- Experimental challenge ! For an optimum fusion reaction candidate
- One of the important aspect : Target-Projectile combination



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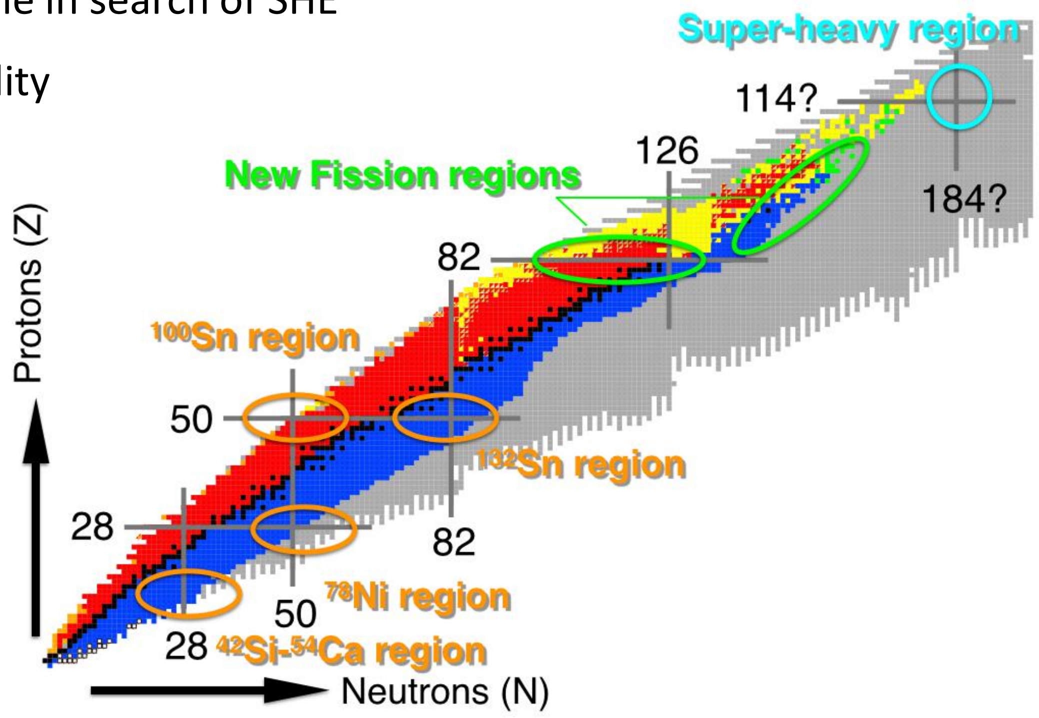
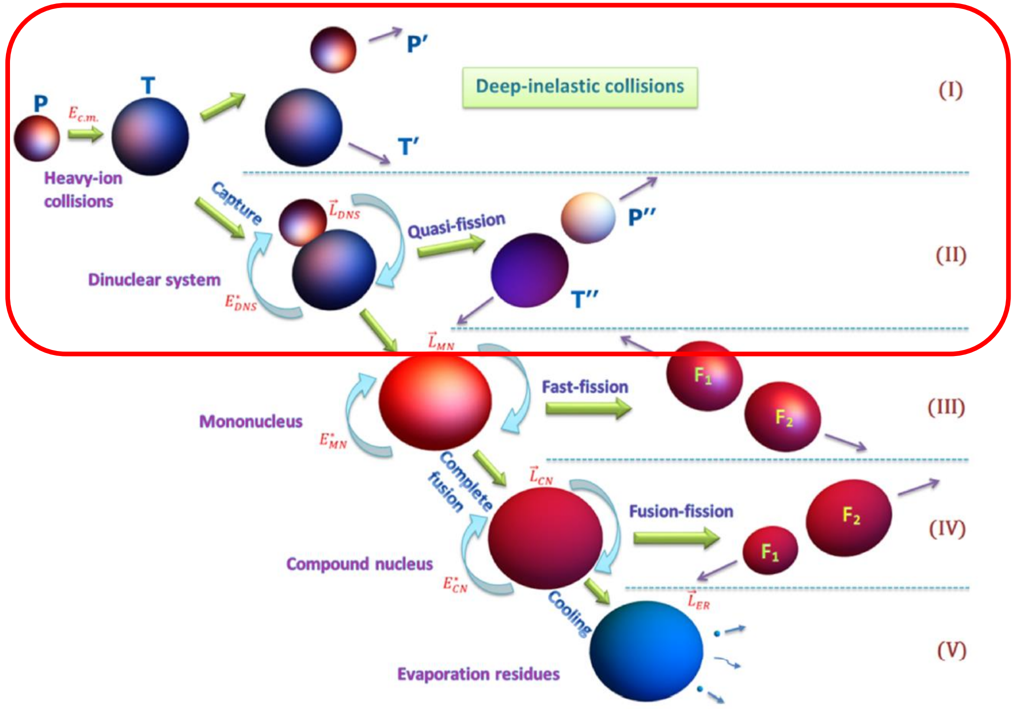
- One of the important aspect : Target-Projectile combination
- Problem : Highly fissile elements, Dinuclear system seems to prefer for non-equilibrium fusion processes





- Asymmetric reactions during the Hot fusion mechanism – Quasifission is the primary competing channel to the formation of compound nucleus
- Dominant mechanism suppressing the formation of SHE
- Detail understanding of this reaction mechanism has become one of the crucial criteria in order to optimize the formation of new heavy and superheavy nuclei.

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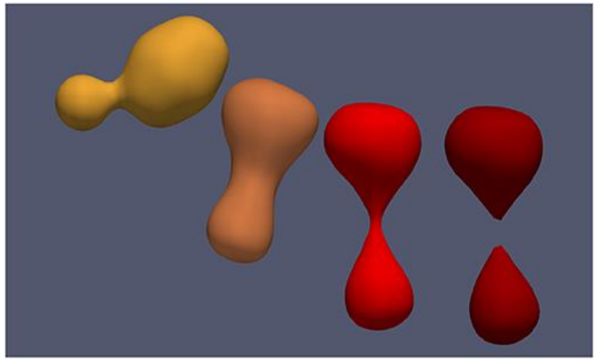
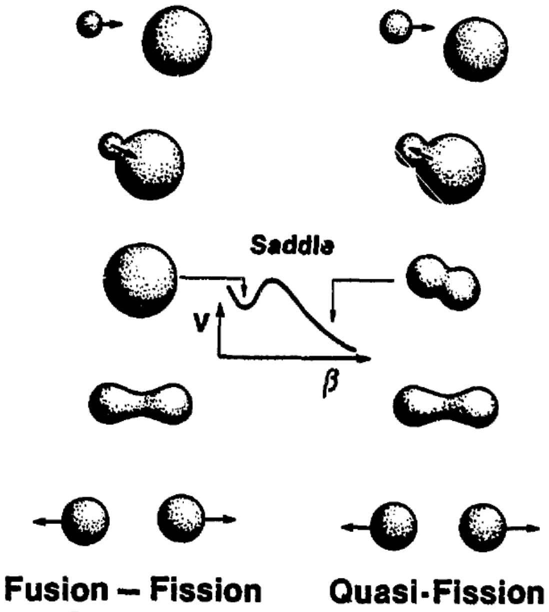
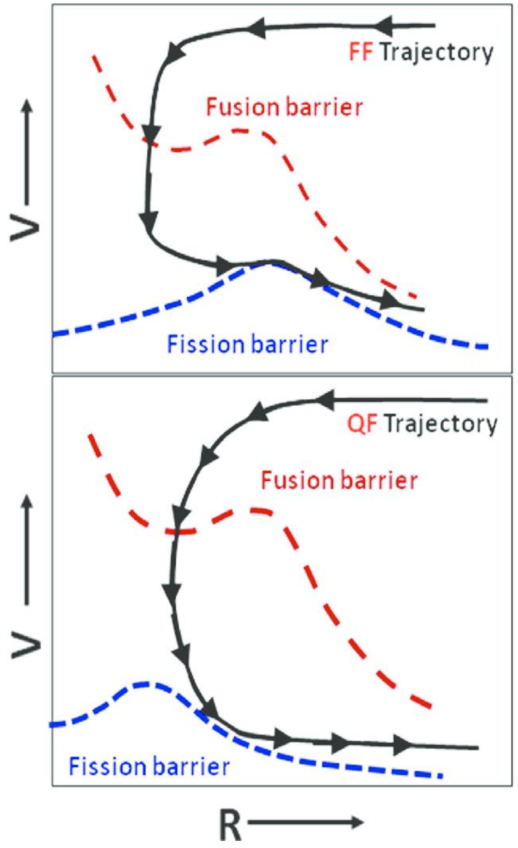
Major hurdle before SHE: Quasifission



- The di-nuclear system fissions before reaching the stage of an equilibrated compound nucleus
- Quasifission process : non-equilibrium dynamical process, Strongly depends on the shell structural effects of the composite dinuclear system
- Takes place before a full rotation of the di-nuclear system, with typical contact times 'sticking time' between the fragments of 5 to 10 zs; Rapid process (10^{-21} s)
- Influencing factors –
  1. Characteristics of the entrance channel – Coulomb factor, Deformation and shell structure of the collision partners
  2. Fissility and excitation energy of the system
  3. Shell effects of fragments in the vicinity of magic nuclei

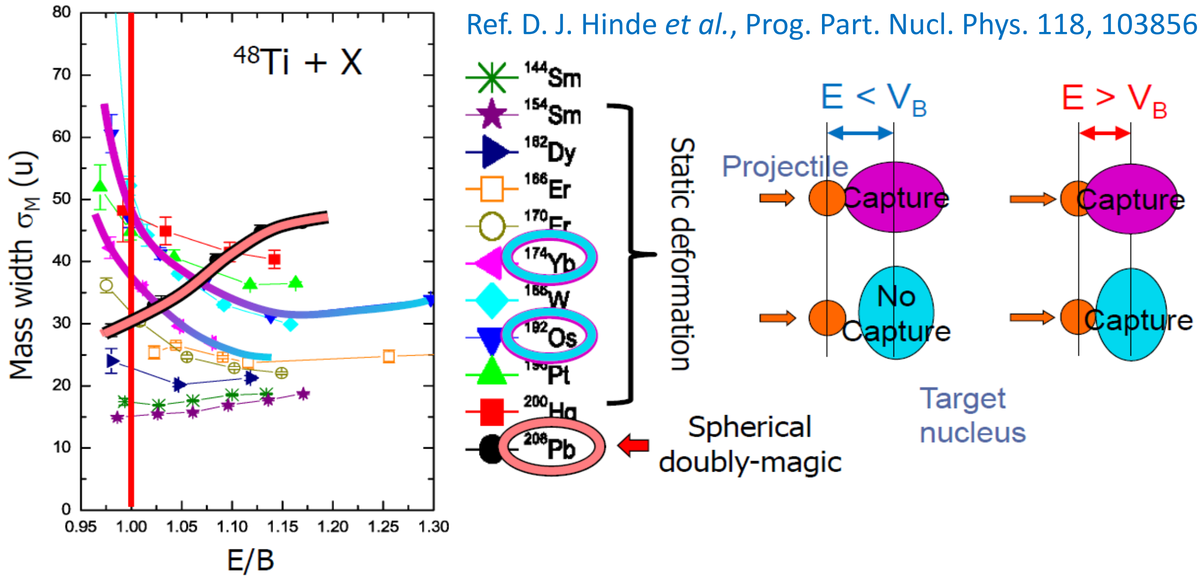




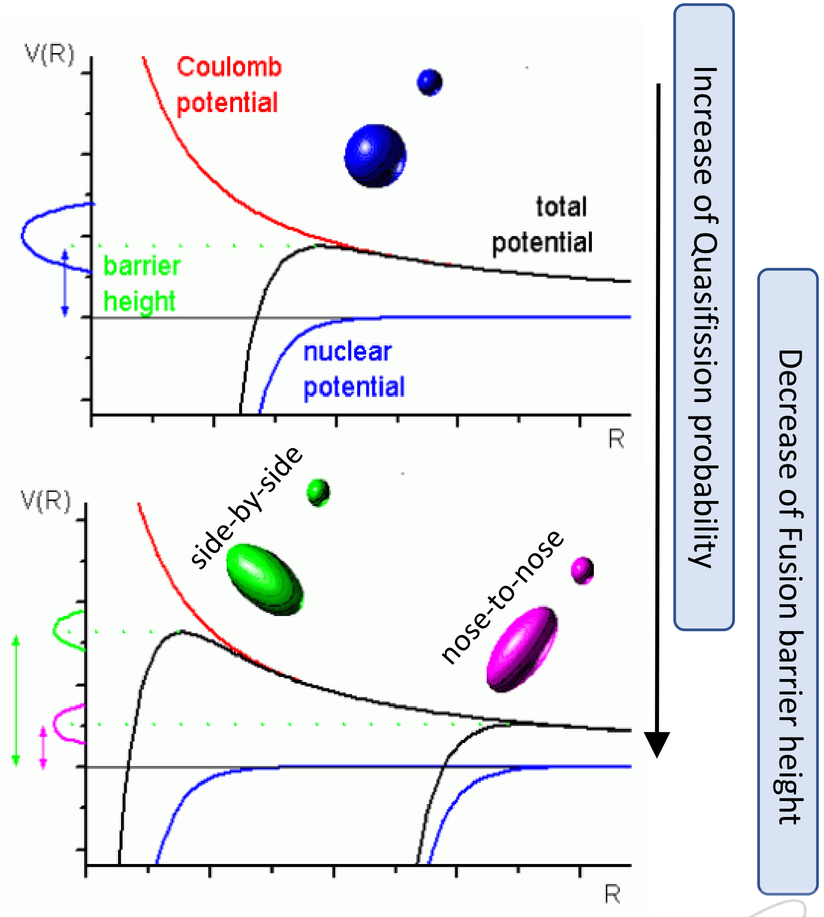
- Experimental Signatures –
  1. Nonequilibrium process and have a large angular anisotropy
  2. Asymmetric components in the mass distribution
  3. Varying mass width with respect to the entrance channel, more stronger dependence on E_{ex}
  4. Mass-angular distributions; forward-backward asymmetry

Role of Deformed Target on Collision Dynamics

- The fusion probability influenced by the relative orientation of deformed nuclei, which changes the Coulomb barrier and the distance between the centers of the colliding nuclei



Ref. D. J. Hinde *et al.*, Prog. Part. Nucl. Phys. 118, 103856 (2021)

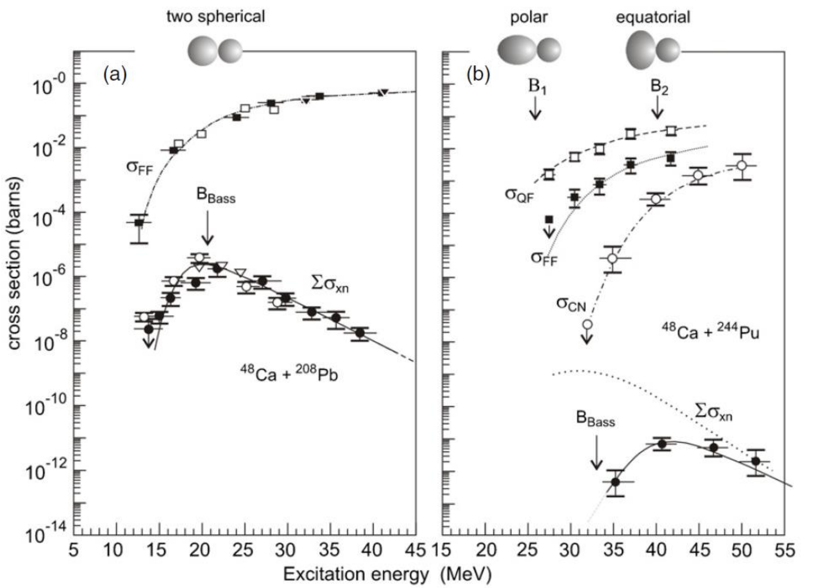


- Our group : ^{48}Ca + ^{144}Sm, ^{154}Sm (Ref. G. N. Knyazheva *et al.*, Phys. Rev. C 75, 064602 (2007)), reported suppression of CN formation, fusion-fission reaction mechanism incase of deformed nuclei collision; In contrast with the liquid drop model calculations
- Rotation angle; due to Coulombic interaction is significantly small
- Shape effects in the collision dynamics is important in SHE formation reactions (Ref. D. J. Hinde *et al.*, Phys. Rev. C 53, 1290 (1996))

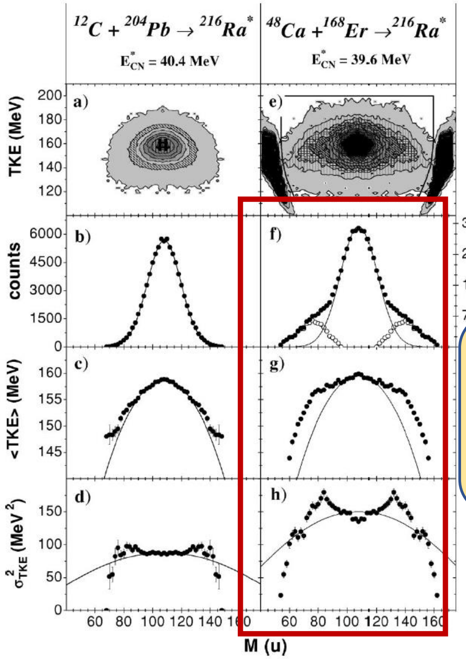
Indicates that orientation of colliding nucleus affects the barrier height, leads to more Non-equilibrium processes

Literature Review: Evidences of Quasifission (QF)

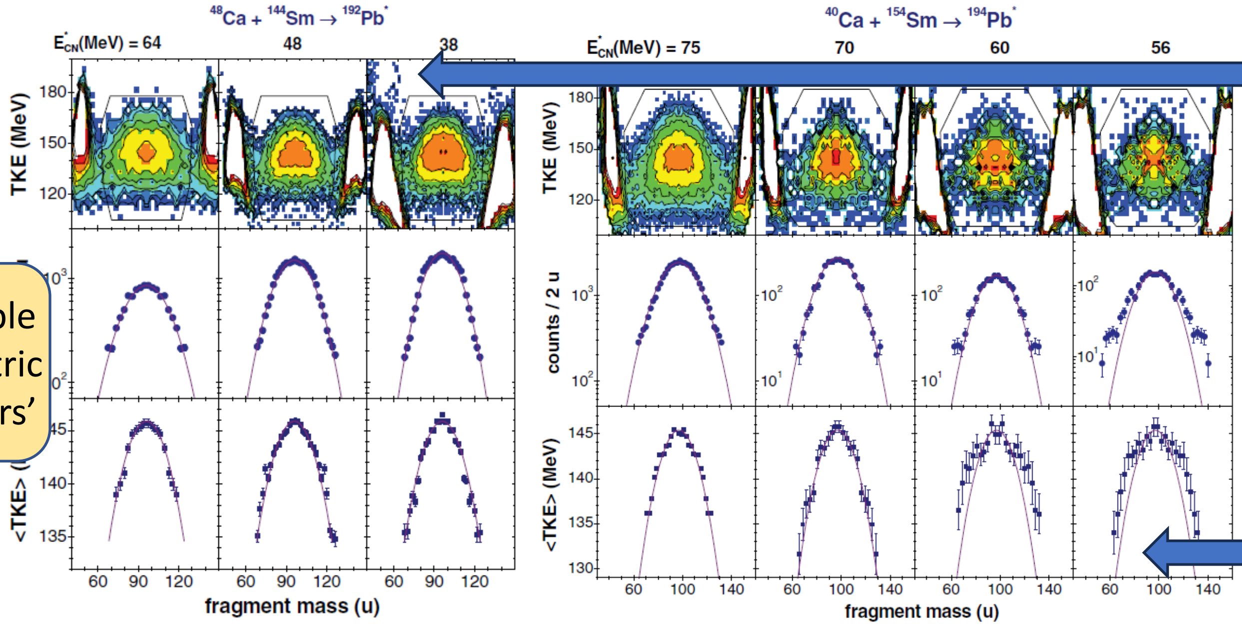
- Fusion of the two spherical nuclei ^{208}Pb and ^{48}Ca corresponds to the optimal conditions for formation of the compound nucleus ^{256}No and its survival
- However, fusion of the spherical ^{48}Ca with the deformed ^{244}Pu nucleus ($\beta_2 \approx 0.25$), the Coulomb barrier and the configuration of the heavy nucleus depend on the orientation of the target nucleus at the touching point
- Asymmetric shoulders in the mass distribution around fusion barrier
- Broader <TKE> distribution; Significantly higher values of σ^2_{TKE} – multiple modes !

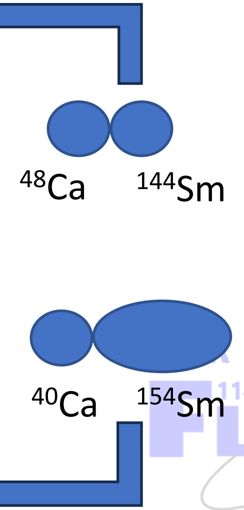


Ref. Yuri Oganessian, J. Phys. G: Nucl. Part. Phys. 34, R165 (2007)



Noticeable asymmetric 'shoulders'



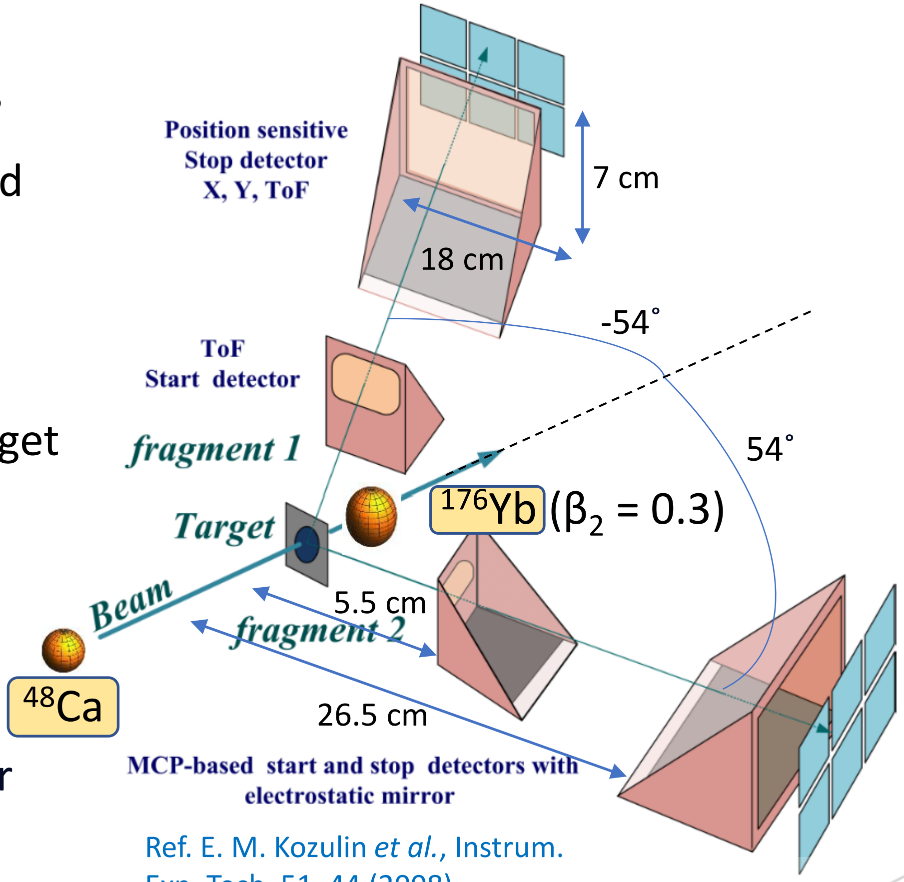


Ref. A. Yu. Chizhov *et al.*, Phys. Rev. C 67, 011603 (R) (2003)

Ref. G. N. Knyazheva *et al.*, Phys. Rev. C 75, 064602 (2007)

CORSET Time-of-Flight Spectrometer

- CORSET (CORrelation SETup) is a two-arm time-of-flight position-sensitive spectrometer developed at the Flerov Laboratory of Nuclear Reactions (FLNR), JINR.
- Consists of two identical TOF arms, measures the velocity of both fragments
- Each movable TOF arm contains MCP (Micro-Channel Plate) based START and STOP detectors
- Distance between the start and stop detectors of each arm (the flight path) ranges from 10 to 20 cm, and the distance from the start detector to the target is 3 - 5 cm



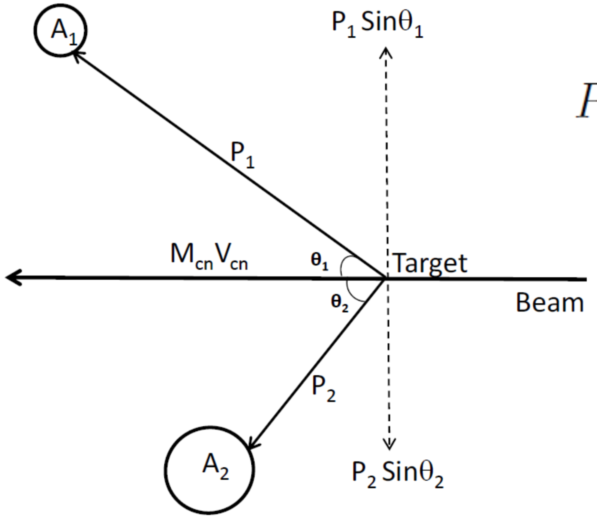
Ref. E. M. Kozulin *et al.*, Instrum. Exp. Tech. 51, 44 (2008)

Experimental Setup

- Time resolution ≈ 180 ps
- Mass resolution ≈ 2-3 amu
- Position resolution ≈ 2 mm
- Angular resolution ≈ ±0.3˚
- Detector size = 18 × 7 cm^2
- Solid angle of each arm ≈ 360 msr
- Arm angles$_{1,2}$ = 50˚ – 60˚
- E_{beam} = 188 to 272 MeV from *U400*
- Target thickness ≈ 214 μg/cm^2 on 1.5 μm thick Titanium backing
- Distance of START, STOP detectors from target = 5.5 cm, 26.5 cm, respectively

Data Processing: Double-Velocity Measurement Technique

Double-velocity measurement



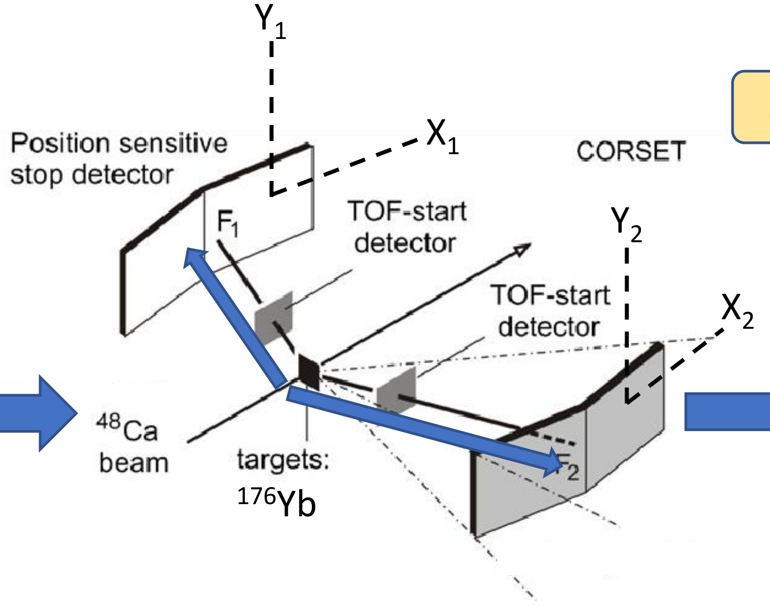
$$P_1 cos\theta_1 + P_2 cos\theta_2 = M_{cn}V_{cn}$$

$$P_1 sin\theta_1 = P_2 sin\theta_2$$

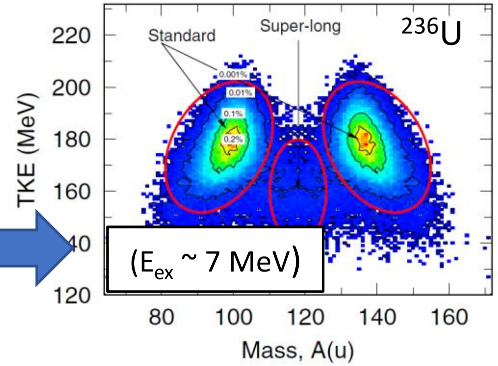
$$A_1 = \frac{(T_1 - T_2) + \delta t_0 + M_{cn}\frac{d_2}{P_2}}{\frac{d_1}{P_1} + \frac{d_2}{P_2}}$$

$$A_2 = M_{cn} - A_1$$

$$T_i = \frac{d_i}{\sqrt{2E_i/A_i}}$$



Subsequent Multimodal analysis



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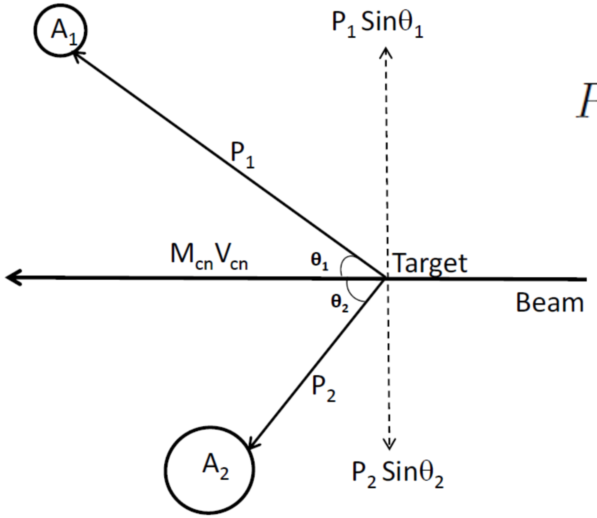

$$P_1 cos\theta_1 + P_2 cos\theta_2 = M_{cn} V_{cn}$$

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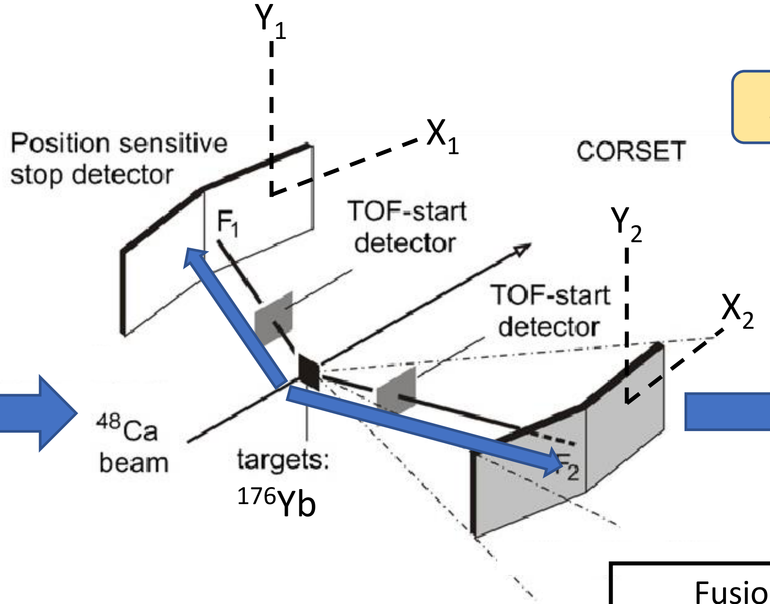

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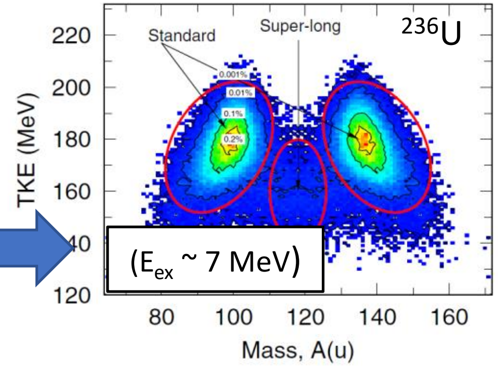
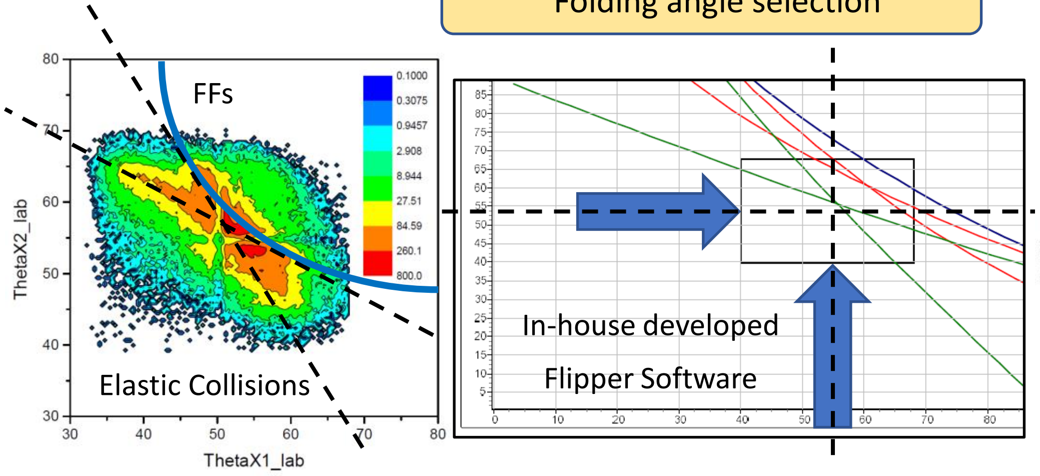


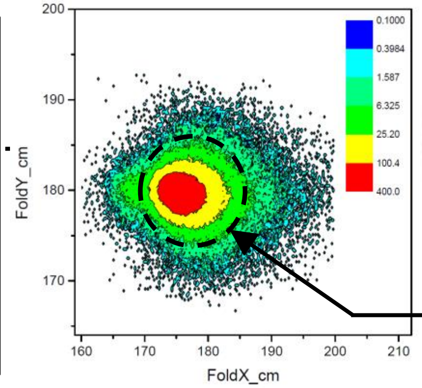
Fusion-fission
+
Symmetric Quasifission

Asymmetric Quasifission

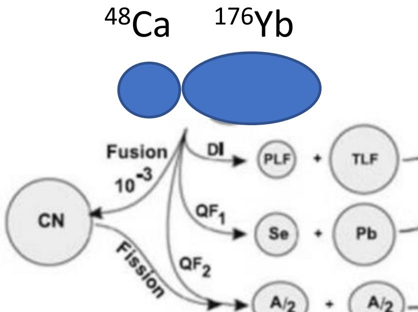
Deep Inelastic

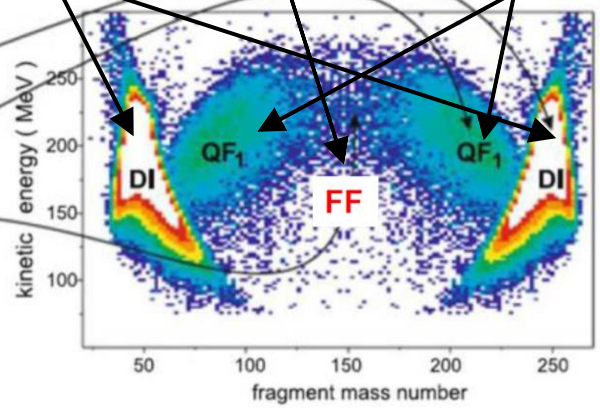
Folding angle selection





Full Momentum Transfer Collisions

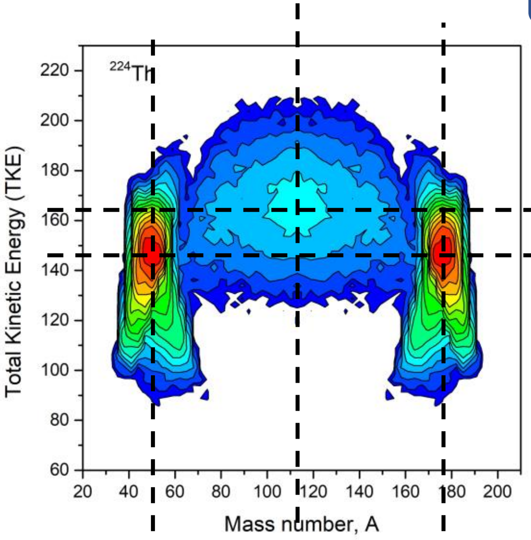




Experimental Results: Measured M-TKEs

Reaction : $^{48}Ca + ^{176}Yb \rightarrow ^{224}Th$

A_{CN} / 2



PLF, ^{48}Ca

N_P/Z_P = 1.4

TLF, ^{176}Yb

N_T/Z_T = 1.51

Viola Systematics

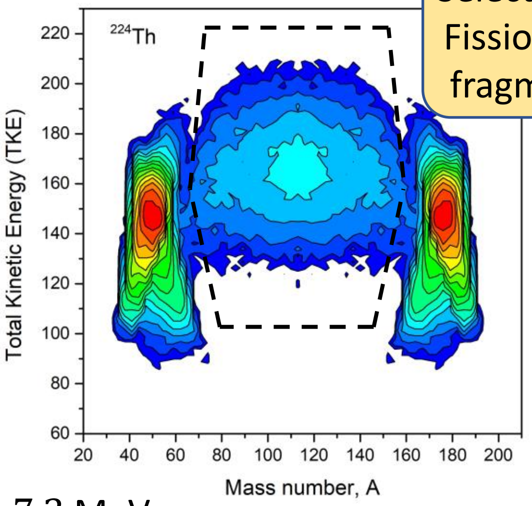
TKE_{FF} = 165.1 MeV

E_{cm} = 147.7 MeV

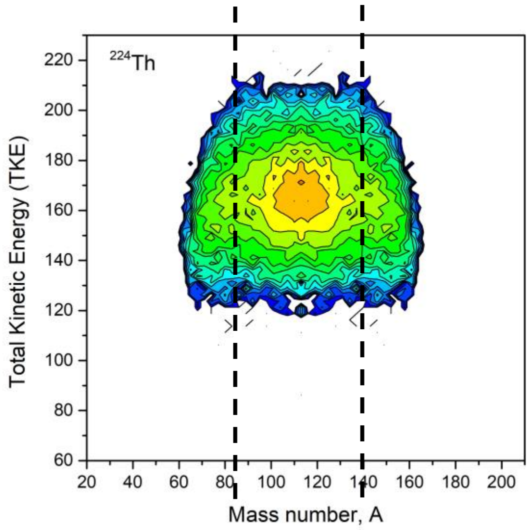
$$\langle TKE \rangle_{viola} = 0.1189 \frac{Z^2}{A^{1/3}} + 7.3 \text{ MeV}$$

Ref. V. E. Viola *et al.*, Phys. Rev. C 31, 1550 (1985)

Selection of Fission-like fragments



~ 84 ~ 140



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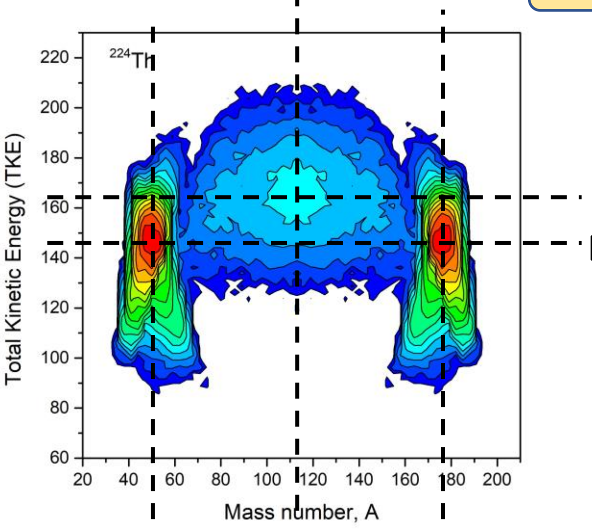

PLF, ^{48}Ca TLF, ^{176}Yb

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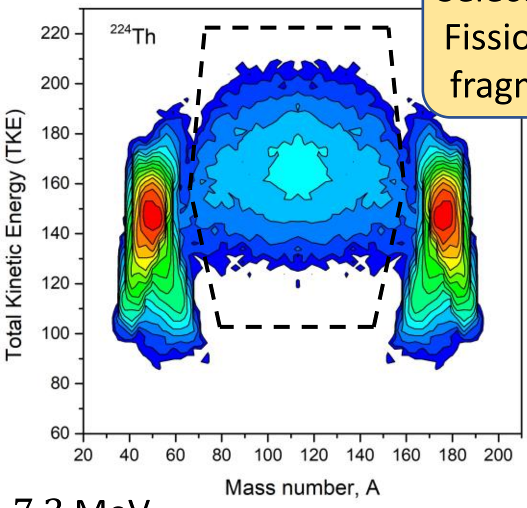

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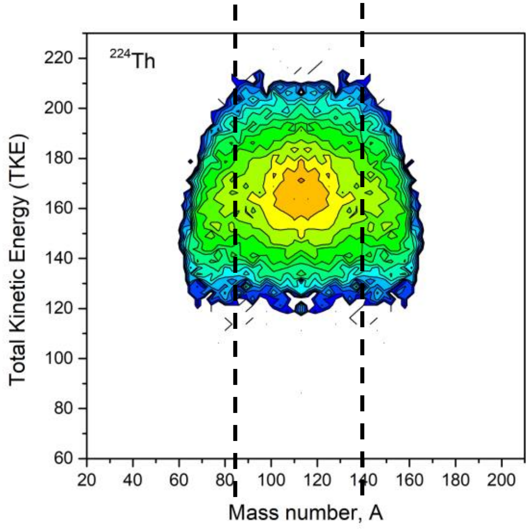

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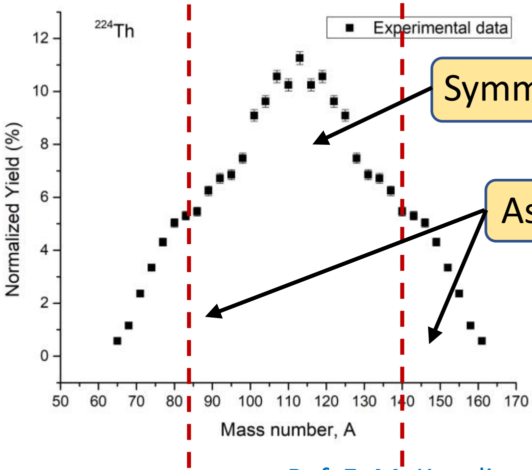
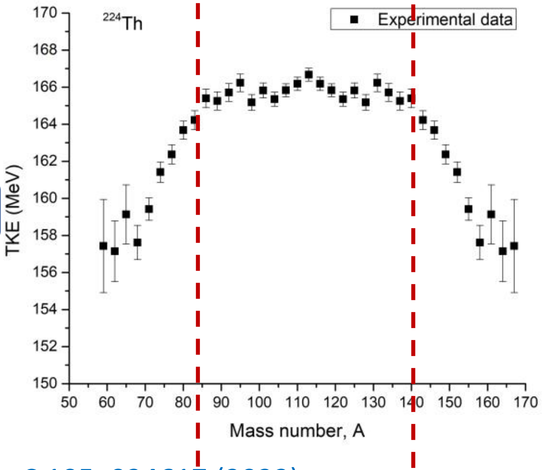


Symmetric

Asymmetric

~ 84   ~ 140



Ref. E. M. Kozulin *et al.*, Phys. Rev. C 105, 024617 (2022)

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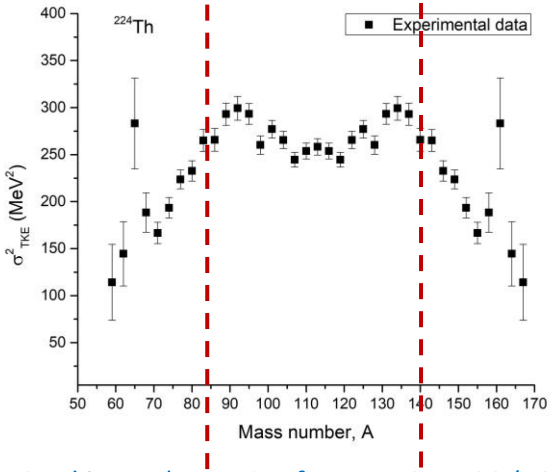
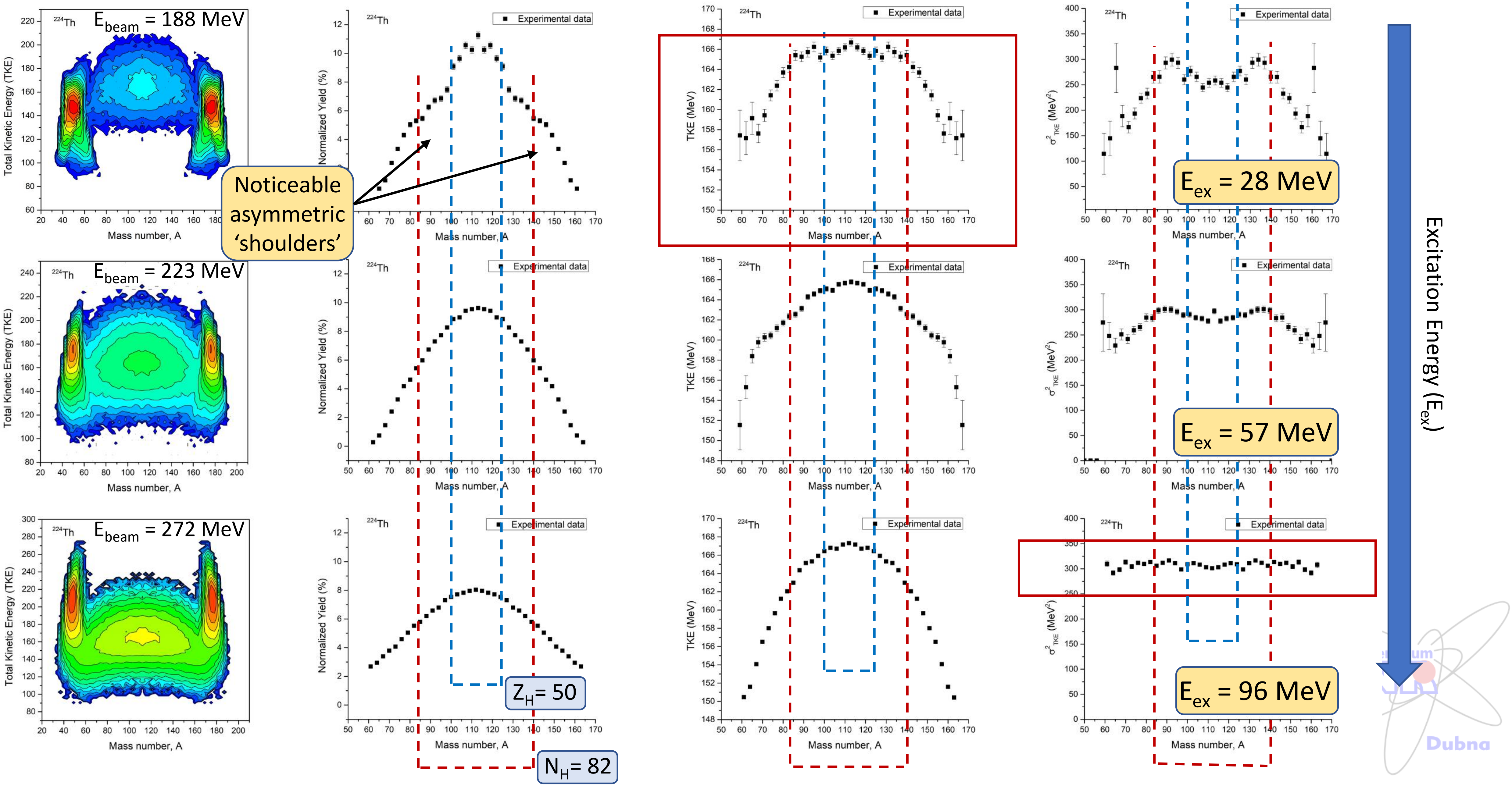


Ref. M. G. Itkis *et al.*, AIP Conf. Proc. 425, 189 (1998)

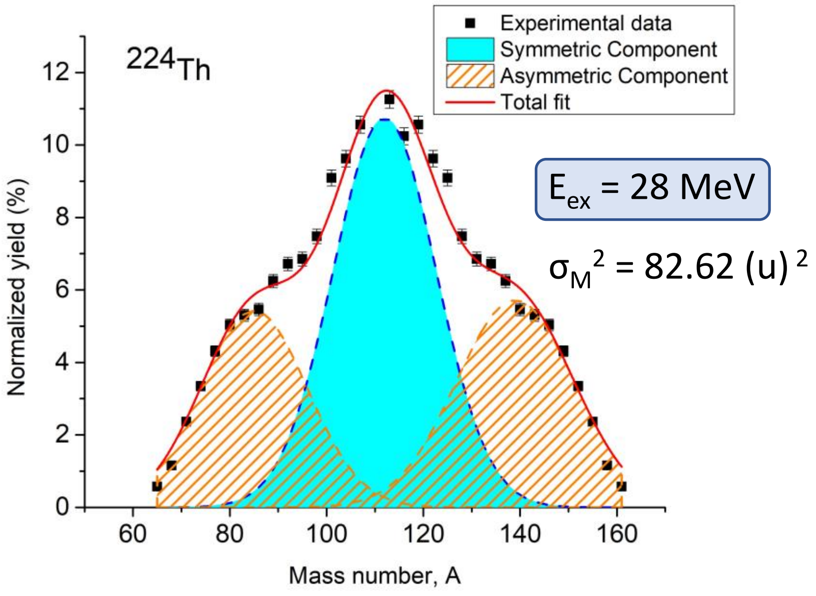
Evidences indicates existence of multiple fission modes

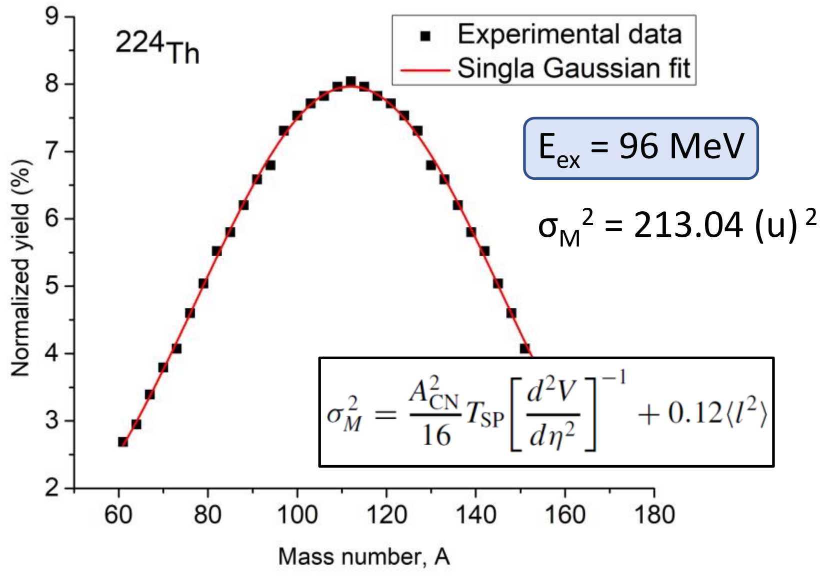
Experimental Results: Measured M-TKEs



Preliminary Results from Multimodal analysis

Excitation Energy (E_{ex})



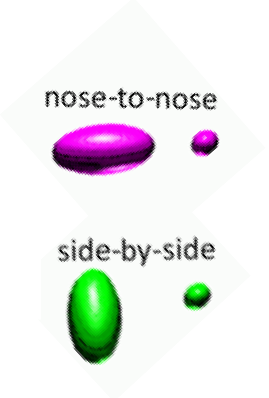


$$\sigma_M^2 = \frac{A_{CN}^2}{16} T_{SP} \left[\frac{d^2V}{d\eta^2}\right]^{-1} + 0.12\langle l^2 \rangle$$

$^{48}Ca + ^{176}Yb \rightarrow ^{224}Th$ $(E_{CM} / E_B \sim 1.33)$

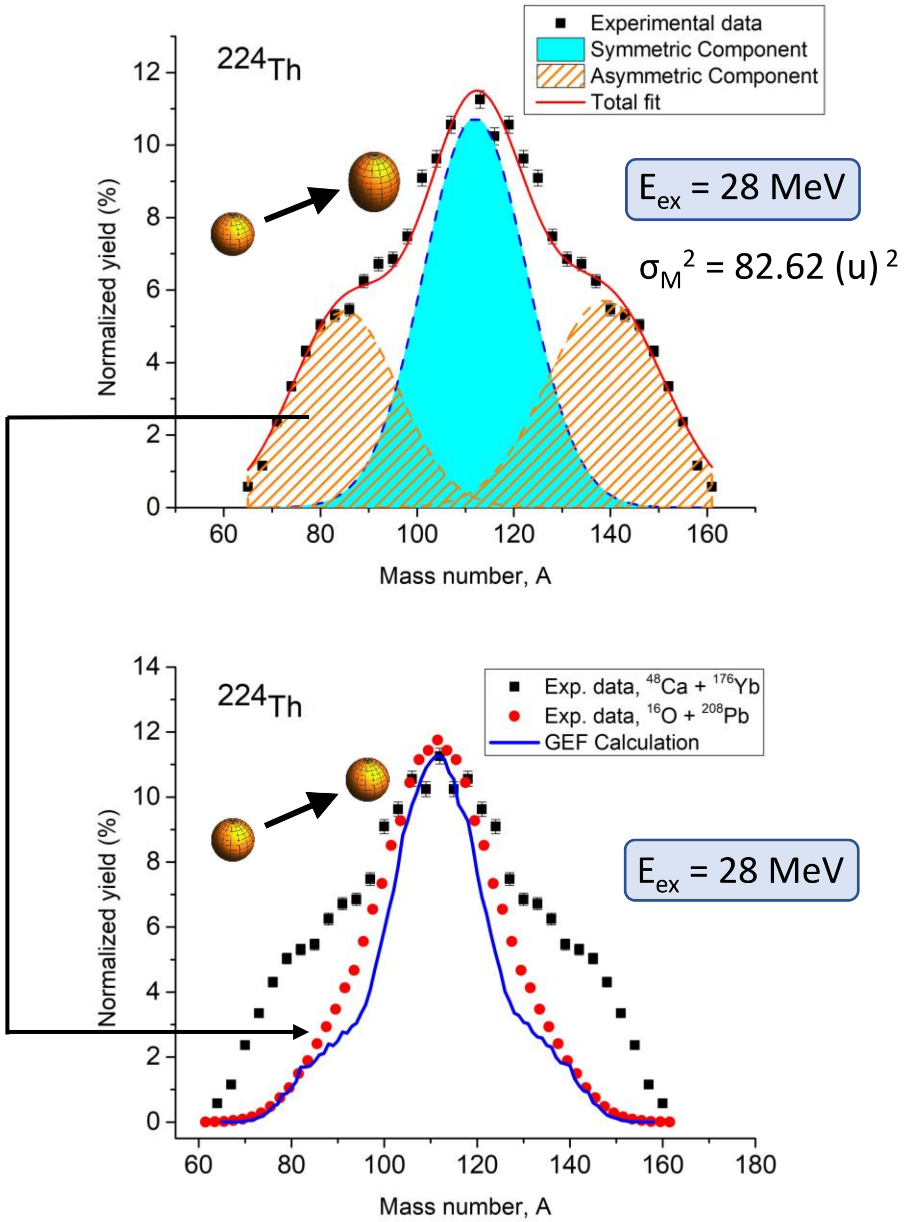
$Z_1Z_2 = 1400$, $\chi_m = 0.76$

$\alpha = \frac{A_T - AP}{A_T + A_P} = 0.57$ $(E_{CM} / E_B \sim 1.16)$



- Nuclei around Ra, Ac and lighter Th are reported as transitional region between Symmetric and Asymmetric modes of fission
- At low-energy, the Mass distributions are superposition of both these modes with comparable contributions
- These 'shoulders' could be due to either bimodal fission of CN or onset of Quasifission (QF) process
- Shell structural effects near A_L = 80-100 and A_H = 125-145 regions are indicated
- With increase in excitation, these asymmetric 'shoulders' vanishes

Preliminary Results from Multimodal analysis



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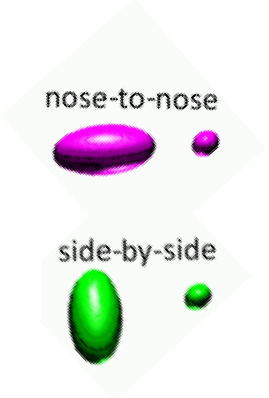

- Due to massive projectile (^{48}Ca), most plausible explanation would be QF
- ^{224}Th populated with channel : $^{16}O + ^{208}Pb$ at similar excitation energy (E_{ex})
- General Description of Fission (GEF) model calculation have been performed for ^{224}Th nucleus at $E_{ex} \sim 28$ MeV
- Clear indication of influence of Quasifission reaction mechanism
- Detail investigation is required to explore the origin of this asymmetric component in ^{224}Th at low-excitation energies, and further analysis is under progress

Conclusion and Summary

- The Mass-Total Kinetic Energy (M-TKE) distributions of the primary binary fragments from ^{224}Th by employing the heavy-ion induced reaction, ^{48}Ca + ^{176}Yb, corresponding to seven different beam energies at above the Coulomb barrier have been measured using the CORSET facility.

- Preliminary analysis have been carried out to explore the multimodal fission structure of the ^{224}Th nucleus at several moderate excitation energies.

- At low-excitation energy, the persistence of asymmetric component indicates the influence of Quasifission in the reaction dynamics. Results have been compared with that of from the reaction, ^{16}O + ^{208}Pb, and GEF theoretical model calculations, that further strengthens our interpretation for the origin of the asymmetric 'shoulders'. Further investigation is required for a detail understanding of the impact of the Quasifission reaction mechanism.

- The present investigation deals with a highly prolate deformed target nucleus, ^{176}Yb being bombarded with a spherical energetic projectile beam, ^{48}Ca. The same composite system, ^{224}Th has been populated through different entrance channels of similar nature of deformed target and spherical beam combinations. The initial investigation have revealed that prolate deformed target nucleus significantly reduces the fusion-fission cross-section, and enhances the possibility of Quasifission. Detail analysis is currently under progress.

THANK YOU FOR YOUR KIND ATTENTION

Спасибо за Ваше внимание !

"EVERY BRILLIANT EXPERIMENT,

LIKE EVERY GREAT WORK OF ART,

STARTS WITH AN ACT OF IMAGINATION"

- JONAH LEHRER -

ACKNOWLEDGEMENTS

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