

Reaction studies from below to well above the Coulomb Barrier energies



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Research Experience

- 2015 - 2021 Doctor of Philosophy**

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- enacted by the Government of India



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Accelerator Centre - (IUAC)**

- 2022 -2024 Post Doctoral research associate**

Experimental Nuclear Physics – Study of Fission Dynamics

Nuclear Reaction Group, Variable Energy Cyclotron Centre

Kolkata, INDIA-700064



Government of India

Department of Atomic Energy

VARIABLE ENERGY CYCLOTRON CENTRE

EXPERIMENTS

Fusion

- **Barrier distributions**, ER cross section experiments, etc
- *Transfer reactions* and their angular distributions

Fission

- **Mass distributions**, Angular Distributions
- **Mass gated Neutron multiplicity**, Charge Particle multiplicity

Barrier Distribution

Mass
distributions

Mass gated
Neutron
multiplicity

RESEARCH MOTIVATION

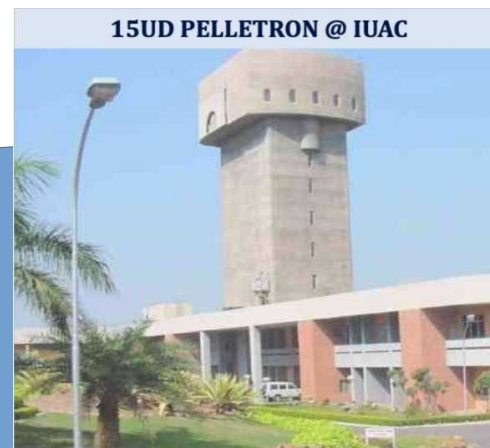
Heavy-Ion fusion-fission reactions

- > nuclear astrophysics
- > energy generation in the stellar environment
- > production of exotic nuclei
- > synthesis of SHE
- > data to reach optimized irradiation conditions for the development of next generation nuclear reactors

Heavy-Ion peripheral reactions

- > QEL - potential parameters for different nuclear reactions
- > ICF and transfer - a promising spectroscopic tool to achieve high spin states
- > provide a sensitive probe for nuclear structure studies

Sets of experiments were performed at Inter-University Accelerator Centre (IUAC), New Delhi and Variable Energy Cyclotron Centre (VECC), Kolkata

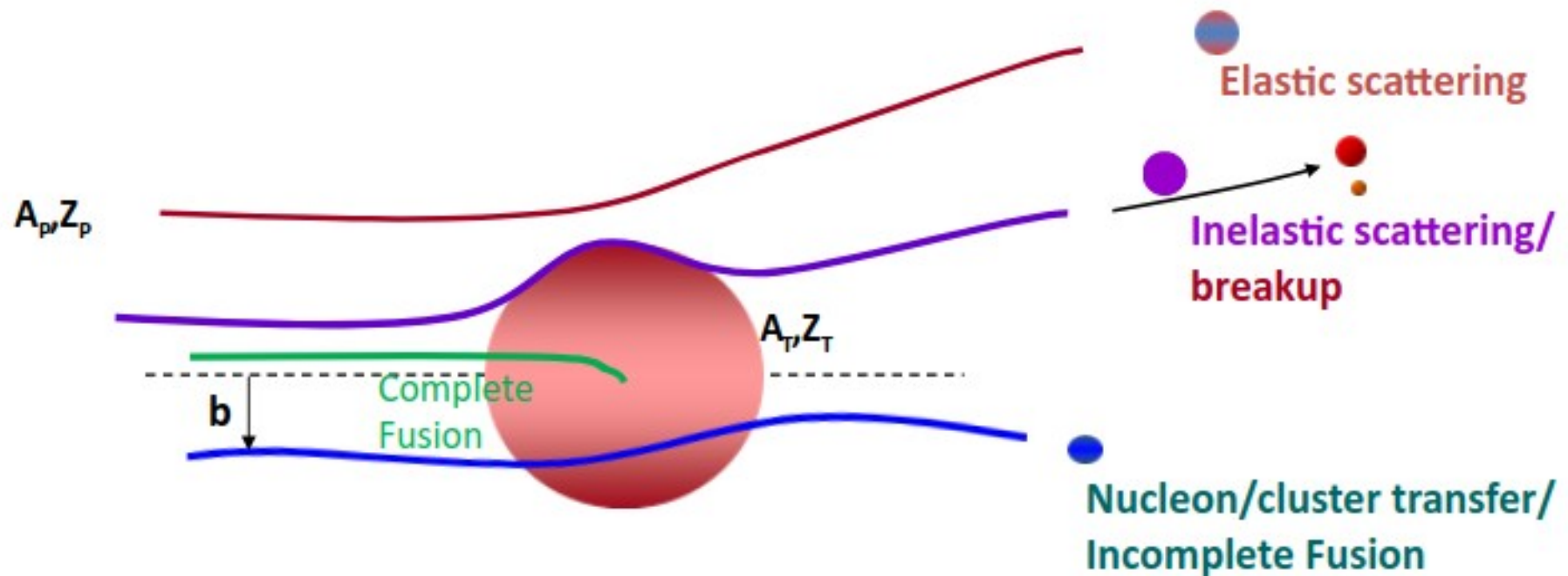


OUTLINE

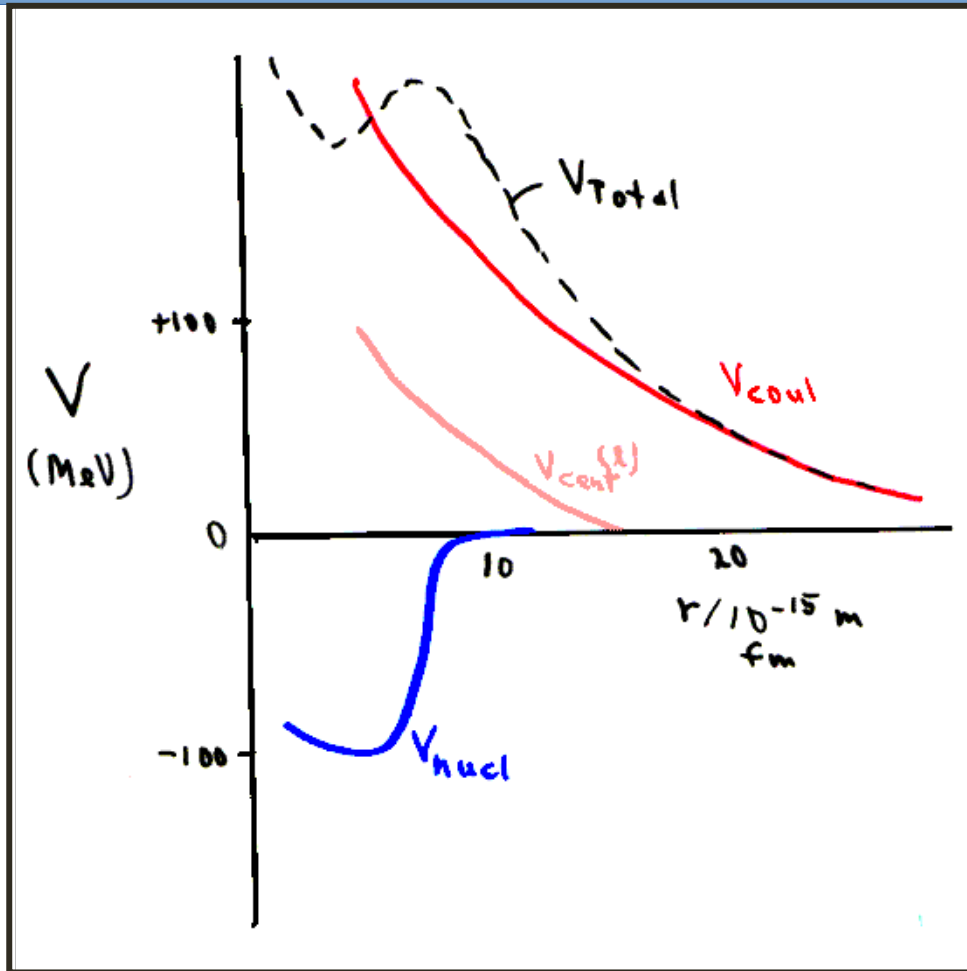
- ◆ Quasi-elastic Measurements for $^{28}\text{Si}+^{144}\text{Sm}$
- ◆ Fusion-Fission Dynamics at wide excitation energy range
- ◆ Neutron Multiplicity Measurements for $\alpha + ^{232}\text{Th}$ reaction

Quasi-elastic Measurements for $^{28}\text{Si}+^{144}\text{Sm}$

Reaction Channels Around the Coulomb Barrier



Inter-nucleus potential



Three forces:

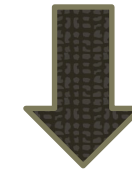
1. Coulomb force

2. Centrifugal force

Long range, repulsive

3. Nuclear force

Short range, attractive



Potential barrier due to the compensation between the three

$$V_{total} = V_c + V_n + V_{cent}$$

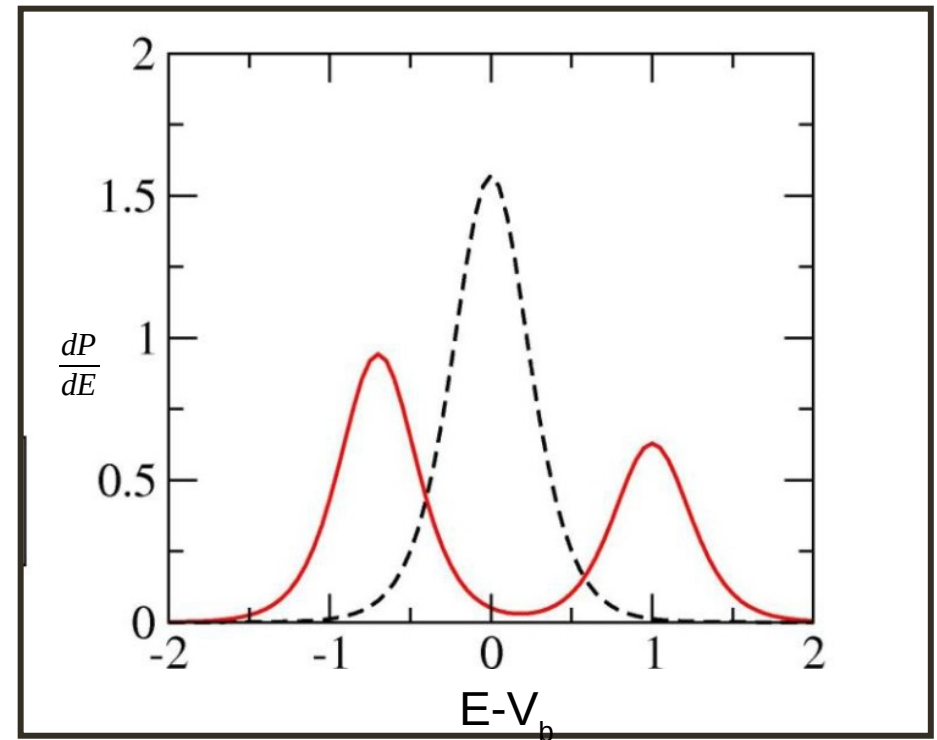
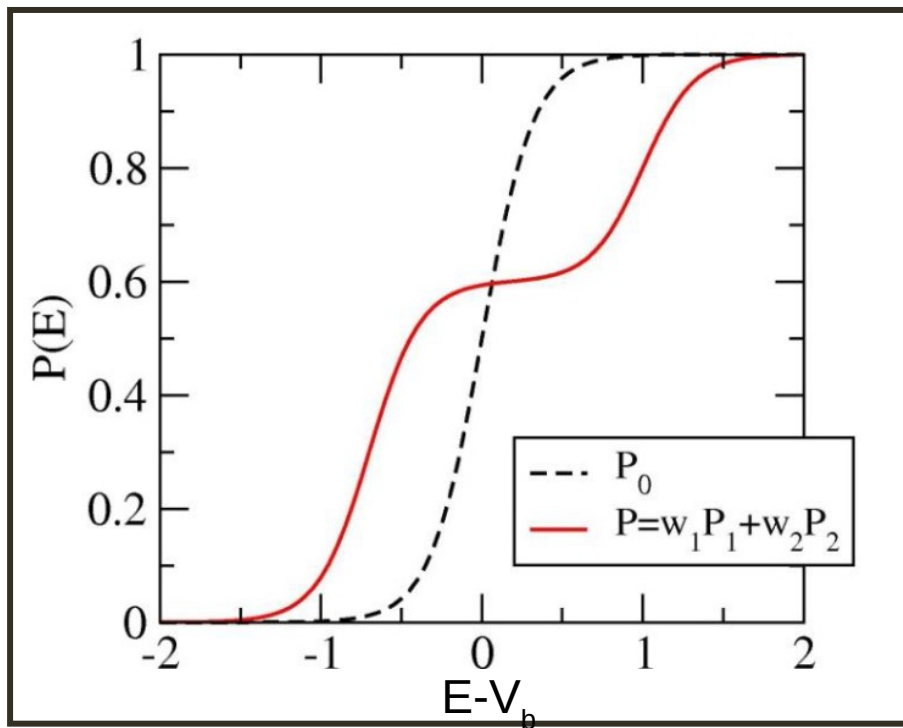
Classically fusion is possible only when $E > V_b$

$$\sigma_{fus}^{cl}(E) = \pi R_b^2 \left(1 - \frac{V_b}{E}\right)$$

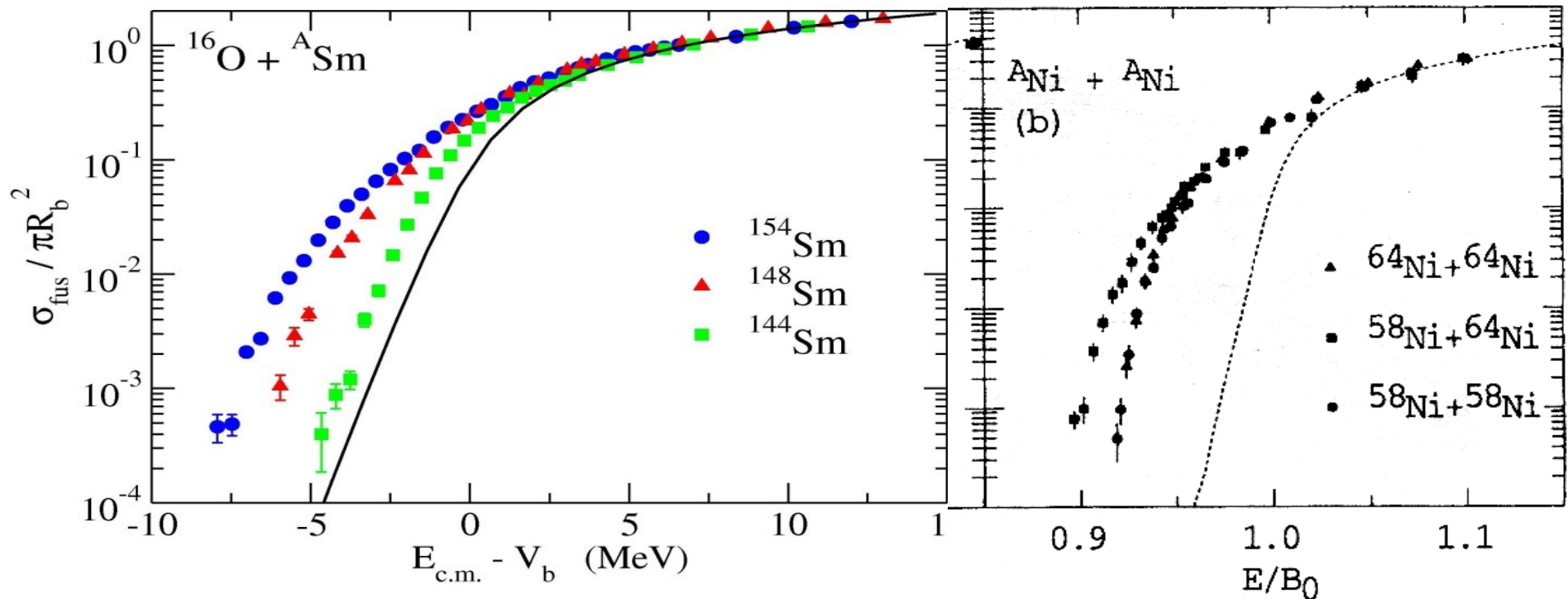
TUNNELING EFFECT

But Fusion takes place by quantum tunneling at low energies

$$\sigma_{\text{fus}}(E) = \frac{\pi}{k^2} \sum_l (2l + 1) P_l(E)$$



Experimental Discrepancies



One dimensional Penetration model successfully explains experimental observations for $E > V_b$ but fails to explain the experimental results at $E < V_b$.

^{154}Sm is highly deformed. The height of the barrier depends on its orientation.

The Q-value for transfer in reaction $^{58}\text{Ni} + ^{64}\text{Ni}$ has positive values which was used to account for the discrepancies from One-D Penetration Model.

Barrier Distribution

- Coupling to other channels during the fusion reaction, splits the potential barrier into a number of barrier. This distribution obtained due to coupling s termed as barrier distribution (BD).
- Fusion Barrier Distribution can be experimentally obtained from the double derivative of the product of projectile energy and experimental fusion cross-section.

$$D_{\text{fus}}(E) \equiv \frac{d^2(E\sigma_{\text{fus}})}{dE^2} \simeq \pi R_b^2 \frac{dP_{l=0}}{dE}$$

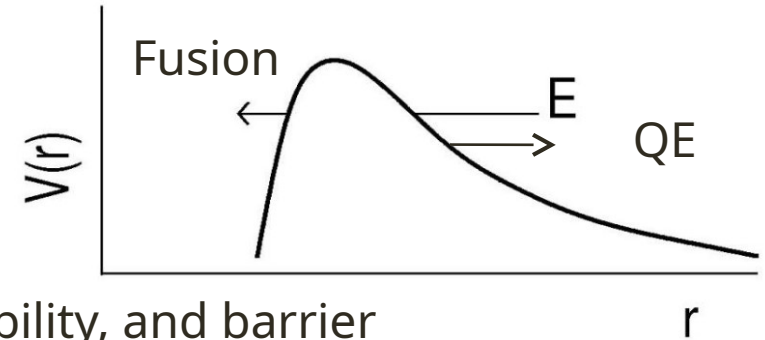
- BD is considered to be better tool to study the reaction dynamics as it is obtained from the derivative of the cross-section. Any small change in the cross-section will bring a bigger change in the shape of the distribution.

N. Rowley, G.R. Satchler, P.H. Stelson, PLB254("91)25

Quasi-Elastic Scattering and Quantum Reflection

In quantum mechanics, reflection occurs even at $E > V_b$
i.e. Quantum Reflection

$$P(E) + R(E) = 1$$



Reflection prob. carries the same information as penetrability, and barrier distribution can be defined in terms of reflection prob.

A sum of all the reaction processes other than fusion (elastic + inelastic + transfer +)

Detect all the particles which reflect at the barrier and hit the detector

Related to reflection and Complementary to fusion

Quasi-elastic barrier distribution

$$D_{\text{qel}}(E) = -\frac{d}{dE} \left(\frac{\sigma_{\text{qel}}(E, \pi)}{\sigma_R(E, \pi)} \right)$$

M.V.Andres et al., Phys. Lett. B, 1988

H. Timmers et al., NPA584("95)190

Advantages for D_{qel}

- **Less statistical error in QE (1st vs. 2nd derivative)**

- **Much easier to be measured**

Qel : a sum of everything

a very simple charged-particle detector

Fusion : requires a specialized recoil separator to separate ER
ER + fission for heavy systems

- **Several effective energies can be measured at a single-beam energy**

$$E_{\text{eff}} = 2E \sin(\theta/2) / [1 + \sin(\theta/2)]$$

Extraction of BD theoretically

- Theoretically, the coupled channels calculations are performed to obtain the fusion/QE cross-section and then using the point difference formula to find the second derivative for obtaining the BD.
- Various codes are available to perform these calculations. These codes include CCDEF, CCFUS, CCFULL.
- CCFULL is employed for the study of fusion. This code takes into consideration the vibrational, rotational nature of the target and projectile into consideration and to a few extent, this code includes only pair transfer.
- For Quasi-elastic scattering, the scattering version of CCFULL i.e CCQUEL is employed. This code gives us the QE excitation function and taking its first derivative w.r.t energy gives us the barrier distribution.
- The details of the inputs to be given in these codes will be discussed later.

C.H. Dasso et al Computer Phys. Commun. 46, 187 (1987).
J. Fernandez-Niello et al Computer Phys. Commun. 54, 409 (1989).
K. Hagino, et al, Comput. Phys. Commun. 123, 143 (1999)
K. Hagino, yet to published..

QE Measurements : $^{28}\text{Si}+^{144}\text{Sm}$; Why interesting??

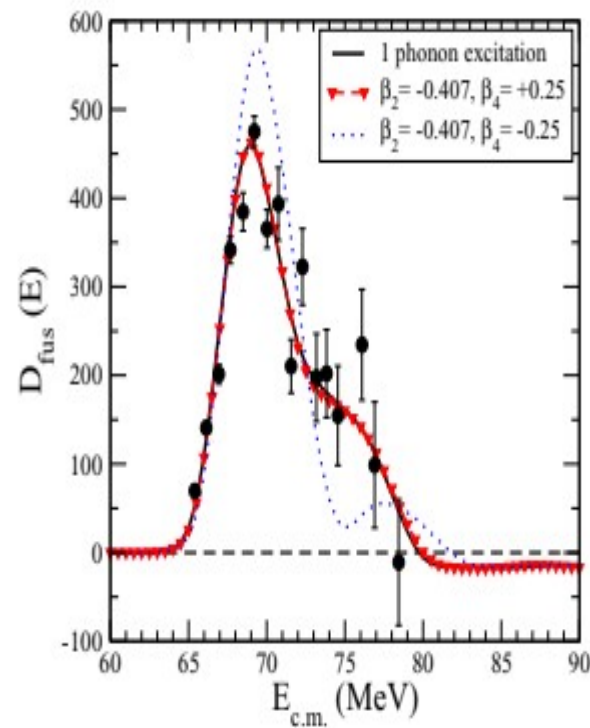
- Role of target excitations on fusion has been widely studied.
- Various fusion studies has shown ^{28}Si as both vibrator as well as rotor.
- For studying the target structural effect, there are number of QE-studies but only few for the study of projectile excitations.
- These are the recent studies which includes ^{28}Si as projectile and are for the systems $^{28}\text{Si}+^{154}\text{Sm}$, $^{142,150}\text{Nd}$, ^{90}Zr .

QE Measurements : $^{28}\text{Si}+^{144}\text{Sm}$; Why interesting??

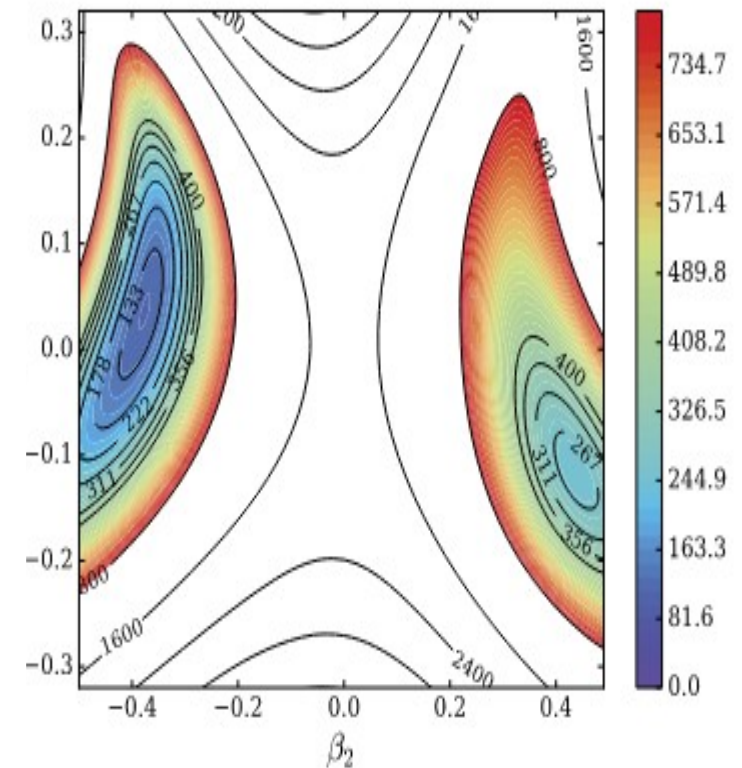
Wide range of determined hexadecupole deformation of ^{28}Si
Insight into projectile structure role on the quasi-elastic barrier distribution(QE-BD)

Experiment	β_2	β_4
Present work	-0.38 ± 0.01	$+0.03 \pm 0.01$
(CE ¹) [27]	-0.39	
(e, e') [26]	-0.39	+0.10
(n, n') [28]	-0.39	
(n, n') [42]	-0.48	0.15
(n, n') [42]	-0.42 ± 0.02	$+0.20 \pm 0.05$
(n, n') [22]	+0.41	
(p, p') [29]	-0.34	+0.25
(p, p') [43]	-0.55	+0.33
(p, p') [23]	+0.41	
(d, d') [24]	+0.45	
(α , α') [25]	+0.36	
(α , α') [30]	$-0.32 \pm .01$	$+0.08 \pm 0.01$
(^{16}O , $^{16}\text{O}'$) [44]	-0.34	

YK Gupta et al., Physics Letters B 845
138120 (2023) and references herein



G Kaur et al., Phy Rev C 97,
064606 (2018)

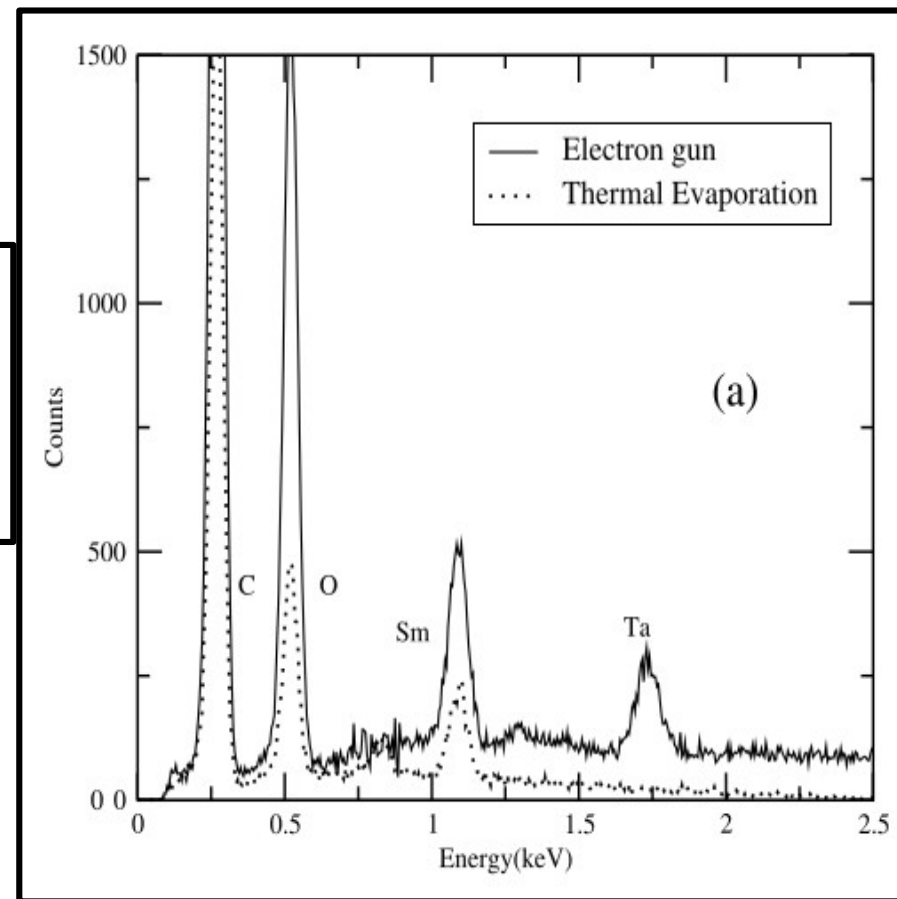
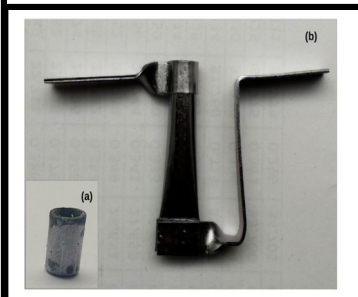
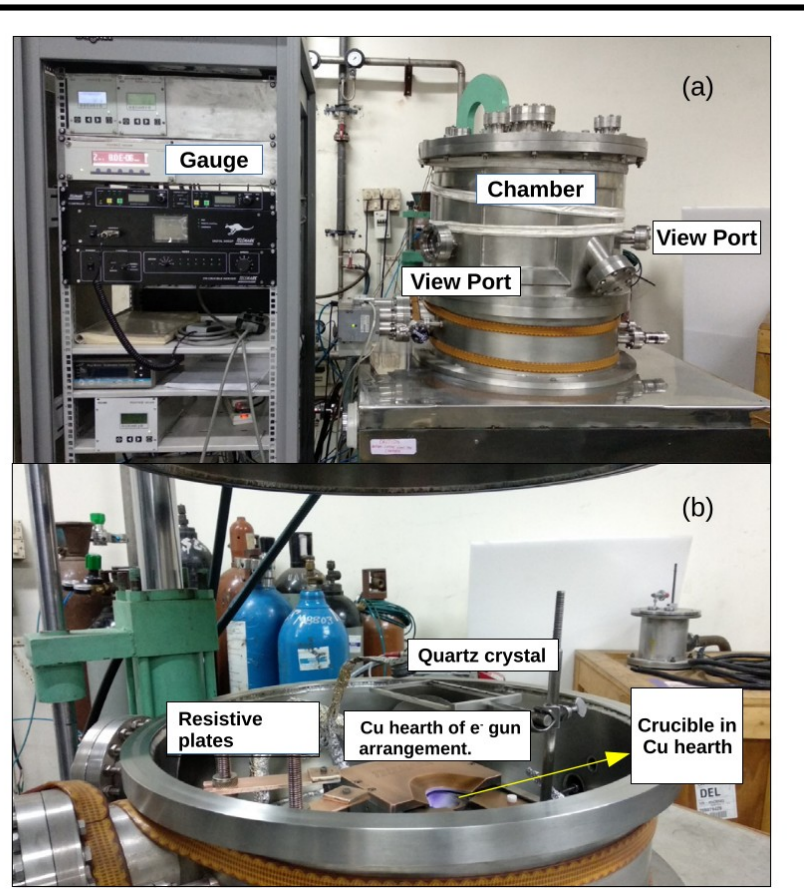


YK Gupta et al., Physics Letters B 845
138120 (2023)

TARGET PREPARATION

$^{144,154}\text{Sm}$ Target Preparation

- For QE measurements, the targets should be thin and self supporting to reduce the energy spread/loss of beam as well as of the reaction products in the target thickness..
- The self supporting targets for Sm isotopes is difficult to prepare because of highly oxidising nature.



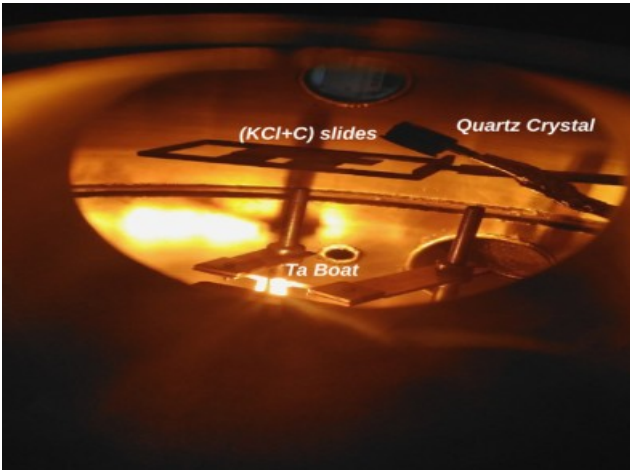
(a) High Vacuum evaporator at IUAC, New Delhi. (b) Inside View of the Chamber.

EDS spectrum (at 15 keV) of the samarium target prepared by Resistive Heating deposition and Electron gun deposition.

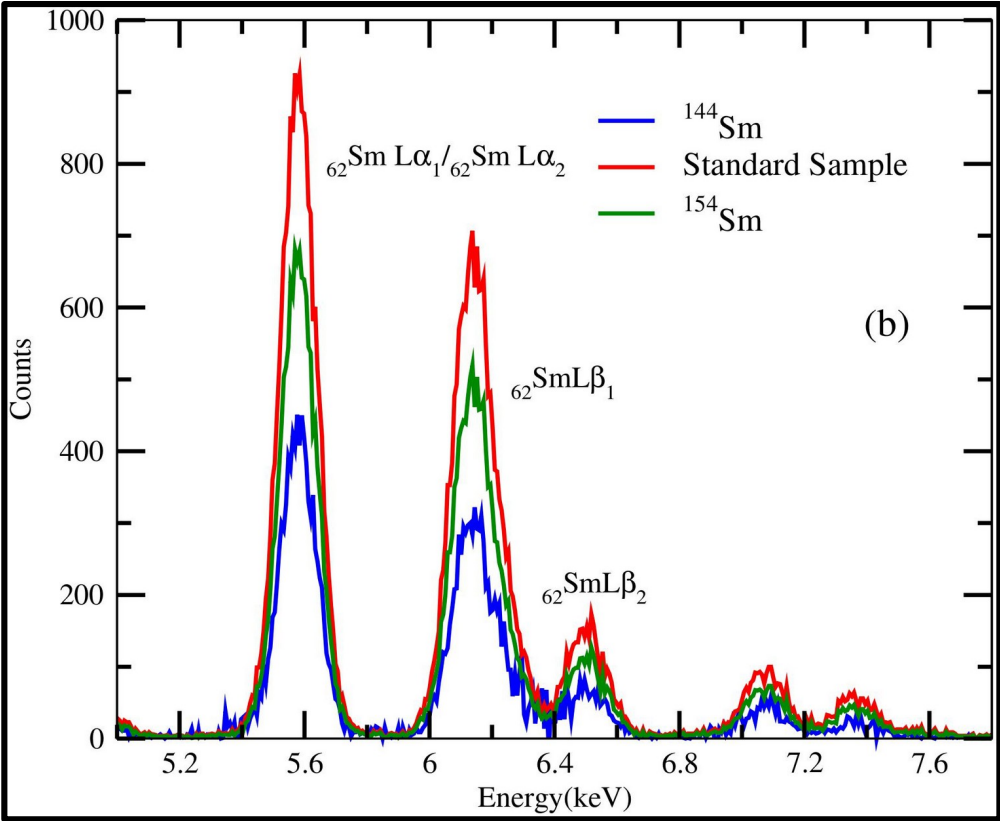
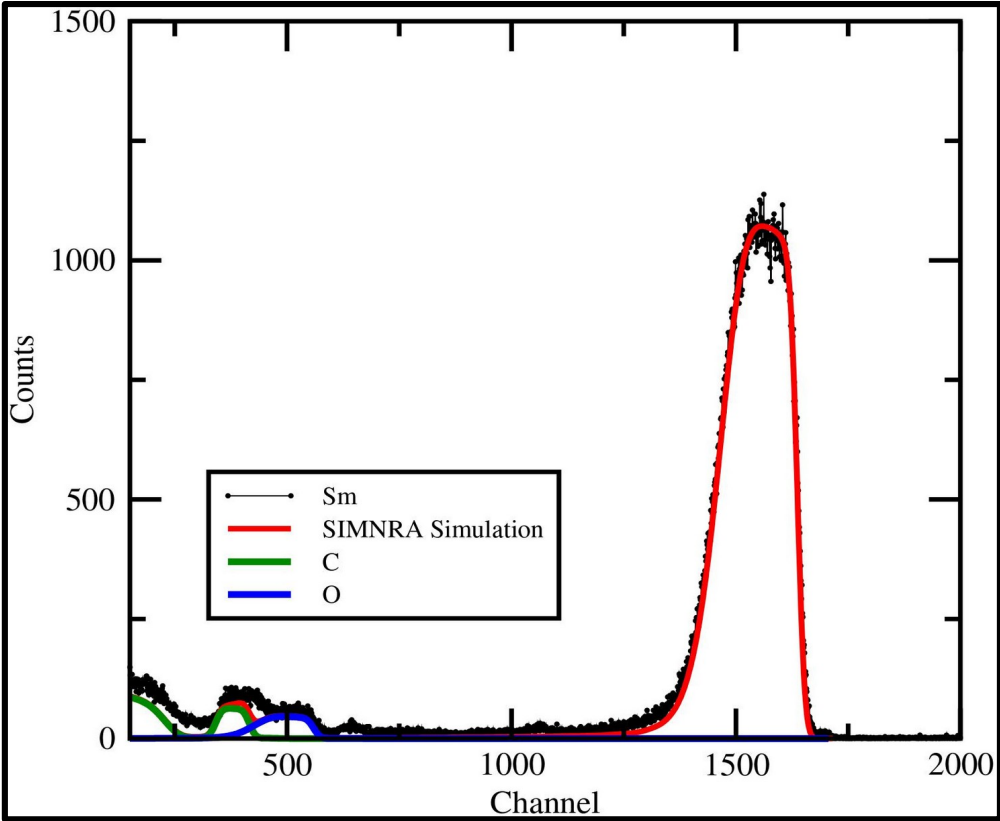
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ISOTOPIC DEPOSITION with thermal evaporation

Inside View of the chamber during thermal evaporation ➡



Characterisation of prepared ^{144,154}Sm Targets



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RBS results

XRF results

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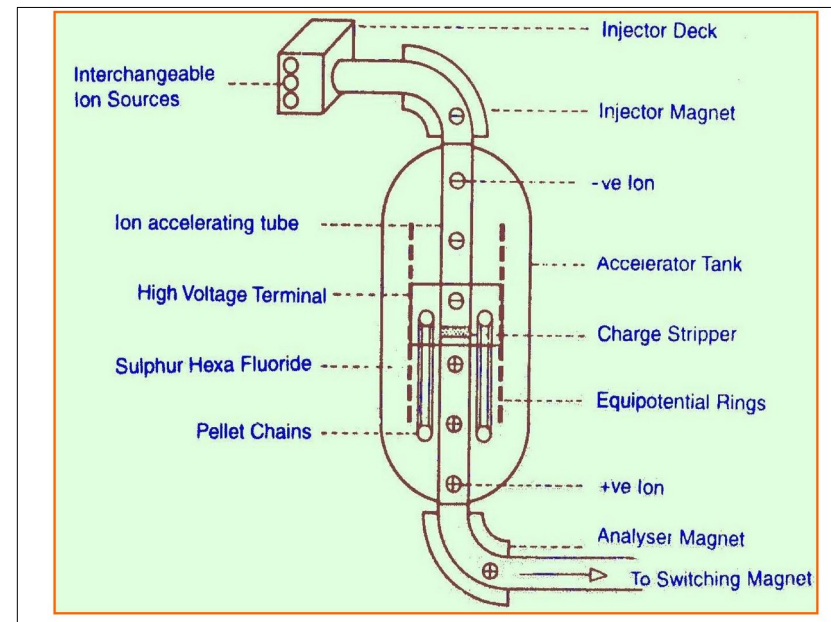
Experimental Facility



- For carrying out the experimental measurements, the experiments have been performed using the General Purpose scattering chamber (GPSC) of IUAC, New Delhi and the beam has been accelerated using the Pelletron accelerator shown in figure below.
- The energy in the Pelletron accelerator is calculated using the formula

$$E = E_i + (q+1)V_T$$

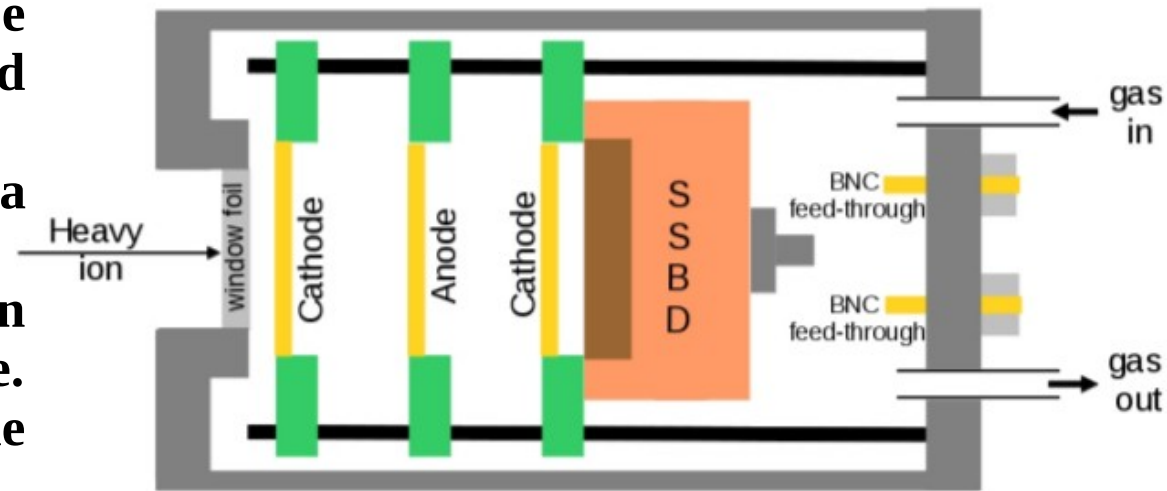
- Here, V_T is the terminal potential and q is the charge state used.



www.iuac.res.in/

Detection Facility: HYTAR

- HYTAR stands for HYbrid Telescope ARray. It is an array of the hybrid telescope developed at IUAC.
- It consists of a gas ΔE detector and a silicon stop E detector.
- The thickness of the ΔE detector can be varied by varying the gas pressure.
- Isobutane gas is used to operate the detectors at pressure 10-100 Torr.



Hybrid telescope detector

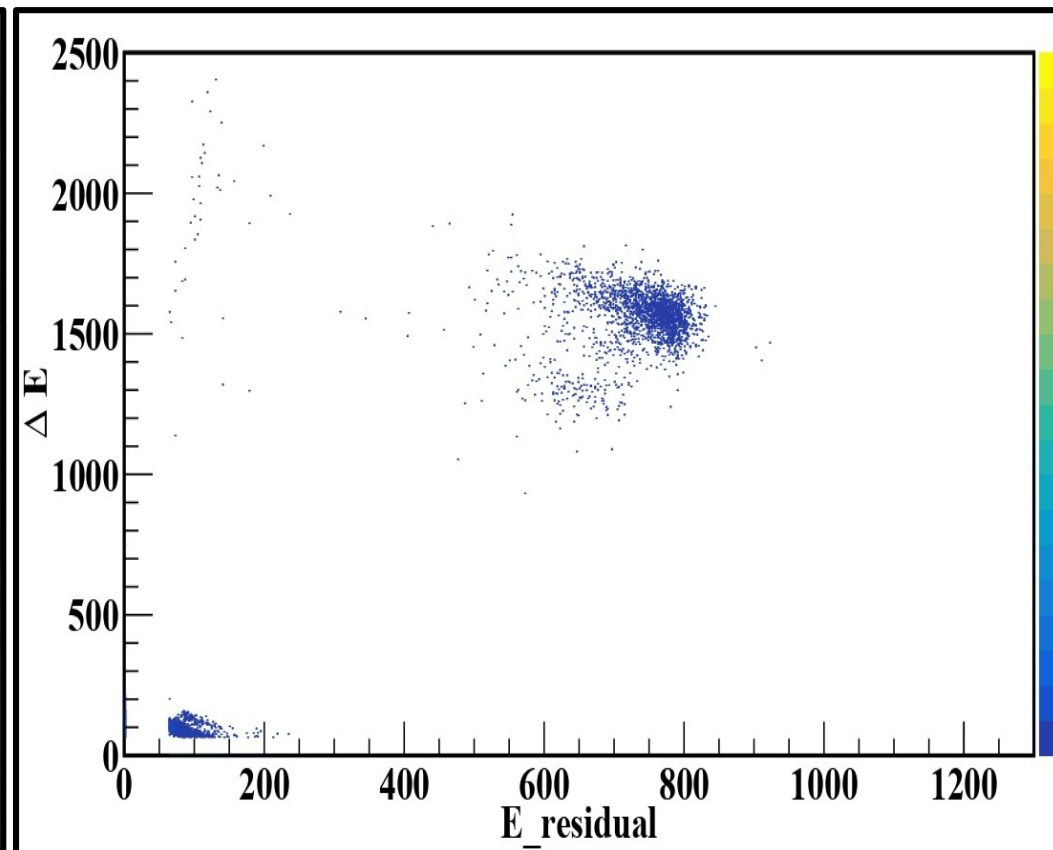
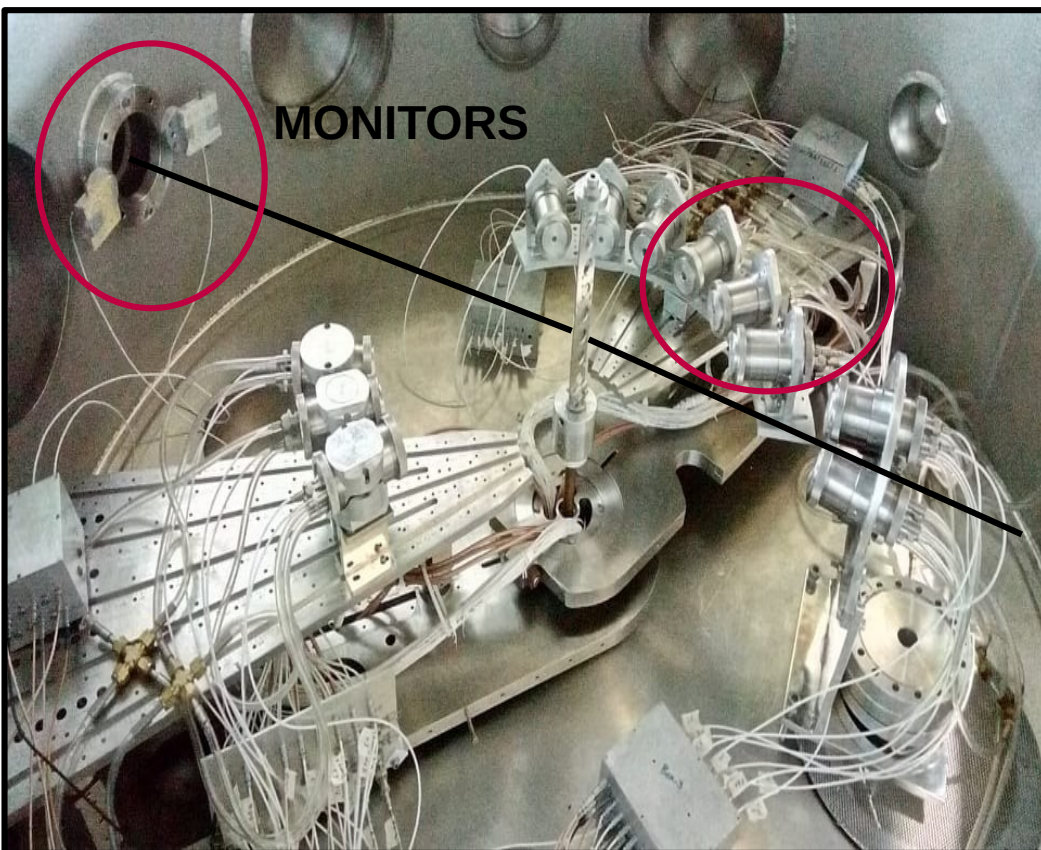
Advantages of HYTAR over Si ΔE -E detectors

For using Si as ΔE detector, the thickness of the detector should be around 10-40 μm . This thin Si detectors are prone to radiation damage and are also opaque to low energy heavy ions. By replacing the Solid state detector with the gas detector, the thickness can be varied as per the ions to be detected by just varying the gas pressure

A. Jhingan et.al. Nuclear Inst. and Methods in
Physics Research, A 903 (2018) 326–334

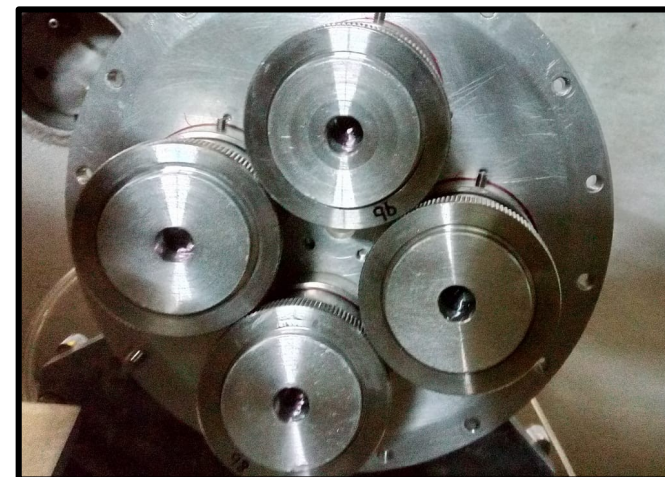
Experiment SET-UP: QE-BD for $^{28}\text{Si}+^{144}\text{Sm}$

- This experiment was performed in GPSC of IUAC using pelletron beam and **HYTAR** detection facility.
- Monitor detectors: SSBD
- Measurements: Quasi-elastic events
- Beams: ^{28}Si
- Target: ^{144}Sm ($\sim 103 \mu\text{g}/\text{cm}^2$)
Energy Range: (90-140)MeV for ^{28}Si
- Online Data Collection : FREEDOM



Pictorial View of the Set Up inside GPSC chamber and online spectra recorded.

Dome having 4 telescopes at 173°



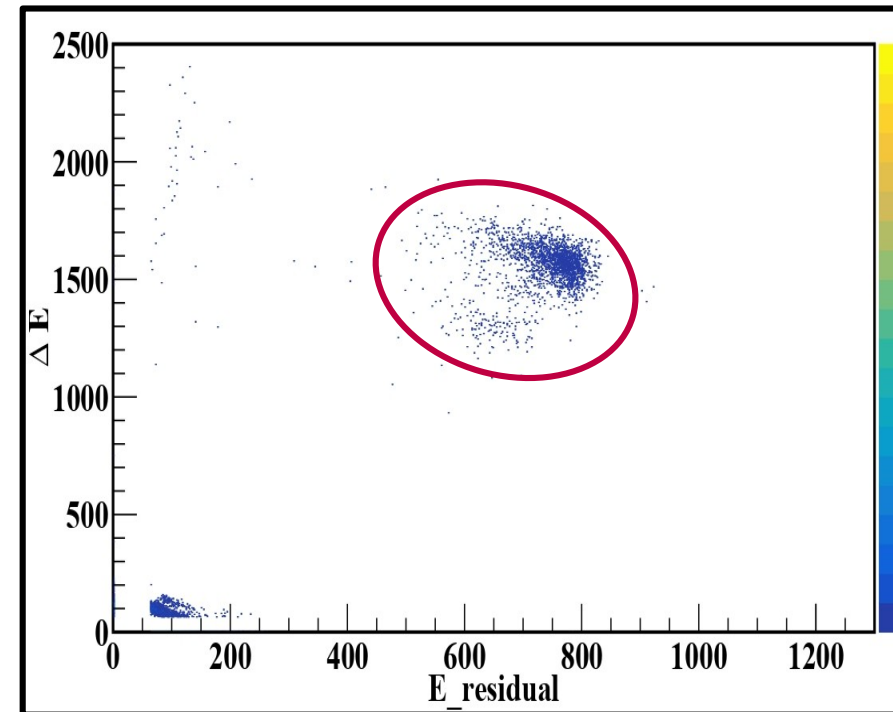
EXPERIMENTAL ANALYSIS

The quasi-elastic excitation function has been calculated using formula

$$\frac{d\sigma_{qel}}{d\sigma_{Ruth}} = \frac{N_{tel}(E, \theta_{tel})}{N_{mon}(E, \theta_{mon})} \times \frac{\Delta\Omega_{mon}}{\Delta\Omega_{tel}} \times \frac{(d\sigma_{Ruth}/d\Omega)(E, \theta_{mon})}{(d\sigma_{Ruth}/d\Omega)(E, \theta_{tel})}$$

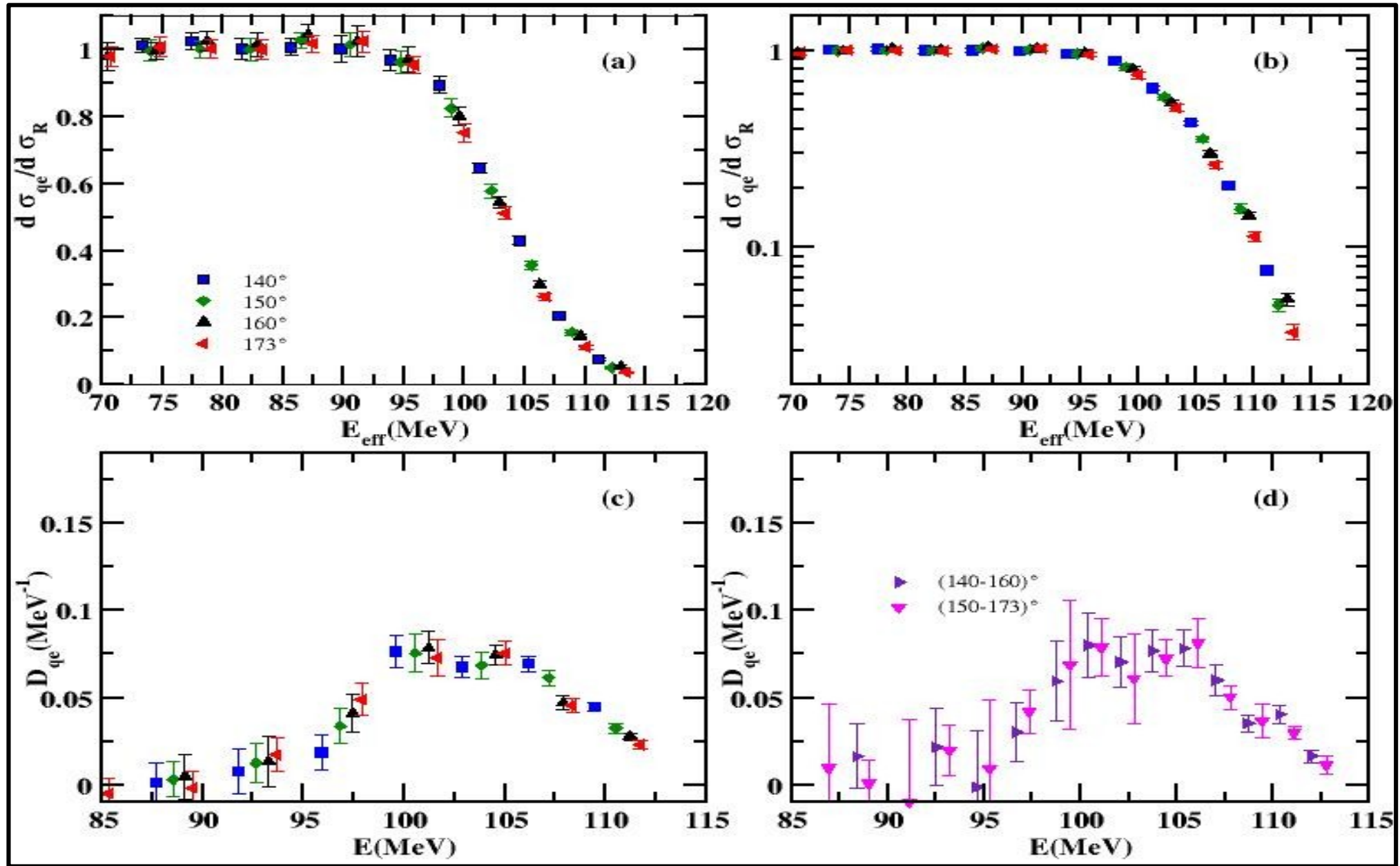
To extract the BD from the measured cross-section, the point difference formula has been employed

$$D_{qel}(E_{eff}) = -\frac{d}{dE_{eff}} \left[\frac{d\sigma_{qel}(E_{eff})}{d\sigma_R(E_{eff})} \right],$$



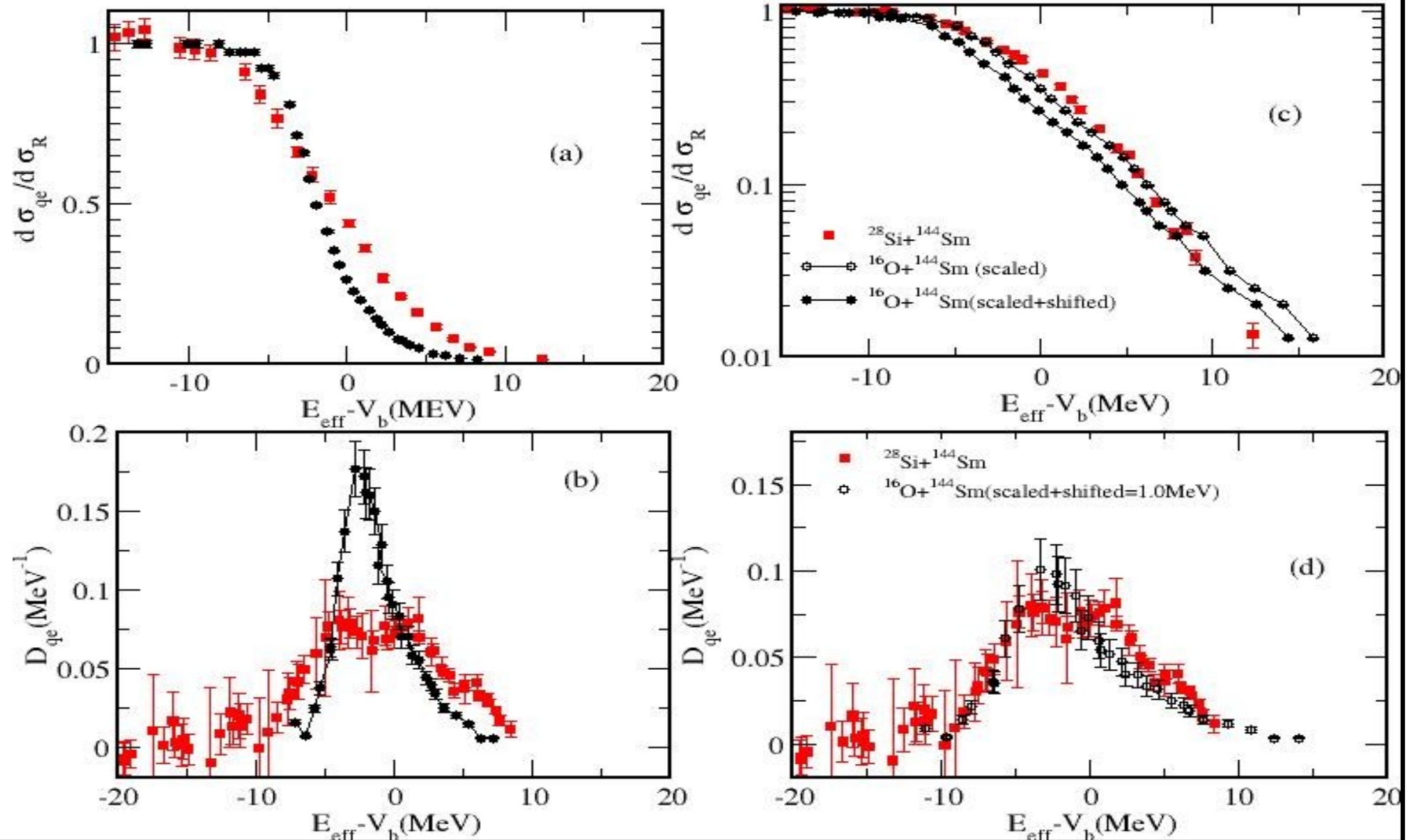
DISCUSSIONS:

$^{28}\text{Si} + ^{144}\text{Sm}$ reaction



Quasielastic scattering excitation function plot for the $^{28}\text{Si} + ^{144}\text{Sm}$ system measured at four different angles (a) Linear Scale (b) Logarithmic Scale (c) Quasielastic BD plot extracted for the $^{28}\text{Si} + ^{144}\text{Sm}$ system measured at four different angles (d) using two angles data with $\Delta E = (1.8-2.2)$ MeV.

Comparison with QE-DATA of $^{16}\text{O}+^{144}\text{Sm}$

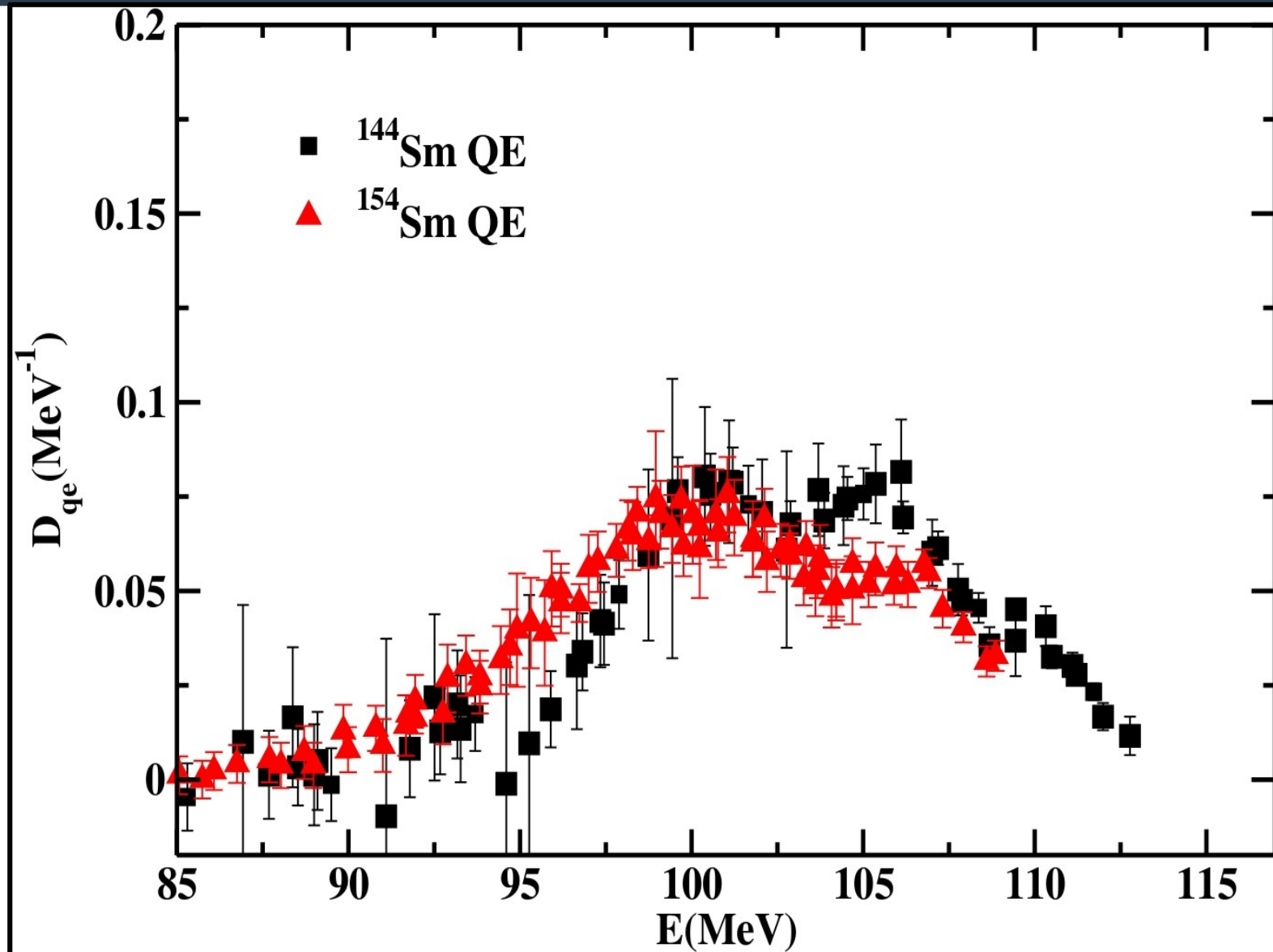


Comparison between (a) QE-excitation function of $^{16}\text{O}+^{144}\text{Sm}$ and $^{28}\text{Si}+^{144}\text{Sm}$ (b) BD of $^{16}\text{O}+^{144}\text{Sm}$ and $^{28}\text{Si}+^{144}\text{Sm}$ (c) QE-excitation function of $^{16}\text{O}+^{144}\text{Sm}$ (scaled+shifted) and $^{28}\text{Si}+^{144}\text{Sm}$ (d) BD of $^{16}\text{O}+^{144}\text{Sm}$ (scaled+shifted) and $^{28}\text{Si}+^{144}\text{Sm}$

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Comparison of BD of $^{28}\text{Si}+^{144}\text{Sm}$ with $^{28}\text{Si}+^{154}\text{Sm}$

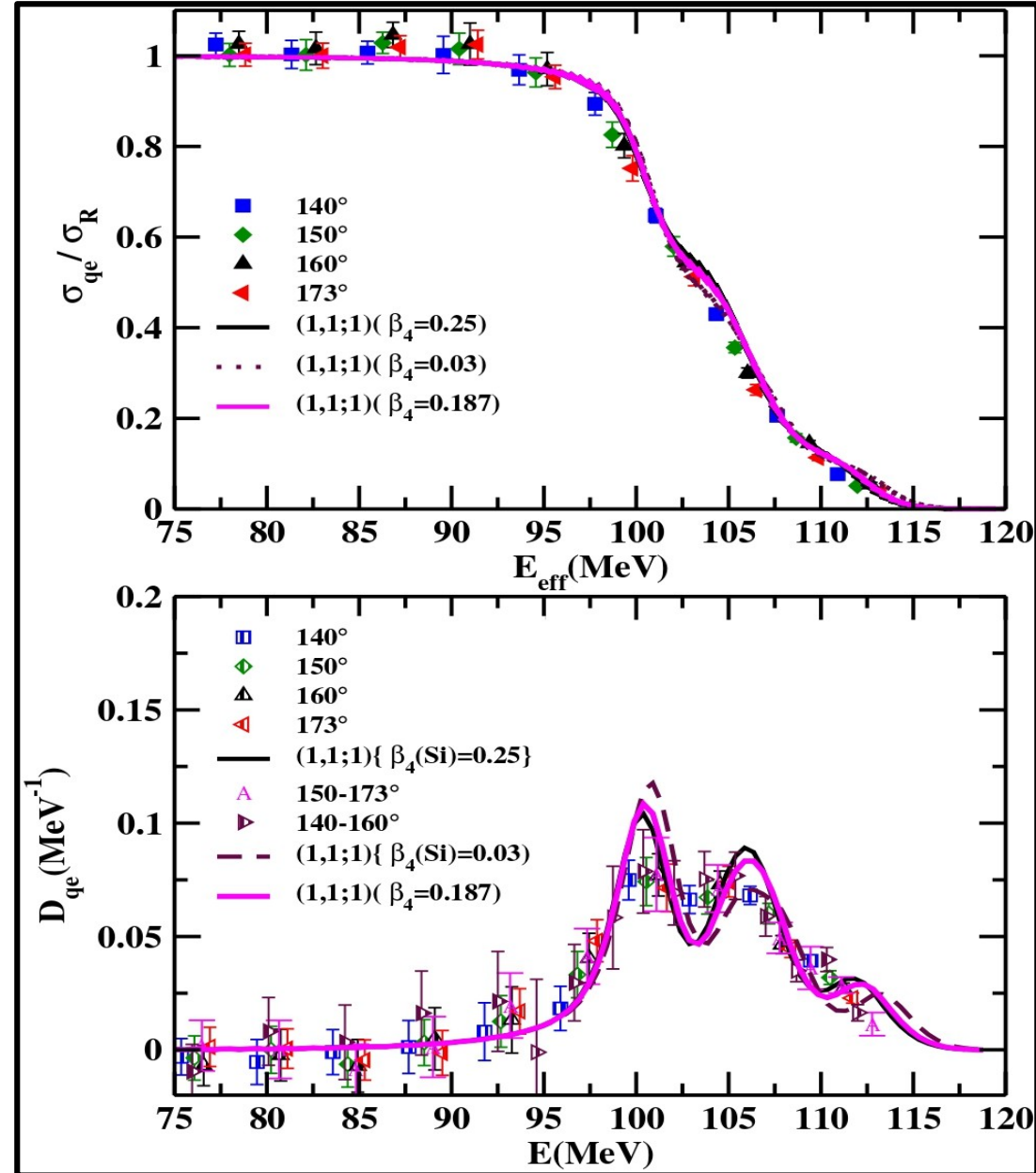


Coupled Channel Analysis For QE-Data

The scattering version of code CCFULL i.e. CCQUEL has been used

- The potential parameters used in the calculation corresponds to the Woods-Saxon potential parameters described as V_0 , r_0 and a_0 . The obtained value of parameters were $V_0 = 185$ MeV, $r_0 = 1.10$ fm and $a_0 = 0.72$ fm.
- The depth parameter value, radius parameter and the surface diffuseness parameter fixed during the calculation were 30 MeV, 1.0 fm and 0.3 fm.
- The calculations were performed including various types of couplings.

Nucleus	E_{exc}	Deformation parameter
^{28}Si	$E_{2+} = 1.77$	$\beta_2 = -0.041$, $\beta_4 = 0.25$, 0.03, 0.18
^{144}Sm	$E_{2+} = 1.66$, $E_{3-} = 1.81$	$\beta_2 = 0.087$, β_3 $= 0.151$



Comparison between the experimental data and CC calculations under the different coupling schemes for the $^{28}\text{Si} + ^{144}\text{Sm}$ system.

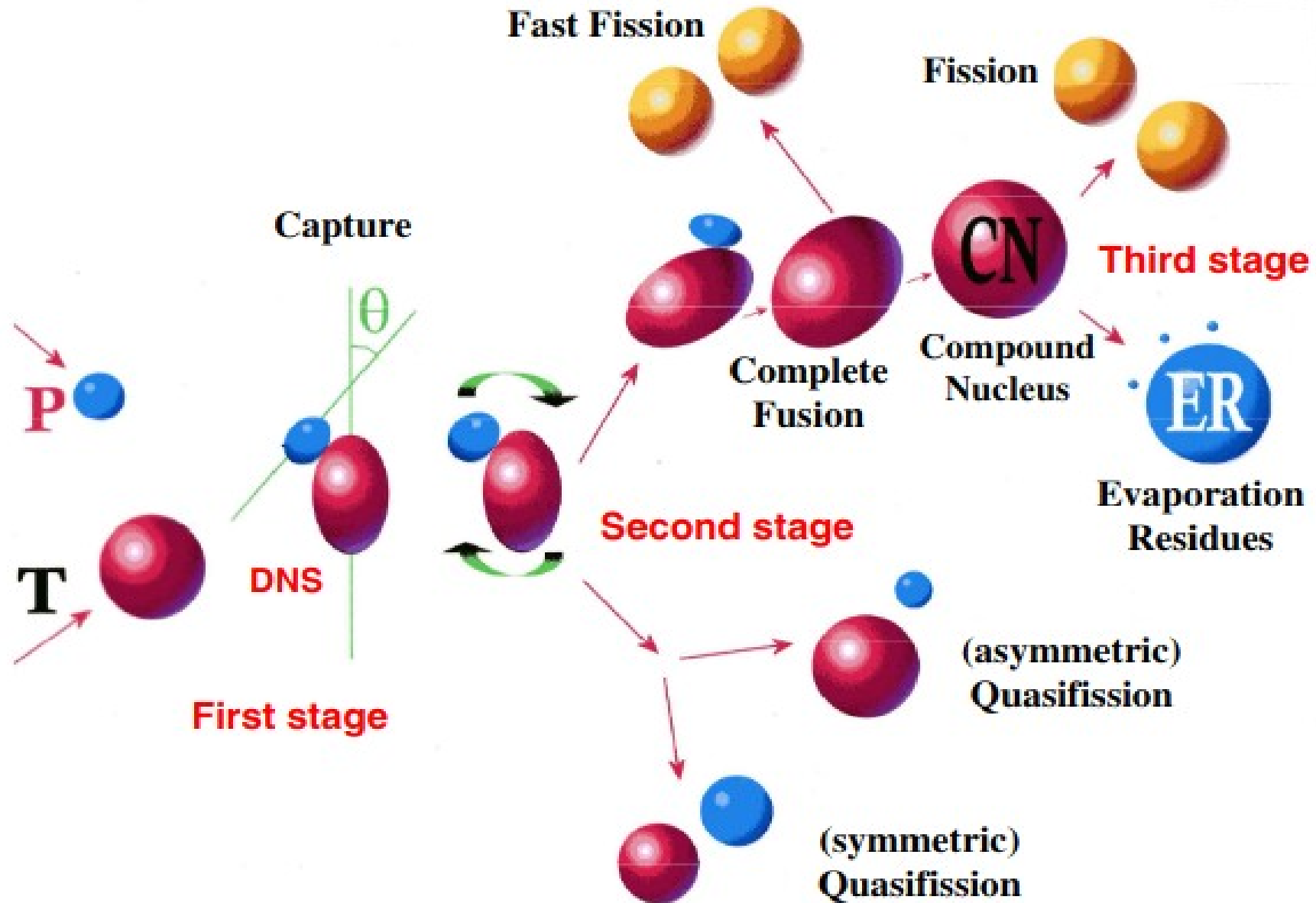
MAJOR CONCLUSIONS

- Distinct multiple peaklike structures were observed in the extracted barrier distribution. To locate the effect of the coupling in the experimentally observed BD, a comparison with the $^{16}\text{O} + ^{144}\text{Sm}$ QE-data shows that ^{28}Si excitations reflects as peaklike structures at higher energy.
- The Quasi-elastic (QE) excitation function and the barrier distribution (BD) method yield distinct deformation parameters, with noteworthy disparities in their outcomes.
- The QE-BD approach exhibits a notably higher positive hexadecupole value compared to the excitation function method, establishing a clear contrast in their predictions.
- This raises the question of employing QE as a potential tool to extract nuclear deformation parameters, while not taking dissipation effects into consideration

(Manuscript prepared)

Fusion-Fission Dynamics at wide excitation energy range

Reaction Dynamics



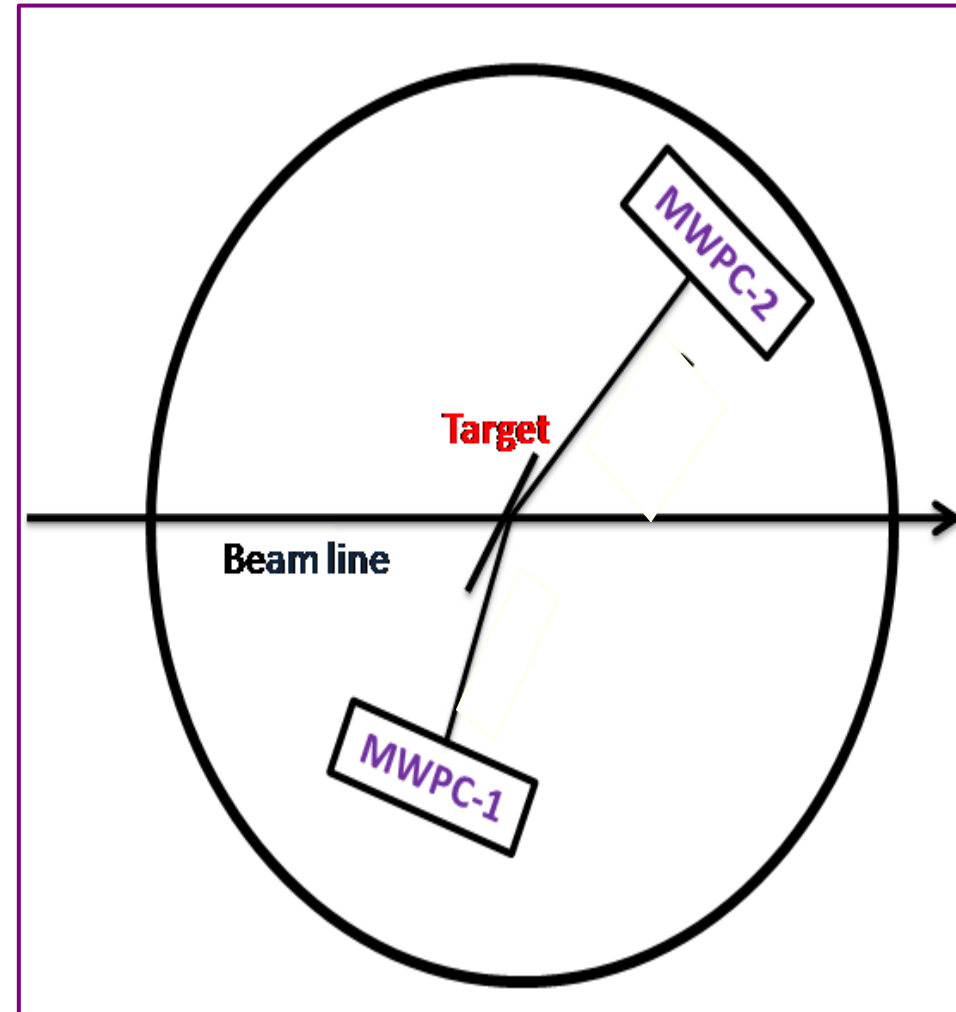
MASS DISTRIBUTION STUDY: EXPERIMENTAL SET-UP & MOTIVATION

This experiment was performed in GPSC of VECC using beam from K130 Cyclotron.

Beam:	^{16}O
Beam energy	116-160 MeV
Target:	^{181}Ta , ^{197}Au , ^{205}Tl , ^{208}Pb

MOTIVATION:

- The excitation energy dependence of the fission fragment mass and folding angle distributions for heavy ion induced reactions on preactinides targets well above the Coulomb barrier energies are not well known due to the scarcity of data.
- The purpose is to understand the fusion fission dynamics well above the Coulomb barrier energies; particularly to address if the theoretical models that are valid near the Coulomb barrier can explain the fission data at high energies.

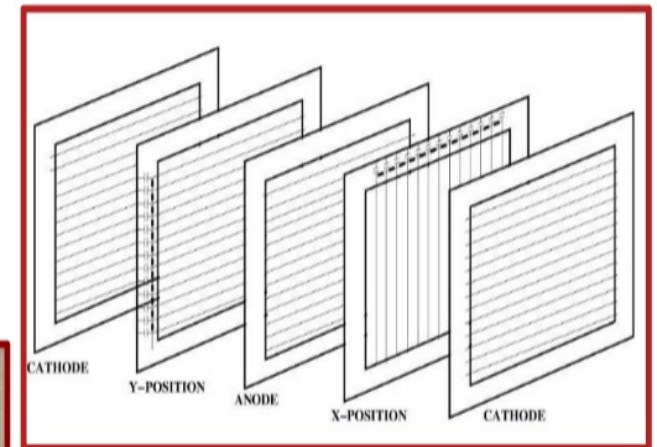


DETECTION FACILITY

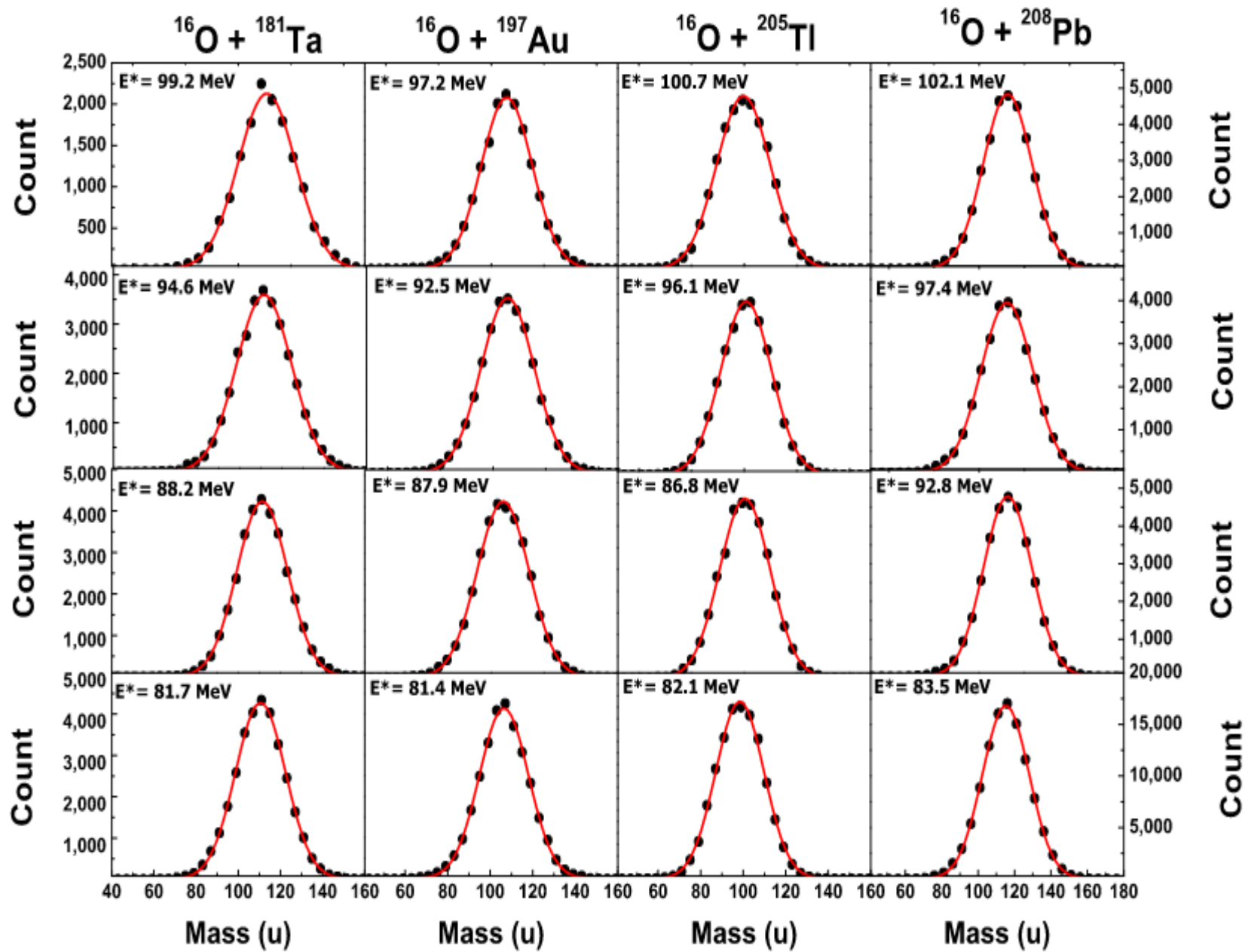
Employed the in-house developed Multi Wire Proportional Counters to record the interested events



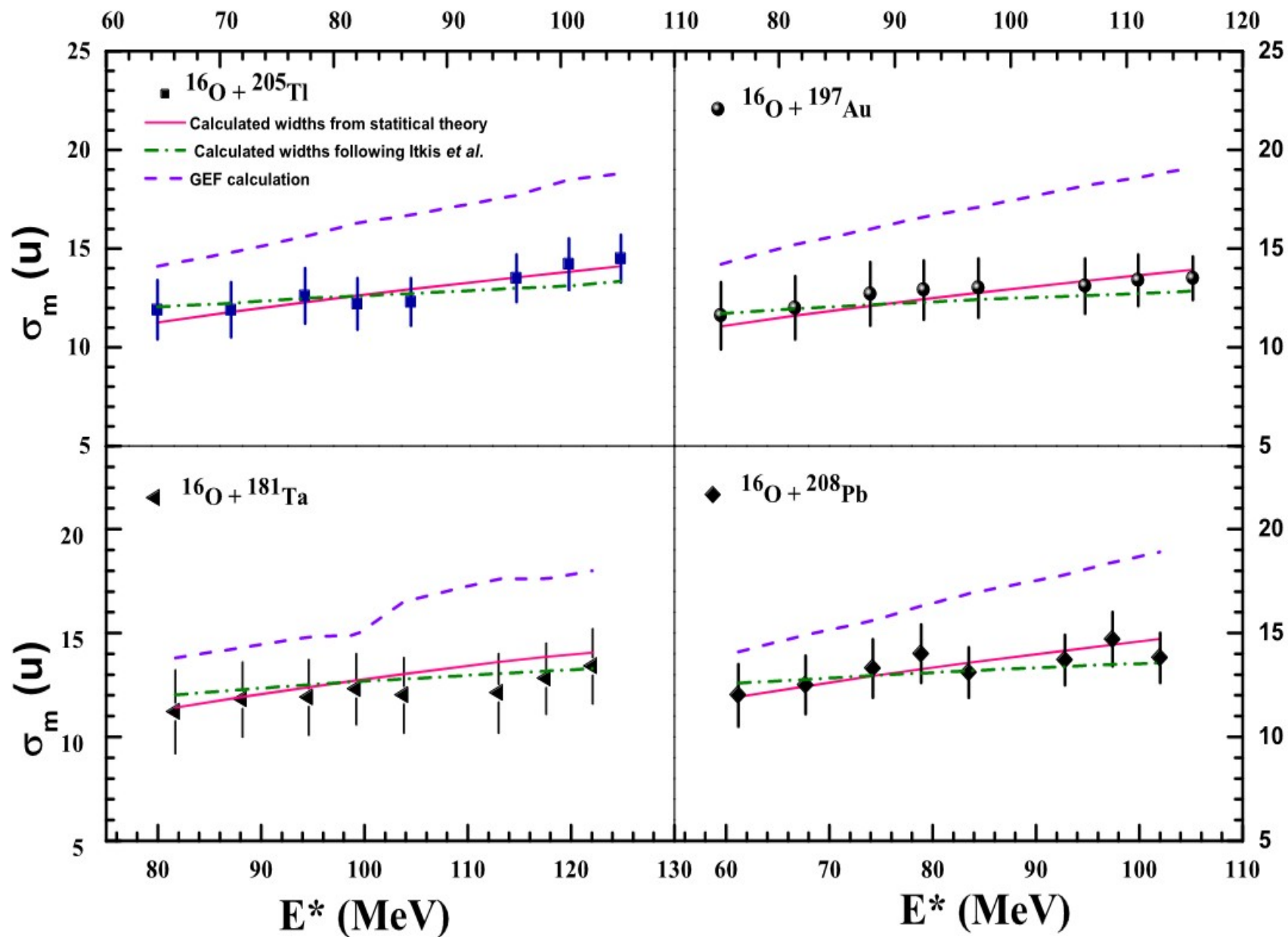
Assembled MWPC



Inside wire plate arrangement

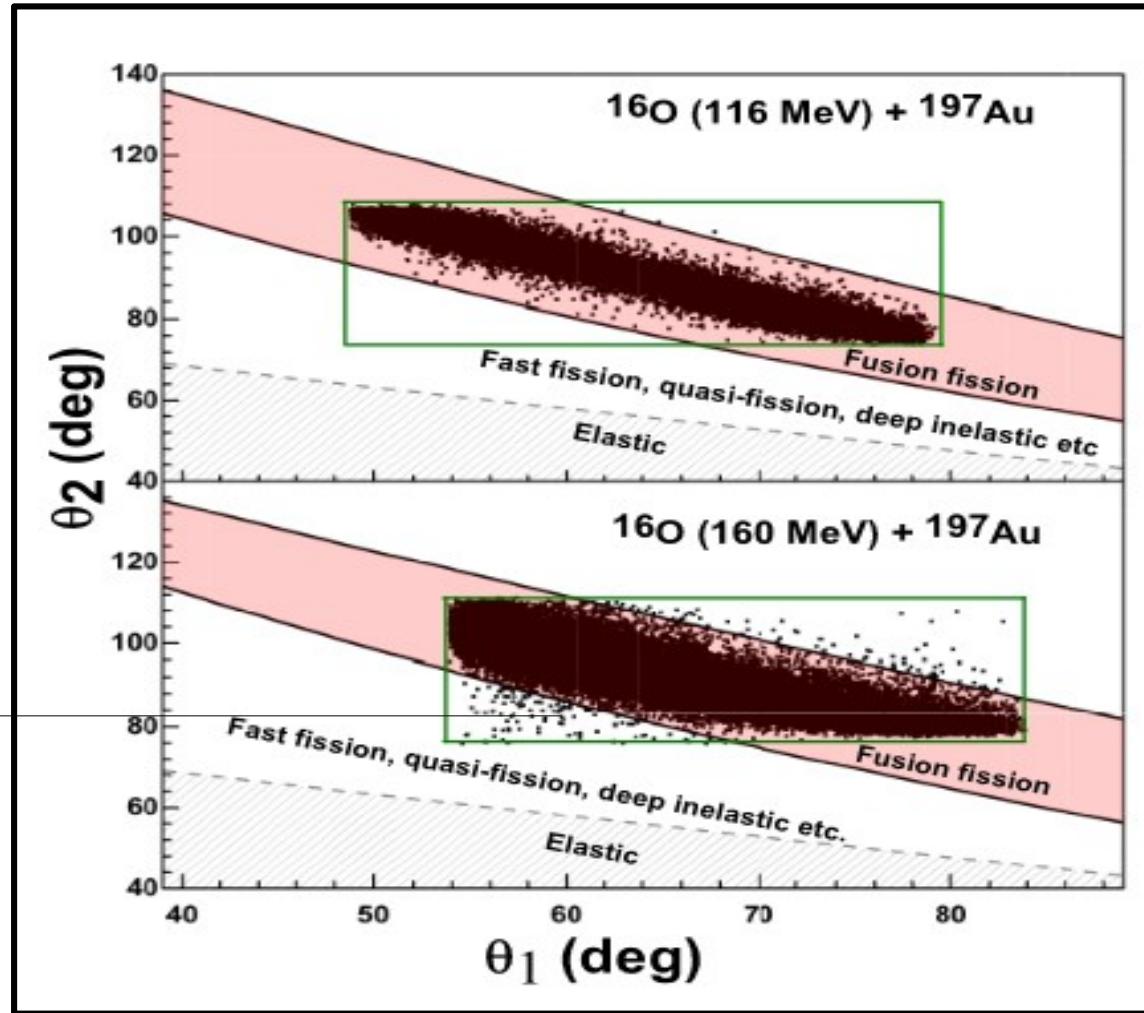


The mass distributions of complementary fission fragments for the reactions $^{16}\text{O} + ^{181}\text{Ta}$, $^{16}\text{O} + ^{197}\text{Au}$, $^{16}\text{O} + ^{205}\text{Tl}$ and $^{16}\text{O} + ^{208}\text{Pb}$ at the mentioned excitation energy.



Variation of the measured standard deviation $\sigma_m(u)$ of the mass distributions with excitation energy.

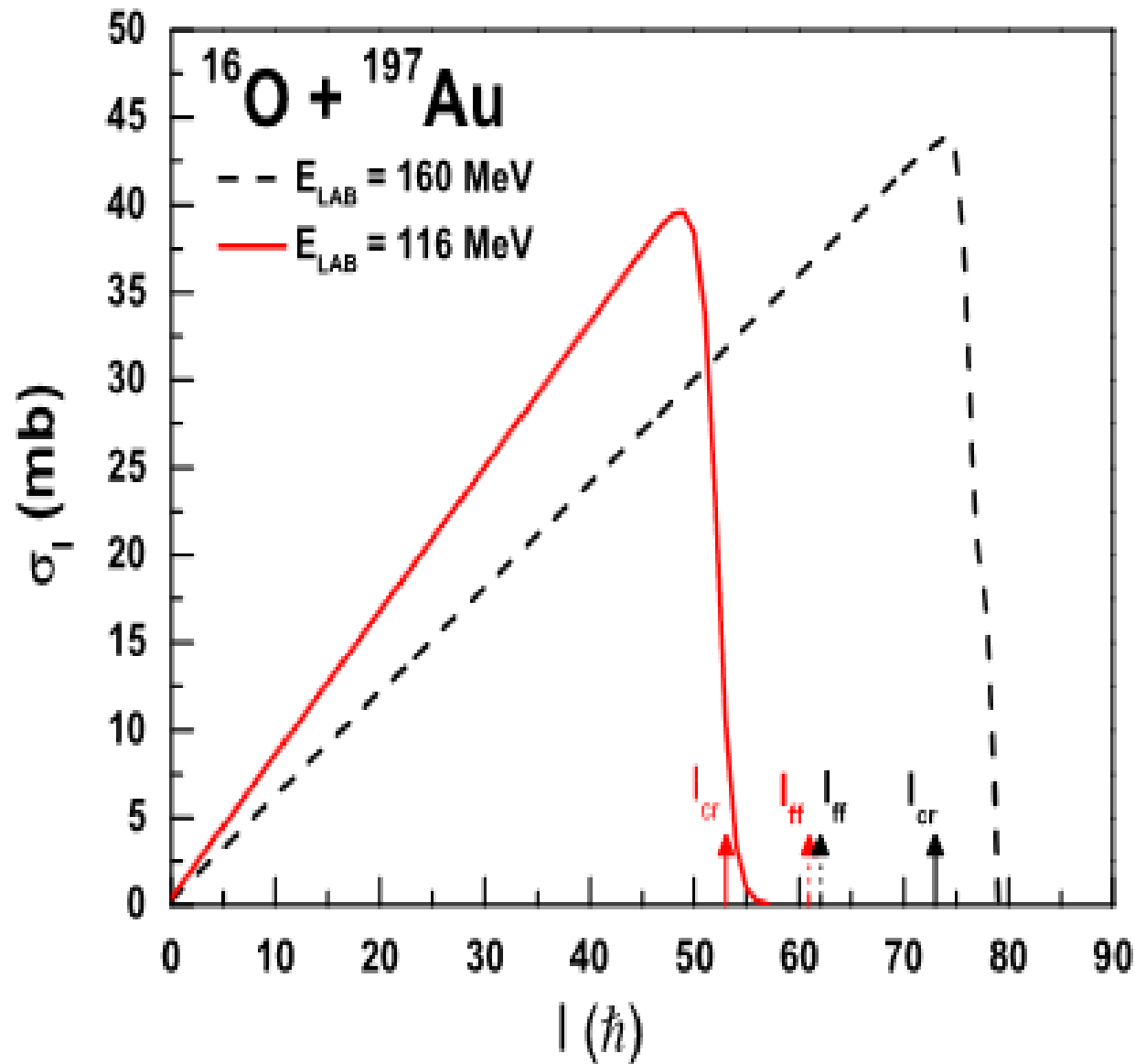
RESULTS OF K130 EXPERIMENT



Indication of the signature of Fast-Fission from the observed large width of mass distribution

A representative correlation plot of the simulated polar angle distributions of the events produced in the reaction $^{16}\text{O} + ^{197}\text{Au}$ at the lowest (above) (116 MeV) and highest (below) beam energy (160 MeV) measured in the experiment.

ANALYSIS



Adjacent figure shows the partial capture cross-sections as a function of angular momentum for $^{16}\text{O} + ^{197}\text{Au}$ at projectile energies of 116 MeV and 160 MeV calculated with the coupled channels code CCFULL.

The values of $l_{(\text{Tsad} > \text{Bf}=0)} = 0$ are obtained using the formulism given by A.J. Sierk, PRC 33, 2039 (1986).

RESULTS AND SUMMARY

- **Reaction mechanism for $^{16}\text{O} + ^{181}\text{Ta}$, $^{16}\text{O} + ^{197}\text{Au}$, $^{16}\text{O} + ^{205}\text{Tl}$ and $^{16}\text{O} + ^{208}\text{Pb}$ have been studied in the above experiment and fission fragment folding angle distributions and mass distributions for all the systems were predominantly symmetric Gaussian, which indicates the fusion fission dynamics is dominant at well above Coulomb energies.**
- **The results show that fissioning nucleus distributions are consistent with statistical model predictions for reactions well above the Coulomb barrier energies.**
- **Half mass asymmetry calculation shows a contribution of the fast-fission collisions in the tail part of the mass distribution.**

Neutron Multiplicity Measurements for $\alpha + {}^{232}\text{Th}$ reaction

INTRODUCTION AND MOTIVATION: Fission neutron multiplicity measurement in ^{236}U

Scientific Motivation:

To understand the evolution of a compound nucleus (CN) in a path to fission

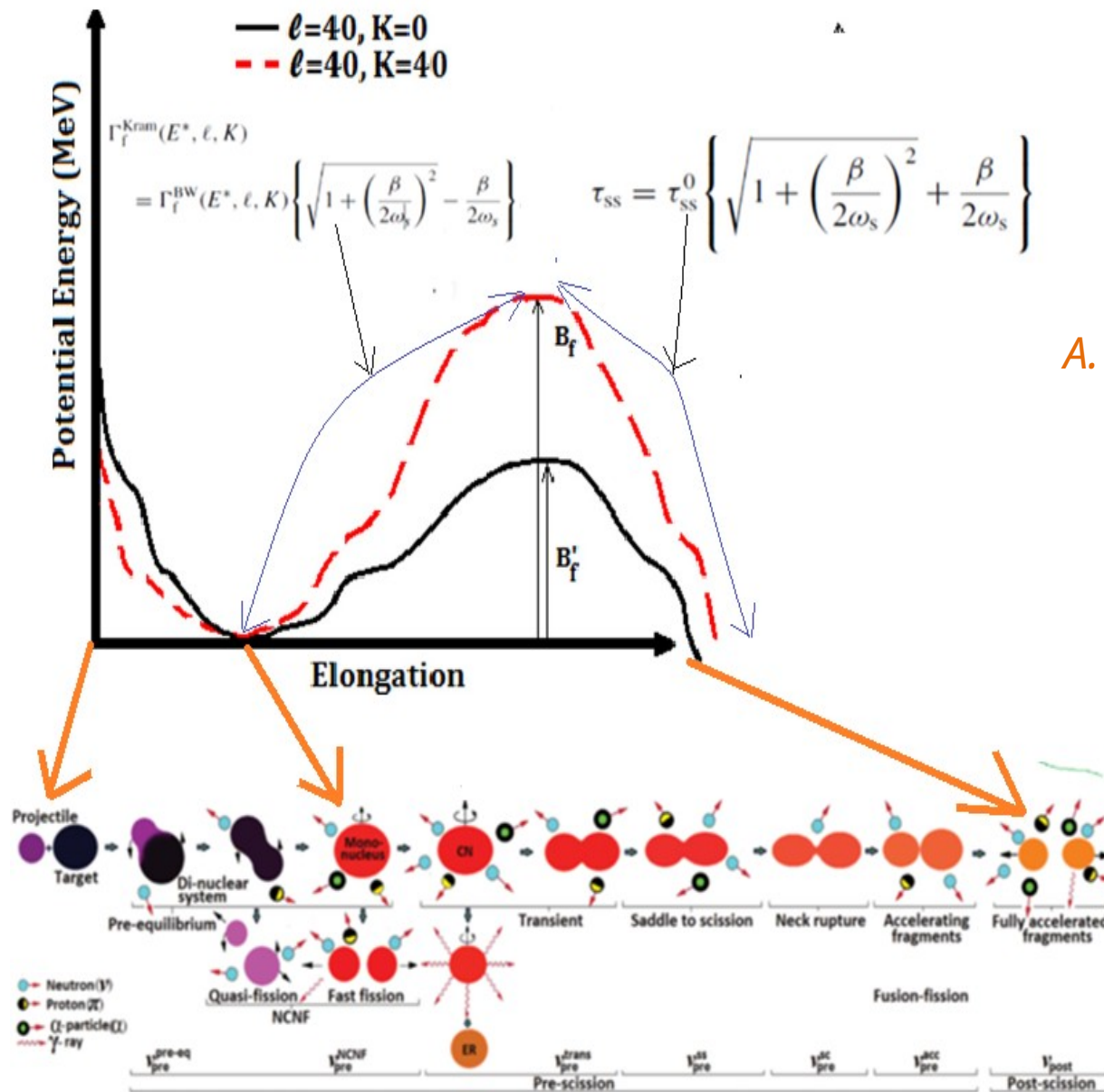
- i) The pre-scission neutron multiplicity is one of the useful probe.
(D. Hilscher et. al; Ann. Phys. 17, 471 (1992).)

The pre-scission neutron multiplicity (ν_{pre}) : Number of neutron emitted per fission during the evolution of CN from its initial shape to scission point.

J. P. Lestone et. al; PRC 79, 044611 (2009).

Pre-scission neutron multiplicity is sensitive to dissipative dynamics occurs during the evolution of a compound nucleus (CN) in a path to fission.

The evolution of a compound nucleus (CN) in a path to fission



A. Saxena et. al; PRC 49, 2 (1994)

Reduction in fission width using dissipative dynamics is proposed by Kramers.

$$\Gamma_f^{\text{BW}}(E^*, \ell, K = 0)$$

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

β is the dissipative coefficient.

Scientific Motivation ...

1. In a recent work, the statistical model simultaneously reproduce the measured σ_{fission} & σ_{ER} but it failed to reproduce the $\mathbf{u}_{\text{pre}}$ simultaneously with the other two for $158 < \mathbf{A}_{\text{CN}} < 225$.
2. Most of the earlier measurements are with heavy ions beam where contribution to the $\mathbf{u}_{\text{pre}}$ from non compound processes like quasi-fission and fast-fission are present in data.

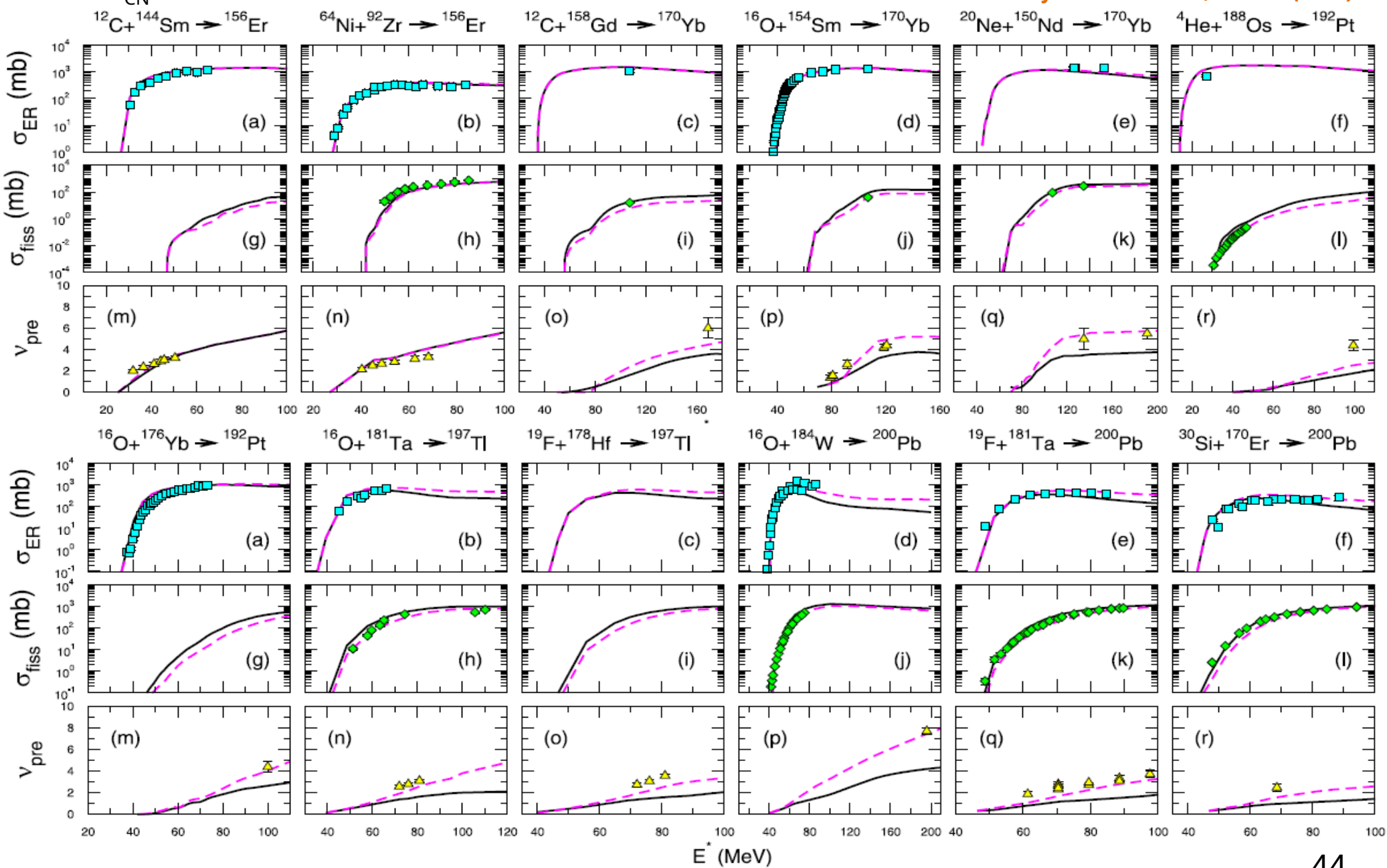
T. Banerjee et. al PRC 99, 024610 (2019)

The SM Predictions without any dissipation

----- The SM Predictions with dissipation , $\beta=2 \times 10^{21} \text{s}^{-1}$

$A_{\text{CN}} = 156-200$

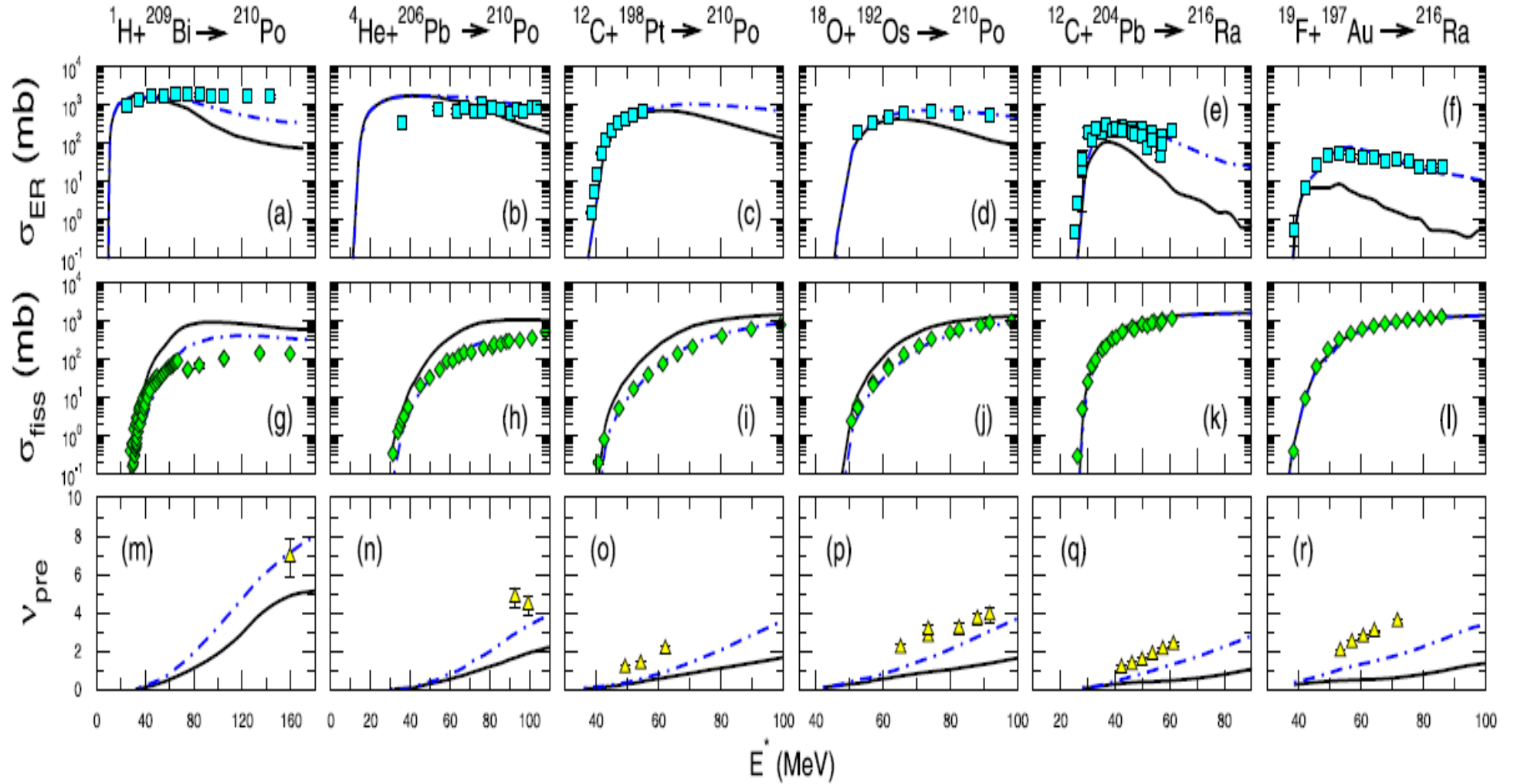
T. Banerjee et. al PRC 99, 024610 (2019)



———— The SM Predictions without any dissipation

- - - - - The SM Predictions with dissipation & $\beta=3 \times 10^{21} \text{s}^{-1}$

$A_{\text{CN}}=210-216$



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Scientific Motivation ...

1. In a recent work, the statistical model simultaneously reproduce the measured σ_{fission} & σ_{ER} but it failed to reproduce the u_{pre} simultaneously with the other two for $158 < A_{\text{CN}} < 225$.
2. Most of the earlier measurements are with heavy ions beam where contribution to the u_{pre} from non compound processes like quasi-fission and fast-fission are present in data.

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Therefore we proposed fission neutron measurement using light ion beam for the $A_{\text{CN}} > 225$

System: $^4\text{He} + ^{232}\text{Th} \rightarrow ^{236}\text{U}$

From present work, we will try to estimate the dissipation strength β for a range of CN as for this system, it is expected to be pure compound nuclear fission & **extracted β value will give true dissipation strength.**

Experimental Details

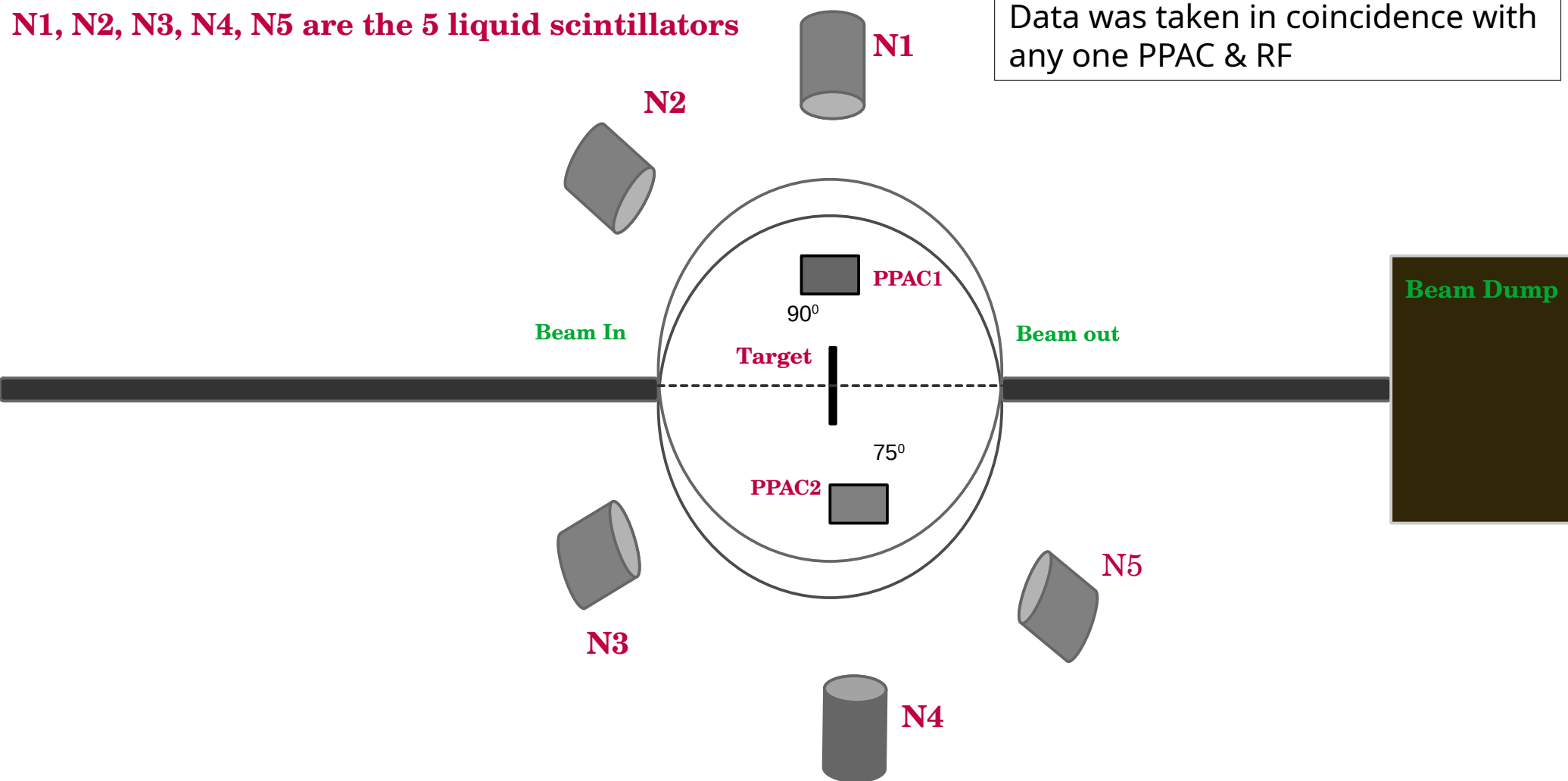
- An experiment was conducted using K130 RTC beam.
- Detectors: 2 PPAC inside the scattering chamber for recording the fission events and 5 liquid scintillator (BC501A) detectors were set up outside the scattering chamber, 1.25 meters from the target center
- Beam : ^4He
- Target: ^{232}Th ($\sim 2.3 \text{ mg/cm}^2$)
- Energy Points: 26 MeV, 29 MeV, 34 MeV, 40 MeV, 44 MeV
- Online Data Collection : VME based data acquisition system

E_{lab} (MeV)	$E^*(\text{CN})(\text{MeV})$
26	20.98
29	23.93
34	28.85
40	34.74
44	38.68

Experimental Set Up

N1, N2, N3, N4, N5 are the 5 liquid scintillators

Data was taken in coincidence with any one PPAC & RF



Efficiency run was taken using ^{252}Cf source

Details of detection methods

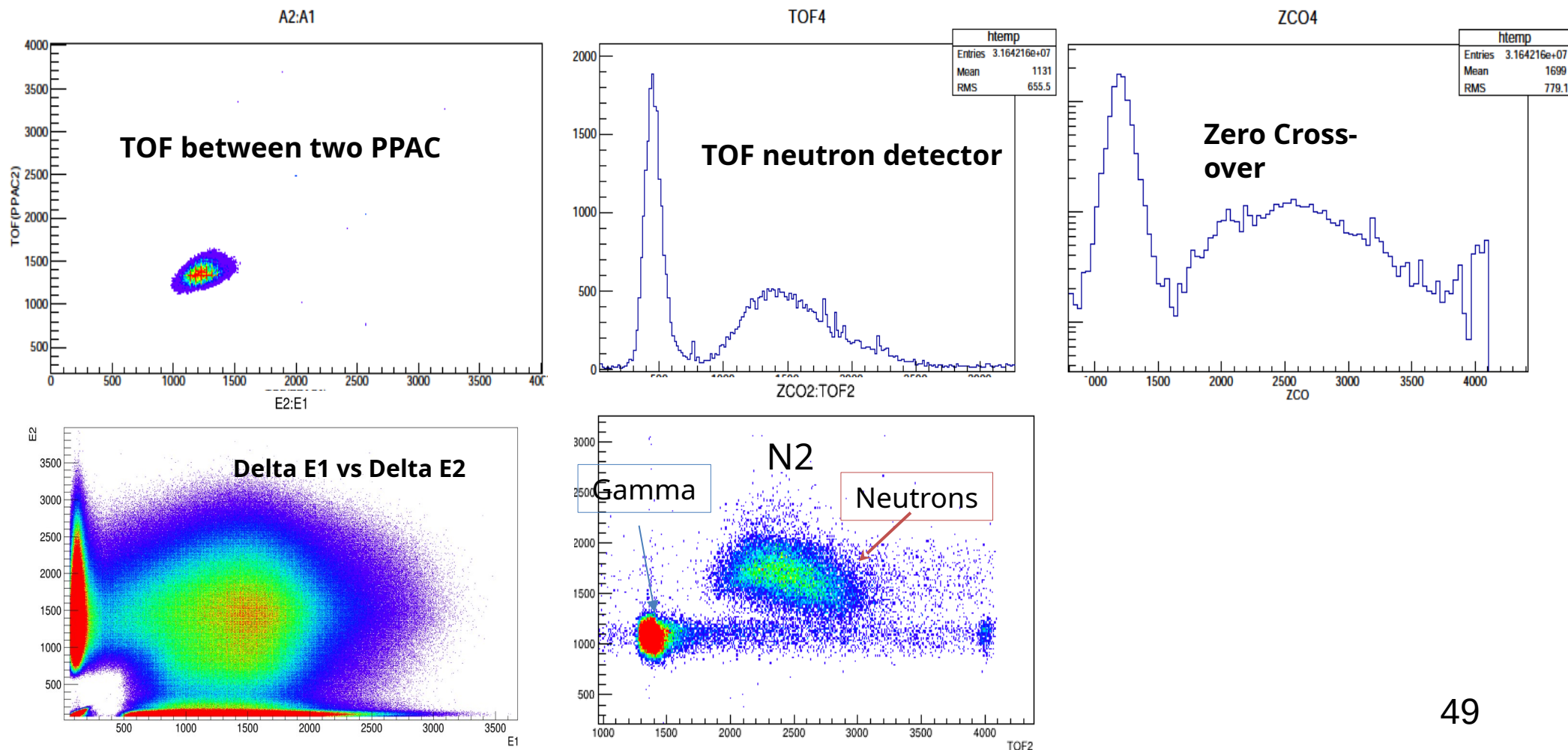
Fission fragments were detected in Parallel Plate Avalanche Counters(PPAC)

- i) **Mass**----Time of flight (TOF) technique with respect to the RF signal of VECC cyclotron.
- ii) **Energy loss**----From the amplitude of PPAC signals

Neutron were detected in liquid scintillator detectors

- i) **Energy**---- Time of flight (TOF) technique with respect to the RF signal.

Raw spectrum for $^4\text{He}+^{232}\text{Th}$ reaction at $E_\alpha=29$ MeV



DATA ANALYSIS

The main aim of this analysis is to extract pre- and post-scission components of neutron multiplicity. The data analysis part comprises the following steps:

- A) Neutron detection efficiency*
- B) Conversion of TOF spectra to neutron energy spectra*
- C) Extraction of neutron multiplicity*

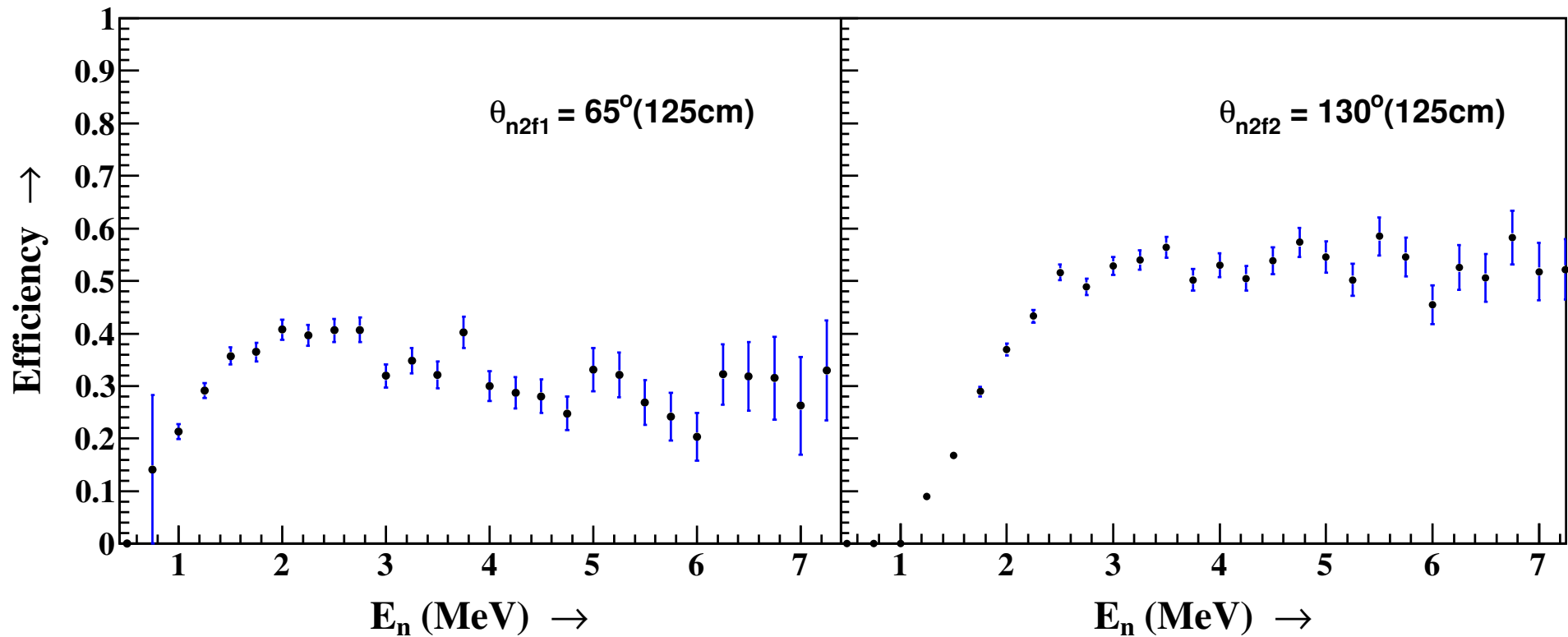
EFFICIENCY OF NEUTRON DETECTORS

- The primary task is to analyse the efficiency of the neutron detectors used.
- The efficiency of each detector was analysed experimentally by measuring the neutron energy spectrum using ^{252}Cf source.
- For the TOF spectrum, the start signal was provided by the timing signal of the PPAC and the stop signal was generated from the neutron detector. The neutron energy deduced from the calibrated TOF was gated with the PPAC timing and the energy loss signal to efficiently select events from fission only and also with the neutron lobe as shown in previous slide 49.
- Standard ^{252}Cf source energy spectrum was normalised with neutron multiplicity $\nu = 3.77$, the neutron detector solid angle and total number of fission detected.
- The Maxwellian neutron energy spectrum of the ^{252}Cf is given as

$$_{ref} = \frac{2\sqrt{E_{lab}} \exp\left(\frac{-E_{lab}}{T}\right)}{\sqrt{(\pi)} T^{\frac{3}{2}}}$$

- The intrinsic efficiency of the neutron detector was determined by taking ratio of the experimentally measured energy to the Maxwellian predicted energy spectrum.

Efficiency Plot (Preliminary) of one of the detector N2



Neutron detector efficiencies can vary with the choice of reference fragment or timing counter—contrary to previous studies.

Neutron Energy Spectra

- TOF spectra were calibrated using a precision TAC calibrator and the prompt γ -ray peak as reference.
- To distinguish the neutrons from γ rays, a two-dimensional neutron gate (TOF vs ZCO) and the energy loss signal from PPAC and 1D gate of PPAC position was applied over the calibrated TOF spectra.
- The calibrated and gated TOF spectra were converted into the neutron energy (E_n) spectra.
- The neutron energy spectra were further corrected with the above obtained efficiency.

Extraction of ν_{pre} and ν_{post}

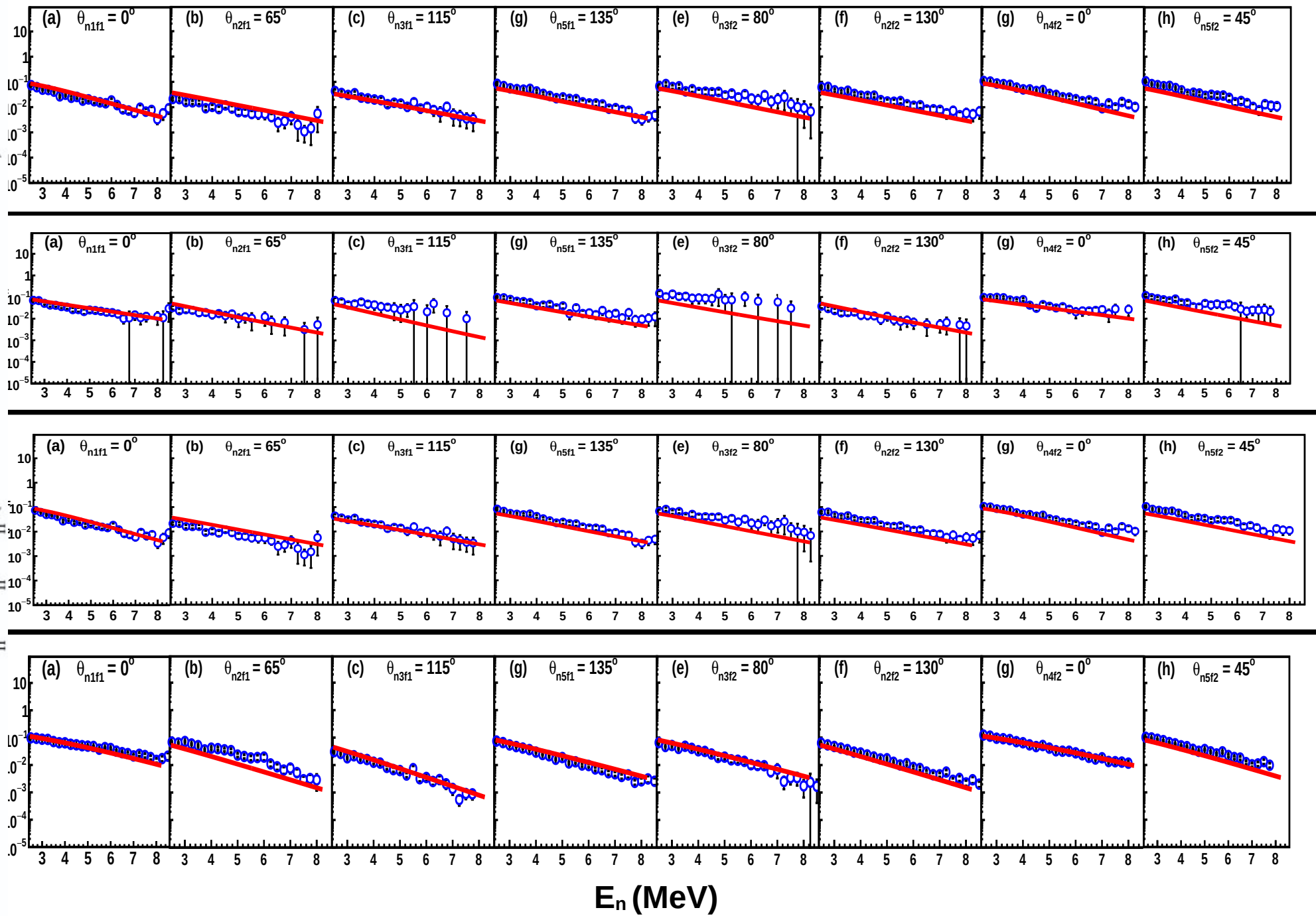
- A multiple-source least-square fitting procedure followed by a χ^2 minimization procedure was used to extract the pre- and post-scission components (ν_{pre} and ν_{post}) of neutron multiplicities and temperatures (T_{pre} and T_{post}) from the measured neutron energy spectra.
- The Watt expression used for fitting procedure is given as

$$\frac{d^2 M_n}{dE_n d\Omega_n} = \sum_{i=1}^3 \frac{M_n^i \sqrt{E_n}}{2(\pi T_i)^{3/2}} \exp \left[-\frac{E_n - 2\sqrt{\epsilon_i E_n} \cos \theta_i + \epsilon_i}{T_i} \right]$$

- Three moving sources of neutrons were considered: neutrons emitted from the CN, which correspond to pre-scission neutron emission (M_{pre}), and neutrons emitted from two fully accelerated fission fragments (FFs), which correspond to post-scission neutron emission (M_{post}).
- Thus, the total neutron multiplicities can be written as the sum

$$\nu_{total} = \nu_{pre} + 2\nu_{post}$$

$d^2M_n/dE_n d\Omega_n$ (neutrons/fission MeV sr)



16/10/2025 Double differential neutron multiplicity spectra for the $^4\text{He} + ^{232}\text{Th}$ reaction at various excitation energies (from top to bottom as 23.93 MeV, 28.85 MeV, 34.75 MeV, 38.68 MeV respectively) for the different neutron detectors. 55

Extracted v_{pre} , v_{Post} and v_{Total} (Preliminary)

$E_{lab} (MeV)$	$E^*(MeV)$	v_{pre}	v_{post}	$v_{Total}=v_{pre}+2v_{post}$
26	20.98	2.30 ± 0.03	0.31 ± 0.032	2.92 ± 0.09
29	23.93	2.17 ± 0.02	0.34 ± 0.05	2.86 ± 0.12
34	28.85	2.69 ± 0.07	0.84 ± 0.04	4.38 ± 0.15
40	34.75	2.54 ± 0.06	0.9 ± 0.02	4.34 ± 0.10
44	38.68	2.33 ± 0.06	1.24 ± 0.02	4.81 ± 0.10

SUMMARY

Comprehensive Reaction Studies:

Investigated nuclear reaction dynamics from below to well above the Coulomb barrier, including quasi-elastic scattering, and fusion-fission processes.

Quasi-Elastic Measurements ($^{28}\text{Si} + ^{144}\text{Sm}$):

Extracted barrier distributions to study projectile structure effects; coupled-channel analysis using CCFULL/CCQUEL revealed significant coupling from ^{28}Si excitations.

Fusion–Fission Dynamics ($^{16}\text{O} + ^{181}\text{Ta}$, ^{197}Au , ^{205}Tl , ^{208}Pb):

Mass and angular distributions confirm dominant compound nuclear fission at high excitation energies, with evidence of fast-fission contributions.

Neutron Multiplicity Measurements ($^4\text{He} + ^{232}\text{Th}$):

Determined pre- and post-scission neutron components to probe nuclear dissipation and extract true dissipation strength (β) for compound fission in ^{236}U .

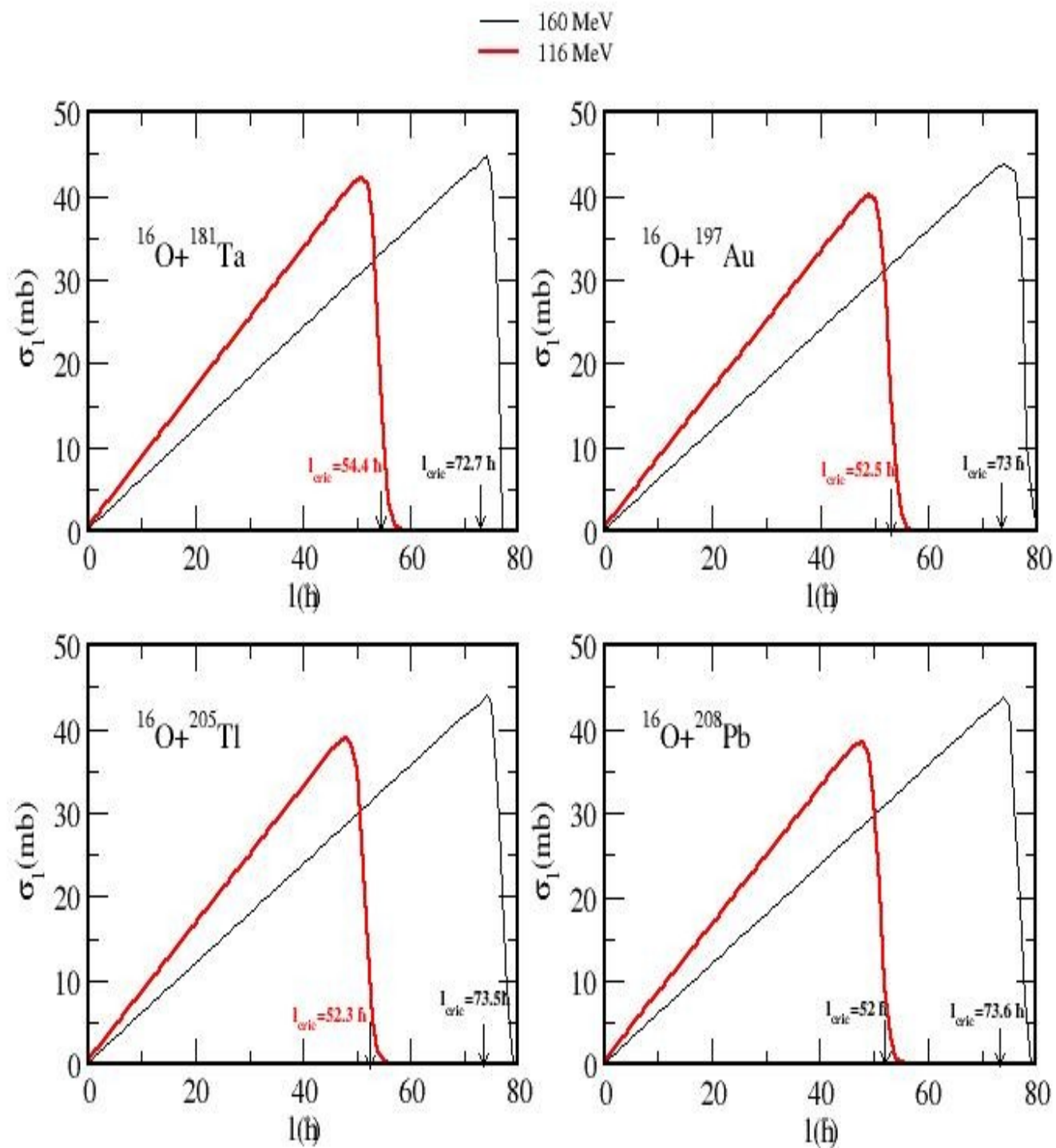
Overall Outcome:

Results bridge reaction dynamics across energy regimes, improving understanding of coupling effects, fission mechanisms, and nuclear dissipation parameters crucial for nuclear structure and astrophysical modeling.

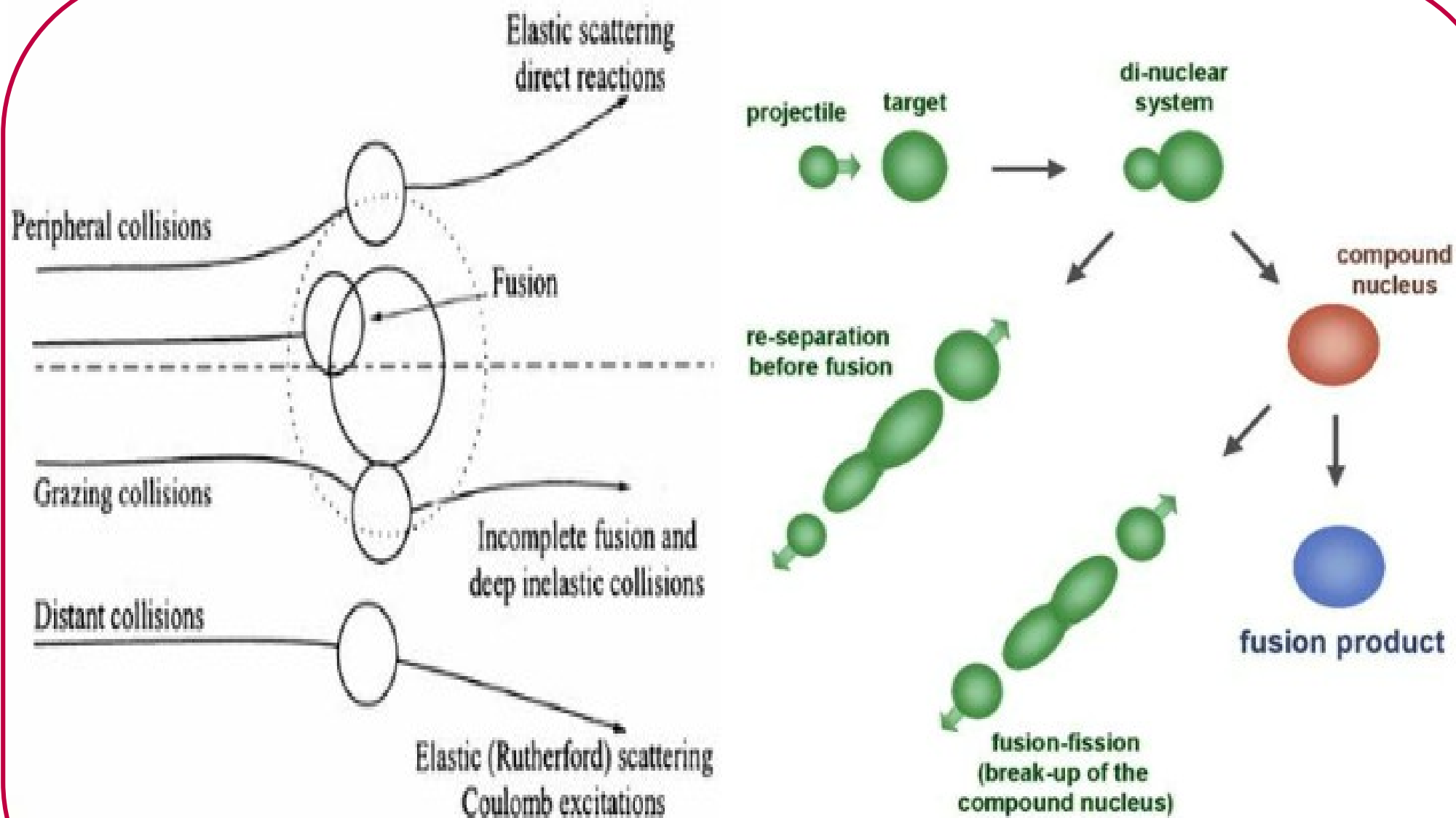


THANK YOU

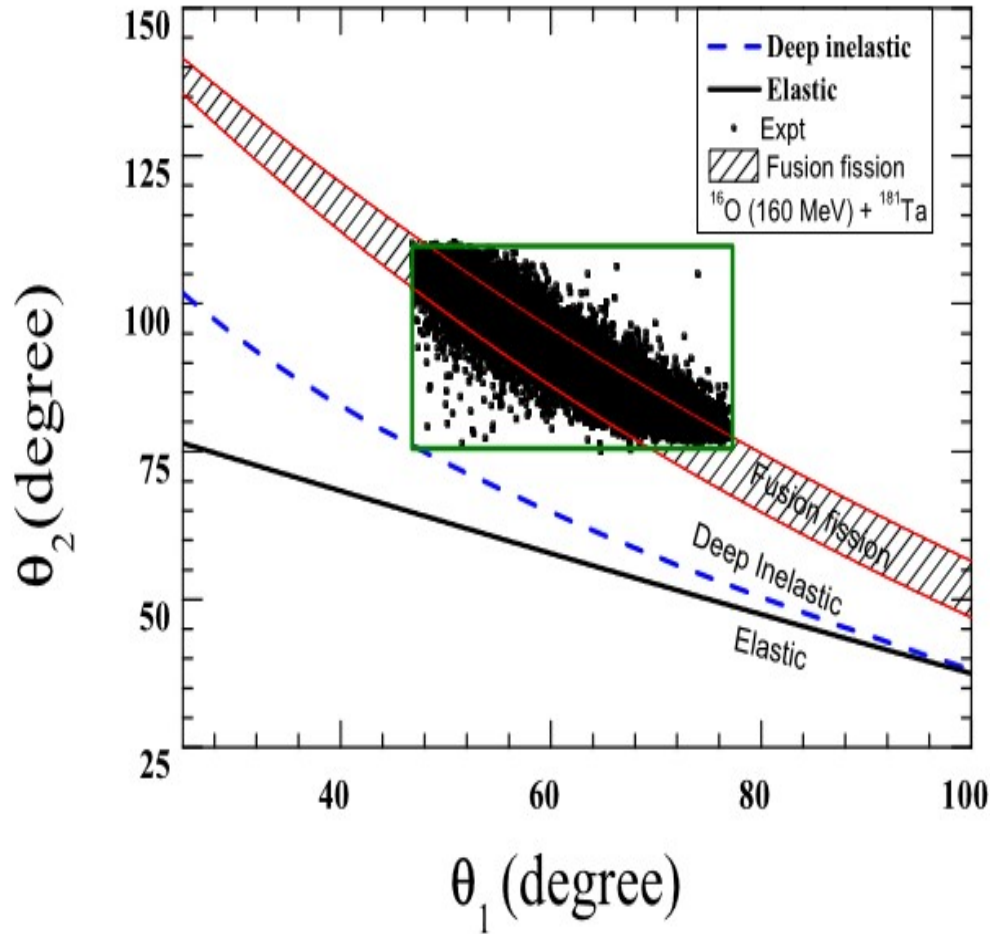
Back up slides



INTRODUCTION:- Nuclear Reactions



DATA ANALYSIS



A representative correlation plot of the simulated polar angle distributions of the events produced in the reaction $^{16}\text{O} + ^{181}\text{Ta}$ at the highest beam energy (160 MeV) measured in the experiment. The hatch area indicates that the symmetric fusion fission events are expected to be contained in this region. The elastics events are expected to be below the black line while the deep inelastic events should lie above the dashed blue lines. The detector coverage is shown by the green rectangular box. The measured events are shown by the black dots.

Time of flight difference technique for measurement of mass distribution

$$m_1 = \frac{(t_1 - t_2) - \delta t_0 + m_{CN} \frac{d_2}{p_2}}{\left(\frac{d_1}{p_1} + \frac{d_2}{p_2} \right)}$$

$$m_2 = m_{CN} - m_1$$

$$p_1 = \frac{m_{CN} V_{CN}}{\cos\theta_1 + \sin\theta_1 \cot\theta_2}$$

$$p_2 = \frac{p_1 \sin\theta_1}{\sin\theta_2}$$