Exploring Fission Valleys of HE & SHE

Tilak Kumar Ghosh

Variable Energy Cyclotron Centre
Kolkata, India

Dubna, Russia; 16 – 19 October, 2023

Plan of the talk

India- JINR Workshop

I. Infrastructure and what we do in VECC

II. Our joint work with JINR

III. How to strengthen the cooperation?

Scientific Infrastructure : VECC, Kolkata

Variable Energy Cyclotron Centre (VECC)

Variable Energy Cyclotron Centre (VECC) is one of the R&D units under the Department of Atomic Energy (DAE)
Primarily engaged in the area of research in Basic Sciences since its inception in 1969.

Major activities of VECC are:

- **Basic Sciences:** Experimental Research in Low and High energy Nuclear Physics using accelerators and Theoretical Nuclear Physics
- **Accelerator based Applied Research** in the field of material science & radiation damage studies
- **Societal applications:** Medical Cyclotron for isotope production
- **Indigenous accelerator development and R&D on Advanced Accelerators**
- **Technology Development:** RF/SRF, Detectors, DAQ, Instrumentation, Power Electronics, Mechanical, Cryogenics, Computer & IT services

2

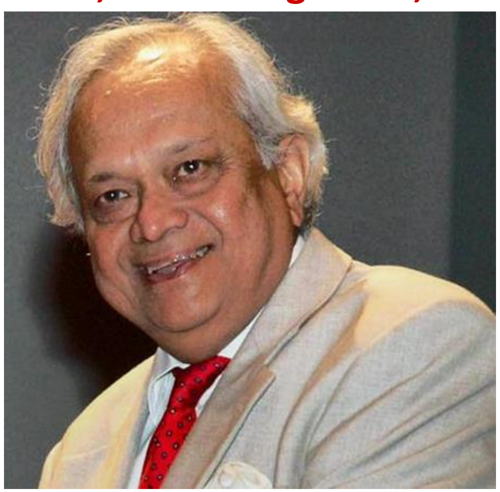
- Staff : 520
- Scientist & Engineer: 179
- PhD students + post doc ~ 50

Typically of the size of Flerov Lab

There is a major overlap in research between JINR and VECC

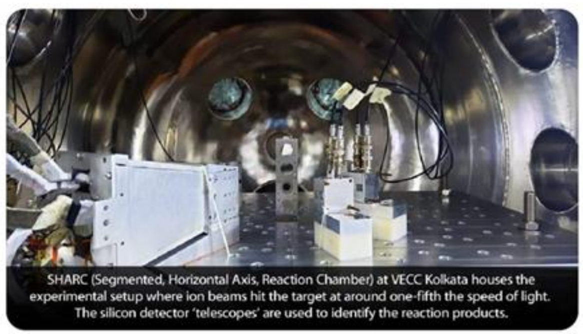
Variable Energy Cyclotron Centre (VECC)

(June 16, 1945 - August 11, 2023)



DAE India @DAEIndia Follow

Revolutionising nuclear physics experiments in India - The VECC Superconducting Cyclotron #SCC, India's most powerful heavy-ion accelerator, delivers a nitrogen beam with 252 MeV energy inside SHARC (Segmented, Horizontal Axis, Reaction Chamber). 1/4 @PMOIndia @DrJitendraSingh



6:55 pm · 03 Sept 23 · 11.3K Views

Major accelerators:

- ❑ Room Temperature Cyclotron (K130)

S. B., C. B., P. D., G. M. and T. K. Ghosh; Eur. Phys. J. A 54, 158 (2018)

- ❑ Superconducting Cyclotron (K500)
- ❑ Medical Cyclotron (K30)

India is a member of several international collaborations which was basically initiated by Prof Bikash Sinha.

Associate member of CERN
India holds 3.5 % FAIR GmbH share

Work in our group

Fission study that we are pursuing at VECC, India….

- Shell effects in nuclei

- Quasi-fission

- Mass distribution as a probe to explore these two counter effective processes.
- Our experiments validate predictive models of HE and SHE production, for guiding future experimental searches of SHE.

Physics related to Super Heavy Elements (SHE)

HE & SHE

Liquid drop binding energy :

$$B(Z,A) = a_v A - a_s A^{2/3} - a_c Z^2/A^{1/3} - a_{asy} (N-Z)^2/2A + a_\delta A^{-3/4}$$

Fissility parameter :

$$\chi = E_C(0)/2E_S(0)$$

Fission barrier:

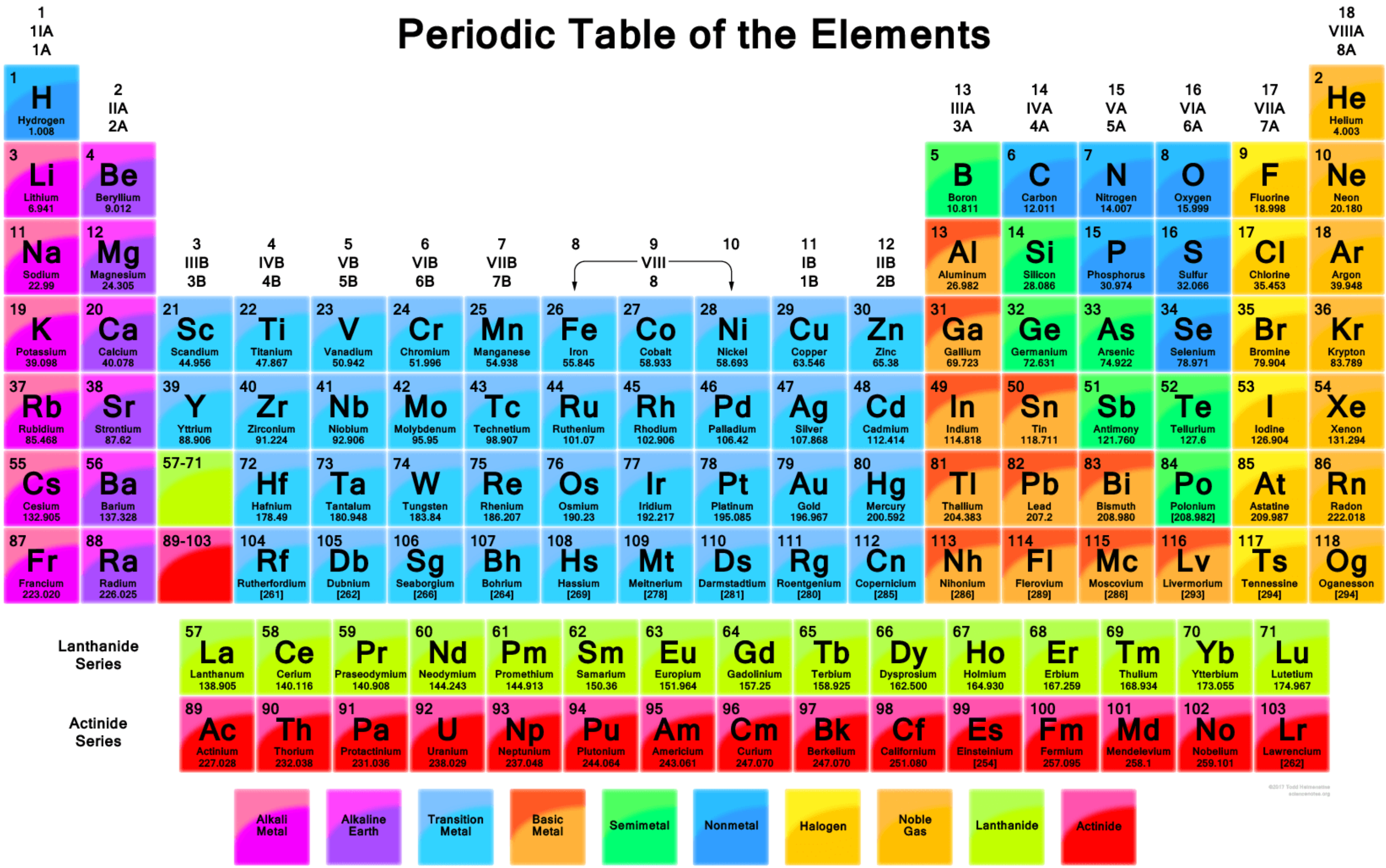
$$B_f = 0.7\ (1-\chi)^3 .\ a_s .\ A^{2/3}$$

For Z=104 , $\chi = 1$ thus $B_f = 0$

Nucleus with Z >104 will not exist since there is no barrier

- Elements in the periodic table beyond Z=104 are usually known as Super Heavy Elements (**SHE**)

- In Fission Physics, Heavy Elements (**HE**) : Z < 104



SHE survives because of nuclear shell effects

Quasi-fission

Why is the production cross section for Super Heavy Elements small ?

Quasi-fission is believed to be the main culprit !

- SHE production cross-section can be written in the form

$$\sigma_{ER}(E_{cm}) = \sigma_{capture}(E_{cm}) \, .P_{CN}(E_{cm}).P_{survival}(E_{cm})$$

Capture cross-section

Probability of CN formation

Survival probability of CN

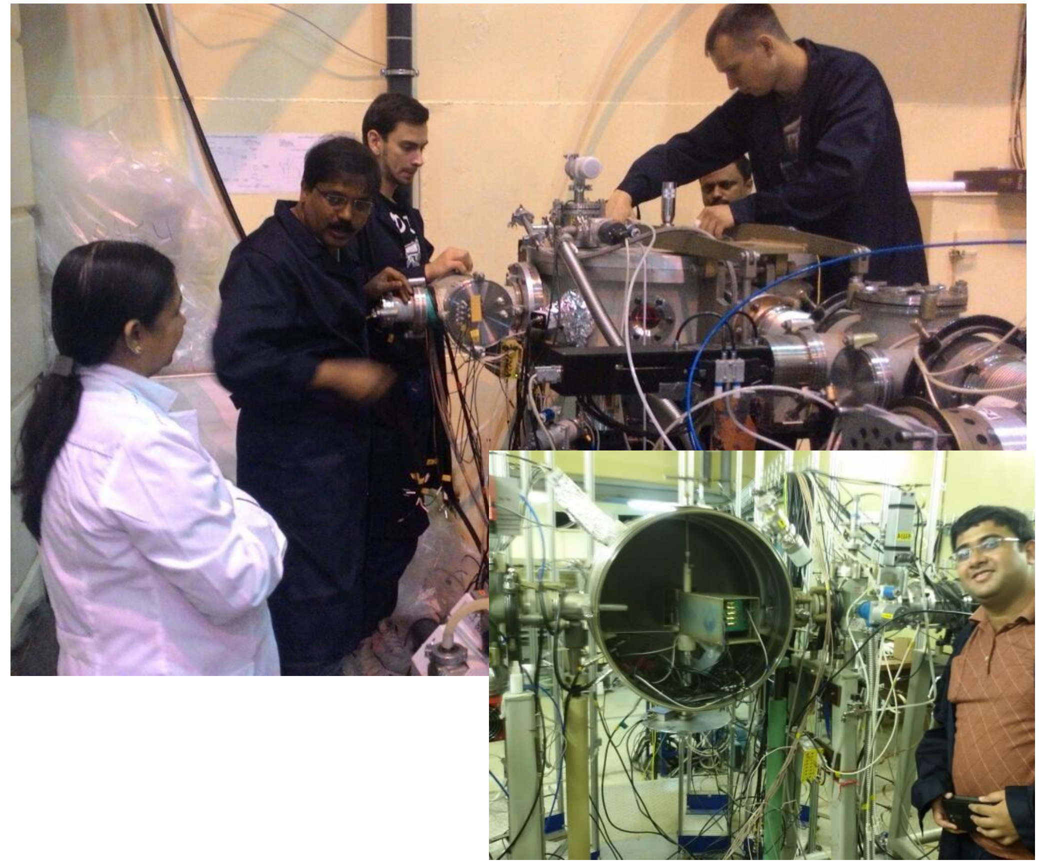
For optimization of SHE production, reliable info of P_{CN} is required

We have initiated experimental program to systematically understand the quasi-fission of HE & SHE

Under the umbrella of this collaboration joint experiments are being carried out to study the fission dynamics of HE and SHE

Fission study of HE in India

Kolkata cyclotron, Mumbai & Delhi pelletron



Fission study of SHE in Russia

Dubna cyclotron

Shell effects and quasi-fission in preactinides

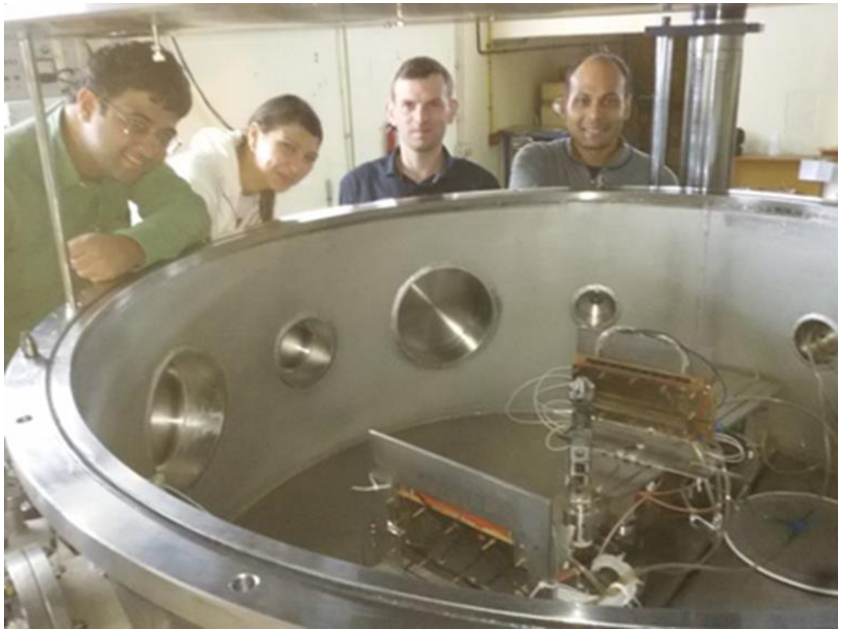
Experiments carried out in INDIA

(VECC K130 cyclotron, IUAC pelletron TIFR pelletron)

Shell effects and role of loosely bound nuclei

^{9}Be + ^{205}Tl,^{238}U > fission

D. Paul, A. Sen , T. K. Ghosh et al; Phys Rev C 102, 054604 (2020)
D. Paul, A. Sen , T. K. Ghosh et al; Phys Rev C 104, 024604 (2021)



Quasi fission for HE

^{16}O+^{209}Bi, ^{20}Ne+^{205}Tl > ^{225}Pa

K. Atreya, A. Sen , T. K. Ghosh, A.K. Nasirov et al;
Phys Rev C 108, 034615 (2023)

Role of entrance channel magicity

$^{16}O + ^{208}Pb \rightarrow ^{224}Th$

Both the target and projectiles are neutron and proton shells closed

$^{18}O + ^{206}Pb \rightarrow ^{224}Th$

Both the target and projectiles are proton shells closed

$^{19}F + ^{205}Tl \rightarrow ^{224}Th$

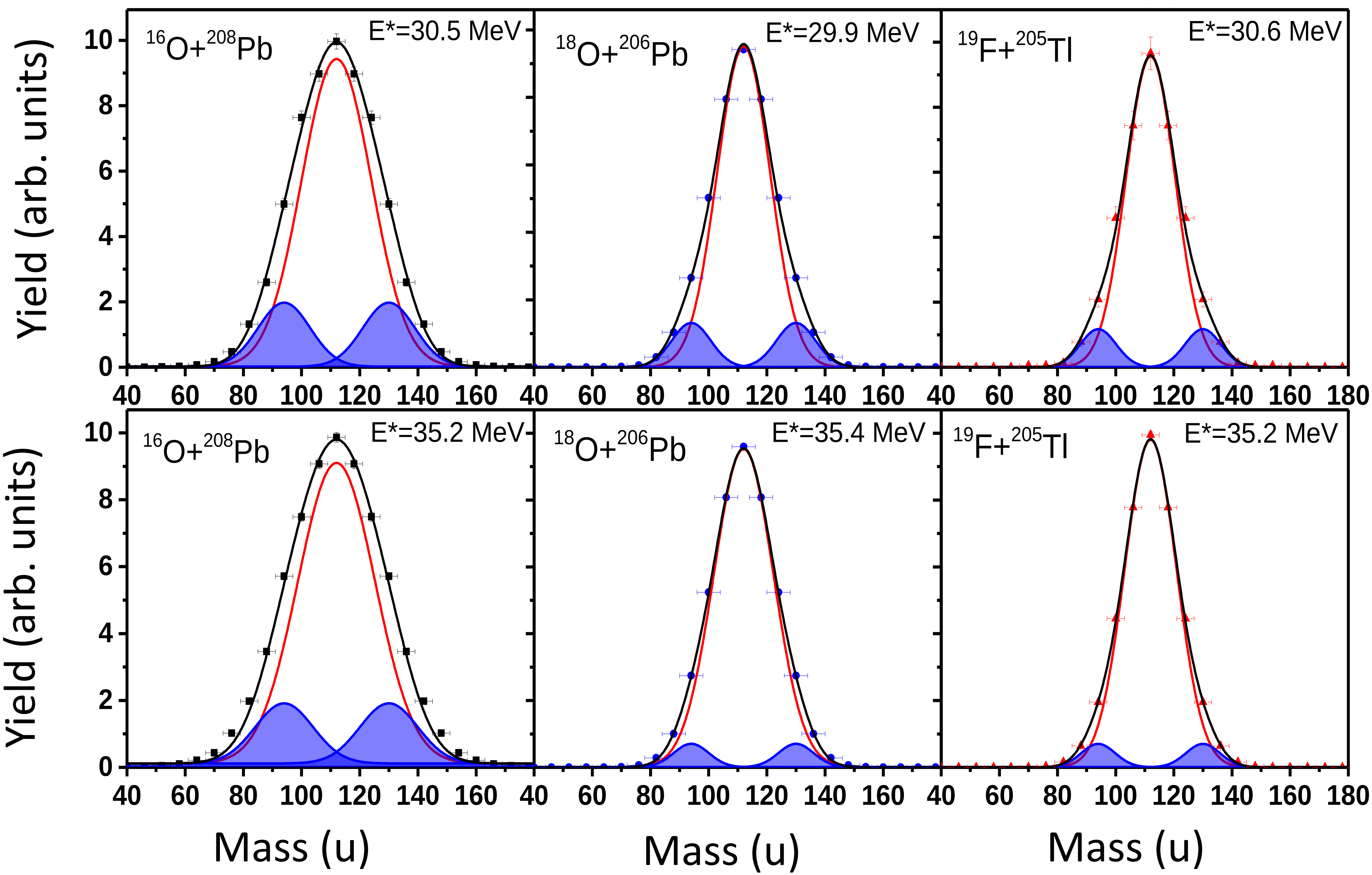
None of the target and projectiles are shells closed

Entrance channel magicity index (N_m) : number of shell closures in the target projectile combination

System:	$^{16}O + ^{208}Pb$	$^{18}O + ^{206}Pb$	$^{19}F + ^{205}Tl$
N_m	4	2	0
$Z_P Z_T$	656	656	729

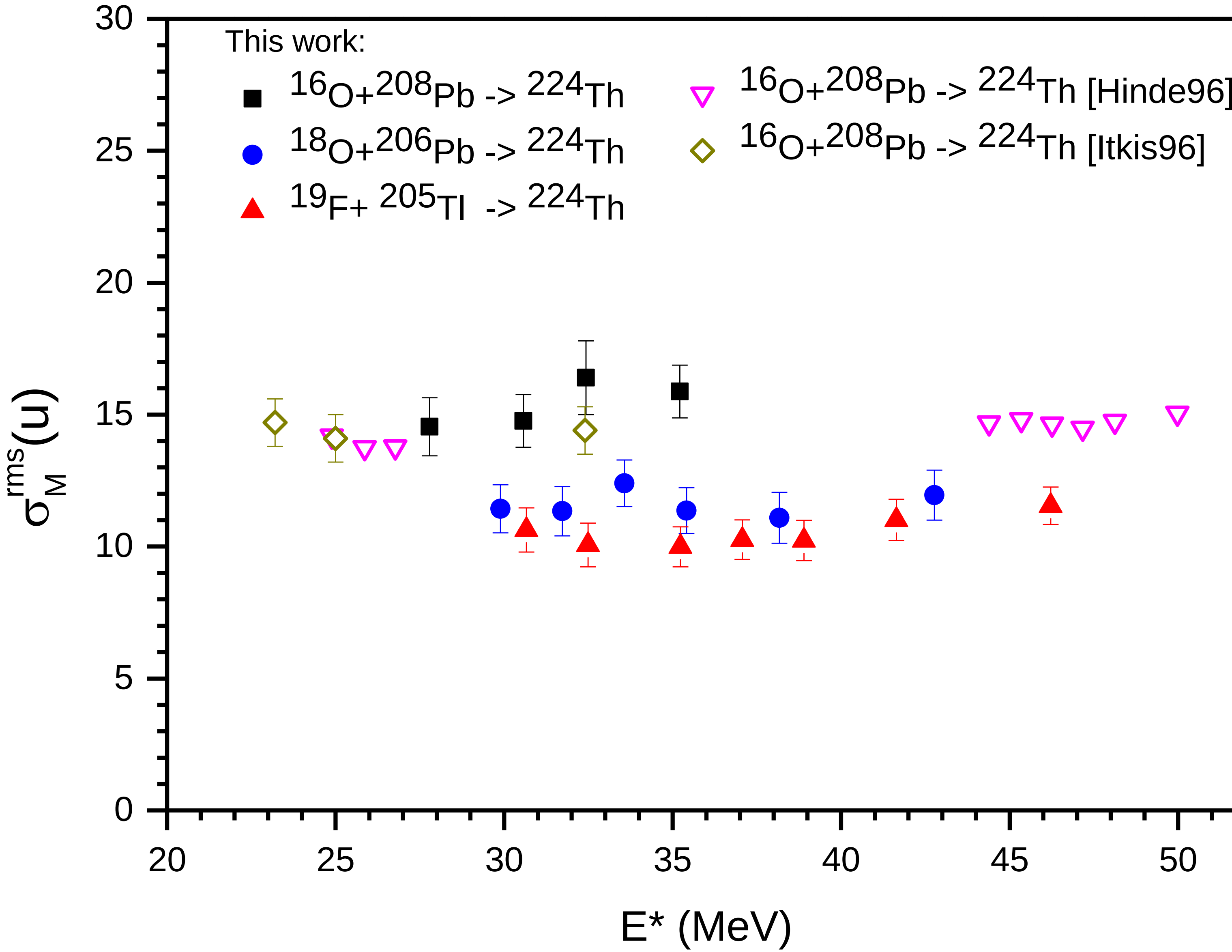
A. Sen, T.K. Ghosh…Kozulin…Nasirov et al; Phys Lett B (2023, under review procedure)

The mass distributions for the reactions:



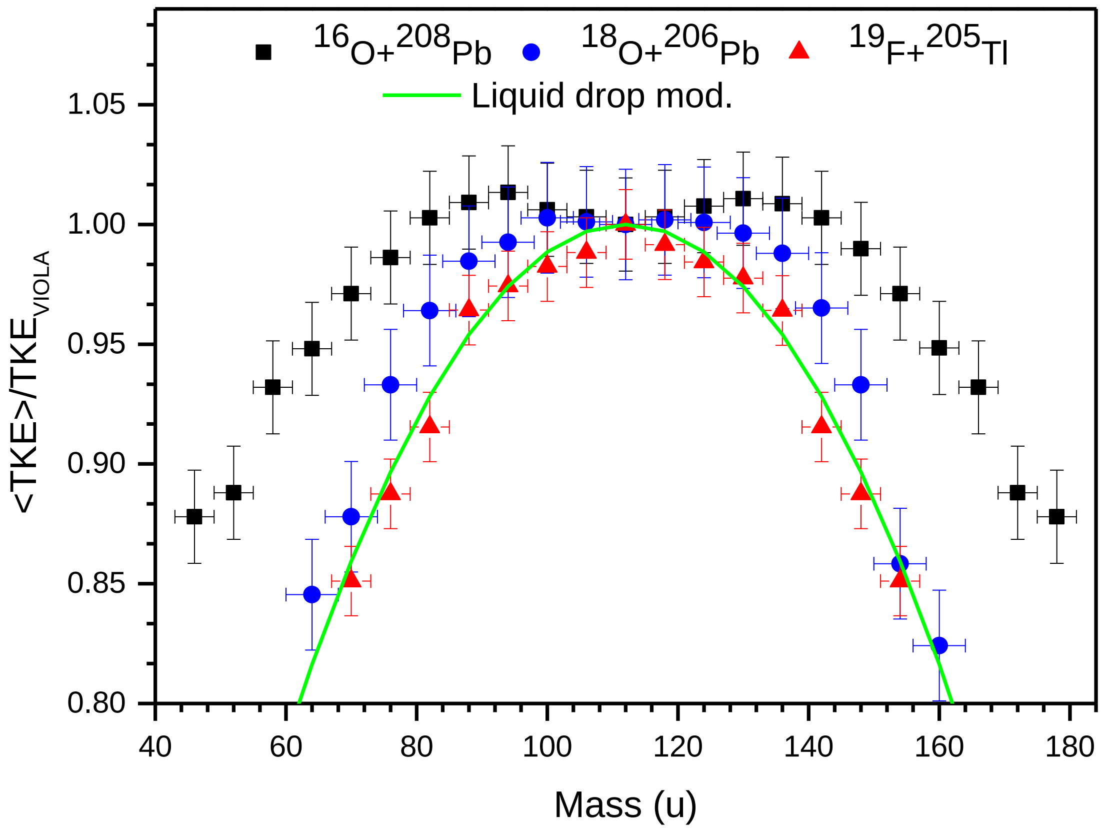
90 Th Thorium 232.038

Width of the mass distributions:



Mean TKE distributions:

The ratio between the measured average TKE and the TKE calculated employing the Viola's systematic, as a function of mass at E*≈ 35 MeV

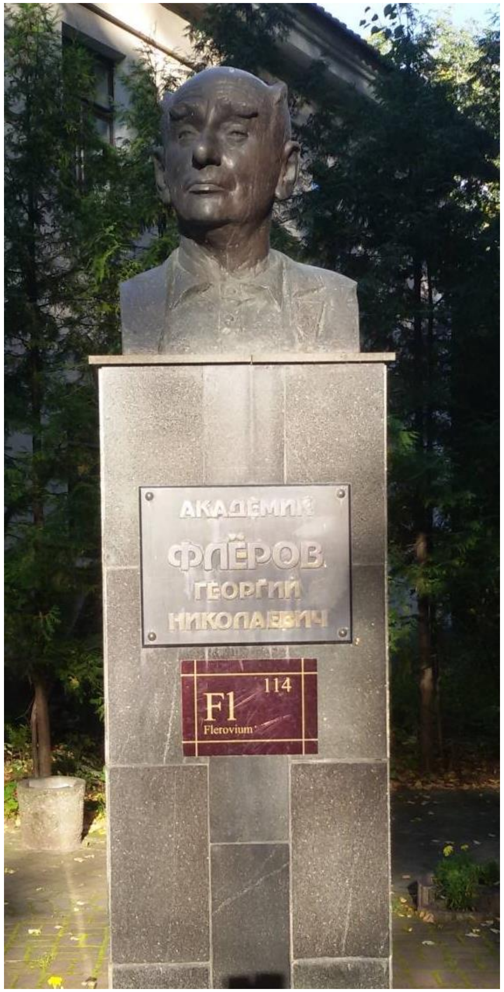


The decay modes of the three reactions are not identical, but show systematic variation as in the case of mass distribution

Role of entrance channel magicity

Dubna experiments

Experiments were carried out in collaboration with Fission Group (CORSET) at JINR, Dubna



^{52}Cr + ^{232}Th
^{86}Kr + ^{198}Pt → ^{284}Fl (Z=114, Flerovium)

$^{86}Kr + ^{198}Pt \rightarrow ^{284}Fl_{114}$

Coulomb barrier: 415 MeV

Beam energies: 389, 419,472 MeV

$^{52}Cr + ^{232}Th \rightarrow ^{284}Fl_{114}$

Coulomb barrier: 281 MeV

Beam energies: 265,288, 303, 320 MeV

Physics motivation

- Elements beyond Z=113 have been discovered only in hot fusion reaction with ^{48}Ca beam with actinides target.

- SHE discovery experiment:

$$^{48}_{20}\boldsymbol{Ca} + ^{249}_{98}\boldsymbol{Cf} = ^{294}_{118}Og + 3\mathrm{n}$$

Oganessian et al;
Phys Rev C 74, 044602 (2006)

\- One can't have target heavier than Cf for long term experiment, so only option to discover SHE > 118 is to use projectile heavier than Calcium

Which projectile heavier than Calcium is better for SHE?

SHE 120 couldn't be found

Efforts to synthesise SHE 120 with Fe, Ni beams were unsuccessful

GSI experiment:

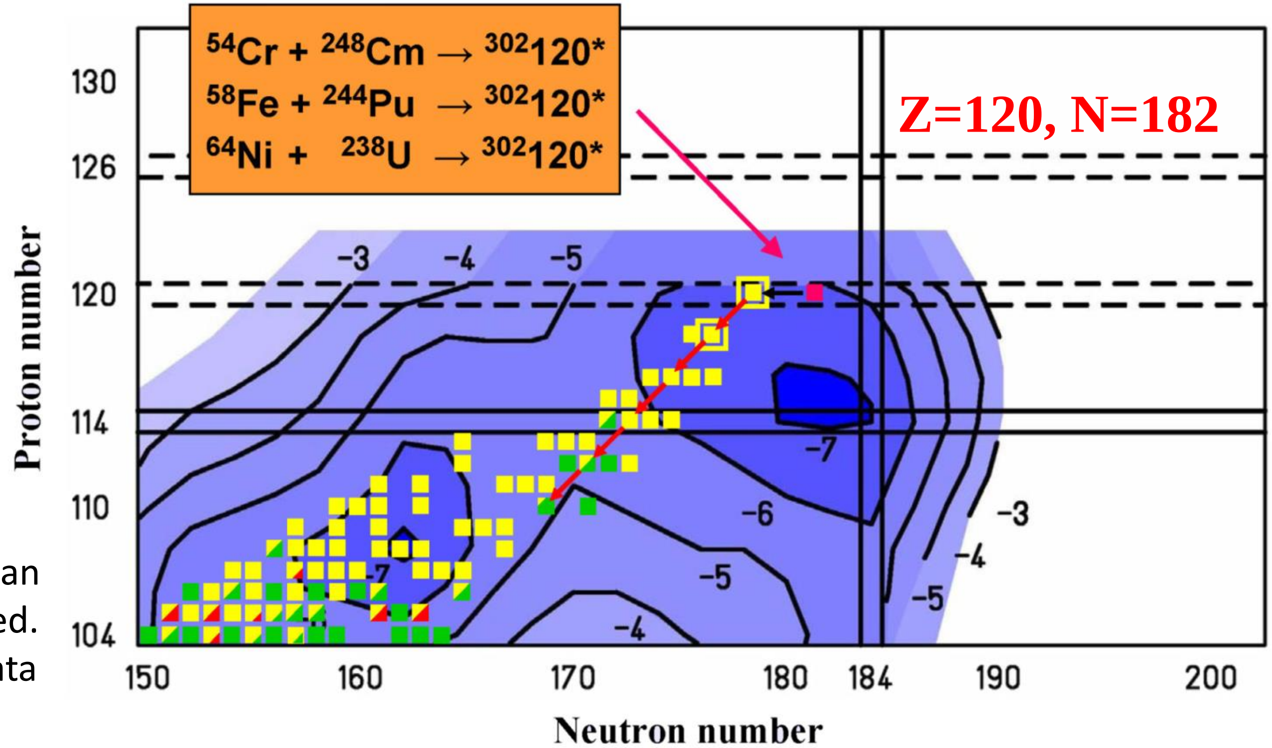
$^{64}Ni + ^{238}U$

Dubna experiment:

$^{58}Fe + ^{244}Pu$

^{54}Cr alternate beam?

Possible assignment to the decay of an isotope of element 120 was discussed. However, recent reanalysis of the data could not confirm it



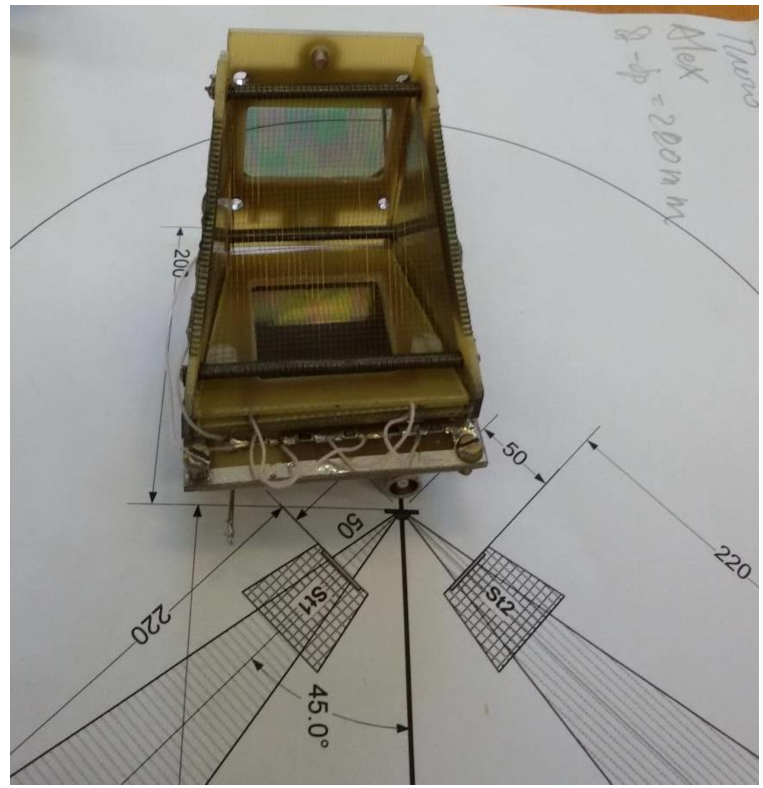
We measured the fusion probability for the formation of SHE (114) Flerovium when Cr beam is used.

Experimental determination of P_{CN} can improve the understanding of the underlying reaction mechanisms

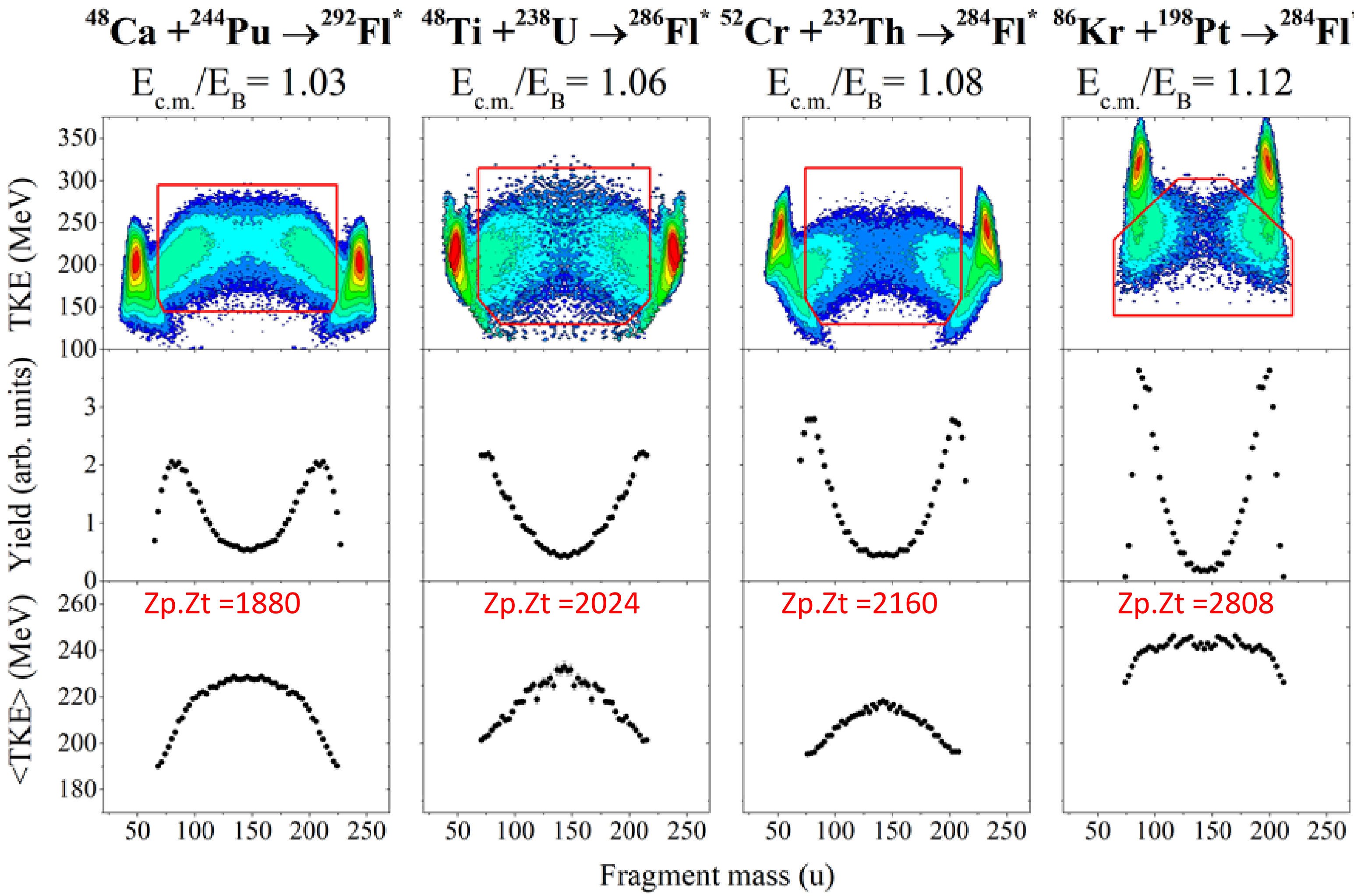
Experiment @ FLNR, Dubna Cyclotron

Double arm time of flight spectrometer **CORSET**

Flight path = 16 cm
Detector dimension: 9 cm x 7 cm
Mass resolution: 4 u
Kinetic energy resolution: ± 10 MeV



Mass & energy distributions

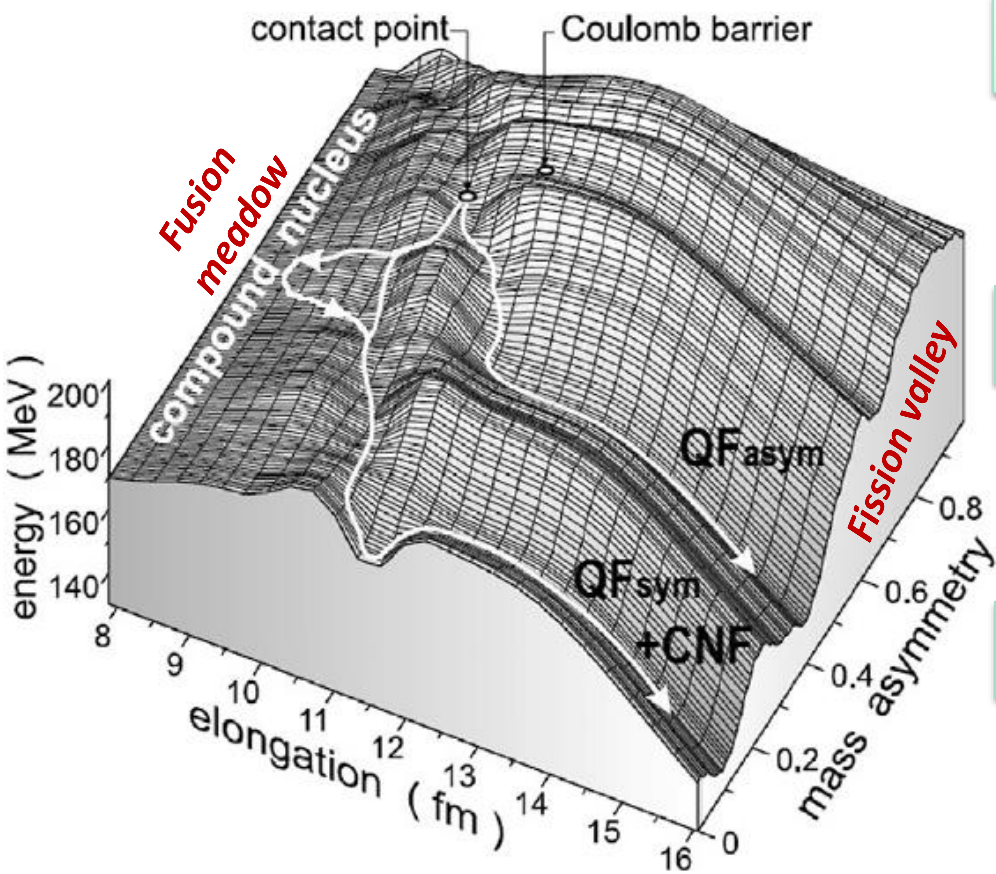


At the transition from ^{48}Ca to ^{48}Ti and ^{52}Cr ions the contribution of symmetric fragments decreases

Kozulin, Knyazheva, T.K. Ghosh, A. Sen et al; Phys. Rev. C. 99, 014616 (2019)

Fission valley

Mass symmetric fragments may be formed by three modes:



V.I. Zagrebaev, W. Greiner / Nuclear Physics A 944 (2015) 257–307

I. Compound nuclear fission (CNF)

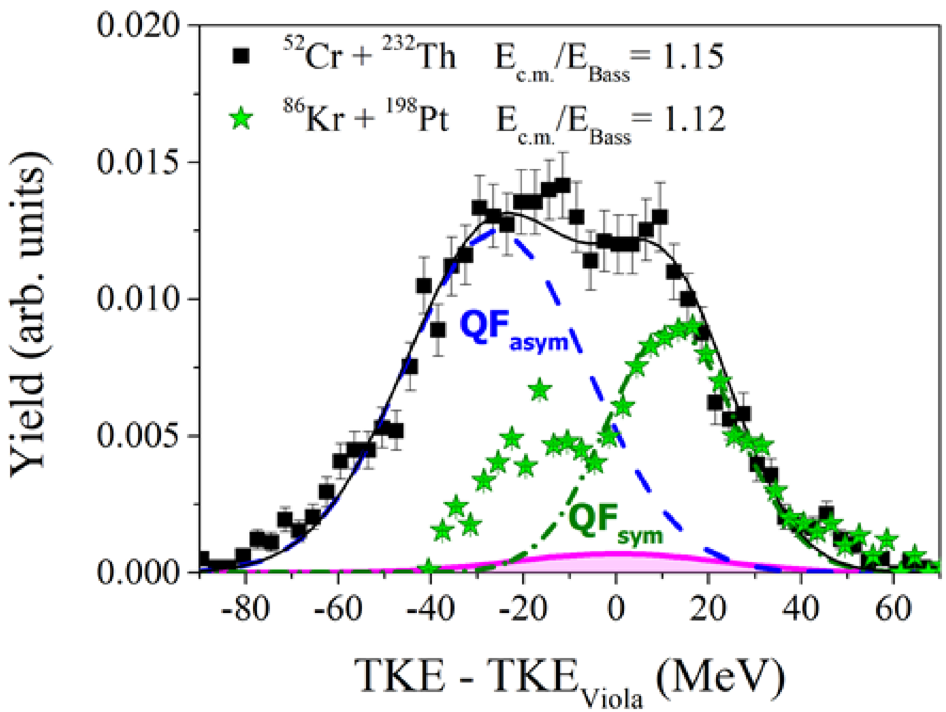
II. Symmetric quasi-fission (QFsym)

III. Asymmetric quasi-fission (QFasym)

The full dissipation of initial energy may not occur in QFsym process makes the TKE higher compared to CN

Kozulin et al; Phys. Rev. C. 94, 054613 (2016)

Total Kinetic Energy

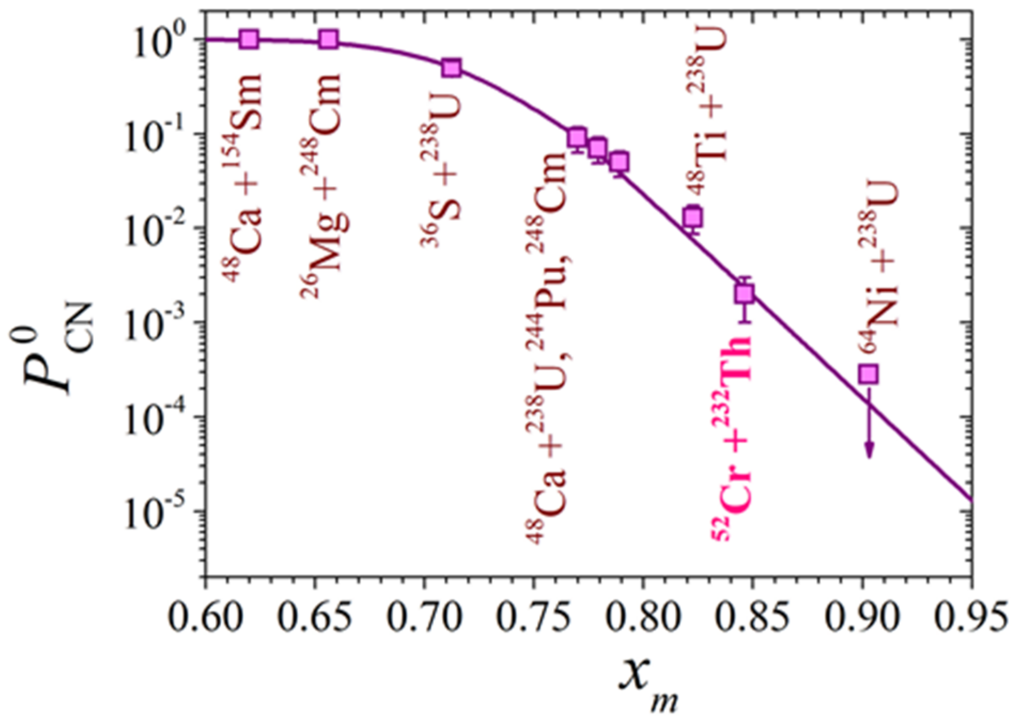


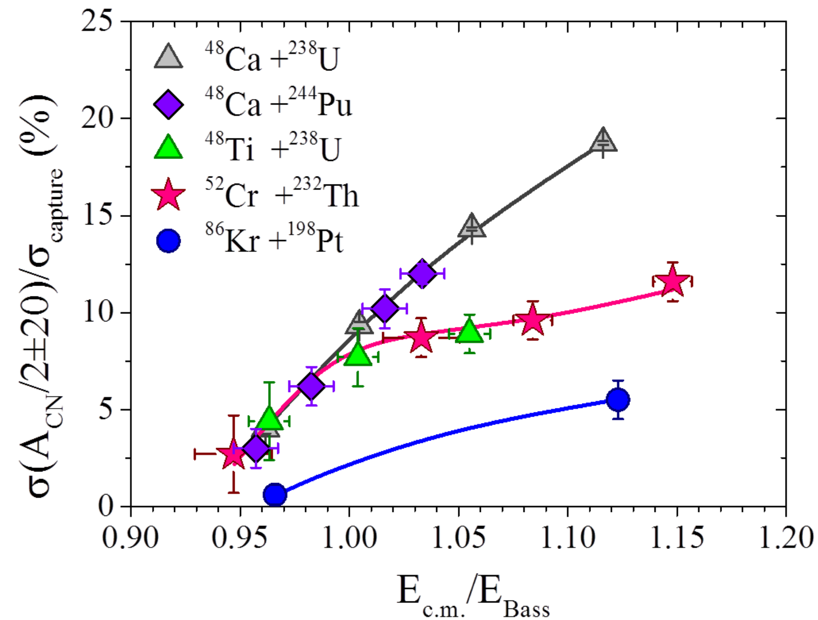
- Contribution of the CN fission is about 4% in the mass region $A_{CN/2} \pm 20$ u.
- Low-energy component is attributed to asymmetric QF, while the high-energy one is connected with symmetric QF

- The parameters for the symmetric QF component were deduced from the decomposition of the TKE distribution for the $^{86}Kr + ^{198}Pt$ reaction
- The variance of the asymmetric QF component equal to the experimental value of TKE variance for the fragment mass corresponding to the maximum yield of asymmetric QF

A. Sen, T.K. Ghosh, Kozulin et al; Phys. Rev. C. 105, 014627 (2022)

Fusion probabilities : Z=114 (Flerovium)





~ 4 times less in Ti reaction
~ 25 times less in Cr reaction
compared to Ca induced reaction

Reaction	ZpZt	Fissility
^{48}Ca + ^{244}Pu	1880	0.780
^{48}Ti + ^{238}U	2024	0.823
^{52}Cr + ^{232}Th	2160	0.846
^{86}Kr + ^{198}Pt	2808	0.917

A. Sen, T.K. Ghosh, Kozulin et al; Phys. Rev. C. 105, 014627 (2022)
Kozulin, Knyazheva, Ghosh, Sen et al; Phys. Rev. C. 99, 014616 (2019)

Summary

Scientific activities

- At VECC we study shell effects and quasi-fission for a wide range of nuclei of HE & SHE, which are the major focus in the field

- We have measured the fusion probability in reactions for the production of super heavy element (Z=114) Flerovium in collaboration with JINR

Outlook: What's next?

- Current worldwide data on fission is fragmentary, need to develop a comprehensive program of fission studies that could address some of the most pressing problems in nuclear fission over the next several decades.

- Predicting all fission properties of every atomic nucleus in the nuclear chart, from light elements to all the way to super heavy elements, remains a formidable challenge.

Possible area of collaboration

- Discovery of new Super Heavy Elements: require facility development like SHE-Factory.

Taking the advantage of accelerator facilities in India

VECC, Kolkata Cyclotron

TIFR, Mumbai, 14 MV pelletron

IUAC, New Delhi, 15 MV pelletron

Higher energies: LINACs at Delhi & Mumbai and K500 Cyclotron in Kolkata

MWPC : work horse for fission studies

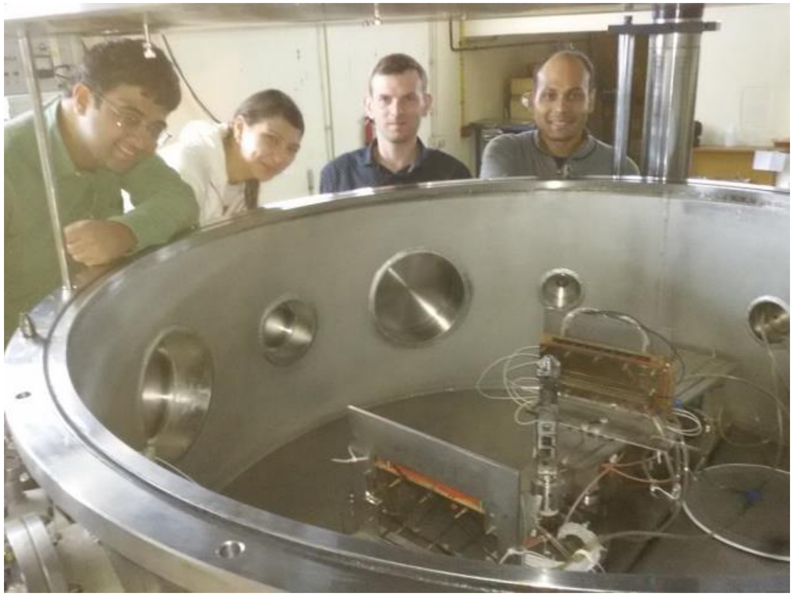
T. K. Ghosh et al., Nucl. Instr. and Meth. A 540, 285 (2005)

Neutron detector: *Nucl. Instr. and Meth. A 608, 440 (2009)*

Silicon detector: *Nucl. Instr. and Meth. A 943, 162411 (2019)*

Experiment @ VECC, Kolkata

Experiment @ IUAC, New Delhi



Experiment @ TIFR, Mumbai

☺ Why experimenters do like to come to Dubna ? ☺

Scientific success is always a good reason to organize a party!!

How to move forward?..... Requirements

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ
JOINT INSTITUTE FOR NUCLEAR RESEARCH
ЛАБОРАТОРИЯ ЯДЕРНЫХ РЕАКЦИЙ ИМ. Г.Н.ФЛЕРОВА
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E-mail: dmitriev@jinr.ru
http://flerovlab.jinr.ru

November 07th, 2014

Indo-Russian Joint Research
DST - RFBR Joint Call for Proposals

A project Proposal entitled "Experimental study of the influence of the reaction entrance channel on the formation probability of heavy and super heavy nuclei" is being submitted to Department of Science and Technology for research funding against the DST-RFBR joint call for proposals.

The project mentioned above offers mutual scientific benefit of interest to both labs and the collaborative work between Variable Energy Cyclotron Centre (VECC), India and Flerov Laboratory of Nuclear Reactions (FLNR), Joint Institute for Nuclear Research, Dubna, Russia will be useful for understanding the dynamics of fusion fission and quasifission reactions. The collaboration will provide opportunities to exchange of expertise between the Indian and Russian nuclear communities.

FLNR, will provide the research resources needed to ensure a productive collaboration work between the two laboratories in the framework of the current project.

Director **S.N. Dmitriev**

Project Coordinator from Russian side E.M. Kozulin

❑ Academic mobility

- Scholarships for graduate students and researchers
- Exchange of both short-term and long-term visits

❑ Scientific events

- Joint schools
- Conferences

e.g; Gateway of collaboration through school

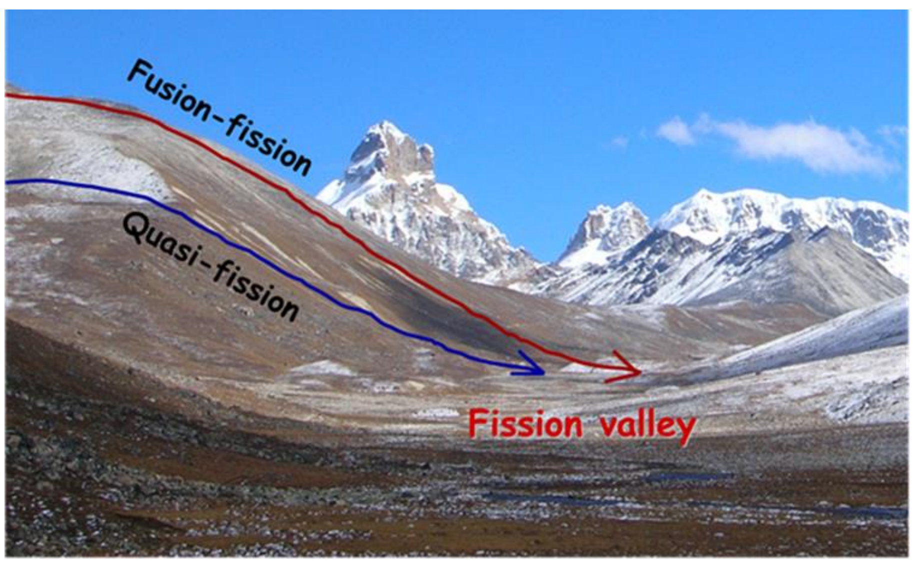
Avazbek Nasirov

He collaborates with 6 different groups in India

9 Papers published with Indian students/scientists

Concluding remarks

- Wider scope of joint activities in Nuclear Physics research between JINR and Indian institutions and universities.
- Hope that in the future we will create more collaborations of mutual benefits.
- We believe that this workshop becomes a milestone for scientific cooperation between JINR and India.



Yumesamdong (15,300 ft), North Sikkim, India

Collaborations

Thank you

- Variable Energy Cyclotron Centre, Kolkata, INDIA
- Inter University Accelerator Centre, New Delhi, INDIA
- Bhabha Atomic Research Centre, Mumbai, INDIA
- Tata Institute of Fundamental Research, Mumbai, INDIA
- Flerov Laboratory for Nuclear Reactions, JINR, Dubna, RUSSIA

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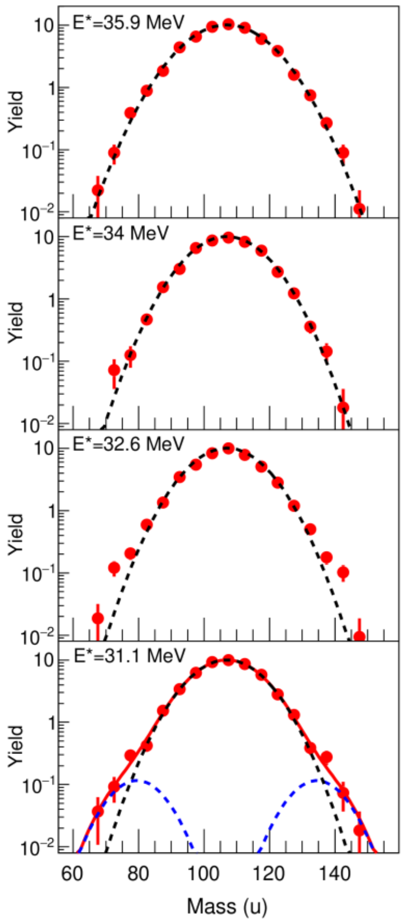
9163183818

fissionvalley

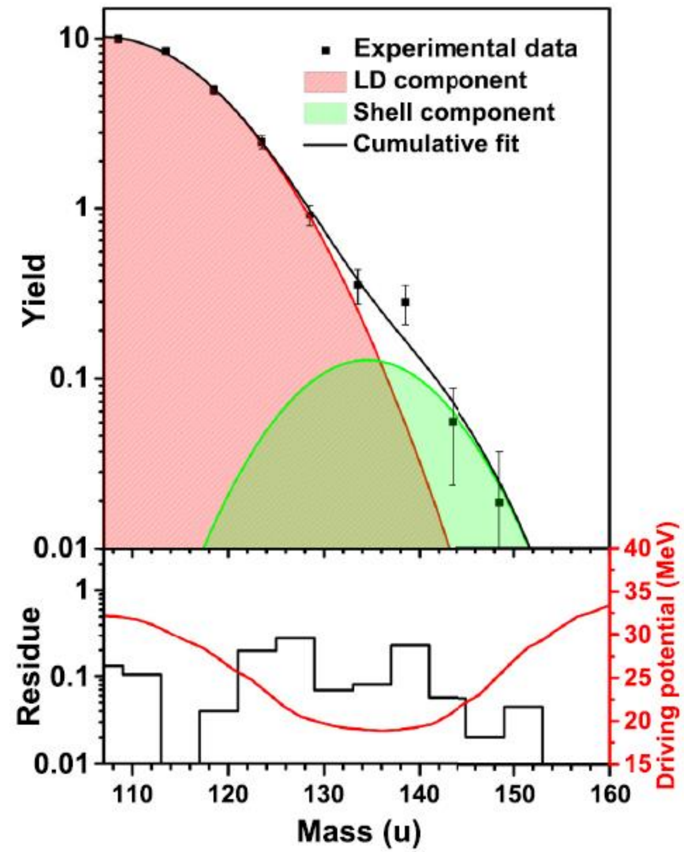
Supporting slides……

Fission of pre-actinides & actinides

Slightly asymmetric mass distribution observed at E* =31 MeV



^{214}At

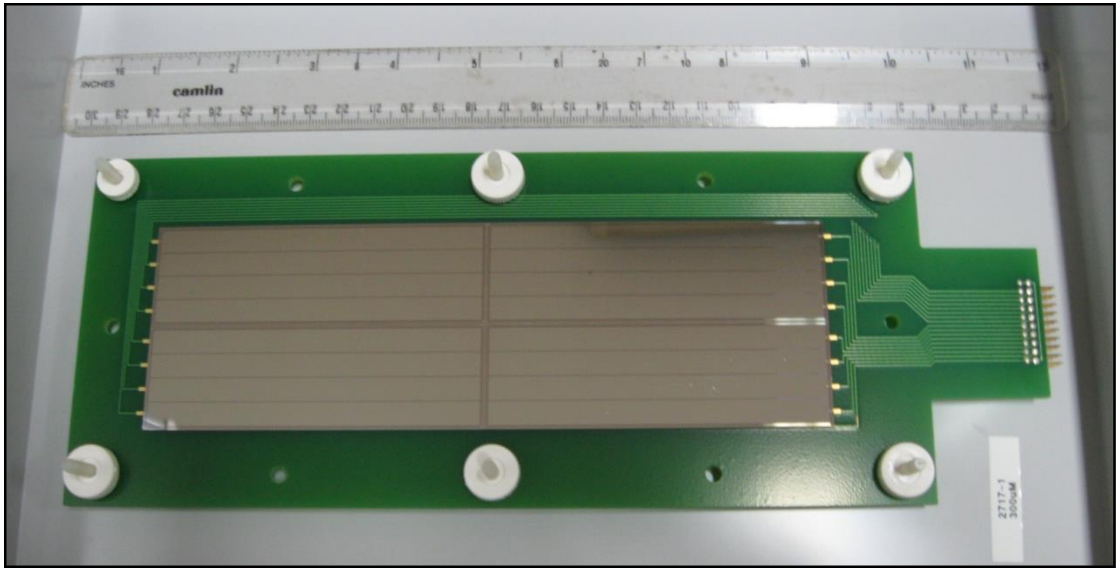


Our experimental measurements of the fission of pre-actinides validates the predictions of recent macroscopic-microscopic calculations

D. Paul, A. Sen , T. K. Ghosh et al; Phys Rev C 102, 054604 (2020)

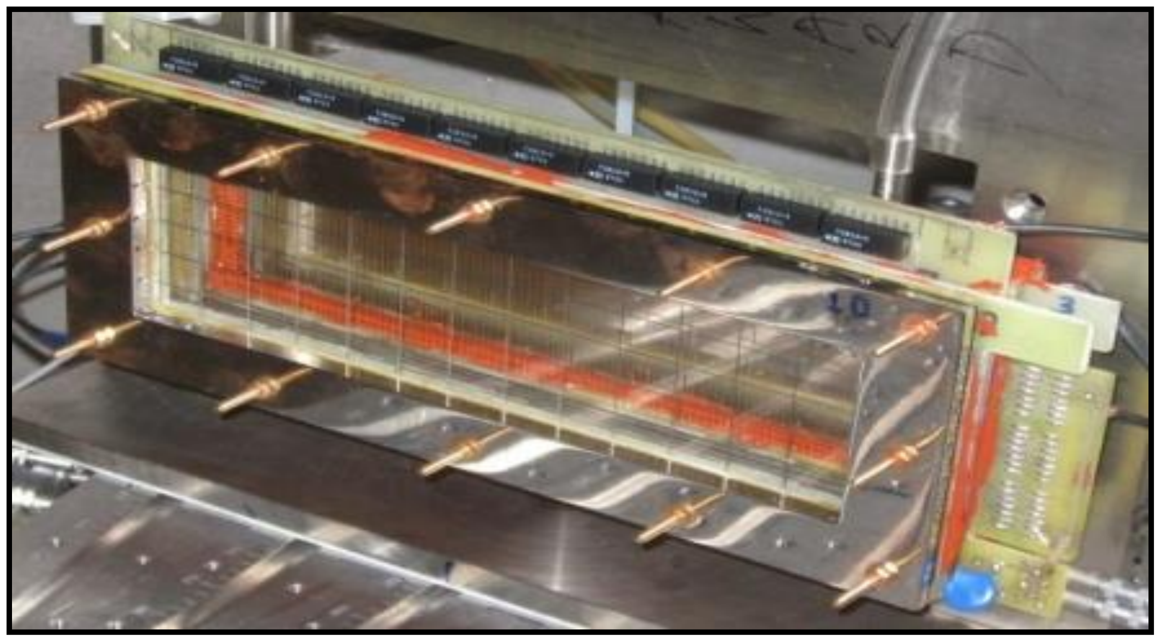
D. Paul, A. Sen , T. K. Ghosh et al; Phys Rev C 104, 024604 (2021)

New hybrid detector development



Segmented silicon detector

Hybrid gas detector



Beams Accelerated through Linac

Ever since the SC Linac has been operational several ion beams have been accelerated and delivered for user experiments in the Hybrid Recoil Mass Analyzer (HYRA) and the Neutron Detector Array (NAND) facilities at the centre. Table 2 below lists the various beam species accelerated through the linac alongside its charge state, the total energy, the maximum energy gain from linac, the experimental facility using the beam and the year of delivery:

S. No.	Beam species	Charge state	Total beam energy	Max. Egain from Linac	Experimental facility (year)
1	^{48}Ti	15+	300 MeV	132 MeV	NAND (2015)
2	^{37}Cl	13+	245 MeV	95 MeV	HYRA (2015)
3	^{35}Cl	13+	259 MeV	109 MeV	HYRA (2015)
4	^{18}O	8+	155 MeV	55 MeV	HYRA/NAND (2017)
5	^{16}O	8+	150 MeV	50 MeV	HYRA/NAND (2017)
6	^{30}Si	11+	212 MeV	92 MeV	HYRA (2020)
7	^{28}Si	11+	210 MeV	85 MeV	NAND (2020)
8	^{19}F	9+	190 MeV	90 MeV	HYRA (2020)

* Energy gain are as per user requirement and is not the maximum achievable value.

TIFR, Mumbai

LINAC Beam Information

The full LINAC booster has become operational since 2007. An estimate of available beam energies, based on measured average Egain ~ 8.6 MeV/q in the previous operations is given below:

Pelletron Terminal voltage =12 MV

Z	A	Q_s	β_{pell}	E_{pell}(MeV)	Q_{s2}	E_{linac}(MeV)
8	16	6	0.106	84	8	**150**
9	19	6	0.097	84	8	**150**
14	28,30	8	0.091	108	12	**210**
16	32,34	8	0.085	108	14	**230**
17	35	9	0.086	120	15	**250**

Pelletron Terminal voltage =11 MV

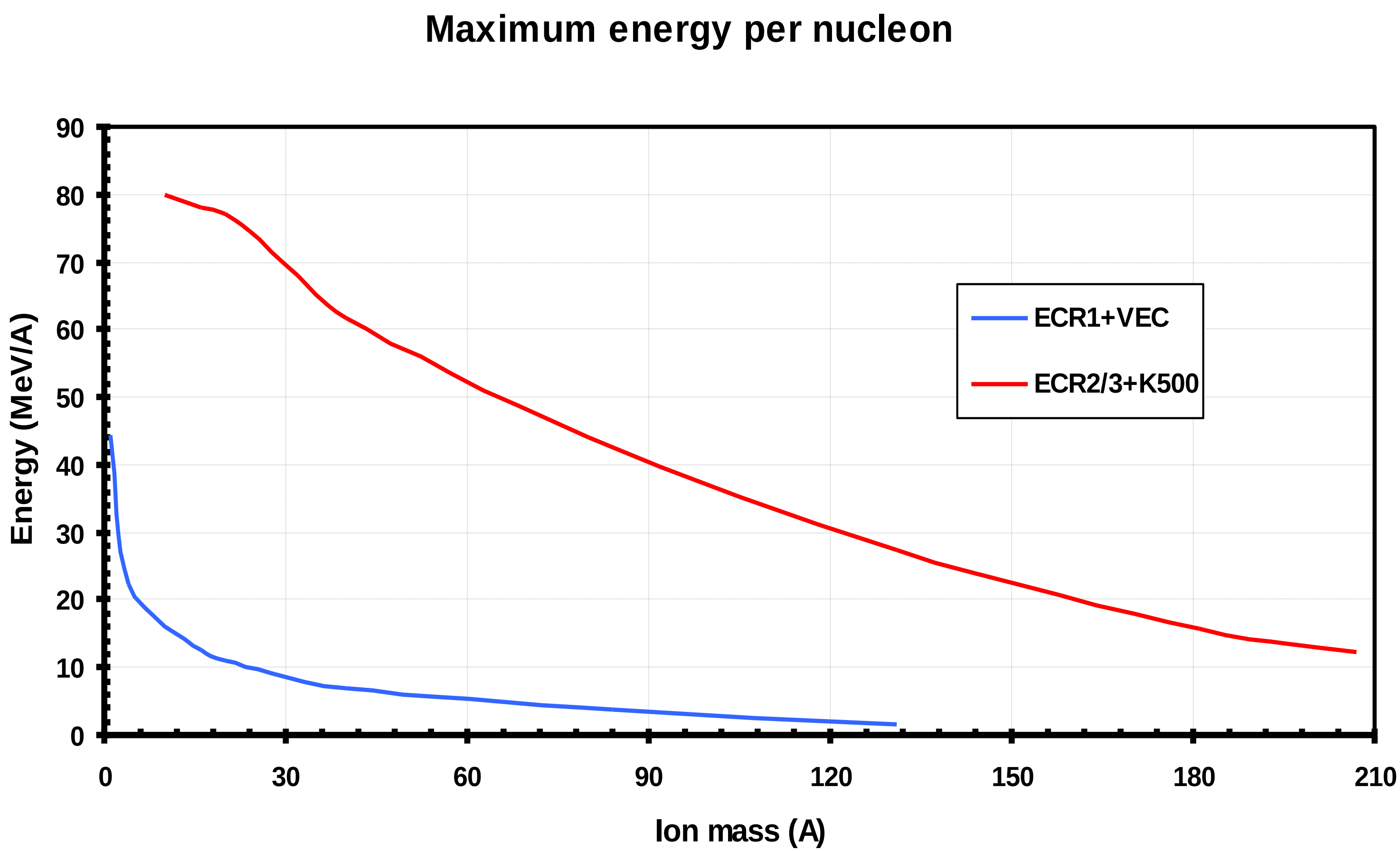
Z	A	Q_s	β_{pell}	E_{pell}(MeV)	Q_{s2}	E_{linac}(MeV)
8	16	7	0.109	88	8	**150**
9	19	7	0.0997	88	8	**150**
14	28,30	8	0.087	99	12	**200**
16	32,34	8	0.0815	99	14	**220**
17	35	9	0.082	110	15	**240**

Q_s: Most probable charge state at terminal foil stripper
E_{pell} (β_{pell}): Energy (velocity) at Pelletron exit
Q_{s2}: Most probable charge state after post tandem foil stripper

- For lower Pelletron terminal voltage (< 12 MV), velocity matching into LINAC will be very poor resulting in significantly lower energy gain than indicated in the above table.
- Taking into account the loss of beam due to bunching and by the post tandem foil stripper, expected beam intensity on the target will be 1-5 pnA (assuming 500 enA injection into the Pelletron).

Expected Ion Beams from K 500

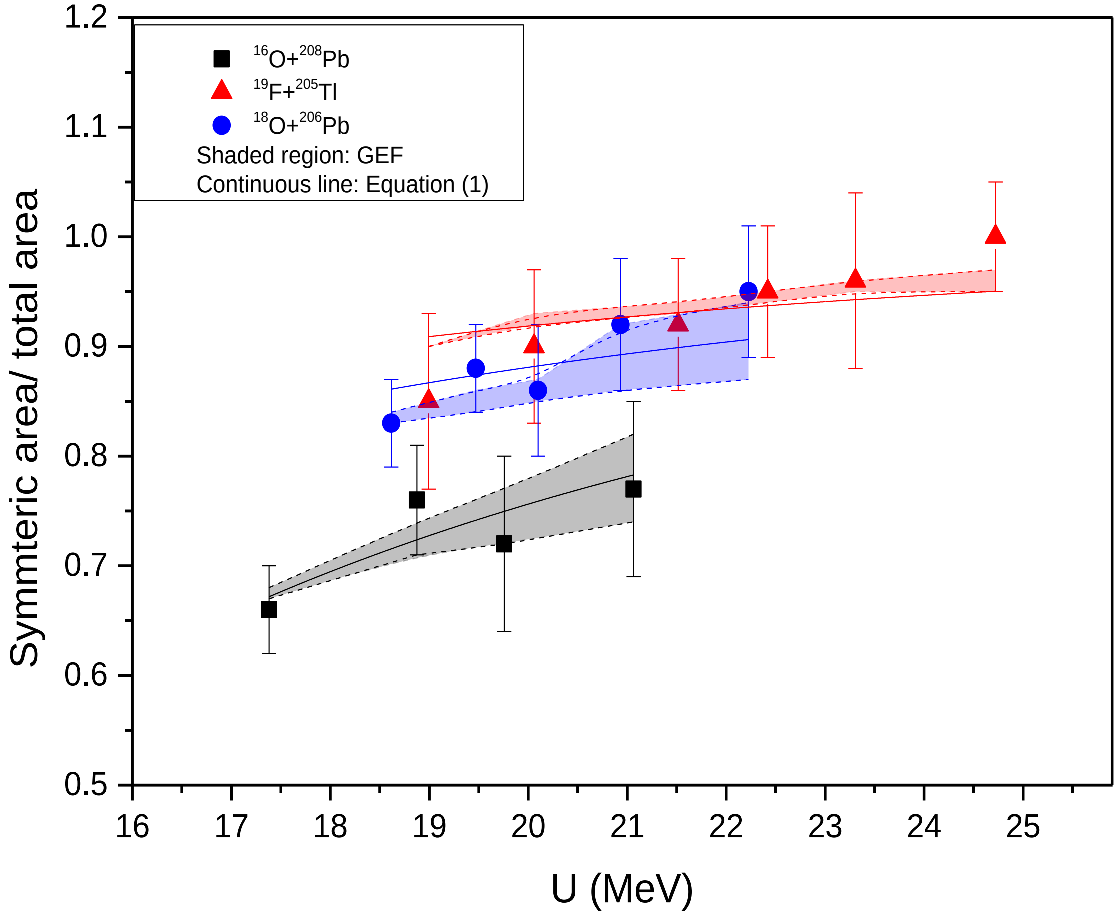
(Design value: based on 10 microamperes extracted from ion source)

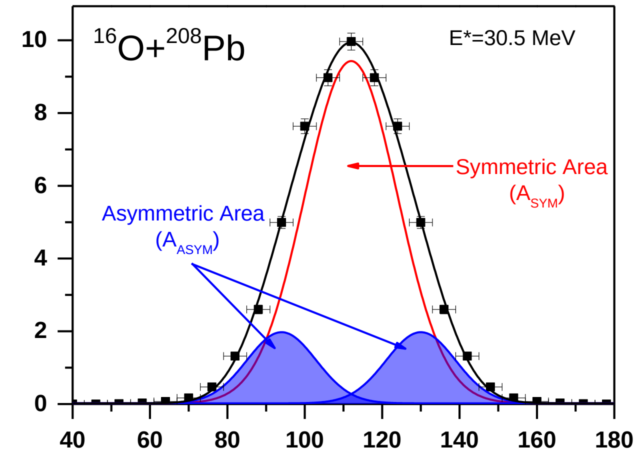


For lighter nuclei : 80 MeV/A

For heavier >A 100 : 5-10 MeV/A

Quantification of symmetric- asymmetric fission I:





The data have been fitted, with an empirical relation: Ignatyuk prescription for shell damping of nuclear level density parameter (Eqn 1):

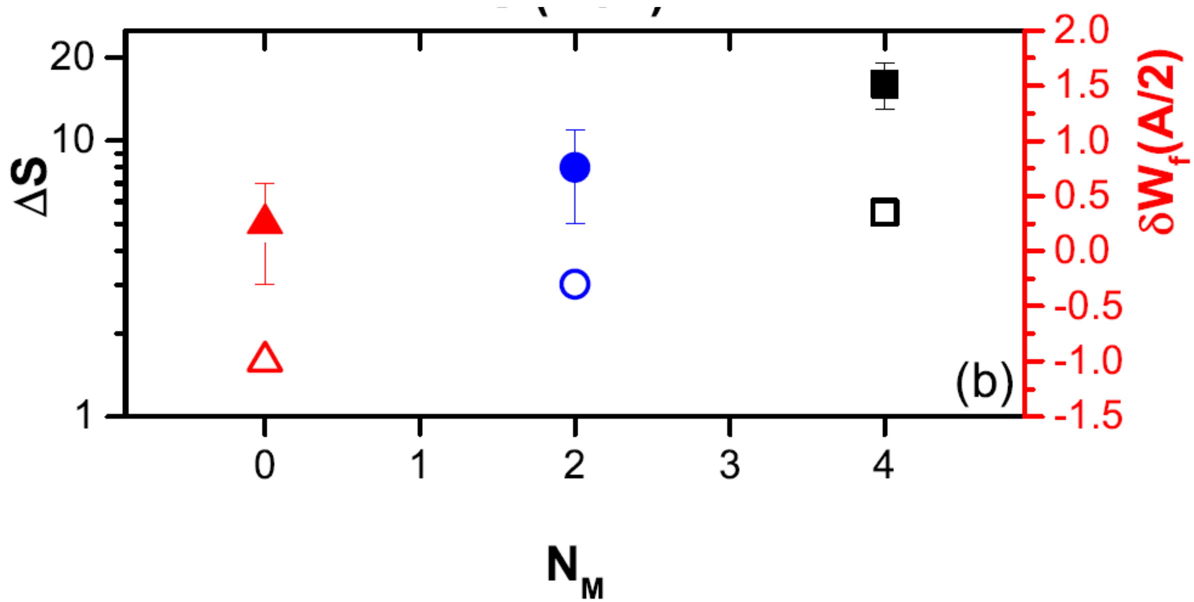
$$\frac{A_{SYM}}{A_T} = 1 - \left(\frac{\Delta S}{U}\, e^{-\gamma U}\right)$$

ΔS is related to the relative strength of the shell effects in the governing dynamics.

U= E^* - $B_f(l)$; γ:shell damping factor

Quantification of symmetric- asymmetric fission II:

To relate the factor ΔS with a known shell parameter, the parametric description proposed by Itkis *et.al is* used, as implemented by the code GEF.



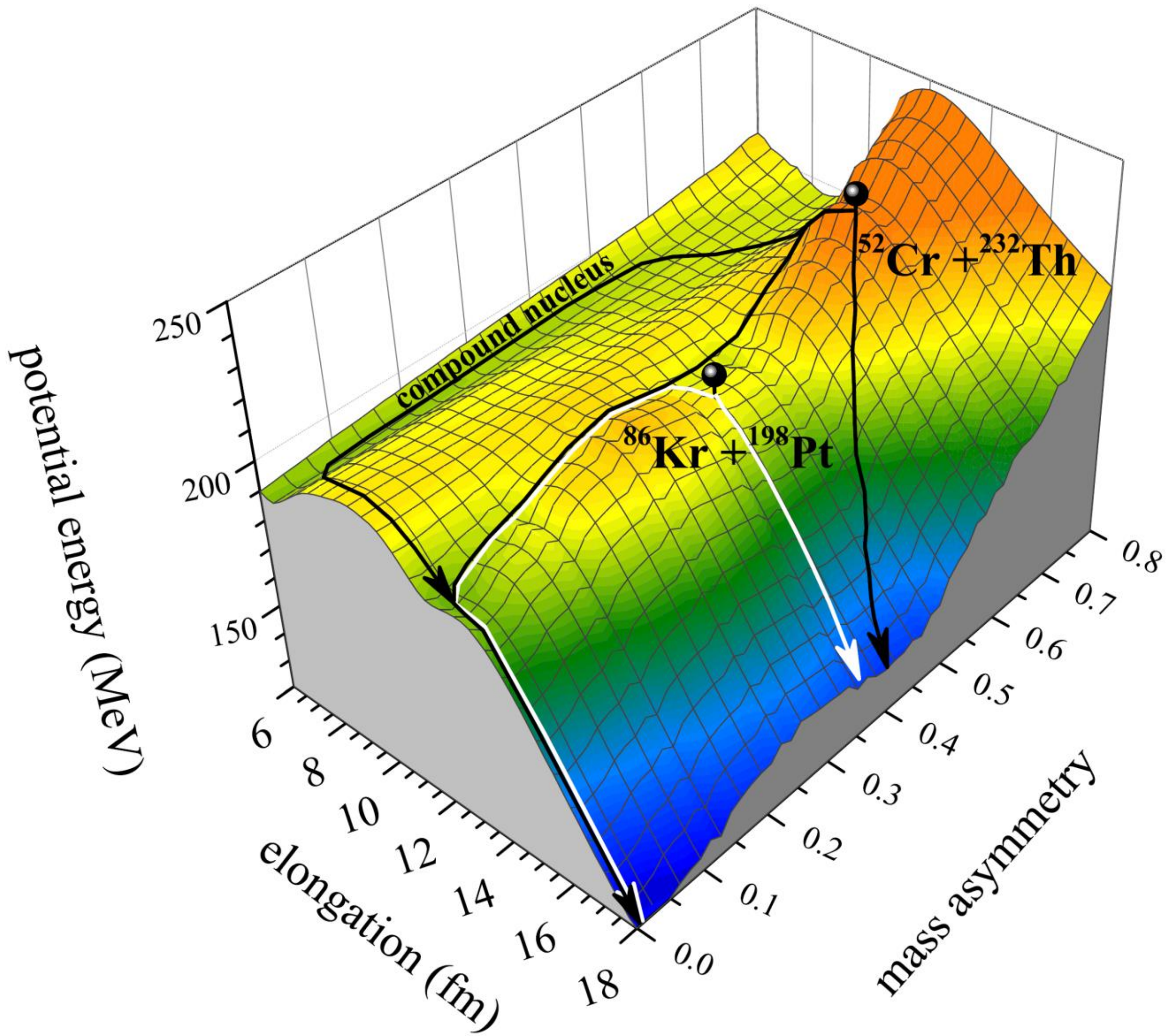
The shell effect at symmetry δW_f (A/2) was varied to best fit the data

$$Y(m) \sim \exp\left(-\frac{q}{2\theta}\left(M-\frac{A}{2}\right)^2 - \frac{\delta W_f(M)}{\theta}\exp(-\gamma U)\right)$$

$$\delta W_f(M) = \delta W_f\left(\frac{A}{2}\right)\exp\left(-\lambda\left(M-\frac{A}{2}\right)^2\right)$$

M.G. Itkis, *et. al.* Yad. Fiz., 1225 (1991)

The entrance channel magicity index is directly correlated with the observable change in the shell effects in the dynamics of the fission process.



potential energy (MeV)
250
200
150
compound nucleus
^{52}Cr + ^{232}Th
^{86}Kr + ^{198}Pt
6
8
10
12
14
16
18
elongation (fm)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
mass asymmetry