Research activities using HIRA and HYRA spectrometers at IUAC, New Delhi and future plans

N. Madhavan, IUAC (New Delhi)

International workshop on Future Plan with Radioactive Ion Beam, SINP Kolkata, April 16, 2012

Plan of the talk:

Brief introduction to Inter University Accelerator Centre (Nuclear Science Centre)

Heavy Ion Reaction Analyzer (HIRA) - An introduction

Experiments using HIRA - Various types, Salient results

Light secondary RIB (7Be) using HIRA in direct reaction & inverse kinematics

Hybrid Recoil mass Analyzer (HYRA) – An introduction

HYRA – TIFR 4π Spin Spectrometer combination for ER spin distribution in heavy CN

Future Plans

Inter University Accelerator Centre (Formerly ' Nuclear Science Centre'), New Delhi (First Inter University Centre in India funded by University Grants Commission)

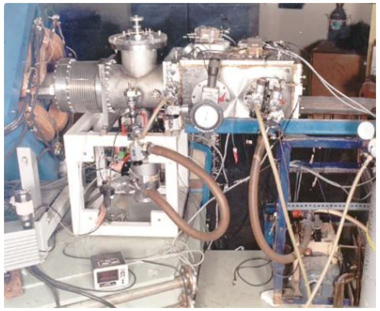
15 UD Pelletron Accelerator + Nb-based SC LINAC booster + High T_c ECR based alternate injector

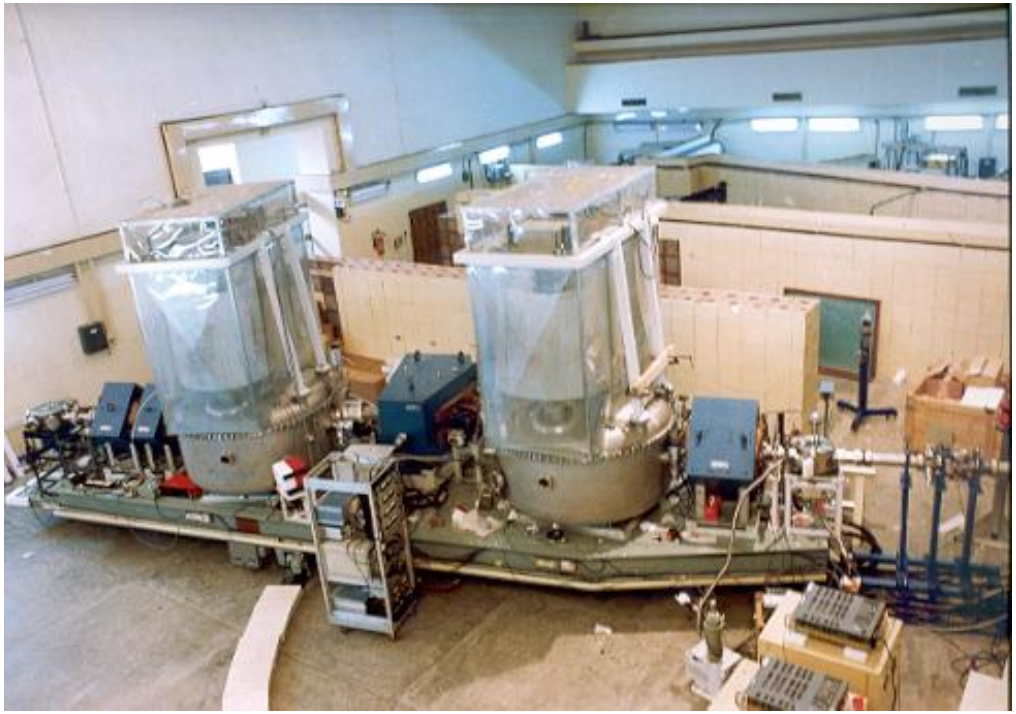
Vacuum mode RMS , Large Gas-filled separator, Gamma Detector Array, Indian National Gamma Array, Large General Purpose Scattering Chamber, Neutron Detector Array

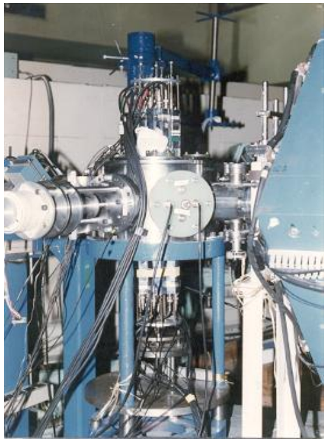
Materials Science, Radiation Biology, Accelerator Mass Spectrometry

Heavy Ion Reaction Analyzer (HIRA)

(A. K. Sinha, N. Madhavan, et al.)







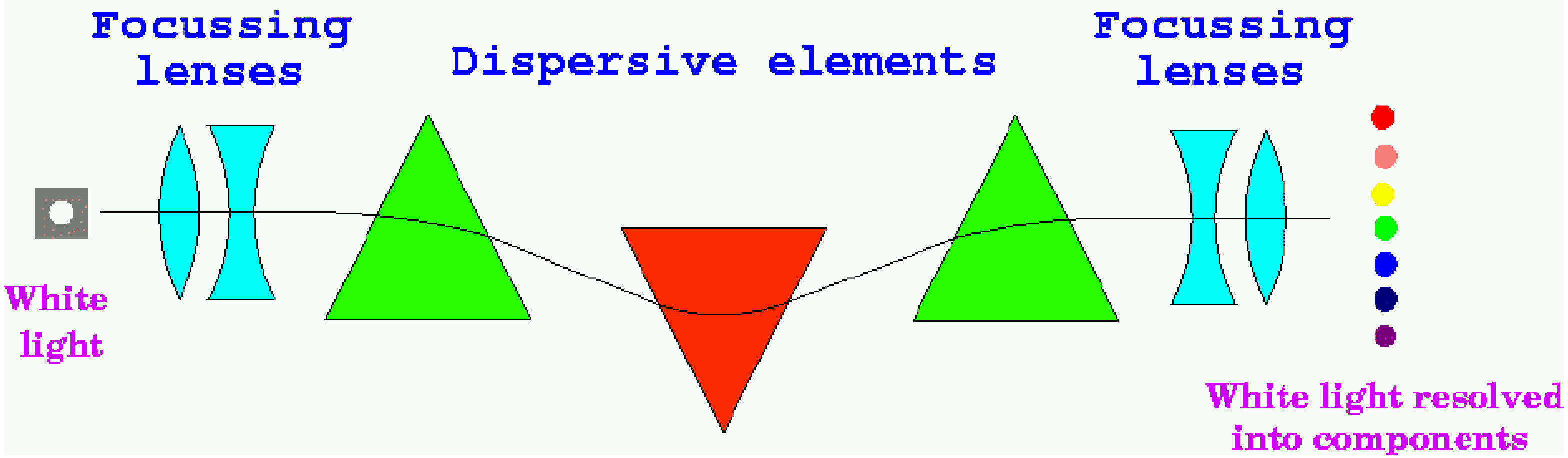
One of 4 recoil mass spectrometers of this kind in the world

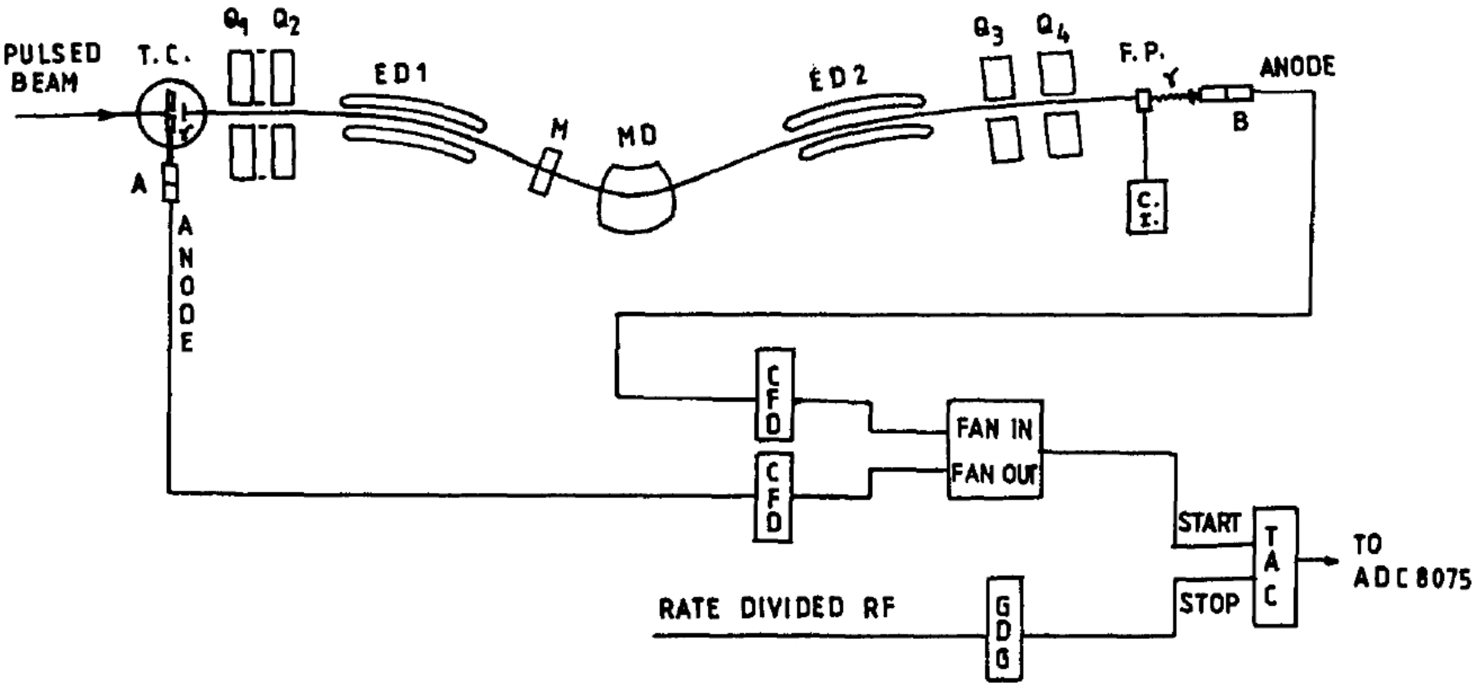
Uses electrostatic and magnetic fields for dispersion and focusing

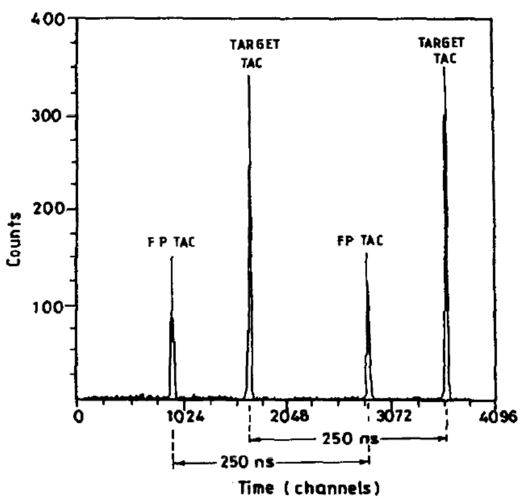
Excellent primary beam rejection at 0^o (~ 10^{10} or better)

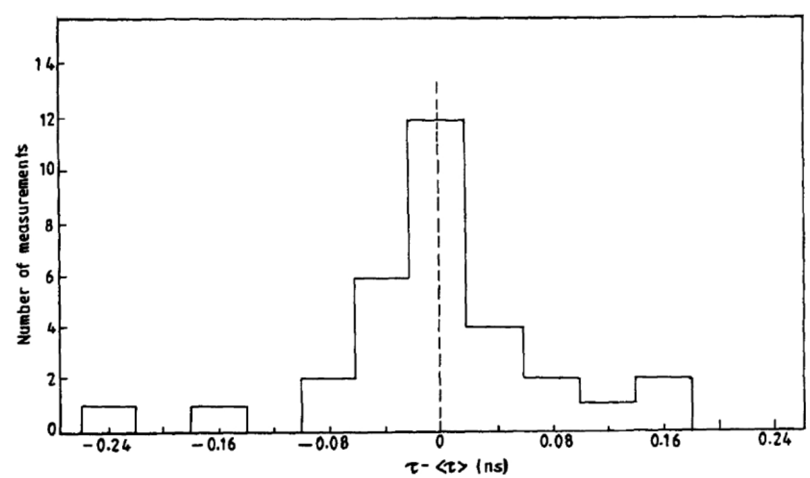
Mass spectrum at focal plane position sensitive detector

Optical analog of HIRA



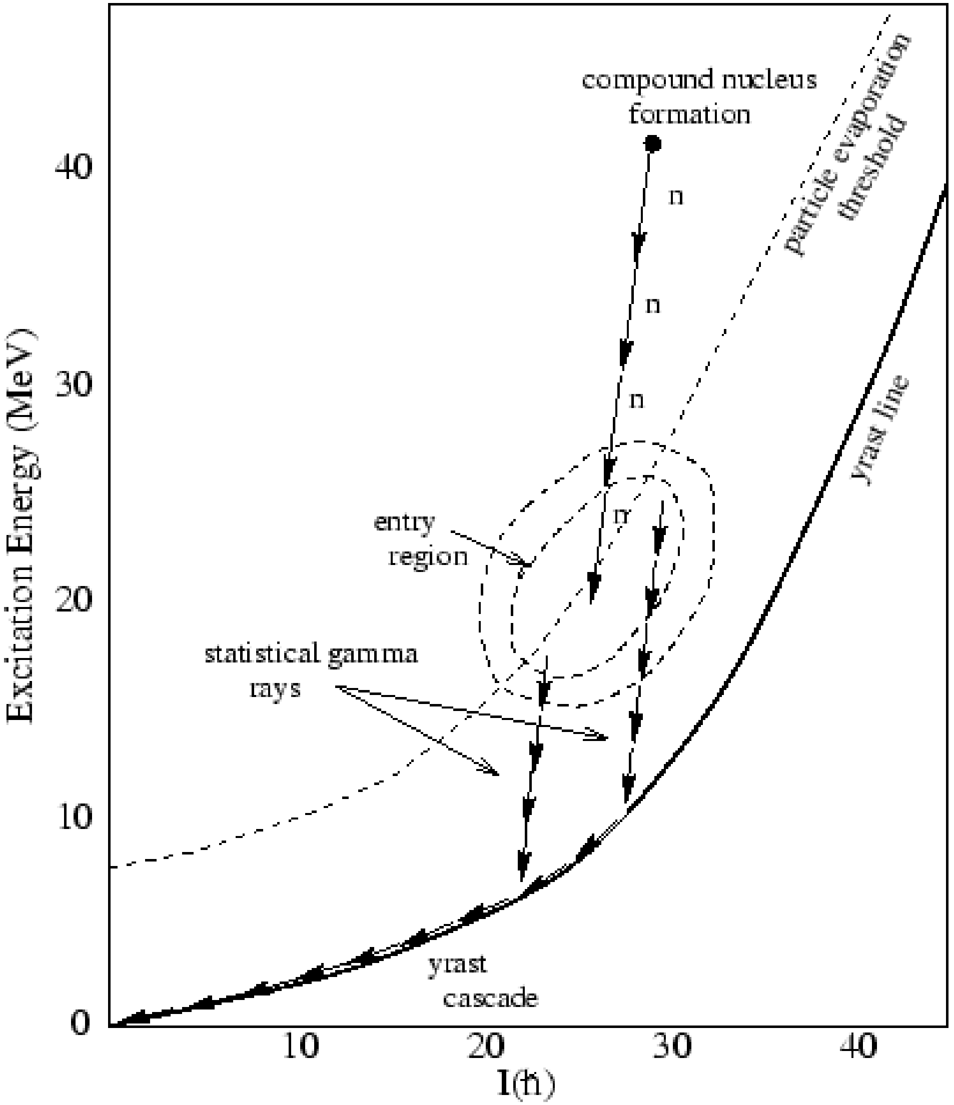


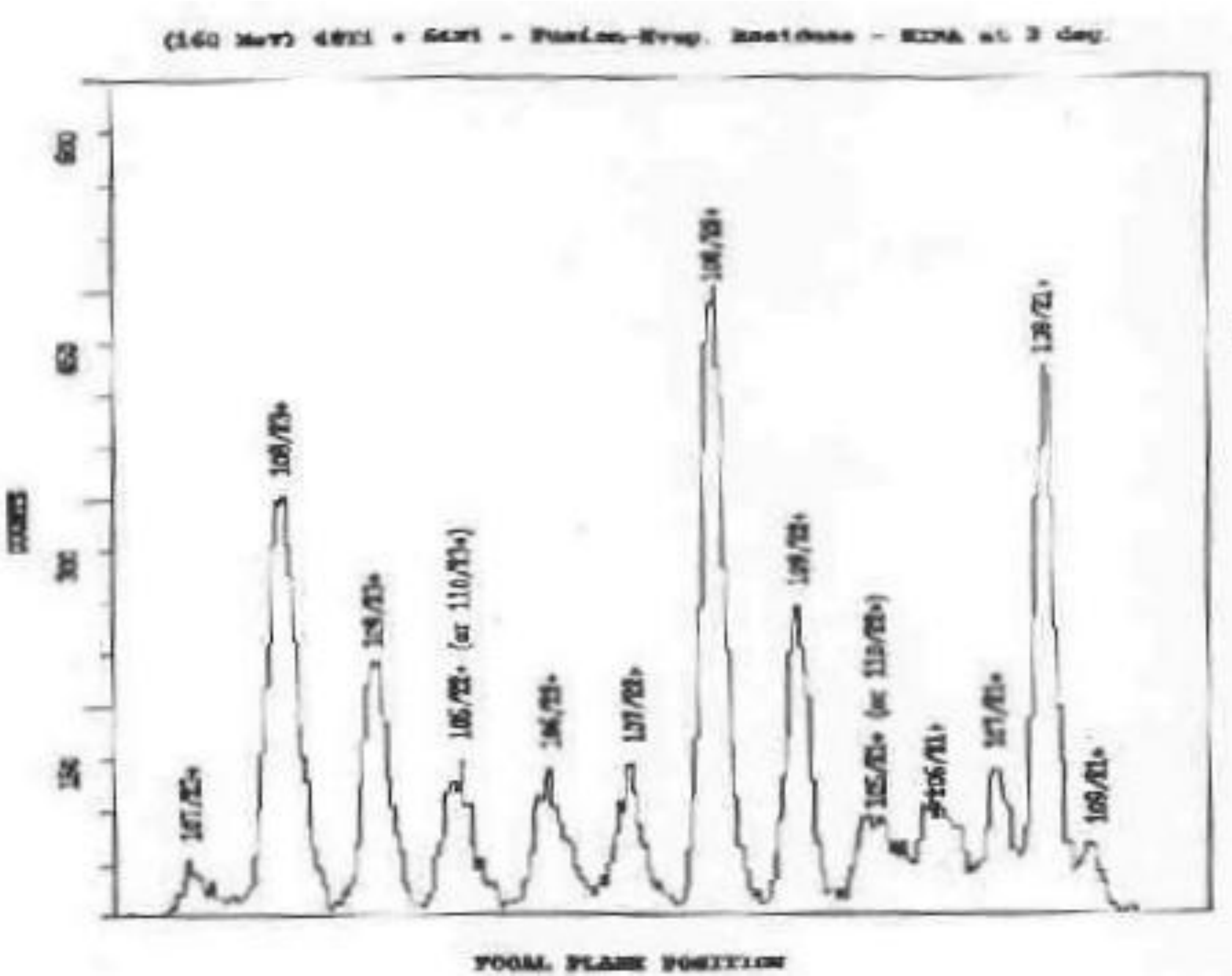




Beam energy (Analyzer magnet) calibration using Time-Of-Flight through HIRA

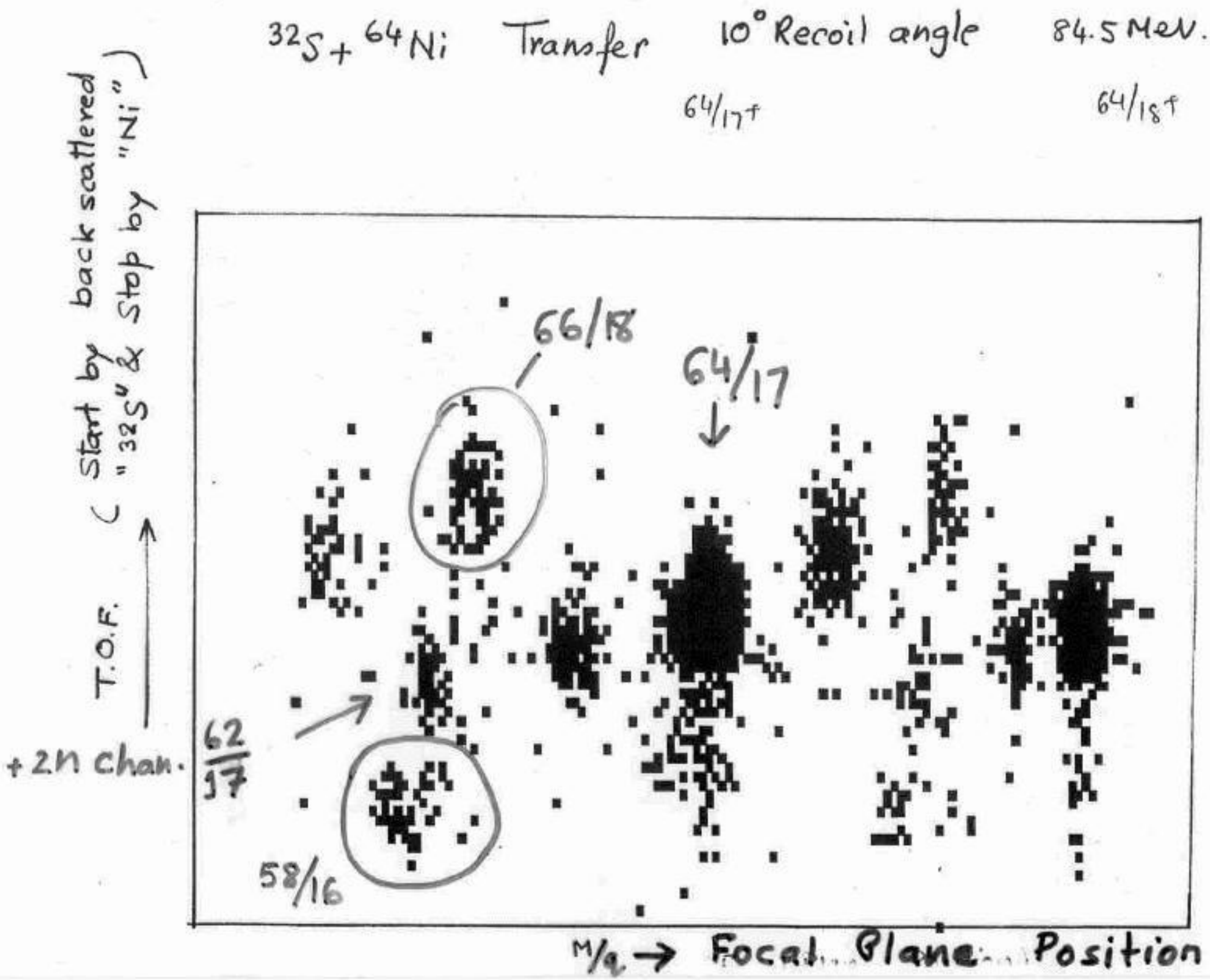
Compound Nucleus (CN) de-excitation





A typical (m/q) spectrum at the focal plane of HIRA

(m/q) ambiguity overcome using energy and TOF measurements in Transfer around barrier



Experiments using HIRA :

Fusion around barrier (channel coupling effects, entrance channel dependence, Effects of shell closure spin distribution, barrier distribution, etc.)

Transfer around barrier (slope anomaly, Z & A identification through coincidence, transfer to excited states and ground state, etc.)

ER tagged gamma spectroscopy of weak channels

Search for microsecond isomers around N ~ 50

ER tagged LCP emission

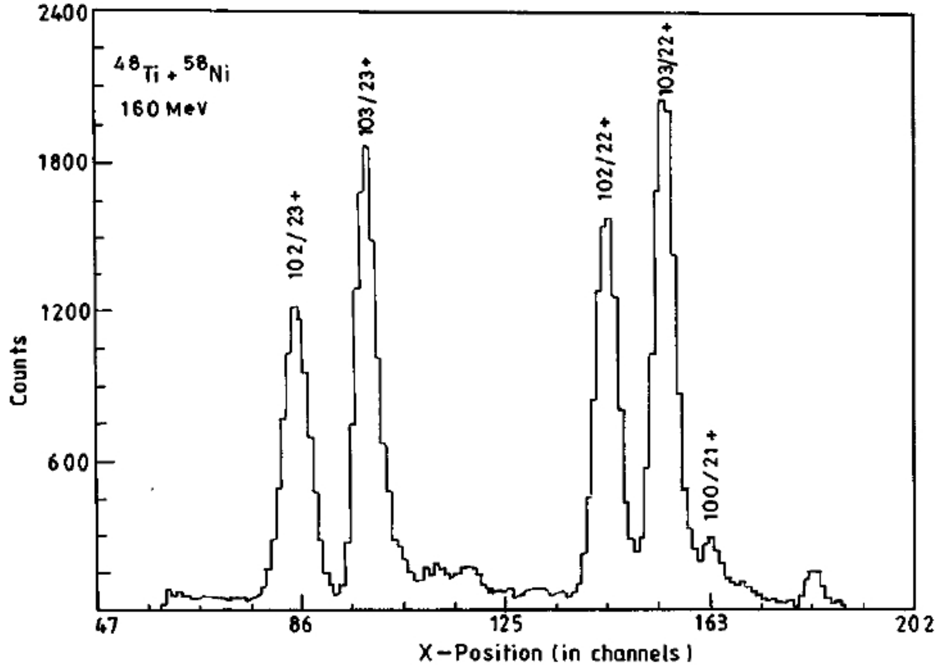
Extraction of $S_{17}(0)$ factor

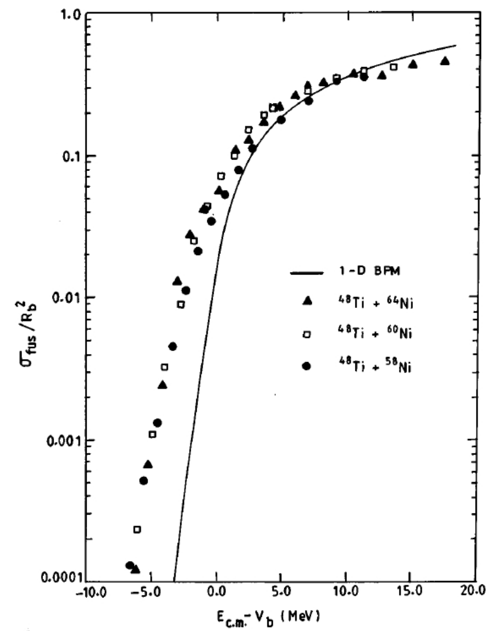
^{7}Be + ^{7}Li mirror nuclear scattering

Effect of electronic environment on decay rate of ^{7}Be

Fission hindrance – (heavier system)

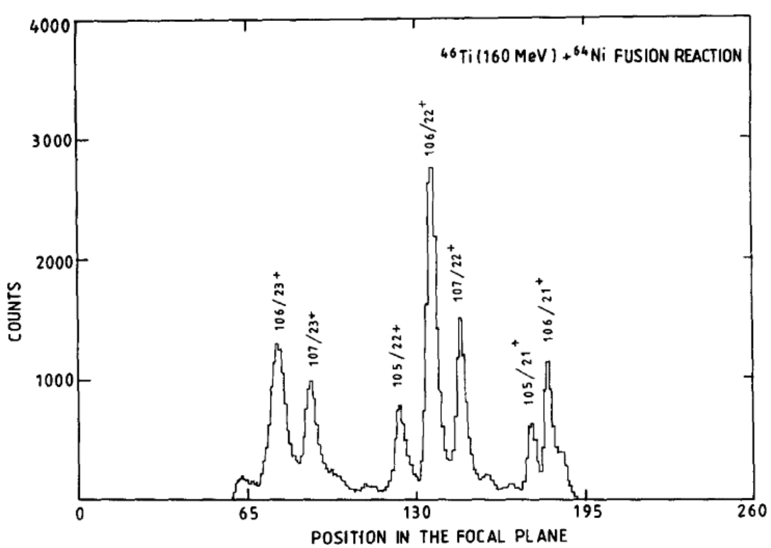
Sub-barrier fusion - Absence of isotopic dependence in $^{48}Ti + ^{58,64}Ni$ - V. Prasad et al.

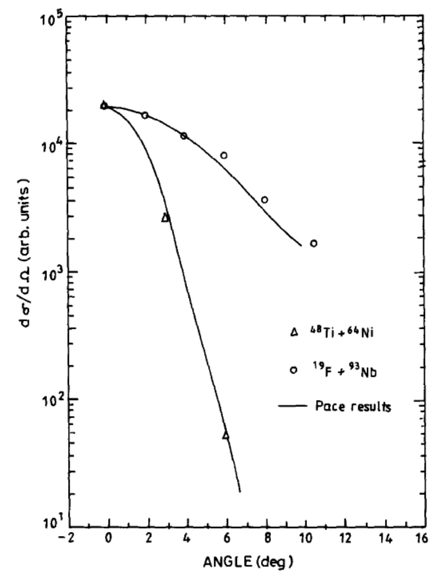




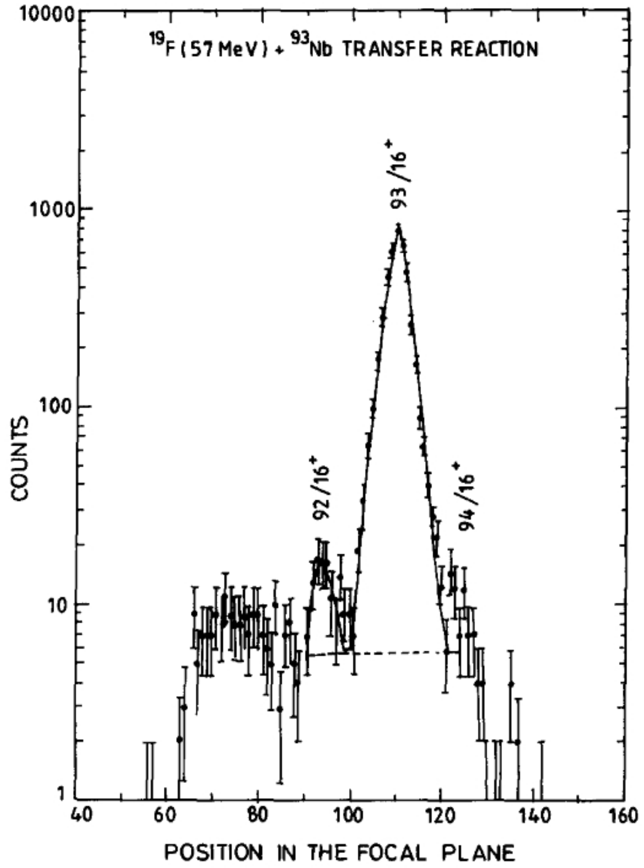
N.V.S.V. Prasad et al. / Nuclear Physics A 603 (1996) 176–202

N.V.S.V. Prasad et al. / Nuclear Physics A 603 (1996) 176–202 183

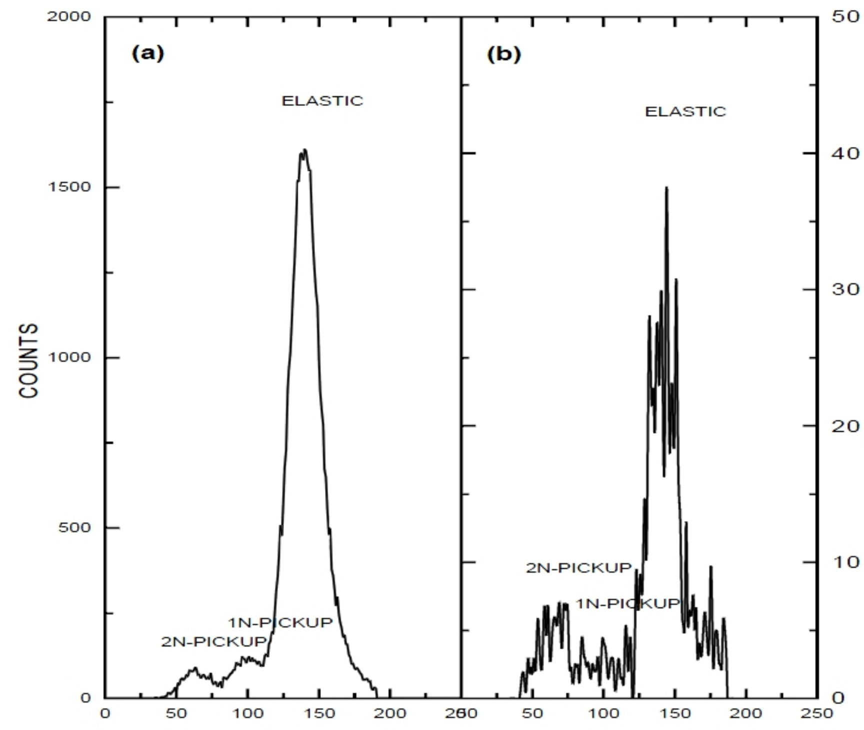




184 N.V.S.V. Prasad et al. / Nuclear Physics A 603 (1996) 176–202



Ground state 2n pickup probability



Transfer around barrier – Associated recoil detection in HIRA – Ground and Excited state transfer

Table 1. Measured transfer probability for the $1n$ and $2n$ pickup channel at 78 MeV.

	$(P_{tr})_{tot}$	$(P_{tr})_{ex.}$	$(P_{tr})_{gs}$
+ $1n$	0.0580 ± 0.0006	-	-
+ $2n$	0.0450 ± 0.0006	0.041 ± 0.002	0.004 ± 0.002

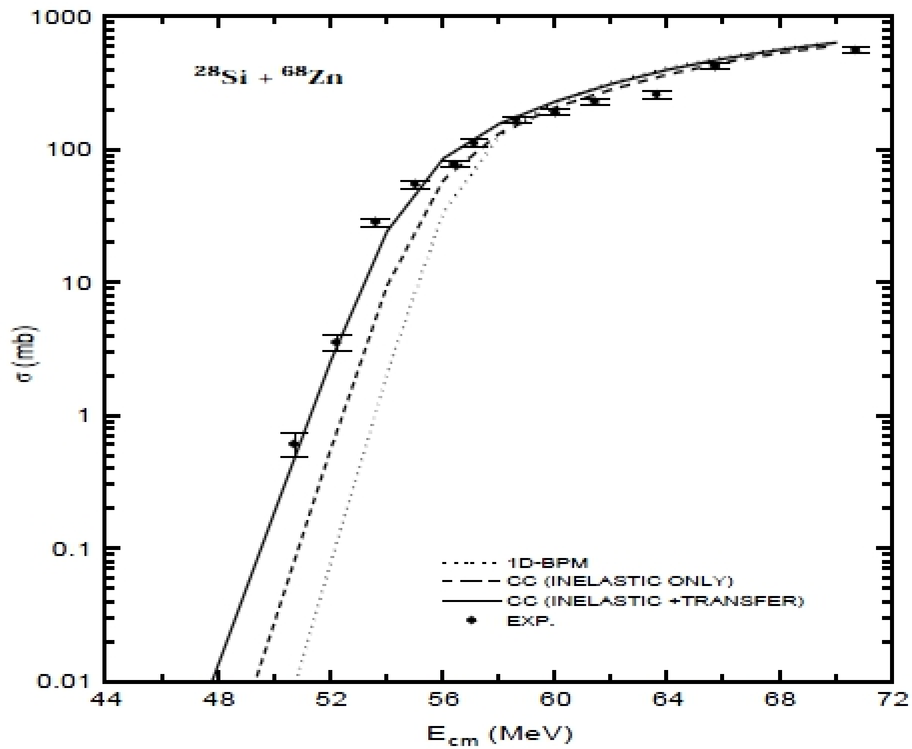
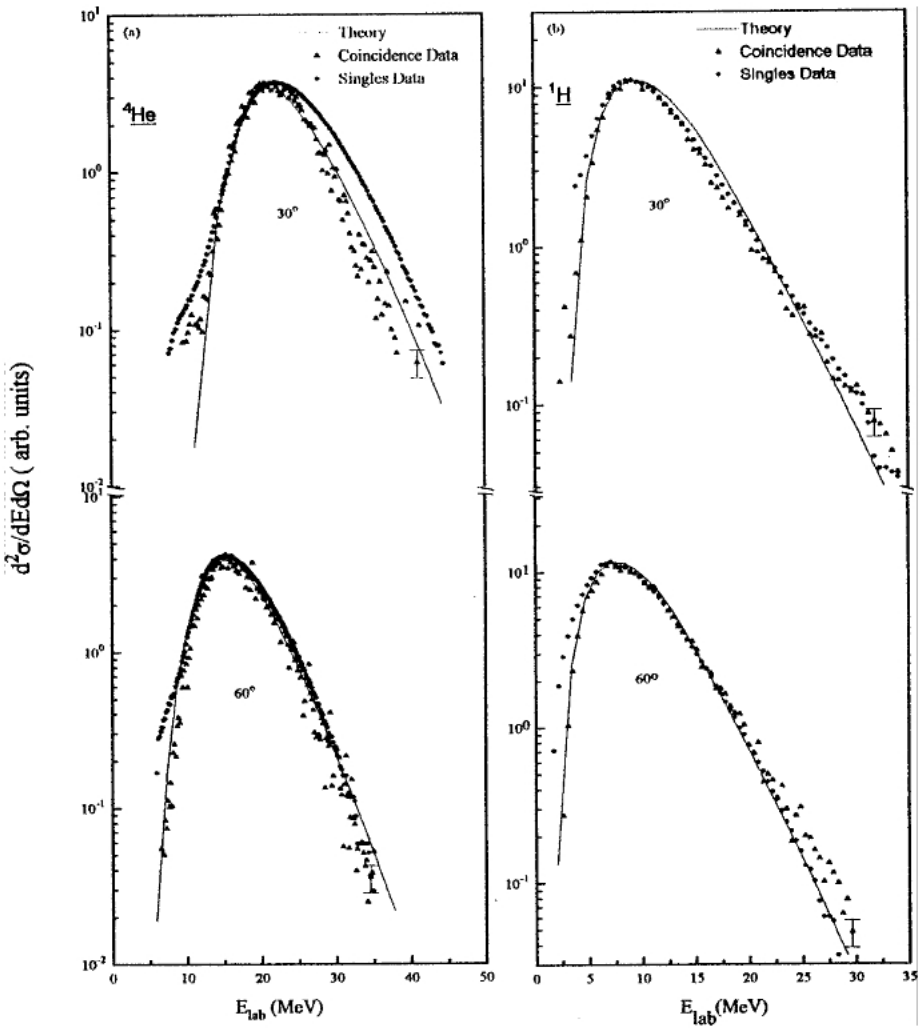
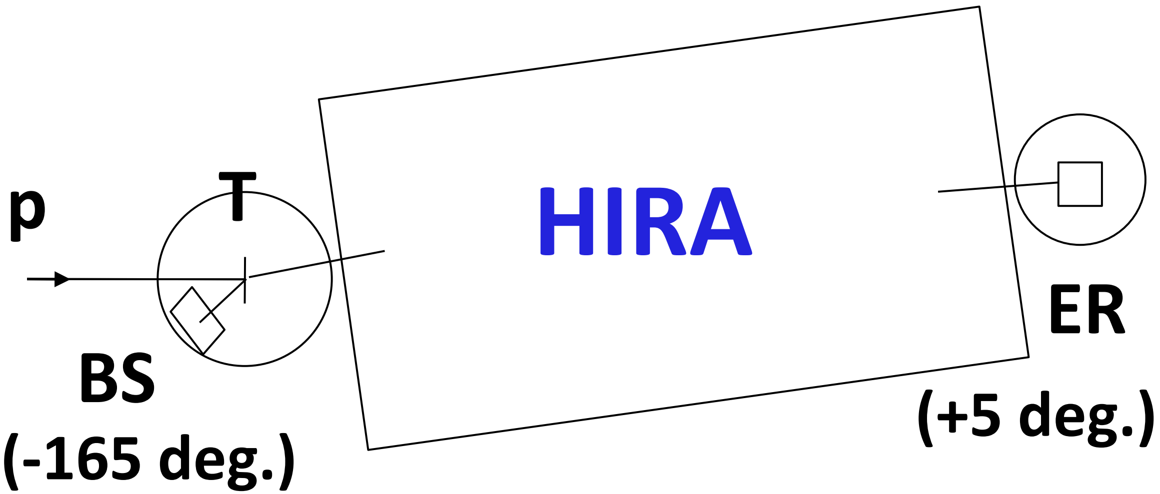


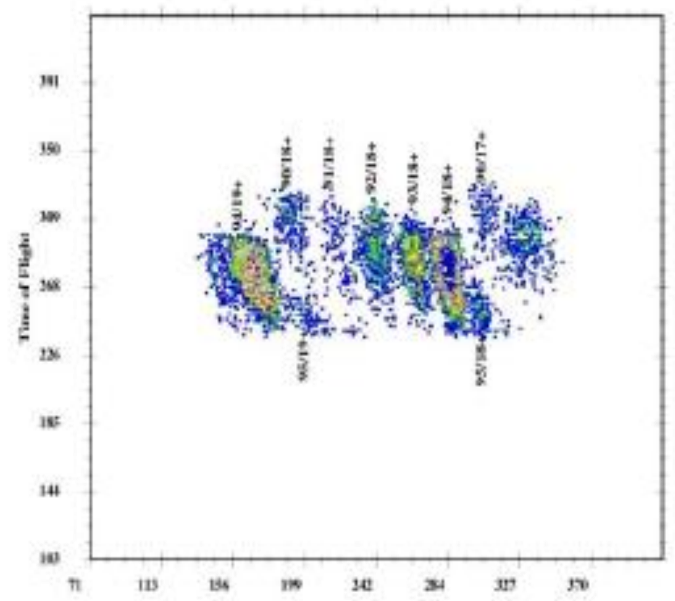
Figure 2. Simplified coupled channel calculations for the system ^{28}Si + ^{68}Zn.



Evaporation Residue tagged Light Charged Particle Emission – I. M. Govil et al.

^{28}Si + ^{51}V fusion reaction - NLD parameter, Deformation and Limiting angular momentum

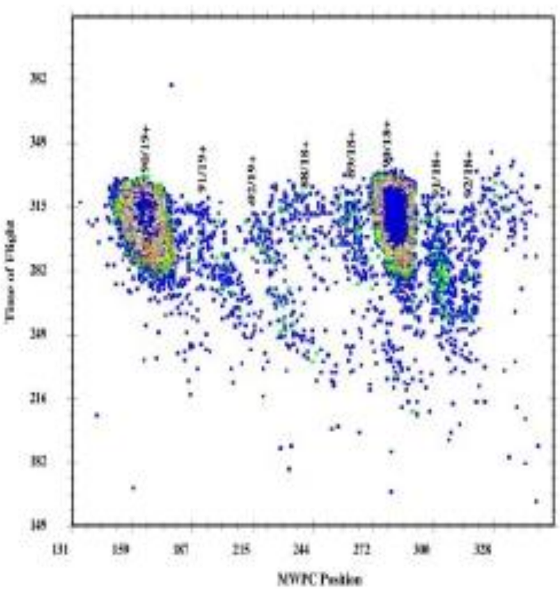




BS: E ; ER: X, DE, TOF ;

Coincidence Measurement, Gamma

^{28}Si (98 MeV) + ^{90}Zr



Transfer Measurements

(S. Kalkal et al.)

. Q-value distribution

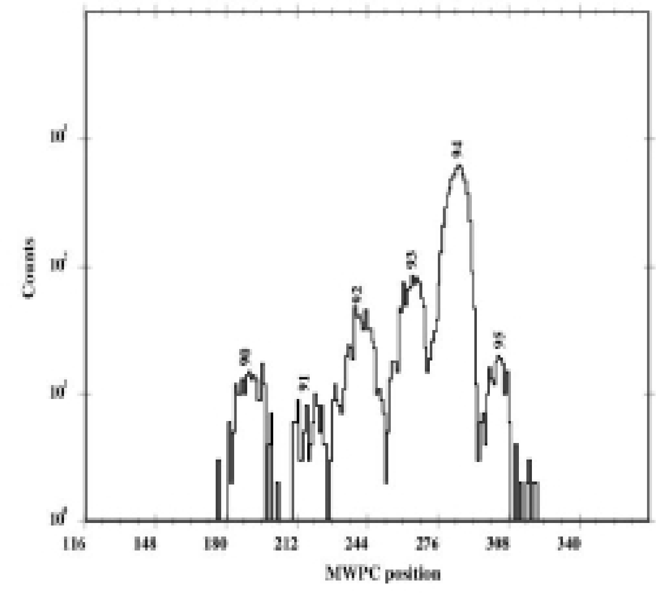
. Multi-nucleon transfer

. Transfer probability

. Cold, Pair transfer (!)

. Effect of large change in E(4+)/E(2+)

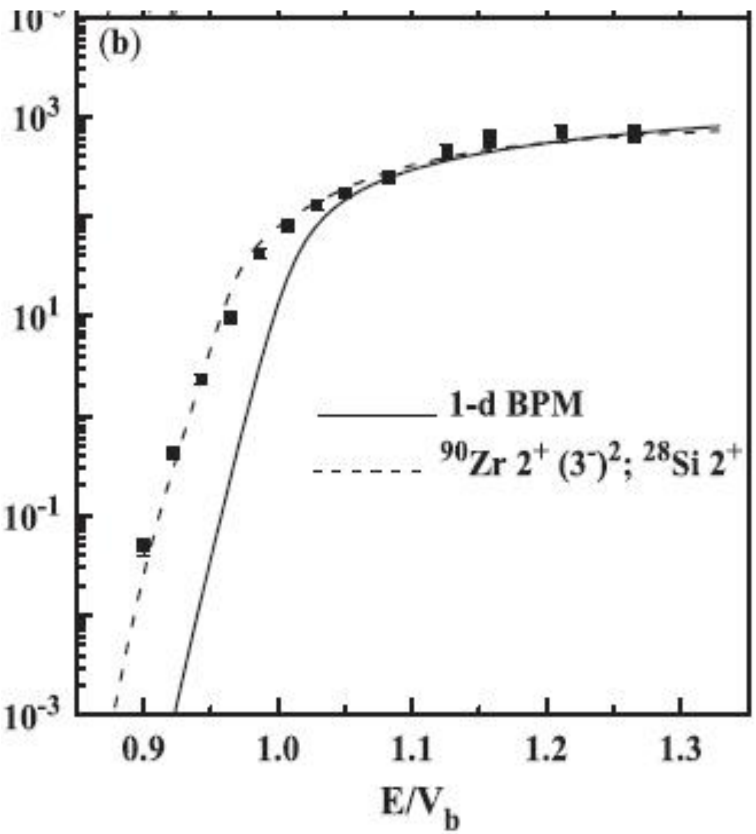
^{28}Si (94 MeV) + ^{94}Zr

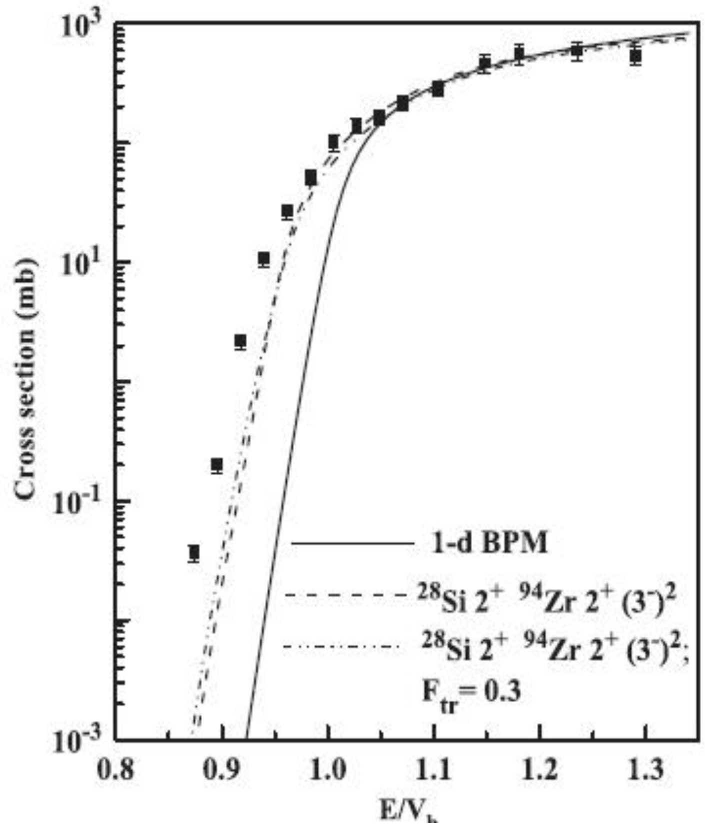


Salient results - S. Kalkal, S. Mandal. N. Madhavan, et al.:

I. Sub barrier fusion cross section showed that $^{28}Si + ^{94}Zr$ has more enhancement than $^{28}Si + ^{90}Zr$ thereby requiring additional transfer channel coupling.

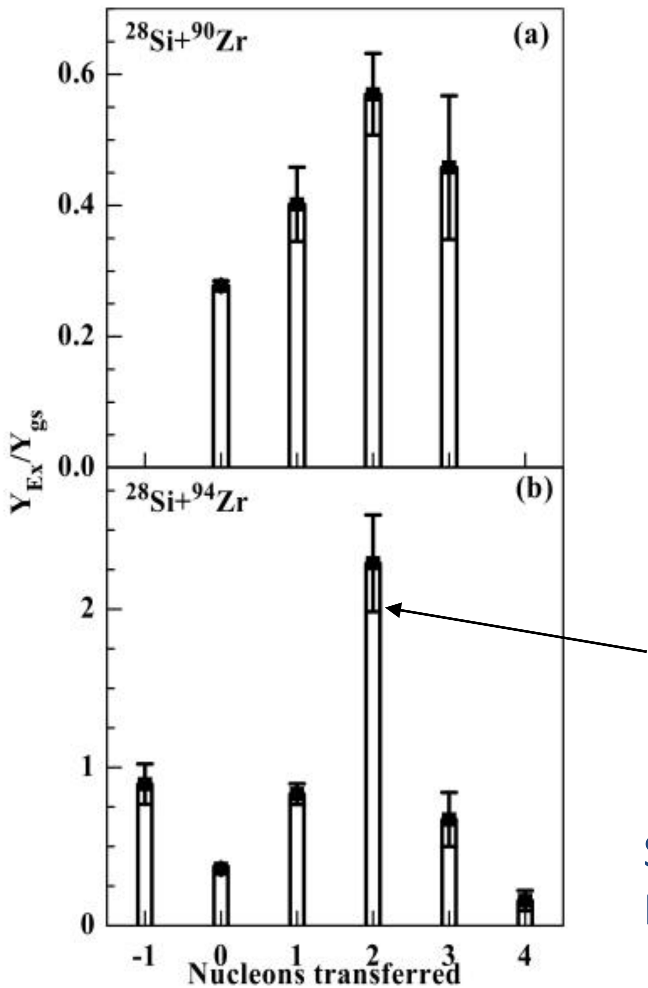
II. Up to 4 neutron pickup and 1 proton stripping observed in $^{28}Si + ^{94}Zr$ transfer around barrier and transfer strengths for $^{28}Si + ^{90}Zr$ were much lesser.





Salient results from S. Kalkal's experimental run:

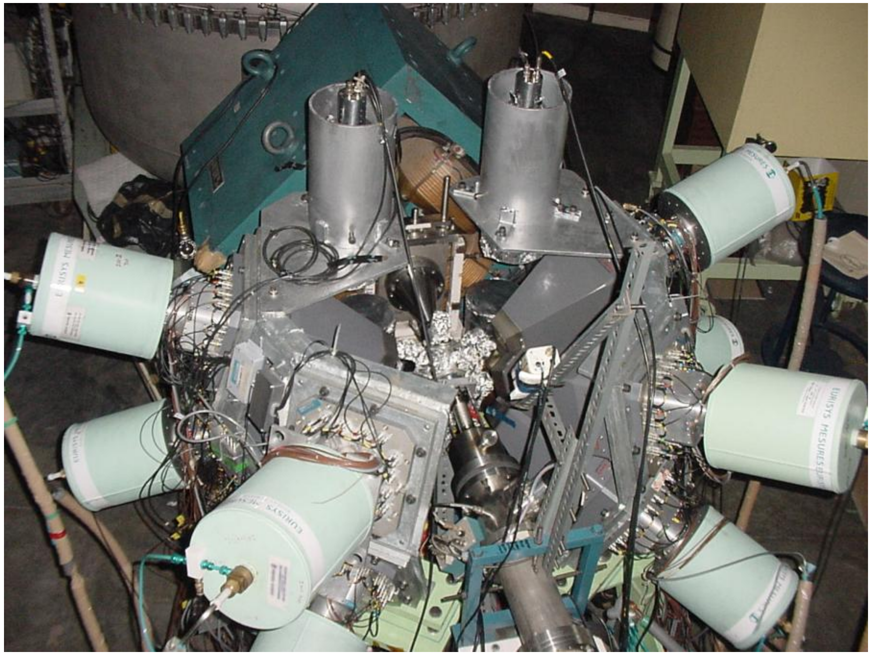
III. Excited state two neutron transfer is twice that of corresponding ground state transfer in ^{28}Si + ^{94}Zr while it is half of ground state transfer for ^{28}Si + ^{90}Zr system.



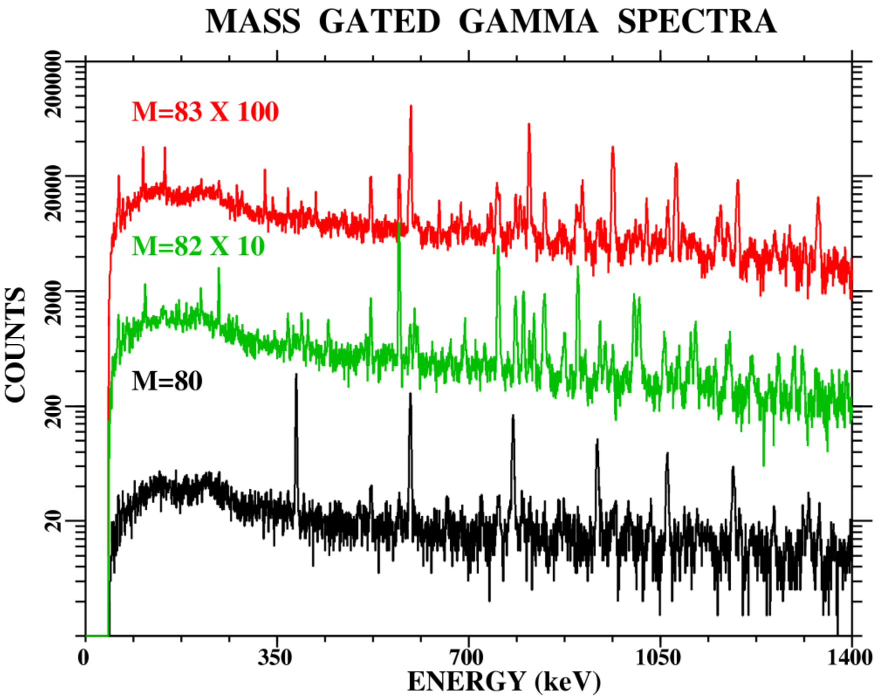
"Sign of correlated neutron pair transfer?!" - NM

S. Kalkal, S. Mandal, N. Madhavan, et al., PHYSICAL REVIEW C **83, 054607 (2011)**

HIRA-INGA-CPDA setup at NSC



Mass gated gamma spectra for masses 80, 82 and 83 amu
Gamma rays from a nucleus are its "finger-prints"

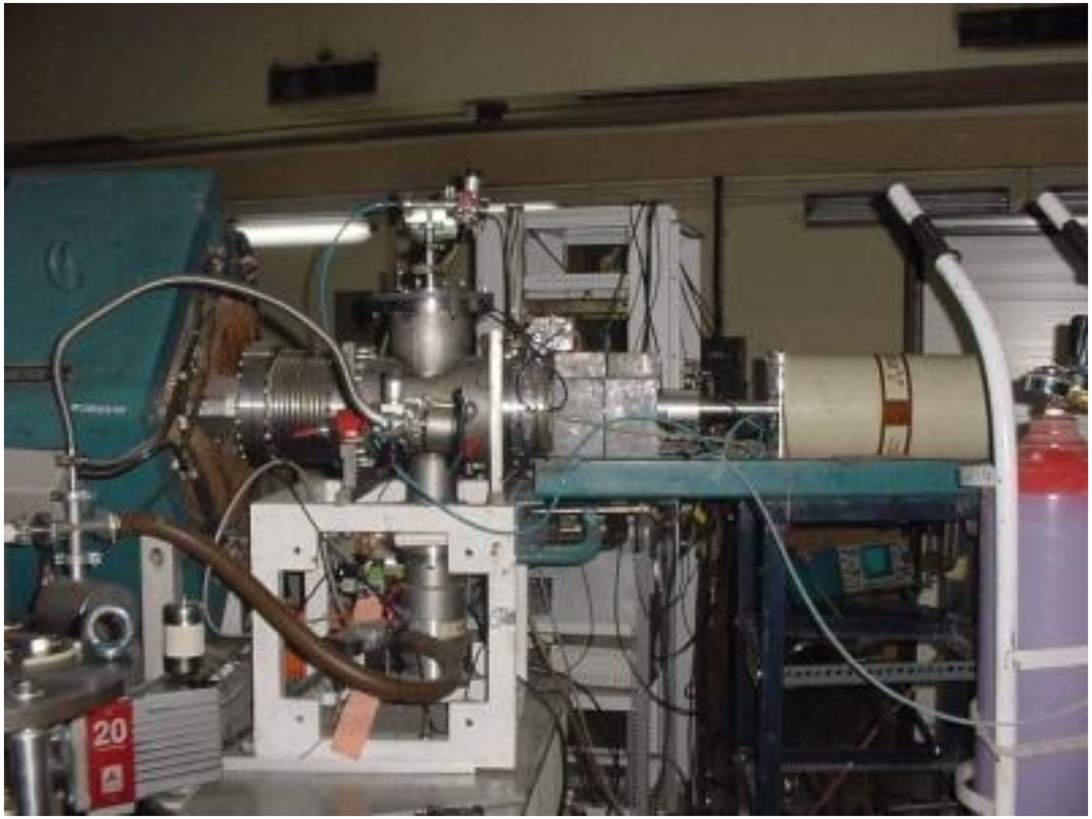


Studying properties of weakly produced nuclei is similar to 'making sense of a child's whisper in a noisy crowd' - poor 'signal-to-noise'

Need to reduce the background by taking the nucleus to less background area before it decays

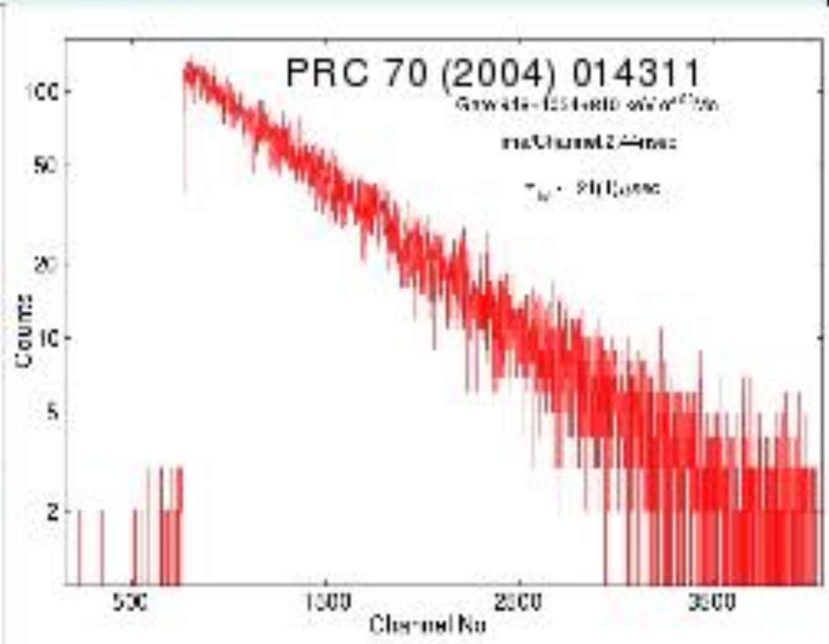
Isomer decay studies at focal plane of HIRA

Ideal for micro-second isomers – Flight time of ERs in HIRA
Excellent, background-free region – Focal plane of HIRA
Mass selected ERs stopped in catcher foil and delayed gamma transitions recorded using gamma detector at focal plane

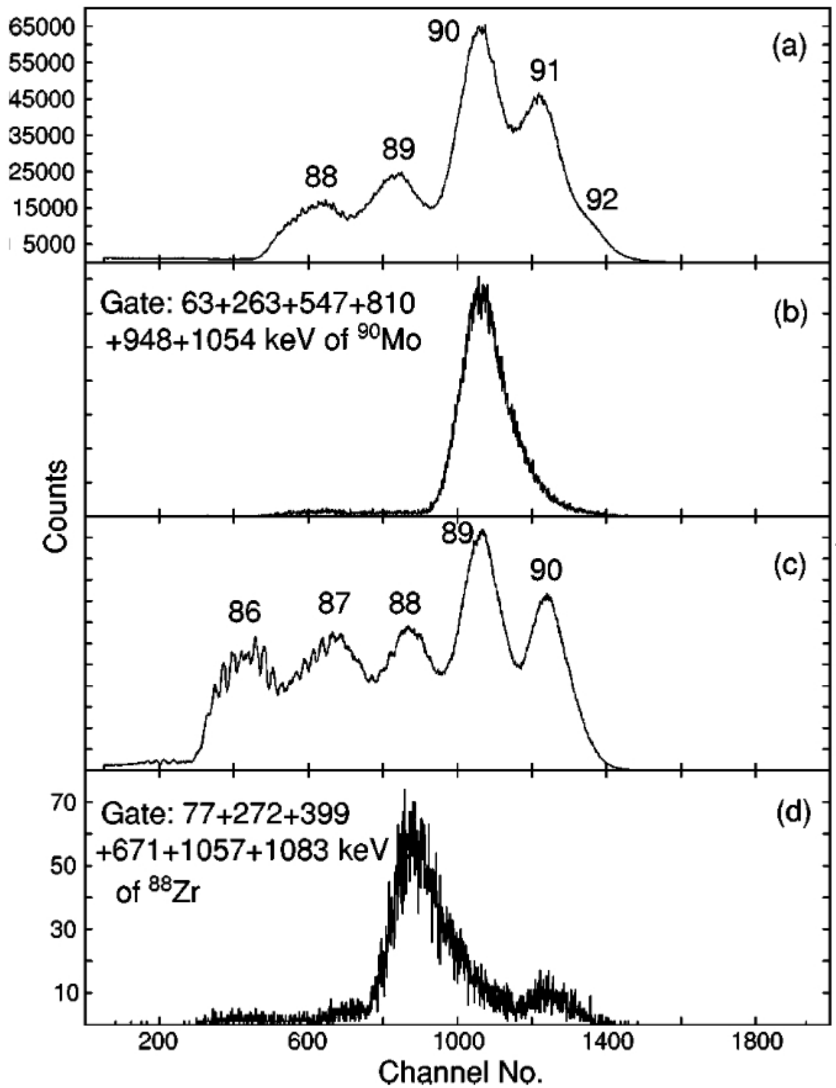


Recoil Tagged Spectroscopy

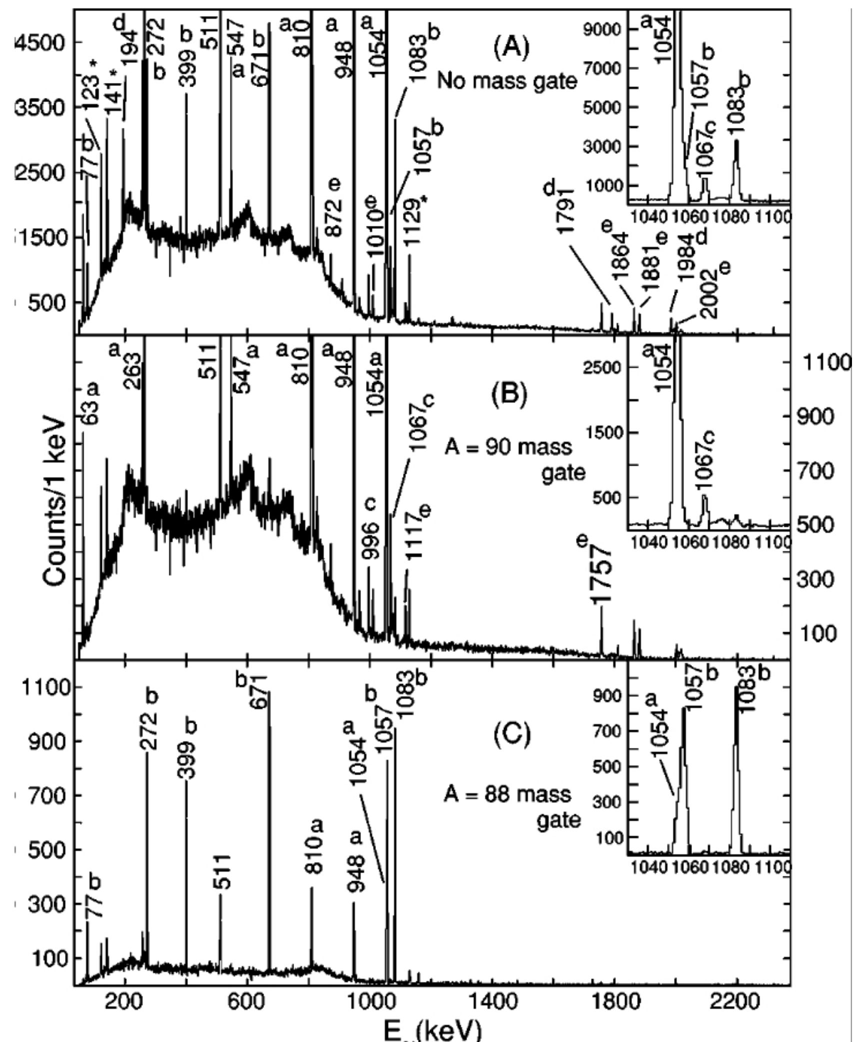
- In Recoil Tagged Spectroscopy, recoil products transported to low-background area using recoil separator
- Time difference between arrival of recoil & γ-decay measured with TAC
- Suitable for life-times μs -ms range



Anagha Chakrabarty, et al.

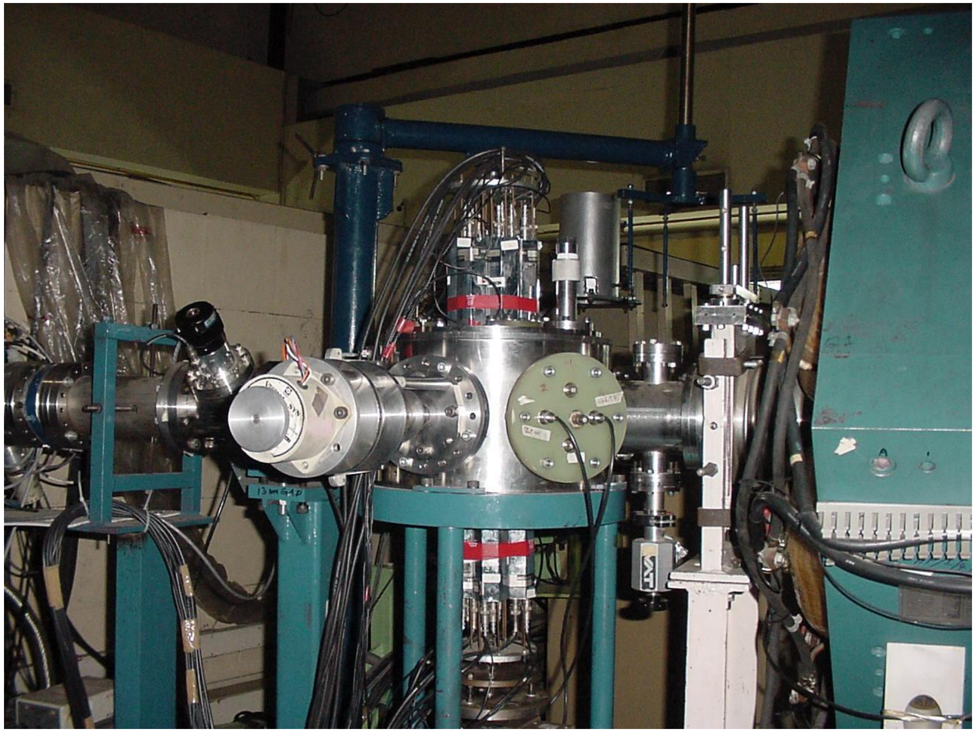


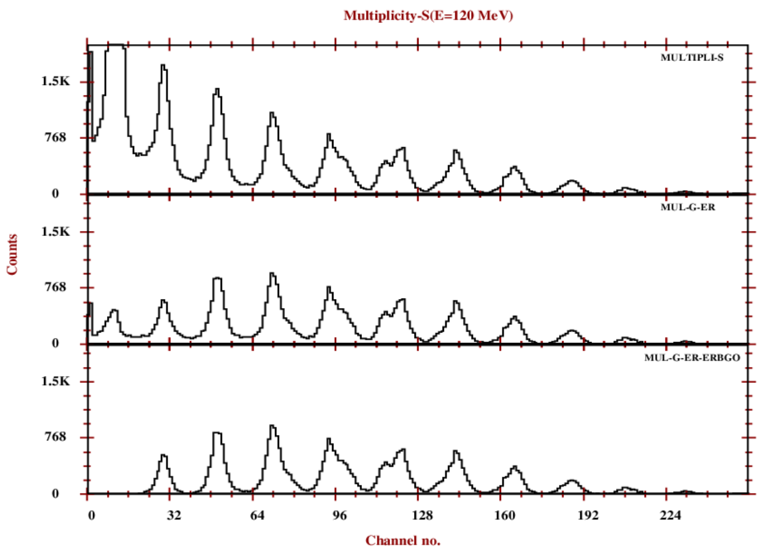
(a)
88
89
90
91
92
(b)
Gate: 63+263+547+810
+948+1054 keV of 90Mo
(c)
86
87
88
89
90
(d)
Gate: 77+272+399
+671+1057+1083 keV
of 88Zr
Counts
Channel No.

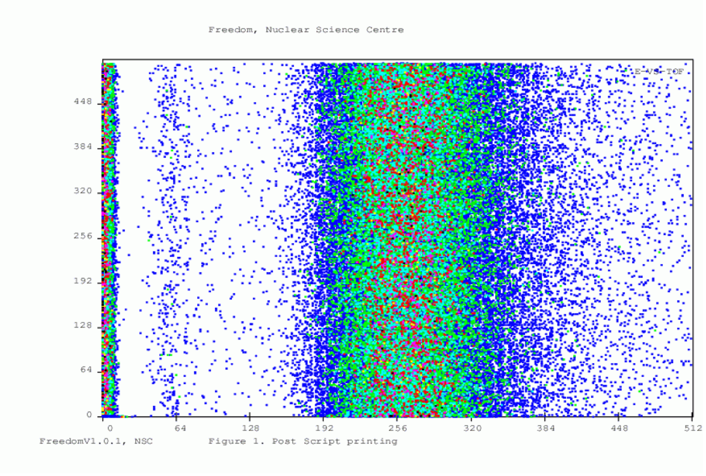


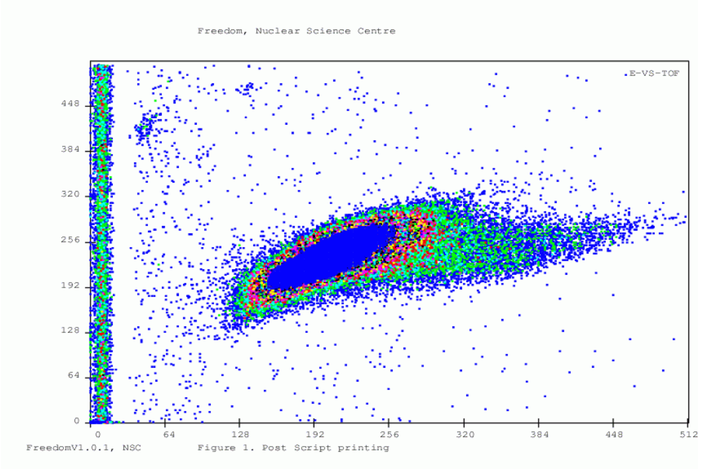
(A)
No mass gate
(B)
A = 90 mass
gate
(C)
A = 88 mass
gate
Counts/1 keV
Eγ(keV)

Experiment to look for fission hindrance through ER cross-section and spin distribution measurements in $^{16}O + ^{184}W \rightarrow ^{200}Pb^*$

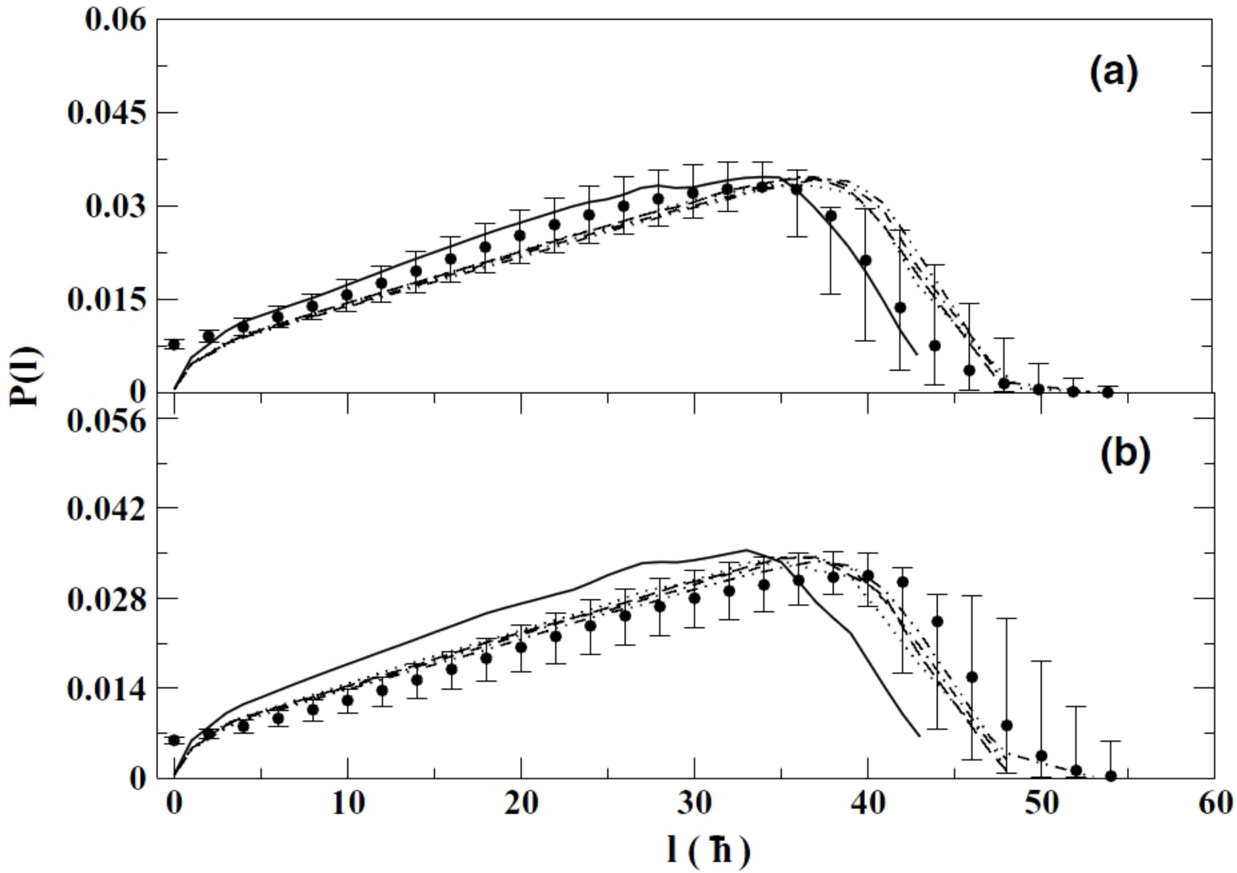






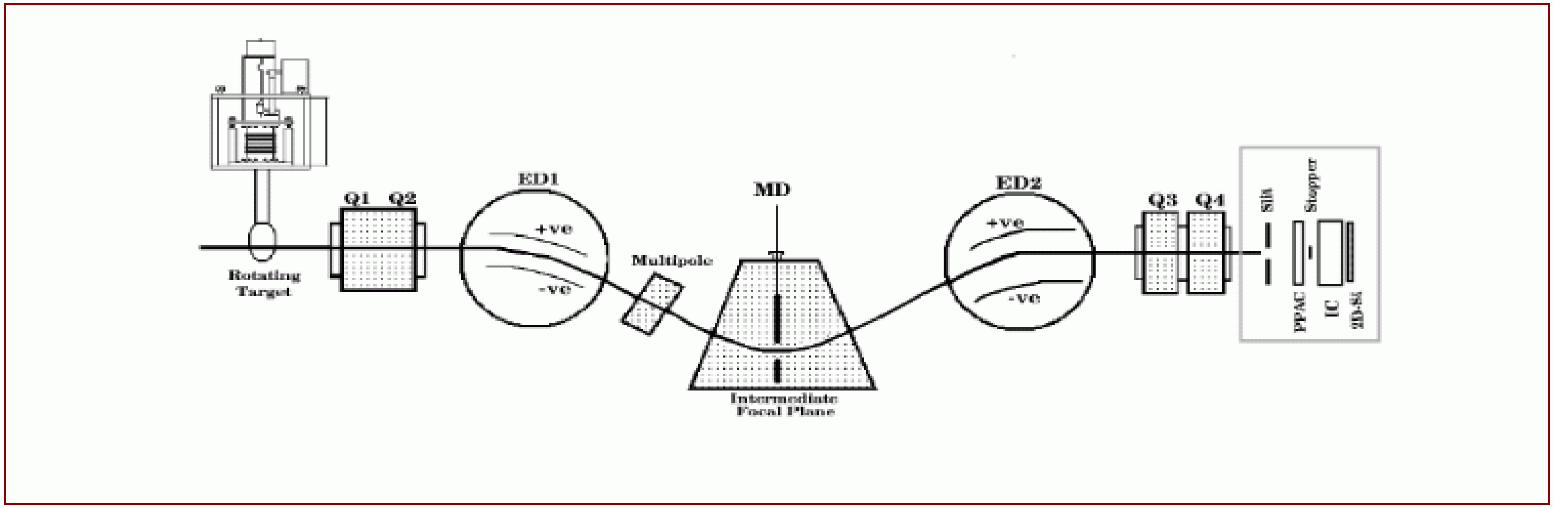


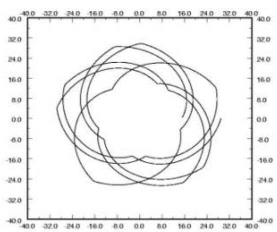
P. D. SHIDLING *et al.*

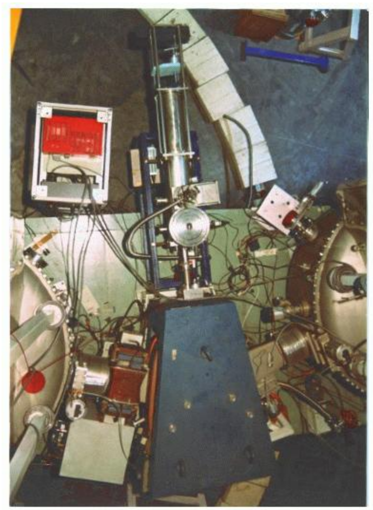


$$\Gamma_f^{\text{Kramers}} = \Gamma_f^{\text{BW}}[(1+\gamma^2)^{1/2} - \gamma]$$

Evaporation residue spin distribution – HIRA + 14-element BGO array







^{7}Be RIB parameters:

Method: p(^{7}Li,^{7}Be)n
Inverse Kinematics

Purity > 99 %

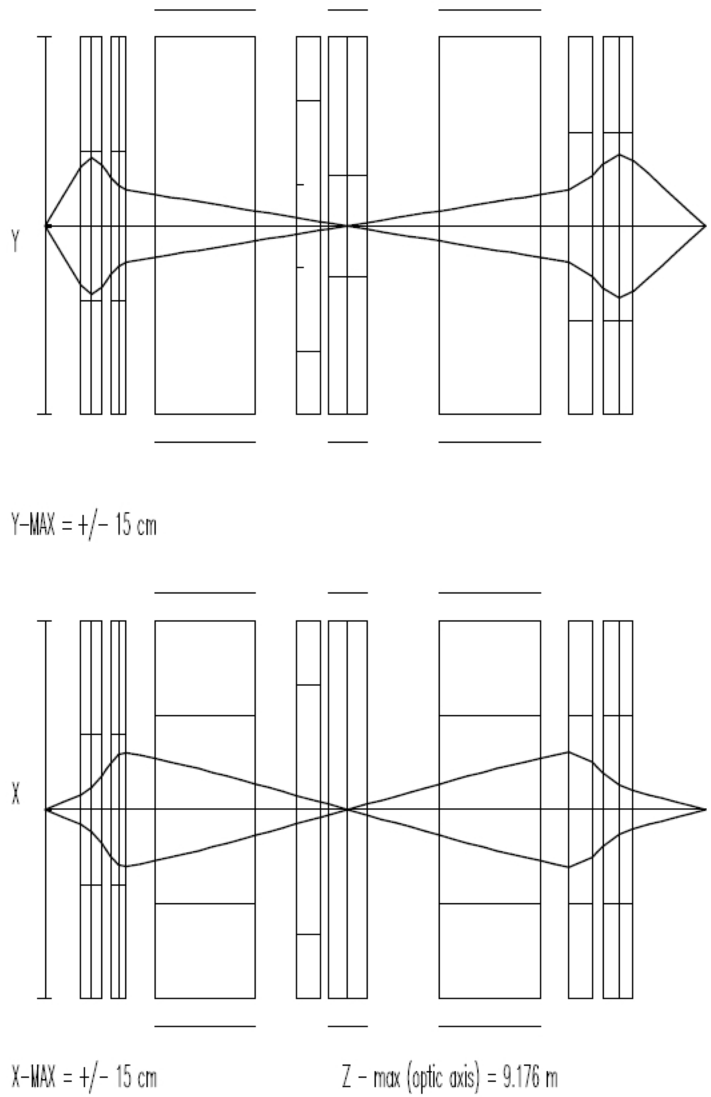
Energy ~ 12 to 21 MeV
(1 MeV spread)

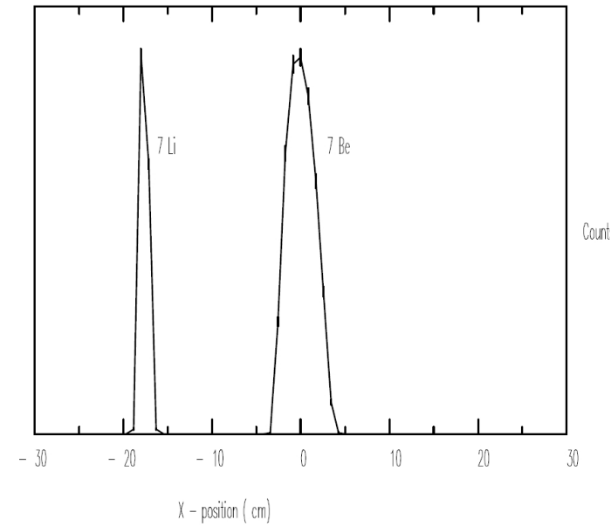
Intensity ~ 10^{3} – 10^{4} pps

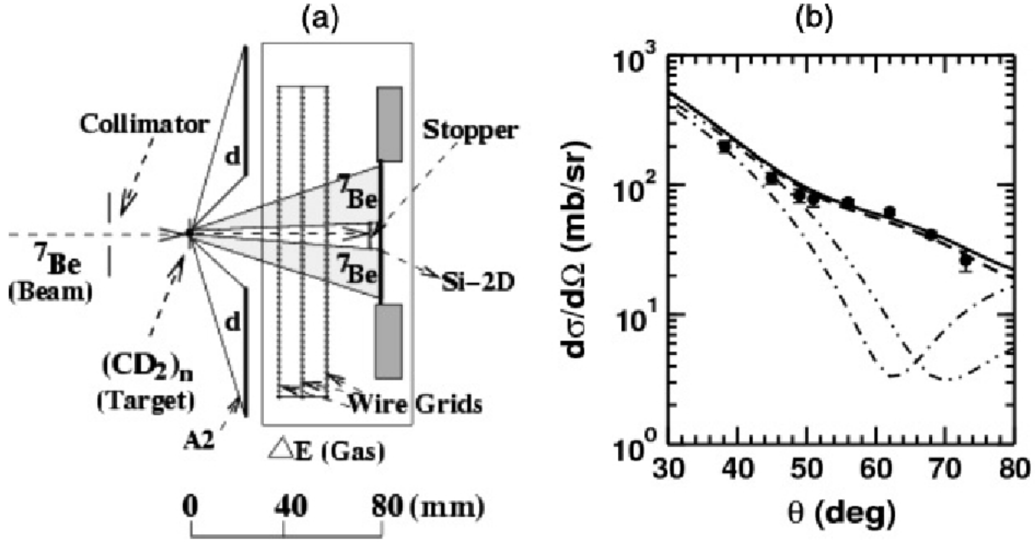
Size ~ 4 mm (FWHM)

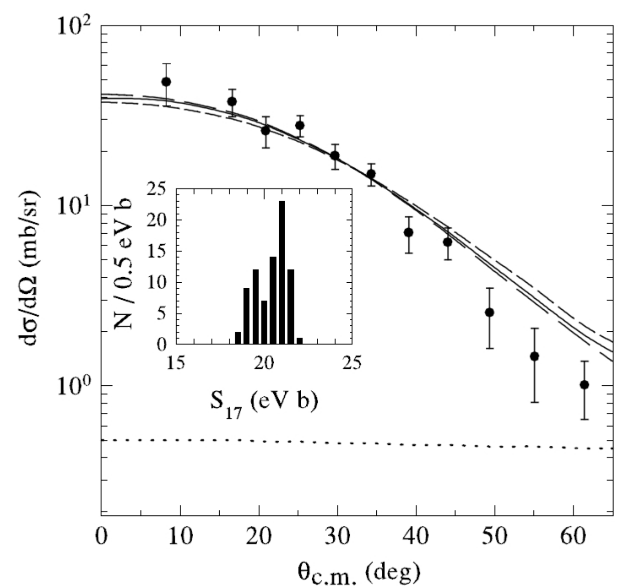
$\Delta\theta$, $\Delta\phi$ ~ +/- 30 mrad

J. J. Das, N. Madhavan, et al.


Y
Y–MAX = +/– 15 cm
X
X–MAX = +/– 15 cm
Z – max (optic axis) = 9.176 m

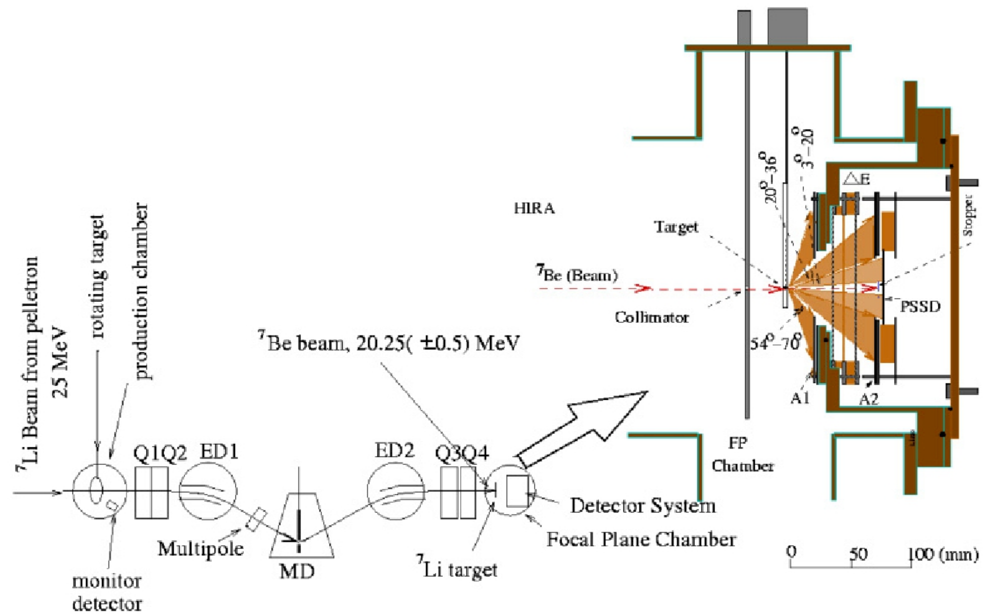

7 Li
7 Be
Counts
– 30
– 20
– 10
0
10
20
30
X – position (cm)


(a)
Collimator
d
7Be
(Beam)
(CD2)n
(Target)
A2
d
7Be
7Be
Stopper
Si-2D
Wire Grids
ΔE (Gas)
0
40
80 (mm)
(b)
dσ/dΩ (mb/sr)
θ (deg)

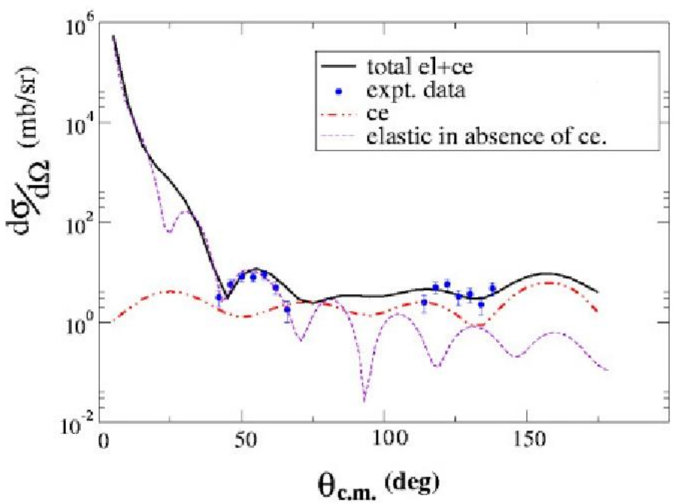

dσ/dΩ (mb/sr)
θc.m. (deg)
N / 0.5 eV b
S17 (eV b)

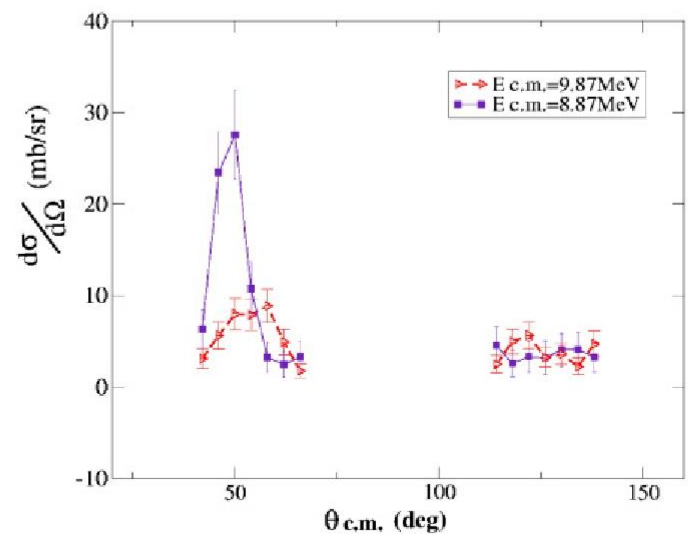
Scattering of mirror nuclei – 7Be + 7Li – Charge exchange process included

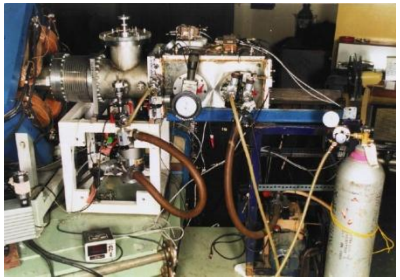
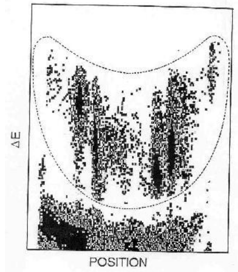
S. BARUA *et al.* PHYSICAL REVIEW C **72**, 044602 (2005)

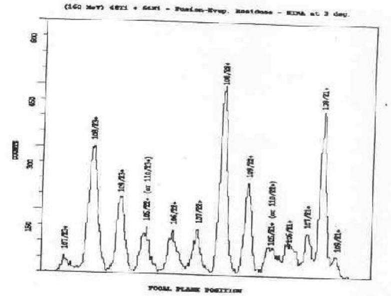
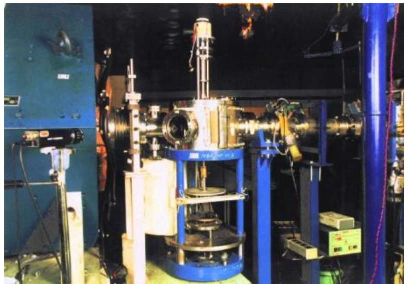
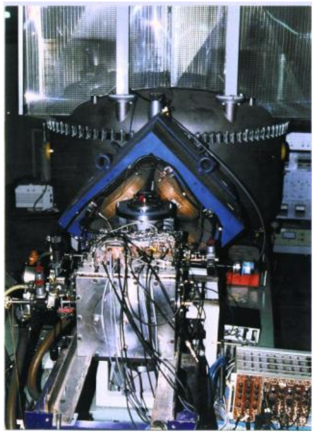
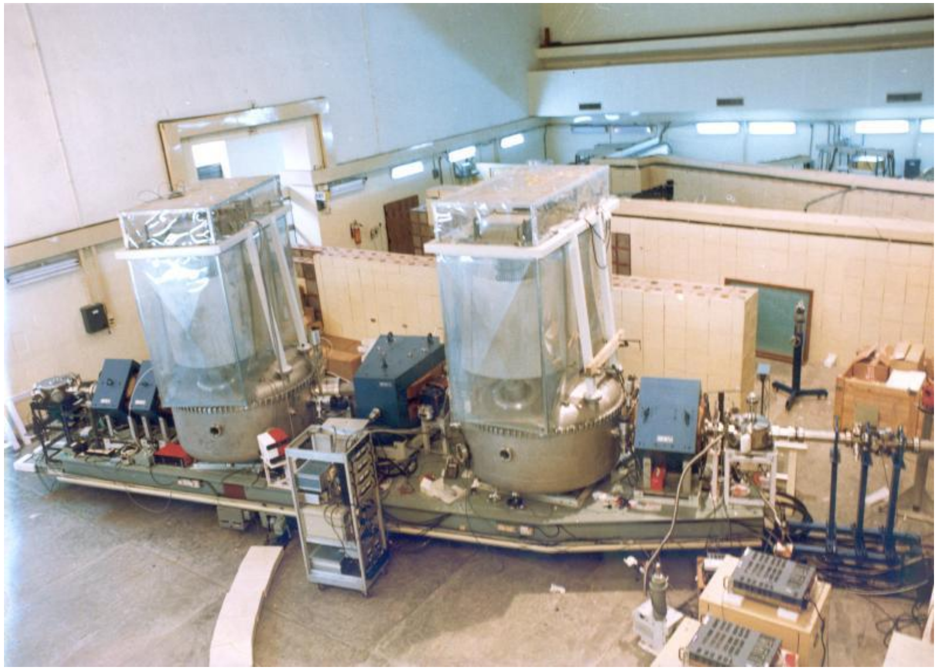
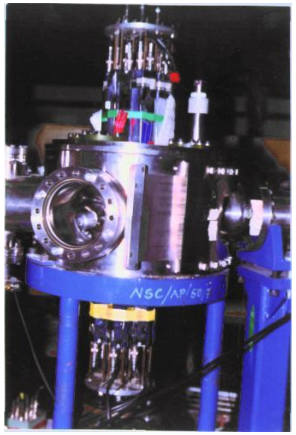


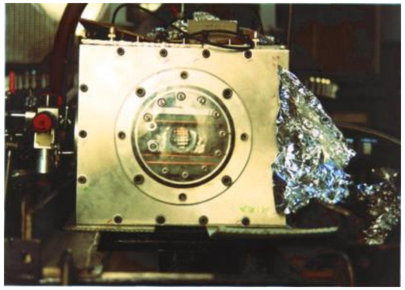
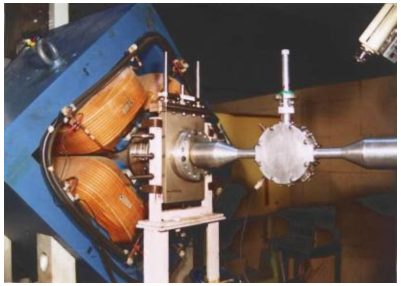
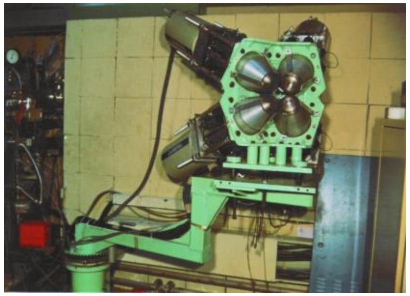
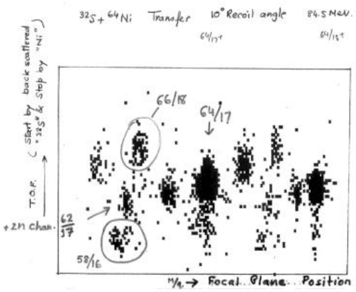
INVESTIGATION OF SCATTERING BETWEEN MIRROR . . . PHYSICAL REVIEW C **72**, 044602 (2005)

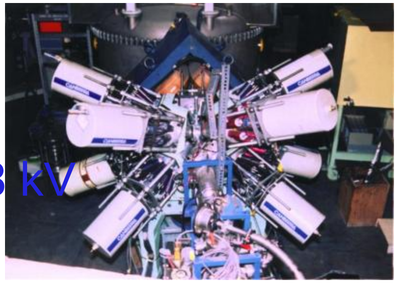






Beam rejection > 10^{11} (best)

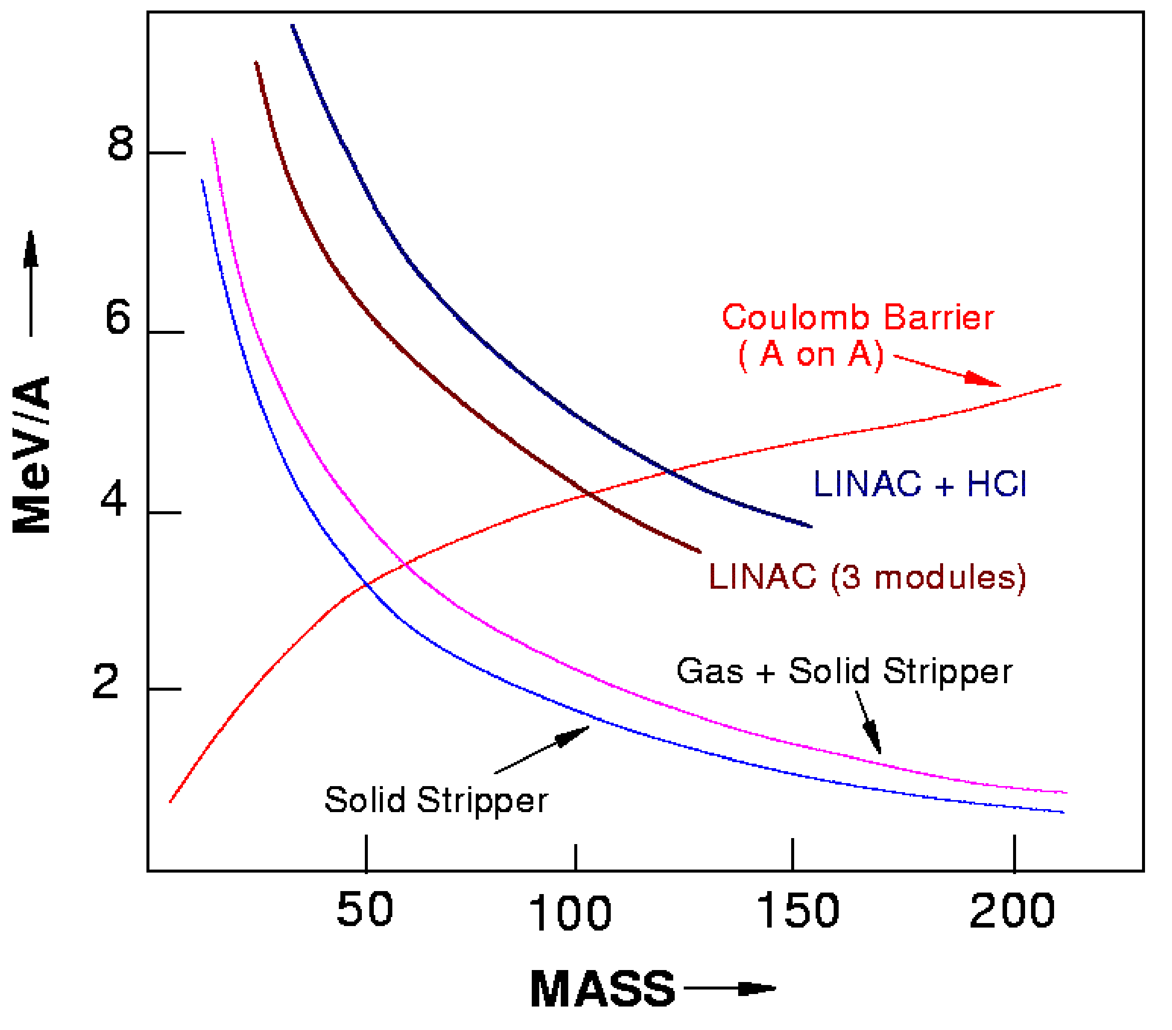
Heaviest CN ~ 201Bi

Highest voltage on EDs ~ 188 kV

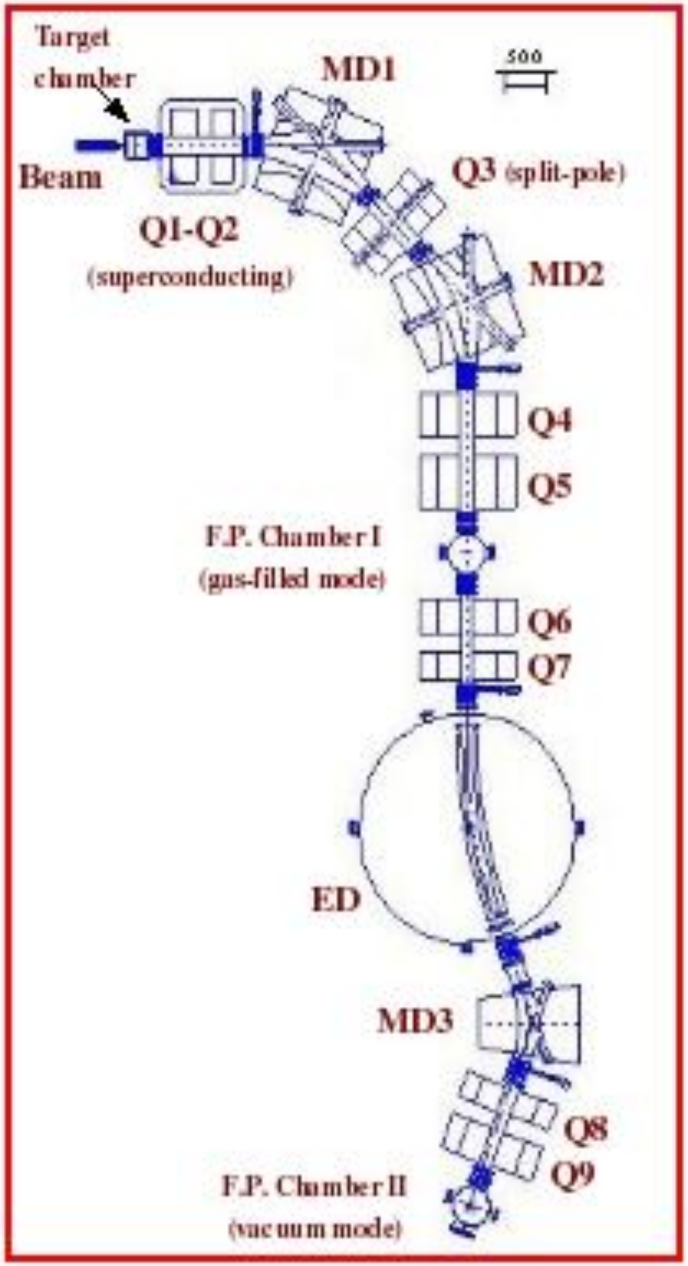
Largest angle ~ 25 degrees

Calibration of NMR for energy

Ion energies from IUAC accelerator systems



Design layout of HYRA :



First stage
(QQ-MD-Q-MD-QQ)

Second stage
(QQ-ED-MD-QQ)

Dual Mode Operation of HYRA

- Gas-Filled Mode: _(First stage)
- For A > 200 amu
- Normal Kinematics
- Good Collection Efficiency (q, v focus)
- Z, A identification using recoil decay technique

- Vacuum Mode: _(Both stages)
- For N ~ Z (~ 100 amu)
- Inverse Kinematics
- Good primary beam rejection (two stage)
- Z, A identification using X, ΔE, E measurement

Hybrid Recoil mass Analyzer (HYRA)

(N. Madhavan et al. Pramana Journal of Physics, 75, 317 (2010))

HYbrid Recoil mass Analyzer - Unique **dual-mode, dual-stage** spectrometer with large acceptances and rigidity at IUAC, New Delhi (to fully exploit ECR + LINAC beams of higher energy and intensity).

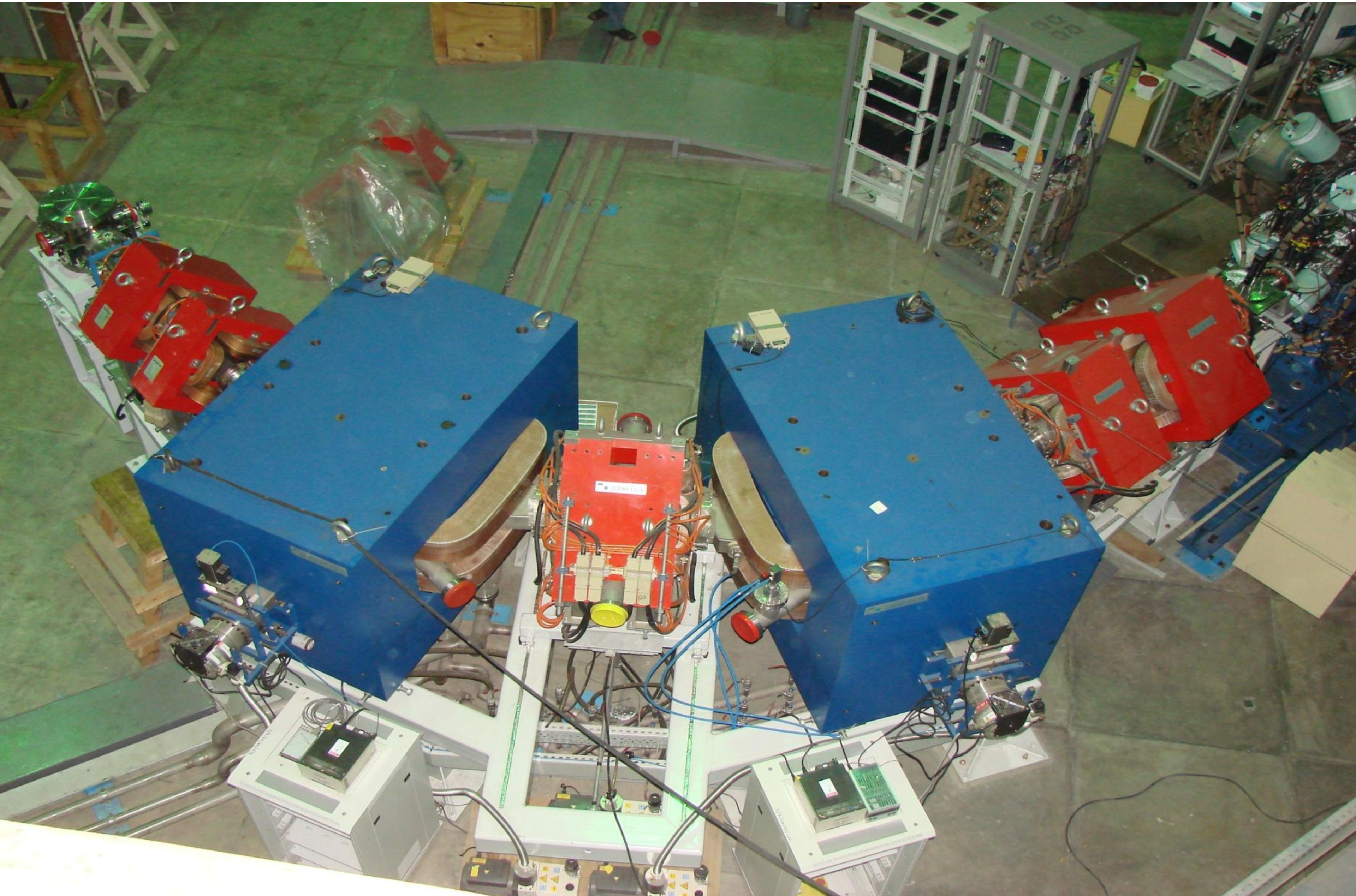
Useful to access heavy fusion evaporation residues with large efficiency along beam direction in **gas-filled mode** rejecting beam-like particles, target-like recoils and fission fragments – First stage only (similar to Dubna, RIKEN, LBL, JYFL, TASCA facilities but unique in design).

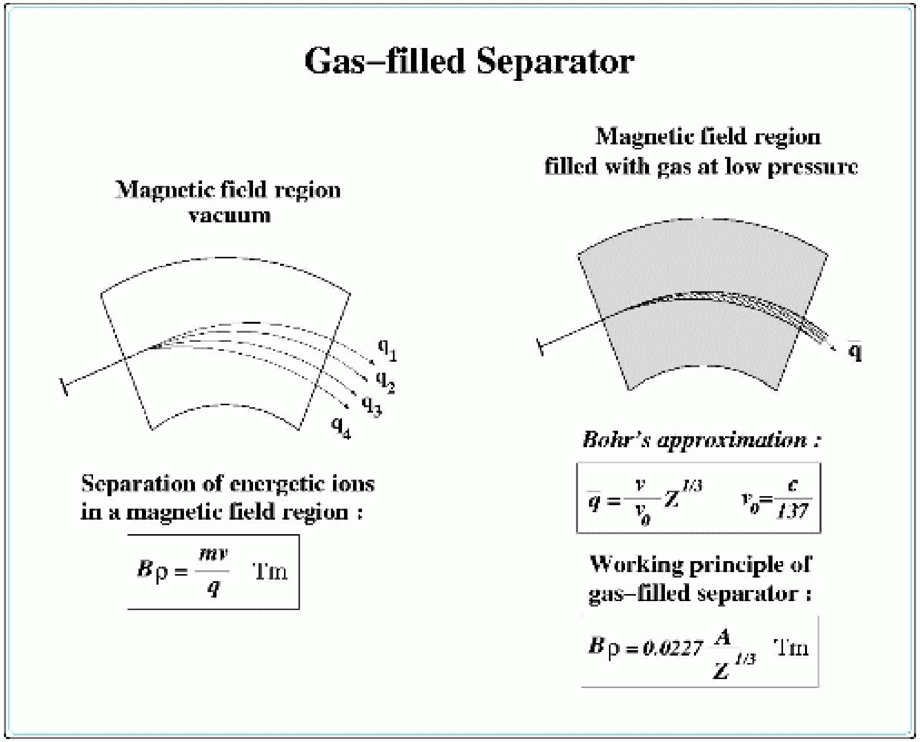
Useful to produce secondary radioactive beams (similar to ^{7}Be in HIRA but with higher energies and lesser purity) in **momentum achromat (vacuum) mode** – First stage only.

Useful to select medium mass fusion evaporation residues with large efficiency along beam direction in inverse kinematics – Complete (similar to Oak Ridge RMS but with changes in design).

HYRA spectrometer (Gas-Filled Separator / Vacuum Mode RMS)

(Funded by Department of Science and Technology, Govt. of India)



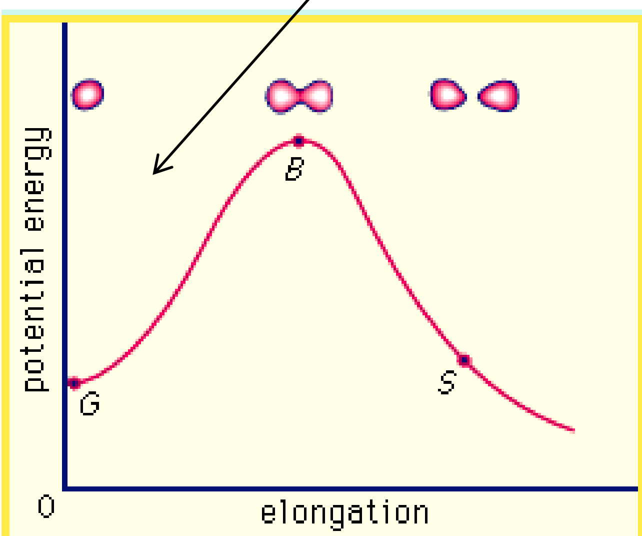


Charge state focusing effect : All charge states settle towards a mean charge state

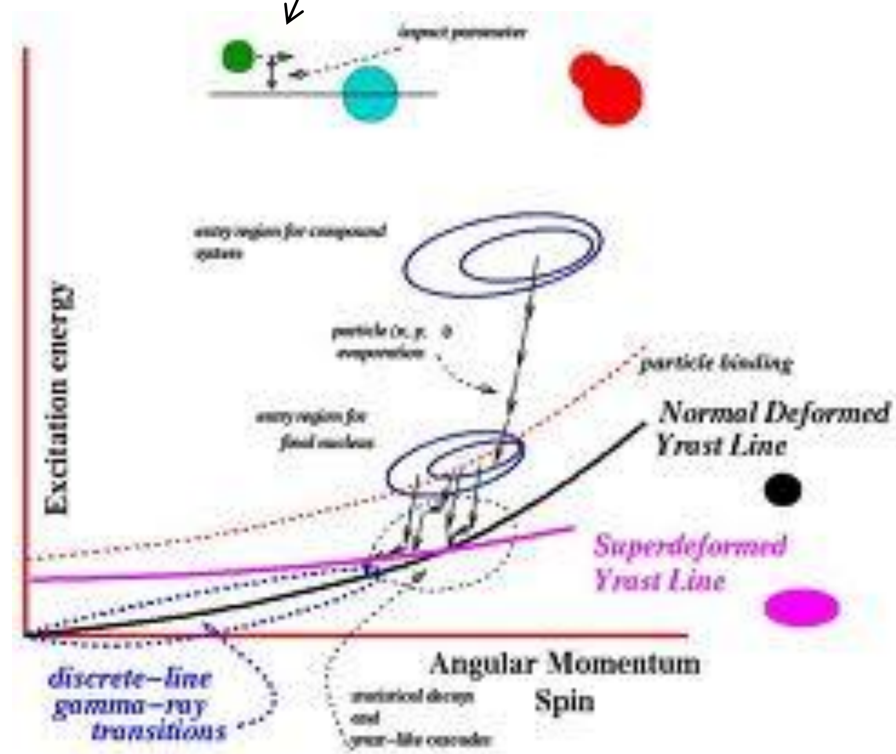
Velocity focusing effect : All velocities come withing the acceptance of the spectrometer

Multiple scattering tends to play spoilsport

ER measurement probes pre-saddle region

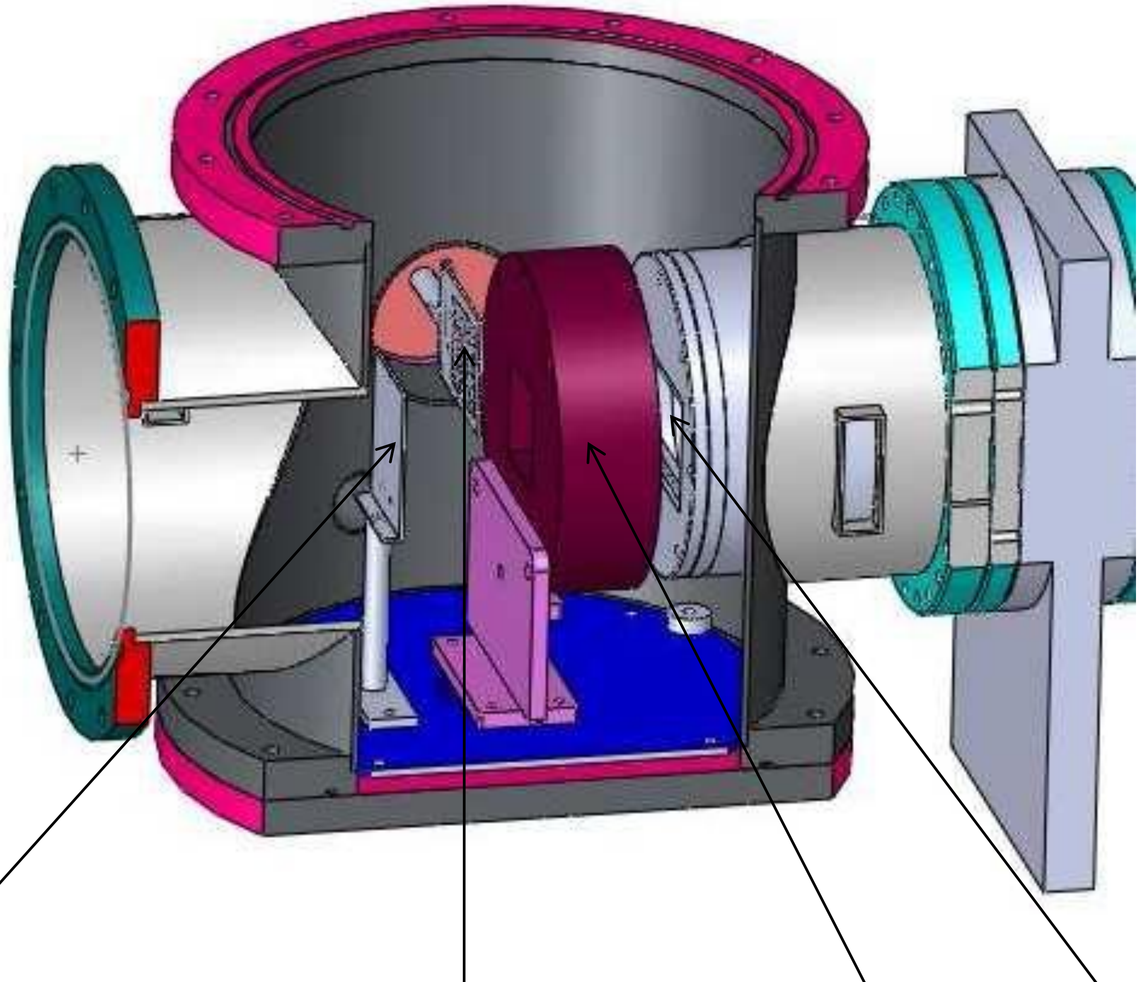


Impact parameter relates to l



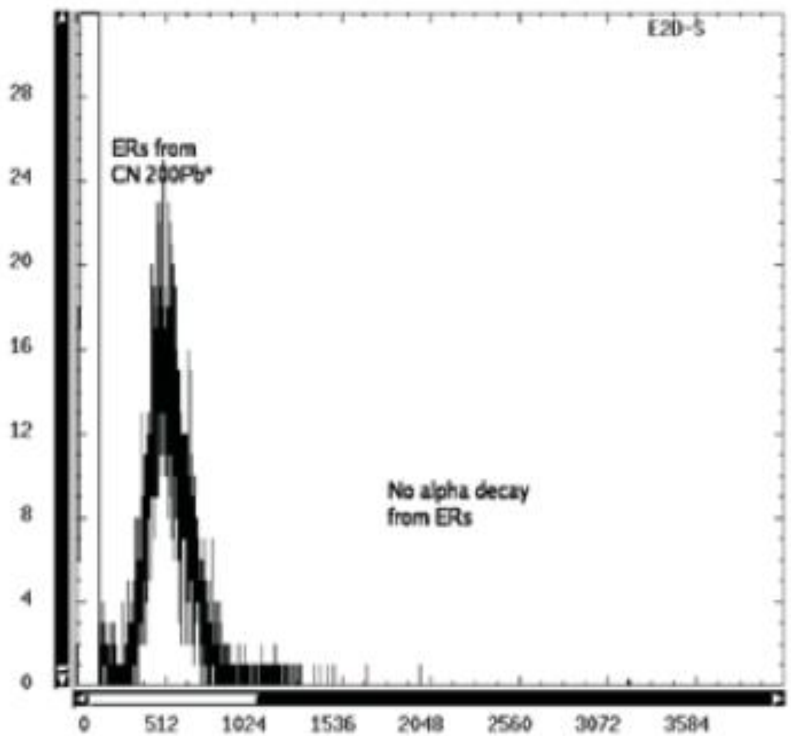
Discrete gamma multiplicity relates to l

Focal plane detection system

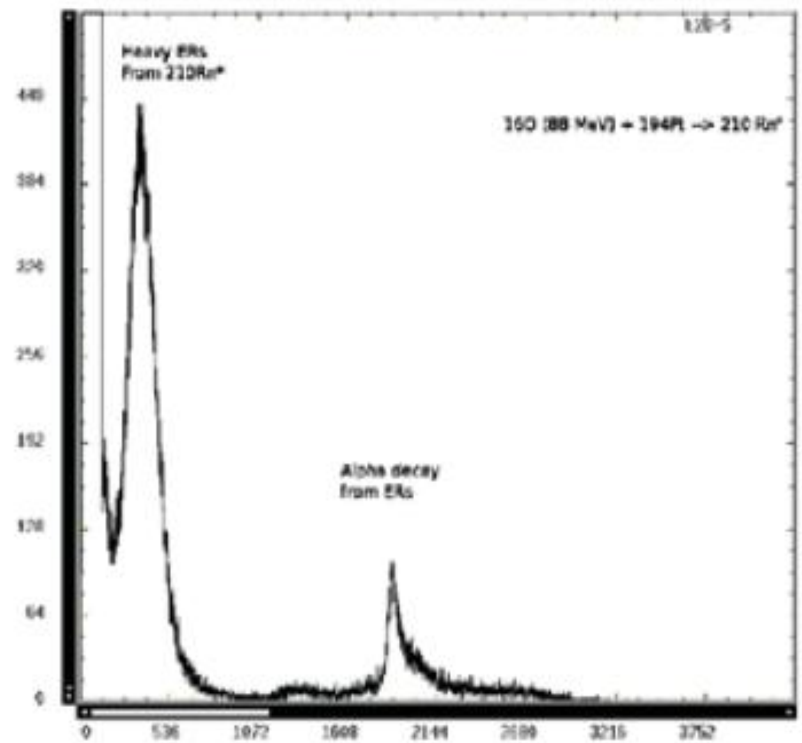


Si Resistive/Strip detector   Removable stopper   MWPC   0.5 μm Mylar foil

Energy spectrum at FP Si detector for 16O + 184W → 200Pb* system; ERs detected (no alpha decay channel)

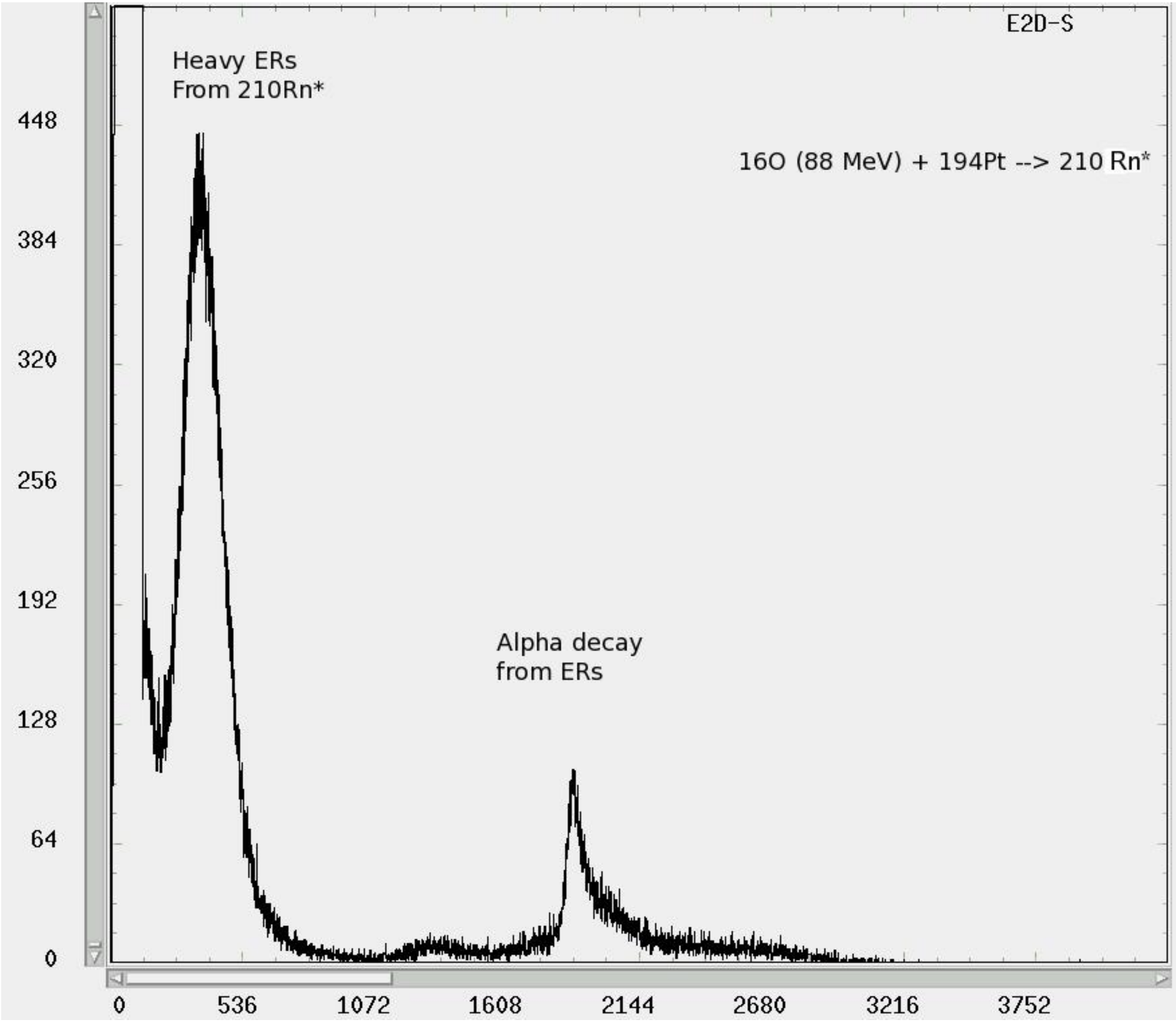


Energy spectrum at FP Si detector for 16O + 194Pt → 210Rn* system; ERs and alpha decay detected



HYRA: One of few major gas-filled separators (first in India)

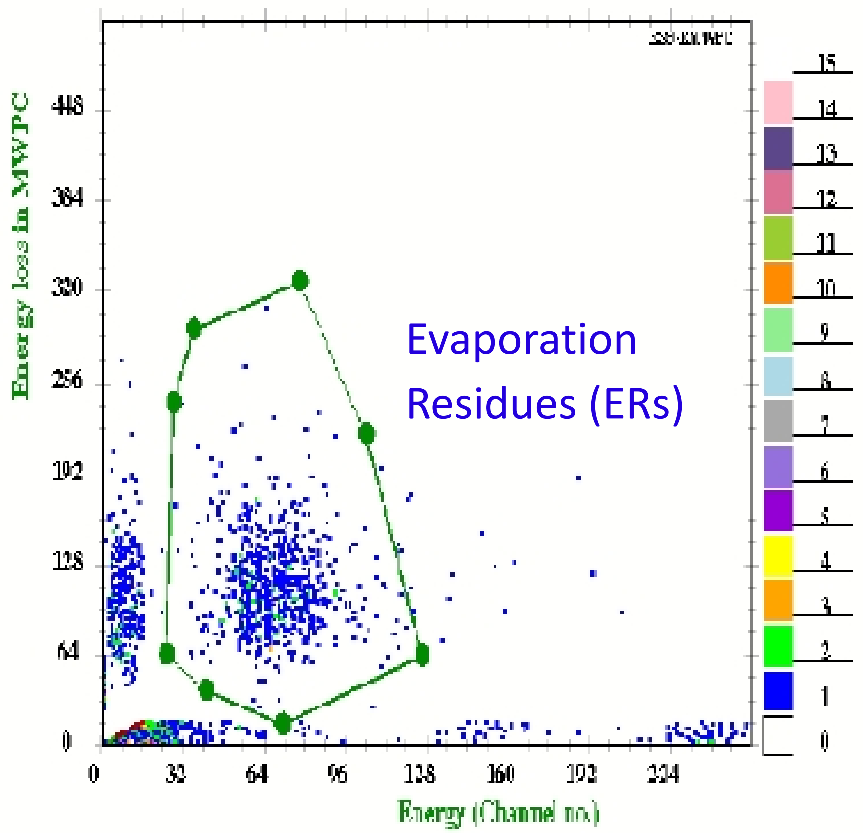
Alpha decay from heavy evaporation residues at focal plane of HYRA



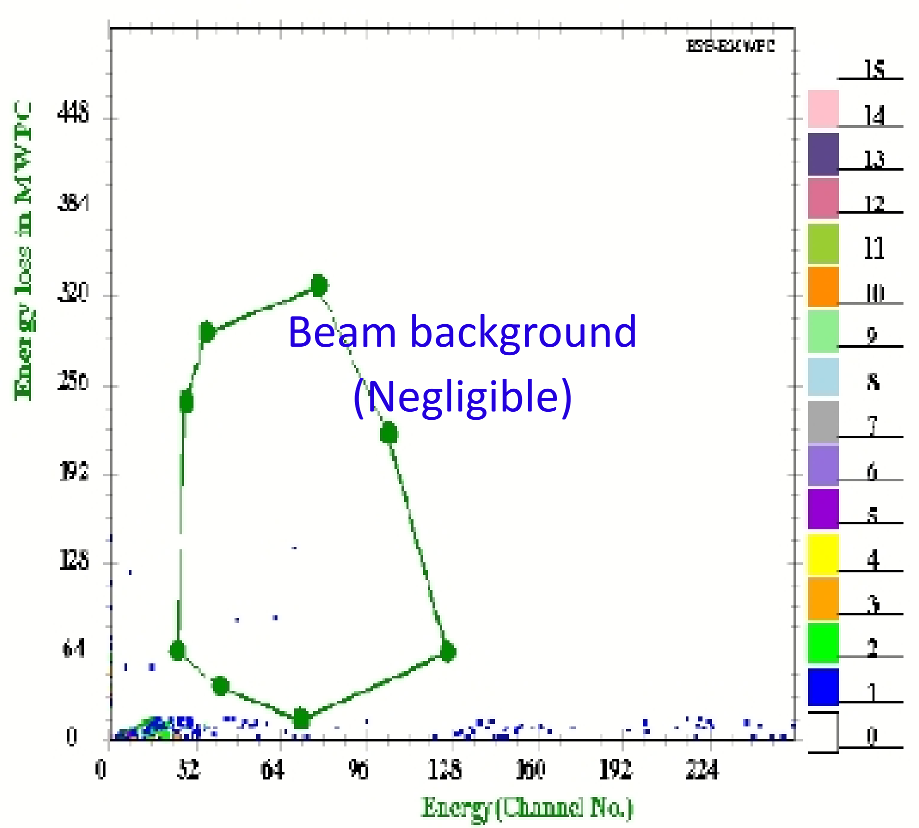
Negligible beam background at FP of gas-filled mode of HYRA:

Primary beam rejection better than 10^{12}

$^{16}O + ^{194}Pt$ reaction at 104.3 MeV

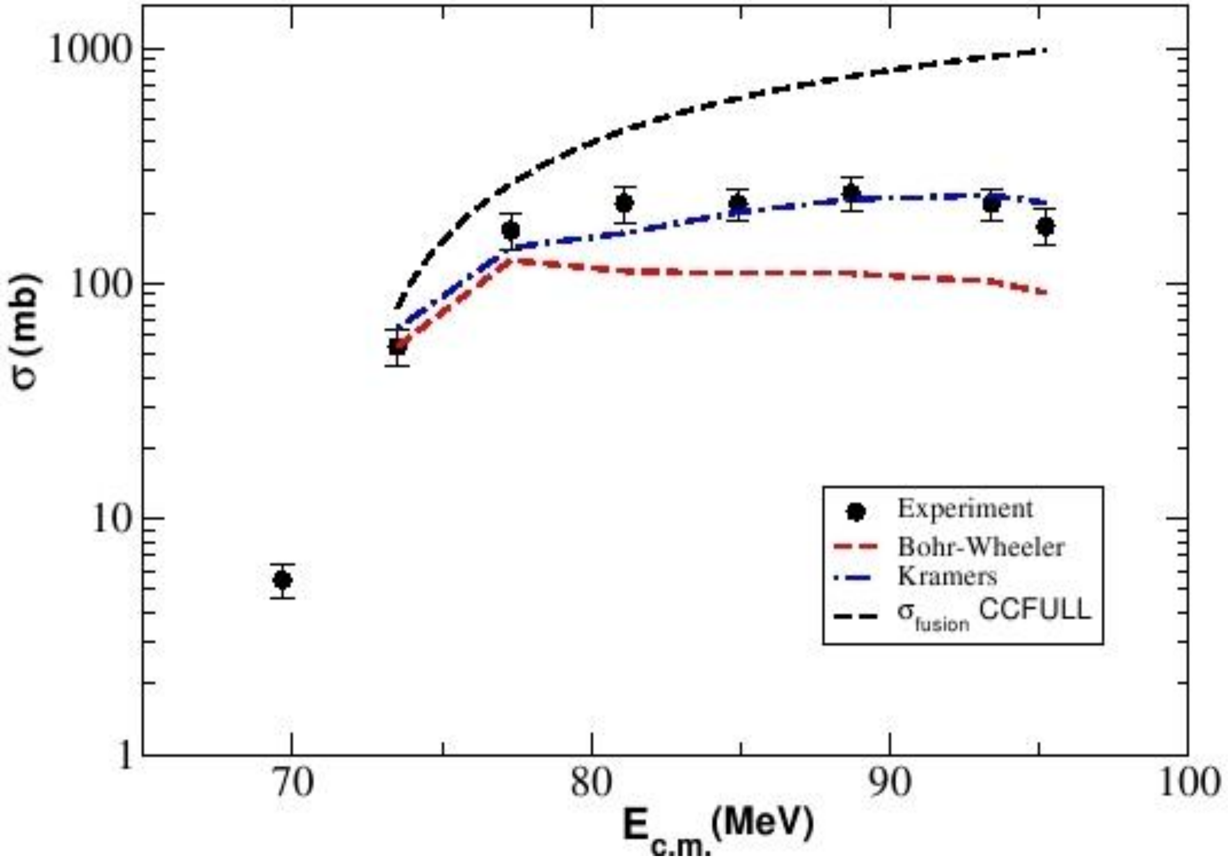


$^{16}O + ^{27}Al$ reaction at 104.3 MeV



Fields set for ERs produced in $^{16}O + ^{194}Pt$ reaction at 104.3 MeV and data collected for same duration in both cases

ER excitation function measured using gas-filled mode of HYRA going below Coulomb barrier for $^{16}O + ^{194}Pt \rightarrow ^{210}Rn^*$



E. Prasad et al., PRC recently published

Importance of angular momentum in heavy element formation:

- **Heavy element formation** through fusion-evaporation reaction **and** its **survival** crucially **depends on** the entrance channel, excitation energy and **angular momentum transferred to the fused system**.

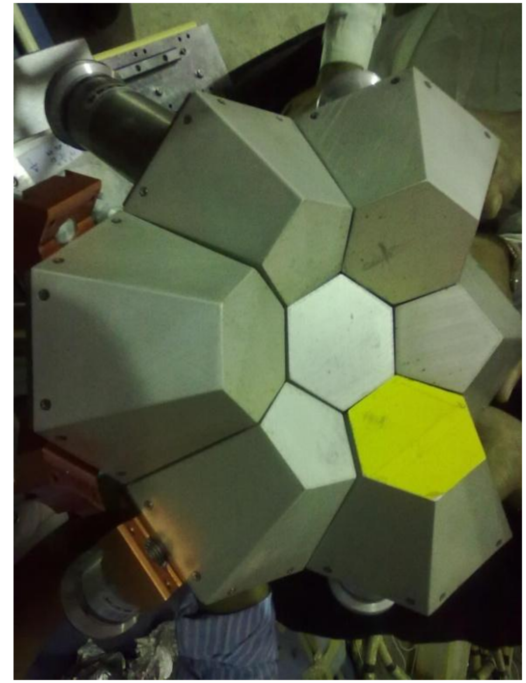
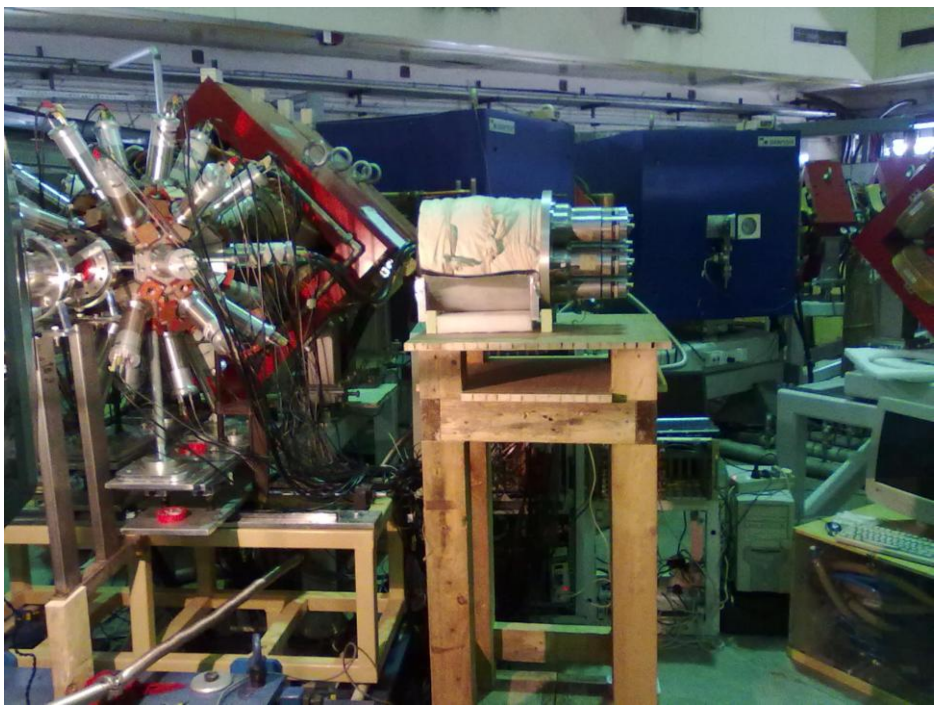
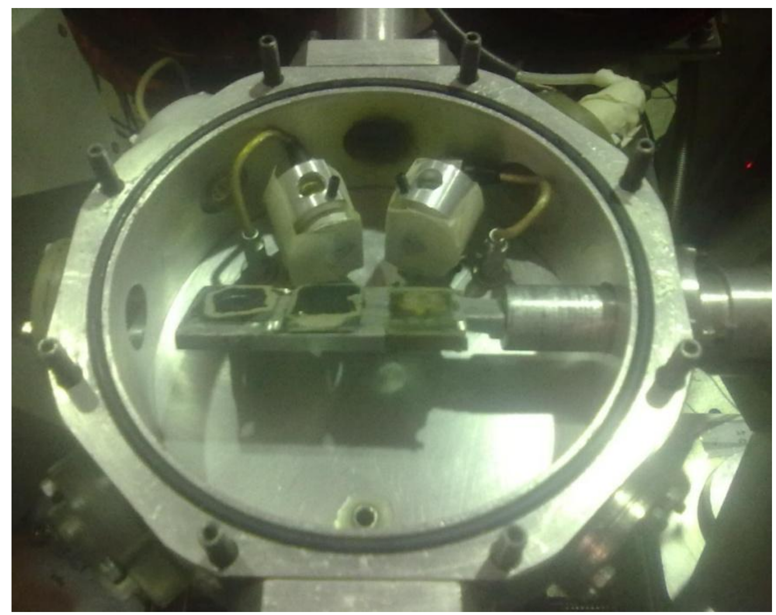
- While a **more symmetric system brings in a higher angular momentum**, **effective angular momentum of the compound nucleus (CN)** [and hence of the evaporation residues (ERs) from it] **is limited**.

- **Depletion of ER cross-section** as one goes to more symmetric entrance channel **should directly correlate with narrowing of angular momentum distribution of ERs**.

- **Experimental angular momentum distribution** sets a **more stringent condition on the various fusion-fission models** than the ER and fission cross-sections alone.

- It is important to know if **fission and quasi-fission processes deplete the angular momentum throughout** the distribution **or predominantly a narrow region** of the distribution.

Studies with HYRA – Spin Spectrometer

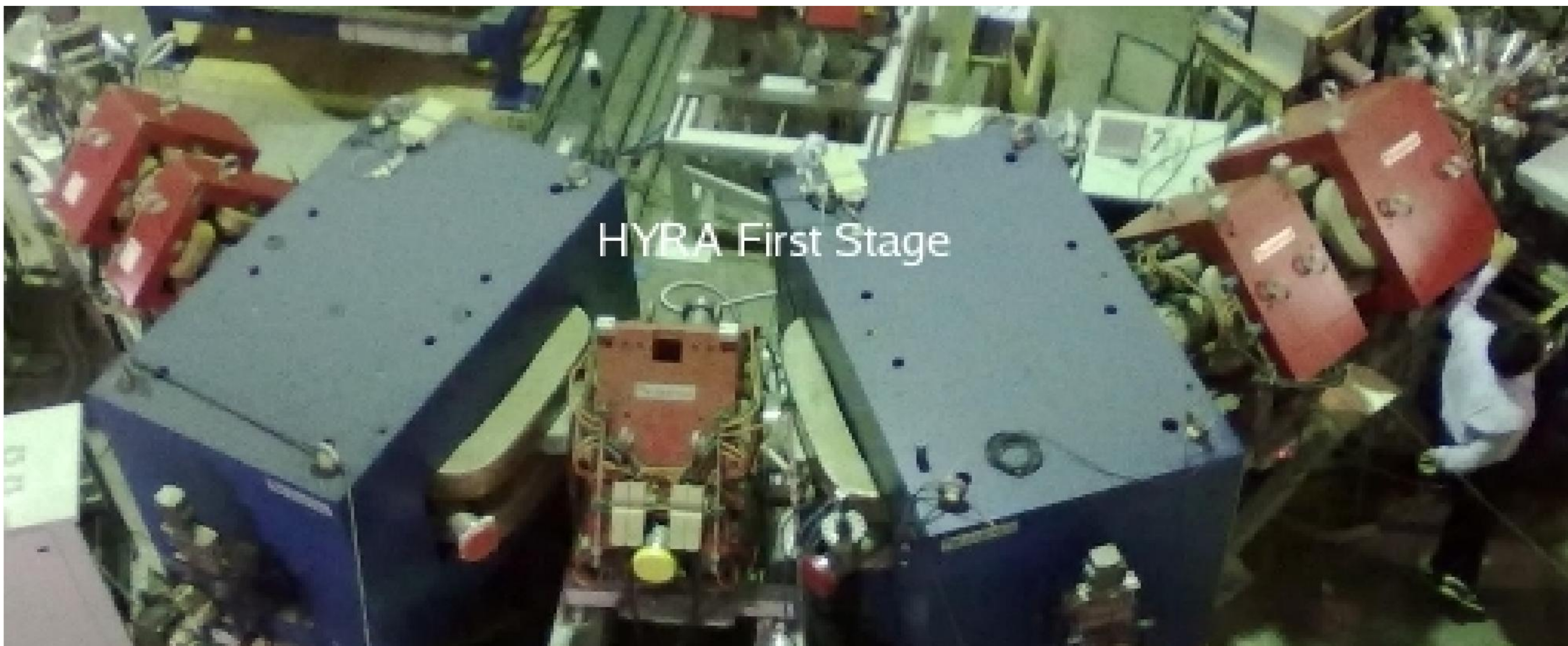
HYRA gas-filled separator coupled with TIFR 4π spin spectrometer

N. Madhavan et al., accepted in EPJA web conference - FUSION11

Focal plane

HYRA first stage
(operated in gas-filled mode)

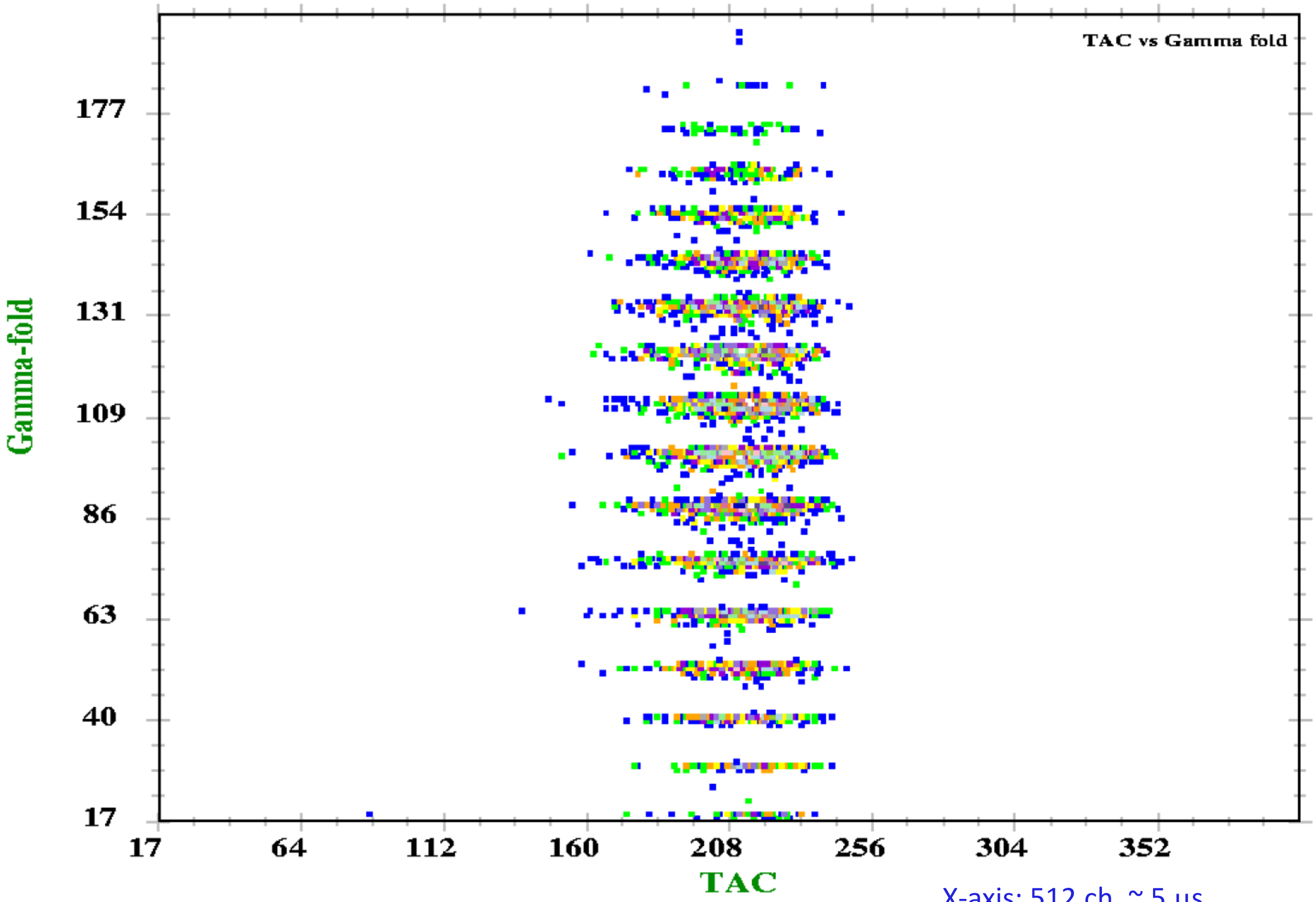
Spin
Spectrometer



^{16}O (120 MeV) + ^{180}Hf → $^{196}Hg^*$

TAC is constructed with focal plane MWPC anode timing as start signal and electronically delayed 'OR' of all NaI detectors as stop signal, to take into account the time-of-flight of ERs through HYRA

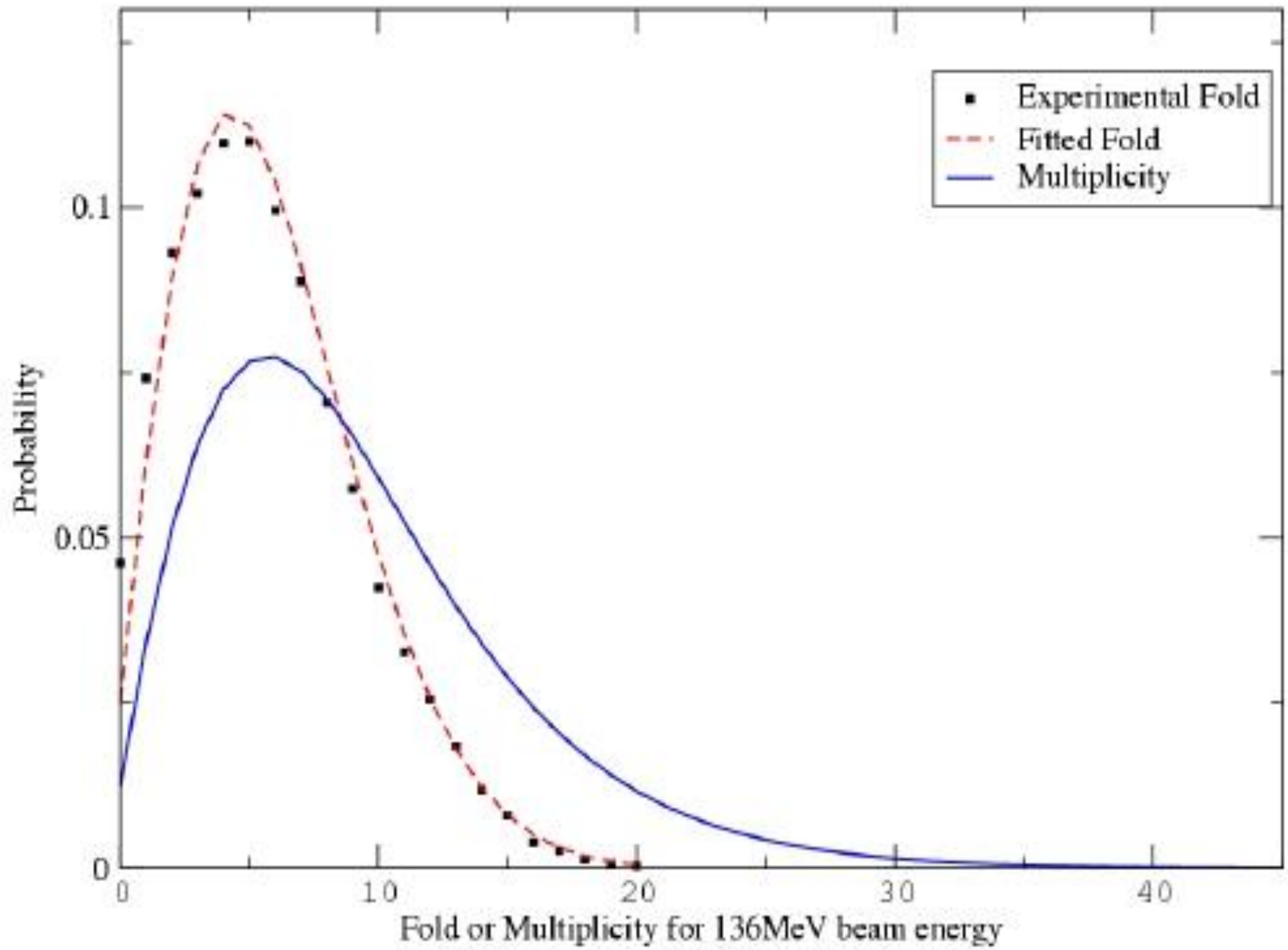
Clean ER group with negligible contamination



X-axis: 512 ch. ~ 5 μs

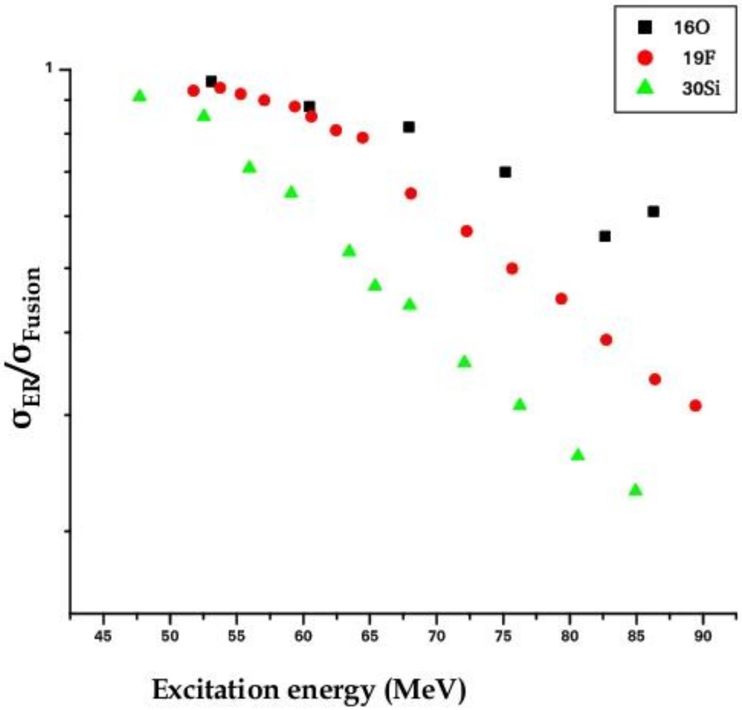
Experimentally observed gamma multiplicity (gamma fold) to actual multiplicity

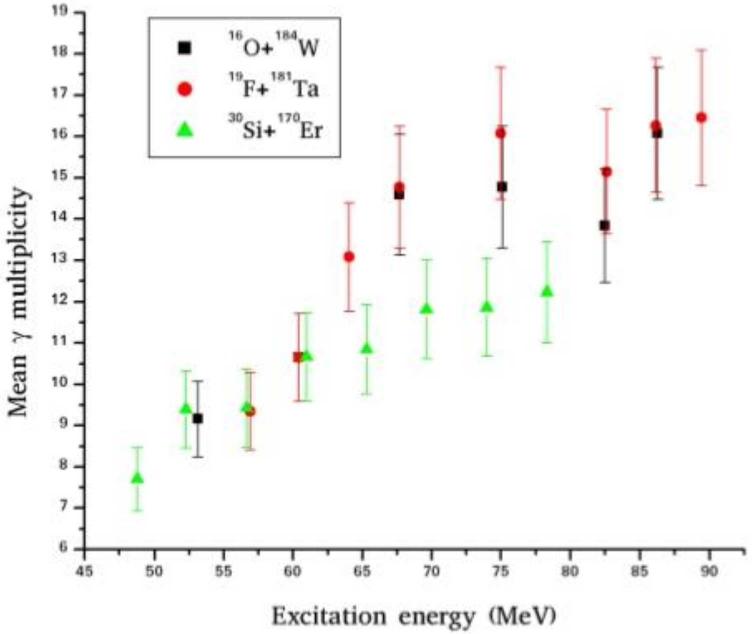
^{30}Si (136 MeV) + $^{170}Er \rightarrow {}^{200}Pb^*$



Comparison of normalised ER cross-section and mean gamma multiplicity

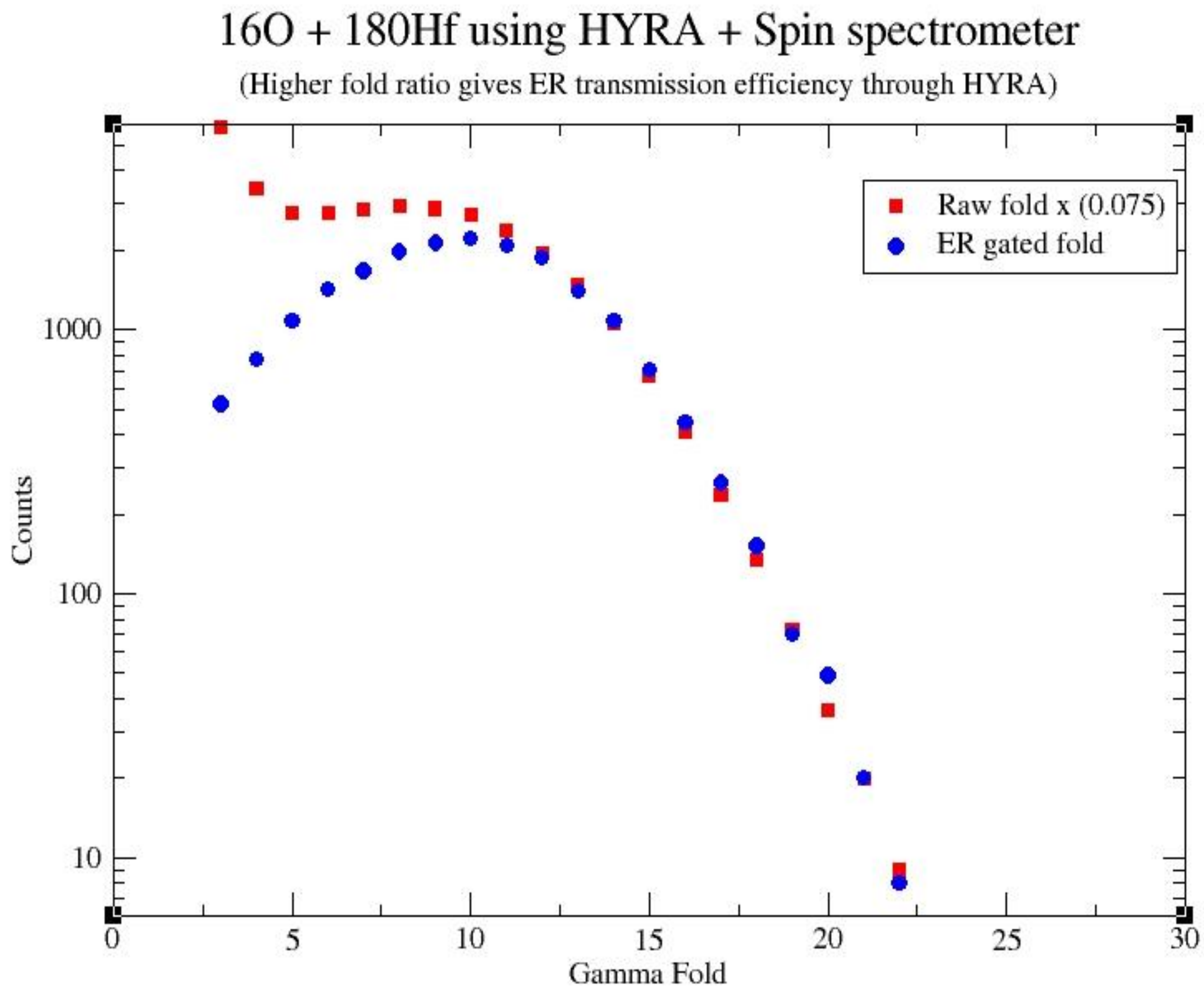
for ^{16}O + ^{184}W, ^{19}F + ^{181}Ta and ^{30}Si + ^{170}Er all leading to CN $^{200}Pb^*$





More asymmetric the system, the better is the ER survival probability and larger is the average angular momentum

G. Mohanto et al., Published in EPJA Web Conference - FUSION11



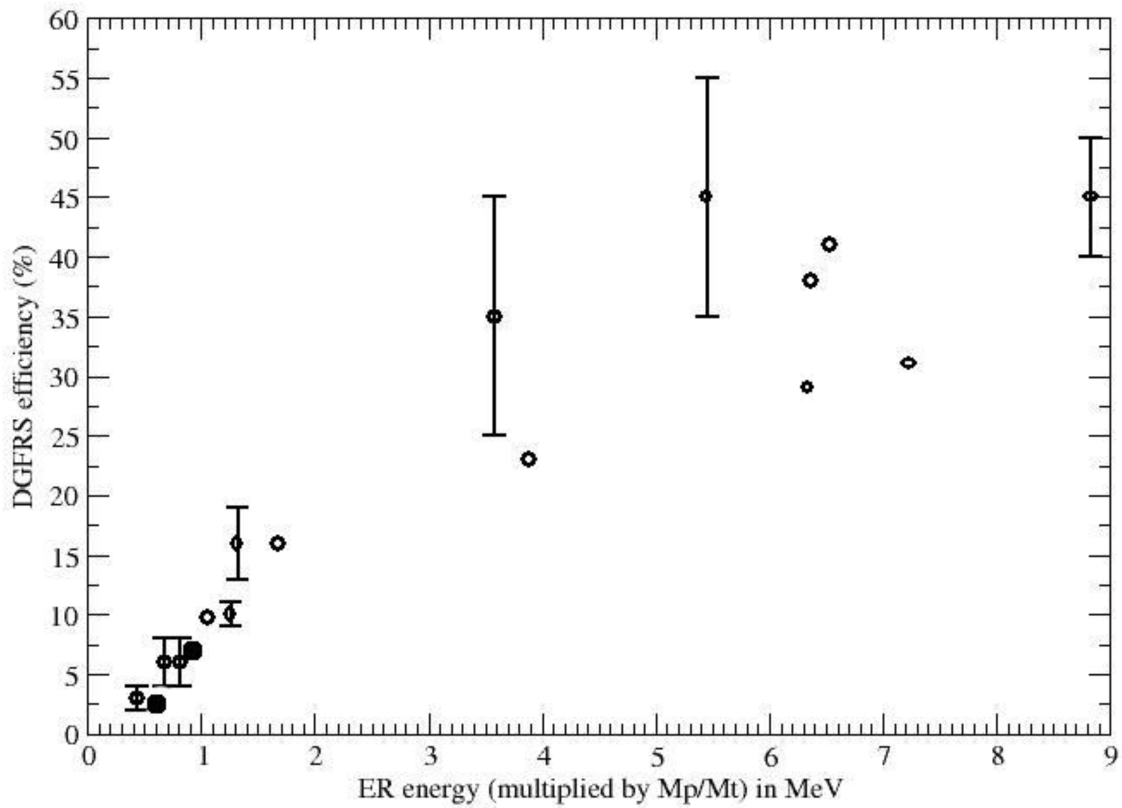
Higher folds match perfectly when singles spectrum is scaled down to 7.5 %;
With negligible contamination, this value gives the average transmission efficiency of HYRA for ERs.

Lower folds in singles spectrum contaminated with Coulomb excitation gamma rays and those emitted in the fusion evaporation of ^{16}O with carbon window foil

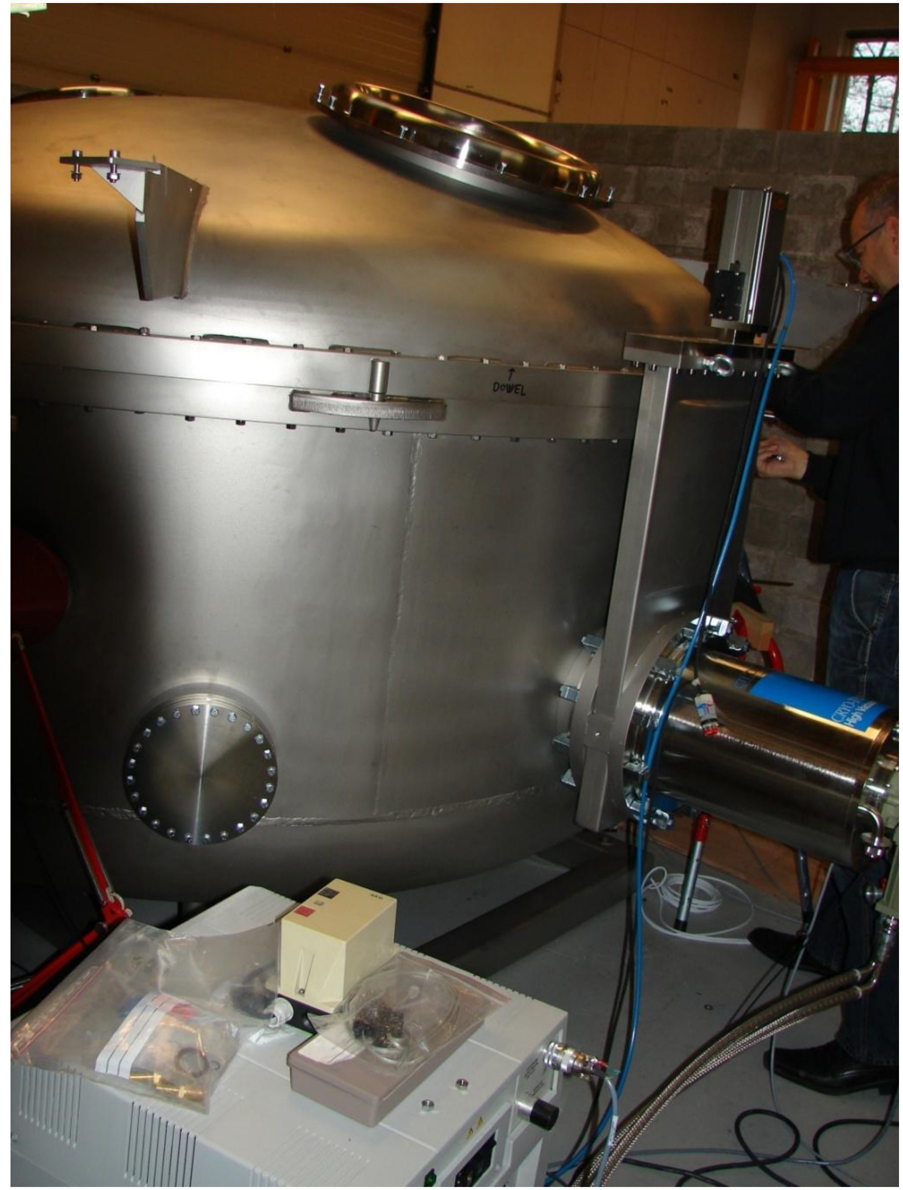
N. Madhavan et al., Published in EPJA Web Conference – FUSION11

Transmission efficiency data presented against the quantity (ER energy x (M_p/M_T)) to take care of kinematic effects

Open circles (Dubna DGFRS data)
Solid circles (HYRA gas-filled mode data)



Electrostatic dipole and accessories
(fabricated and tested for high voltage and vacuum)



Plans:

ER cross-section measurements for heavier systems – Entrance channel, closed shell and fission hindrance effects

Focal plane decay measurements (Alpha, Beta,…)

Microsecond isomer – Lifetime measurements at FP (near N ~ 126)
(Microsecond isomers near N ~ 50 already studied using HIRA)

HYRA as tagging device for spectroscopy of heavy residues using INGA
(can throw away the fission fragments and other impurity gamma rays)
16 Clover detectors (8 at 90 deg. and 8 at backward angles possible)
HIMALAY - Heavy Ion Mass Analyzer coupled to Large gAmma arraY (!)

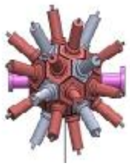
Spin gated ER cross-section using TIFR spin spectrometer and HYRA

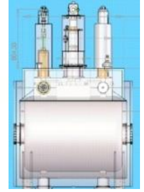
Secondary unstable beams of higher energy using direct reactions in inverse kinematics

Heavy ERs selected by Q1Q2-MD1 transported through straight-thru flange in MD2 into a trap !

FUTURE PLANS - HYRA

TIFR Spin Spectrometer

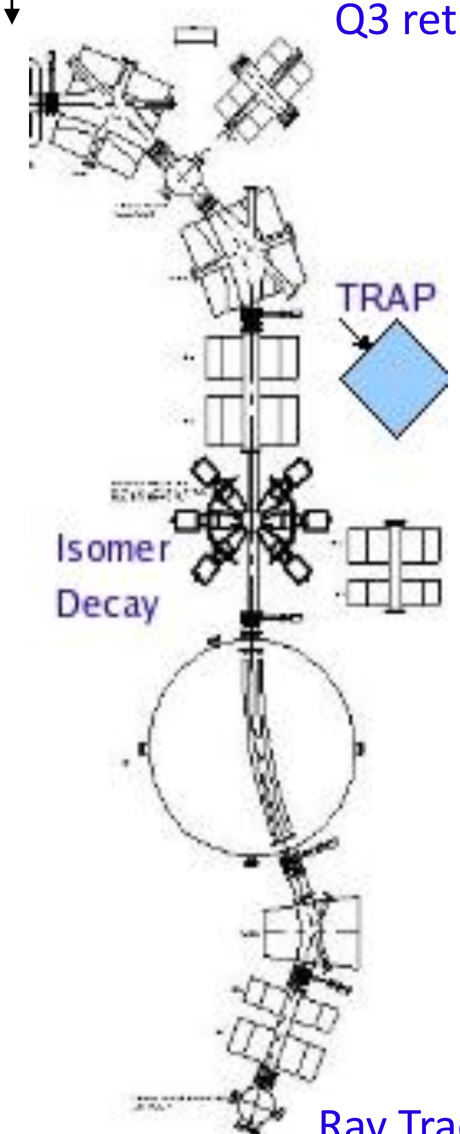




Superconducting Q1Q2

Indian National Gamma Array

Q3 retracted



Q6Q7 retracted

Ray Tracing (vacuum mode)

India Gate – World War Memorial

Qutab Minar ~ 1200 A.D.

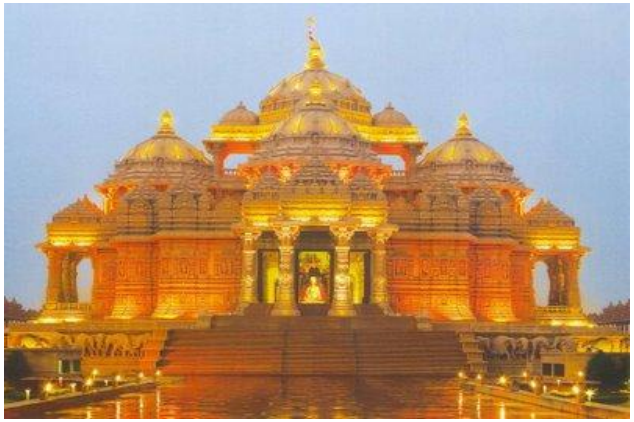
Lotus Temple – Baha'i Faith

FUSION14

IUAC, Delhi

Red Fort – Mughal Period

Akshardham Temple - 21st Century (Hindu)



Essence of India:
Fusion (of culture) involving large time scales (centuries), surviving fission and revealing the inherent nature through periodic excitation and de-excitation.
Madhavan

Thank You

Welcome to FUSION14 at IUAC – Early 2014