Limits of angular momentum in heavy evaporation residues using HYRA gas-filled separator and TIFR 4π spin spectrometer at IUAC, New Delhi

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Plan of the talk:

Brief introduction to IUAC (NSC)

Importance of angular momentum data in heavy element formation

HYRA spectrometer/separator

TIFR 4π spin spectrometer

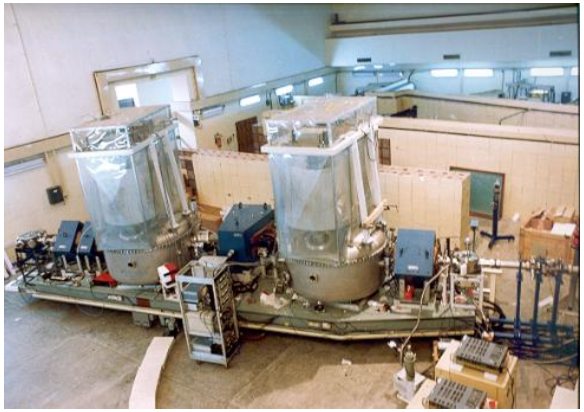
Studies with the combined facility

Extraction of transmission efficiency of HYRA

Probing fusion-fission processes using spin distribution

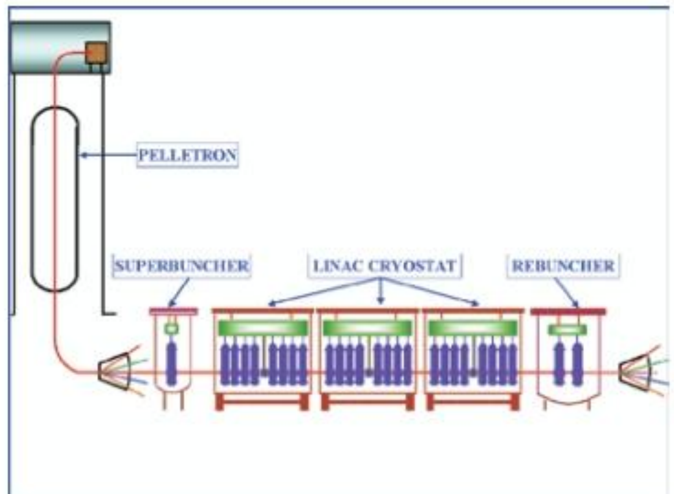
Inter University Accelerator Centre (IUAC)

[Formerly "Nuclear Science Centre (NSC)]



Heavy Ion Reaction Analyzer (HIRA), recoil mass spectrometer
in beam hall I

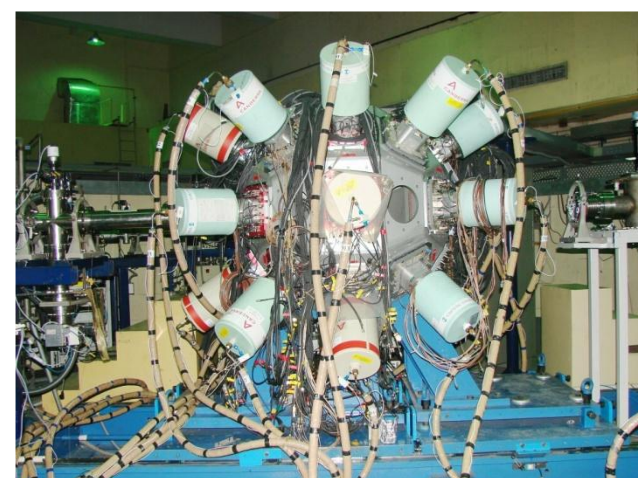
Hybrid Recoil mass Analyzer (HYRA), dual stage, dual mode Spectrometer/separator in beam hall II



Schematic of 15 UD Pelletron and Superconducting LINAC booster at IUAC
(Alternate high current injector to LINAC is underway using high Tc Superconducting ECR source)

General Purpose Scattering Chamber (GPSC)
in beam hall I

Indian National Gamma Array (INGA), pooled Ge clover array
in beam hall II



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**.

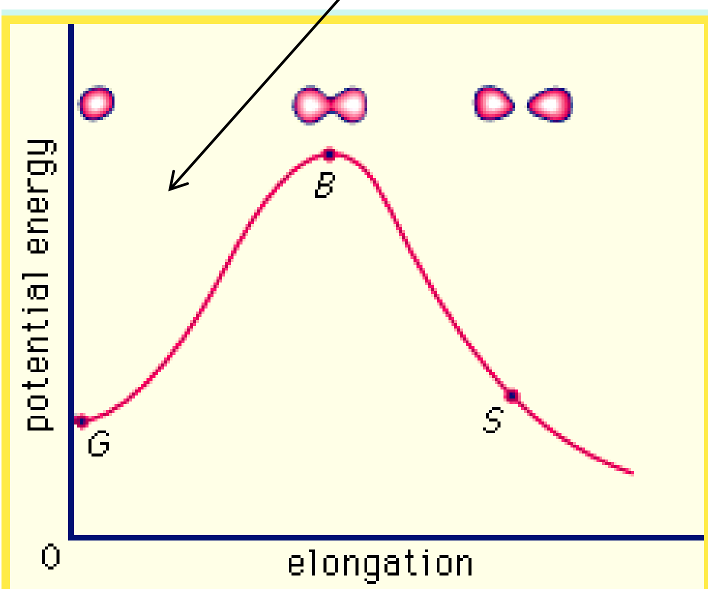
- While a **more symmetric system brings in a higher angular momentum**, **effective angular momentum of the compound nucleus (CN)** [and hence of the evaporation residues (ERs) from it] **is limited**.

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

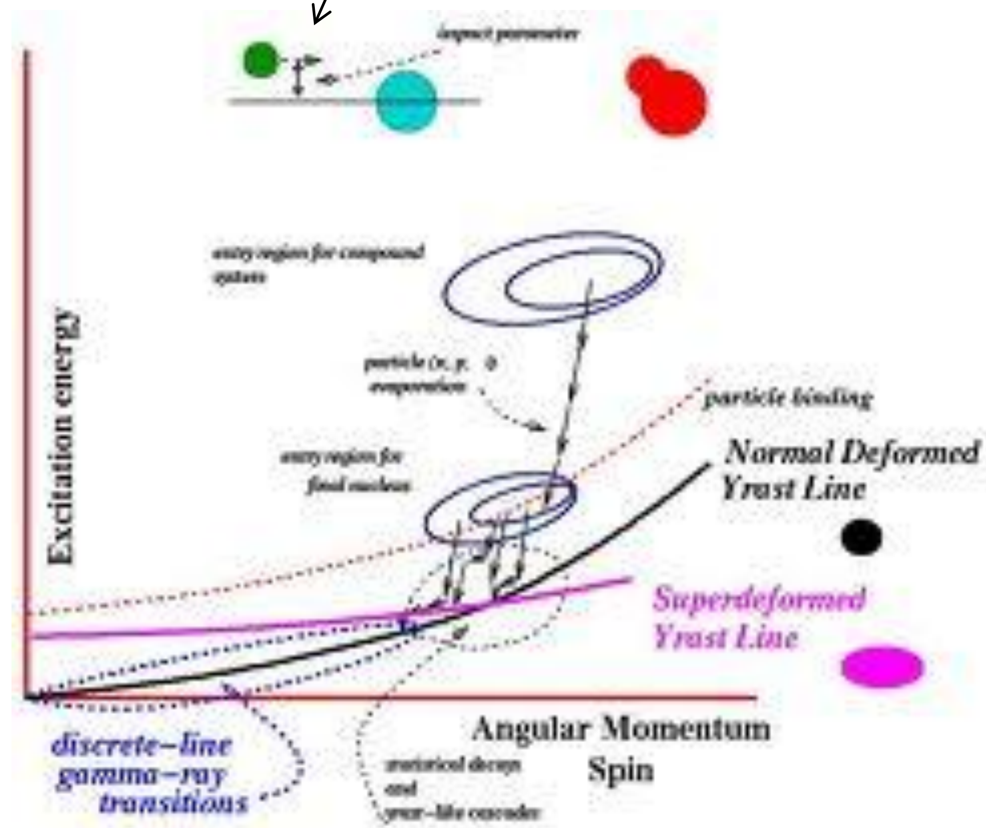
- **Experimental angular momentum distribution** sets a **more stringent condition on the various fusion-fission models** than the ER and fission cross-sections alone.

- 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.

ER measurement probes pre-saddle region



Impact parameter relates to I



Discrete gamma multiplicity relates to I

Current status in this field:

Quite a few measurements of angular momentum distribution have been carried out in **CN mass 180 amu and below using Heidelberg crystal ball and other gamma multiplicity setup more than a decade ago**.

High spin spectroscopy of ^{254}No carried out at JYFL and ANL showed the **limiting spin (angular momentum**) to be **around 20 ħ**.

Experiments carried out at **IUAC (NSC)** using the **recoil mass spectrometer HIRA and** a modest **14-element BGO array** have yielded the **lower moments of spin distribution in CN ^{194}Hg, ^{200}Pb and ^{203}Bi**.

Measurement of angular momentum distribution of ERs beyond 200 amu region gets severely restricted due to the limitations in the coincidence efficiency arising from increased fission probability and reduced ER transmission efficiency in vacuum mode spectrometers.

Efficient and highly selective ER separator and efficient and granular gamma multiplicity detector are required to overcome the limitations.

HYRA spectrometer/separator

Hybrid Recoil mass Analyzer (HYRA)

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

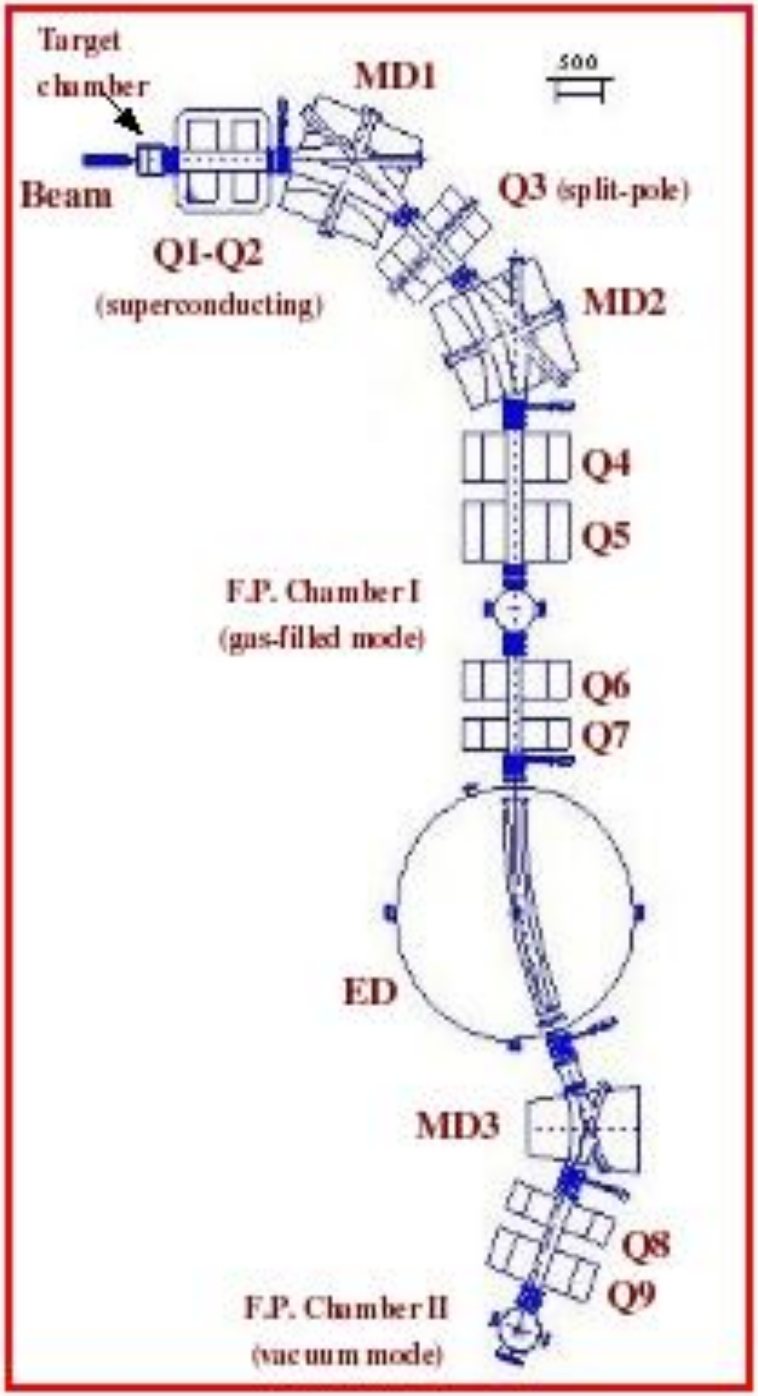
HYbrid Recoil mass Analyzer - Unique **dual-mode, dual-stage** spectrometer with large acceptances and rigidity at IUAC, New Delhi (to fully exploit ECR + LINAC beams of higher energy and intensity).

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).

Design layout of HYRA :

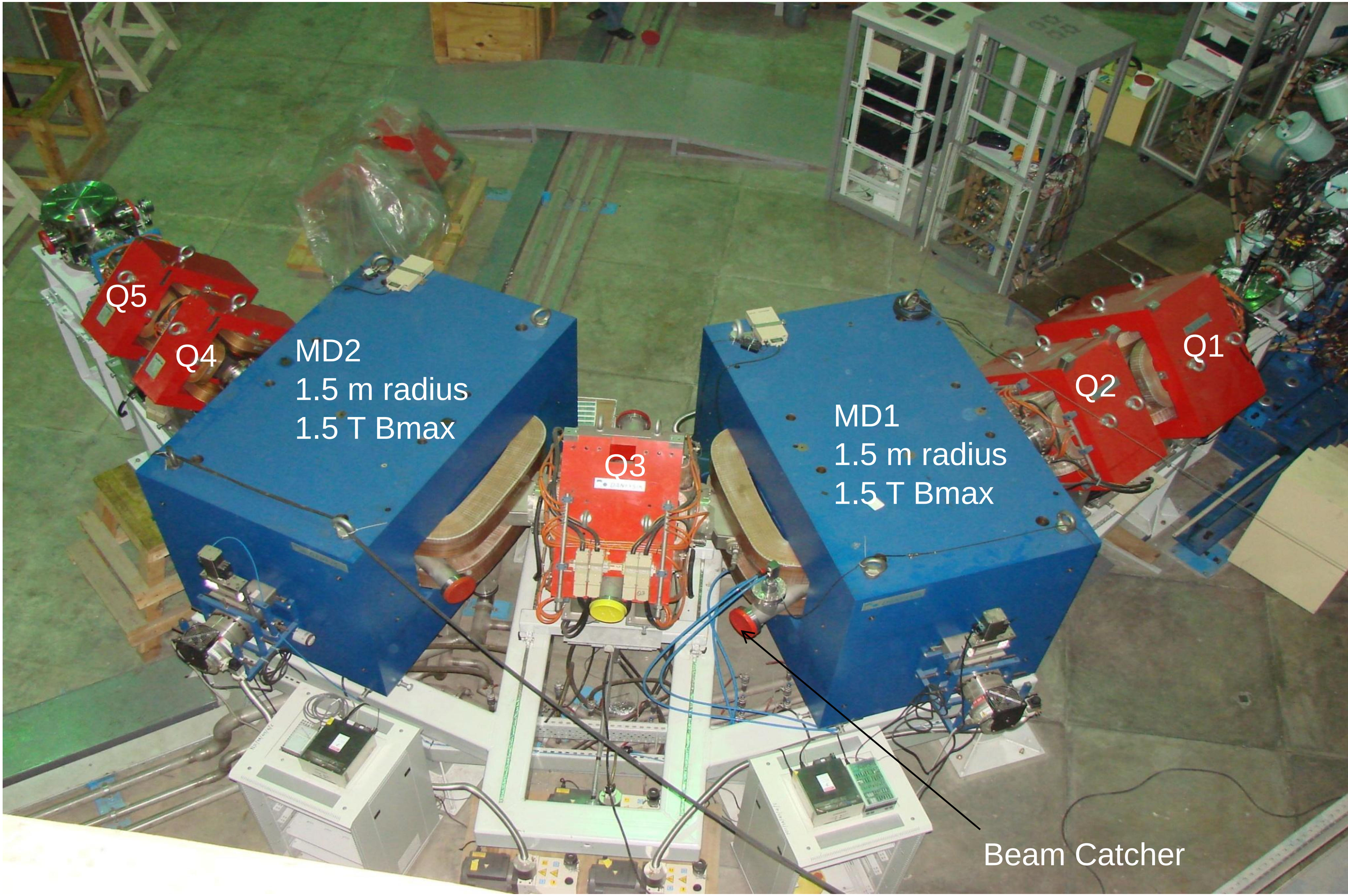


First stage
(QQ-MD-Q-MD-QQ)

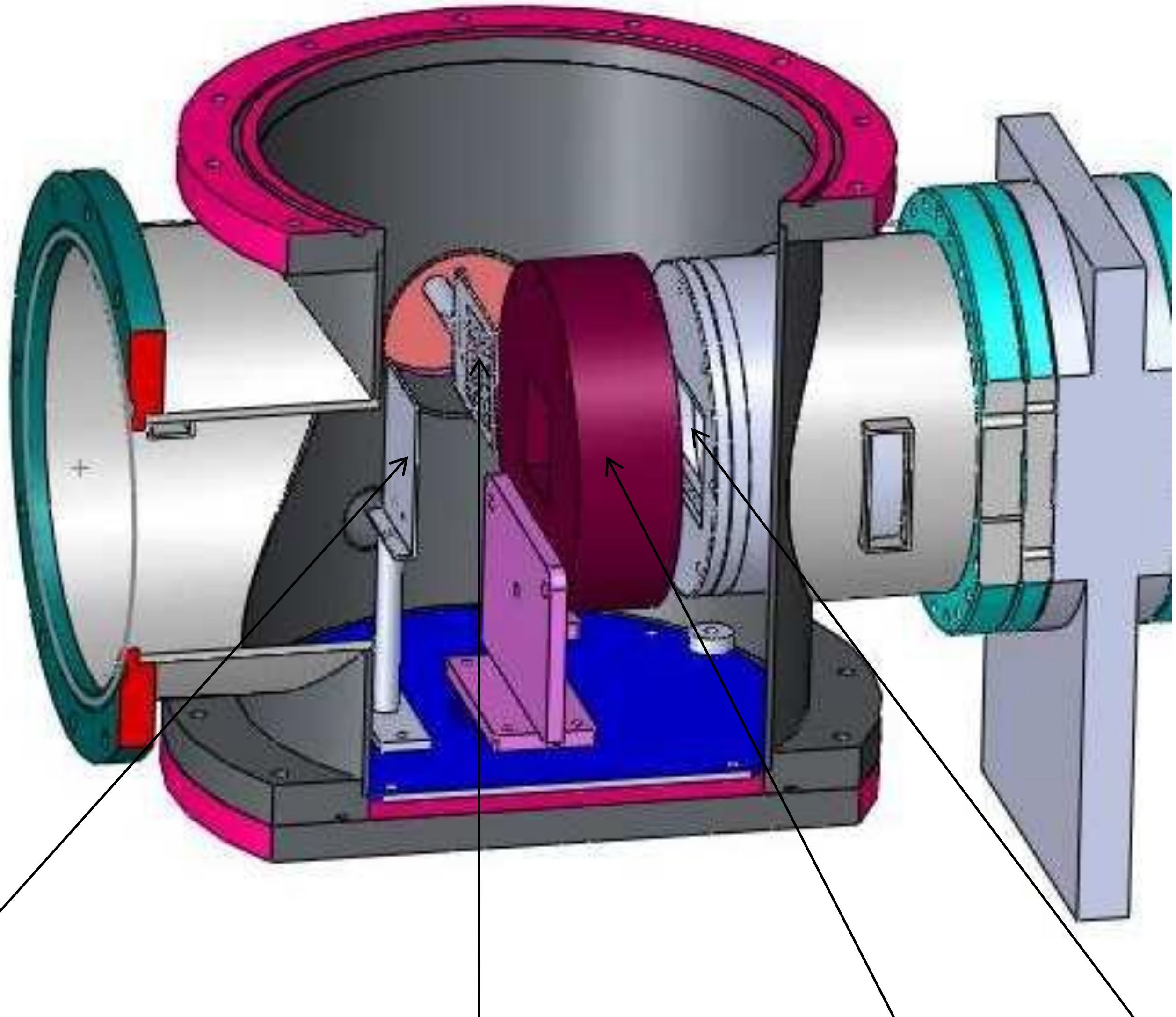
Second stage
(QQ-ED-MD-QQ)

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

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



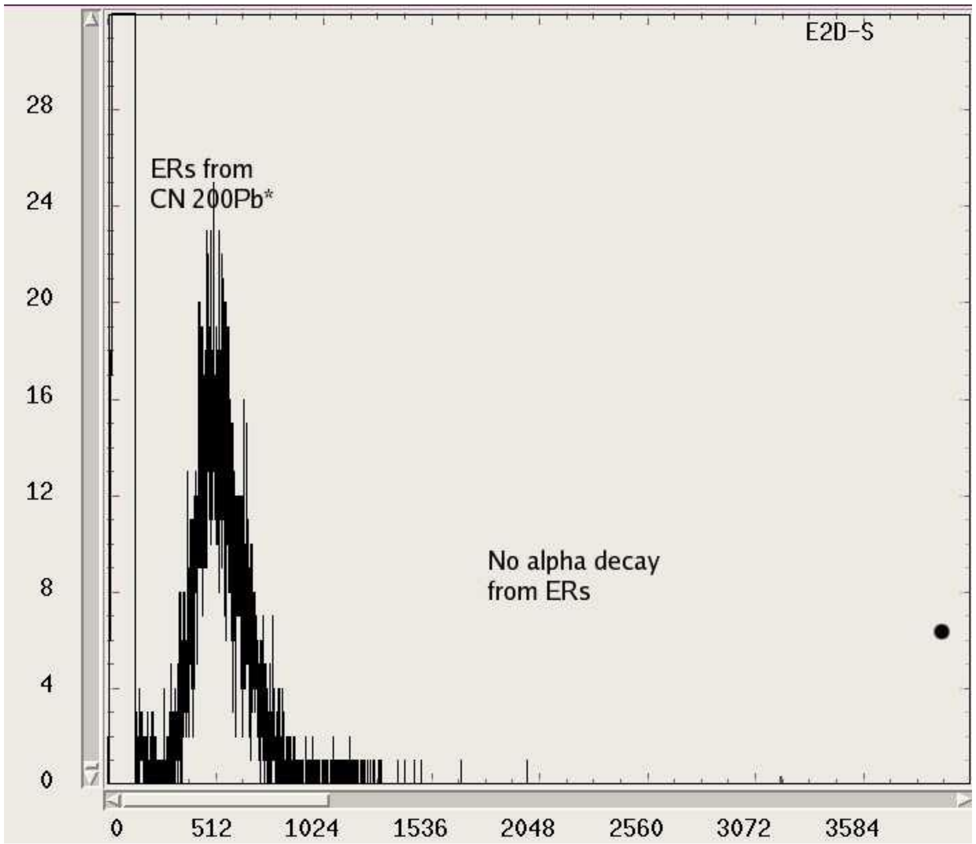
Focal plane detection system

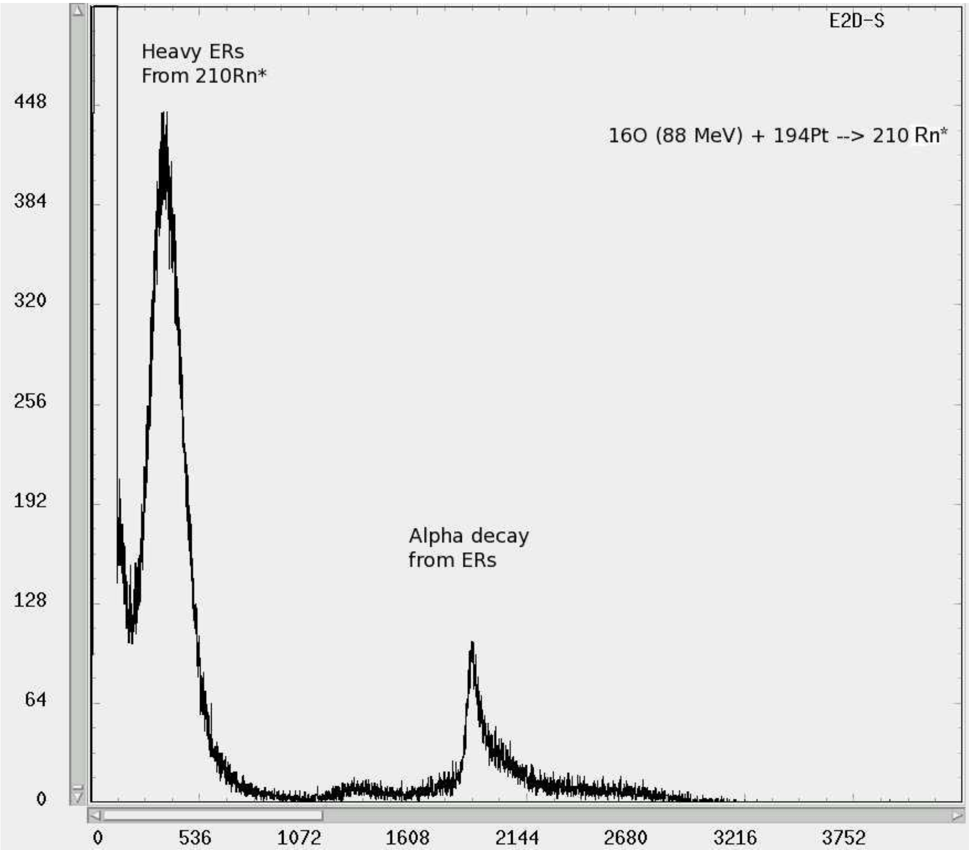


Si Resistive/Strip detector   Removable stopper   MWPC   0.5 μm Mylar foil

Energy spectrum at FP Si detector for $^{16}O + ^{184}W \rightarrow ^{200}Pb^*$ system; ERs detected (no alpha decay channel)

Energy spectrum at FP Si detector for $^{16}O + ^{194}Pt \rightarrow ^{210}Rn^*$ system; ERs and alpha decay detected

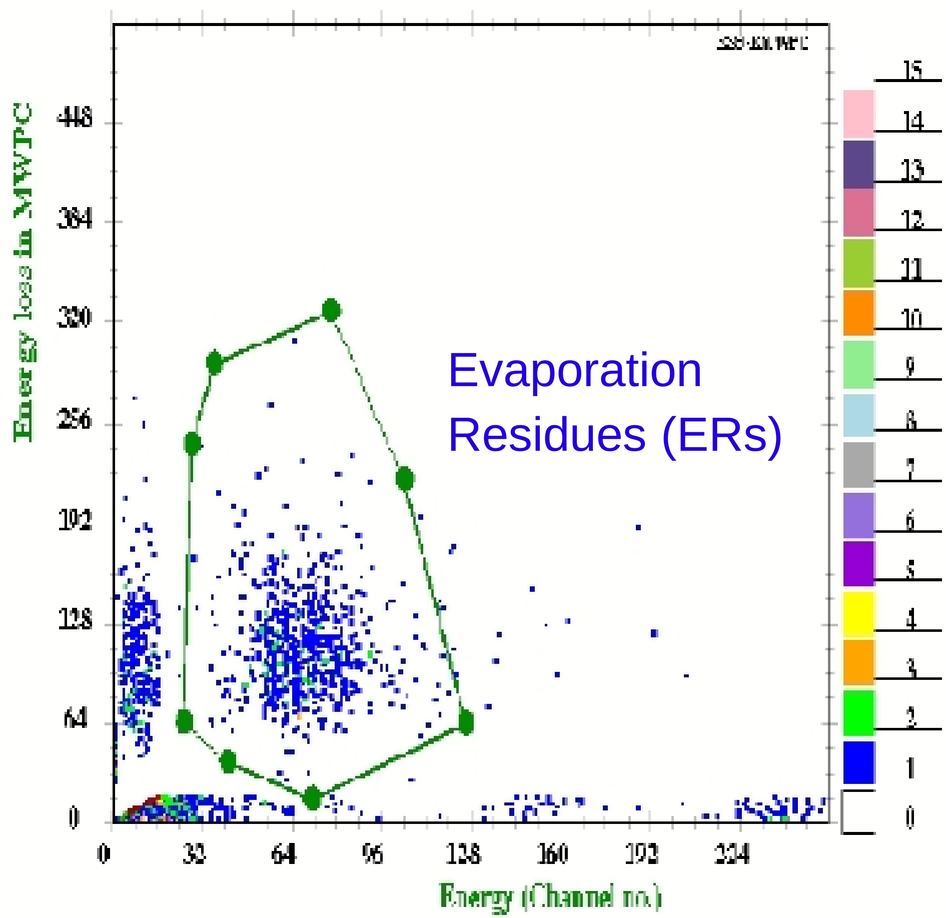




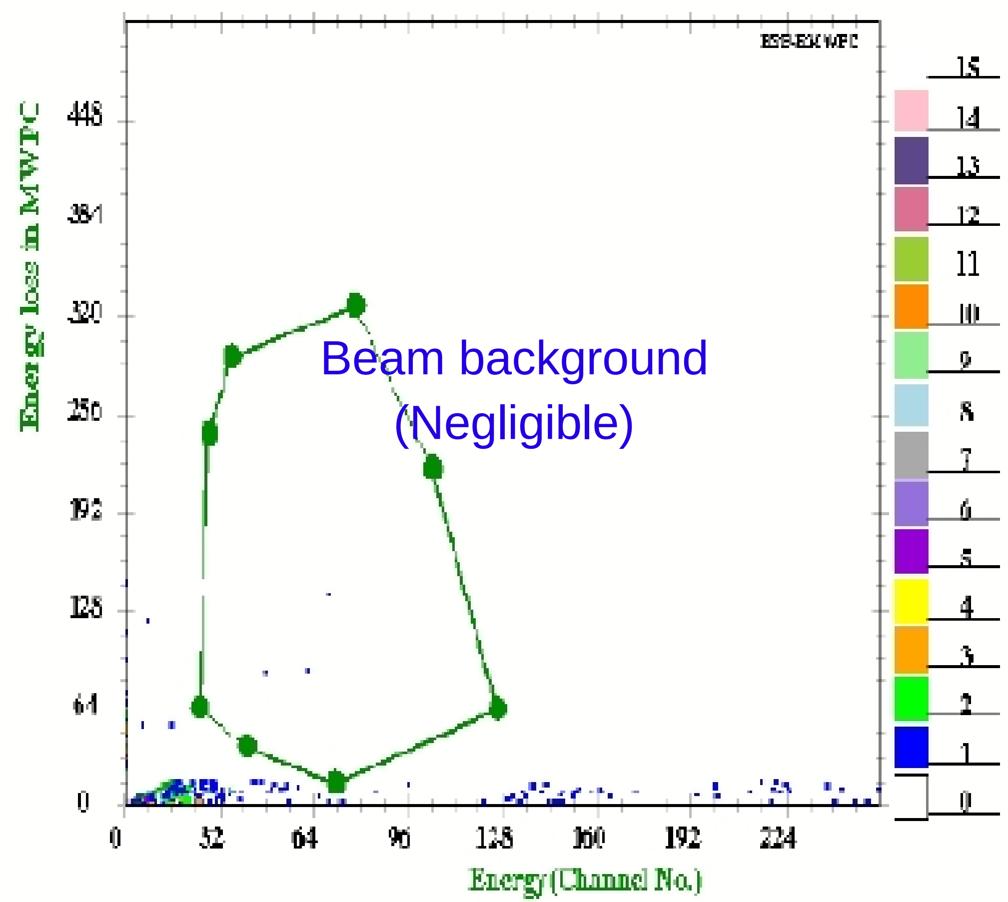
Negligible beam background at FP of gas-filled mode of HYRA:

Primary beam rejection better than 10^{12}

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

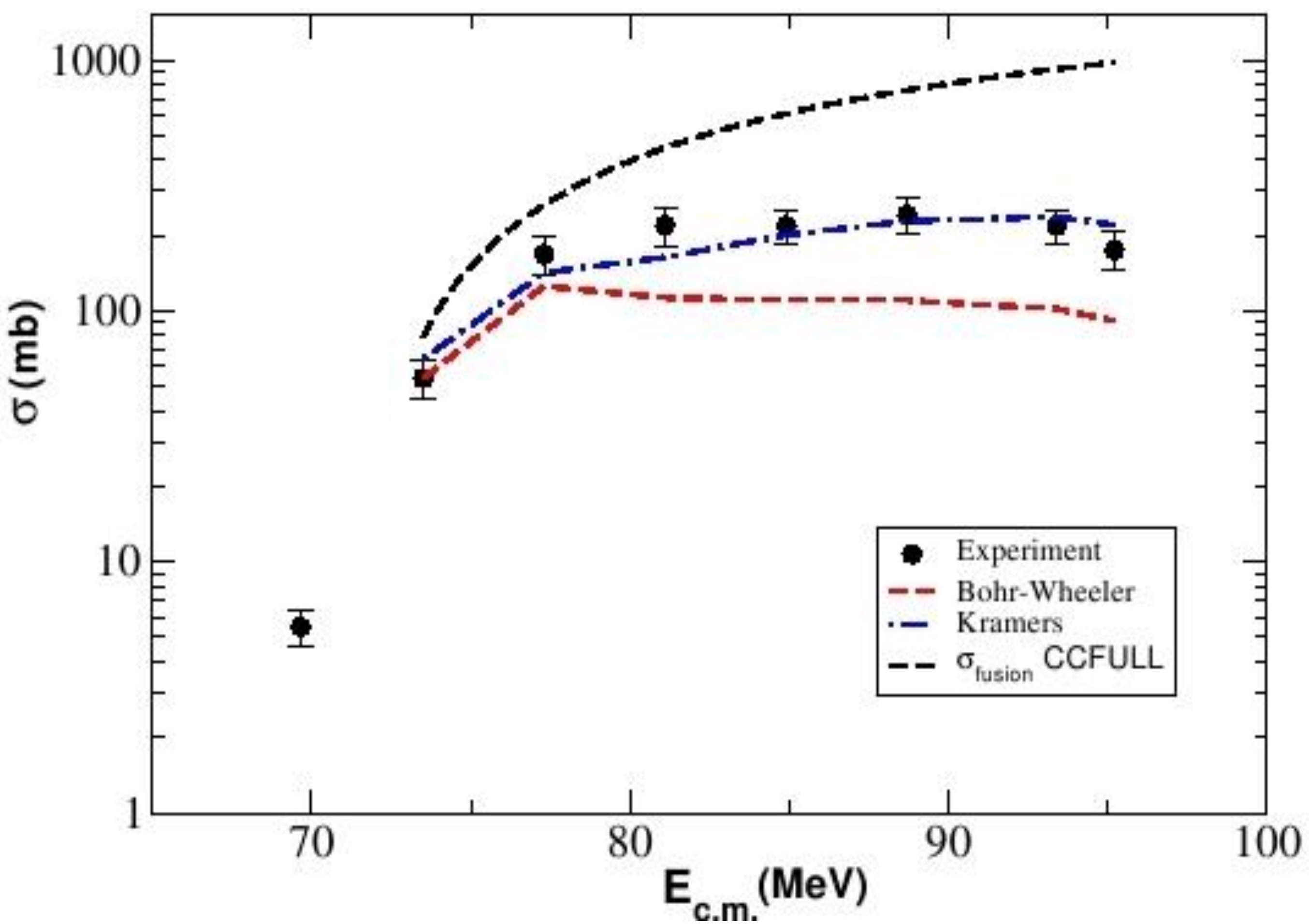


$^{16}O + ^{27}Al$ reaction at 104.3 MeV



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 $^{16}O + ^{194}Pt \rightarrow ^{210}Rn^*$



TIFR 4π spin spectrometer

TIFR 4π spin spectrometer: (I. Mazumdar et al., DAE Symp. on Nucl. Phys. **53**, 713 (2008))

Initially set up for spin-gated GDR studies at TIFR

32 nos. NaI (Tl) detector (20 hexagons and 12 pentagons)

Efficiency for 660 keV gamma detection: ~ 3 % for each hexagon
~ 2 % for each pentagon

Inner clearance ~ 200 mm diameter

Threshold set: ~ 100 keV

Output Signals Sum energy and 'OR' of all the detectors for TAC

Array separable into two halves to access the target chamber

When used with HYRA:

Two diametrically opposite pentagons removed for beam entrance and exit and one hexagon at 90^o for target ladder movement

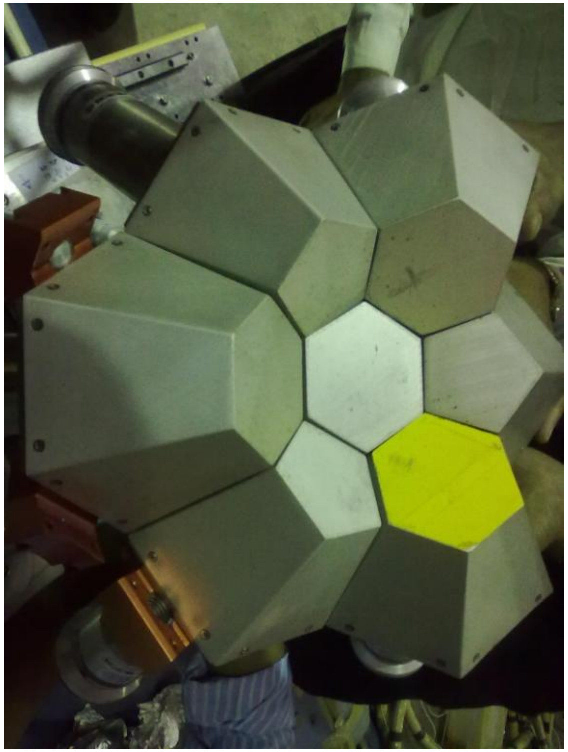
PMTs of forward most detectors wrapped with mu-metal shield due to proximity of entrance quadrupole magnet

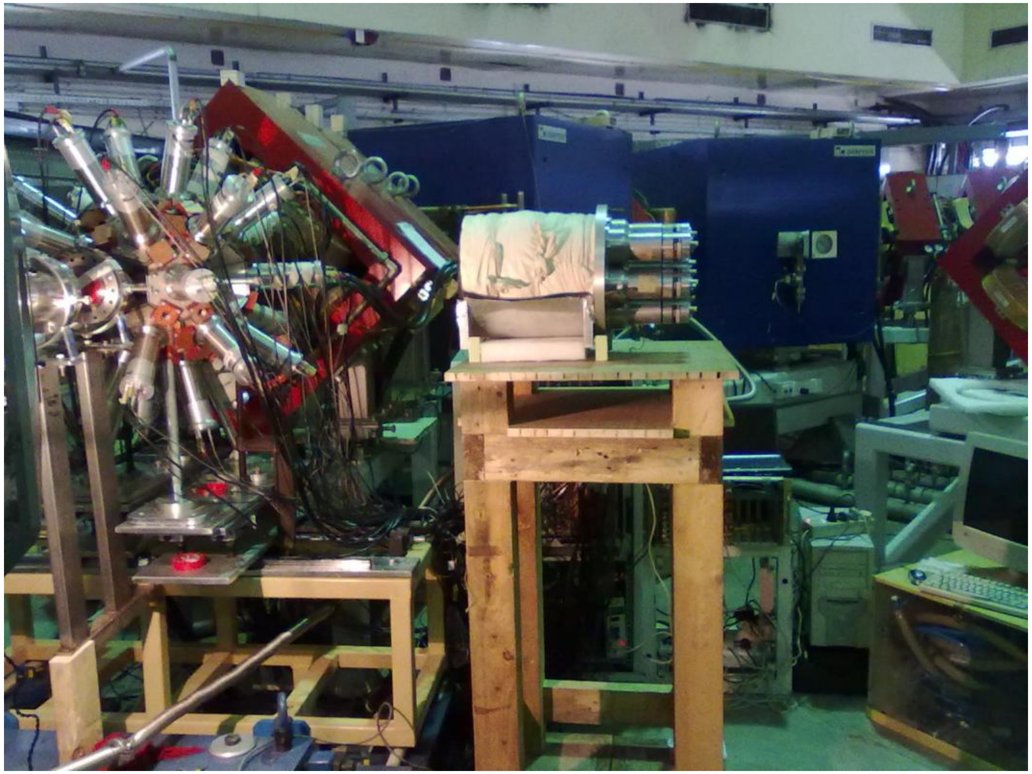
Studies with HYRA – Spin Spectrometer

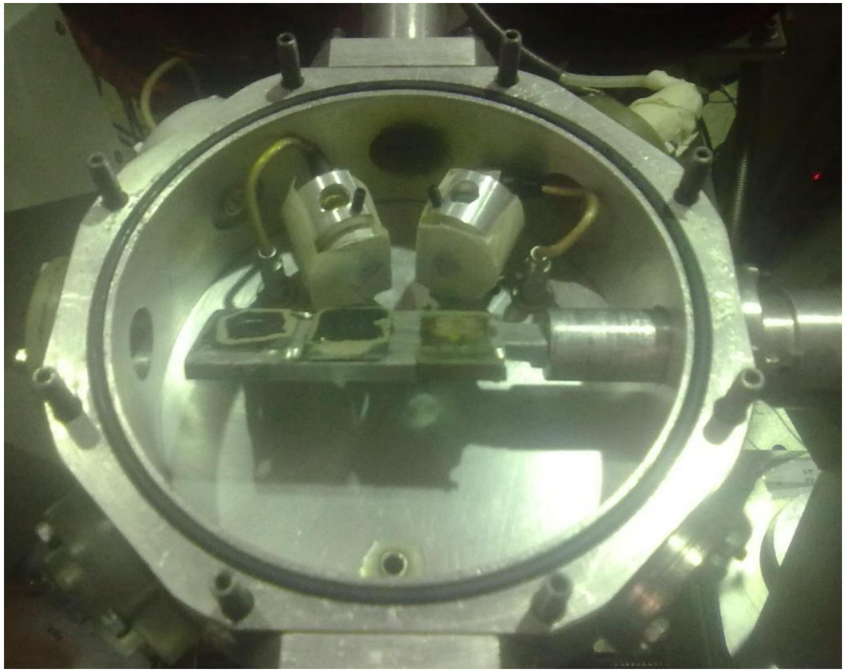
Recent effort at IUAC – HYRA-spin spectrometer combined facility:

Comparison of ^{254}No high spin data from JYFL and ANL showed that the larger transmission efficiency of RITU gas-filled separator in comparison with FMA for ER detection resulted in fewer clover detectors rather than the entire Gammasphere for similar coincidence statistics.

Encouraged us to combine the new gas-filled first stage of Hybrid Recoil mass Analyzer (HYRA), funded by Department of Science and Technology, Govt. of India, with the 4π spin spectrometer from TIFR, Mumbai for ER tagged spin distribution measurements in heavy nuclei where fission increasingly limits ER survival.





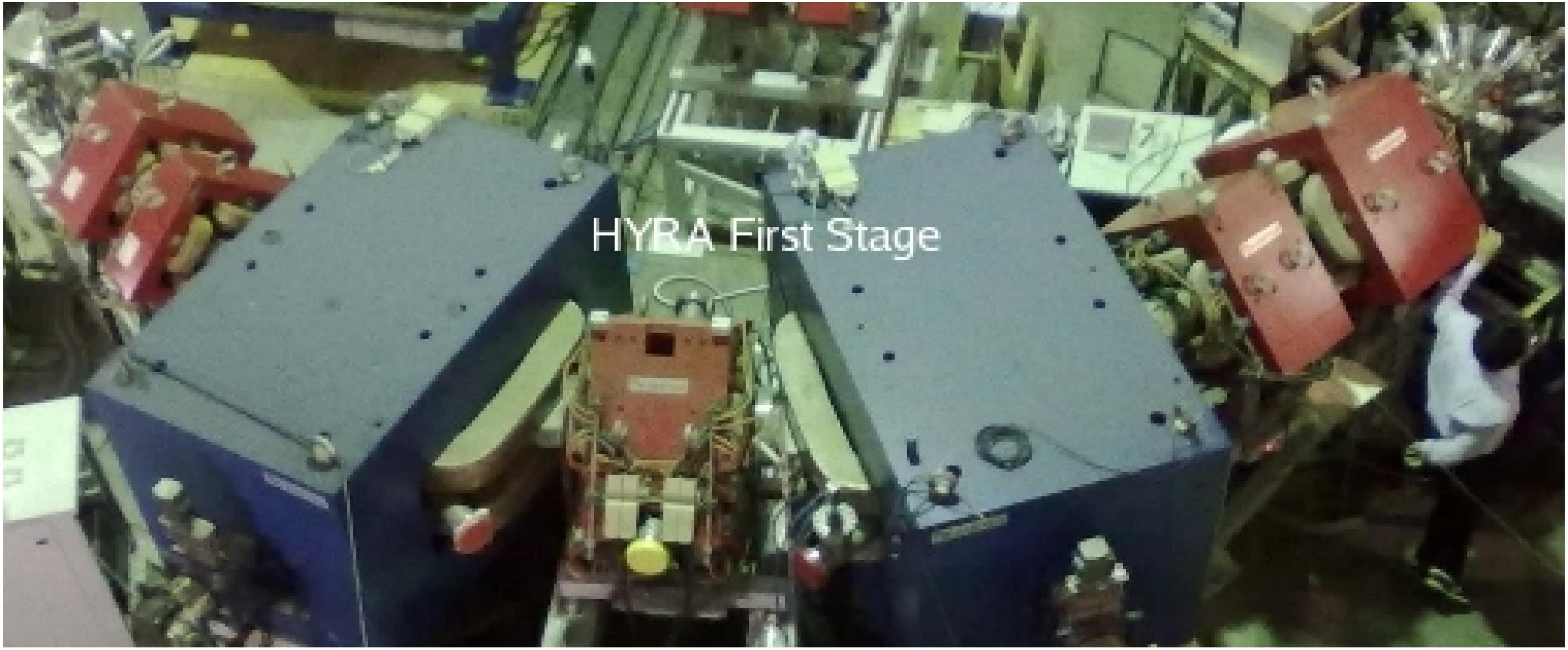


HYRA gas-filled separator coupled with TIFR 4π spin spectrometer
N. Madhavan et al., accepted in EPJA web conference - FUSION11

Focal plane

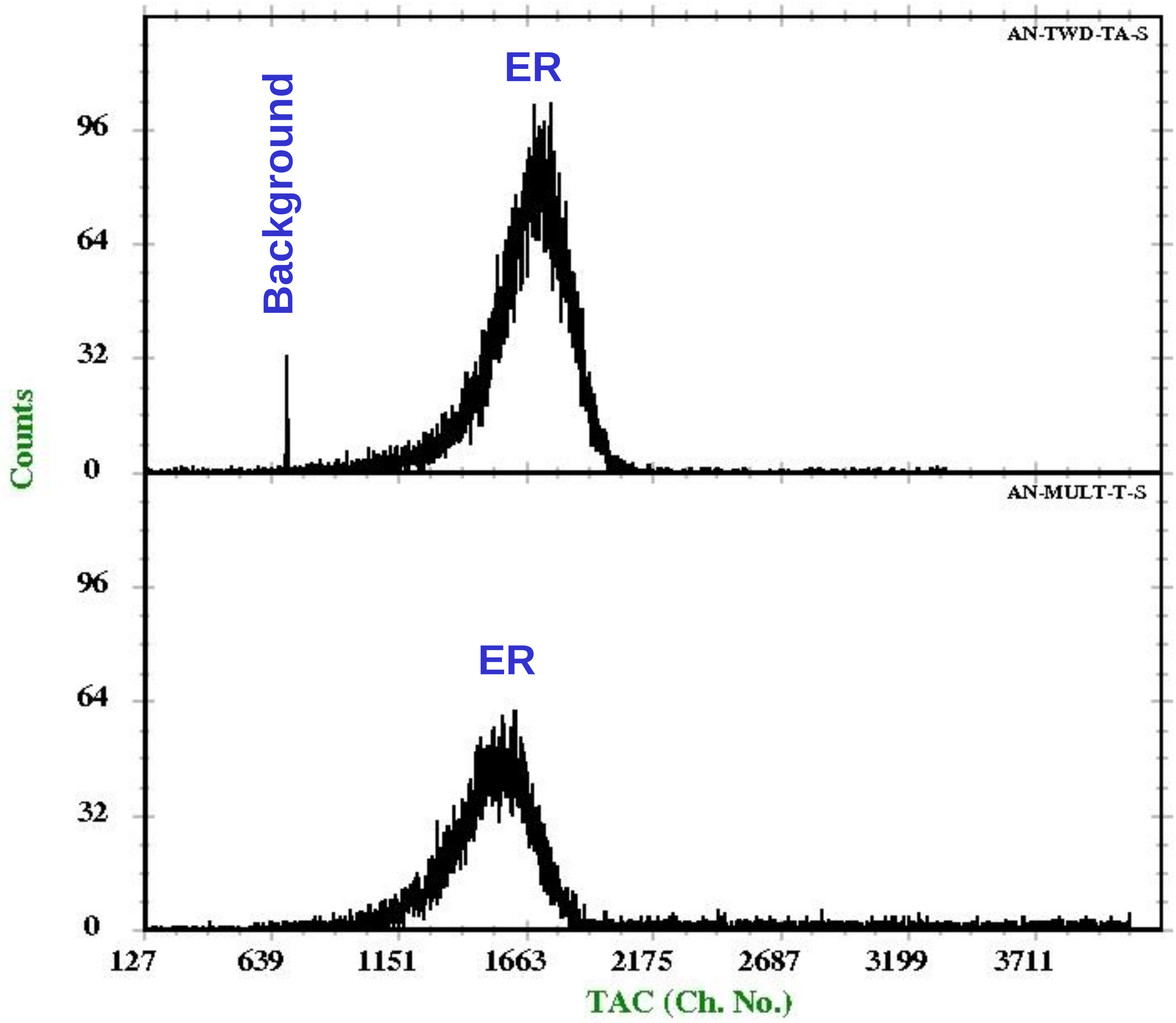
HYRA first stage
(operated in gas-filled mode)

Spin
Spectrometer



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

Focal plane is quite free from contamination except for the small spike at ~ 650 ch)



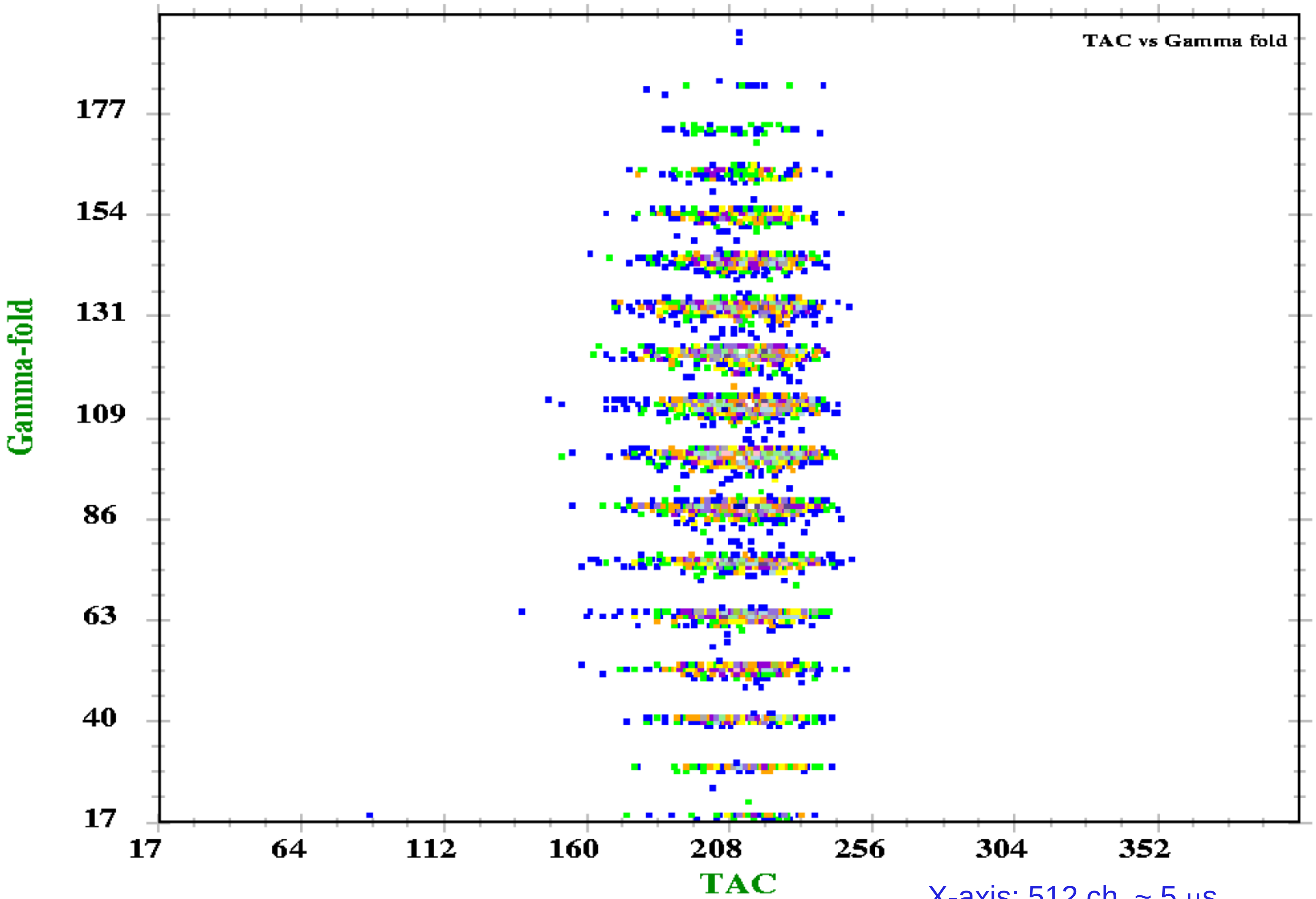
TAC started by FP MWPC anode and stopped by beam RF (4096 ch. ~ 5 μs)

TAC started by FP MWPC anode and stopped by delayed gamma 'OR' from spin spectrometer (4096 ch. ~ 5 μs)

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

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

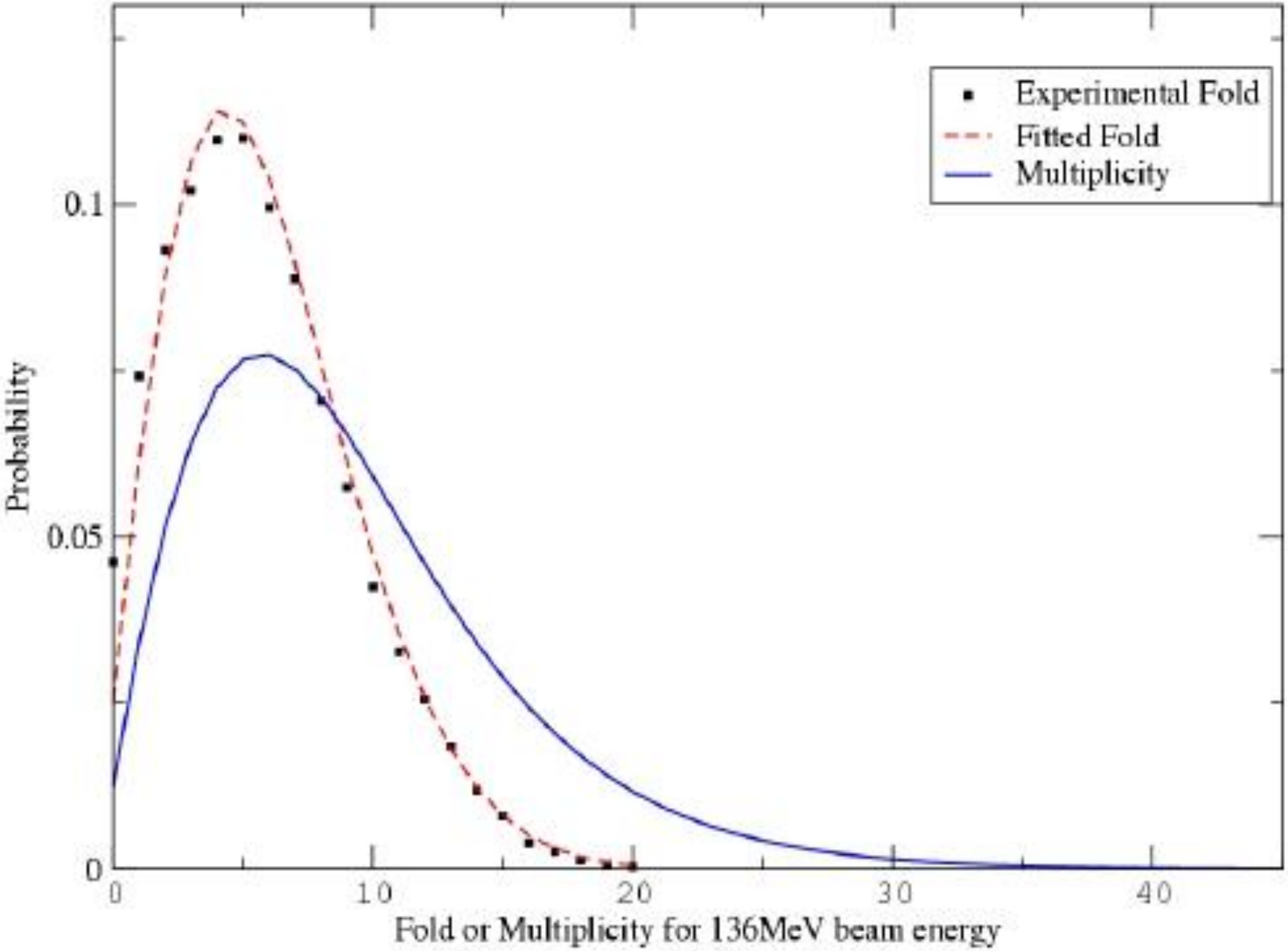
Clean ER group with negligible contamination



X-axis: 512 ch. ~ 5 μs

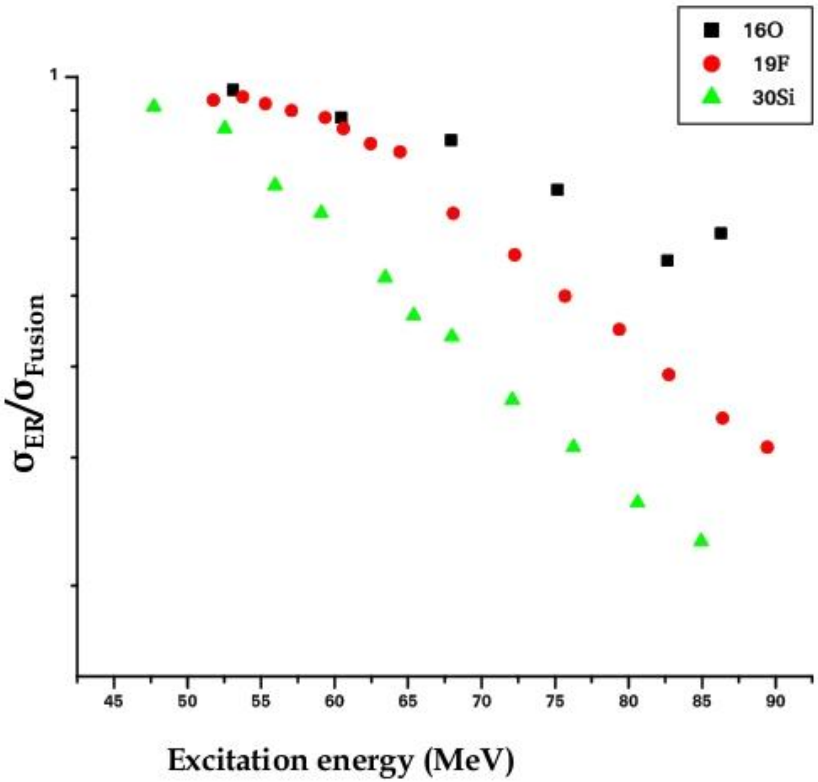
Experimentally observed gamma multiplicity (gamma fold) to actual multiplicity

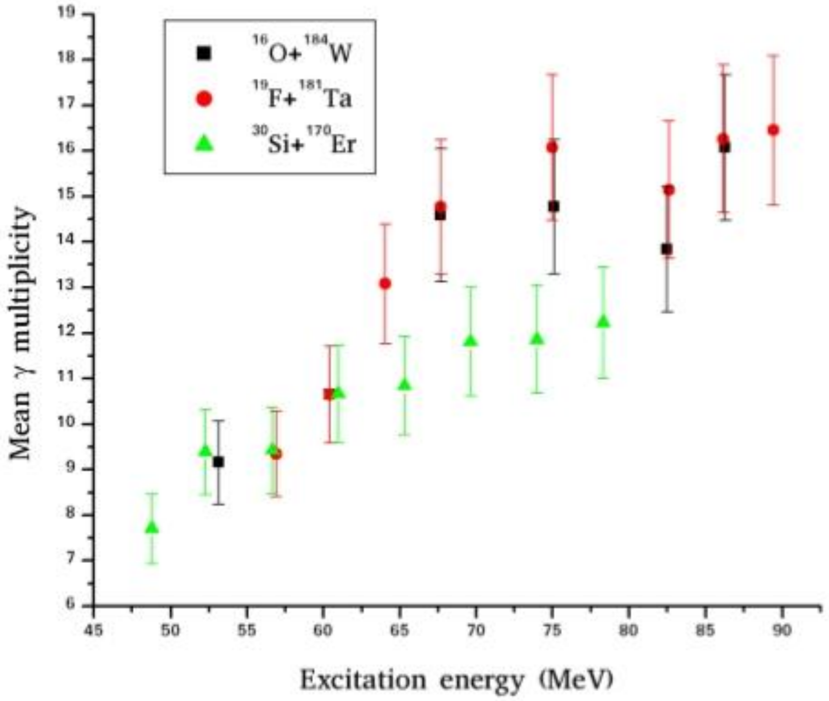
^{30}Si (136 MeV) + $^{170}Er \rightarrow {}^{200}Pb^*$



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., submitted to EPJA Web Conference - FUSION11

Extraction of transmission efficiency of HYRA

Transmission efficiency using ER gated gamma fold method

Known method:

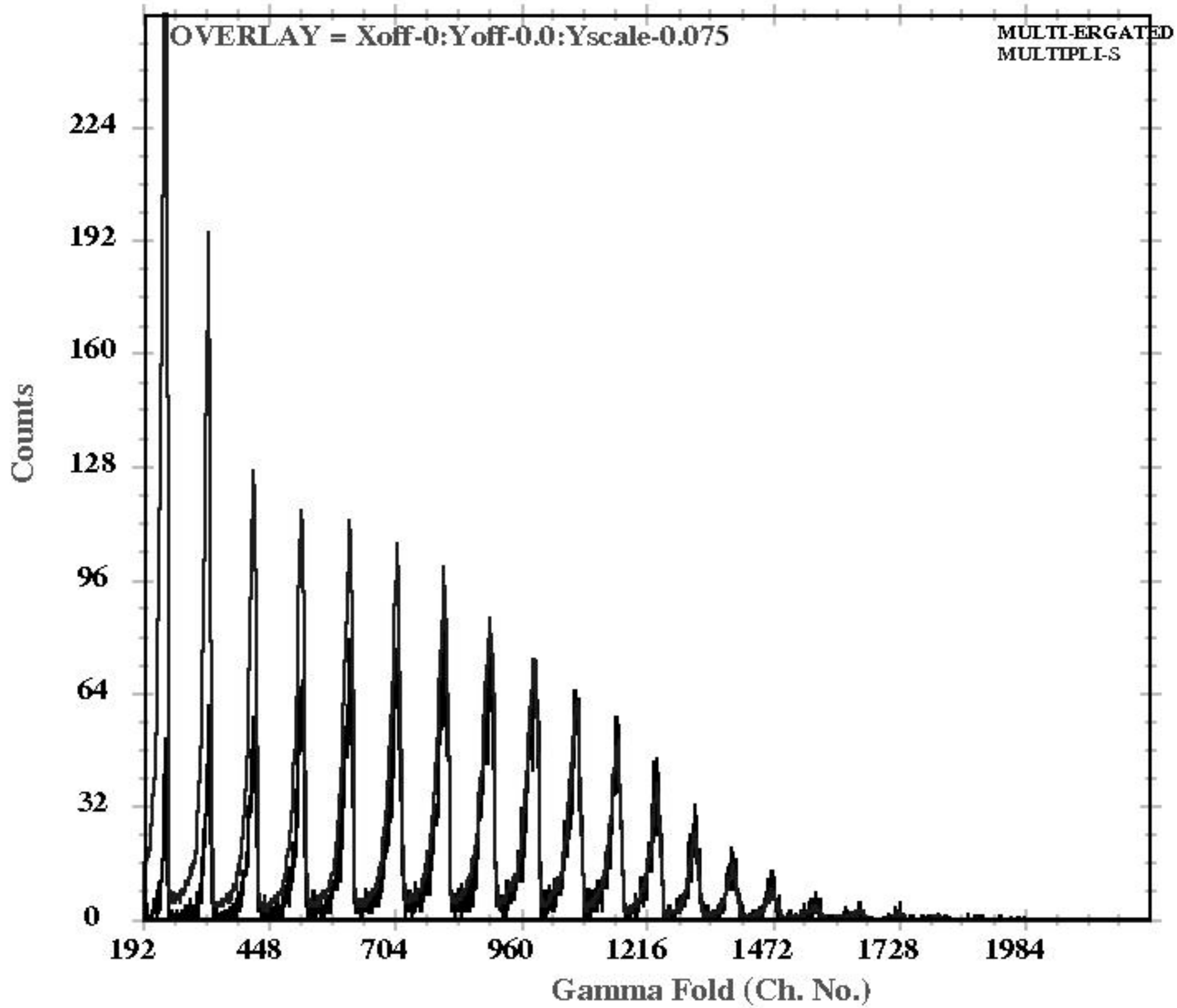
Transmission efficiency of any spectrometer **for detection of a particular ER** may be extracted using the **coincident characteristic gamma technique**. The efficiency of the gamma detector gets canceled while taking the ratio of counts in the ER gated gamma spectrum to that in singles gamma spectrum for the chosen gamma ray emitted by that ER.

Modified approach:

Using spin spectrometer and **comparing the higher folds** (which are free from contamination from gamma rays originating from Coulomb excitation, fission fragments and ERs produced from fusion of beam with carbon entrance foil), we extract the **average transmission efficiency of all ERs** transported to the focal plane of gas-filled separator HYRA.

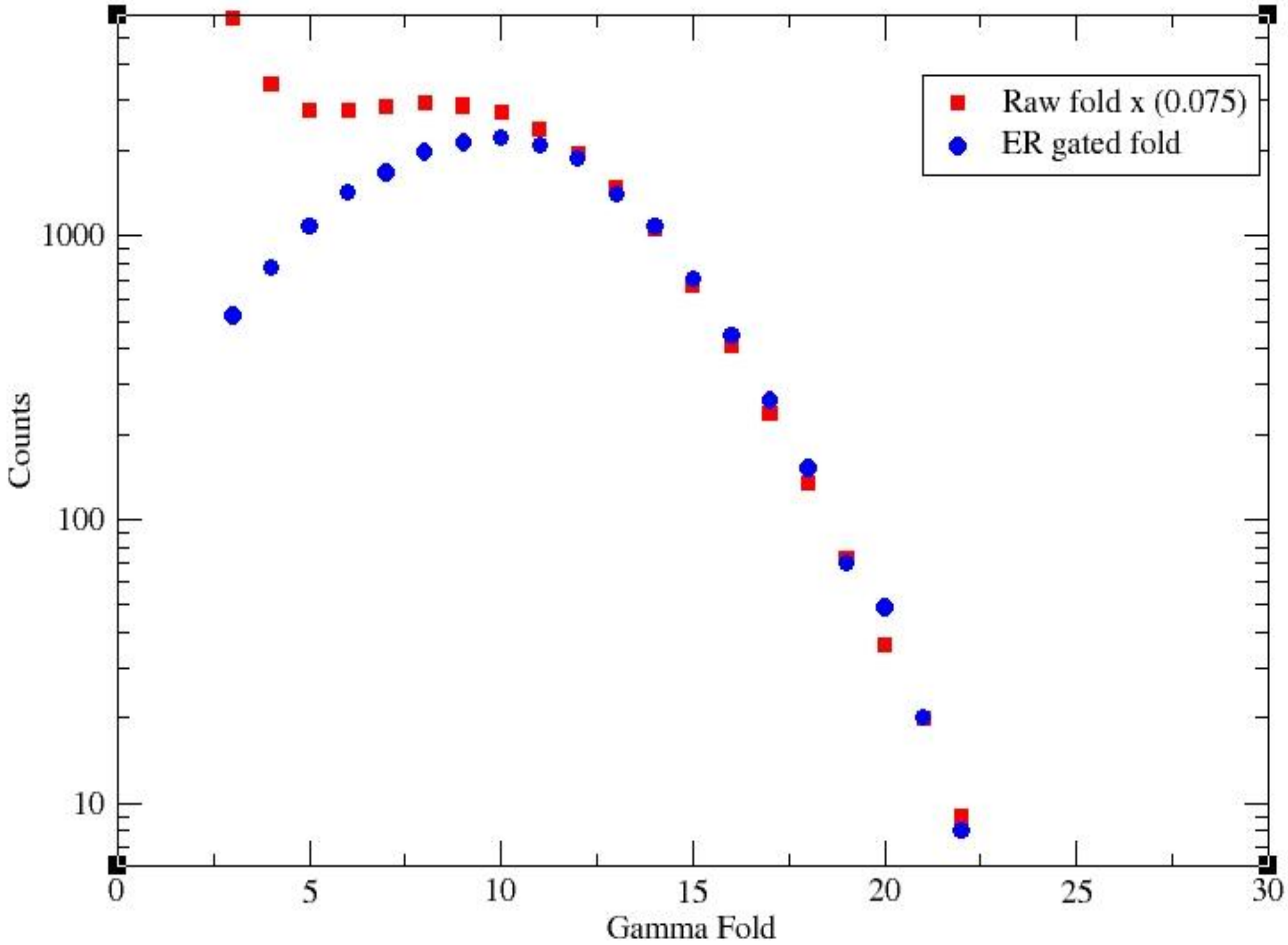
ER gated gamma fold spectrum overlayed with singles gamma fold spectrum (scaled down to 7.5%) for ^{16}O (120 MeV) + $^{180}Hf \rightarrow {}^{196}Hg^*$

Higher folds, free from background, match well suggesting a 7.5% transmission efficiency of ERs



16O + 180Hf using HYRA + Spin spectrometer

(Higher fold ratio gives ER transmission efficiency through HYRA)

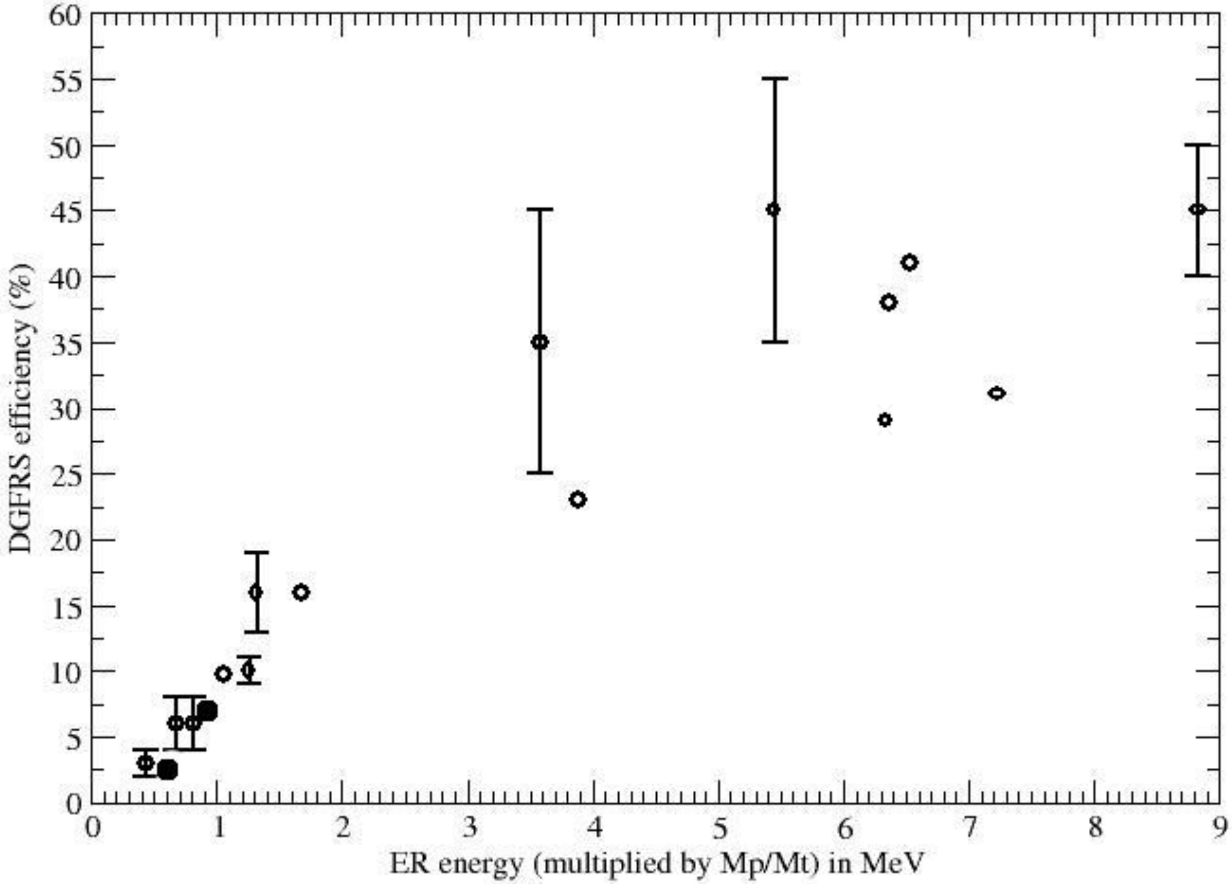


Higher folds match perfectly when singles spectrum is scaled down to 7.5 %; With negligible contamination, this value gives the average transmission efficiency of HYRA for ERs.

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

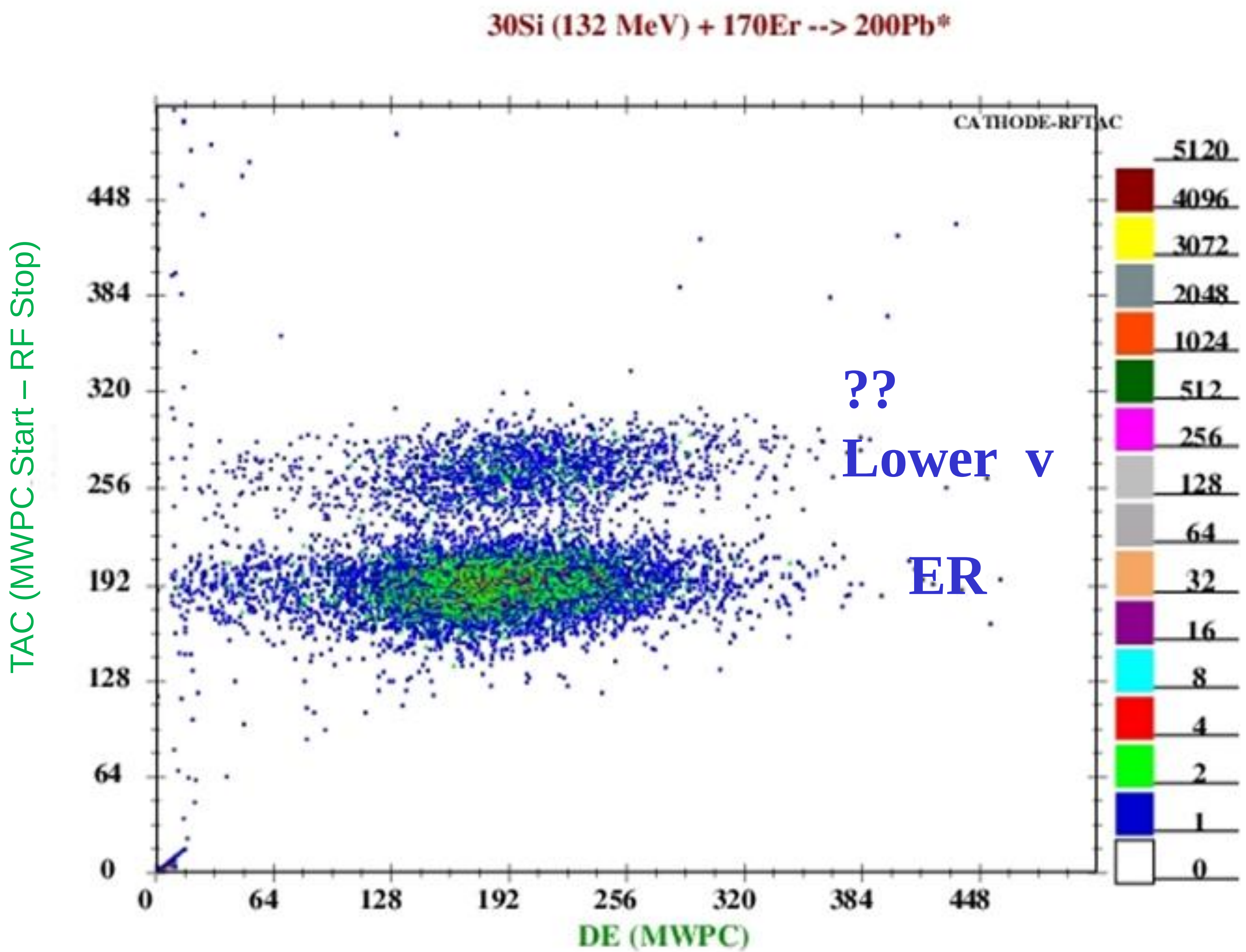
Transmission efficiency data presented against the quantity (ER energy x (M_p/M_T)) to take care of kinematic effects

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

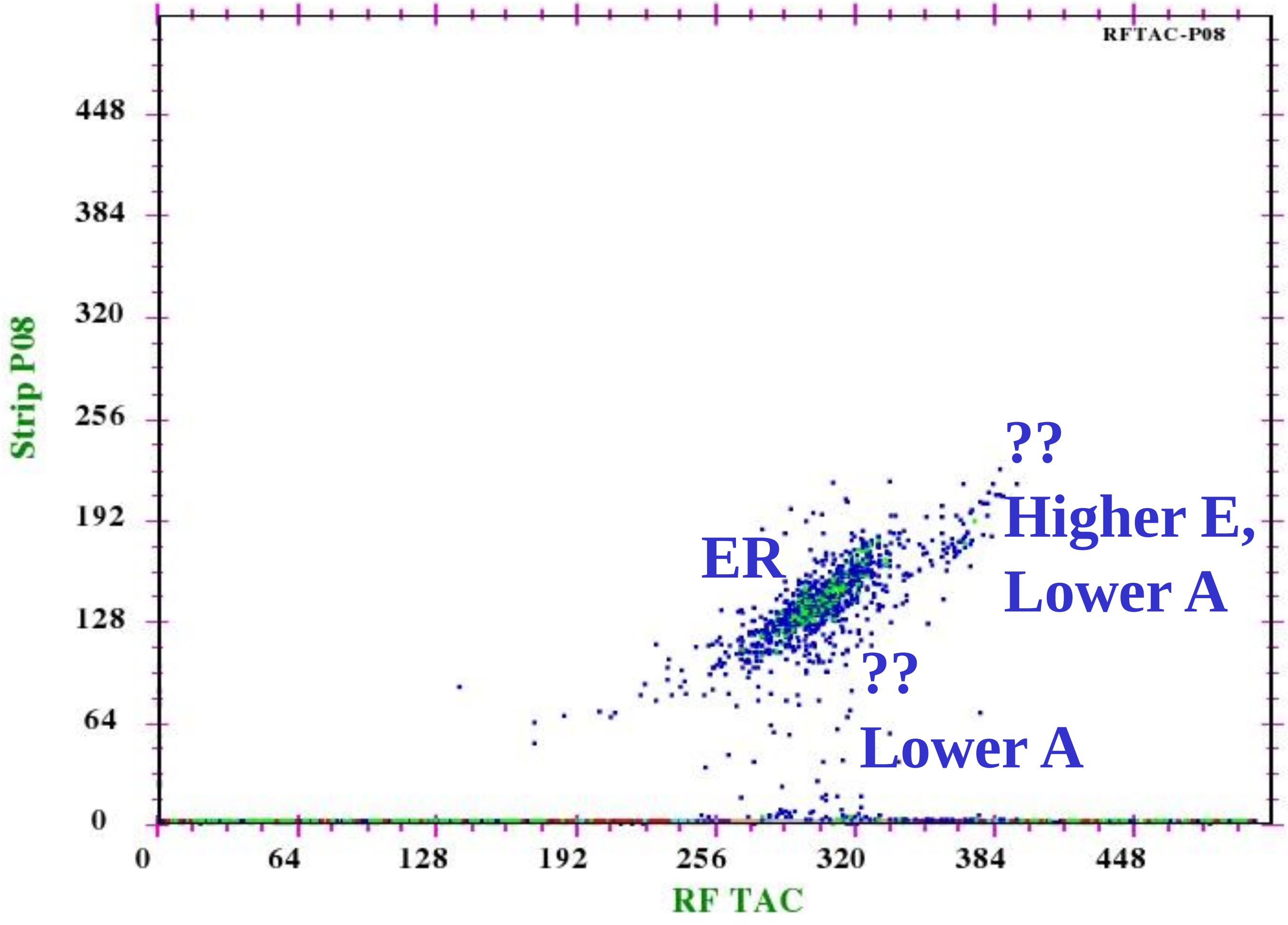


Probing Fusion-Fission processes using spin distribution

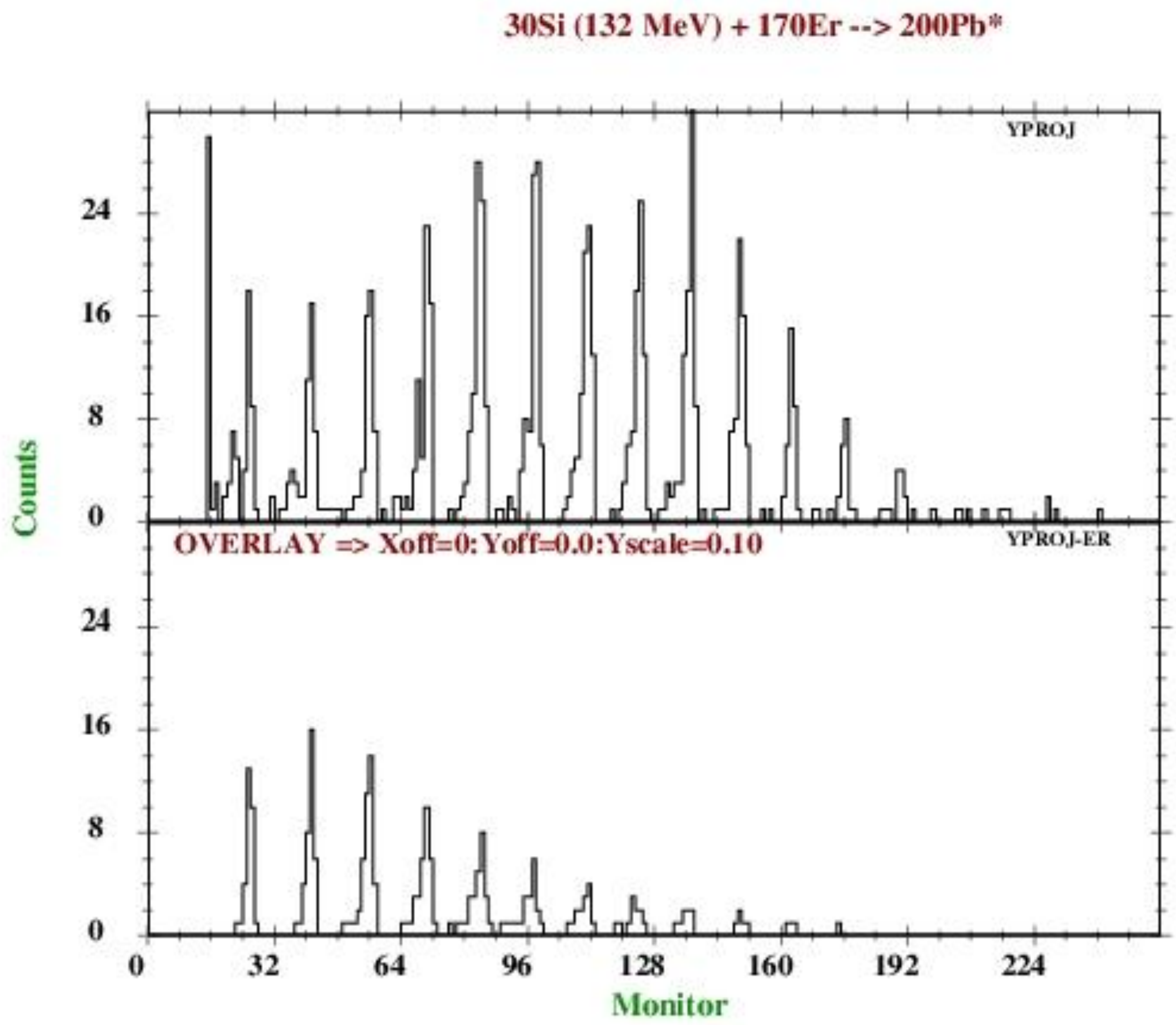
ER formation in competition with other processes at around Coulomb barrier (similarly above barrier too)



$^{30}Si + ^{170}Er \rightarrow ^{200}Pb^*$, E_{lab} ~ 160 MeV



Around Coulomb barrier



??
Higher γ-fold

ER γ-fold
(Scale 1/10)

Points to asymmetric quasi-fission ?!

Future Plans:

1) On completion of accelerator augmentation programme, we plan to go to heavier CN with more symmetric reactions.

2) Plan to probe, in detail, origin of non-ER events at the focal plane through spin measurement which can shed more light on other competing processes.

Summary:

a) Unique combination of gas-filled separator and 4π Spin spectrometer has been realised at IUAC, New Delhi in collaboration with TIFR, Mumbai

b) New facility has been successfully used for spin distribution of ERs looking for entrance channel effect and also to extract average ER transmission efficiency.

c) Origin of other processes competing with ER formation can be better understood with spin gating.

Thank You

Welcome to FUSION14 at IUAC – Early 2014