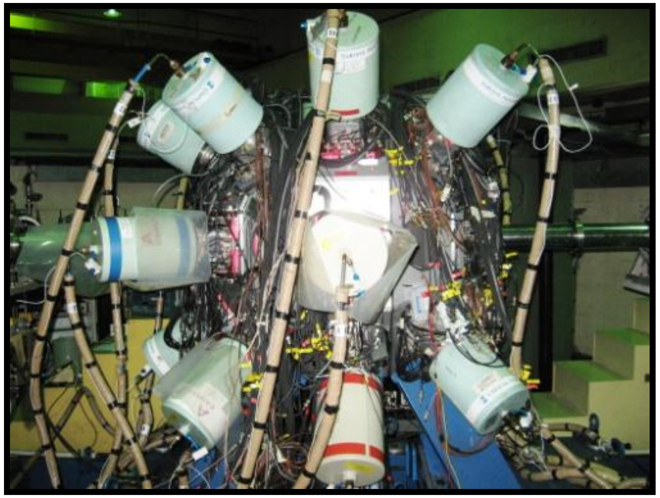


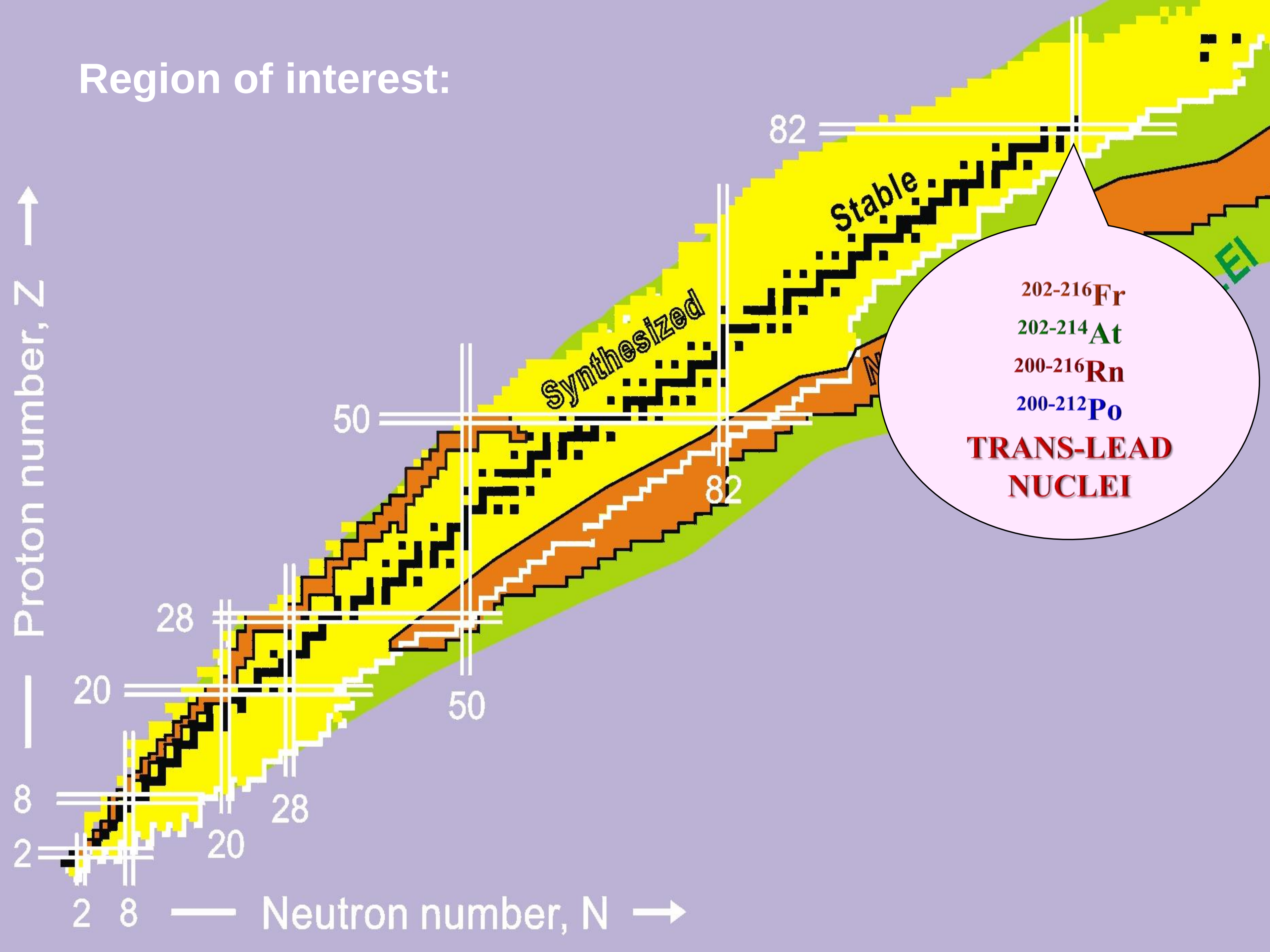
Exploring nuclear structure of neutron deficient heavy nuclei at the CERN-ISOLDE facility

Satyajit Saha
Applied Nuclear Physics Division
SAHA INSTITUTE OF NUCLEAR PHYSICS

Outline

- MOTIVATION
- DIFFICULTIES AND CHALLENGES INVOLVED
- RESULTS FROM RECENT INDIAN NATIONAL GAMMA ARRAY (INGA) EXPERIMENT ON HEAVY NUCLEI
- FUTURE PLAN INVOLVING CERN-ISOLDE FACILITY

Region of interest:



Why explore trans-lead nuclei?

- Poor knowledge of nuclear structure in this domain
  - Investigate by experiment
  - Look for single particle behaviour and co-operative phenomena

    Shell model calculation of nuclear structure

    RMF PHF

    Collective behaviour

    Small deformation → perhaps only M1 band ? **At Fr Ra**

    $(\beta_2 \leq 0.1)$

    Large deformation →

    Rotational bands

    Octupole correlation in nuclei

    - ΔL=3, ΔJ=3 orbitals co-exist near the Fermi surface

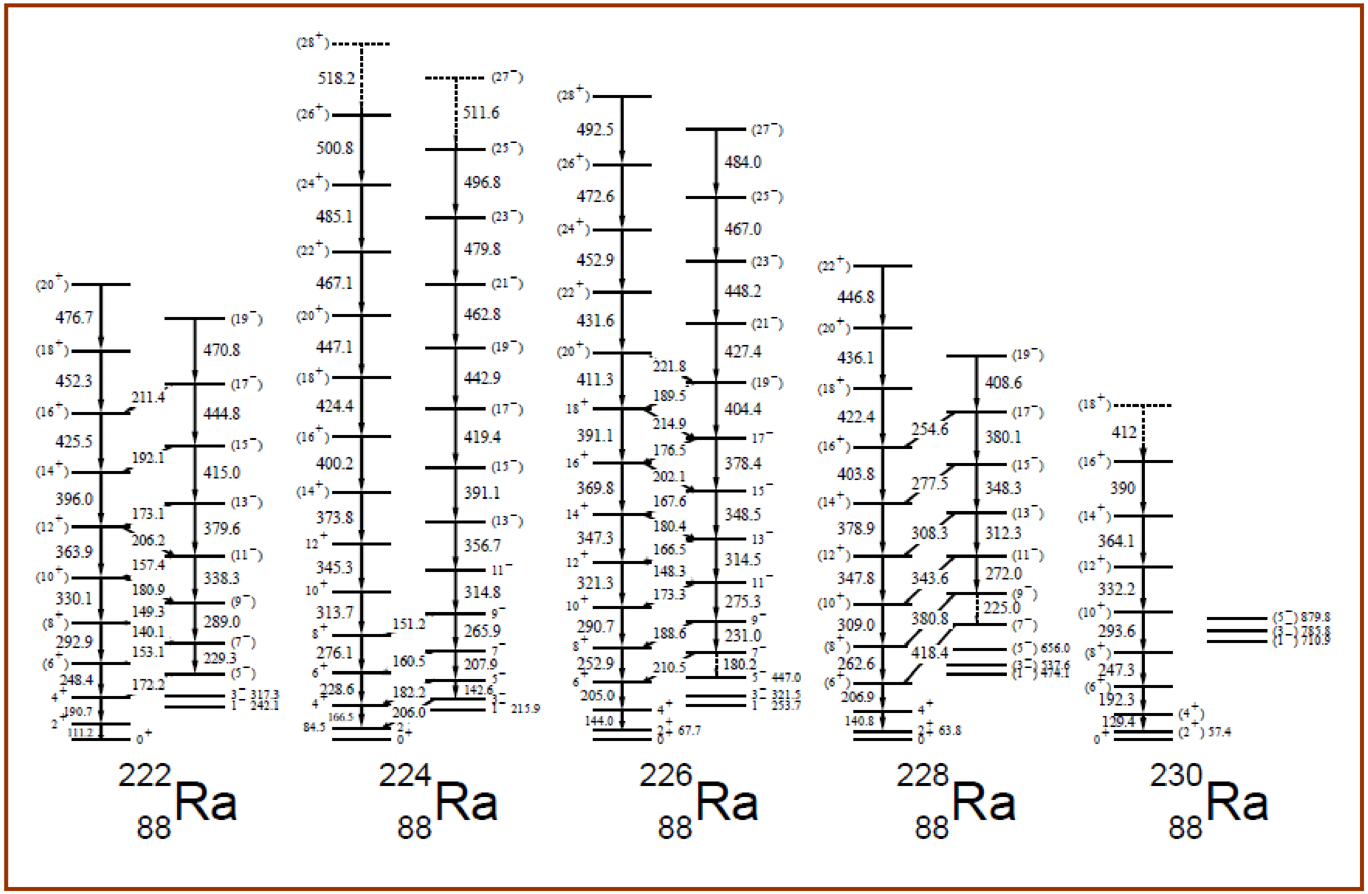
      (proton: i13/2, f7/2 neutron: j15/2, g9/2)

      (proton: h11/2, d5/2 neutron: i13/2, f7/2)

    - Both protons and neutrons satisfy the condition
    - Have similar single particle energy values

Octupole correlation in trans-lead nuclei (Z=88, N ~ 134): Benchmark example

p(i13/2,f7/2) n(j15/2, g9/2)



J F Cocks et al, PRL78 (1997) 2920 (Jyvaskyla group)

Exploring nuclear structure of Trans-lead nuclei: difficulties

- Prone to fission

  Need good knowledge of fission barrier to predict production rate.

→ Important for prediction of the end point of the r-process nucleosynthesis [I. V. Panov et al, *A & A* 513, A61 (2010)]

- heavy n-rich element production.
- superheavy elements.

Fission barrier modifies due to shell effect near the shell closure.

LDM FRLDM FT-HFB TF (Myers & Swiatecki) ETFSI

Two-centre shell model (TCSM) for PES calculation

Bottom line: Need to know fission barrier better to predict ER production rate by heavy ion fusion. (Statistical model)

Summary:

- Expect increase in ER production cross-section for trans-Lead heavy elements.
- Super heavy element production.

Why explore trans-lead nuclei?

o Abundance of isomers:

- How isomers are generated in nuclei?
  - Smaller level spacing
  - Change of single particle configuration
  - Relatively higher multipolarity Spin Trap Isomer
  - Shape isomer / fission isomer

- Advantages of having isomers:
  - Corroborates the nuclear models through experiment.
  - Facilitates observation and detection of excited states below the isomers
    - Detect isomers at the focal plane of RFD.
  - Energy storage mechanism in nuclei.

- Disadvantages of having isomers:
  In-beam prompt spectroscopic investigation incomplete.

Interest in nuclear structure of proton-rich Fr (Z=87) isotopes:
Candidate for PNC search for anapole moment in 208-210Fr (odd or odd-odd nuclei of alkali metals).

Possible participating configurations for trans-lead region

NILSSON DIAGRAM

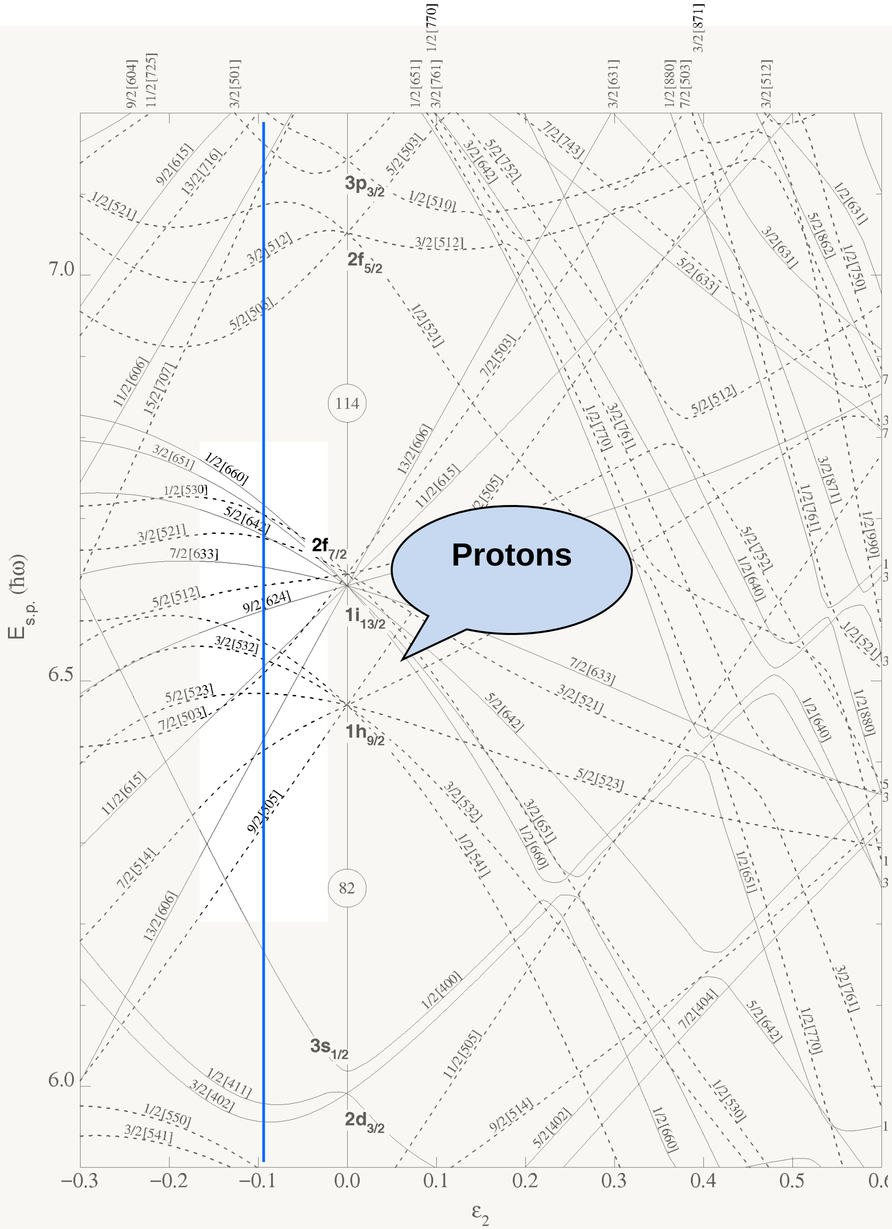


Figure 14. Nilsson diagram for protons, Z ≥ 82 ($\varepsilon_4 = -\varepsilon_2^2/6$).

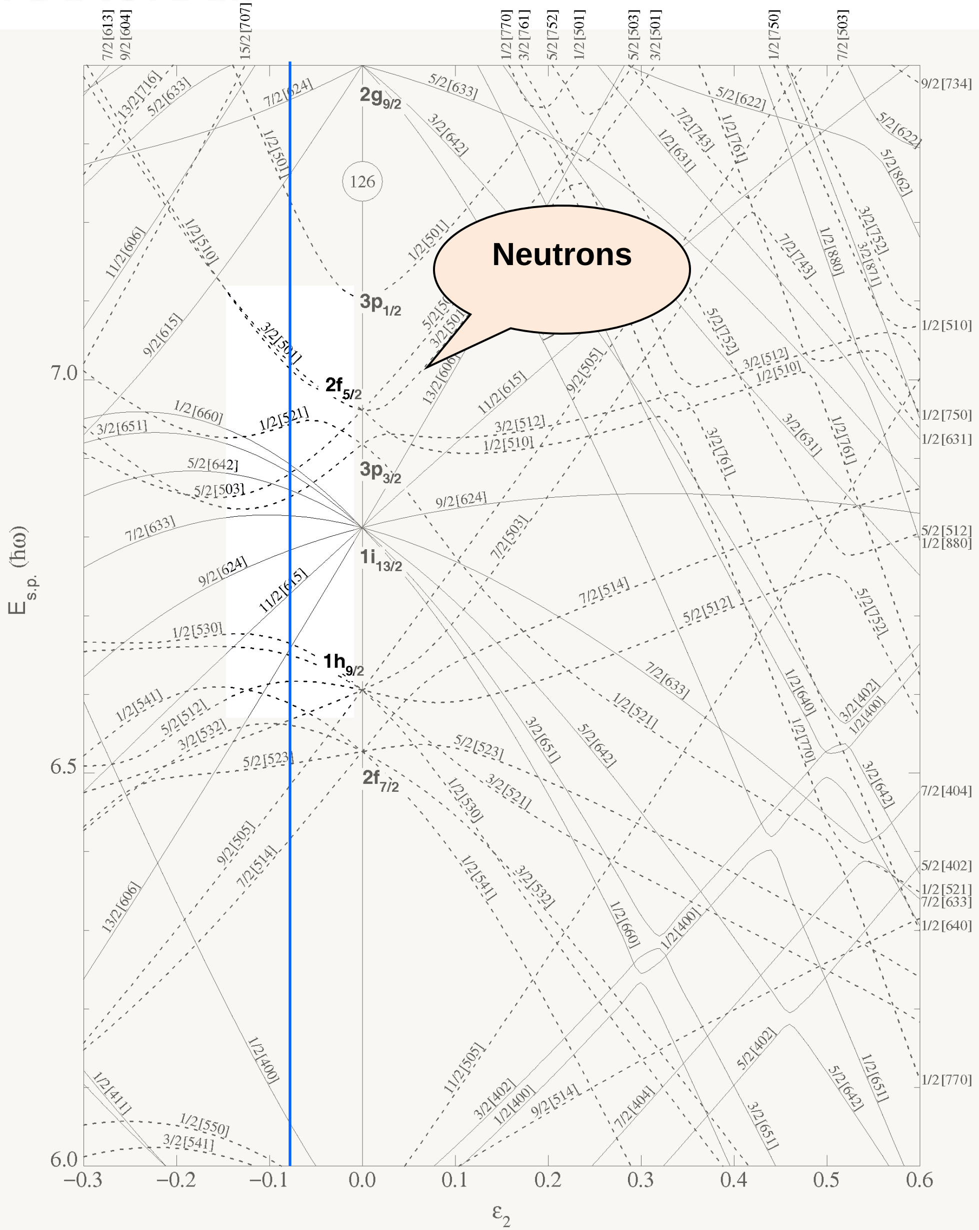


Figure 7. Nilsson diagram for neutrons, 82 ≤ N ≤ 126 ($\varepsilon_4 = \varepsilon_2^2/6$).

Difficulties & Challenges Involved

Two major production mechanisms:

- **Evaporation Residues(ER) produced at high excitation energy and angular momenta (CN reactions around CB)**

Difficulties:

- **Very low ER cross-section (20-30% at 100 MeV for Z~84-88)**
- **Huge fission back ground**

Tools and techniques to get around:

- **Recoil identification or very good reaction channel selectivity (RFD).**
- **Use the power of high resolution and high efficiency gamma detector array.**
- **X-ray gating and / or validation by x-rays.**
- **Use BGO sum-multiplicity filter.**

- **Projectile fragmentation reactions (~ 1GeV/A for ^{238}U / ^{208}Pb)**

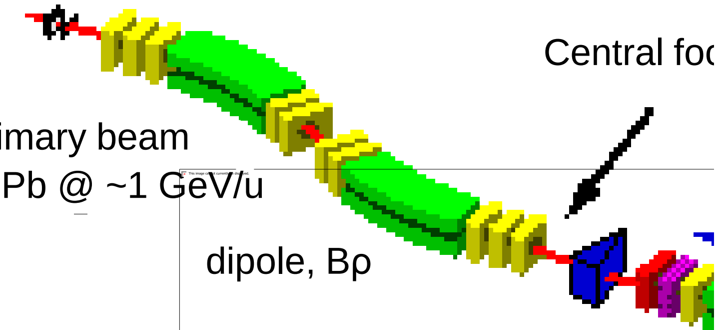
Difficulties:

- **Wide range of *A*, *Z* of fragments produced (n-rich to n-deficient).**
- **Large Doppler effect (v/c ~ 15% as compared to 2-4% for ERs).**
- **Relatively lower yield (w.r.t ER) for each nucleus.**

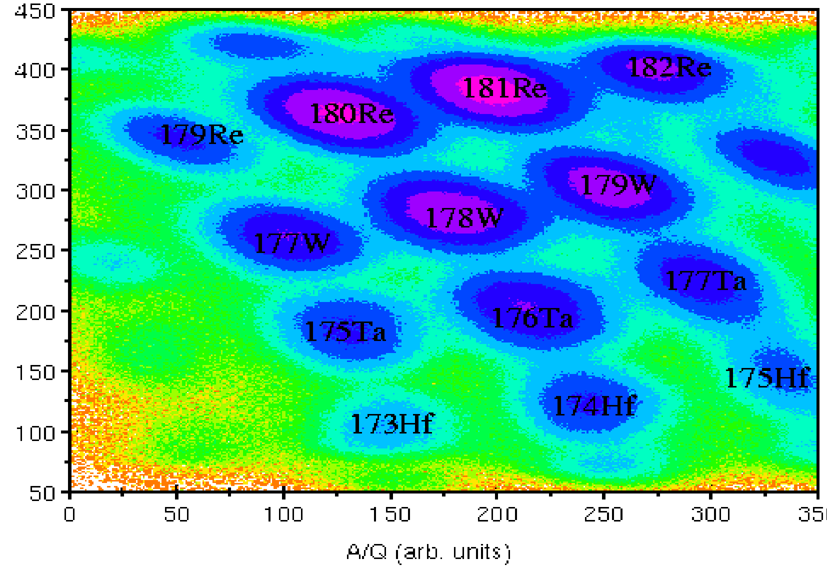
Tools and techniques to get around:

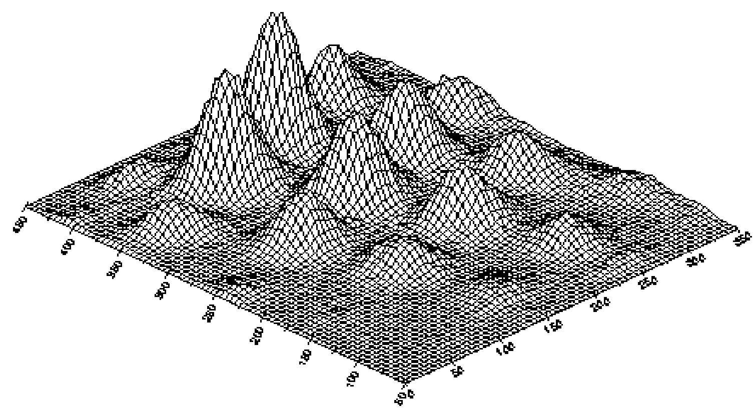
- **Fragment identification and measure energy / velocity.**
- **Very efficient method of Doppler correction / adequate segmentation.**
- **Only long lived isomers (~ 100s of ns and above) can be studied.**
- **Secondary beam excitation (possibly Coulex?) for populating excited states bypassing isomers.**

In-Flight Technique Using Projectile Fragmentation



$$\frac{A}{Q} = \frac{B\rho}{\beta\gamma c u}$$





FRS@GSI to identify nuclei.
Transport some in isomeric states
Stop and correlate isomeric decays

High spin and isomer decays: ^{208}Fr / ^{210}Fr

Ph D student : DEBASMITA KANJILAL

Collaborators: SINP / TIFR / IUAC / VECC / Visva-Bharati

Motivation

4. PRC 79, 054313 (2009, May)

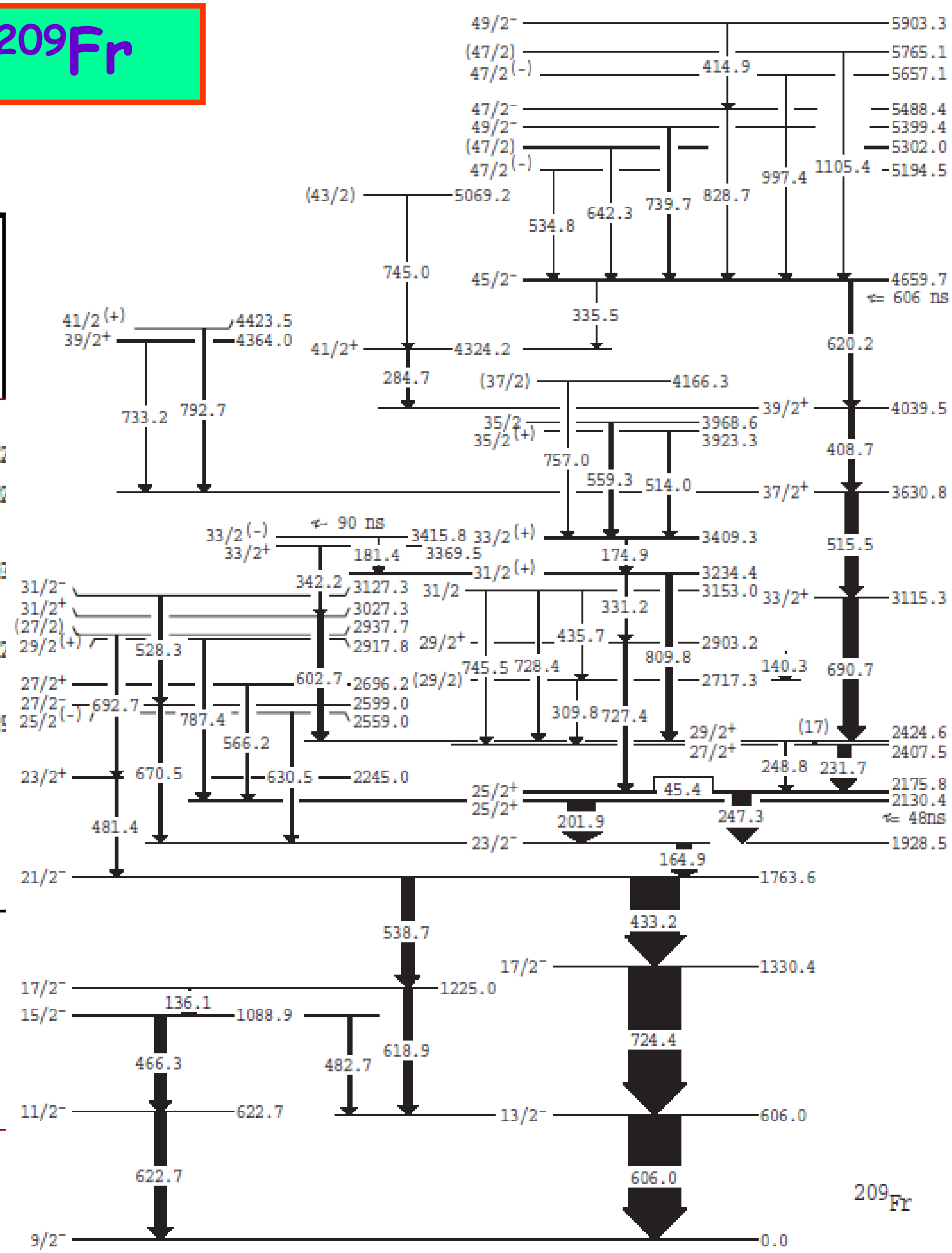
1. AIP Conf. Proc. 831 (2006)

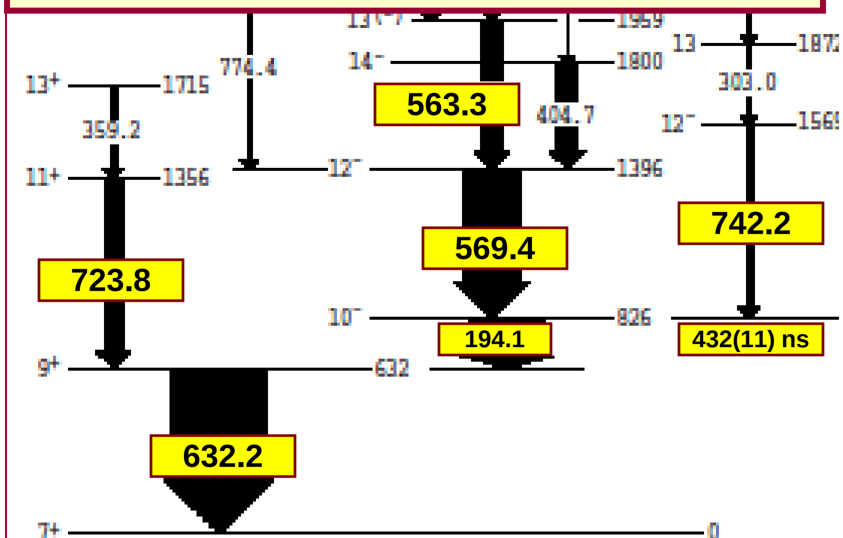
2

3

❖ ^{197}Au($^{16, 17, 18}$O, 5n) @ 82-99 MeV
❖Pulsed beam of 1 ns width and 1716 ns and 19 μs separation from ANU, 14UD Pelletron accelerator
❖CAESAR array of 6 Compton suppressed HPGe (± 97º, ± 148º, ± 48º) , 3 larger volume Compton suppressed Ge detectors and 2 LEPS

^{209}Fr



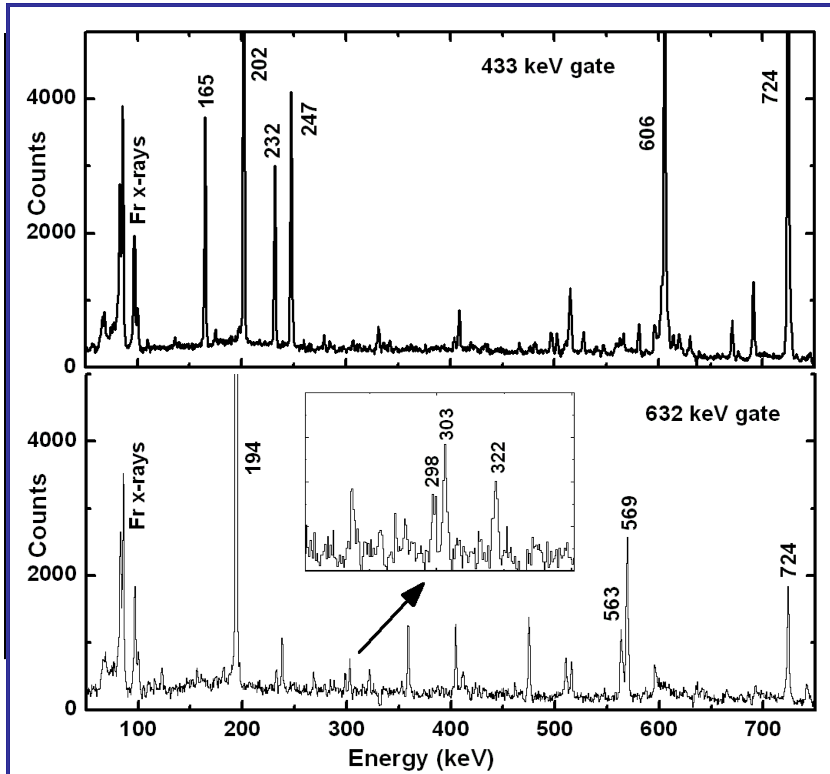


^{208}Fr

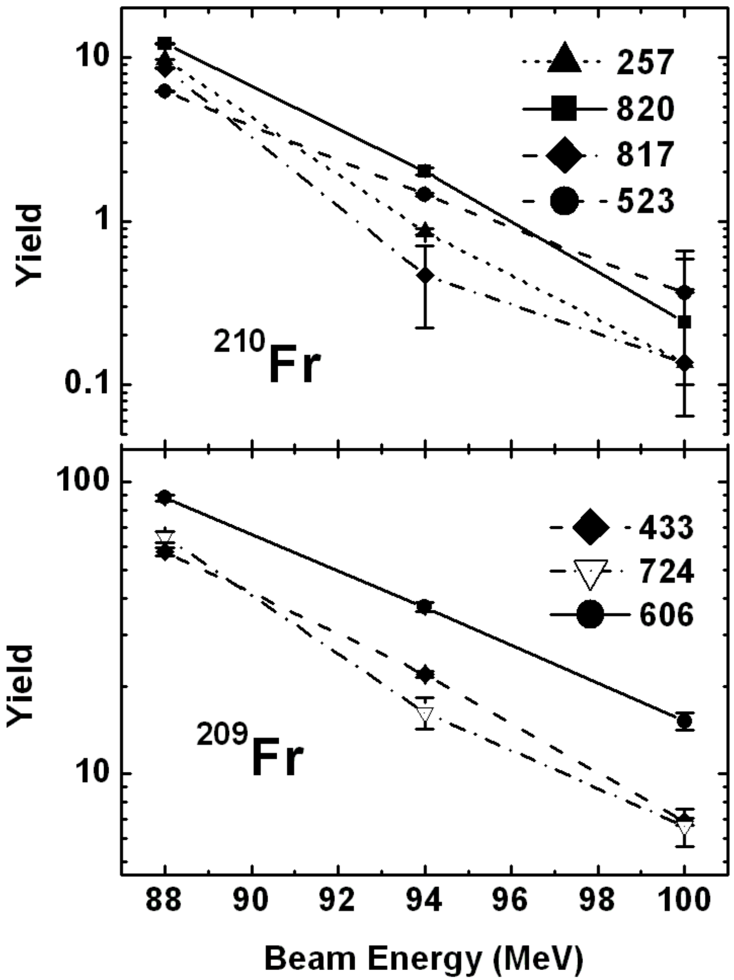
18 April 2012

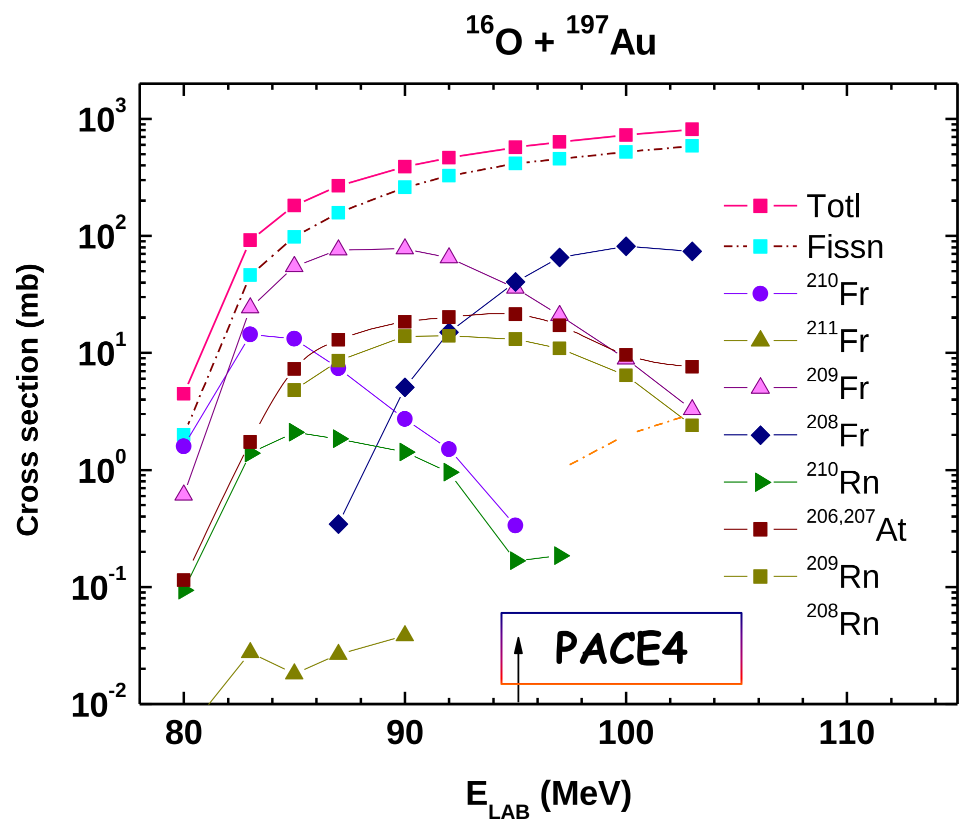
Our Experiment at INGA

Beam :- ^{16}O
Target :- ^{197}Au (99.95% purity)
Target thickness :- 3.5 mg / cm^2
Beam Energy :- 88, 94, 100 MeV
Clover position :- 4 at 148°, 4 at 123°, 6 at 90° & 4 at 57°
Events (100 MeV) : 2fold : 315×10^6 3fold: 48×10^6
4fold : 7.3×10^6 5fold : 8.7×10^5 6fold : 10^4
DAQ :- CANDLE

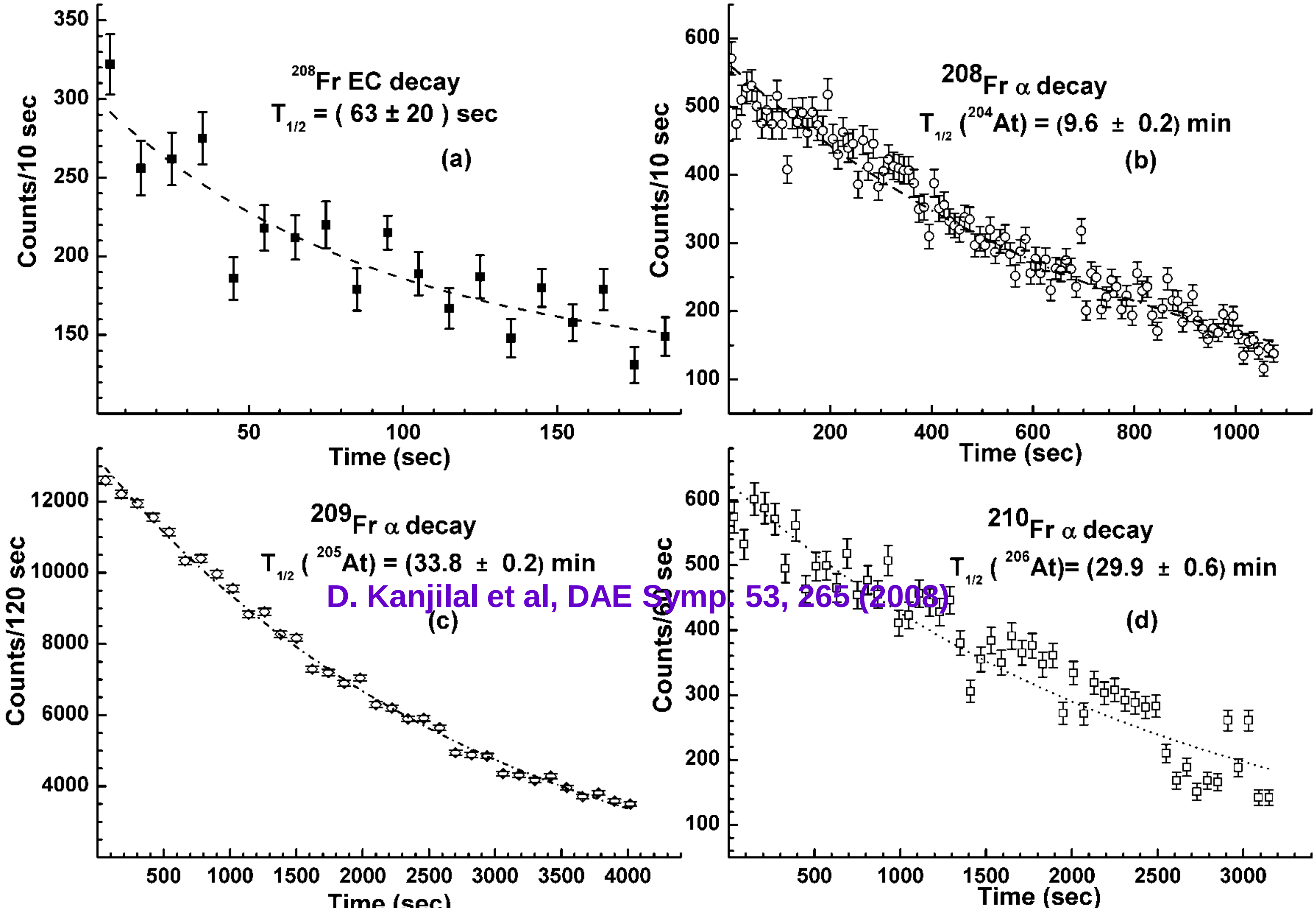


Excitation Function Measurement



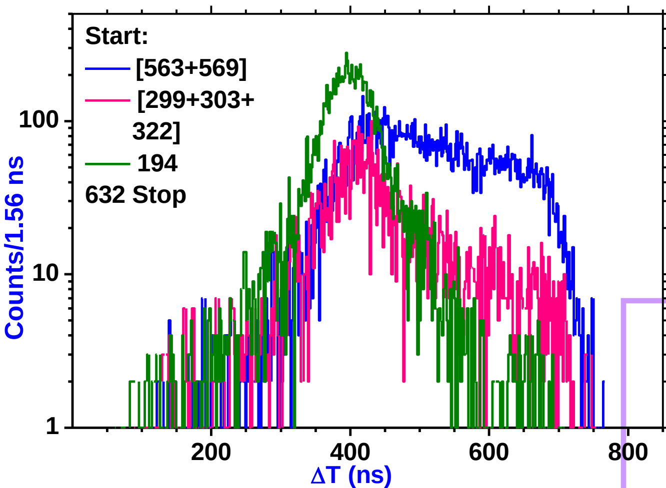


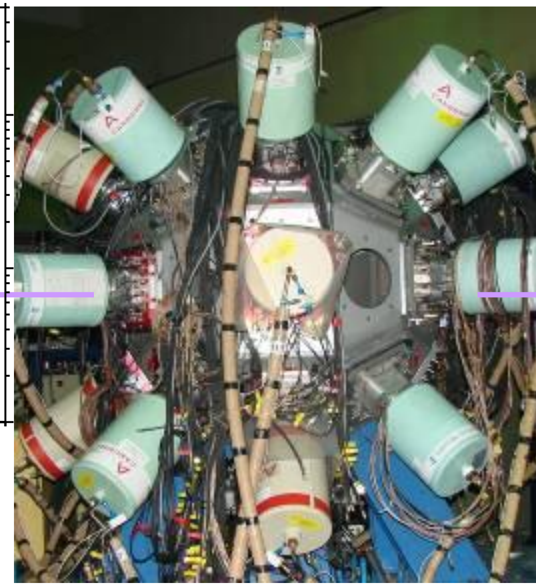
Yields and decay half lives Results from the offline decay run

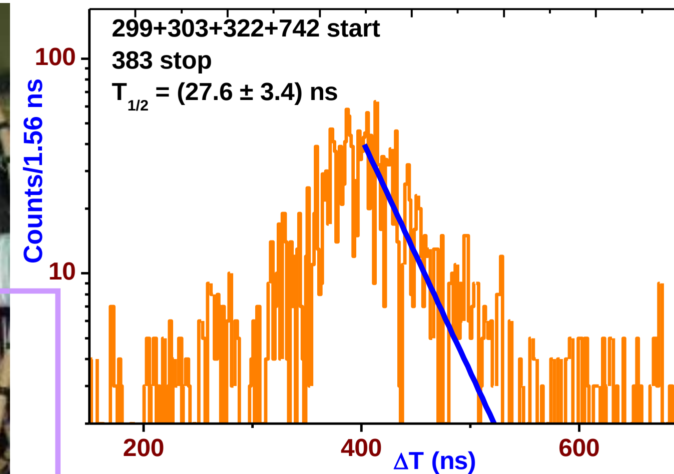


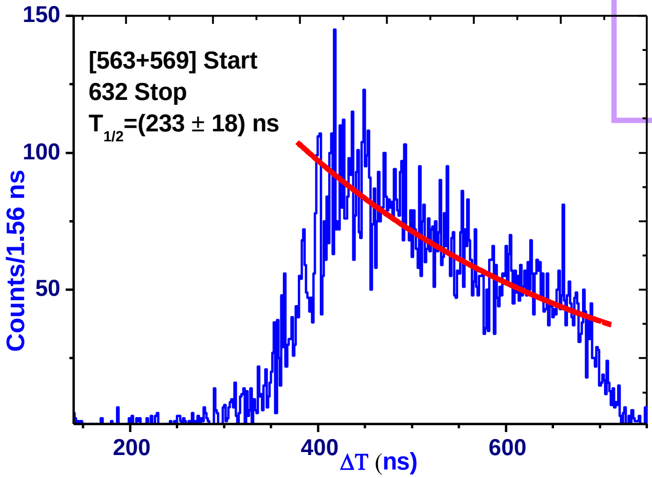
D. Kanjilal et al, DAE Symp. 53, 265 (2008)

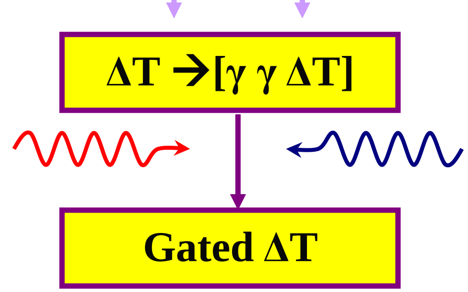
Time Difference Analysis: Isomer decay study

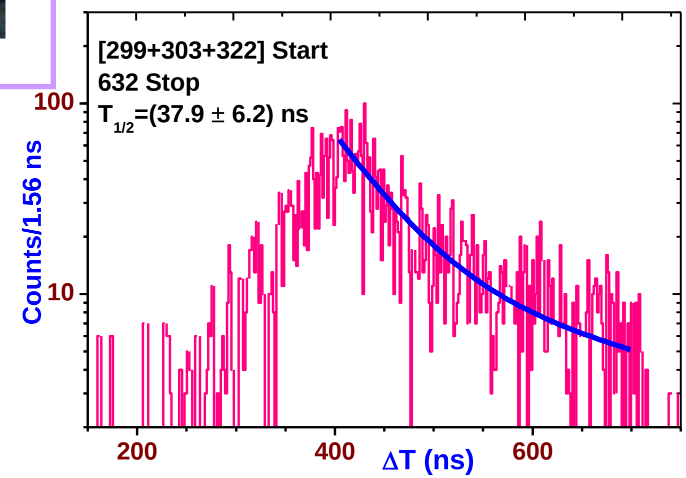










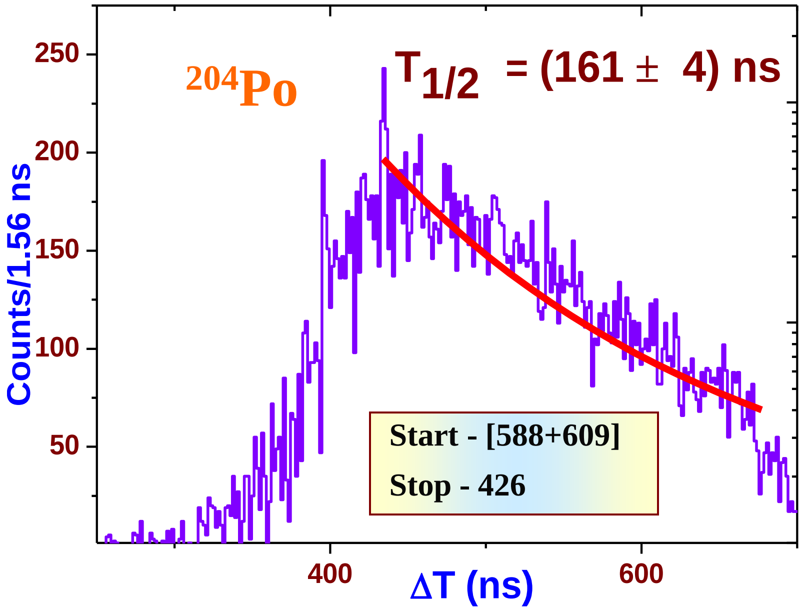


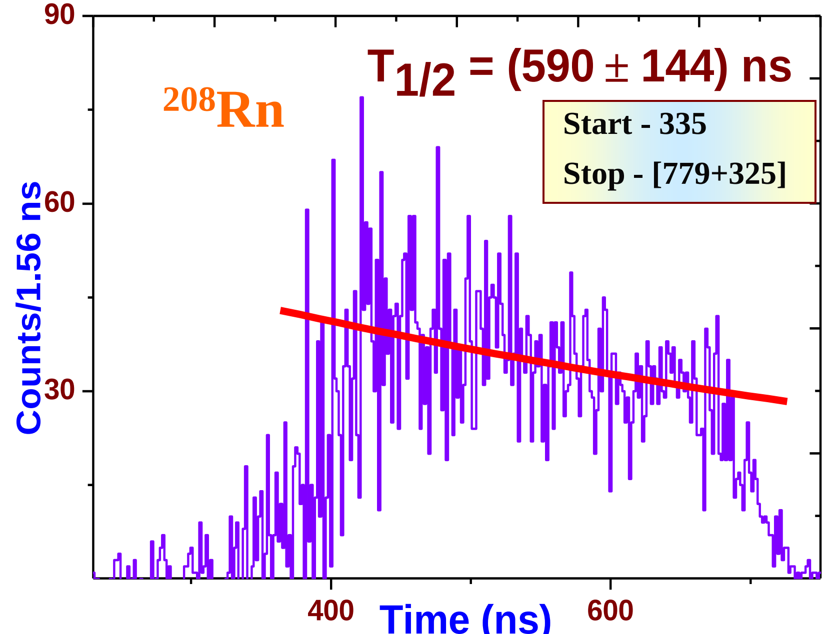
ΔT covered ± 400 ns TDC range

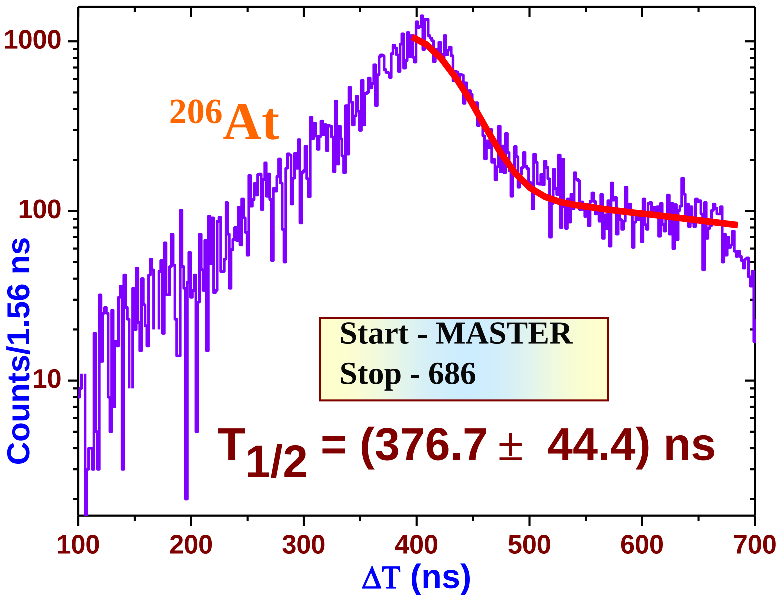
Useful range of ~ 500 ns

D. Kanjilal et al, Nucl Phys A 842 (2010) 1

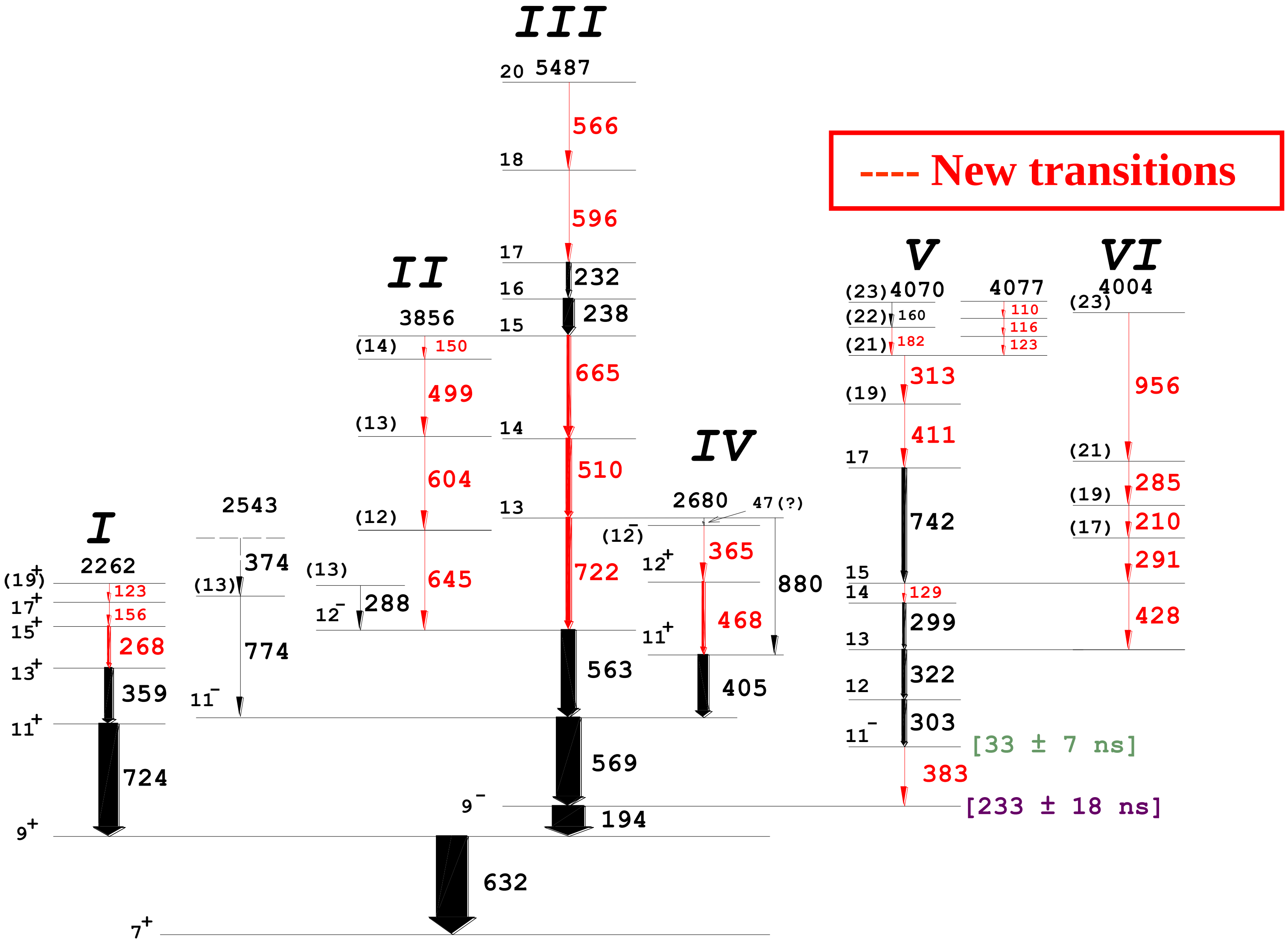
Half life measurements of some known isomers produced in this expt







ER	Level (keV)	E_γ (keV)	ML	$T_{1/2}$ (ns) (this expt)	$T_{1/2}$ (ns) (earlier)
^{208}Fr	826	194.1	E1	233 (18)	432 (11) ~200
^{208}Fr	1209	382.9	E2	33 (7)	
^{208}Rn	1828	88.7	E2	590 (144)	509 (14)
^{206}At	807	121.6	E1	377 (44)	410 (80) 813 (21)
^{204}Po	1639	12.1	E2	161 (4)	158 (2)

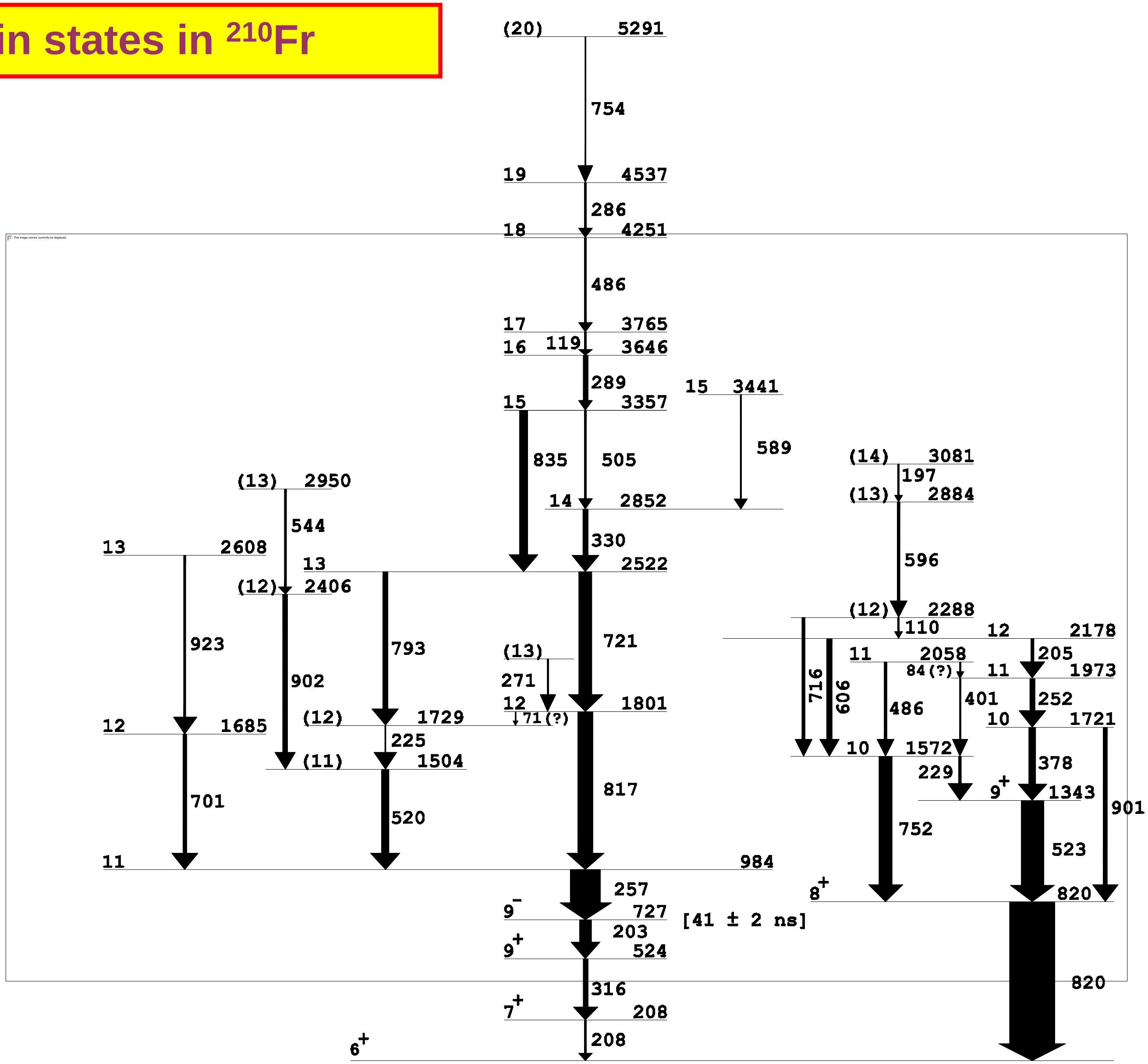


LEVEL SCHEME OF ^{208}Fr

D. Kanjilal et al, arXiv: 0911.2968 (Nov 2009)

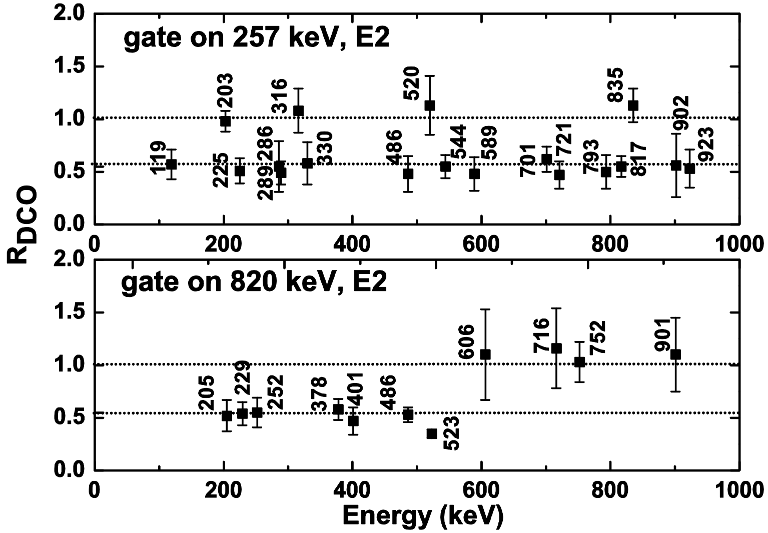
Nucl. Phys A 842 (2010) 1

High spin states in ^{210}Fr

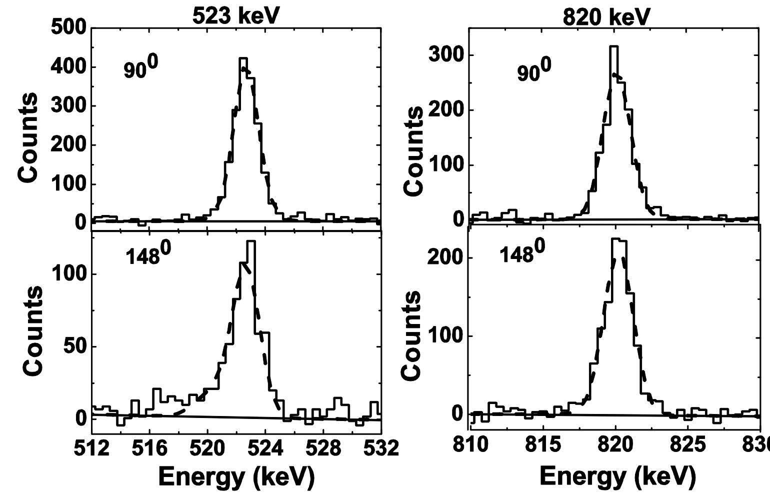


D. Kanjilal et al, Phys Rev C 2011

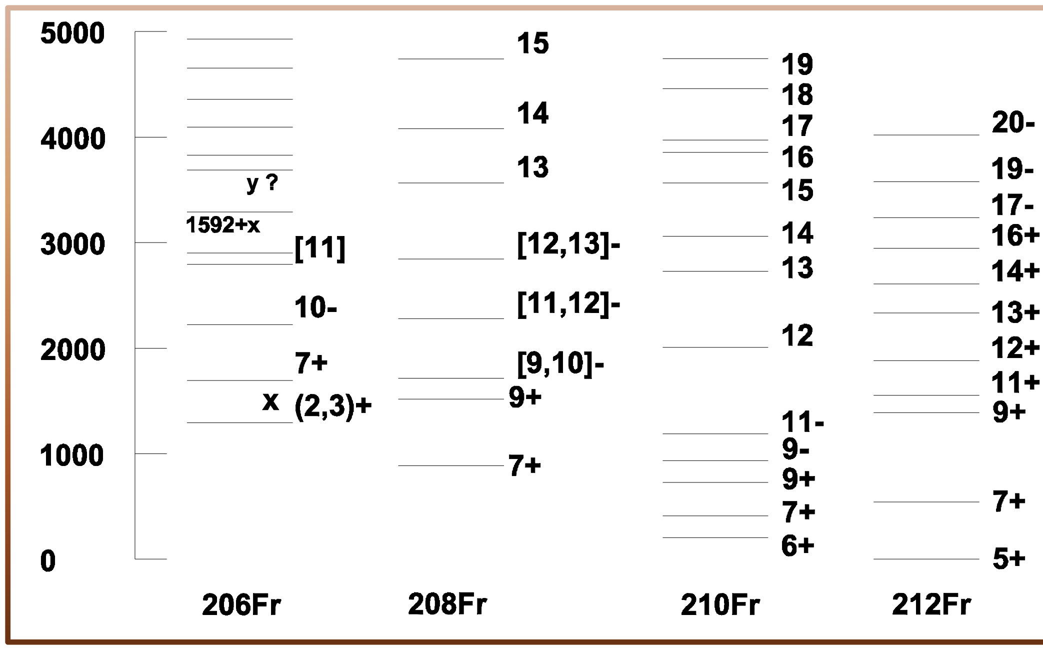
DCO Plots



DSAM

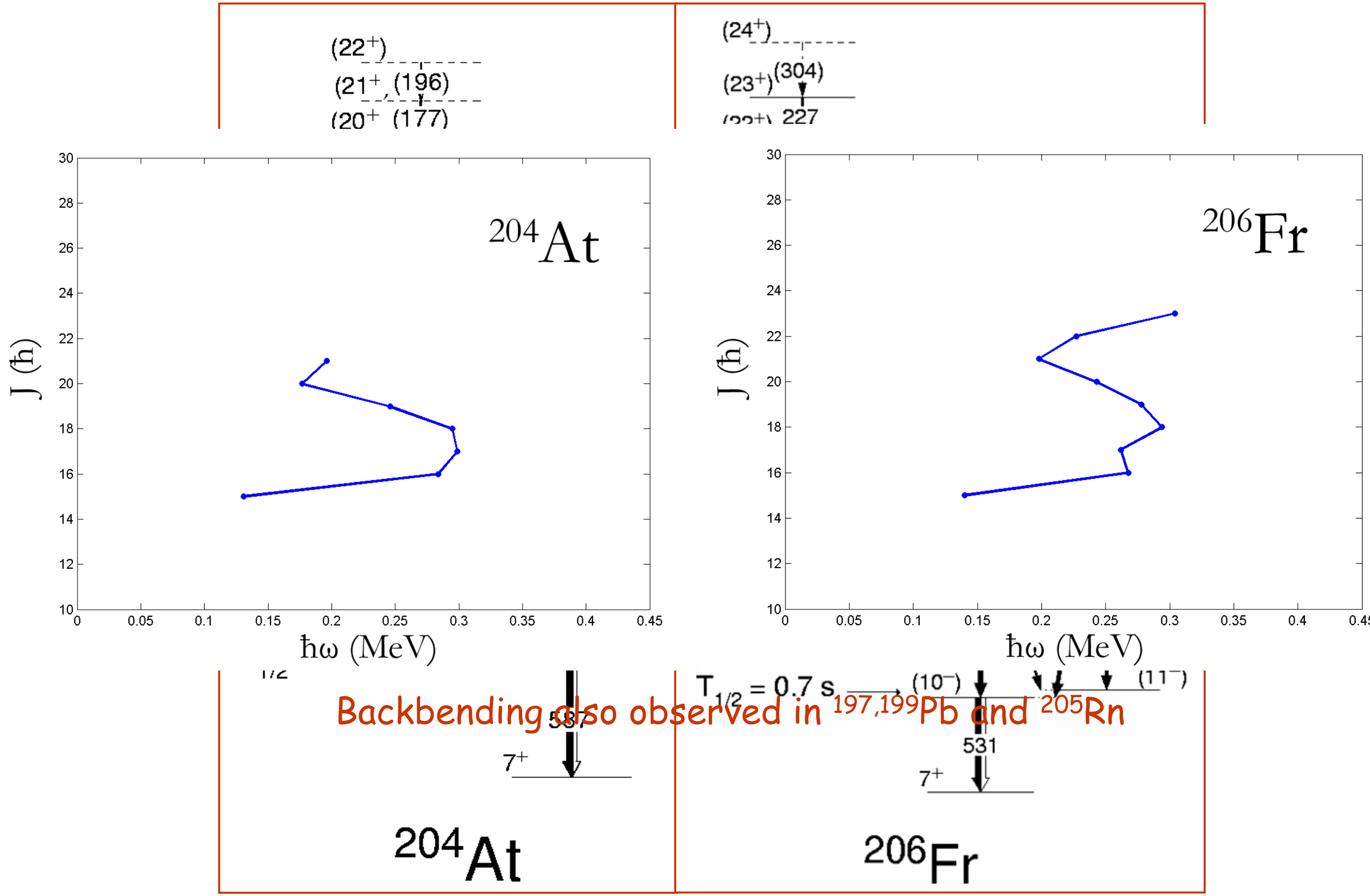


Level Systematics



Level systematics of $^{206-212}Fr$

Shears Bands in ^{204}At and ^{206}Fr



Backbending also observed in ^{197,199}Pb and ^{205}Rn

Hartley et al, PRC 78, 054319 (2008)

What can be done at CERN-ISOLDE along this line of research ?

- Alpha / beta decay rate study of the proton-rich nuclei (Ra, Fr, Rn, At, Po)
- Look for isomers; measure Isomer decay rates for nuclei near Z=82 N=126 → correlate with single particle strength, occurrence of spin traps, level energy difference
- Coulomb excitation across the isomeric level, spectroscopy to explore nuclear structure

HIE-ISOLDE beam at 5.5 MeV/u MINIBALL + Tagging detectors + CE spectrometer

- Use multiple Coulomb excitation to populate moderate spin states coupled by dipoles and quadrupoles → Revisit energy levels of the single particle states and look for change in magic numbers
- Interplay of the single particle and the collective degrees of freedom through spectroscopic investigation (energy levels, spin-parities, life time) near Z=82 and N=126.
- Precision mass and isomeric shift measurements on the chain of nuclei (Fr, At) using ISOLTRAP.

Search for long lived low lying isomers

- Production of heavier nuclei through asymmetric fusion and transfer reactions at HIE-ISOLDE (after energy upgrade) and subsequent spectroscopic investigation using MINIBALL + Residue tagging detectors

DSSD detectors with forward angle coverage for ER tagging

Summary

1. Gamma spectroscopy of trans-lead nuclei done at the recent INGA campaign has lead to building up of near-complete level schemes in proton-rich Francium isotopes. Unknown level scheme in ^{210}Fr could be built up with INGA experiment based on little or no information.
2. Residue tagging or channel selection for exclusive spectroscopy will be the way to go for the next phase to look for exotic collective behavior in trans-lead nuclei.
3. Need detailed theoretical calculations on nuclear structure of the high spin states in these nuclei.
4. Explore the evolution of nuclear structure along the north-west of the valley of stability above Z=82 and N=126 using the unique HIE-ISOLDE facility.

Thank You