Targets in Nuclear Reaction Studies

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Acknowledgement

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Structure of the talk

- **Target preparation methods**
- **Our studies**
- **Special targets with specific science motivations**
    - Fission cross section with neutrons
      Special emphasis on transmutaion,
      Nuclear astrophysics, Th fuel cycle
    - Nuclear spectroscopy
    - Synthesis of heavy actinides (SHE)
    - Radioactive ion beam
- **Summary**

Nuclear Reaction

- Projectile (particle and energy, beam intensity)
- Target (elemental composition, thickness, homogeneity thermo-mechanical, morphology & chemical properties)

Combination : What physics and chemistry we want to do.

Actinide as well as long lived radioactive nuclei as targets with stable beam help achieve exotic reaction channels

Target Preparation methods

(1) Vacuum evaporation, cold work
(2) Electrodeposition/molecular plating
(3) Painting
(4) Polymer assisted deposition

For actinide/radioactive targets, the purity is ascertained and if needed Chemical separation is carried out. Facility for handling alpha-activity!

	Target Thicknesses	Homogeneity	Efficiency	Contamination
Molecular Plating / Electro-deposition[1]	0.1-2 mg/cm^2	Granular growth at 1-3 mg/cm^2	20-90%	Minimal
Vacuum Deposition[1]	Thin targets	Homogeneous	1% for a 1mm circular target	Significant
Painting[1]	Up to 8 mg/cm^2	Homogeneous	>90%	Minimal

Heavy ion reaction studies at Radiochemistry Div.

Nuclear fission

Non-compound nucleus fission
Role of entrance channel mass asymmetry, target deformation by measuring fission fragment angular distribution
16O+188Os, 19F+197Au, 28Si+176Yb, 11B+243Am
Phys. Rev. *C* 71, 044616 (2005), 75, 024609 (2007), 79, 064607 (2009)

Mass distribution and saddle to scission dynamics
Phys. Rev. *C* 69, 024613 (2004); 74, 014610 (2006)

Incomplete fusion reactions

Dependence on beam energy and entrance channel mass asymmetry
Phys. Rev. *C* 79, 064604 (2009); J. Phys. *G* 35, 025101 (2008)

Localization in angular momentum window
Phys. Rev. *C* 69, 027603 (2004)

Projectile structure effect
J. Phys. *G* 29, 1011 (2003); Nucl. Phys. *A* 739, 229 (2004)

Experimental measurements

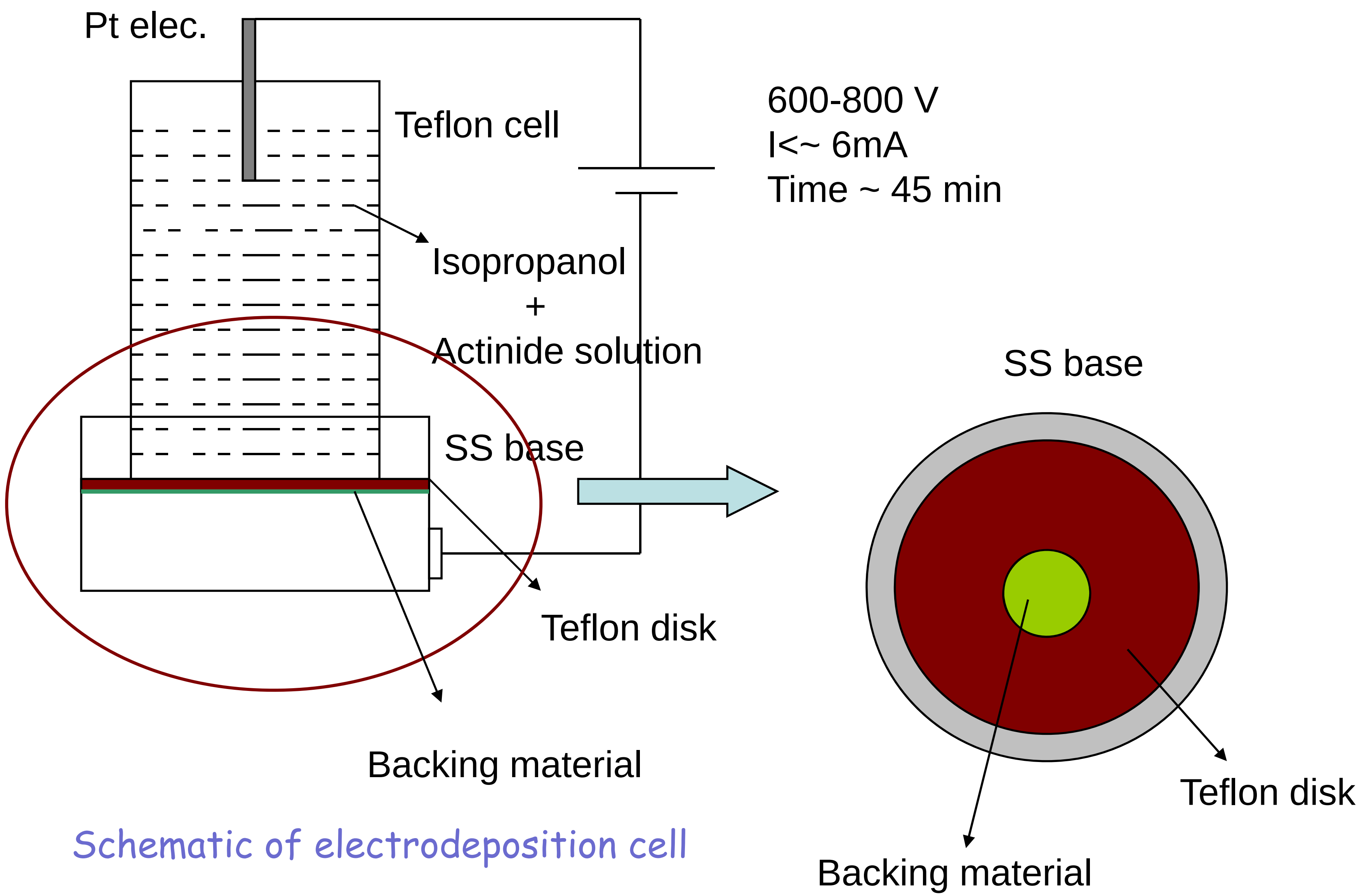
On-line Measurement of fission fragment angular distribution, projectile like fragments using Si detector telescopes

Off-line radiochemical measurement of formation cross sections using recoil catcher technique followed by off-line gamma-ray spectrometry, recoil range distribution

Target requirements

- Targets ~100 μg/cm2- ~3mg/cm2
- Thin targets required for on-line measurements to minimize energy loss of the ejectiles in the target
- Targets of a few hundreds of μg/cm2 used for fission fragment angular distribution measurement
- Targets prepared by electrodeposition / vacuum evaporation

Target preparation by electrodeposition



Schematic of electrodeposition cell

Targets

- $^{235, 238}U$, ^{237}Np, ^{243}Am
- $^{144, 152}Sm$, ^{169}Tm, ^{176}Yb

α-Sources

^{229}Th, ^{239}Pu, ^{241}Am

Preparation of targets with very thin backing ~ 100 μg/cm²

Use of two layer foil Ni-Cu
Ni: thin ~100 $\mu g/cm^2$, Cu: ~ mg/cm^2
Etching of Cu layer after electro deposition using tri chloro acetic acid

Targets used for fission fragment folding angle measurement → Mass distribution

Preparation of metallic Os targets by electro-deposition

Preparation of $OsCl_4$ solution

Os metal powder

↓ **Dissolution in aquaregia**

$OsCl_4$ solution

↓ **Heating**

Collection of $OsCl_4$ vapors in water

Electro-deposition in aqueous medium

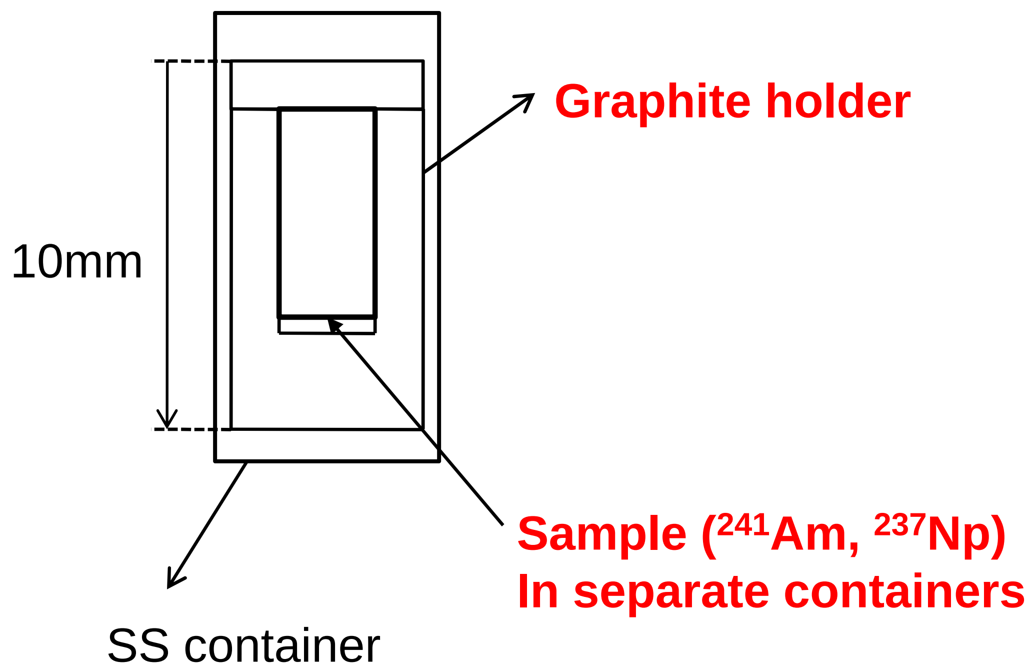
$OsCl_4$ solution
\+
Sulphamic acid
\+
Na_2HPO_4
\+
KOH

Temperature: 80-90^{0}C
Time: 30-45 min
Deposition efficiency: 60-70%

Actinide targets for transmutation studies

- It is planned to study the burning of minor actinides in fast reactors
- A few long-lived fission products have been selected for the determination of fission rate
- Exploratory studies have been carried out to determine fission cross sections using long-lived fission products in fission of ^{241}Am

Schematic of the target mounting for transmutation studies in fast reactor



Nuclide	$T_{1/2}$	E_γ (keV)	a_γ (%)
^{144}Ce	285 d	133.5	11.1
^{134}Cs	2.06 y	604.7	97.6
^{125}Sb	2.73 y	427.9	29.4
^{95}Zr	64 d	756.7	55.4

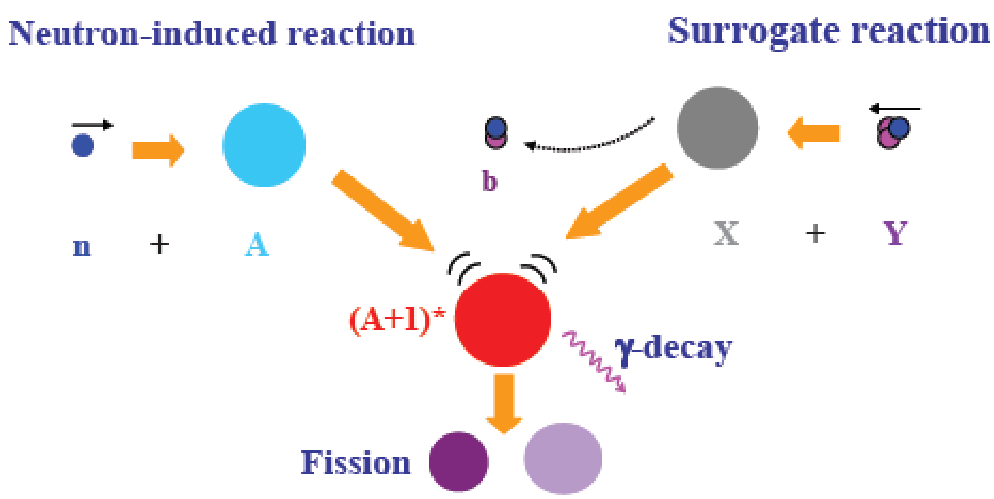
Determination of fission rate

Characterization of neutron spectrum: Using threshold detectors

Detector	Energy (MeV)	Half Life
$^{115}In\ (n, n')\ ^{115m}In$	0.5	4.5 hrs
$^{58}Ni\ (n, p)\ ^{58}Co$	1.9	70.9 days
64Zn(n,p)64Cu	2.0	12.7 hrs
$^{27}Al\ (n, \alpha)\ ^{24}Na$	4.9	15.02 hrs
$^{56}Fe(n, p)^{56}Mn$	4.9	2.56 hrs
$^{59}Co(n, \alpha)^{56}Mn$	5.2	2.56 hrs
$^{197}Au\ (n, 2n)\ ^{196}Au$	8.6	6.18 days
$^{65}Cu\ (n, 2n)\ ^{64}Cu$	11.9	12.7 hrs
$^{58}Ni\ (n, 2n)\ ^{57}Ni$	13.0	36 hrs

In this context fission cross sections of the minor actinides are important over a wide energy range of neutron energy

- Neutron TOF technique (very well defined neutron energy)
- Surrogate reaction



$$\sigma_{n,i}(E_n) = \sigma_{CN}^{cal}(E_n) \cdot P_i^{\exp}(E_n)$$

Advantages

- Need not have the nuclide of interest (say shortlived)

- Production of various residues possible- diff. transfer channels
  ⟹ One projectile-target combo : σ for different nuclei

- Excitation energy (CN) follows a broad probability distribution
  Tag the KE and angle of the ejectile for EE which can be translated to neutron energy En

$$E^* = B_n + A.E_n/(A+1)$$

Determine cross section over a broad neutron energy range

^{233}Pa (27 d) - n capture as well as fission cross section (0-1 MeV)
using $^{232}Th(^{3}He,p)^{234}Pa$

$^{242,243}Cm$, ^{241}Am Fission cross section $^{243}Am+^{3}He$

- 100 $\mu g/cm^2$ on 80 $\mu g/cm^2$ C backing

- Purity, thickness and backing materials are to be taken care of

- Fission cross section of minor actinides of interest (transmutation)

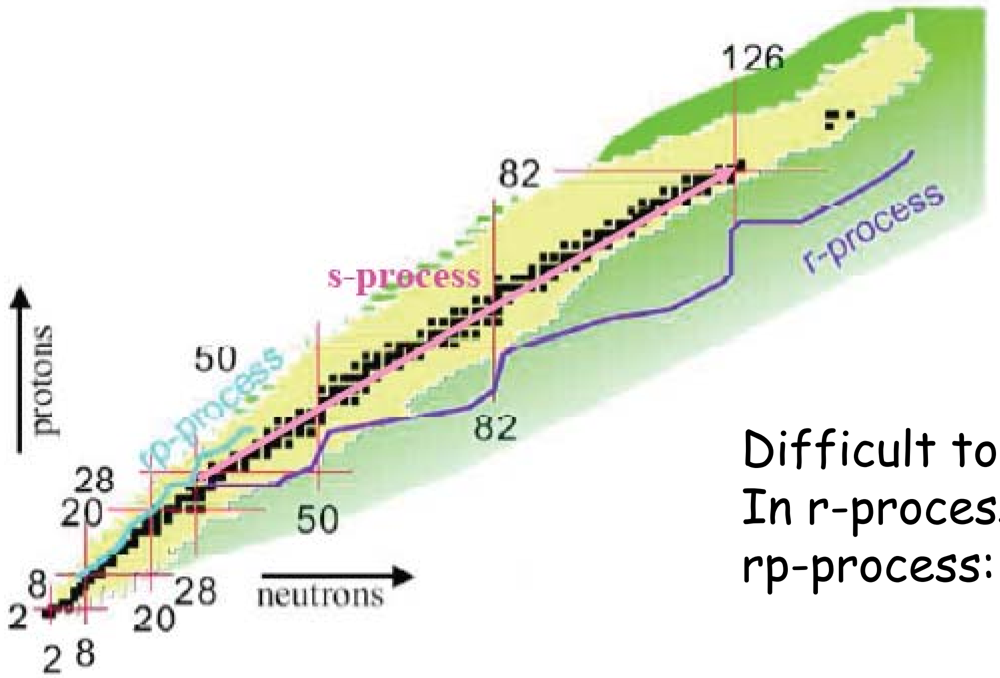
^{237}Np, $^{240,241,242,243}Am$, $^{242,243,244,245}Cm$

- Th-U cycle : Neutron capture crossection

^{232}Th, ^{233}U plus ^{231}Th, $^{231,233}Pa$, $^{232,233,234,235}U$

Nuclear astrophysics:

Theories of nucleosynthesis are tested by calculating isotopic abundances with stellar models: require reliable neutron and proton capture crossection



Difficult to get targets involved In r-process and heavier part of rp-process: RIB

s-process : demand for radioactive targets to measure σ_n especially at branching points i.e. half-life comparable to neutron capture time scales (300 ev-several keV n)

^{79}Se, ^{85}Kr, ^{147} Pm, ^{151}Sm, ^{163}Ho, ^{170,171}Tm, ^{179}Ta (129 d to 10^7 years)

Nuclear Spectroscopy:

Transfer reaction to produce heavy nuclei

$^{18}O + ^{238}U$ @ 200 MeV

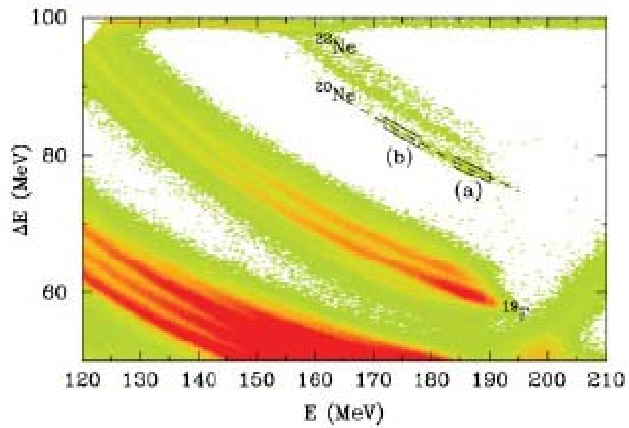


FIG. 1. (Color online) E-ΔE plot of scattered nuclei measured by a Si ΔE-E detector in the reaction of a 200-MeV ^{18}O beam with a ^{238}U target. The dashed line represents a calculated energy loss for ^{20}Ne nuclei. See the caption of Fig. 2 for the enclosed areas (a) and (b).

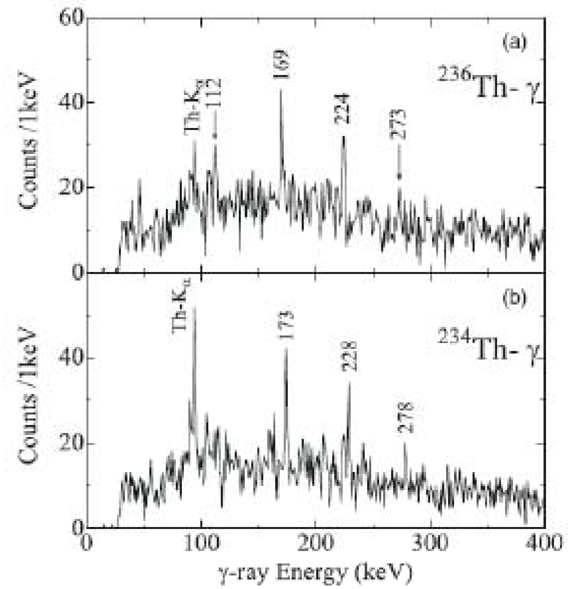


FIG. 2. γ-ray spectra obtained by setting the gates on ^{20}Ne whose kinetic energies correspond to E_x of (a) 5–11 and (b) 17–23 MeV, respectively. These gates are depicted as the regions (a) and (b) in Fig. 1, respectively. γ peaks labeled by energies in the spectra of (a) and (b) are the transitions in ^{236}Th and ^{234}Th, respectively.

20 mm dia, 80 μ   ΔE Si detectors

T. Ishii, et al., PRC76, 011303(R) 2007

Structure of ^{234}U with ICF

Experimental Condition:

52 MeV 9Be beam

1 mg/cm2 self supporting 232Th target

4 x 10^6 a-g-g coincidence

6 CS-HPGe (25%)

Coincidence with CPD array

ICF ER: 10 mb

ER: ~ 5 mb

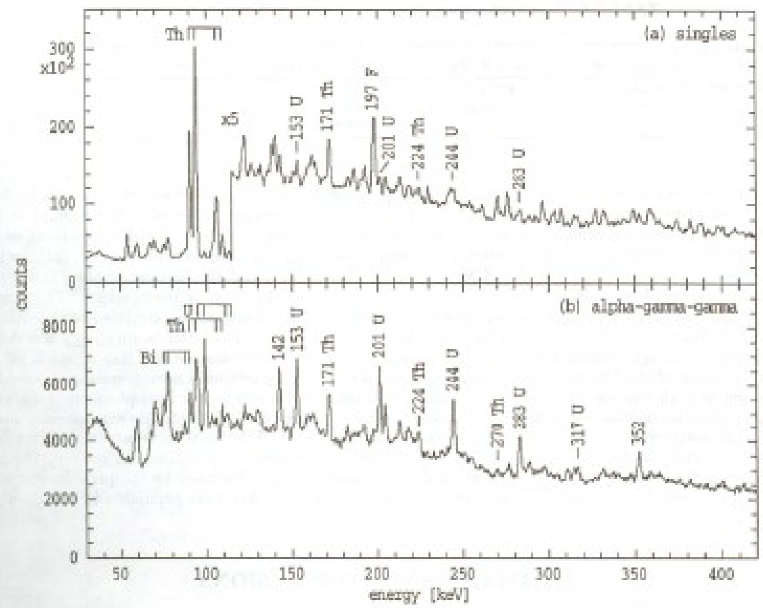


FIGURE 3. (a) Singles spectrum for the ^{9}Be + ^{232}Th reaction at 52 MeV. (b) Projection of the α-gated γ-γ matrix.

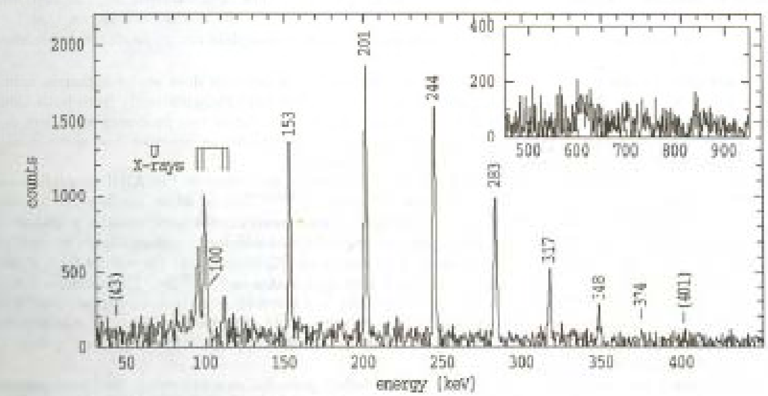
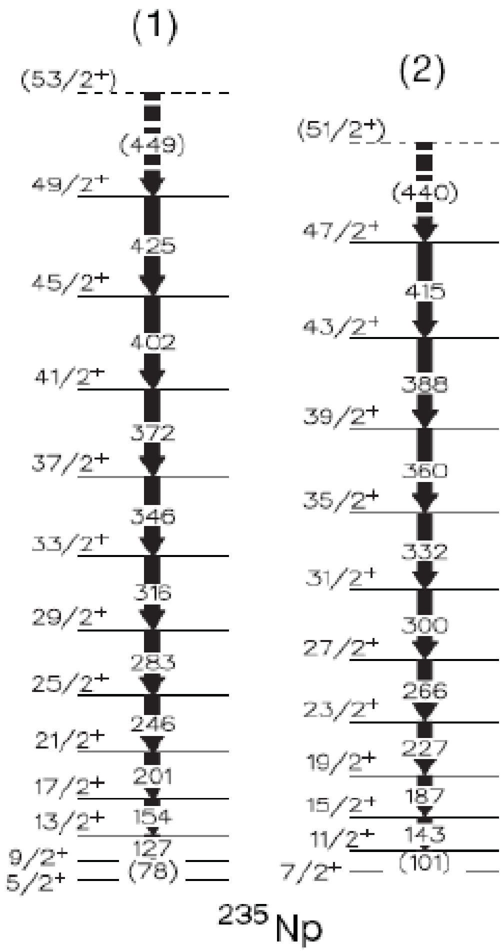


FIGURE 4. Sum of spectra with gates on the E2 transitions between the 4^{+} and 14^{+} excited states in the ground-state band of ^{234}U.

G. J. Lane et al. page 304, NS98

High spin structure of ^{235}Np



^{116}Sn + ^{237}Np @ 801 MeV

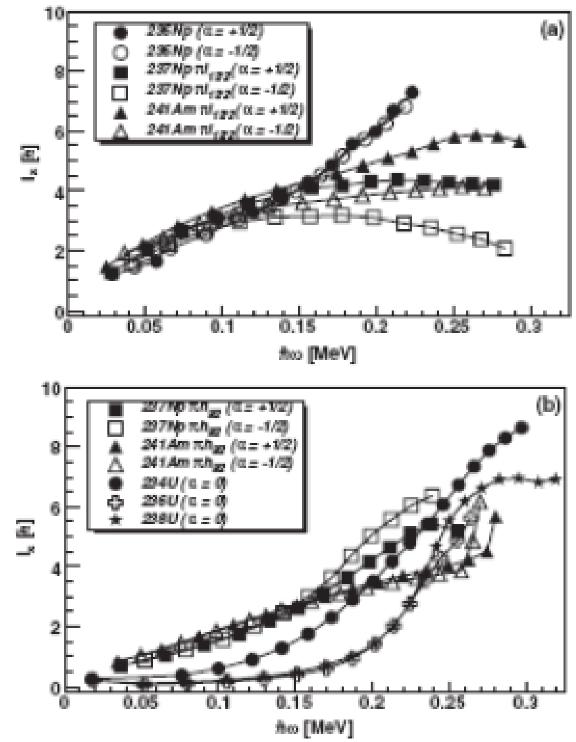


FIG. 9. Aligned angular momentum as a function of rotational frequency for (a) the $\pi i_{13/2}$ [642]5/2$^+$ bands in ^{237}Np (ground state) and ^{241}Am (excited quasiproton), and the observed band in ^{235}Np and (b) the $\pi h_{9/2}$ [523]5/2$^-$ bands in ^{237}Np (excited quasiproton) and ^{241}Am (ground state) and the yrast ($\alpha = 0$) bands in the even-even nuclei ^{234}U [12,30], ^{236}U [12], and ^{238}U [11,31]. For all data points, a reference configuration with the Harris parameters [32] $J_0 = 65$ MeV$^{-1}\hbar^2$ and $J_1 = 365$ MeV$^{-3}\hbar^4$ has been subtracted.

Structure of heavy nuclei using 7Li induced reaction with heavy (stable & radioactive) targets

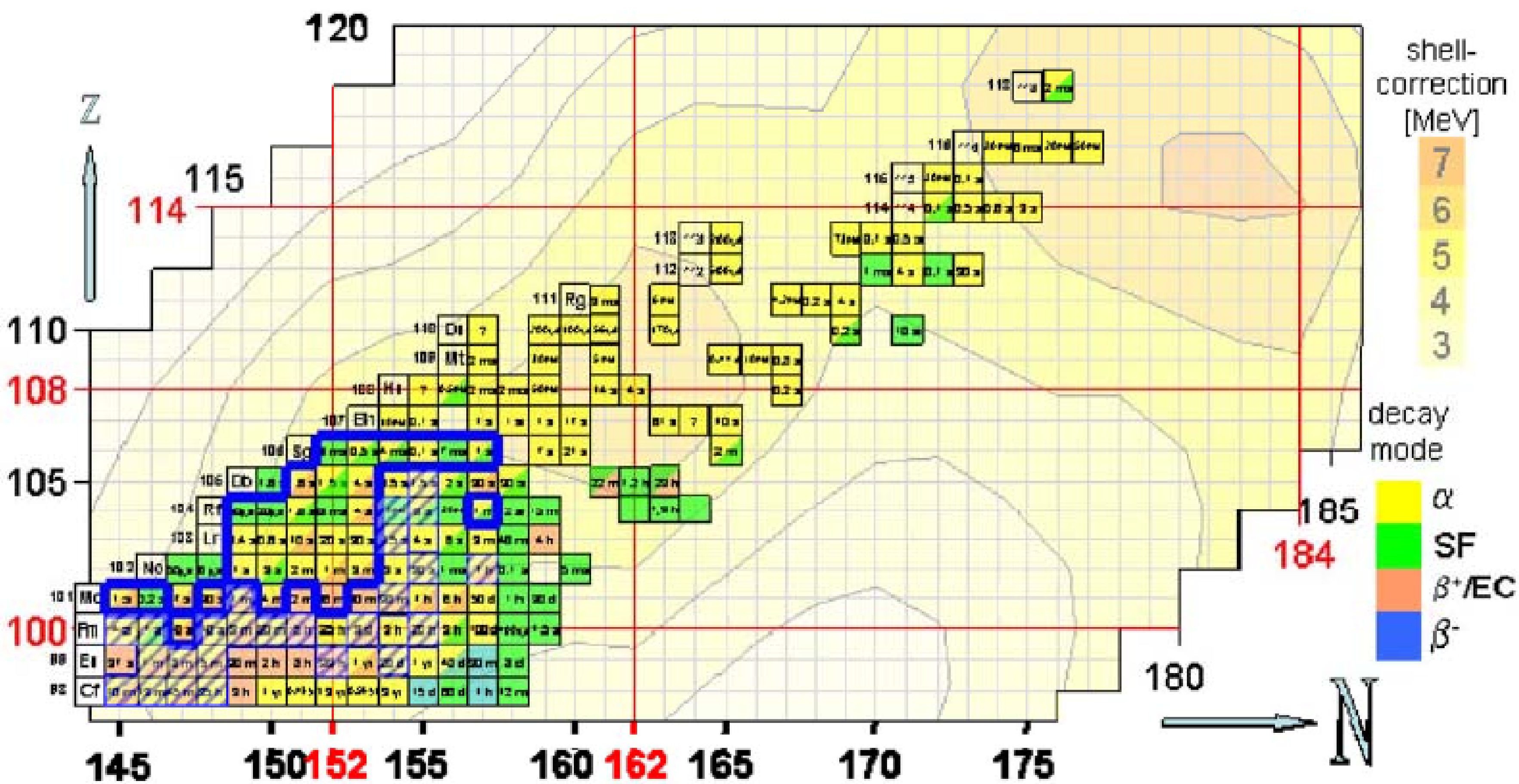
- ^{7}Li + ^{230,232}Th at 45 MeV (^{235,236}Np) better resolution for gammas
- Clover array with 2 LEPS
- CsI(Tl) particle array
- Trigger g-g-g or g-g-particle
- Future with CE measurements & other radioactive targets
  ^{230}Th, ^{237}Np, ^{241}Am and ^{243}Am.

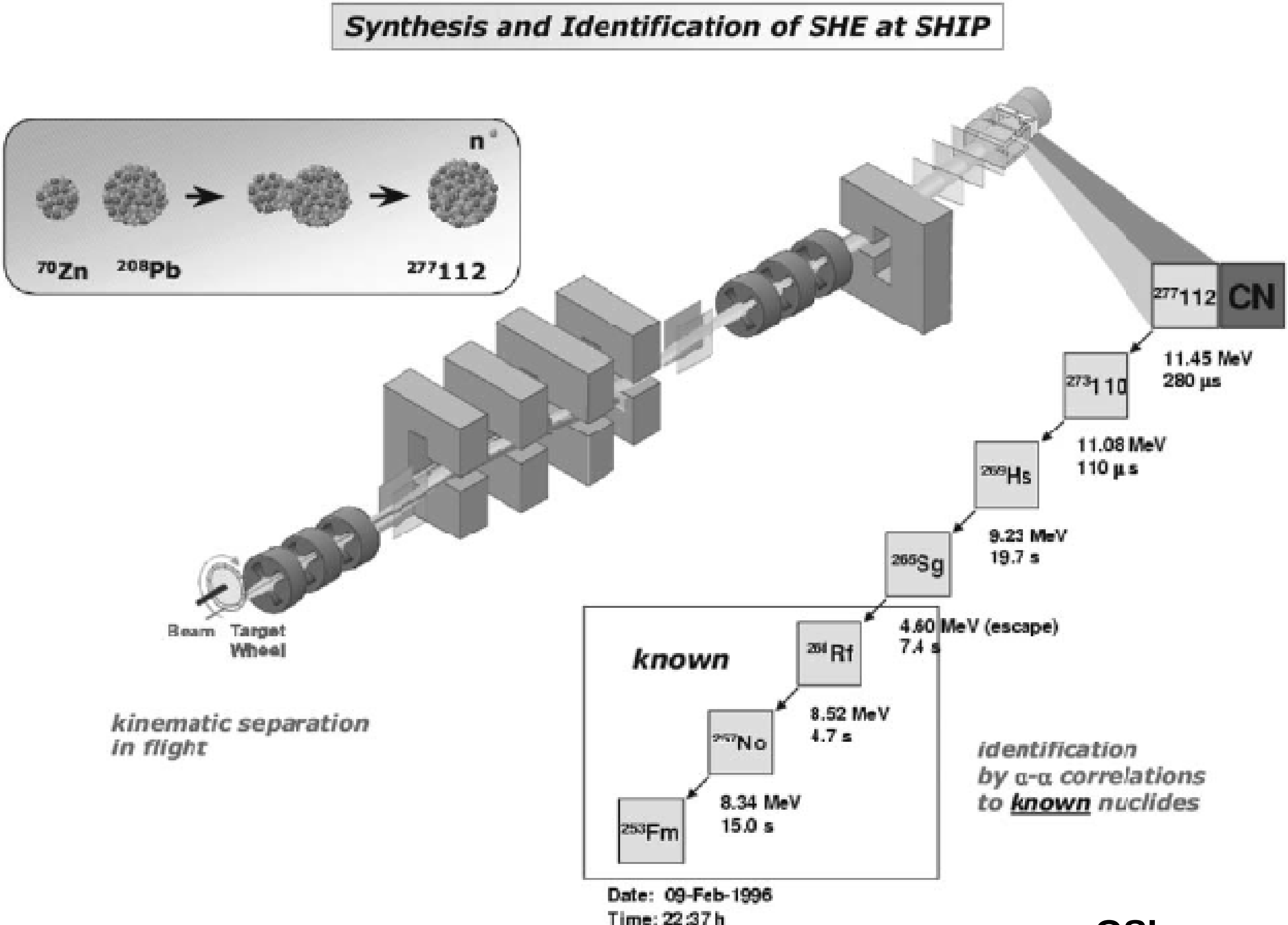
R. Palit(TIFR)
TIFR, BARC(RCD), BARC(NPD), ANL, VECC, PU, GNDU, DU, IUAC, UGC-DAE-CSIR, And others

Study of nuclear and chemical properties of Super Heavy Nuclei

- Very challenging to the low production cross section and 'single atom chemistry'
- Placement of SHE in the periodic table
- Chemical properties affected by the relativistic effects
- Identification of SHE
- Determination of half-life and production cross section
- Testing of models to predict cross sections at pico-barn level
- Determination of fission barrier to estimate shell corrections

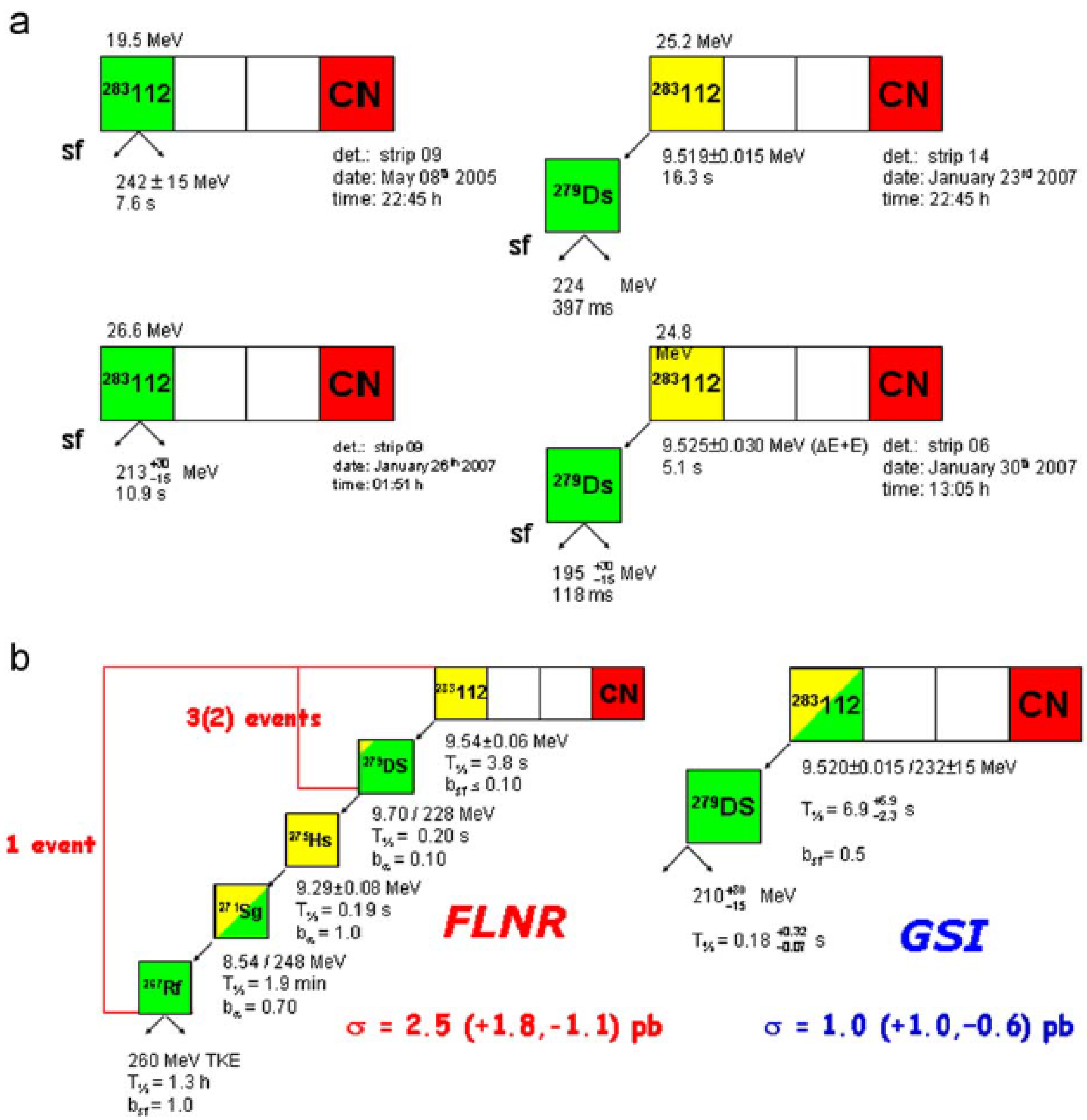
SHE region in the chart of nuclides





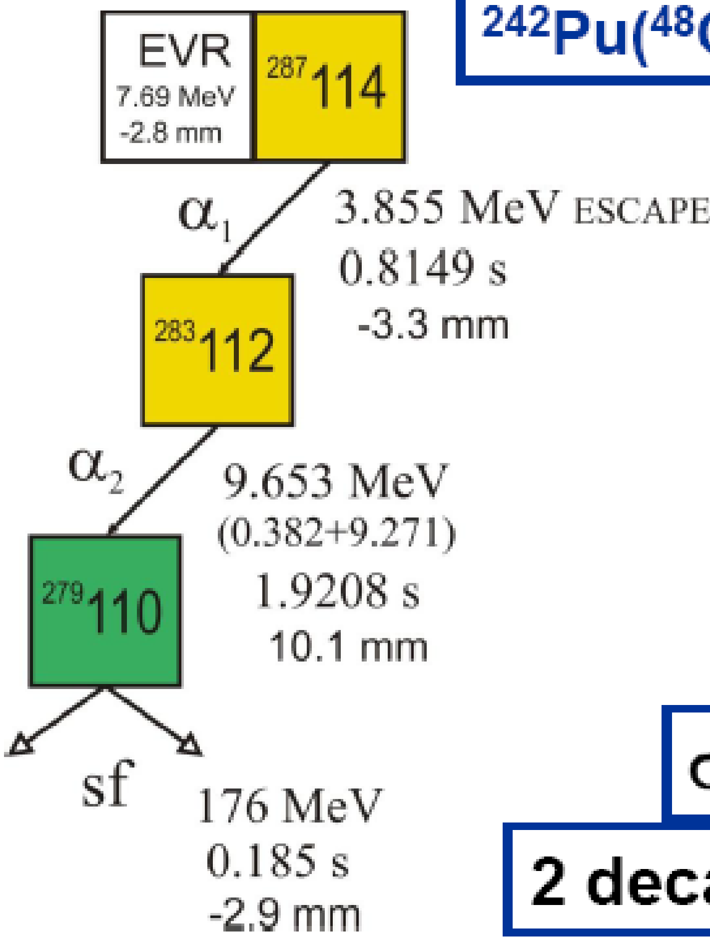
GSI

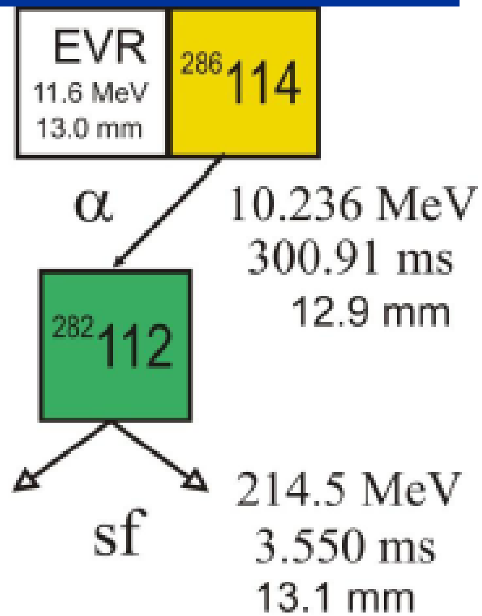
D. Ackermann, Nucl. Instr. Meth. A 613, 371 (2010)



D. Ackermann, Nucl. Instr. Meth. A 613, 371 (2010)

$^{242}Pu(^{48}Ca,3,4n)^{287,\,286}114$





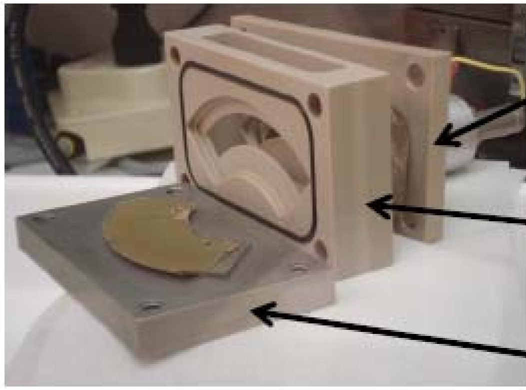
$$\sigma(3n) = \sigma(4n) = 1.4^{+3.2}_{-1.2}\ \text{pb}$$

2 decay chains + 4 SF-like events

L. Stavsetra, K. E. Gregorich, J. Dvorak, P.A. Ellison, I. Dragojević, M.A. Garcia, H. Nitsche, Independent verification of element 114 production in the ^{48}Ca + ^{242}Pu reaction. Phys. Rev. Lett., 103, 132502, 2009,.

LBNL

Target preparation: Reasonably thick and should take care of heat generation

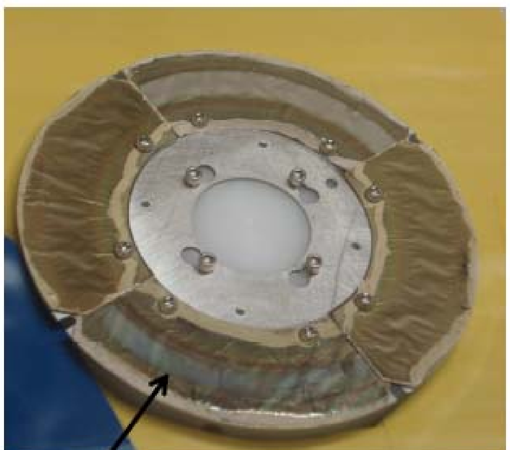


Pd anode

PEEK body

Base/cathode

Electrochemical cell



440, 340, 320, and 270 μg/cm², 2.4 mm Ti

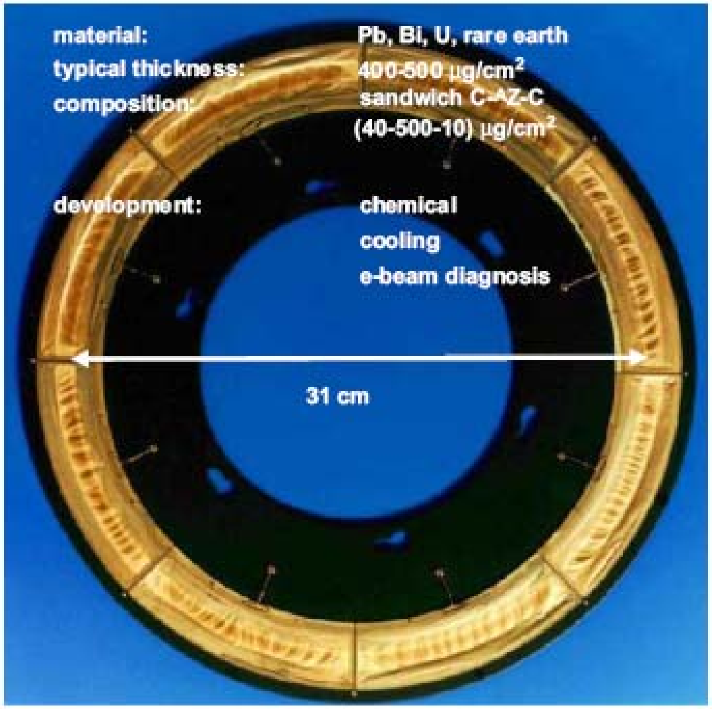
Cooling water channel inside

$$^{26}\mathrm{Mg} + {}^{242}\mathrm{Pu} \longrightarrow {}^{268}\mathrm{Sg}^* \begin{cases} {}^{263}\mathrm{Sg} + 5n \\ {}^{262}\mathrm{Sg} + 6n \end{cases}$$

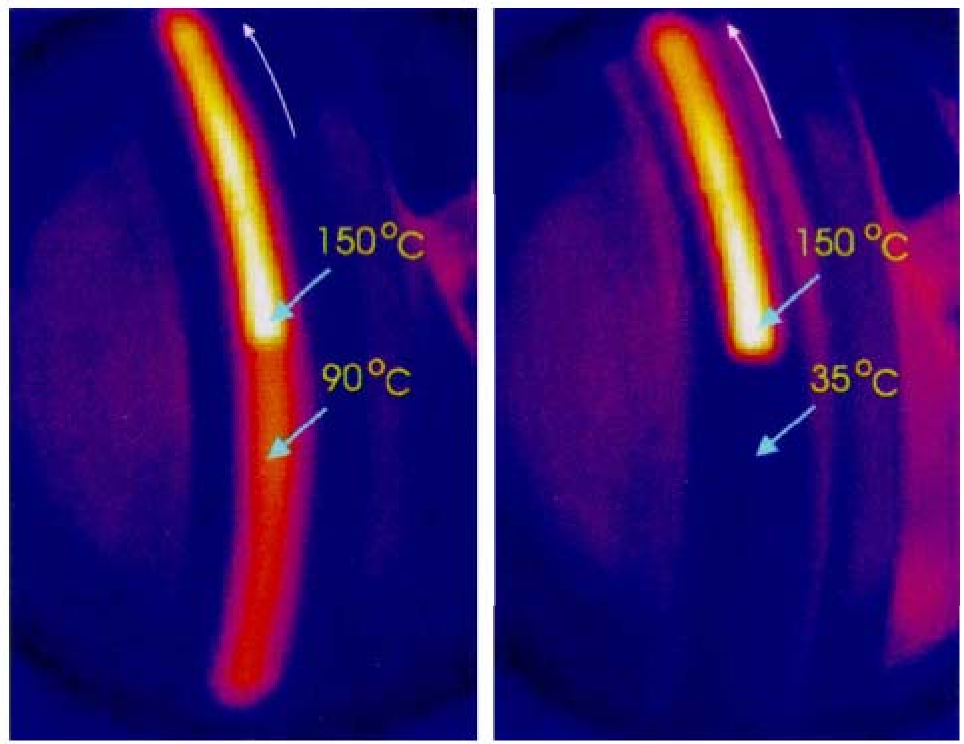
LBNL

E_{beam} = 157 MeV ==> E^*_{CN} = 57 MeV

E_{beam} = 149.5 MeV ==> E^*_{CN} = 50 MeV

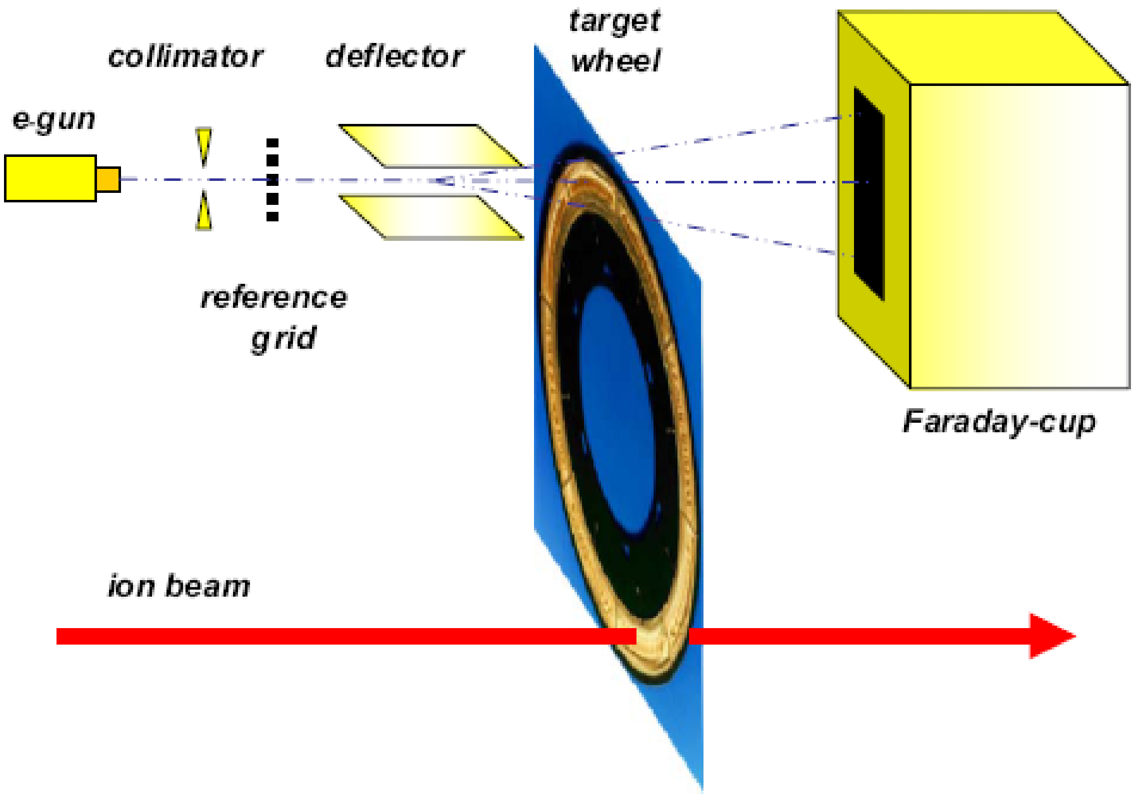


Target wheel configuration, with dimensions and typical parameters, as presently used at SHIP.



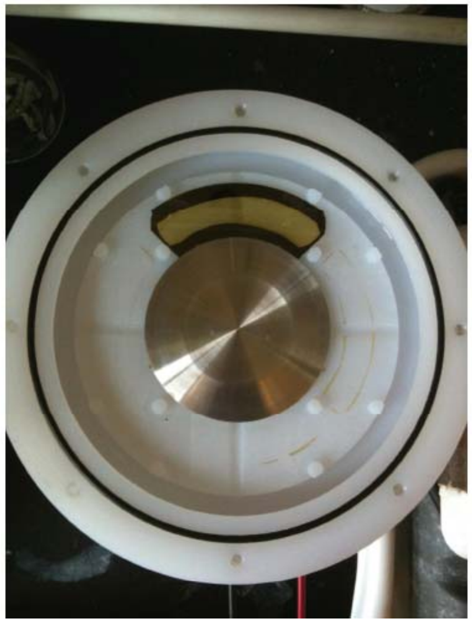
Temperature profile for a target wheel in vacuum and 0.6 mbar He

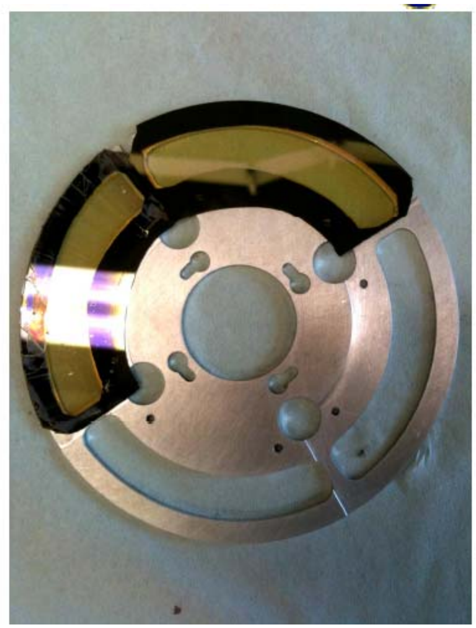
C-Pb-C with average thicknesses of 37-460-10 mg/cm2.



Electron beam target control system implemented at SHIP

Polymer Assisted Deposition





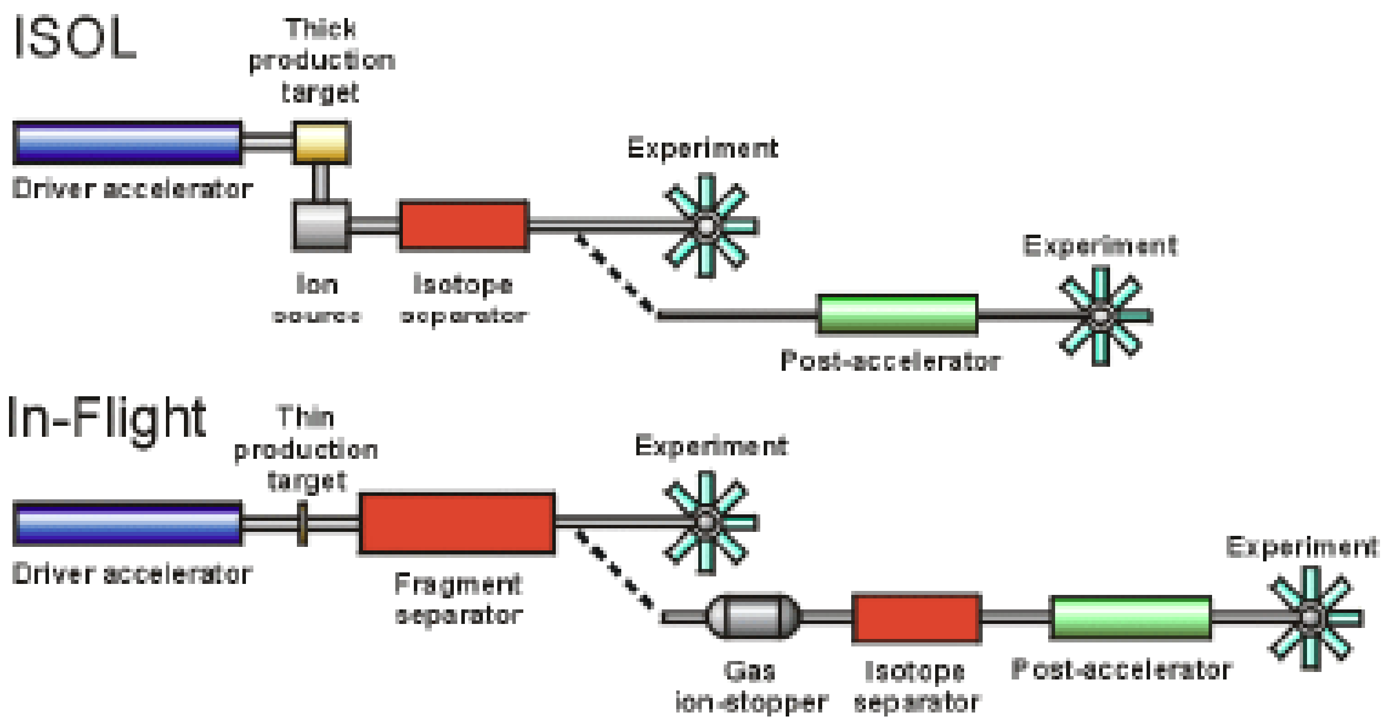
Spin coater and target wheel

- Spin coating of metals chelated to a multi-dentate aqueous polymer (polyethylenimine(PEI))

- Annealing of spin-coated films yields a crack-free, uniform and homogenous metal oxide film

- PAD reapplication can produce film of desired thickness

Target for RIB



- Oxides, carbides ; stability wrt temperature
- Diffusion, effusion of products of interest
- Dependence of solubility of nuclide of interest
- Dependence on the morphology

Summary

- Radioactive targets offer a wide range of choices for research problems using accelerators

- Target preparation:
  Electrodeposition technique is the work horse
  Polymer assisted deposition - several advantages

- Ensuring isotopic purity (actinides-needing chem. Sep.), deposition , assay , target characterisation for variety of applications is a challenge to nuclear chemists