Study of fission and multinucleon transfer reaction at JAEA tandem accelerator facility

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Nuclear Astrophysics Experiments with HIAF

Contents

- ☑ Brief introduction of JAEA tandem faciliy
- ☑ Fission of mendelevium (^{258}Md, atomic number 101)
- ☑ Study of multinucleon transfer (MNT) reaction
- ☑ Summary

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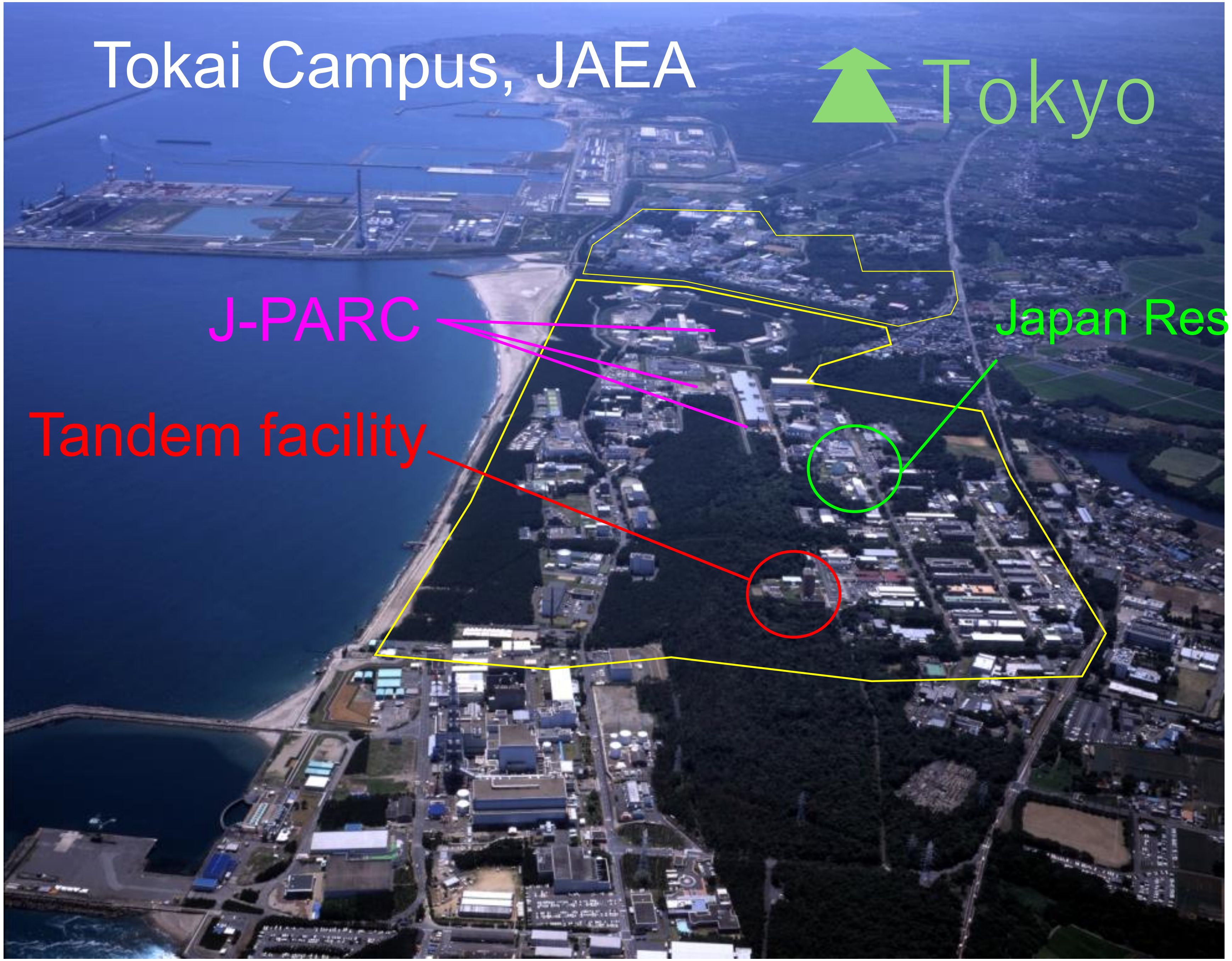
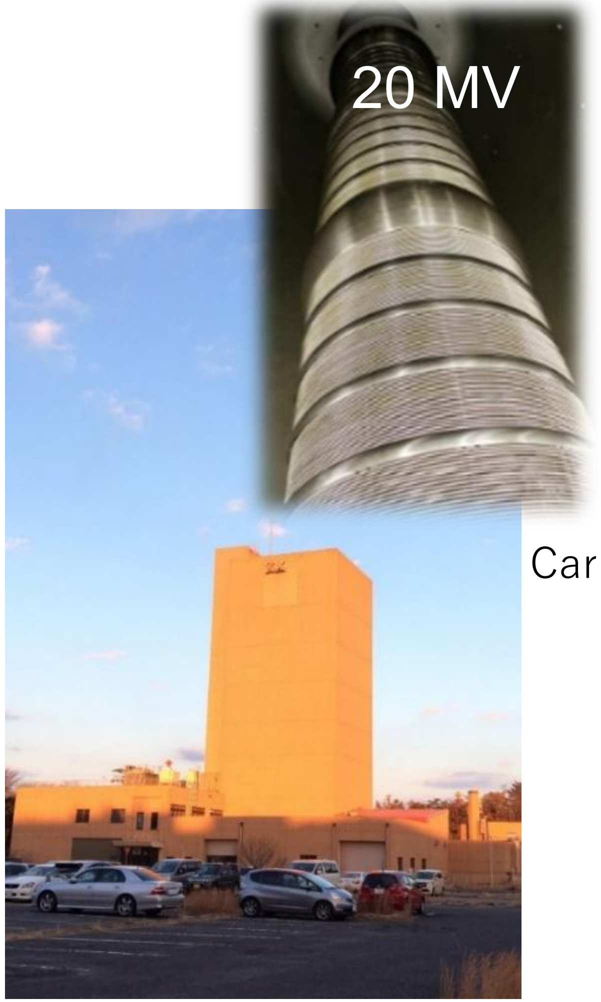
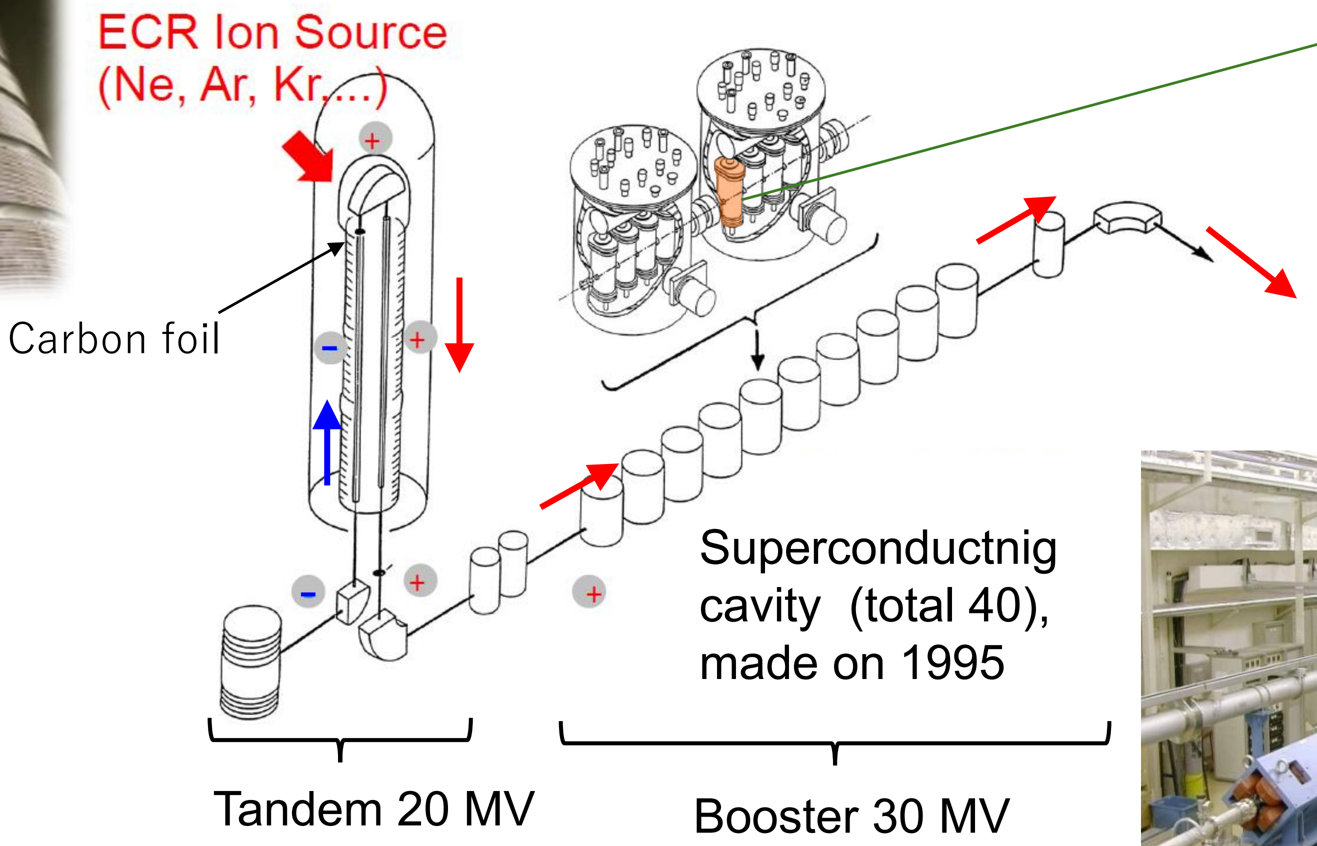
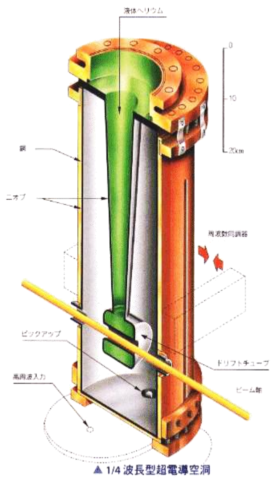

Tokai Campus, JAEA
Tokyo
J-PARC
Japan Research Reactor 3
Tandem facility


Tokai
Tokyo

Tandem (20MV) and Booster Accelerator

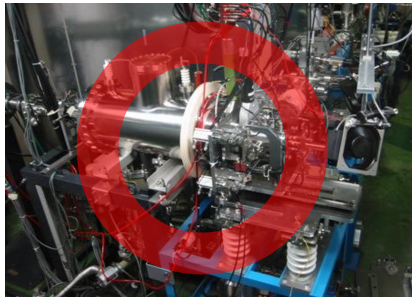




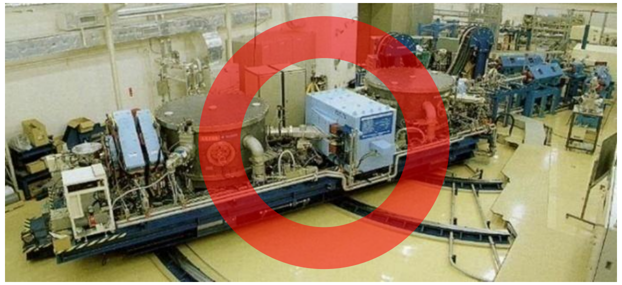


5 - 6 MV/m
Quarter Wave
Resonator

Experimental Setup



Isotope Separator Online (ISOL)



Recoil Mass Separator （JAEA-RMS）

Magnetic Spectrometer (ENMA)

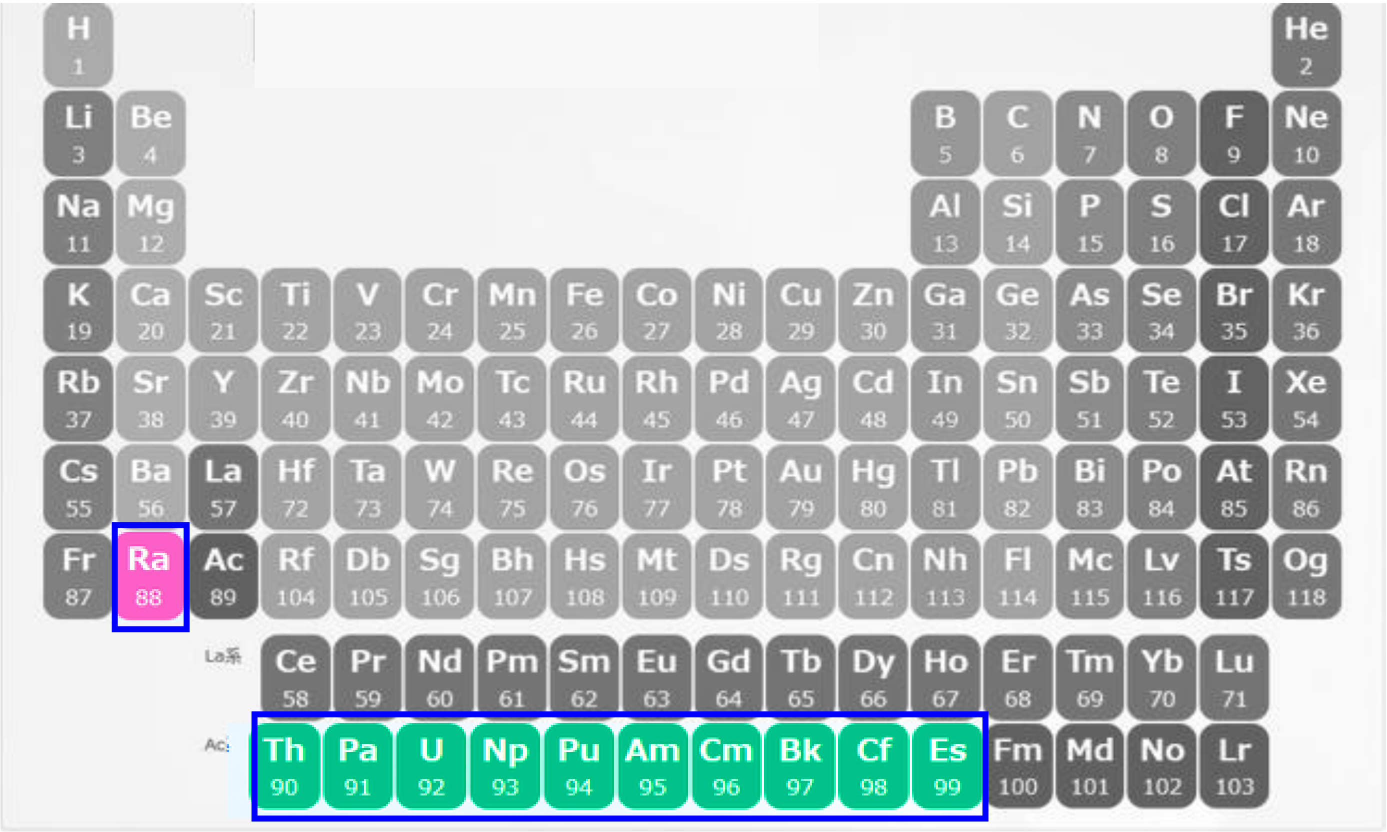
Prompt fission setup

In-beam gamma-ray measurement setup

Radioactive target material

Many α-radioactive target material can be used

^{226}Ra, ^{232}Th, ^{233,235,238}U, ^{237}Np, ^{239,242,244}Pu, ^{241,243}Am, ^{248}Cm, ^{249}Bk, ^{249,250,251}Cf, ^{254}Es



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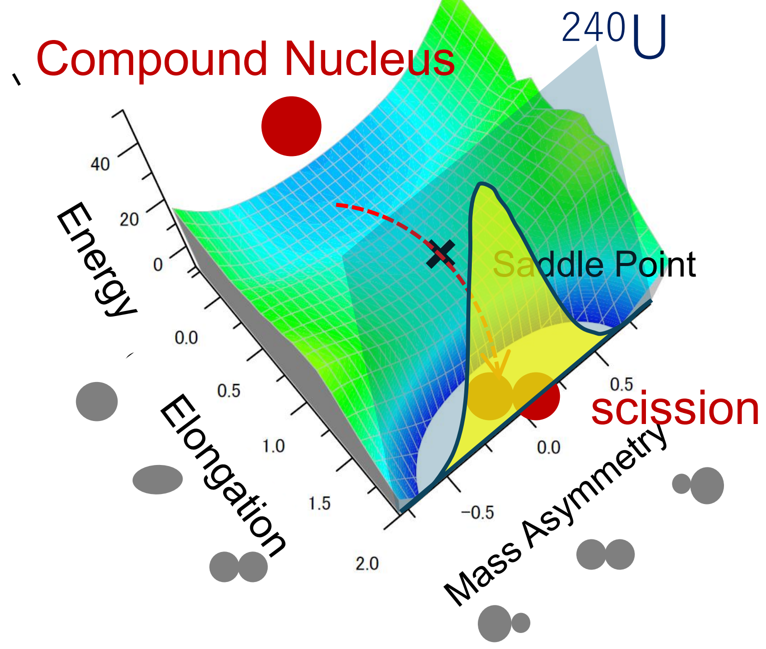
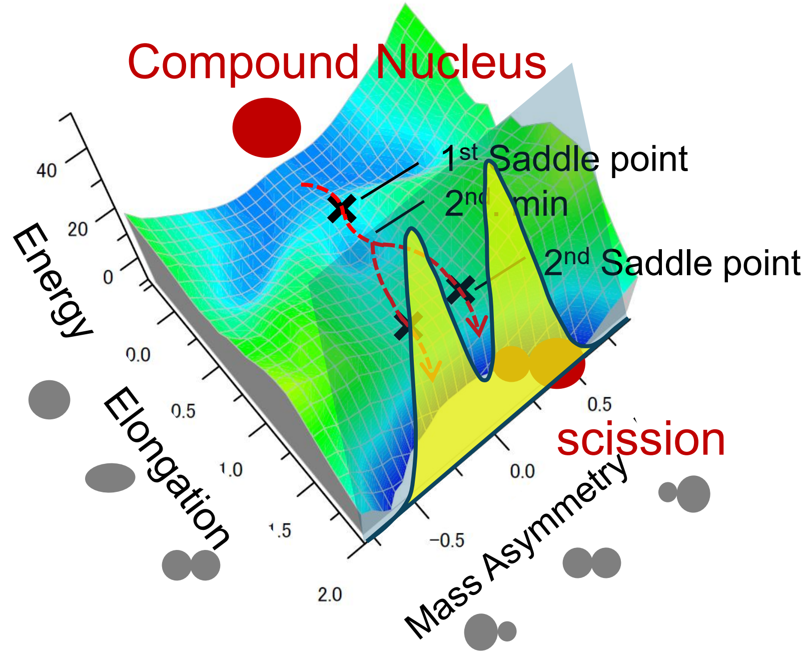
Potential Energy Surface and Fission

Liquid drop model



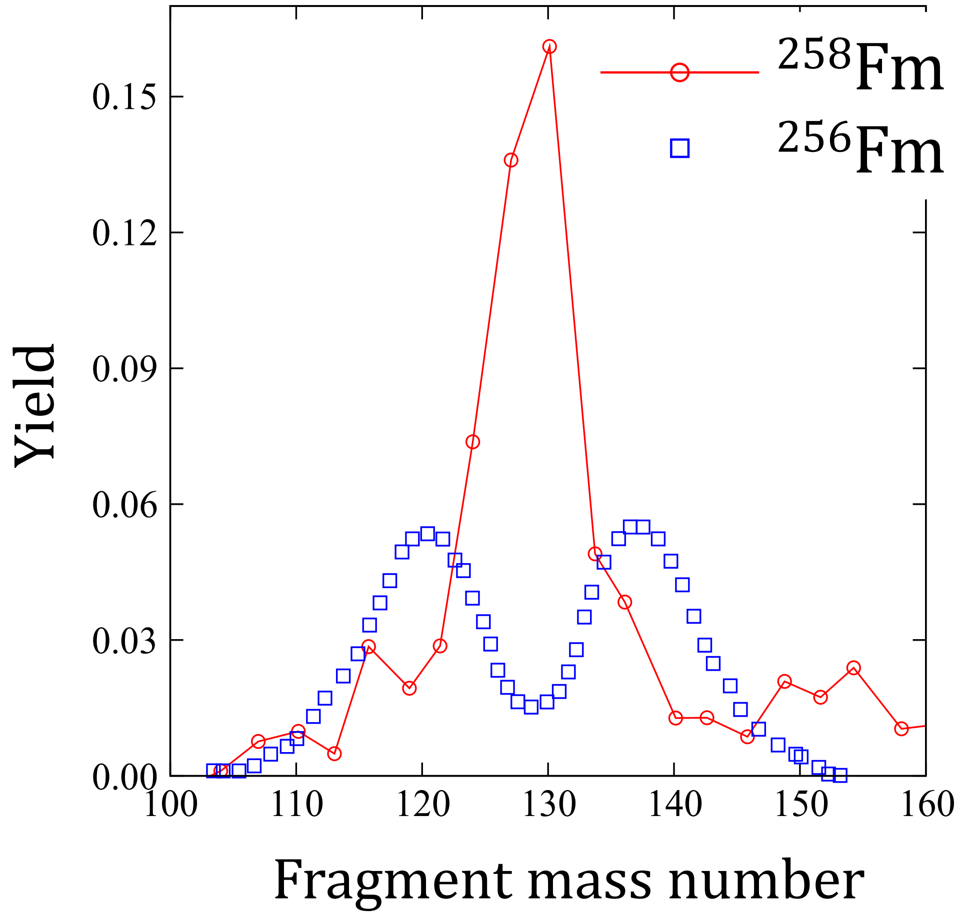
After shell energy correction



Nuclear fission is a unique process to study nuclear structure of deformed shape.
Also, dynamical effects of nucleus can be observed.
Fission-fragment mass distributions is a key observables to investigate structure.

Fission of ^{256}Fm and ^{258}Fm

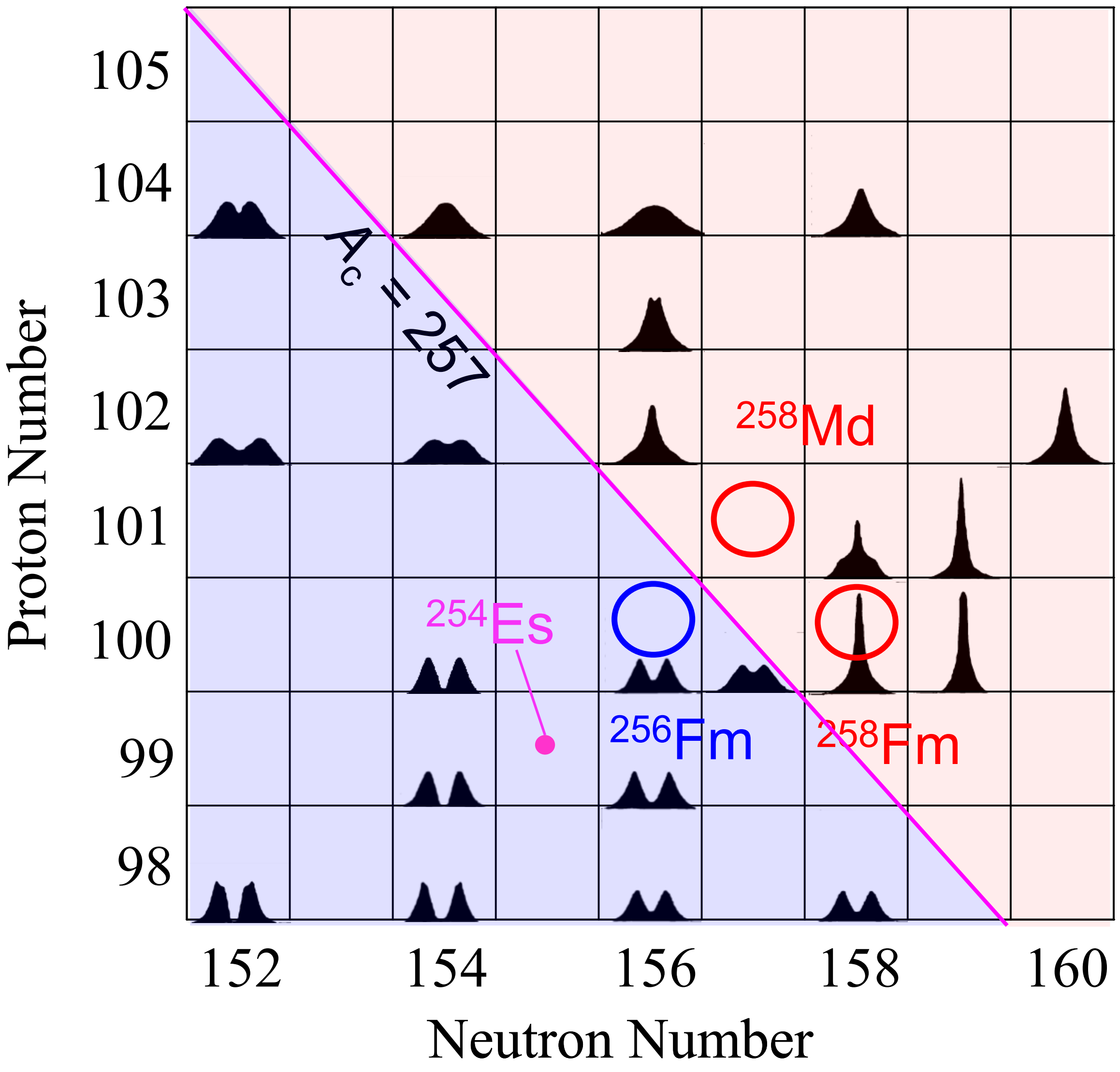
Spontaneous fission of ^{258}Fm shows mass-symmetric fission.



D. C. Hoffman *et al.*, Phys. Rev. **C** 21, 972, (1980).

Spontaneous Fission (SF)

SF properties changes dramatically in $A_c > 257$.



(1) At JAEA we studied fission of ^{258}Md

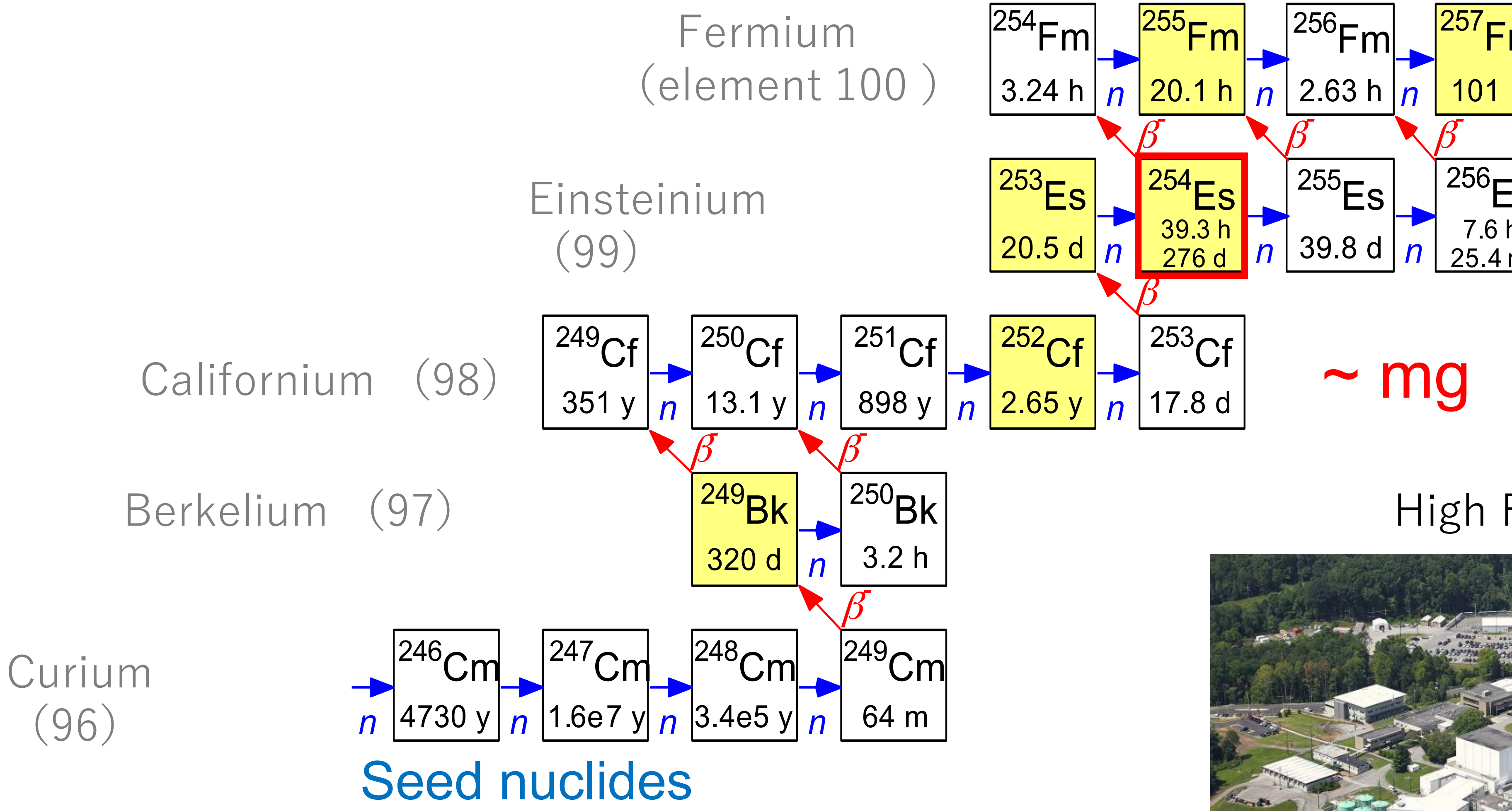
$^{4}He + ^{254}_{99}Es \longrightarrow ^{258}_{101}Md^{*}$

(2) Also SF of ^{256,258}Fm was measured using multinucleon-transfer evaporation reaction

$^{18}O + ^{254}Es \longrightarrow ^{256,258}_{100}Fm$

M.R. Lane et al., Phys. Rev. C **53** (1996) 2893.

Production Scheme of ^{254}Es



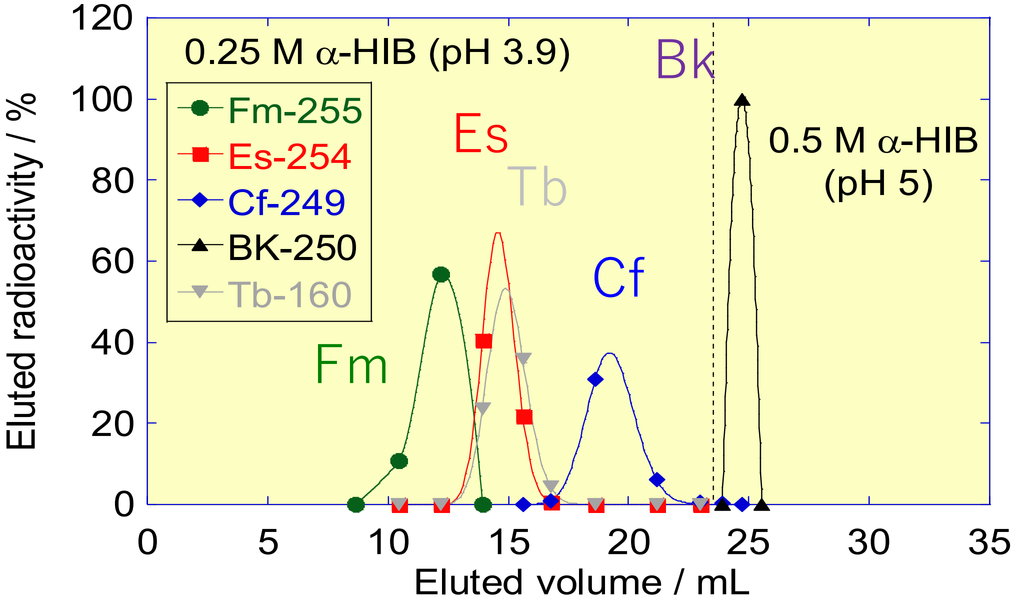
Oak Ridge National Laboratory

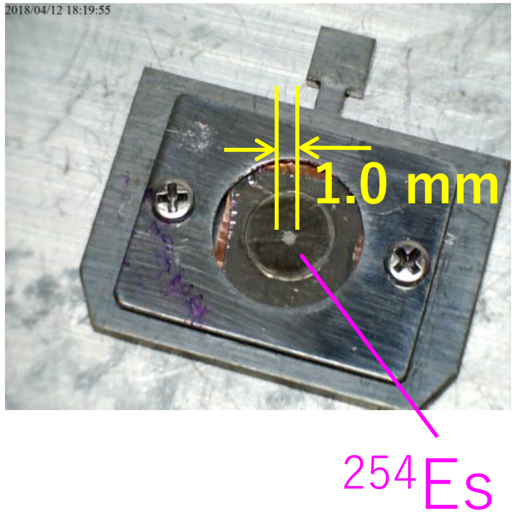
High Flux Isotope Reactor

https://neutrons.ornl.gov/hfir

^{254}Es Target Preparation at JAEA Tandem

Available material is ~ 0.1μg
Half-life is 276 day

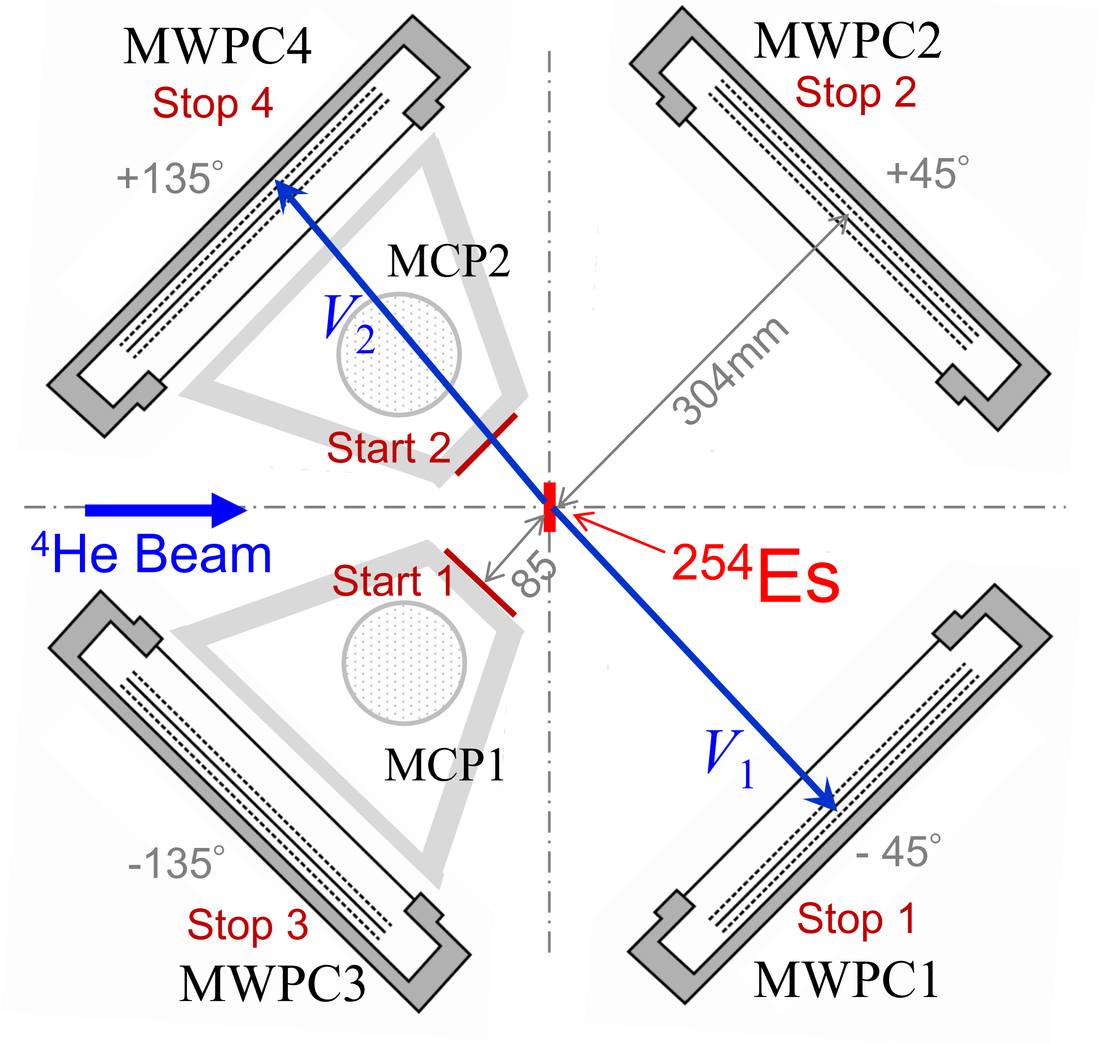


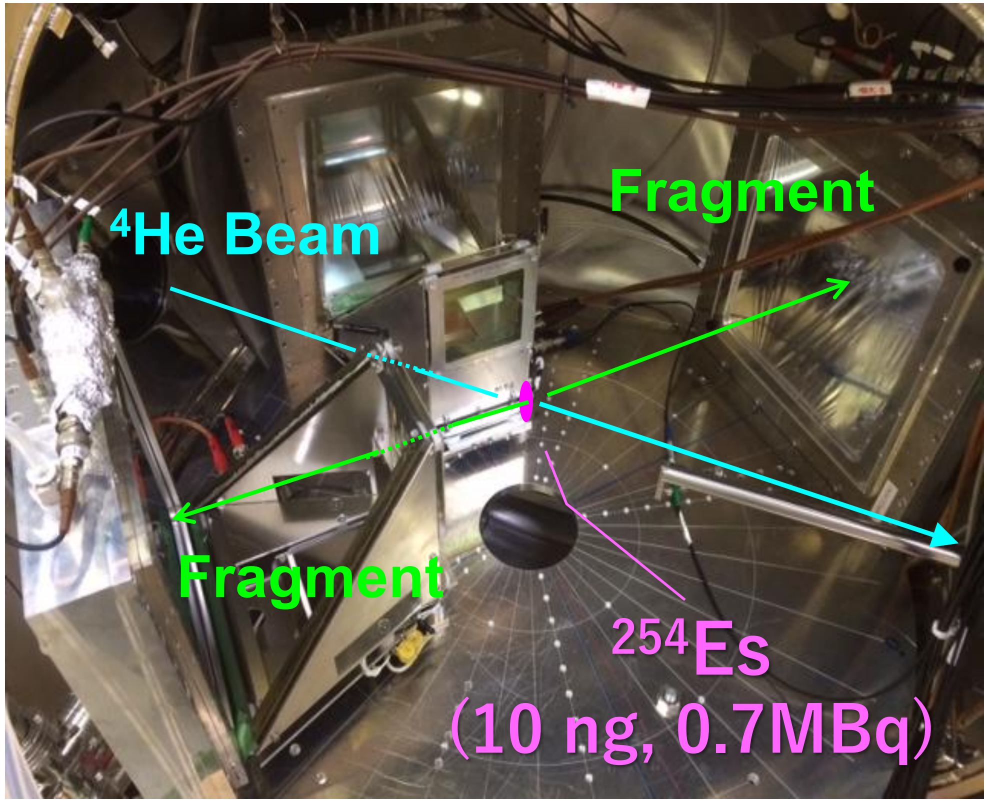


^{254}Es target made by electrodeposition
10 ng (~ 0.7 MBq α decay)

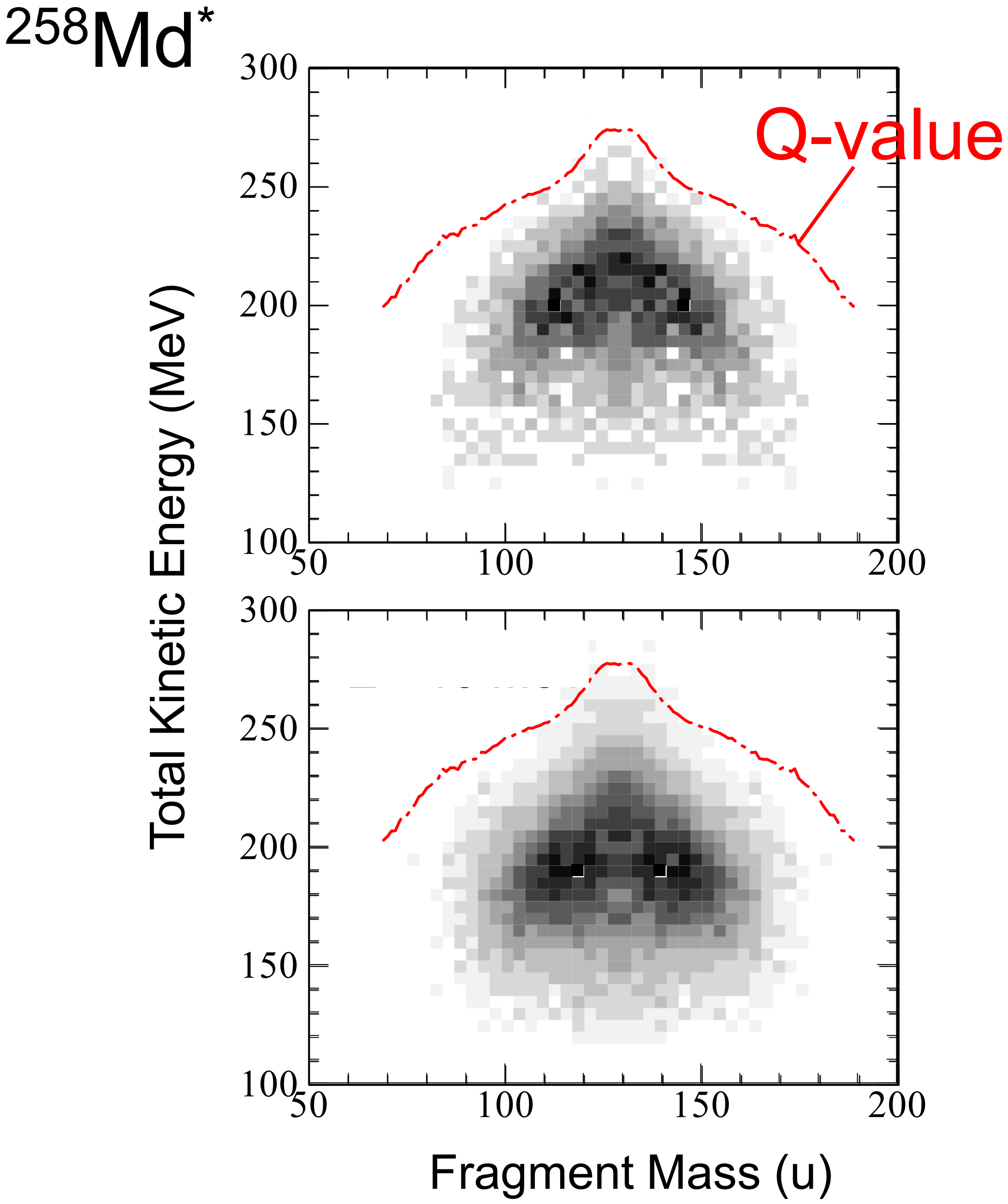
Experimental setup
$^{4}He + ^{254}Es = ^{258}Md^* \rightarrow$ fission

Double velocity measurement of fission fragments.





Fragment Mass-TKE distribution

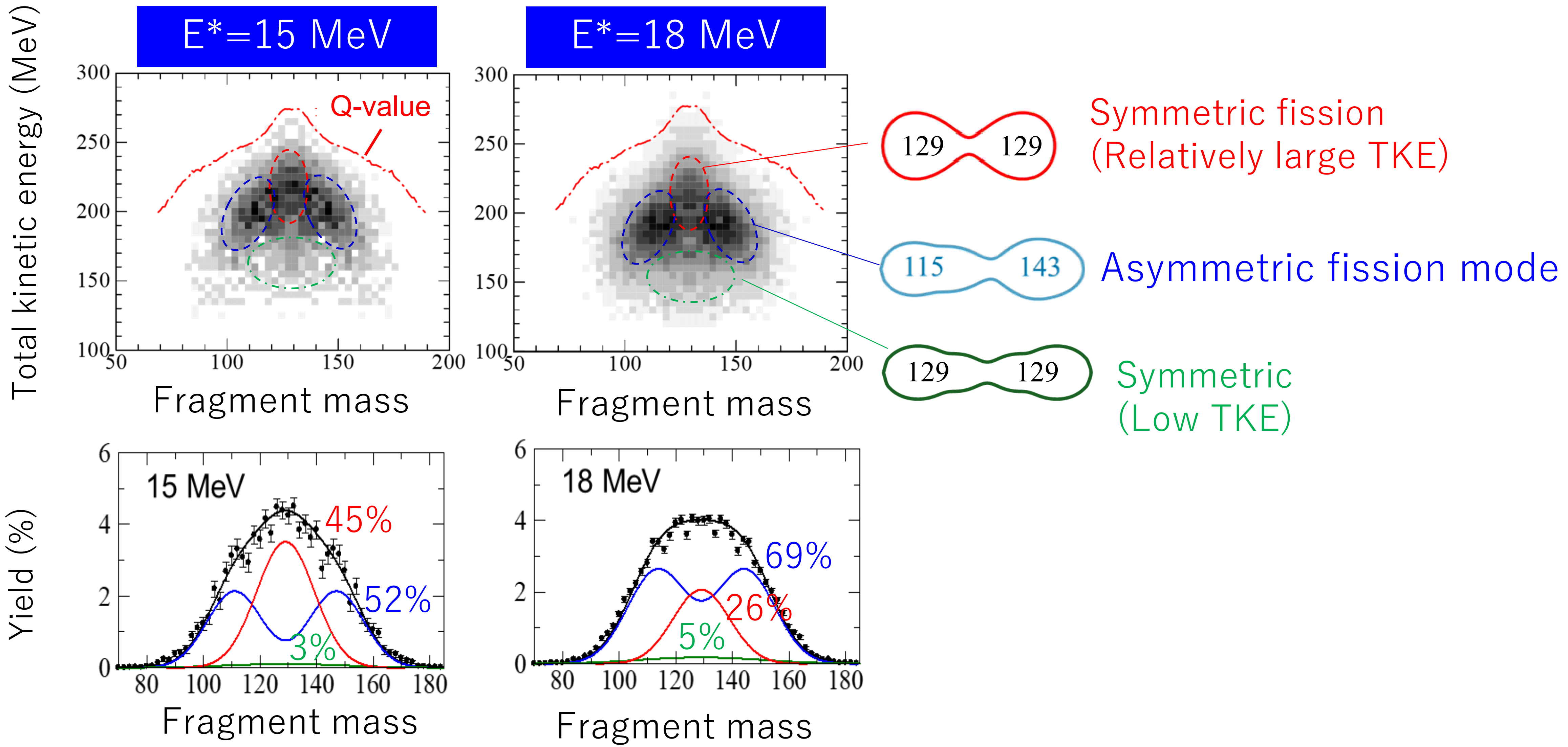


Excitation Energy
E*=**15 MeV**

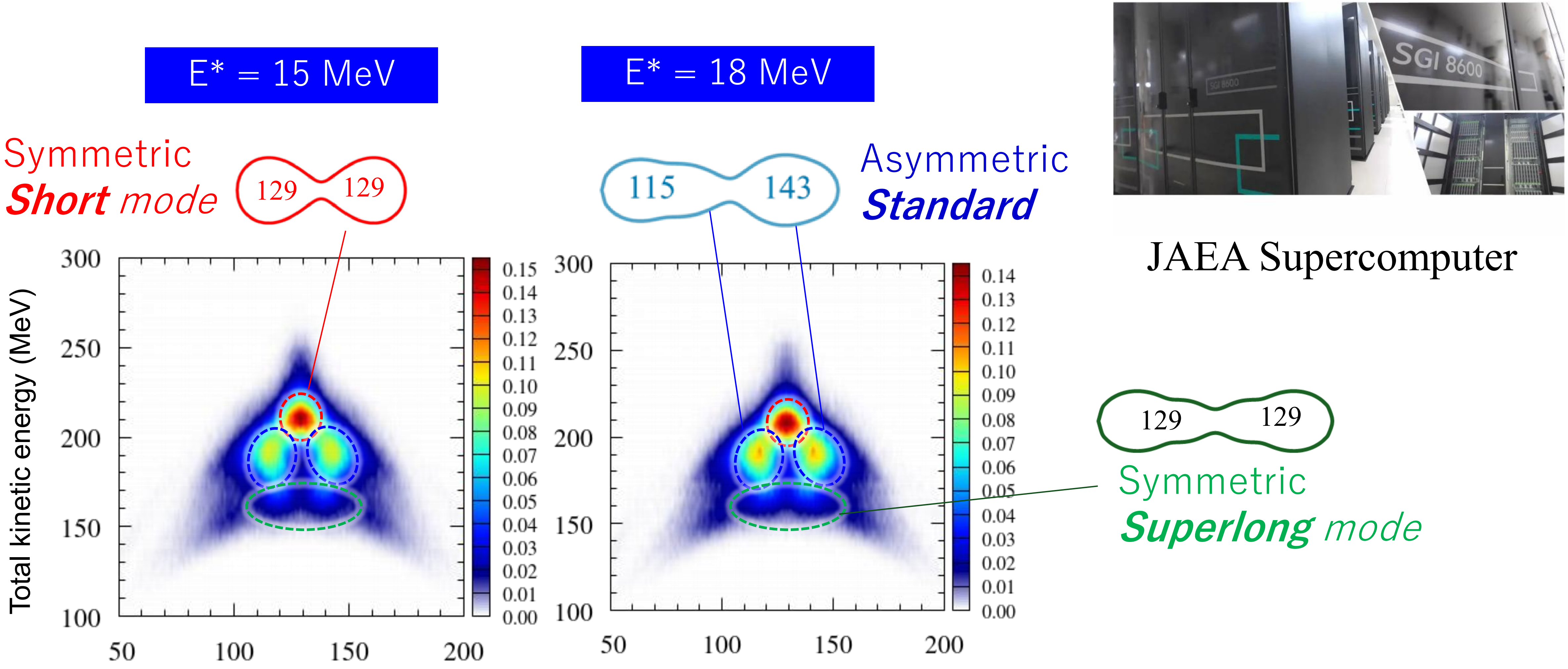
Excitation Energy
E*=**18 MeV**

K. Nishio et al., Phys. Rev. C **111**, 044609 (2025).

Fragment Mass-TKE distribution

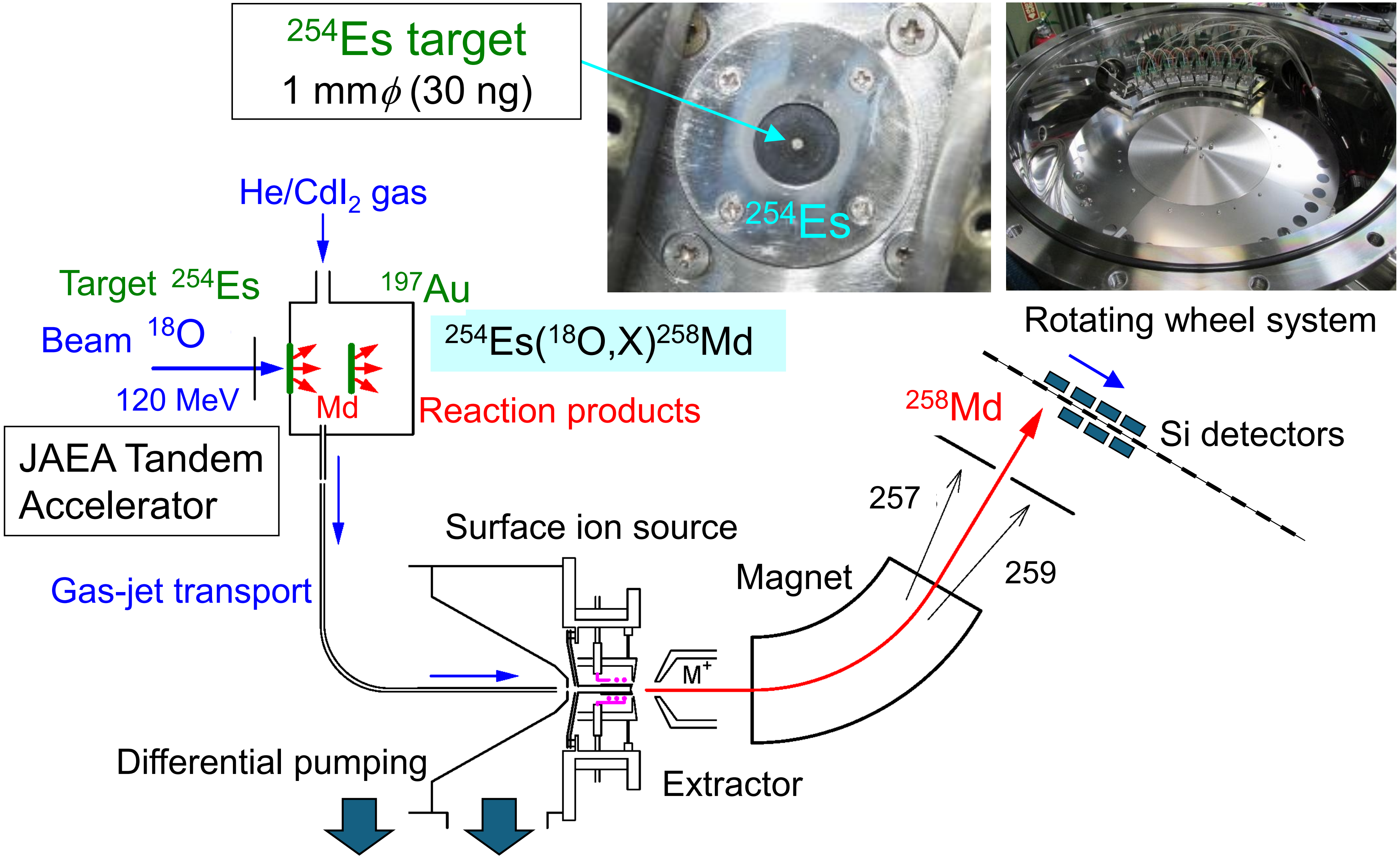


6 dimensional Langevin Calculation

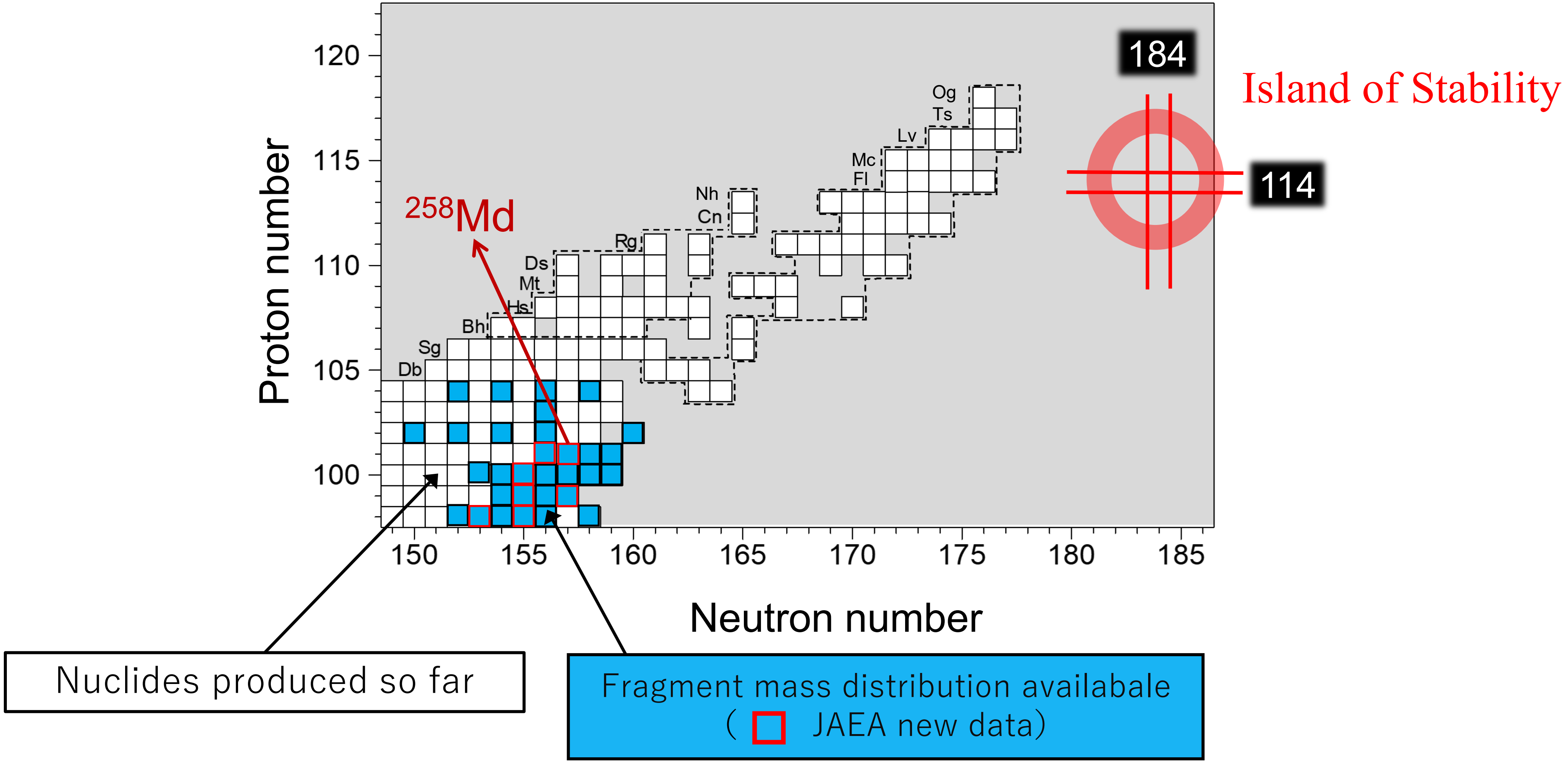


Calculated by Kazuki Okada

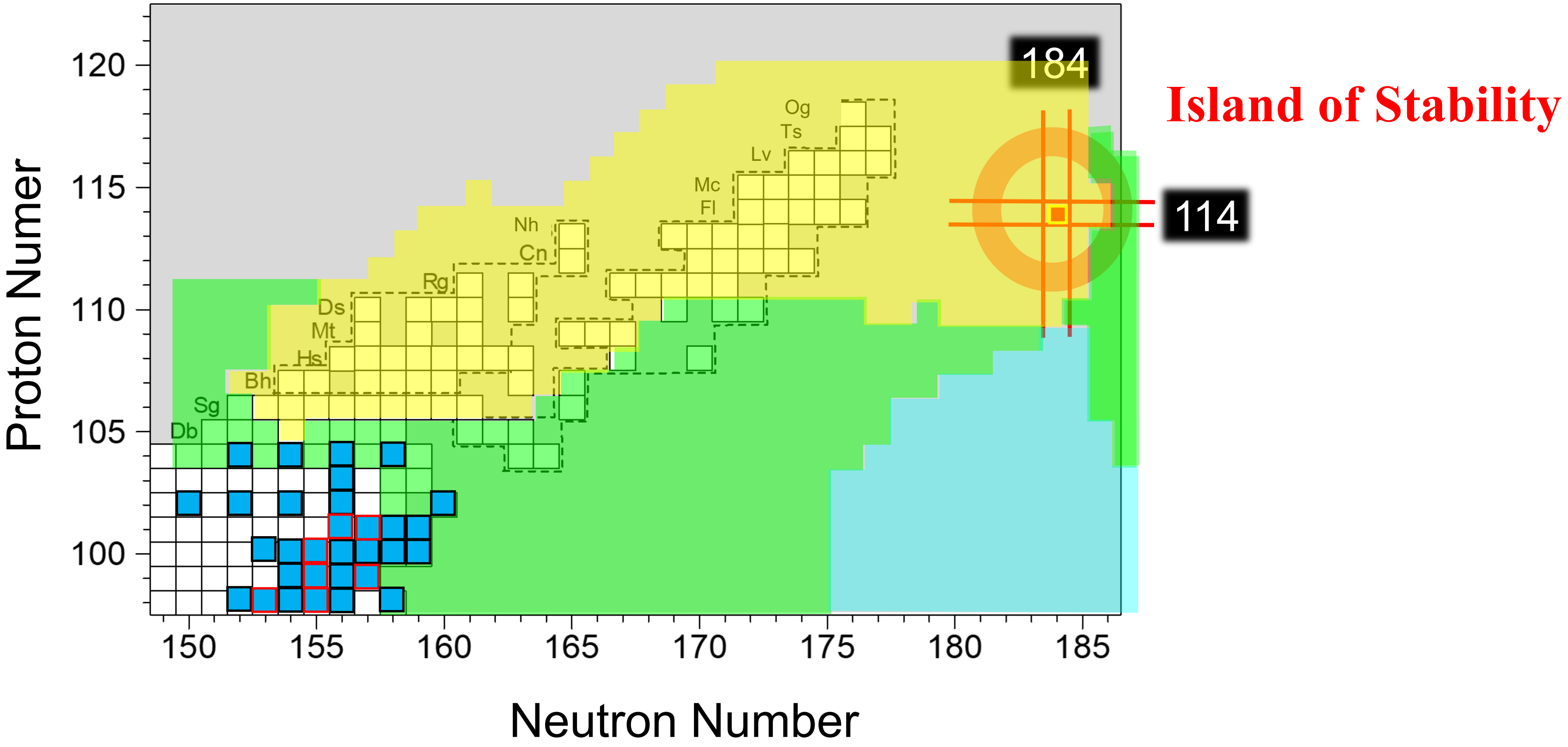
Measurement of spontaneous fission of $^{256,258}Fm$ at JAEA ISOL



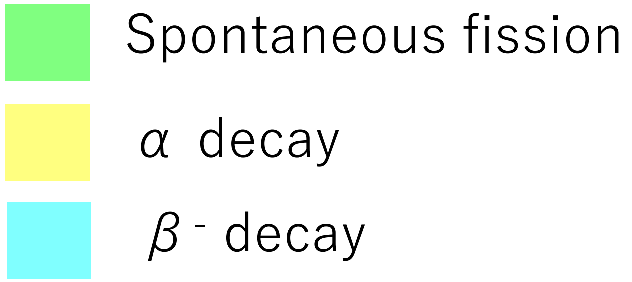
Available fission data for heavy-element region



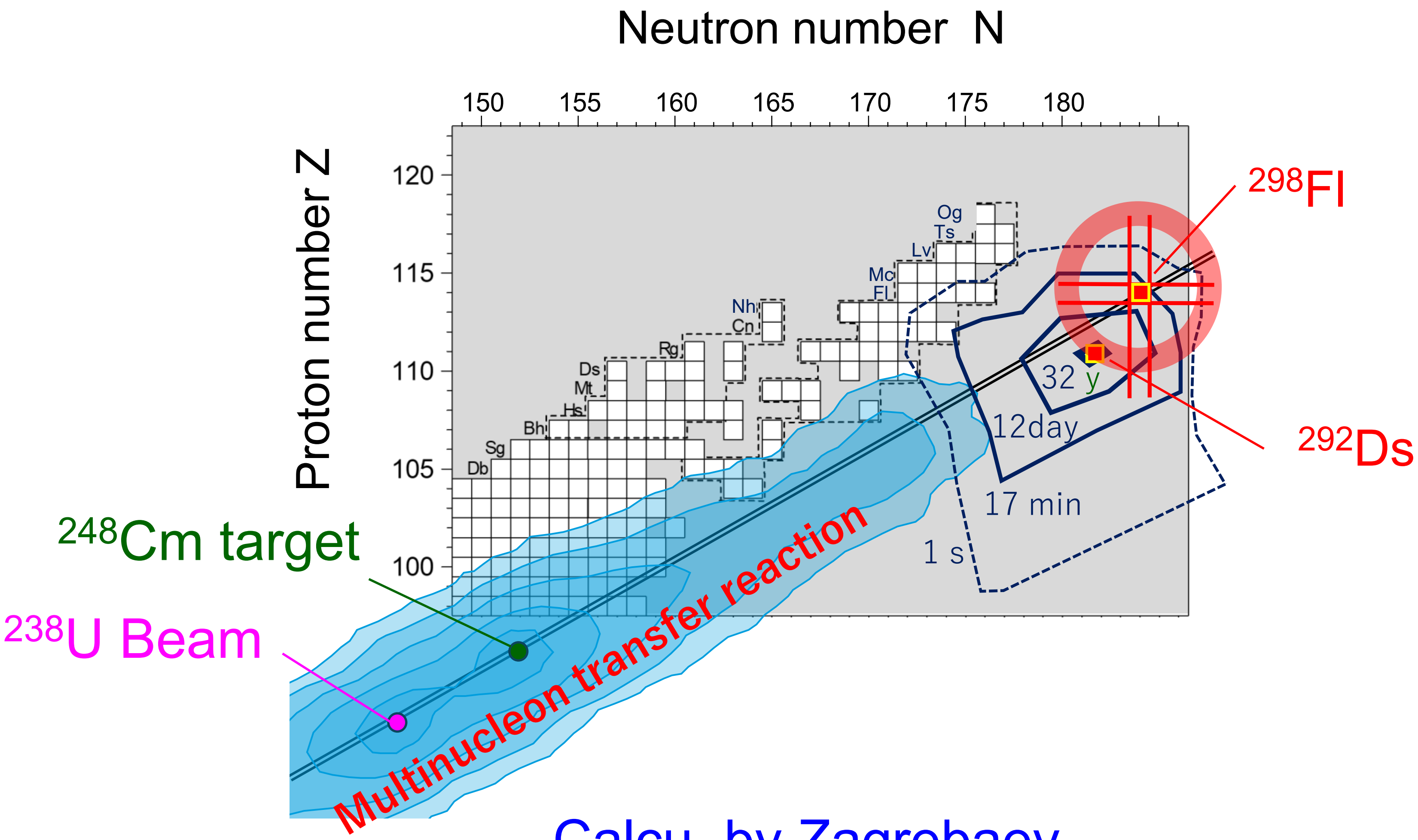
Main decay mode



Theory



Multinucleon transfer reaction



Calcu. by Zagrebaev

Contents

Setups for separating MNT products

Gas-catcher method

- WNSC, KEK (Japan) : KISS
- HIAF (China)
- Groningen (Netherland): NEXT
- GSI (Germany) : FRS/Super-FRS Ion Catcher
- Jyväskylä (Finland) : IGISOL
- Argonne (US) : N=126 factory

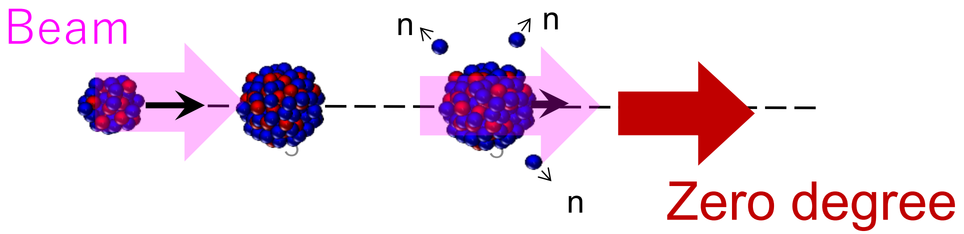
In-flight separation at ZERO degree

- GSI (Germany) : SHIP
- FNLR (Russia) : SHELS
- Jyväskylä (Finland) : RITU and MARA
- Argonne (US) : AGFA

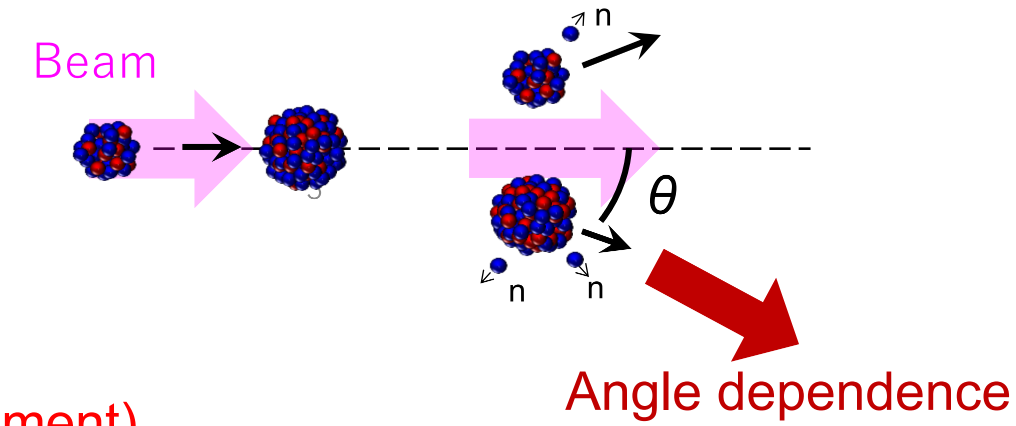
In-flight separation at finite angle
(→ Suitable for reaction study)

- JAEA (Japan) : RMS (on-line radioactive decay measurement)
- IUAC (India) : RMS (not for radioactive decay measurement)

Fusion



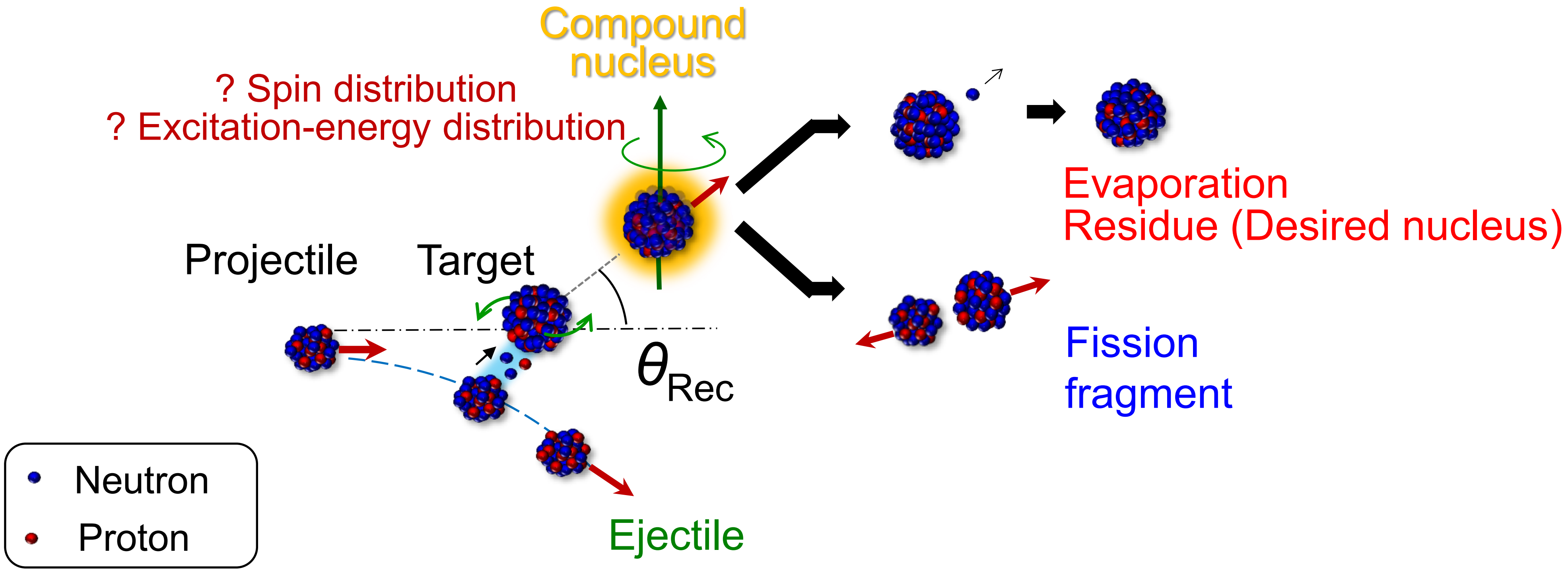
Multinucleon Transfer Reaction



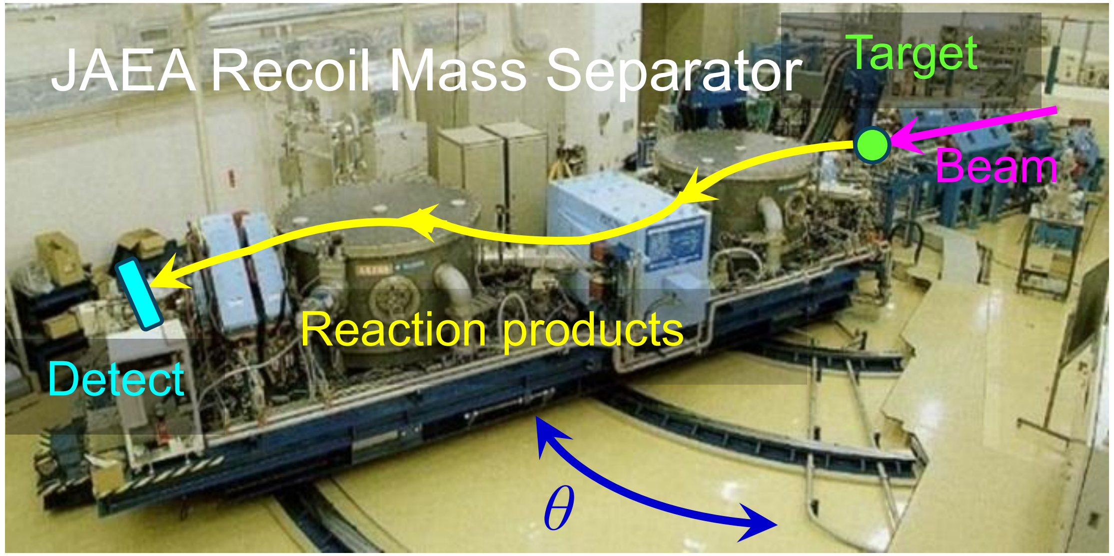
Two steps to produce evaporation residues in MNT reactions

Step1
Populate compound nucleus.
Cross section depends on $E_{c.m.}$ and θ_{Rec}

× Step 2
Survival probability (actinide and superheavy elements)
It depends on excitation energy and spin distribution of compound nucleus

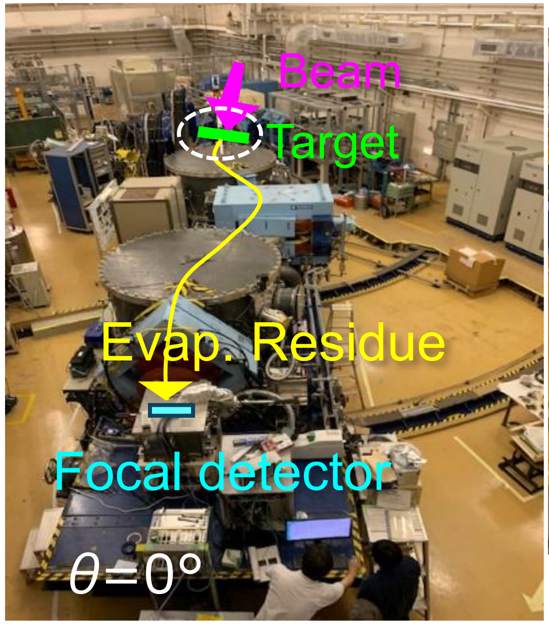


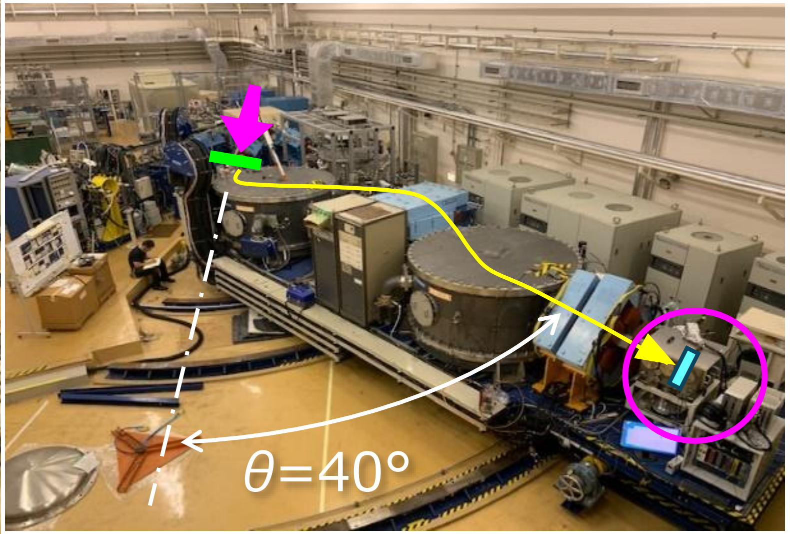
Study of MNT reactions using JAEA RMS



H. Ikezoe et al., Nucl. Instrum. Meth. A **376**, 420 (1996).

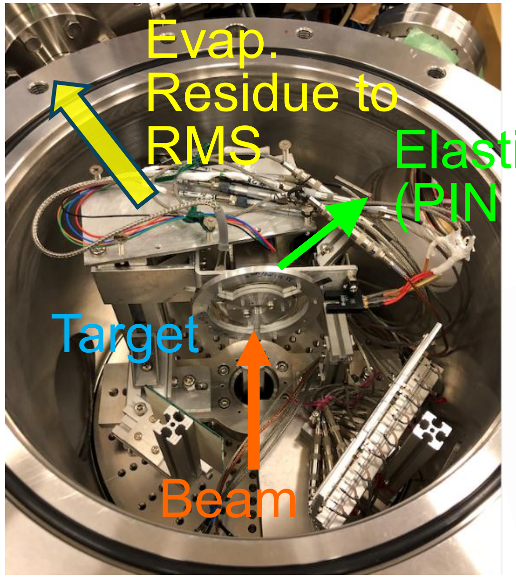
We can rotate RMS freely without breaking the vacuum of the target chamber

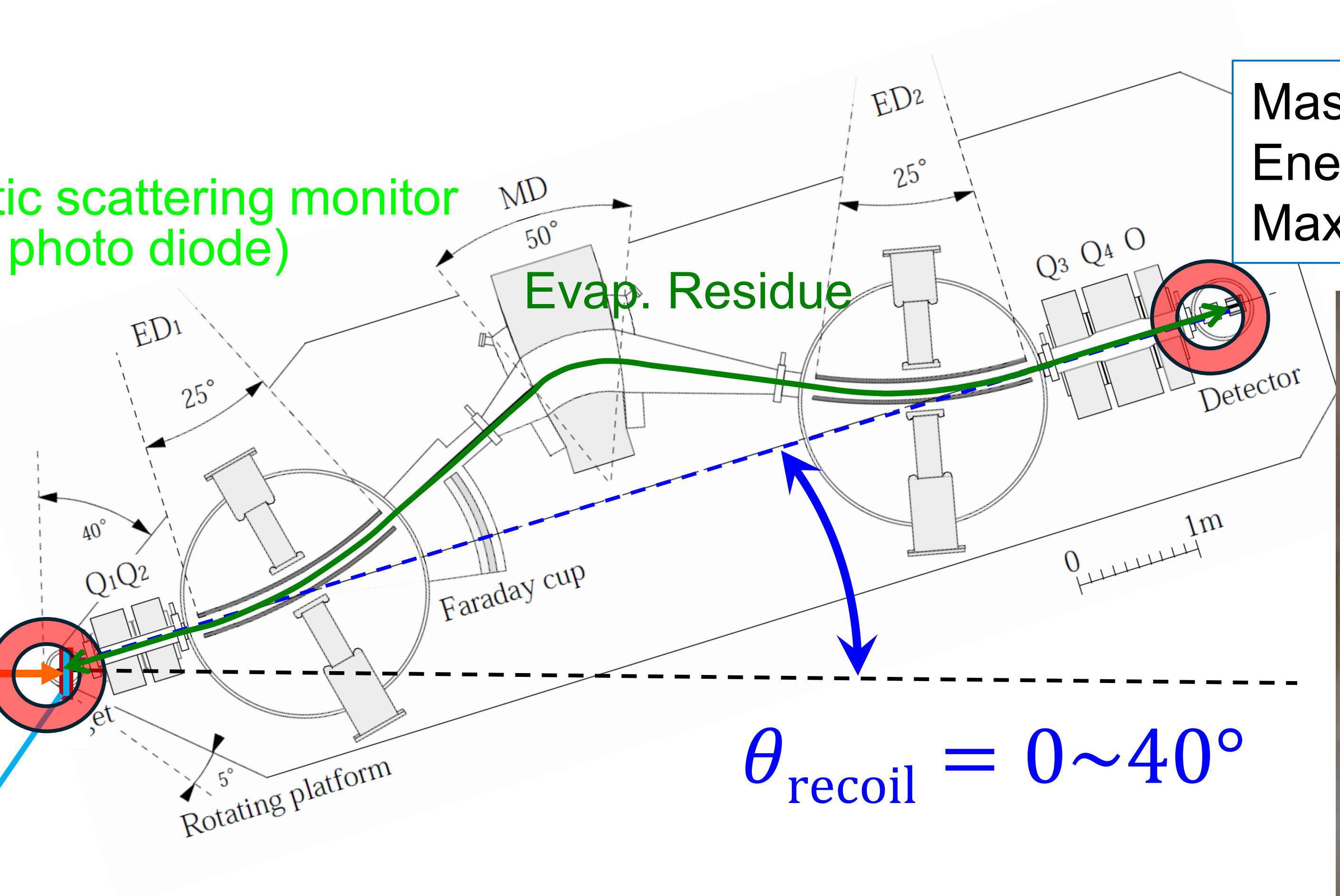




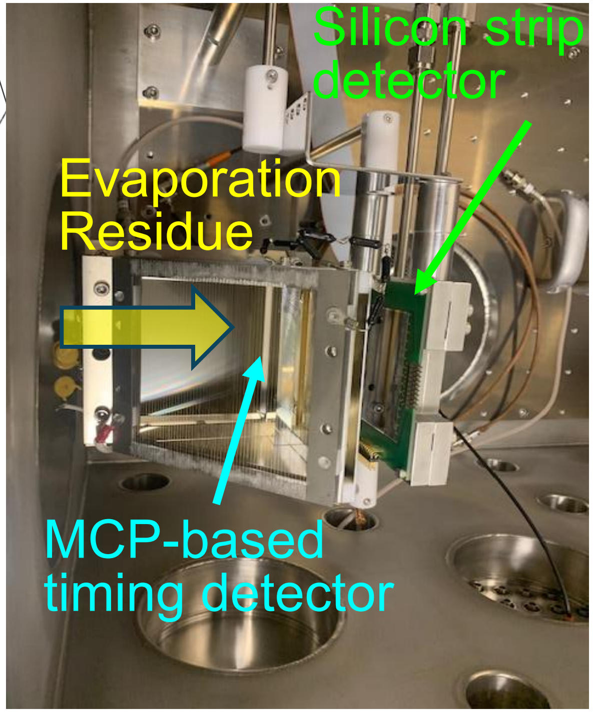
Setup at JAEA Recoil Mass Separator

Cross section as a function of Recoil Angle θ_{recoil} and Recoil Energy E_{recoil}



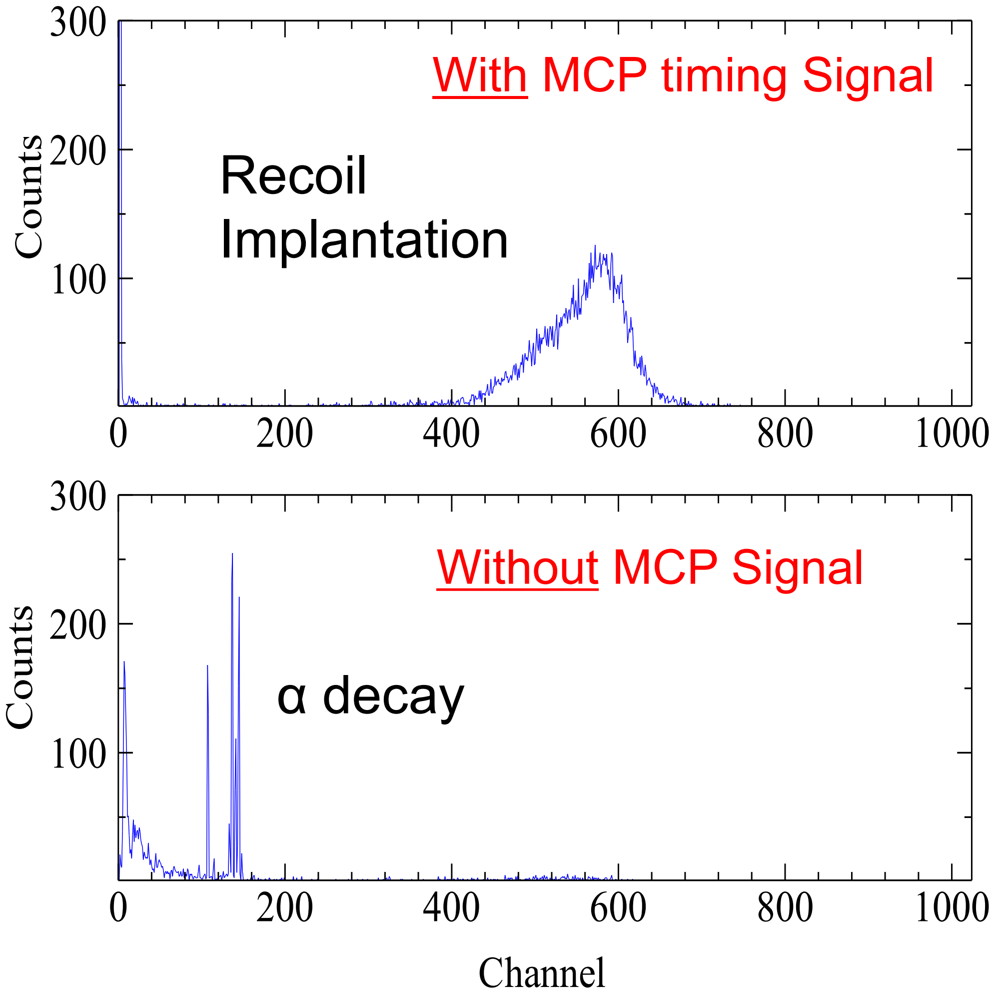


Mass Acceptance : ±4%
Energy Acceptance : ±12%
Max. Solid Angle : 20msr



Separation of recoil implantation and α decay in MNT reaction of $^{30}Si + ^{209}Bi$

Identification of nucleus is made by the measurement of α decay



Pulse height spectrum from Si-strip detector at focal plane

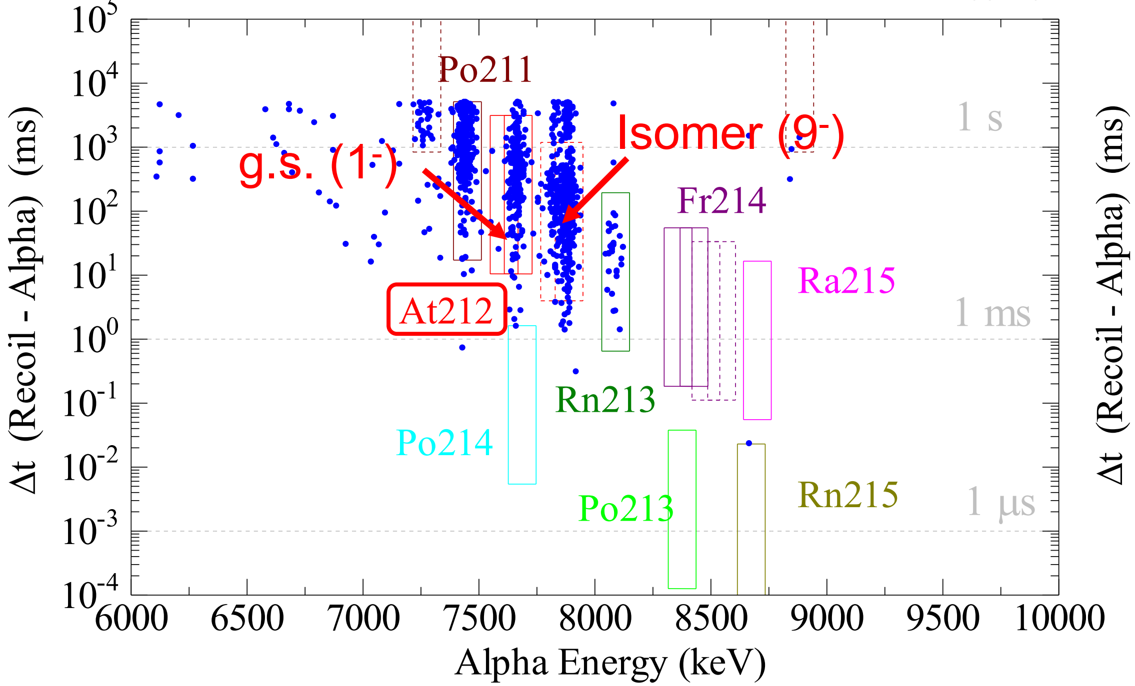
【RMS Setting】

E_{recoil} = 45.5 MeV, θ_{recoil} = 20°

Identification of produced isotpes in Recoil – α decay correlation

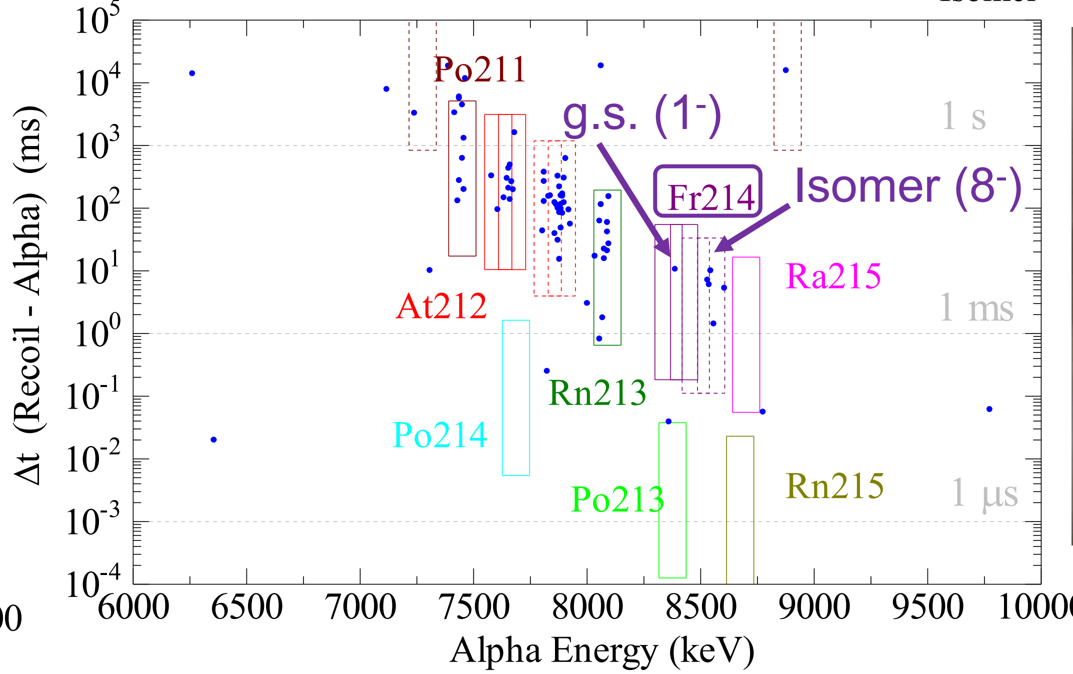
θ_{recoil} = 20.0°
E_{recoil} = 45.5 MeV
(Q = - 30 ～ - 69 MeV)

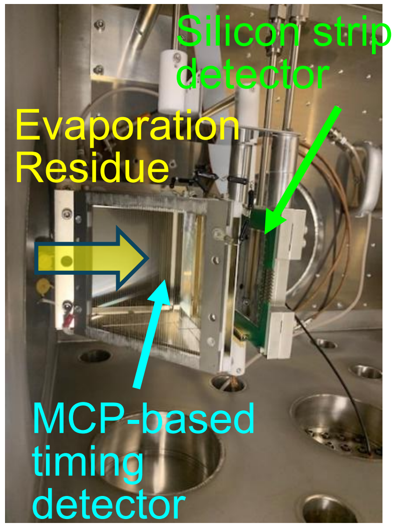
G.S.
Isomer



θ_{recoil} = 20.0°
E_{recoil} = 35.1 MeV
(Q = - 70 ～ - 92 MeV)

G.S.
Isomer



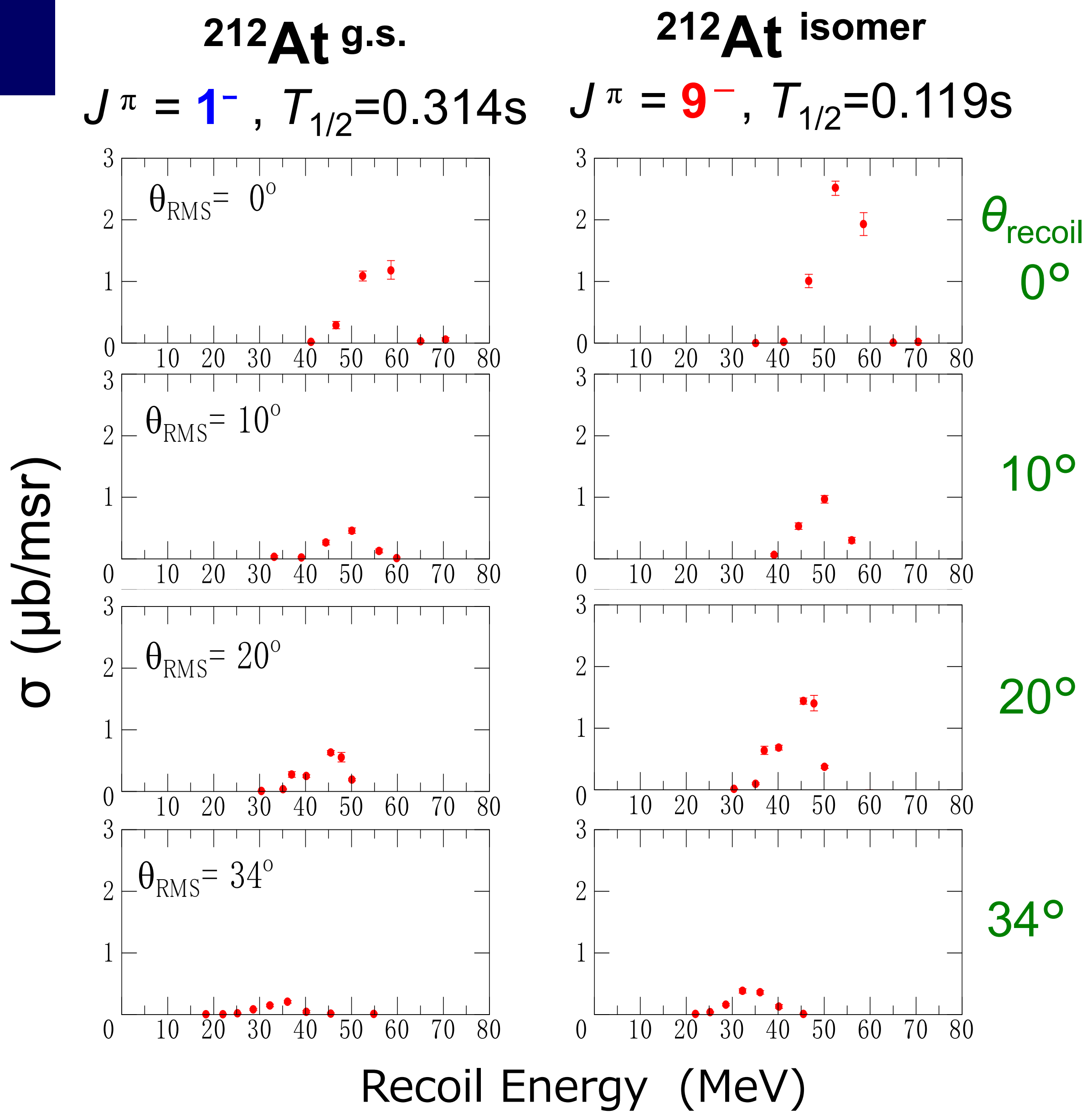


$E_{c.m.}$ = 1.03 x V_{Coul}
(V_{Coul} = 128.5 MeV)

$l_{grazing}$ = 18.0 $\hbar$

Cross section of ERs produced in MNT Reaction of ^{30}Si + ^{209}Bi

High-spin Isomeric state is more populated

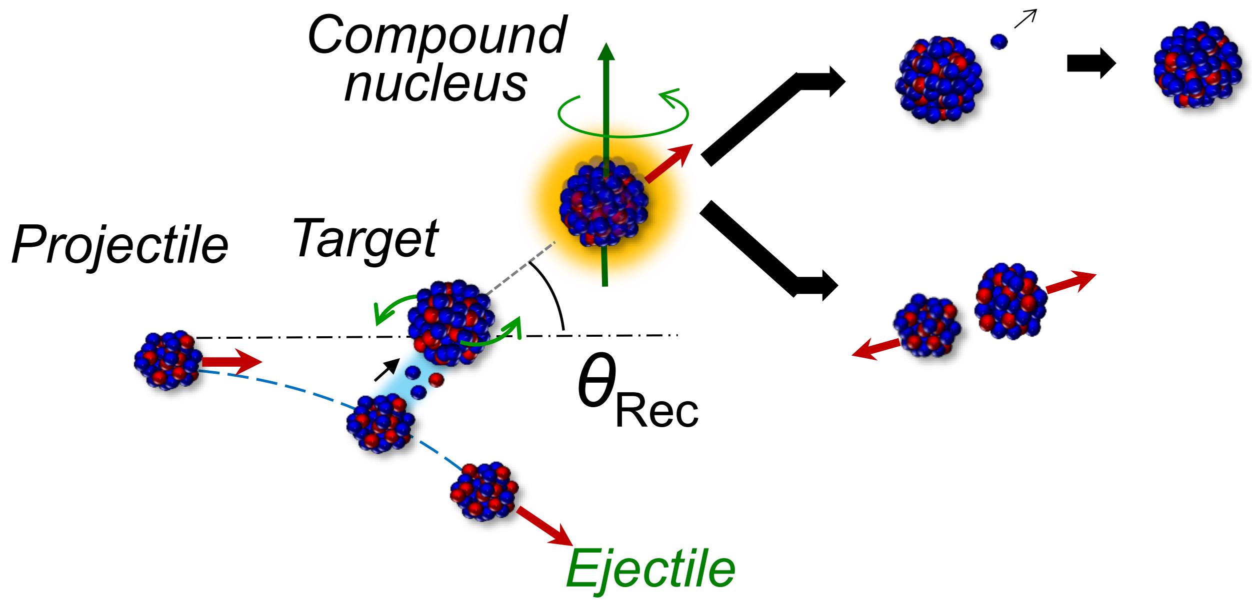


$E_{c.m.} = 1.03 \times V_{Coul}$

Strategy to study MNT reaction

Step1
Compound nucleus cross section

× **Step 2**
Survival probability

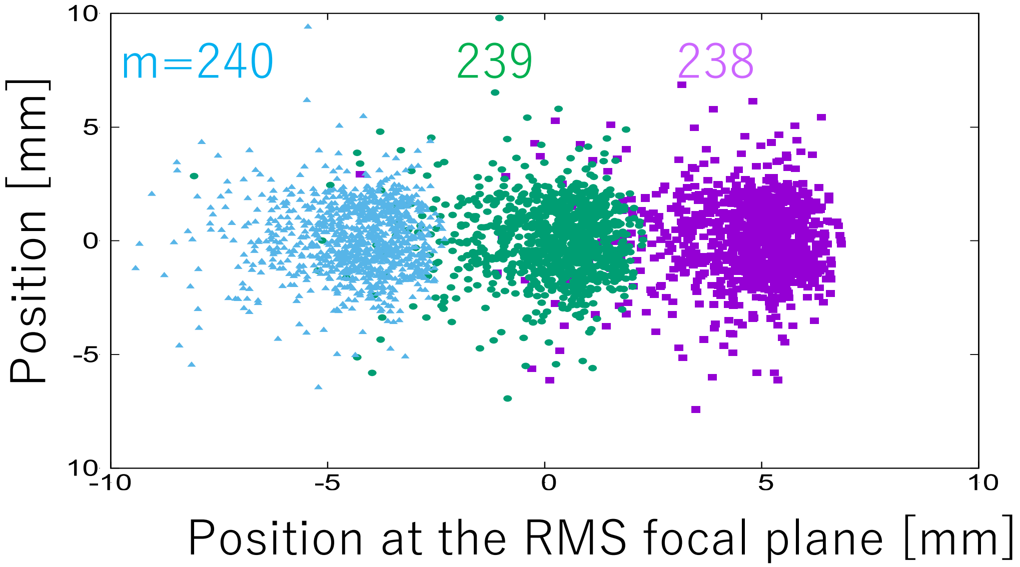


Evaporation residue → Dominant for
^{30}Si, ^{36}S, ^{40}Ar ... + **^{208}Pb,^{209}Bi**

Fission fragment → Important for actinide-target based reaction
^{30}Si, ^{36}S, ^{40}Ar ... + **^{238}U, ^{248}Cm**

Next plan

- We investigate the MNT reaction using actinide target such as ^{238}U
- In-flight mass separation is attempted using JAEA-RMS.
  Isobars are separated using MTROF



Calculation

$$^{238}U(^{18}O,\ ^{16}O)^{240}U^{*} \rightarrow\ ^{240\text{-}xn}U$$

Summary

Heavy actinides have several fission modes associated with different shell structure. Each fission mode has different sensitivity with excitation energy.

In multinucleon transfer reactions, spin-distribution of compound nucleus is studied by isomeric to ground state ratio.

Thank you.