Measurement of evaporation residue following the multi nucleon transfer reaction using the JAEA Recoil Mass Separator

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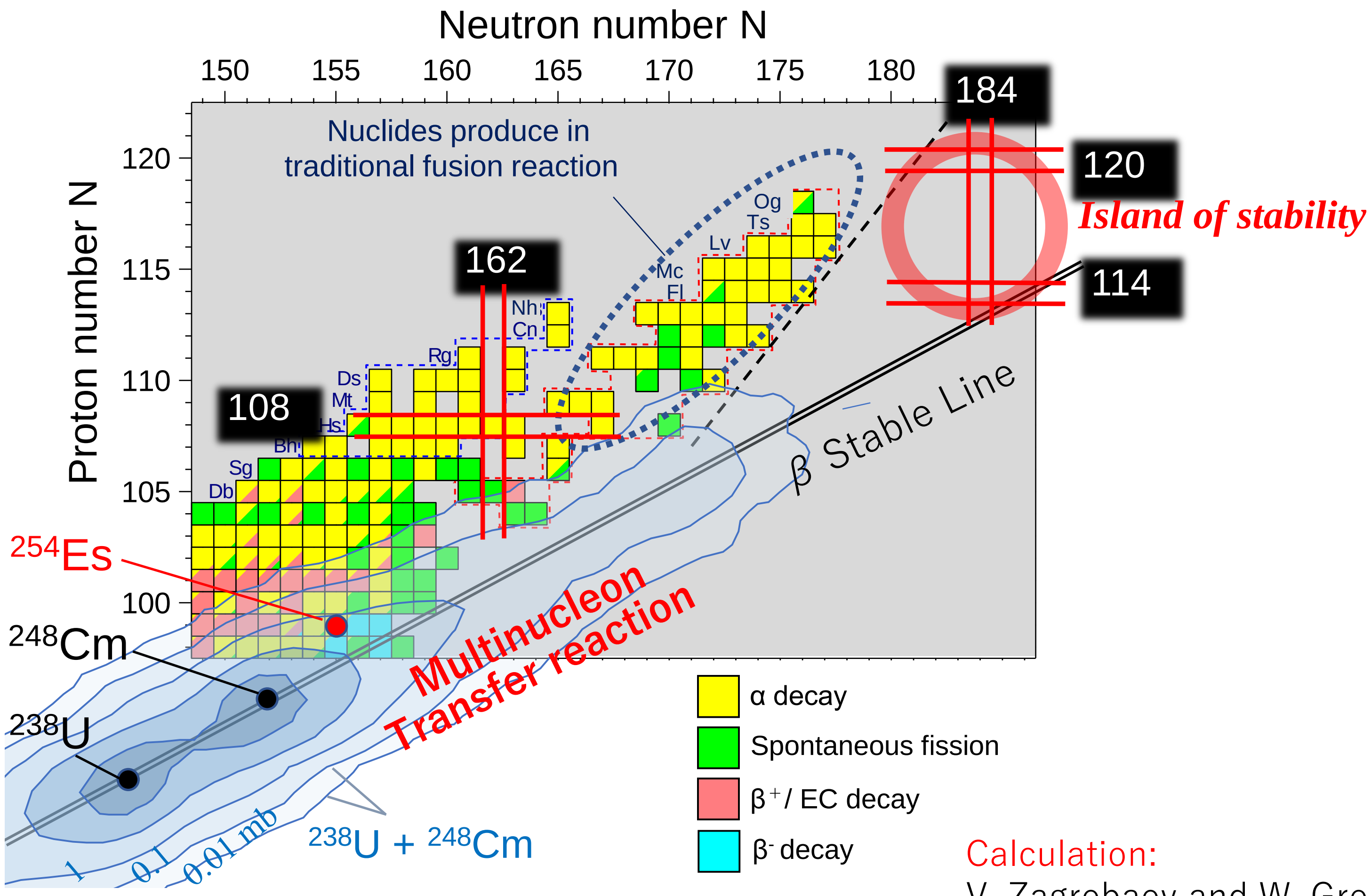
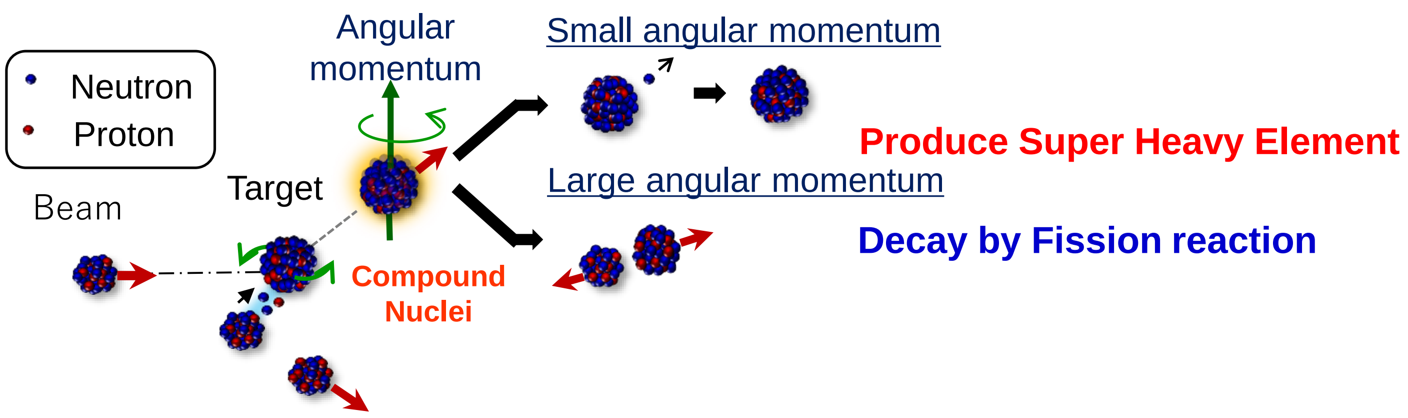
Multi Nucleon Transfer reaction

Multinucleon transfer (MNT) reactions have attracted attention in the field of superheavy-elements and astrophysical nucleosynthesis because they can produce neutron-rich nuclei. For example, the $^{238}U+^{248}Cm$ reaction can produce isotopes of superheavy elements close to the beta stability line.

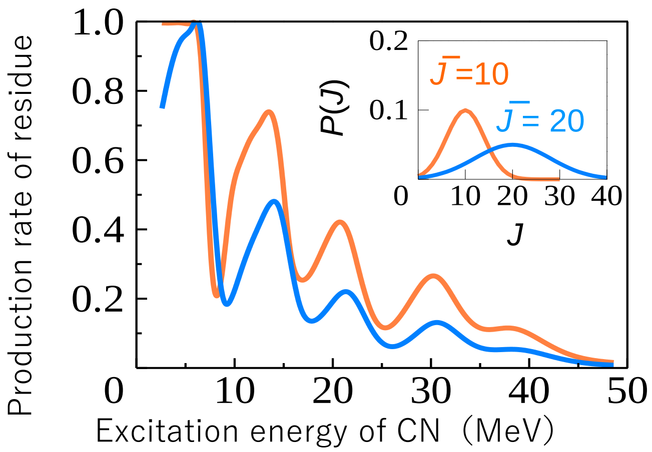


Calculation:
V. Zagrebaev and W. Greiner, J. Phys. G 31, 825 (2005)

Goal : understanding the mechanism of MNT reaction



Calculated by HIVAP

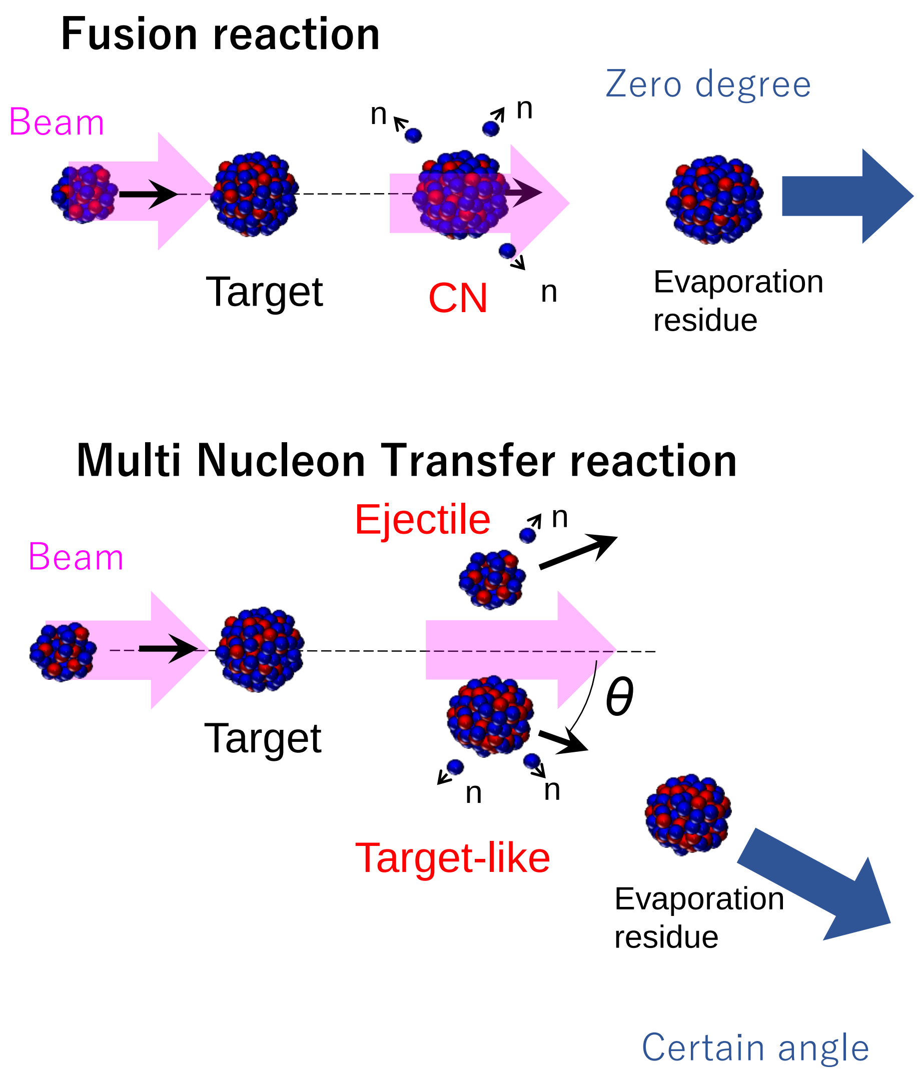


Process of forming superheavy elements in MNT reactions consists of two parts
(1) Produce compound nucleus (CN) with excited states
(2) The CN must survive in competition with fission, to form evaporation residue (Superheavy nuclei)

In this study, we promote the direct measurement of evaporation residues (ERs) produced in MNT reactions.

In this talk, we will present the measurement of ERs in the reaction ^{30}Si + ^{209}Bi. As the CN around ^{209}Bi do not fission in the deexcitation process, we can focus the process (1).

Angular distribution of pronounce nucleus

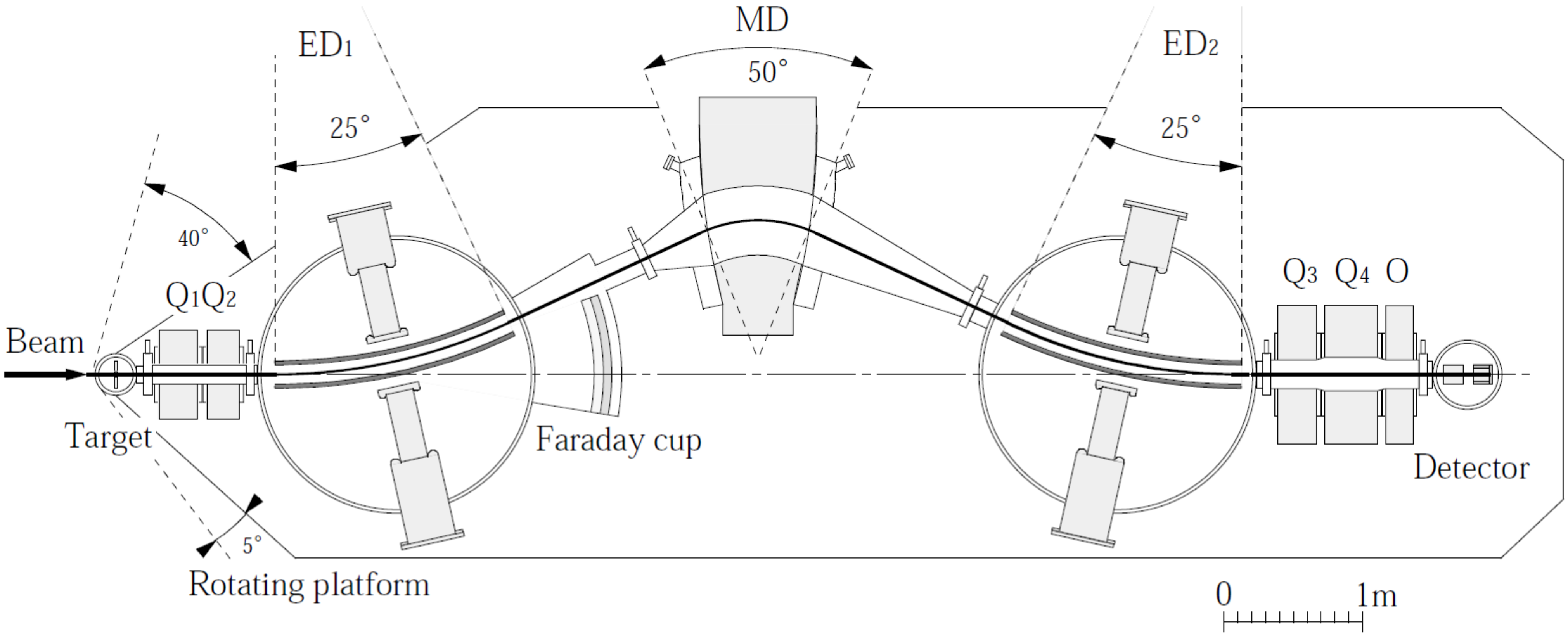


Fusion reactions recoils out the ERs in the beam direction, whereas in the MNT reaction, nuclei are ejected at a certain angle θ.

→In order to study MNT reactions, it is important to measure anglar distribution of ERs.

We measure the cross sections of ERs produced in the MNT reaction and their angular dependence using JAEA Recoil Mass Separator(RMS) at the tandem facility.

Recoil Mass Separator(RMS) at JAEA Tandem

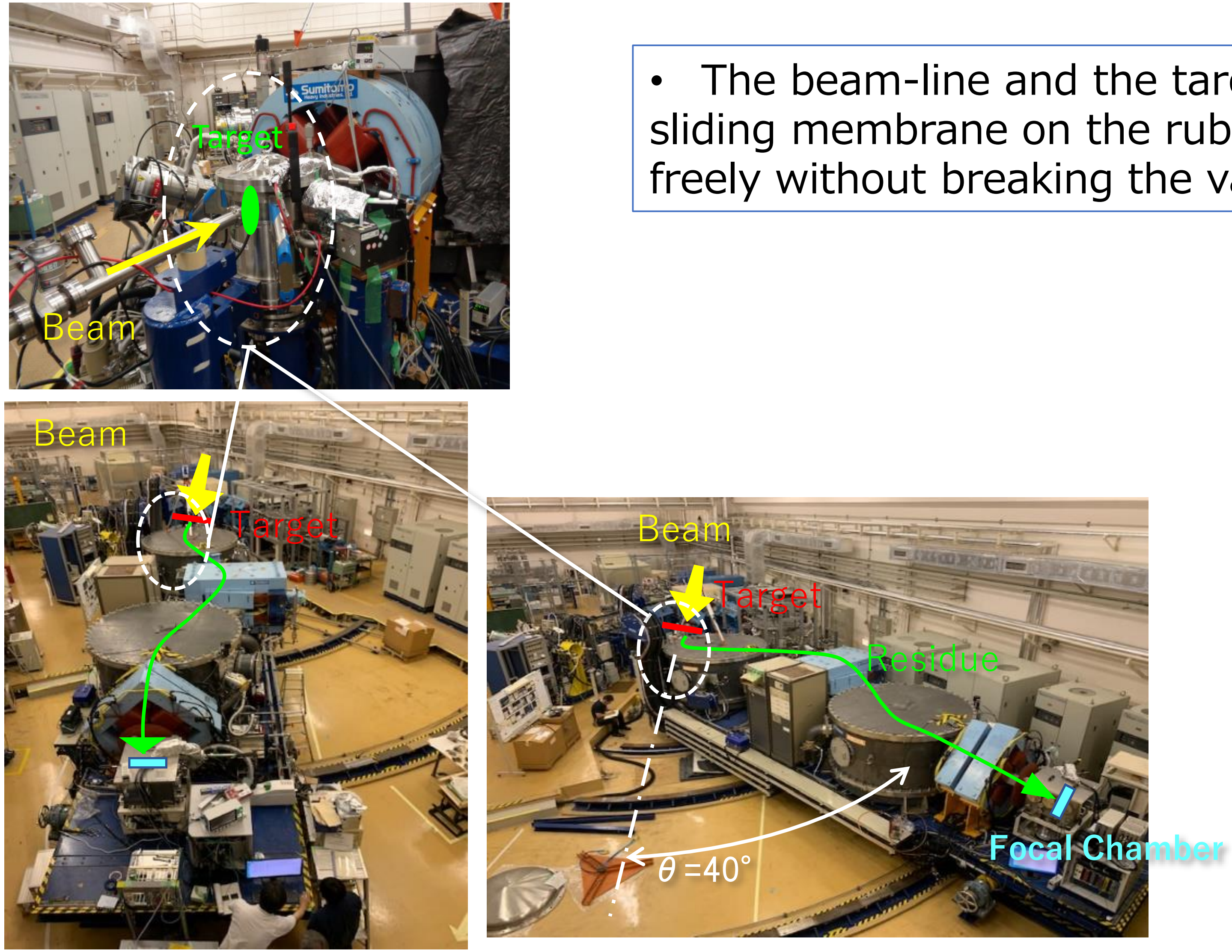


Mass Acceptance: ±4%
Energy Acceptance: ±12%
Solid angle: 20msr
Rotating angle = -5 ~ +40°

H. Ikezoe et al., NIMA 376(1996) 420

Update of RMS for MNT reaction

- The beam-line and the target chamber are connected with a sliding membrane on the rubber seal so that RMS can rotate freely without breaking the vacuum (-5°~ +40°)

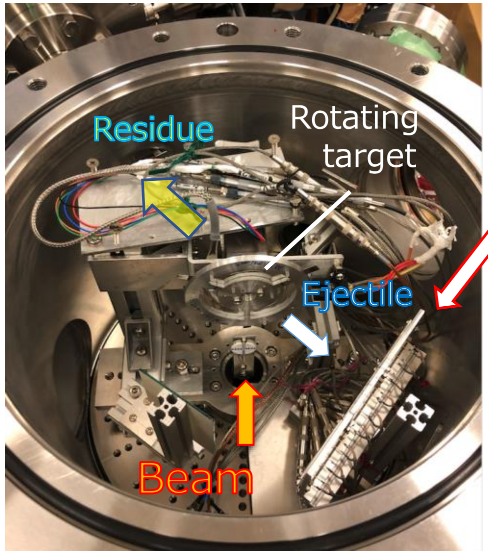


0°

40° rotation

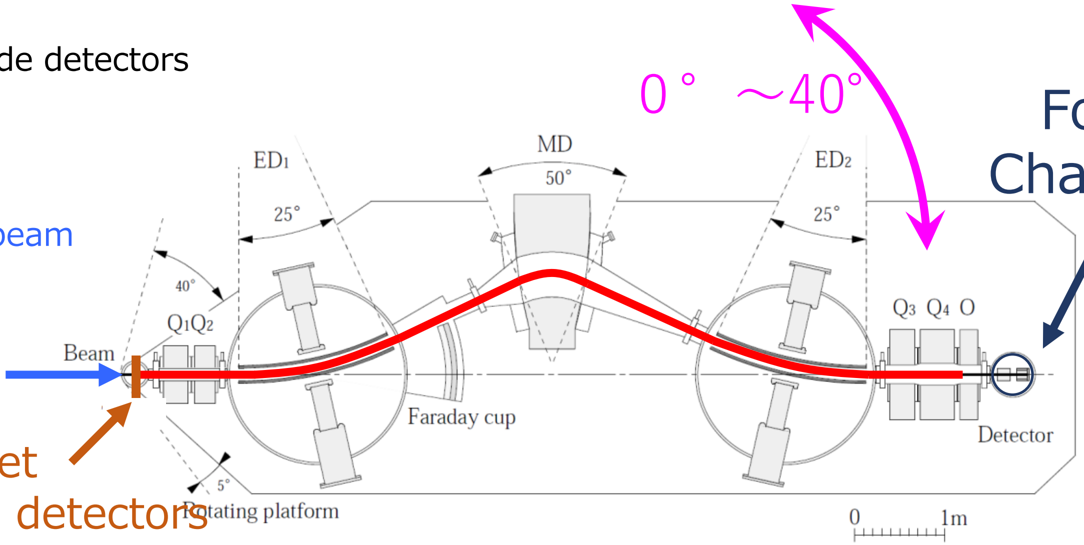
Detectors

(e.g.) $^{209}Bi(^{30}Si,^{26}Mg)^{213}At^{*} \rightarrow {}^{213\text{-}xn}At \rightarrow \alpha$ decay



PIN diode detectors

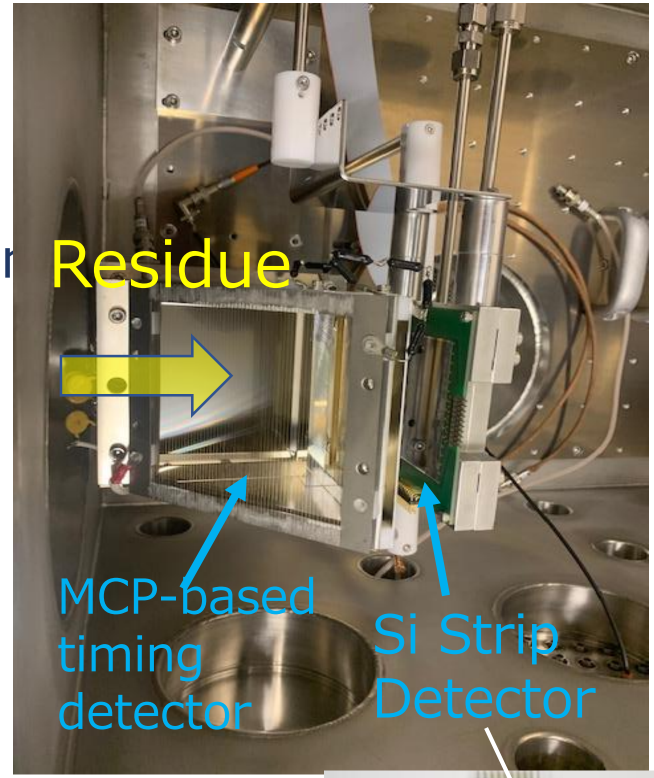
^{30}Si beam

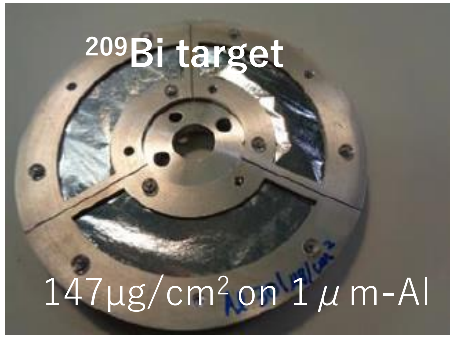


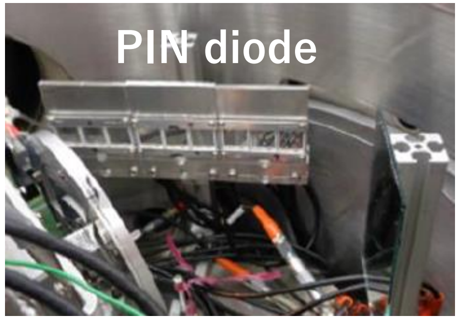
^{209}Bi Target
PIN diode detectors
Elastic monitor

Focal Chamber

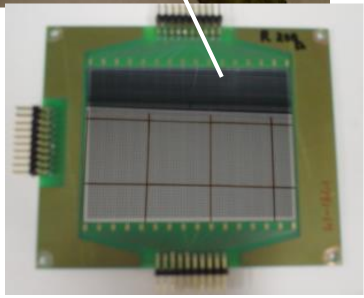
RMS@JAEA Tandem







Place an MCP-based timing detector to distinguish implant residual nuclei from alpha decay



Kinematics and RMS setting

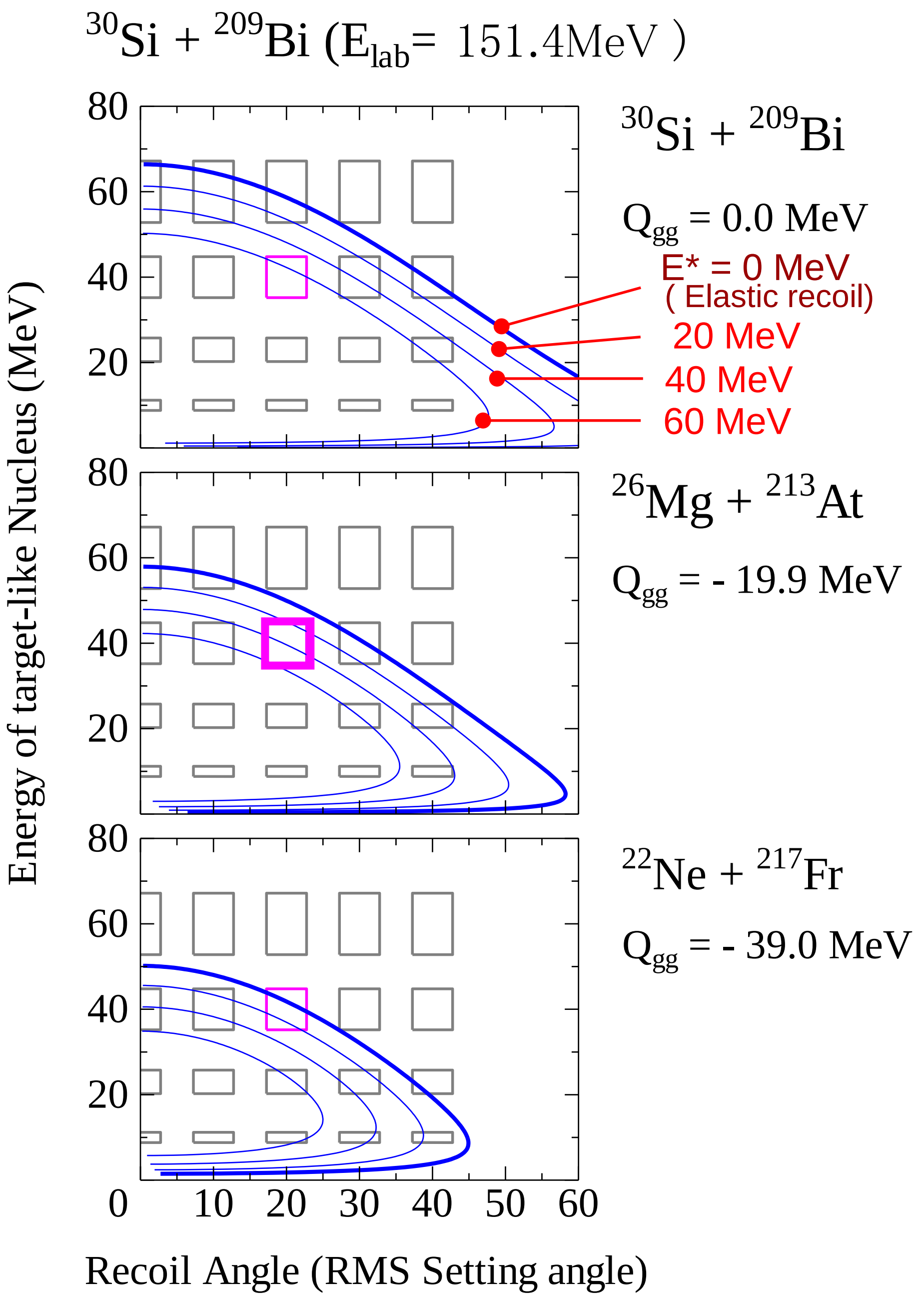
The blue line shows the example of kinetic-energy of a recoiled ERs produced in the MNT reactions as a function of its emission angle
(= RMS setting angle).

The recoil energies depends on the MNT channel (Q_{gg}) and excitation energy.
Here, curves for elastic/inelastic channel ($^{30}Si+^{209}Bi$) and MNT channels ($^{26}Mg+^{213}At$, $^{22}Ne+^{217}Fr$) are shown with different excitation energies of 0, 20, 40, and 60 MeV.

The squares indicate the examples of the RMS setting, with the angular and energy range accepted by the RMS

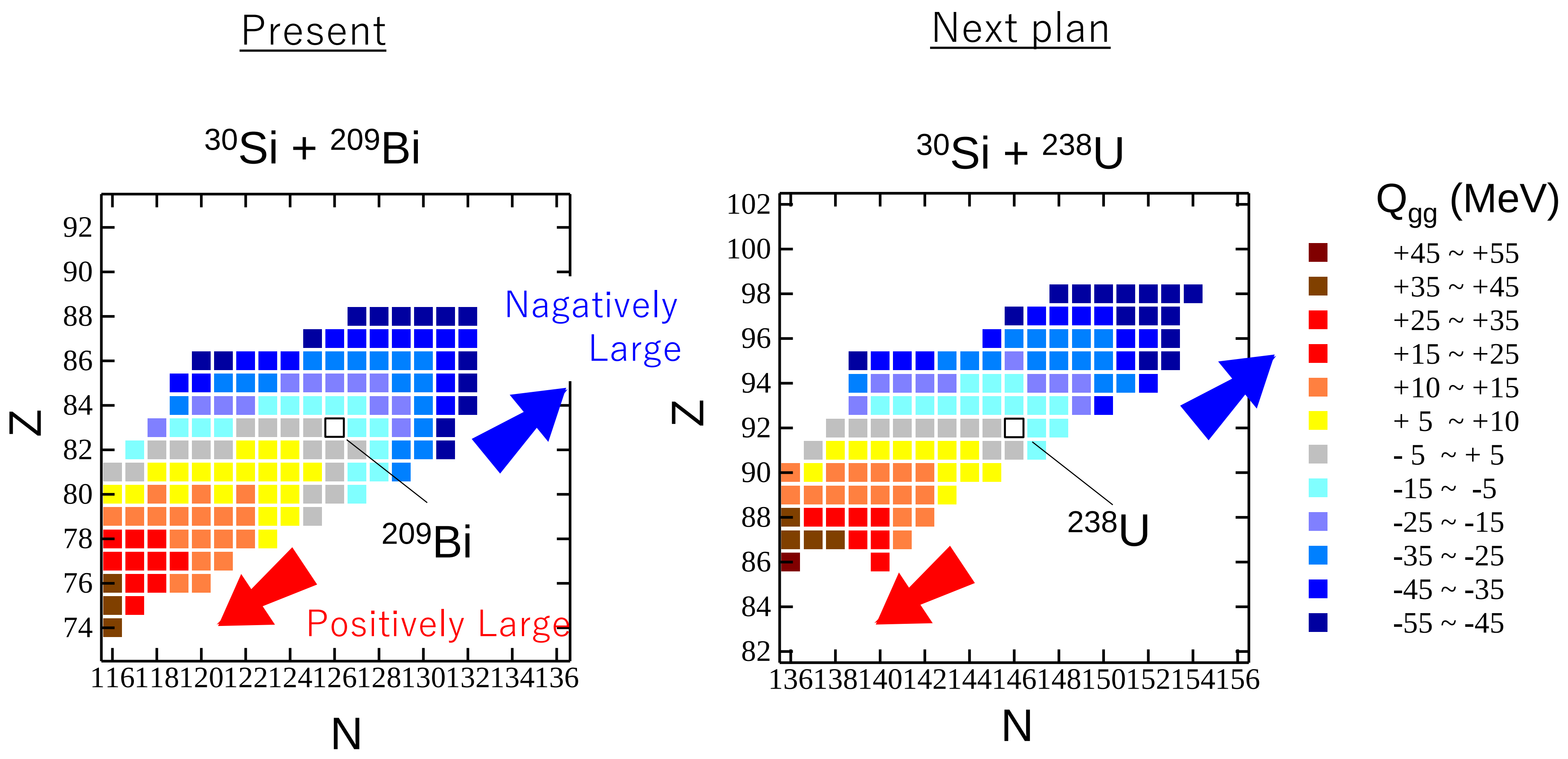
Since the mass acceptance is as large as ±4%, evaporation residues of different masses can be transported through the RMS. For example, when the mass center is set at m_{00} =213, residues from 204 to 222 can be detected.
Depending on the MNT channel (Q_{gg}), ERs originating from the different excitation energy of CN will be transported.

RMS mass setting
m_{00} =213 u
Acceptance (±4%) → 204 - 222 u



Q_{gg} of MNT

Q-value of the MNT reaction is negatively large when heavier nuclei than the target nucleus is produced.



Digital DAQ system

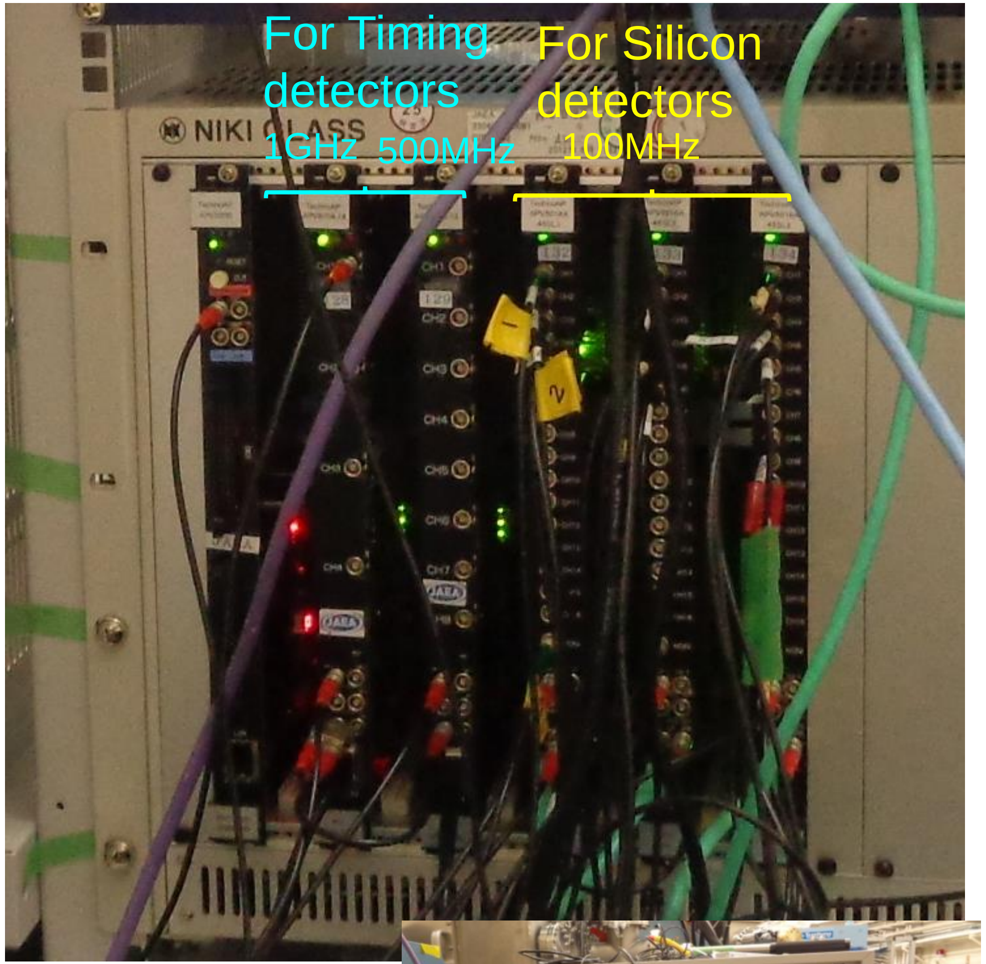
We developed a FPGA based digital data acquisition system,.

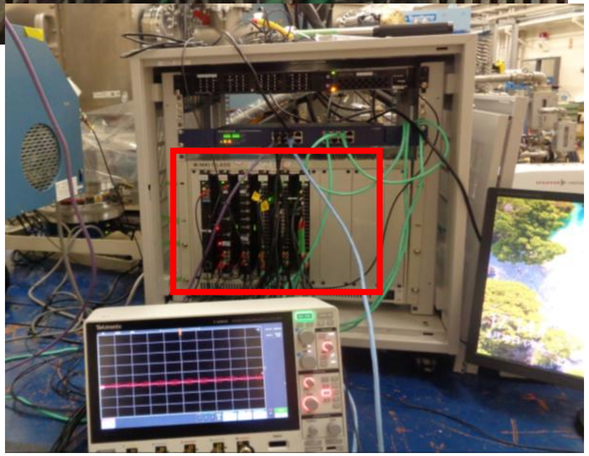
(1)For silicon detector (Silicon strip detector, Si PIN diode, ···)
- 100 MHz, 16 bit, 16ch, 100 kcps/ch
- pile up detection, wave recording, signal-polarity judgement

(Techno AP, APV8016A)

(2) For timing detector (MCP detector, ..)
- 1 GHz, 14 bit, 8 ch
- pile up detection, wave recording

(Techno AP, APV8108-14)

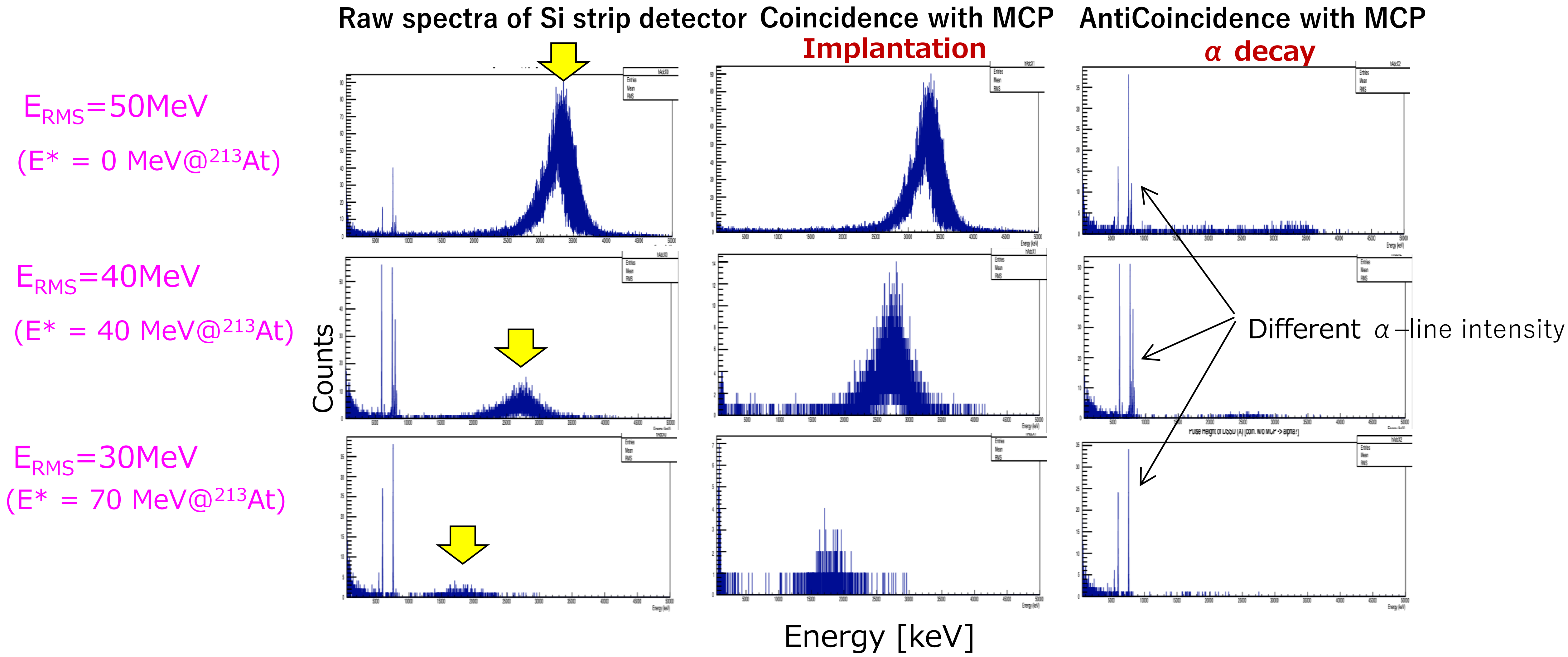




Scanning the kinetic energy of ERs through RMS

$^{30}Si + ^{209}Bi$
$E_{beam}=1.03*V_{Coulomb}$
$\theta_{RMS} = 20°$

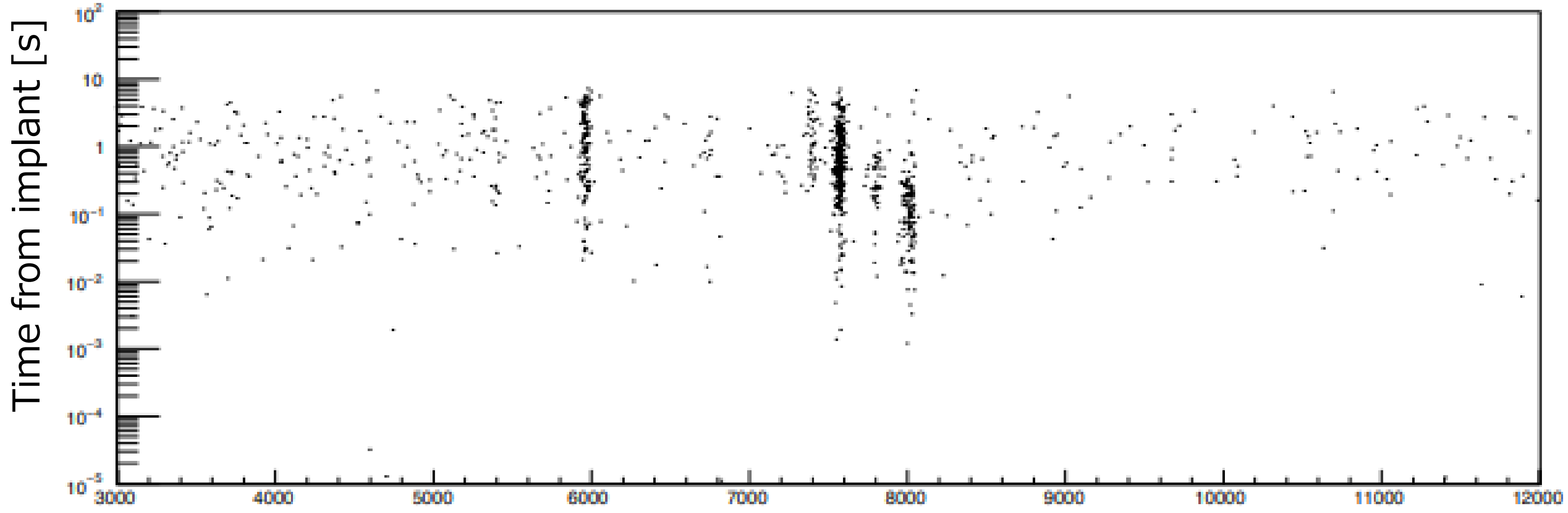
Kinetic-energy of the RMS setting is changed. We found a significant change of the α-lines with energy, showing that nuclides from different MNT channel or initial excitation energy are produced.



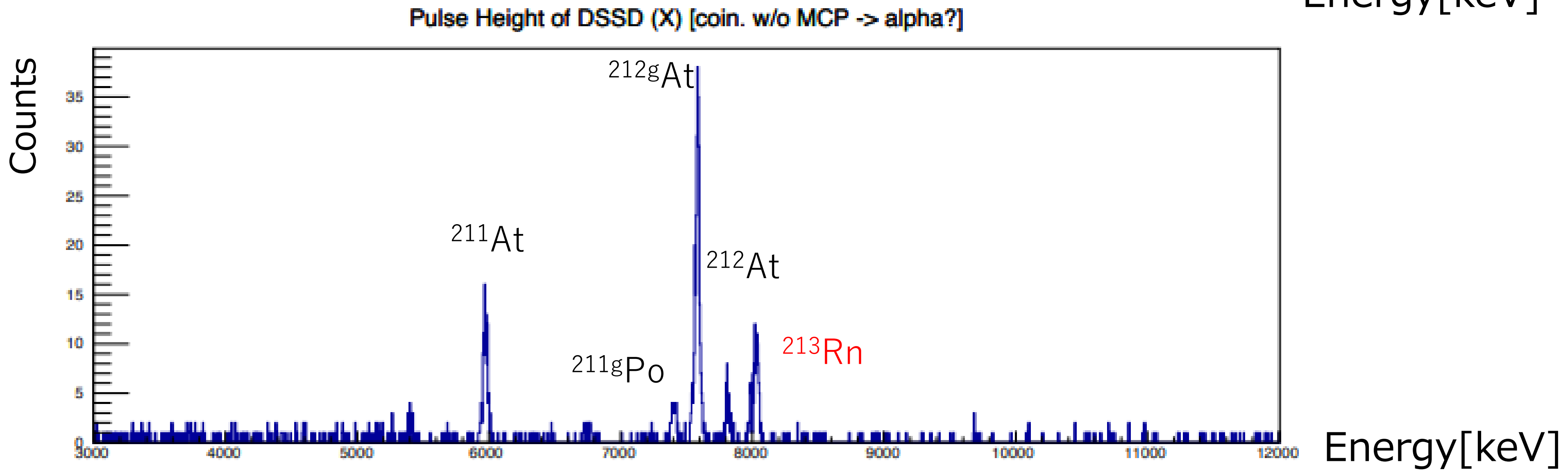
Identification of nuclides

^{30}**Si +** ^{209}**Bi**
$E_{beam}=1.03*V_{Coulomb}$
$\theta_{RMS} = 20°$

Correlation between implanted recoil and α–decay was found to identify the produced nuclides.



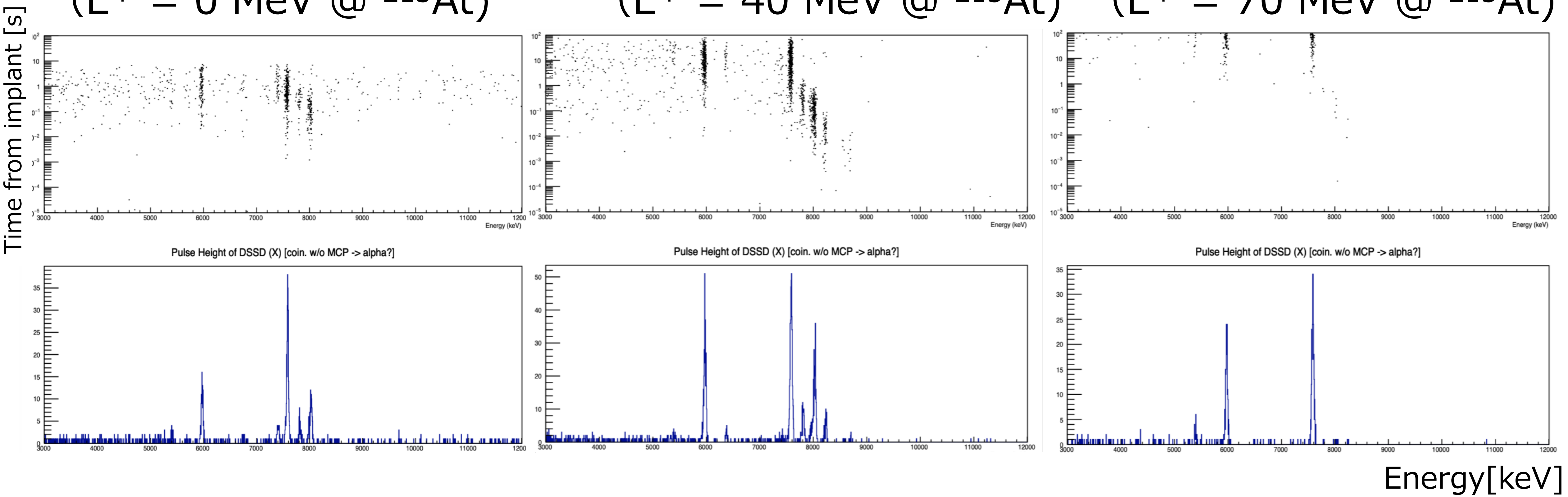
Projection



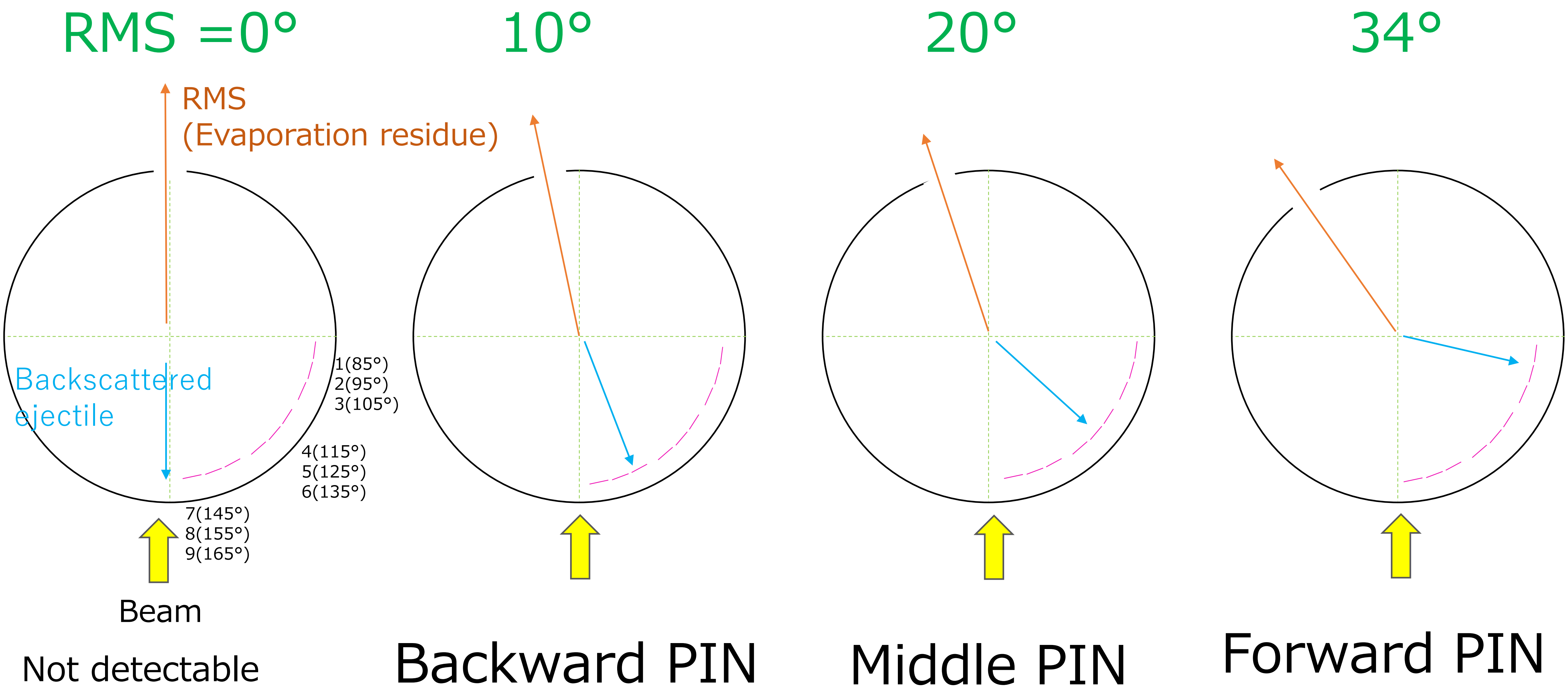
Identification of nuclides
◇ Kinetic Energy(E_{RMS})dependence

$^{30}Si + ^{209}Bi$
$E_{beam}=1.03*V_{Coulomb}$
$\theta_{RMS} = 20°$

E_{RMS}=50MeV (E* = 0 MeV @ ^{213}At) | E_{RMS}=40MeV (E* = 40 MeV @ ^{213}At) | E_{RMS}=30MeV (E* = 70 MeV @ ^{213}At)



Coincidence of ERs with backscattered ejectile nucleus



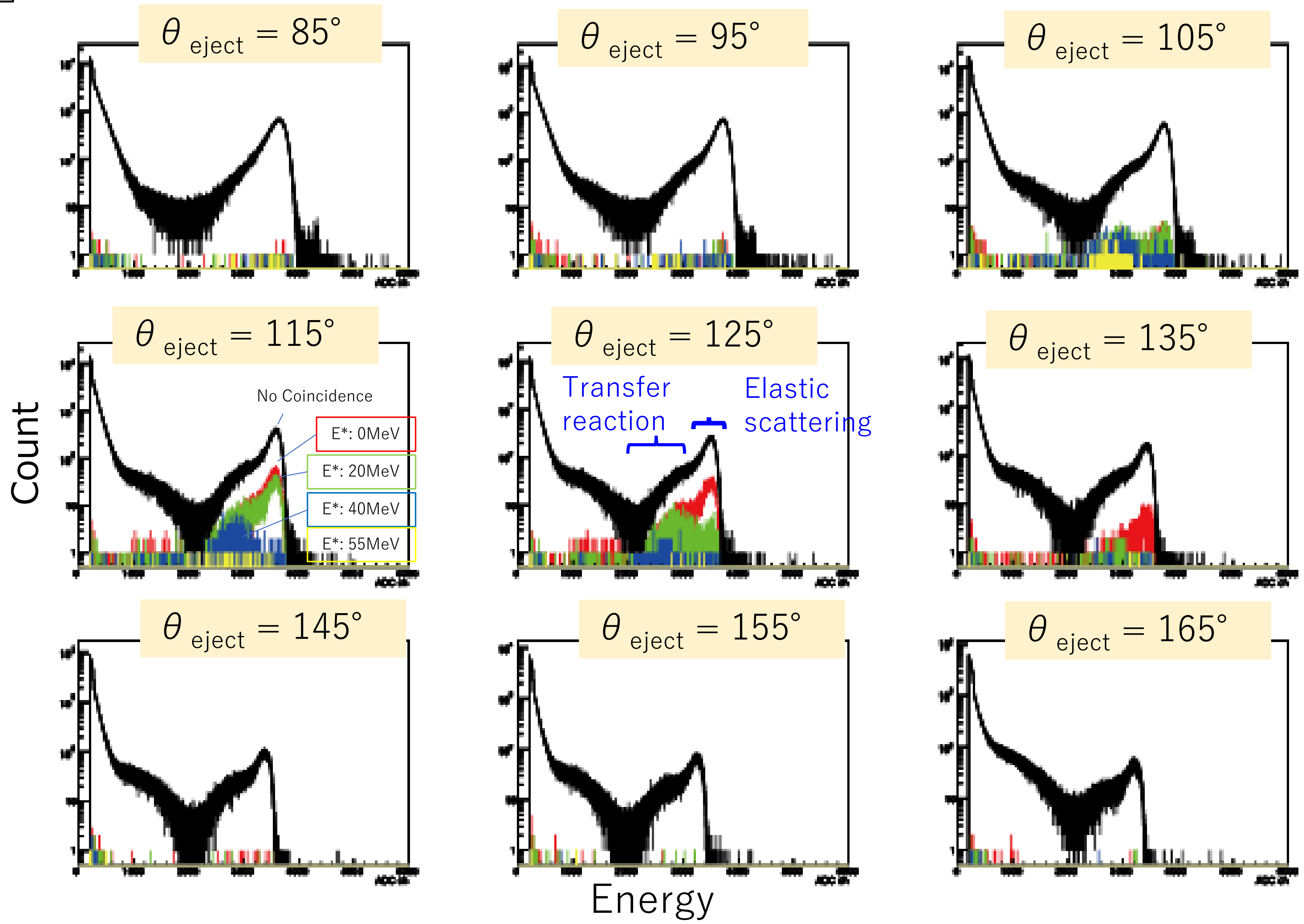
PIN diode detector Energy Spectrum

Backscattered ejectile energy spectra. Colored spectra are events coincided with ERs through the RMS.

$^{30}Si + ^{209}Bi$
$E_{beam}=1.03*V_{Coulomb}$
θ_{RMS} = 20 °

Black: All

(color) Coincidence with
Red: E_{RMS}= 50MeV
Green: E_{RMS}= 46MeV
Blue: E_{RMS}= 40MeV
Yellow E_{RMS}= 35MeV



When the kinetic-energy setting of the RMS is small, RMS accept nuclei produced only by the MNT reaction, and the elastic recoil nucleus is not transported.
This condition is attained when very heavy nuclei than the target nucleus are produced (negatively large Qgg)

(Color)
Coincidence with implanted Recoil

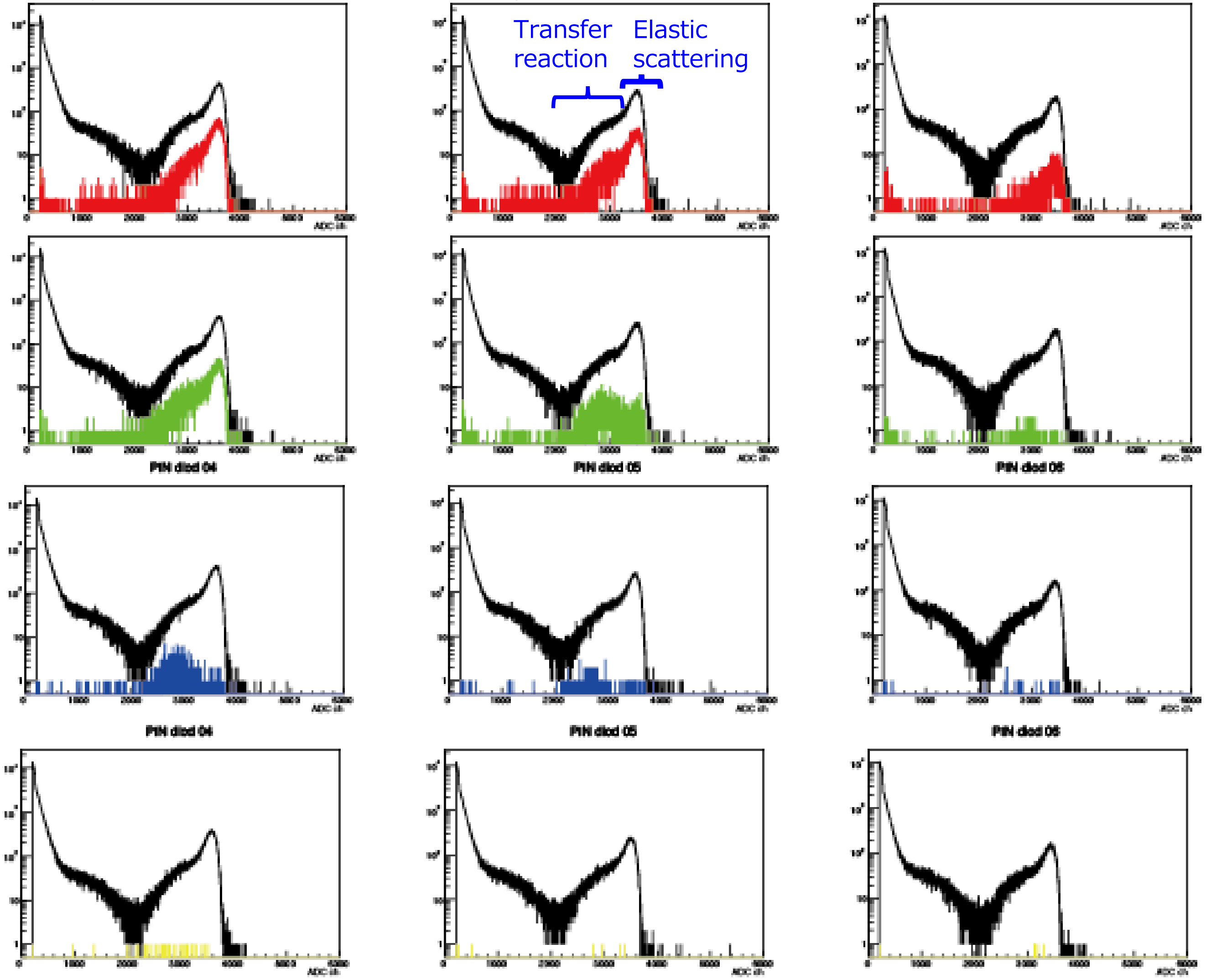
θ_{eject} = 115° | θ_{eject} = 125° | θ_{eject} = 135°

E_{00} = 50 MeV
(E^* = 0 MeV)
M_{00} = 213
Q_{00}^+ = 21+

E_{00} = 46 MeV
(E^* = 20 MeV)
M_{00} = 213
Q_{00}^+ = 21+

E_{00} = 40 MeV
(E^* = 40 MeV)
M_{00} = 213
Q_{00}^+ = 20+

E_{00} = 35 MeV
(E^* = 55 MeV)
M_{00} = 213
Q_{00}^+ = 18+



Ejectile energy (ch)

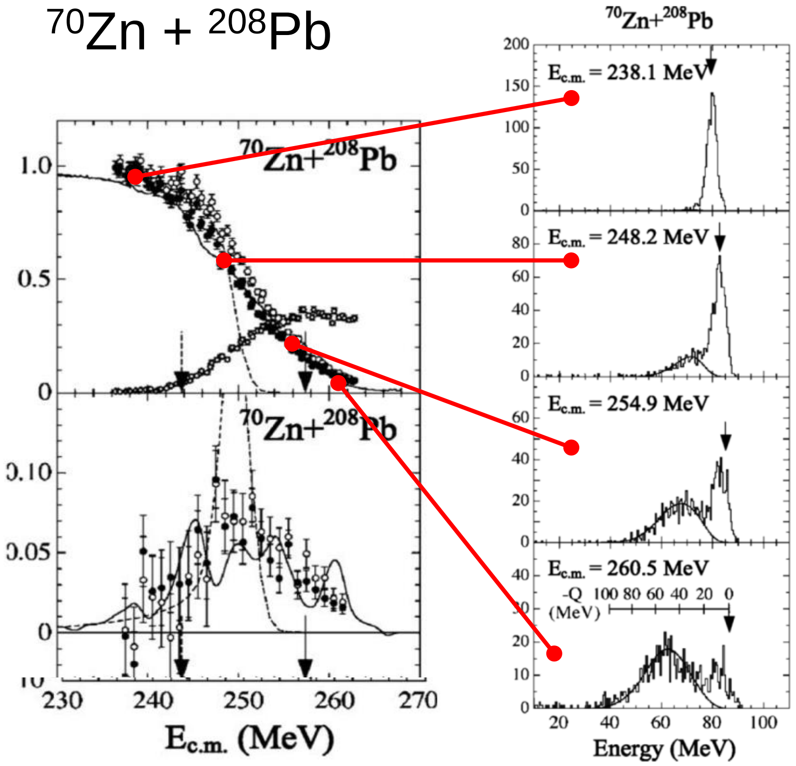
^{30}Si + ^{209}Bi
E_{beam}=1.03*$V_{Coulomb}$
θ_{RMS} = 20 °

Quasi-elastic (QE) and Deep-inelastic (DI) scattering in the measurement of Coulomb barrier distribution

Separation between QE and DI scattering is an important issue for the measurement of barrier distribution. Measurement of ERs at the JAEA-RMS and backscattered ejectile in coincidence offer data to unveil their origin and fraction.

✤ Measurement of ejectile nucleus at backward angle using silicon detector (JAEA)

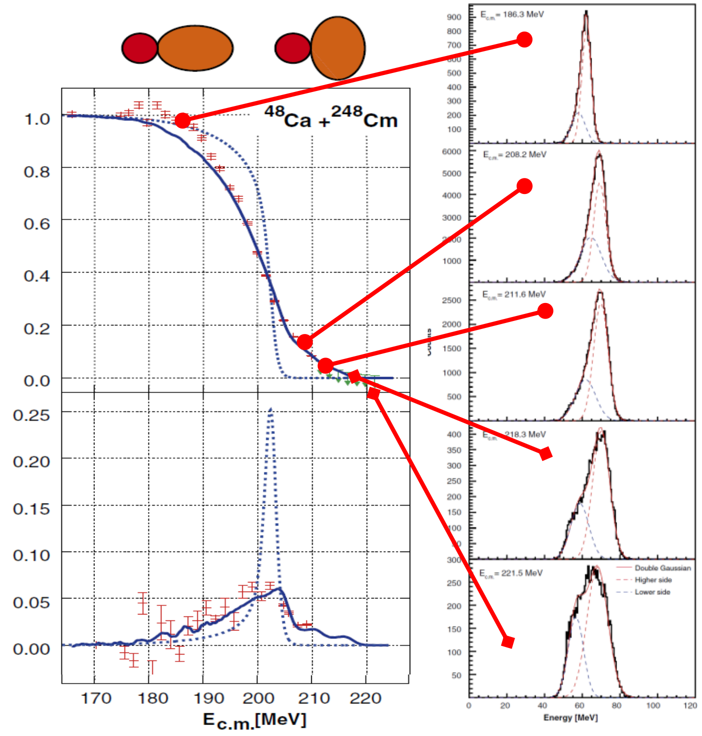
$^{70}Zn + ^{208}Pb$



S. Mitsuoka et al., Phys. Rev. Lett., 99, 182701 (2007).

✤ Measurement of Target-like Nucleus using GARIS (RIKEN)

$^{48}Ca + ^{248}Cm$



T. Tanaka et al., J. Phys. Soc. Jpn. 87, 014201 (2018).

Summary

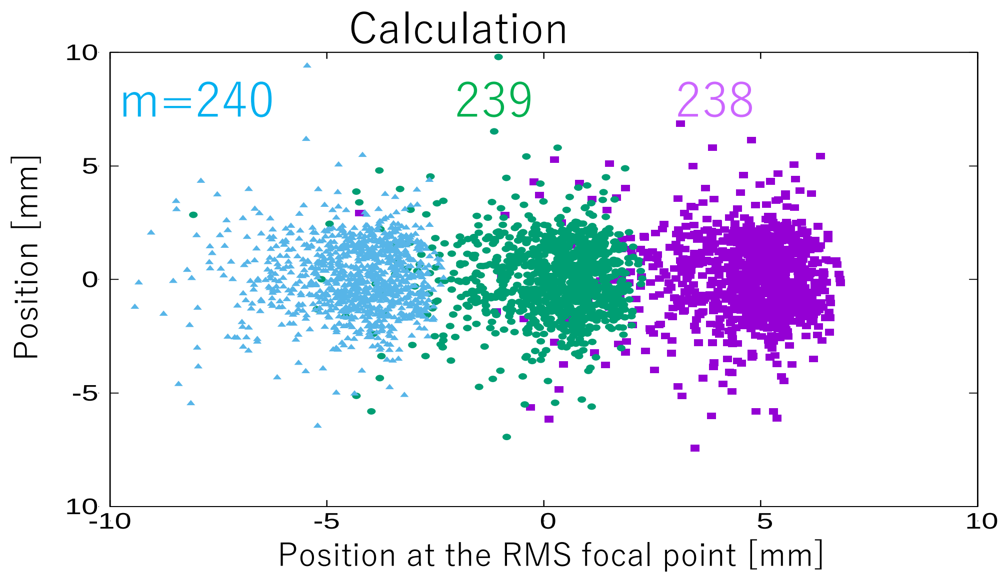
- In order to elucidate the reaction mechanism of multi-nucleon transfer reactions, we started a measurement of evaporation residue using the JAEA Recoil Mass Separator.

- For the first time, we have succeeded the online decay measurement at the focal plane, correlated with ER implantation at finite angle.

Future

- We investigate the reaction using actinide target, where fission strongly compete in the deexcitation process of the compound nucleus (effects of angular momentum is significant).

- In-flight mass separation will be attempted, which allows the identification of the mass of ERs without detecting the decay (useful for very long-lived nuclei).



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