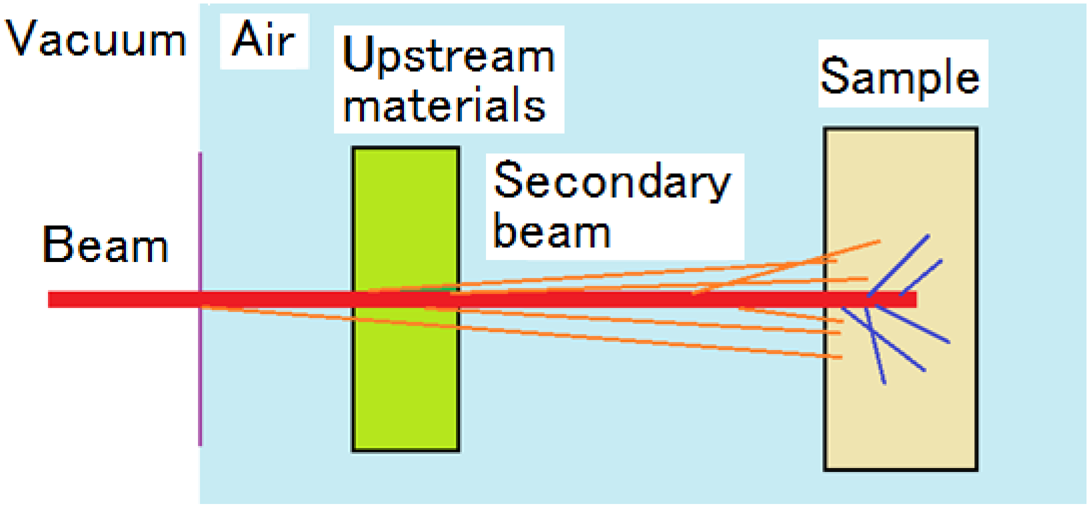
Simulation and Radiochemical Analyses of Impurity Beam in Kr beam at RIBF

July 2018

NSREC

Background

- When fast heavy-ion beam pass matter, part of the ion-beam nuclei collide with nuclei in the matter and are converted to other nuclide with nearly same velocities.
- These secondary ions contaminate the primary beam as impurity beam, and may affect beam quality (LET distribution).
- Nuclear reaction may also occur in samples.



Radiochemical analyses

- The production probabilities of impurity–beam nuclides were evaluated with radiochemical analyses.
- Test samples were irradiated and the amount of radionuclides were measured through gamma–ray analyses.
- The beam condition:

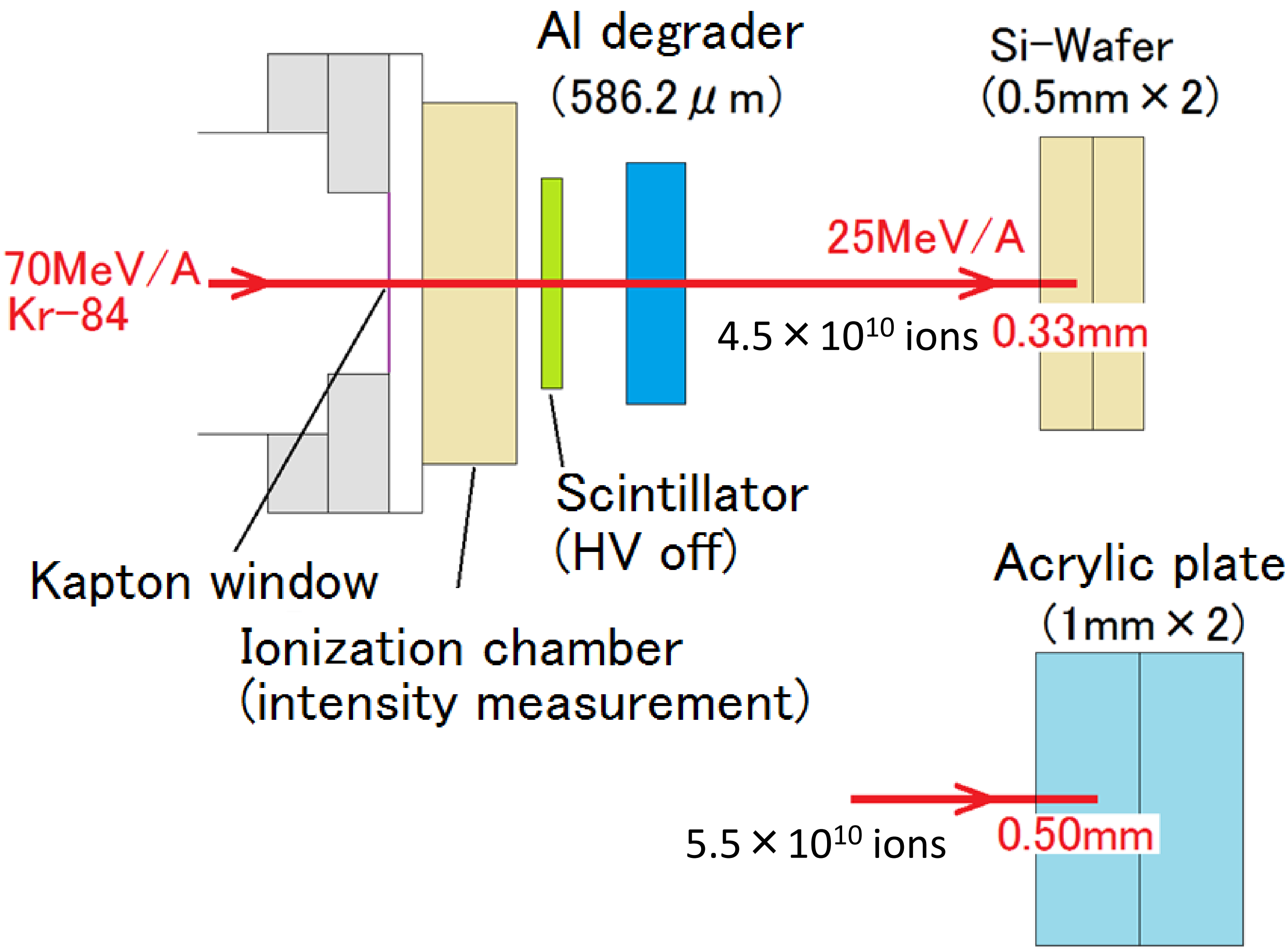
  Kr–84 beam at 70 MeV/u from accelerator

  Al–degrader thickness=586.2 μ m

  Energy of Kr–84 at Si =25 MeV/u, LET in Si =19MeV/(mg/cm^2)
- Two kinds of Test samples

  Si–wafer（0.5mm–thick, 2 plates） to simulate client's sample

  Acrylic （1mm–thick, 2 plates） for comparison
- Kr–beam is stopped in the 1st plate
- 10–minutes irradiation each
- Gamma rays were measured from 7 min to 3 months after irradiation


Al degrader
(586.2 μm)
Si−Wafer
(0.5mm × 2)
70MeV/A
Kr−84
25MeV/A
4.5 × 10^10 ions
0.33mm
Scintillator
(HV off)
Kapton window
Ionization chamber
(intensity measurement)
Acrylic plate
(1mm × 2)
5.5 × 10^10 ions
0.50mm

Identification of nuclides

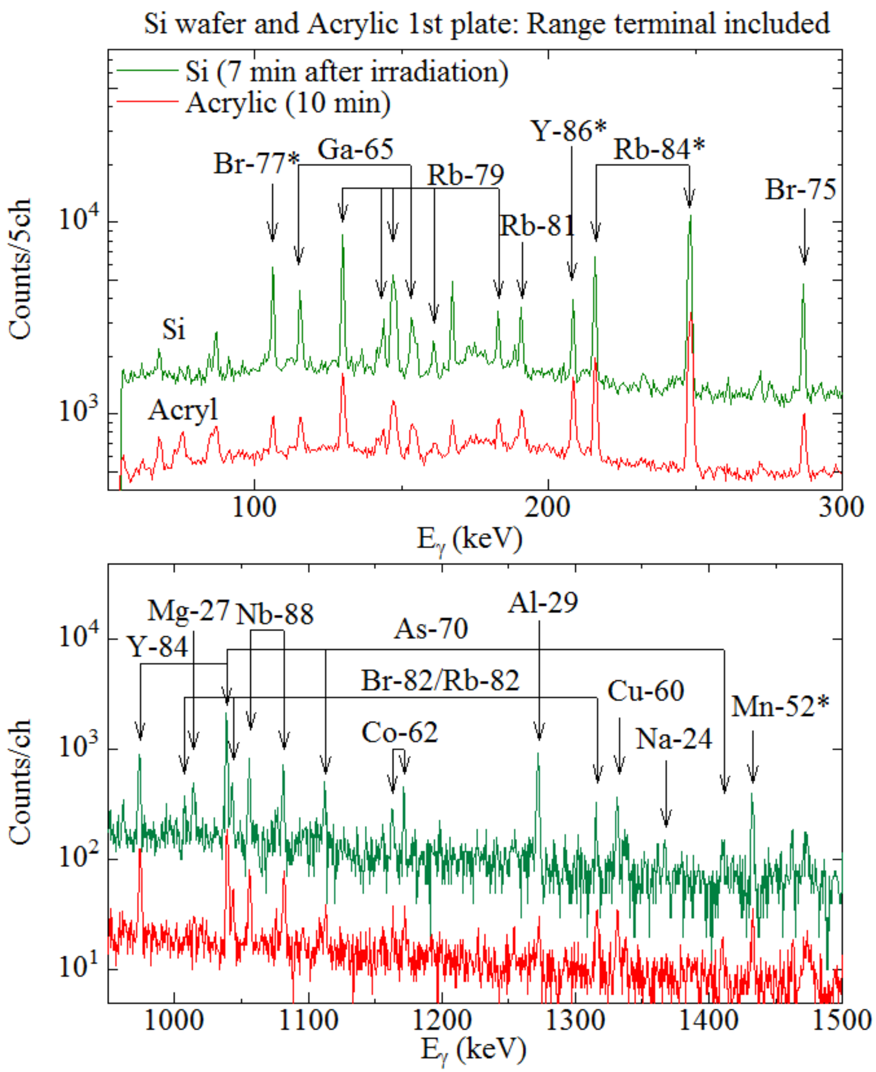
- On the basis of gamma-ray energy, half life, and branching ratio
- In acrylic, 49 nuclides from Na to Mo, in Si wafer 61 nuclides from Na to Ag (isomers included)

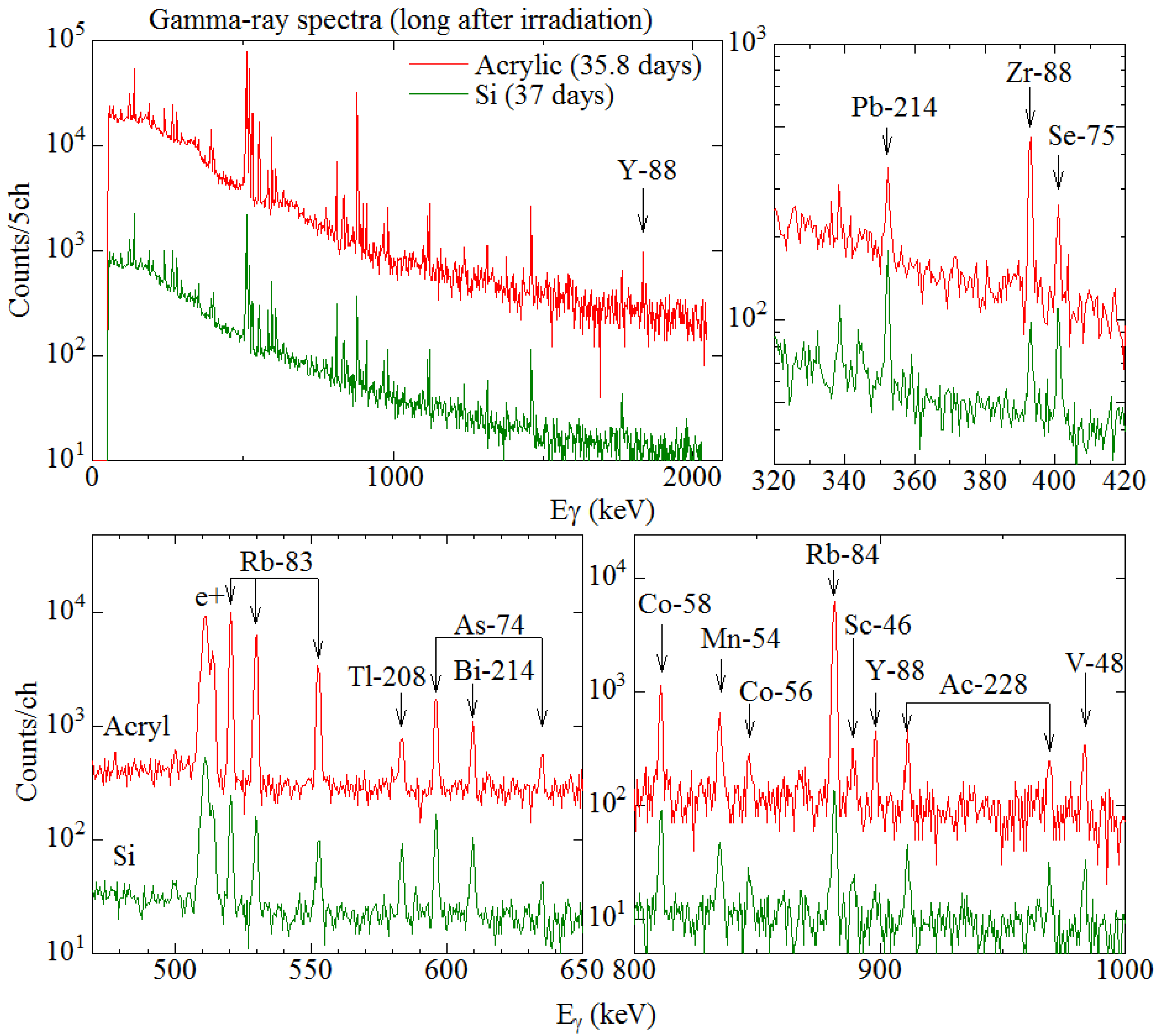
Production probabilities of RI

- Decay curve is fitted to measurements for each nuclide（cascade corrections if necessary）
- Decay curve is extrapolated to irradiation-end time, radioactivity⇒number of RI nuclei
- Correction for decay during irradiation ⇒ Number of produced RI nuclei during 10 min of irradiation
- Number of produced RI nuclei ÷ number of Kr ions

  = RI production probability

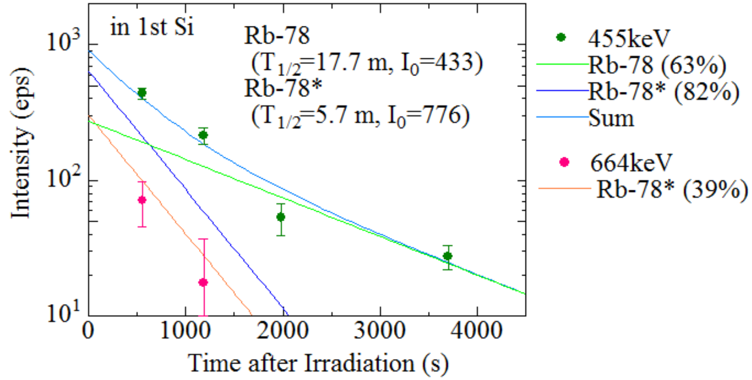
Gamma-ray spectra

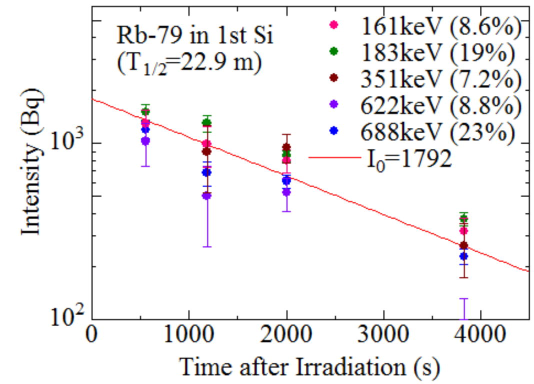


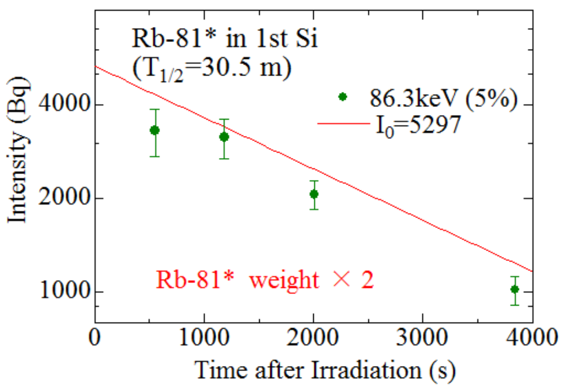


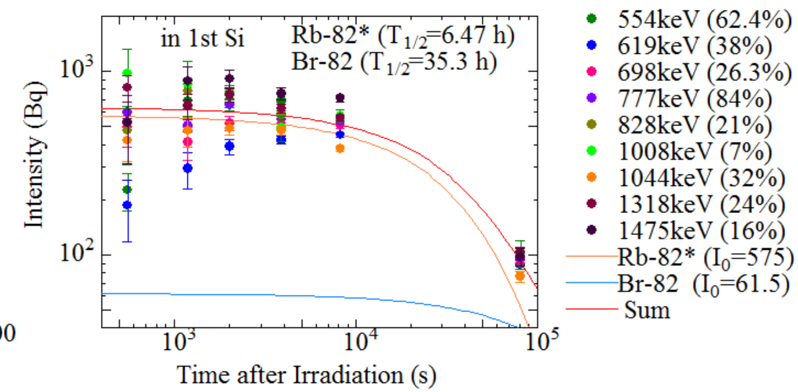
Gamma-ray spectra (long after irradiation)
Acrylic (35.8 days)
Si (37 days)
Counts/5ch
Y-88
Pb-214
Zr-88
Se-75
Eγ (keV)
Counts/ch
Acryl
Si
e+
Rb-83
Tl-208
As-74
Bi-214
Co-58
Mn-54
Co-56
Rb-84
Sc-46
Y-88
Ac-228
V-48
Eγ (keV)

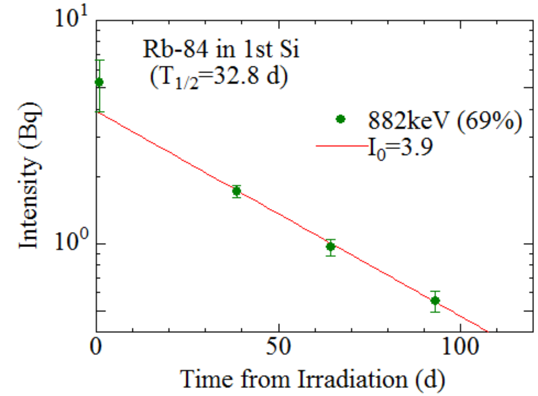
Examples of Decay curves Rb isotopes in Si

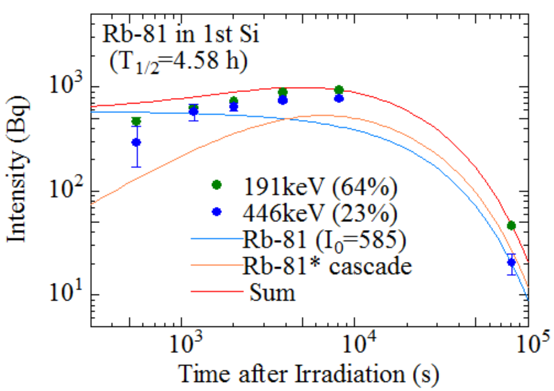


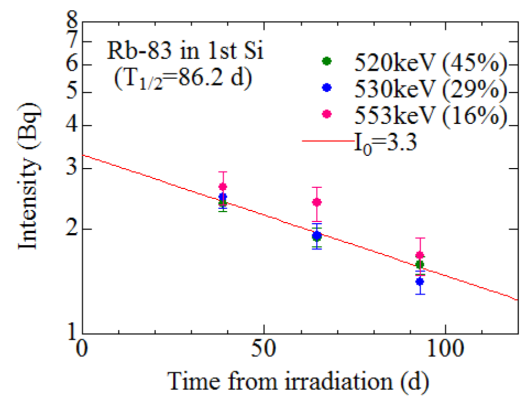


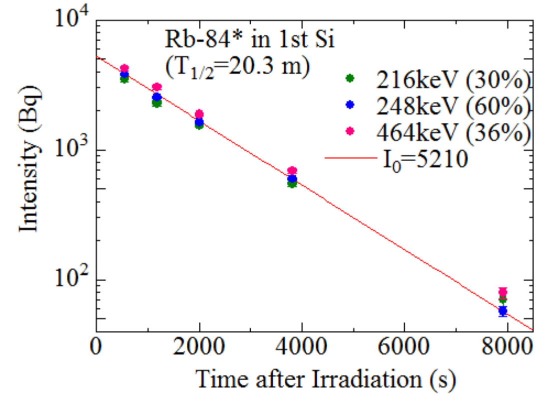




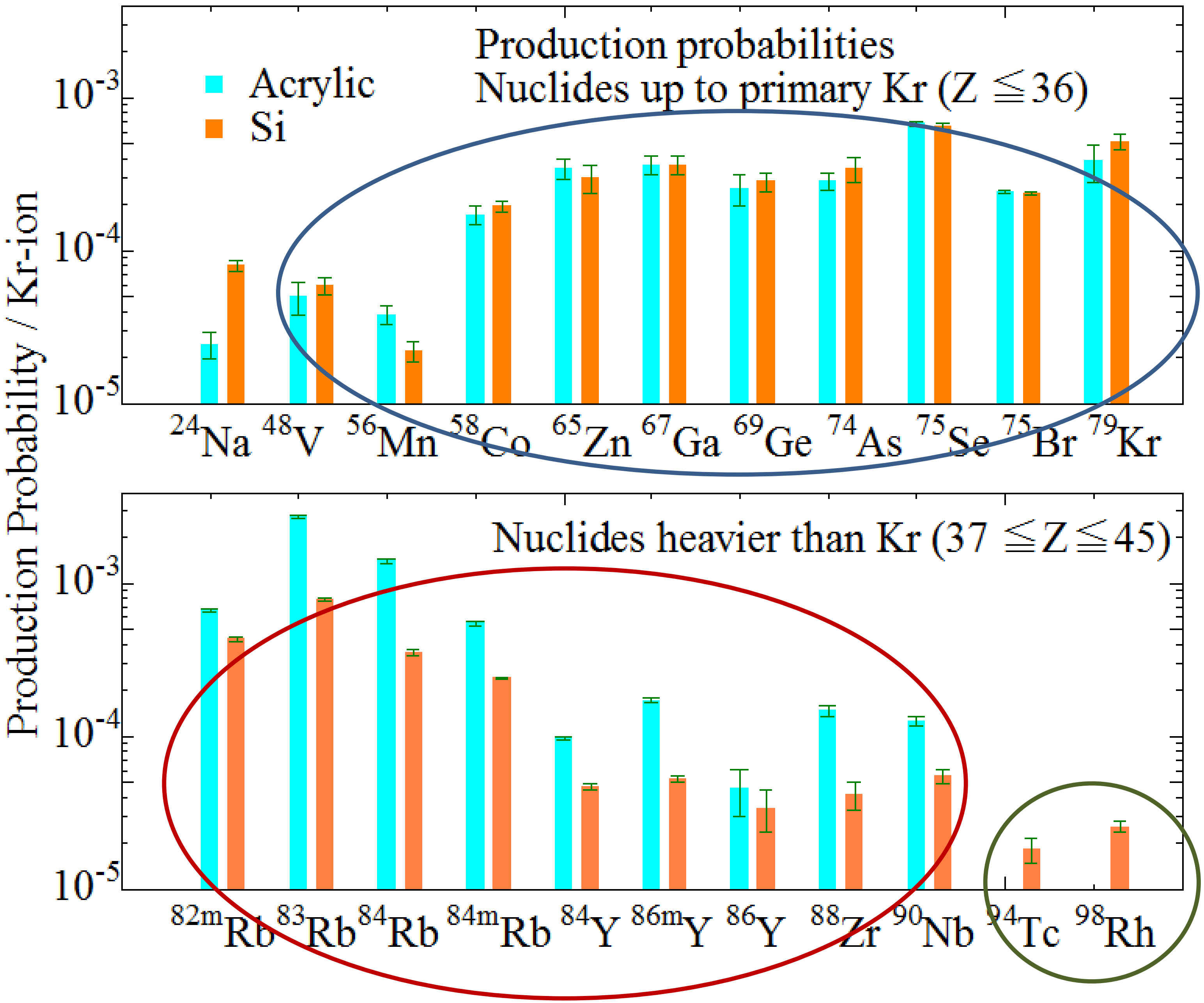




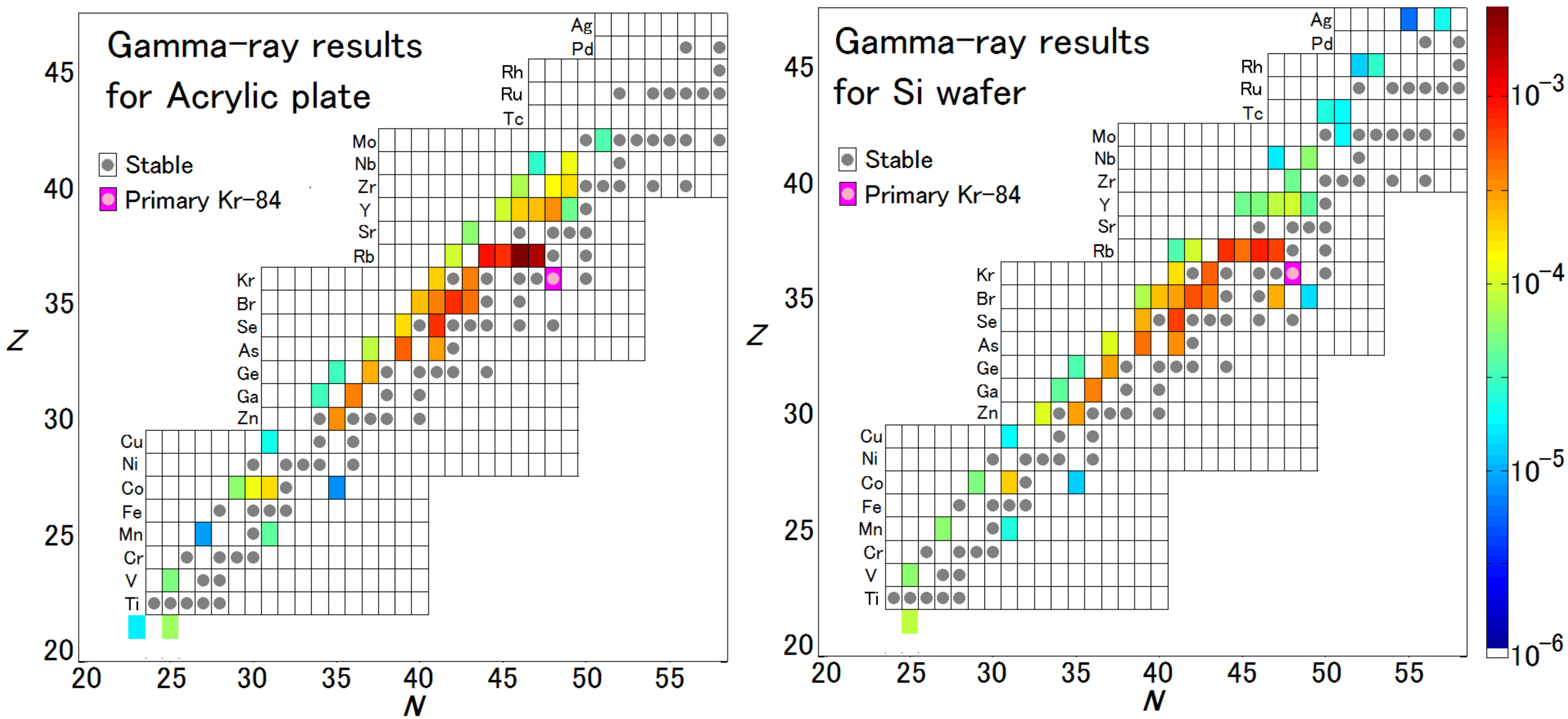




Probability of radionuclides production



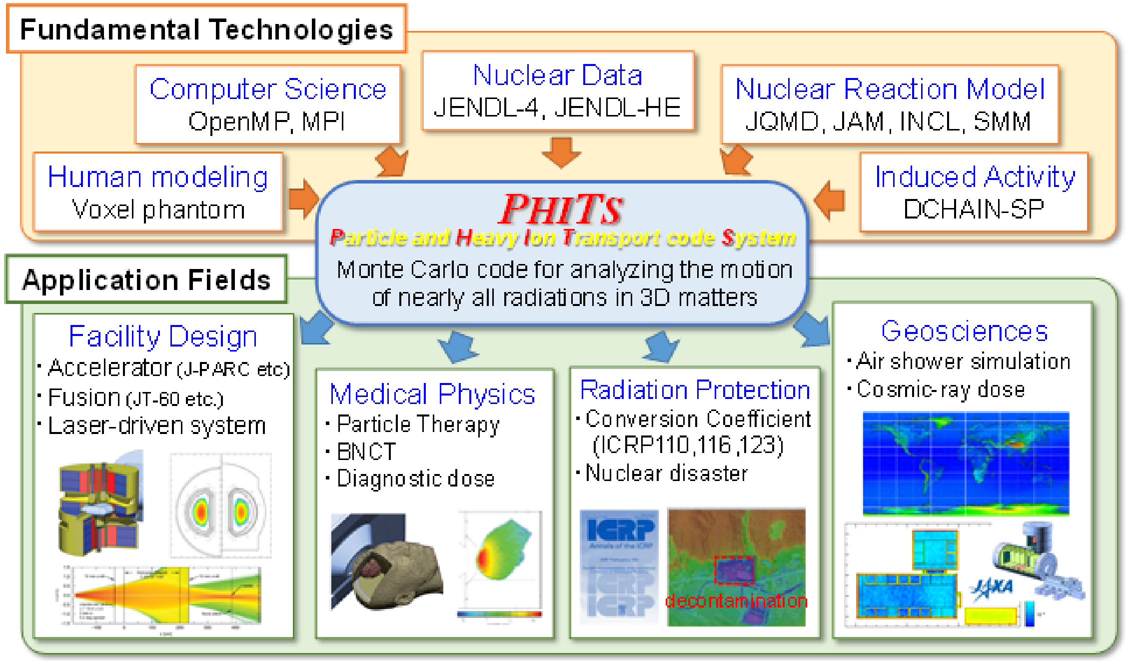
Probability of radionuclides production



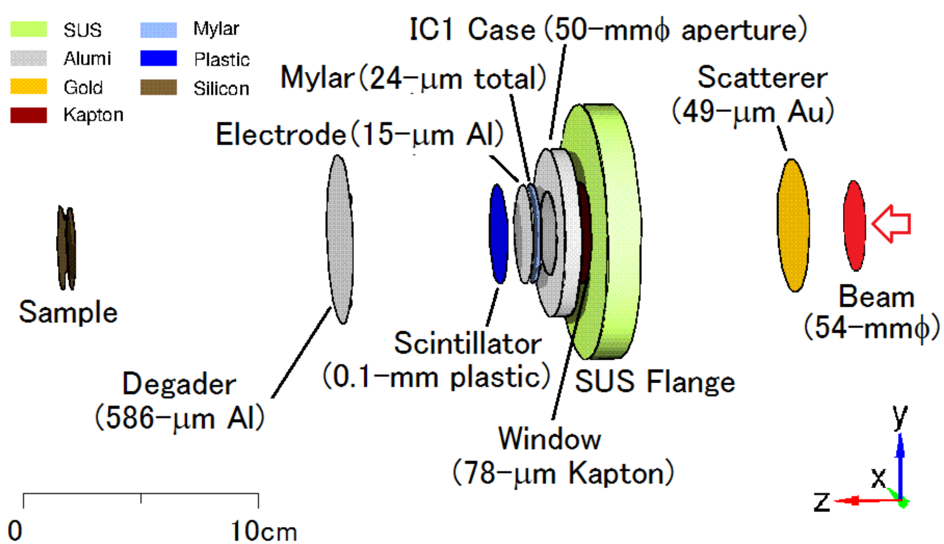
PHITS

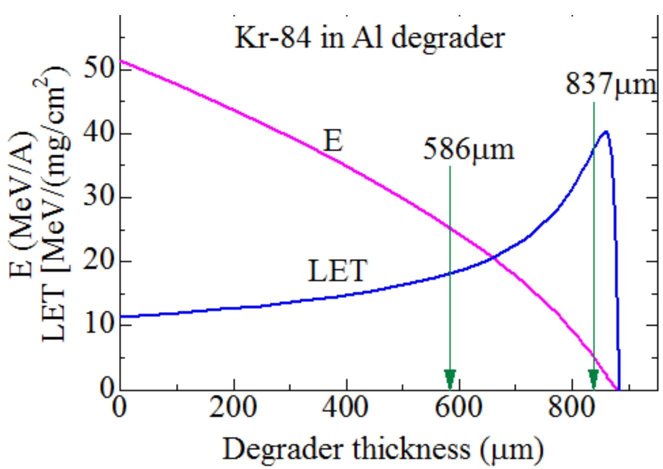
- Multi-Purpose Particle and Heavy Ion Transport code System
- PHITS is a general purpose Monte Carlo particle transport simulation code developed under collaboration between JAEA, RIST, KEK and several other institutes. It can deal with the transport of all particles over wide energy ranges, using several nuclear reaction models and nuclear data libraries.
- PHITS can support your researches in the fields of accelerator technology, radiotherapy, space radiation, and in many other fields which are related to particle and heavy ion transport phenomena.

https://phits.jaea.go.jp/index.html



Setup

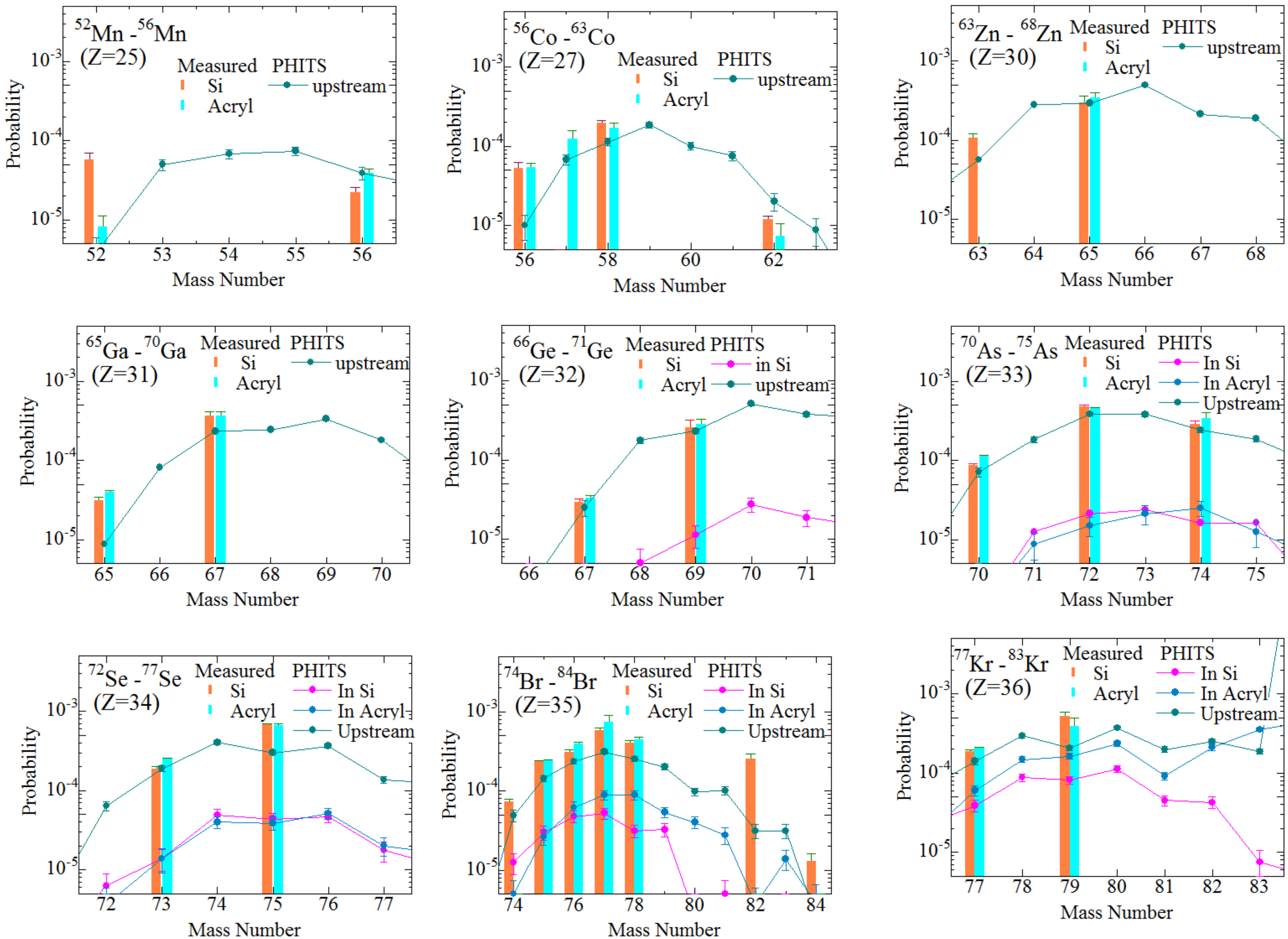




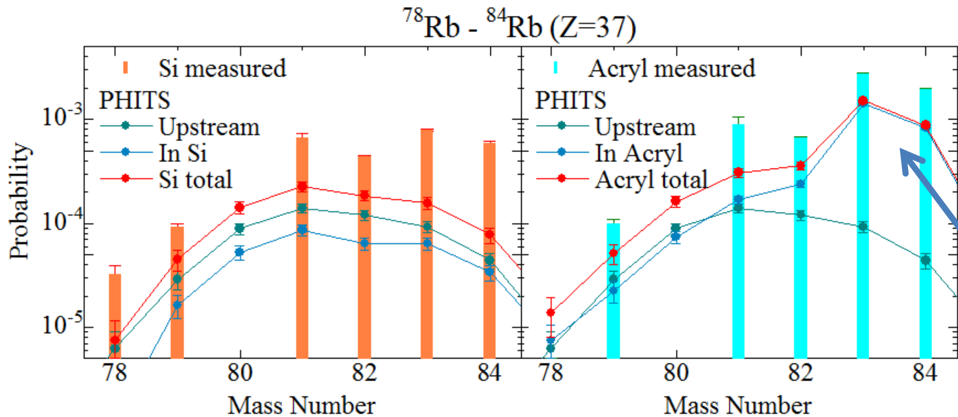
- Si-wafer (5cm or 10cm -diameter, 10μm-thick) is placed
- From left, a Kr-beam with 70mm or 54mm-diameter comes.
- Nuclide, intensity, energy distribution, LET of ions that impinge Si-wafer
- Degrader thickness varied

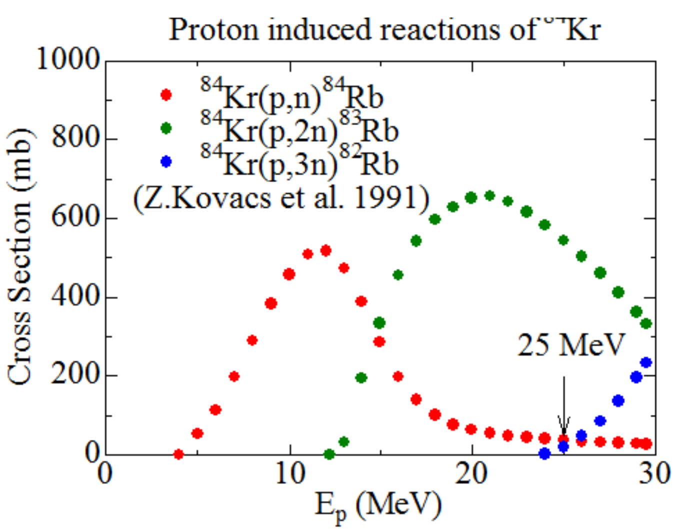
Degrader thickness (μm)	0	586	837
LET in SI MeV/(mg/cm^2)	12	19	38

Measurement and PHITS (Z=25-36)



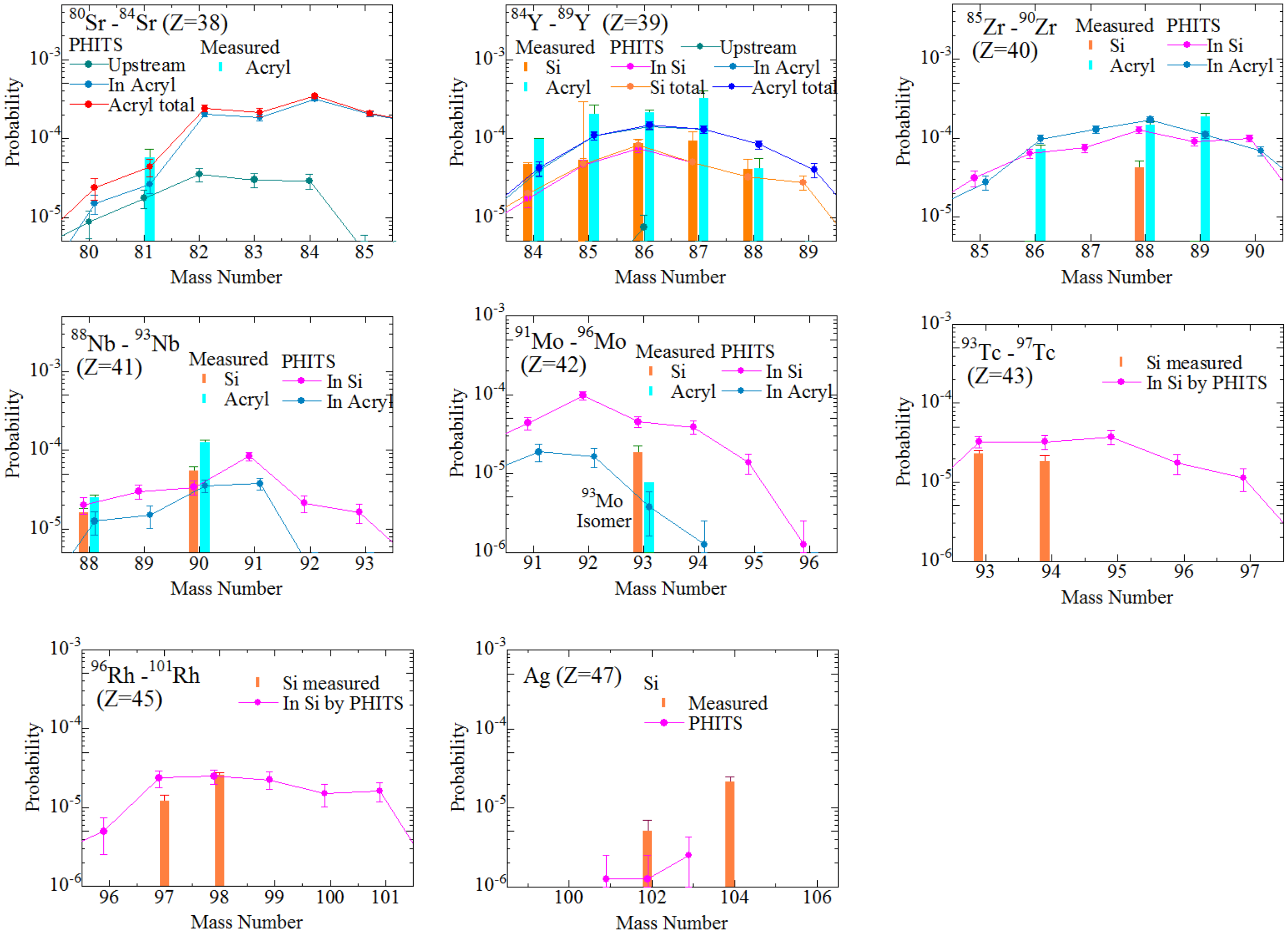
Measurement and PHITS
Rb-isotopes (Z=37)



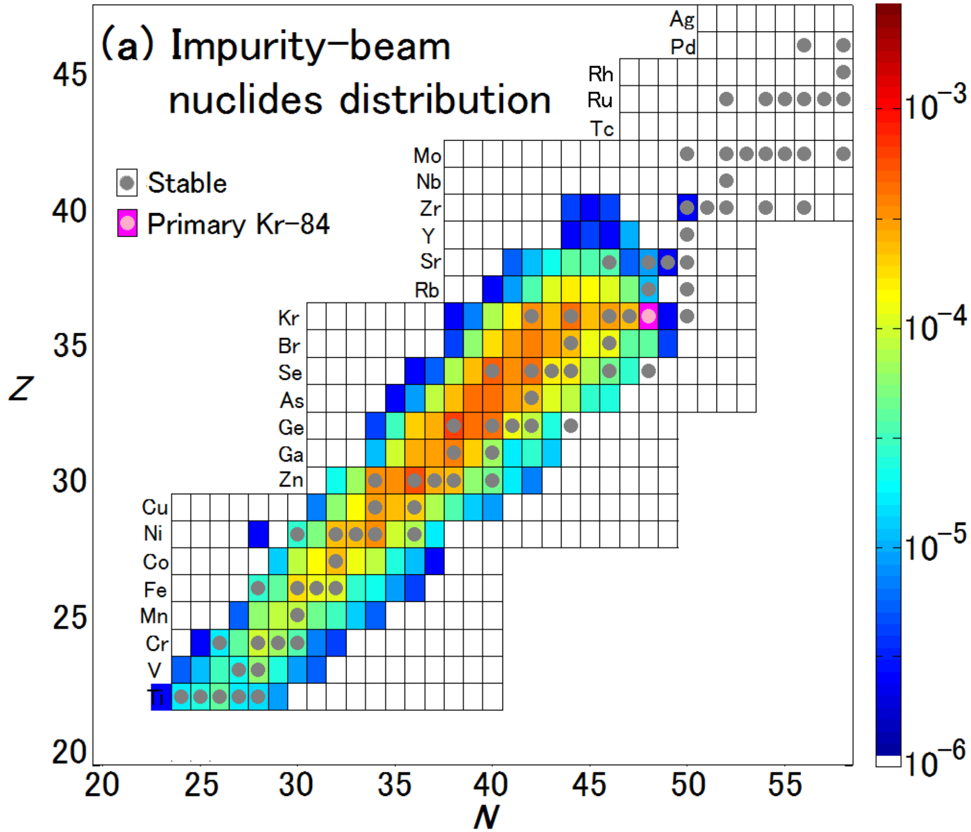


^{84}Rb and ^{83}Rb produced by inverse kinematics
^{84}Kr(p,n), (p,2n) reactions with hydrogen in acrylic

Measurements and PHITS (Z=38-45)

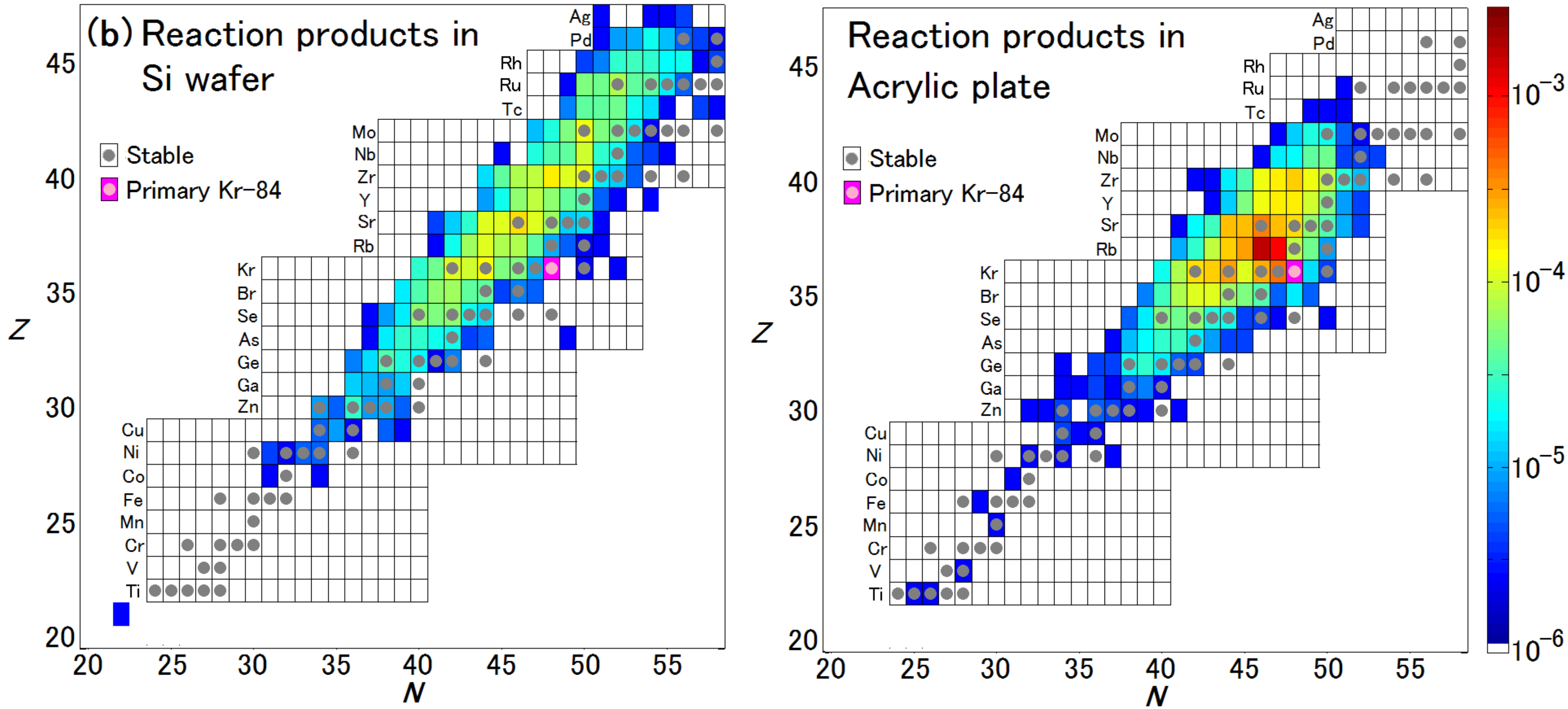


Impurity beam nuclides



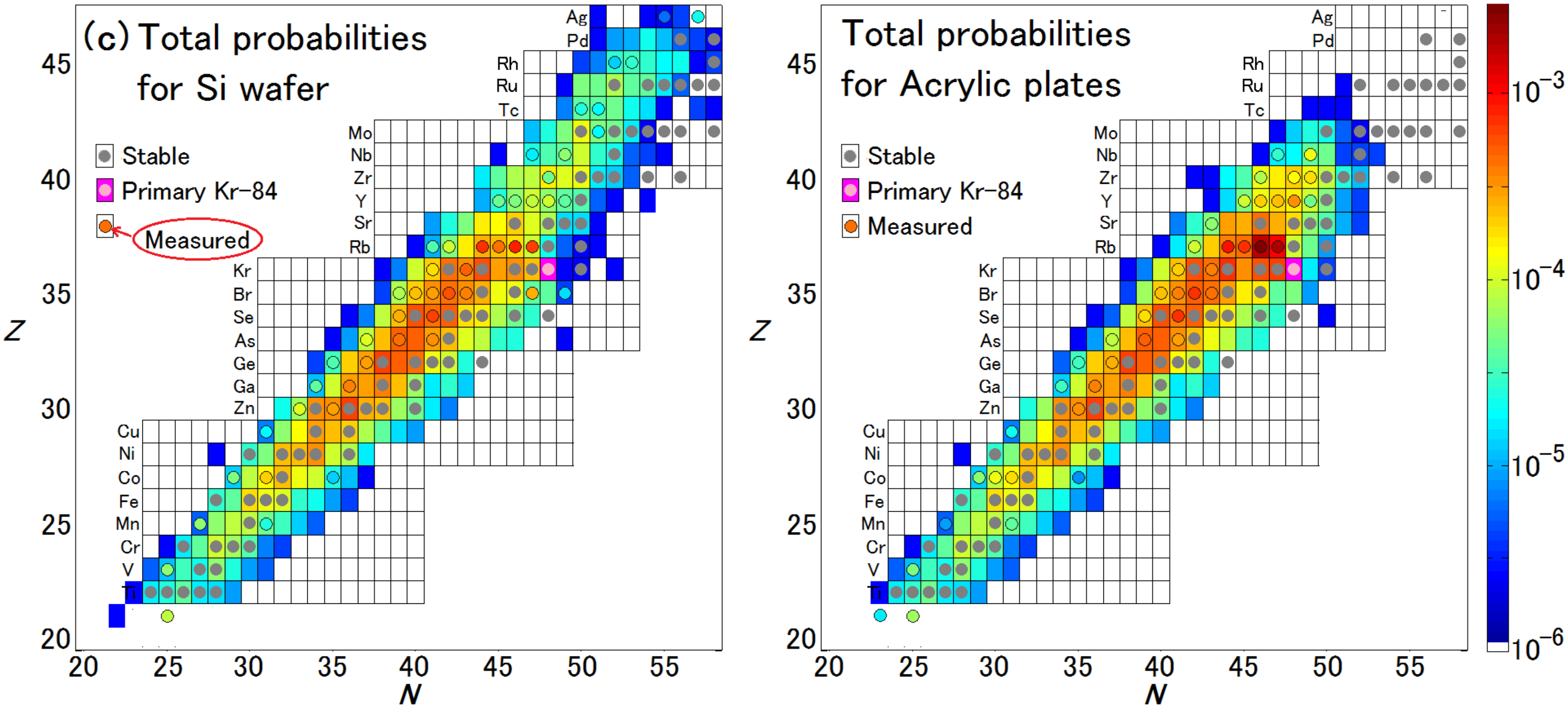
Impurity beam consists mainly of nuclides with Z ≤ 36.

Nuclides produced in the samples



Nuclides produced in Si are more broadly distributed than those in acrylic.
Rb isotopes are markedly produced in acrylic by the inverse (p,xn) reactions.

Total probabilities of nuclides in samples

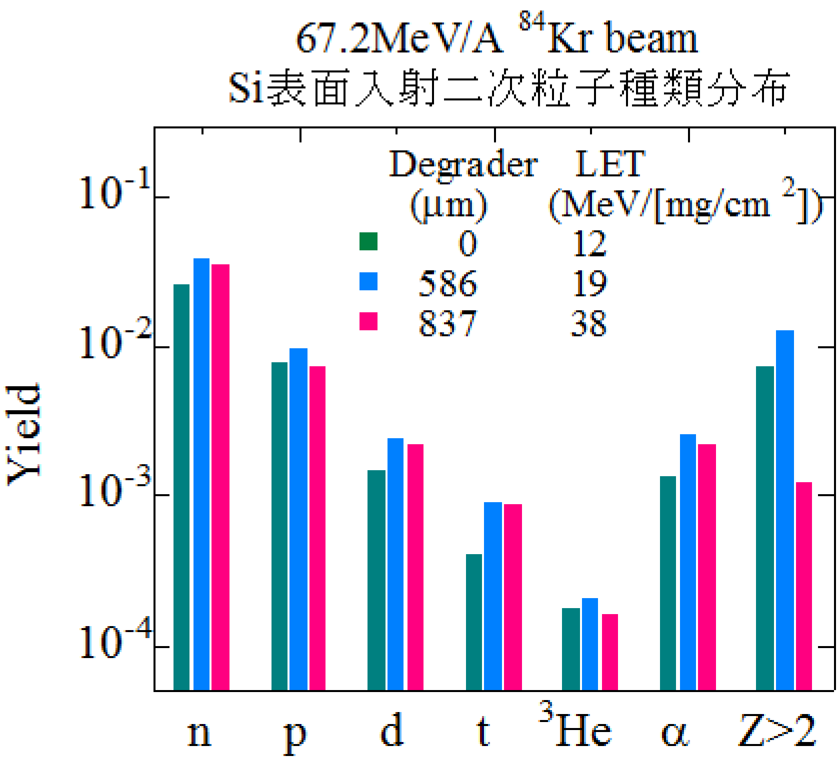


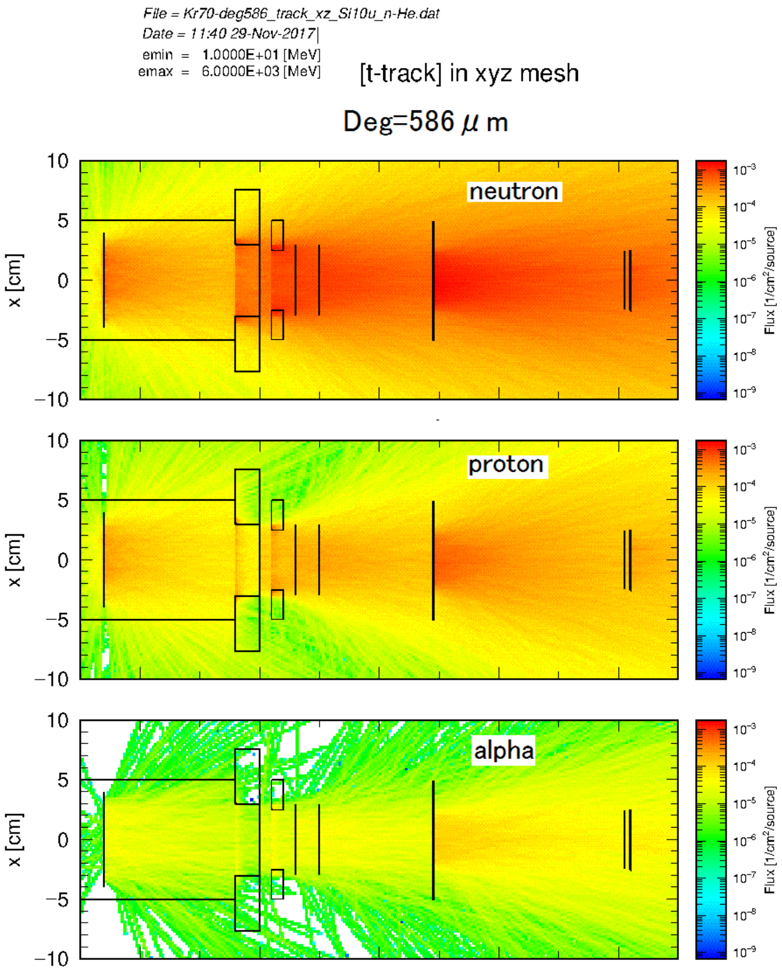
Total probabilities by PHITS reproduce overall behavior of our experimental RI probabilities. (There are some exceptions in Rb isotopes and low-Z nuclides.)

PHITS can be used for simulation of our irradiations.

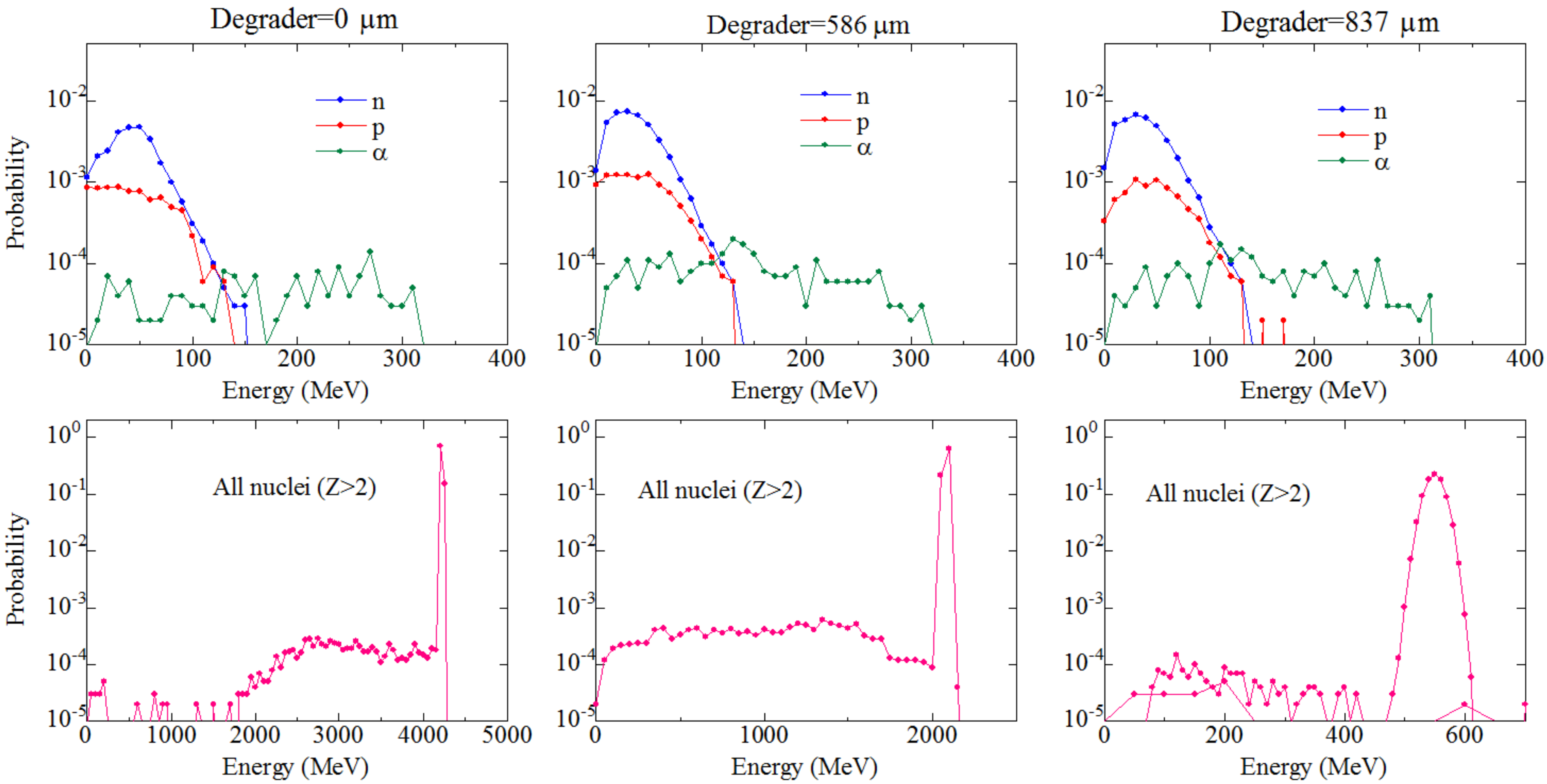
⇒ Degrader thickness dependence of the beam cleanness is studied.

Light impurities



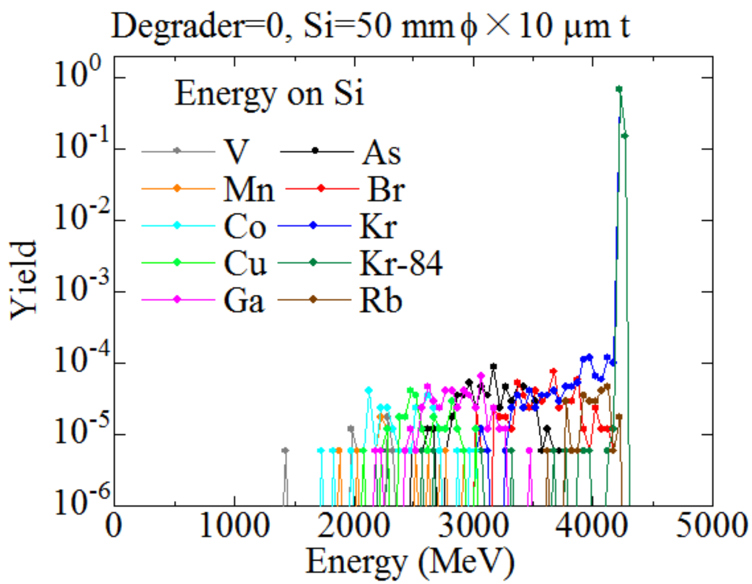


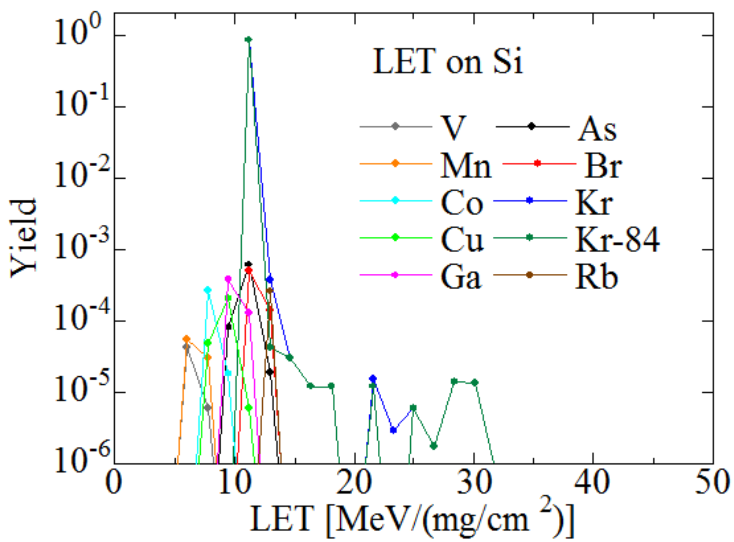
Energy distribution

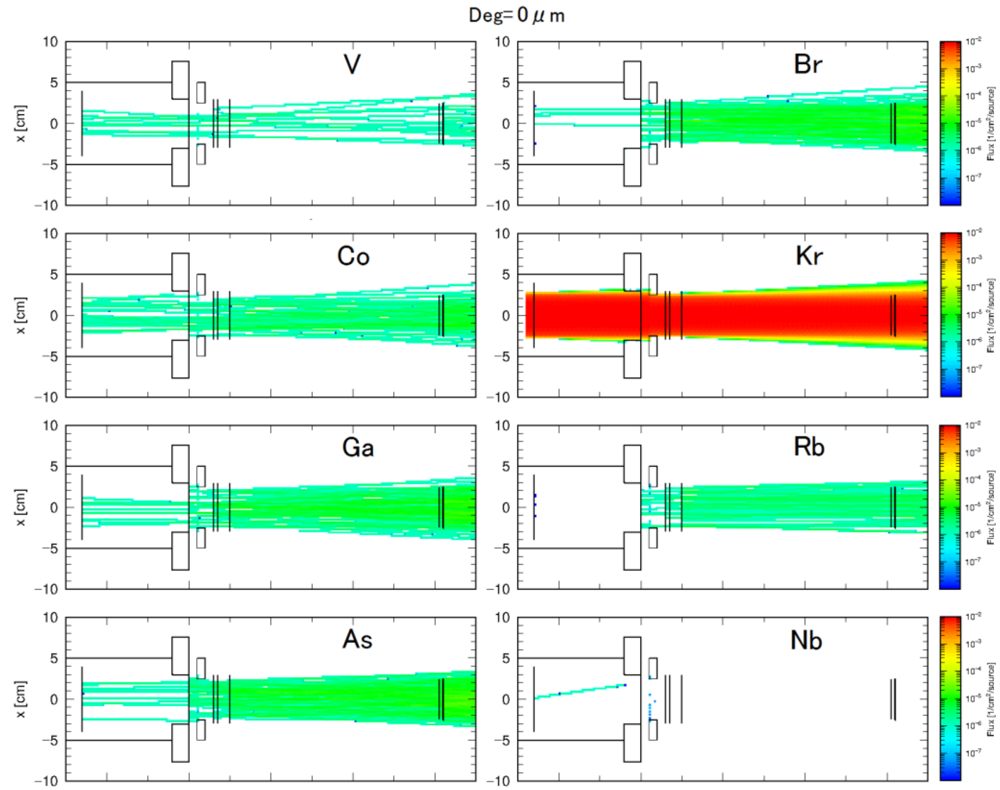


- Energy distributions of light particles don't depend on the degrader thickness.
- P and n below 100MeV , α below 300MeV
- Energy distributions of heavy particles depend on the degrader thickness.

Heavy ions (1) without degrader (LET=12)

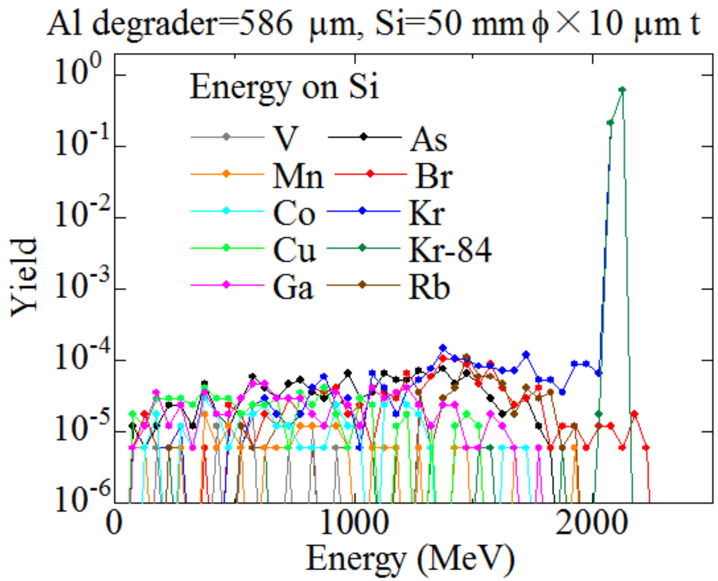


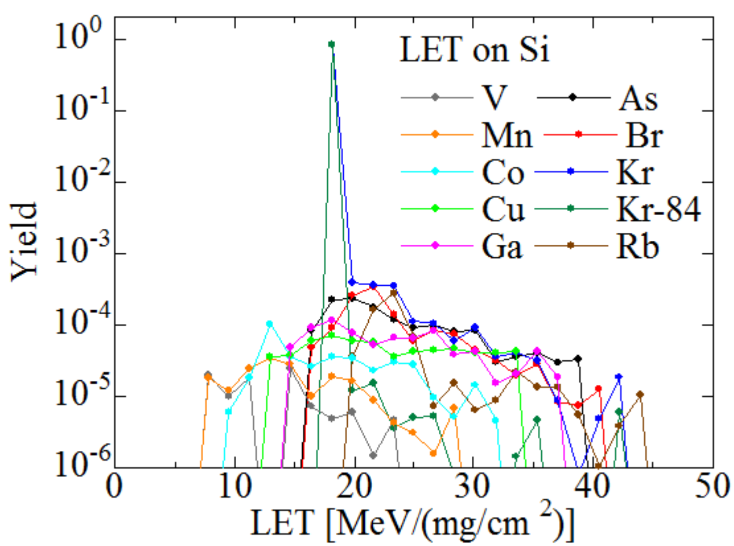


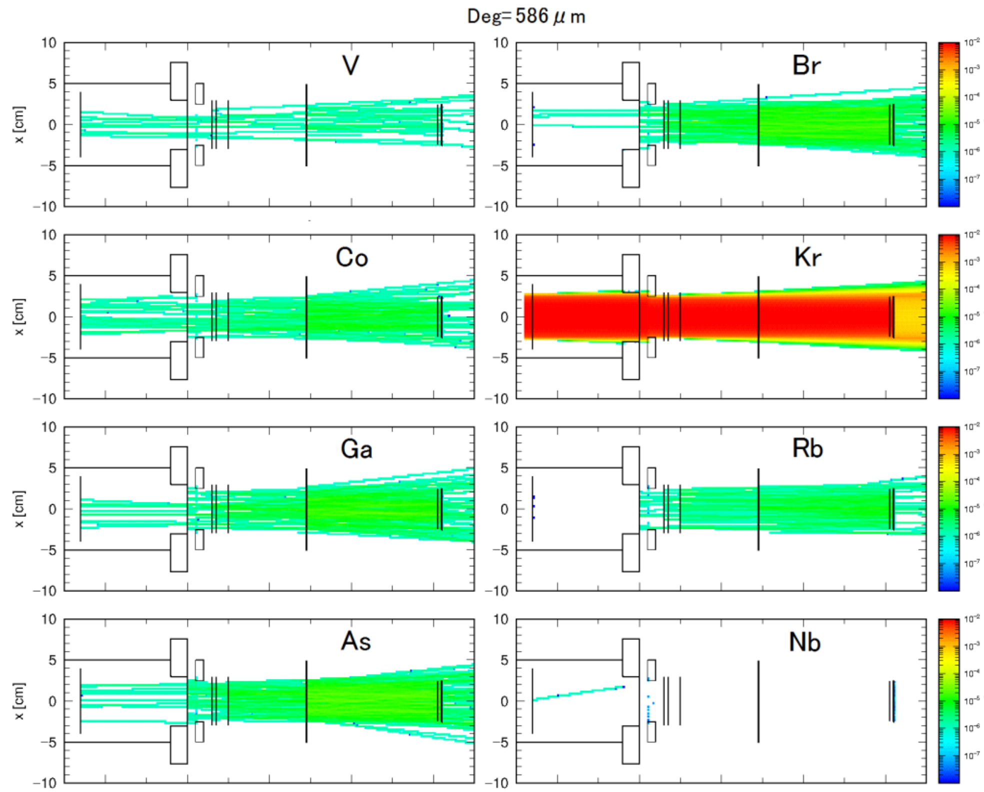


Ion energy distributes between 2000-4200 MeV.
Lighter nuclides have lower energy.
Impurity nuclides have LET lower than Kr-84.

Heavy impurities (2) 586-µm degrader (LET=19)

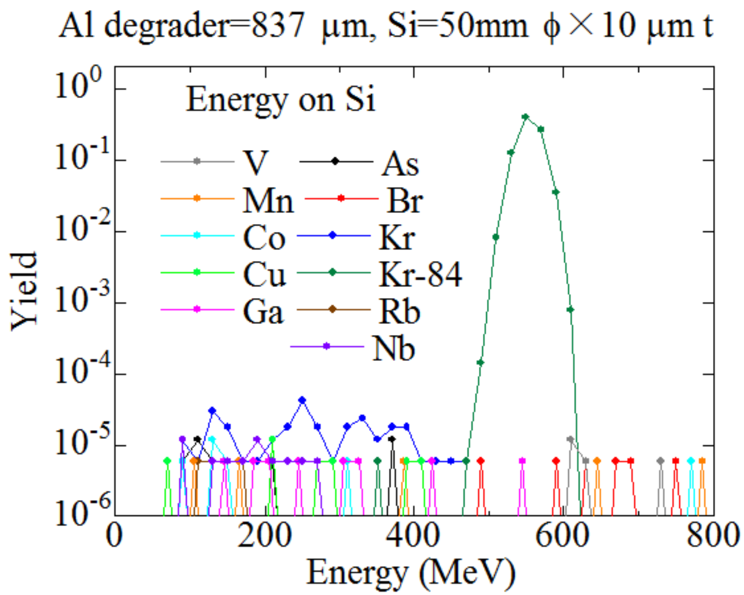


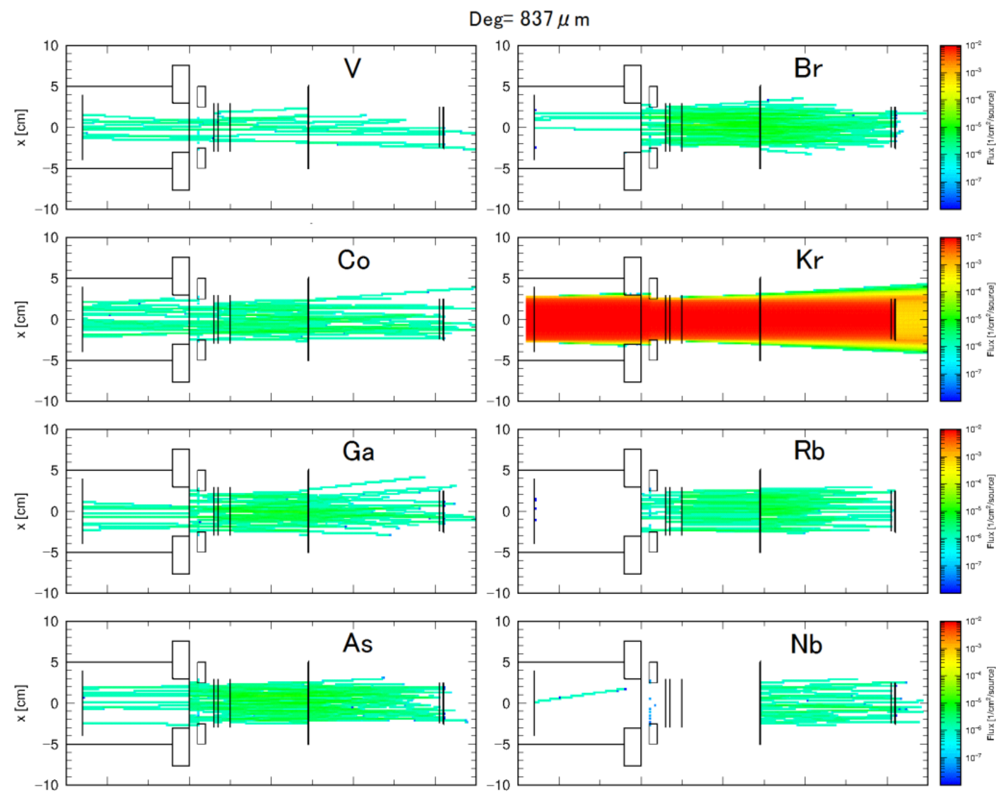


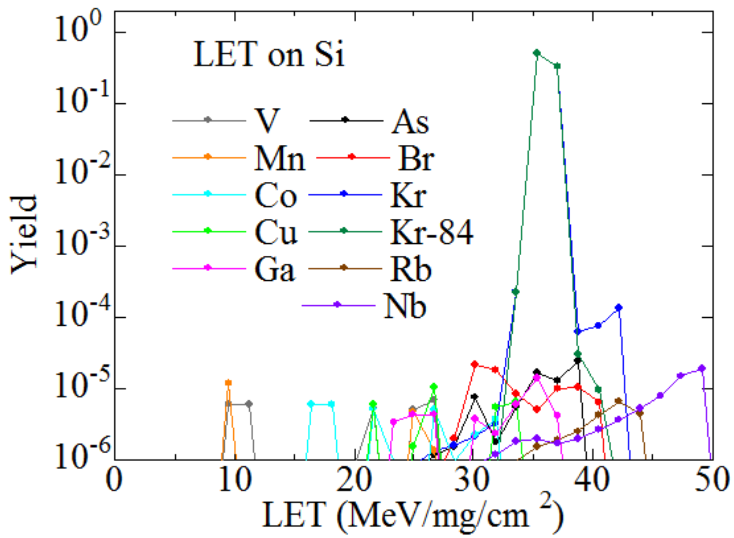


Impurity energy distributes from 0 to 2100MeV
Lighter nuclides have lower energy.
Most nuclides have higher LET than Kr-84.
LET distributes up to 43 MeV/mg/cm^2

Heavy impurities (3) 837-μm degrader (LET=38)







- Very heavy nuclides (Nb) with LET up to 50 MeV/(mg/cm^2) are found in the impurity
- Most of lighter impurity nuclides are stopped before the sample.

High-LET impurity

- Ratio of heavy nuclides with higher LET than primary Kr ions is calculated with PHITS
- Maximum contamination ratio of 1.2 % is found at about 0.6-mm thick degrader [LET＝19MeV/(mg/cm^2)]