RISP and nuclear reactions for RAON

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Rare Isotope Science Project (RISP)

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RAON(라온): RISP accelerator complex,

a pure Korean word, meaning “delightful” or “happy”

or 樂

Rare Isotope Science Project

RAON

- Goal : To build a world class heavy ion accelerator RAON, for rare isotope science research in Korea
- Project period : 2011.12-2020.02
- Budget : 460BWon (1BWon~1M$)
  - include initial experimental apparatus
  - does not include civil engineering, conventional facilities

RAON

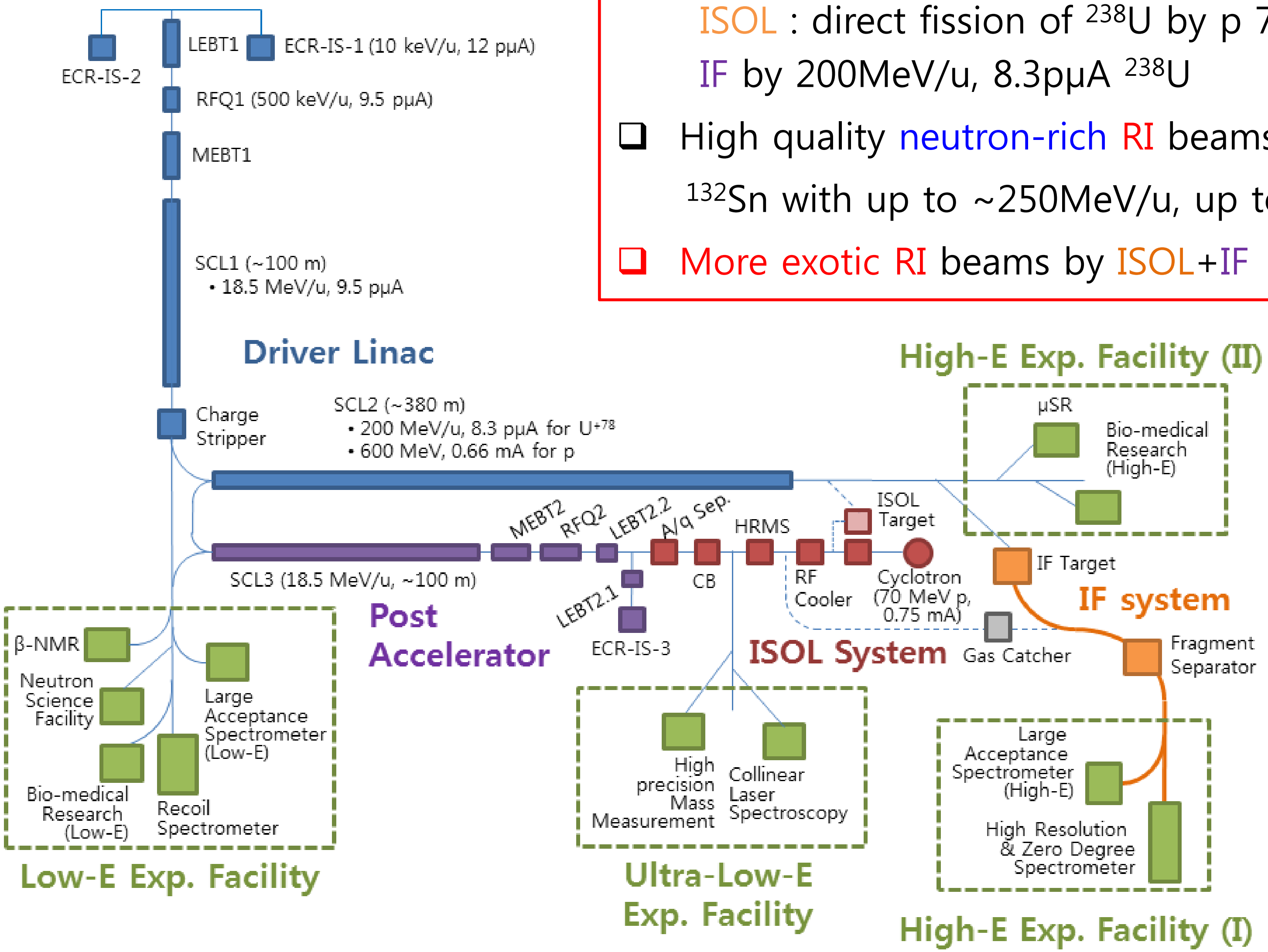
High intensity rare isotope beam with ISOL and IF methods

- **70MeV, 1mA proton beam, ^{238}U target - 70kW ISOL system**
- **200MeV/u, 8.3pμA, ^{238}U beam and other SI beam - 400kW IF system**
  - **600 MeV for proton**

- High current high purity neutron-rich RI beam
  For example, ^{132}Sn : ~250MeV/u, ~ 10^8 pps
- Production of exotic beams combining ISOL and IF methods
- Simultaneous operation of IF and ISOL systems

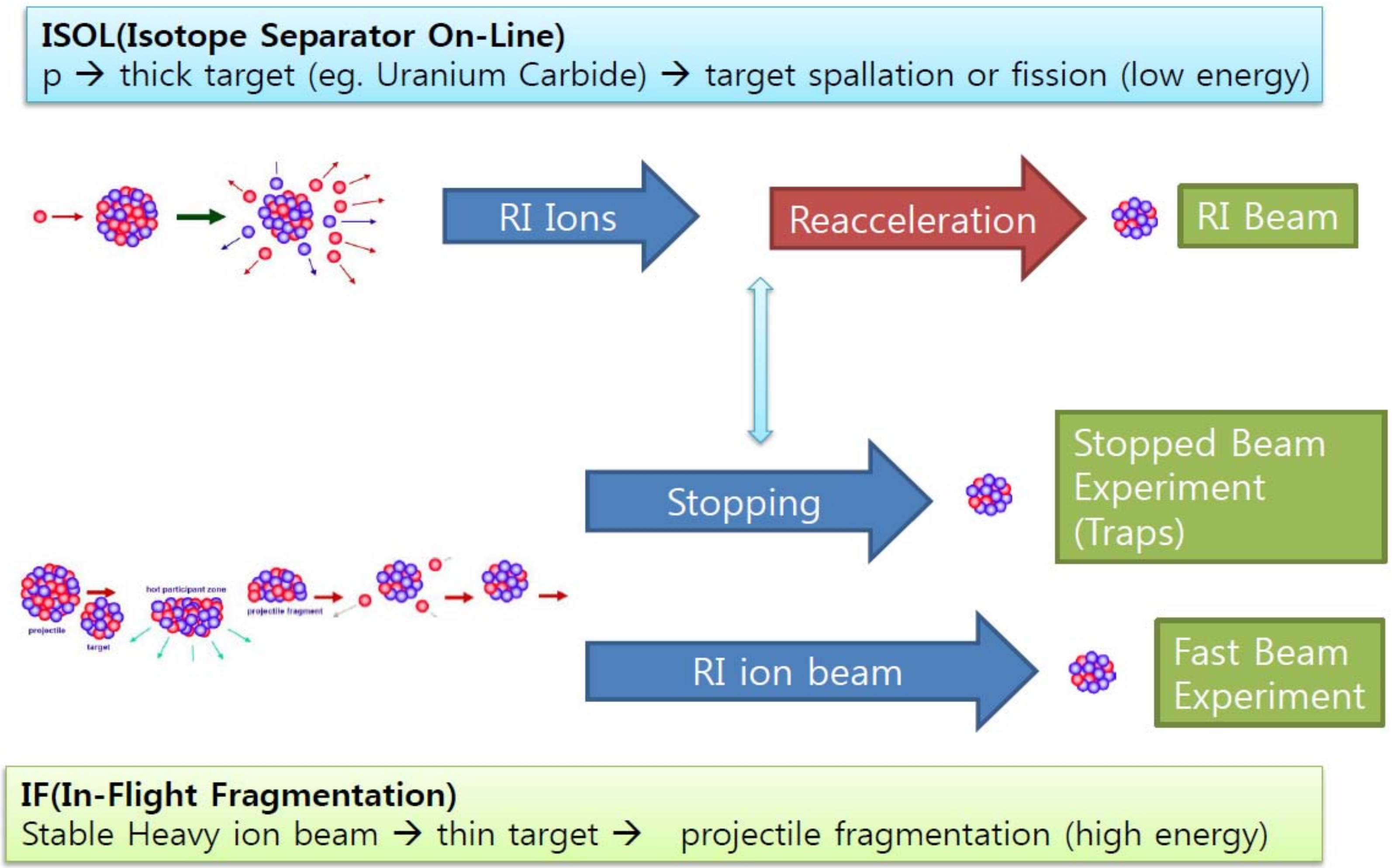
RAON

- High intensity RI beams by ISOL & IF
  - ISOL : direct fission of ^{238}U by p 70MeV
  - IF by 200MeV/u, 8.3pμA ^{238}U
- High quality neutron-rich RI beams
  - ^{132}Sn with up to ~250MeV/u, up to 10^8 pps
- More exotic RI beams by ISOL+IF



* ISOL-type facilities: radioactive ions are produced at rest in a thick target either by direct bombardment with particles from a driver accelerator or via fission induced both by fast and thermal secondary neutrons.

* In-flight (IF) facilities: a high energy ion beam is fragmented in a suitable thin target and the reaction products are and then transported to the secondary target.



Key Science Drivers of RISP

- **Highest priority research subjects**
  - Nuclear reaction experiments important to synthesize elements in Universe
  - Search for super heavy elements : $Z > 119$ ($Z \sim 120$)
  - Abnormal nuclear structure of exotic rare isotopes
  - Nuclear symmetry energy at sub-saturation density
  - Precision mass measurement & Laser spectroscopy

- **Important scientific applications**
  - Material science : β-NMR, μSR
  - Medical and bio-science : RI beam irradiation
  - Nuclear data for Gen-IV NPP and nuclear waste transmutation

RAON: Past, Present, and Future

2009

LoIs from domestic users

- **Science program** with RI beams up to 200 AMeV
- **83 LoI's**
  (nuclear/astrophysics, nuclear data, standard model, biomedical, mass measurement, material science, ERD analysis)

2010 ~ 2011

Science classification

- Nuclear science
- Atomic & Molecular science
- Material science
- Medical & Bio science

2011 ~ 2013

Facility specifications

- Beam specifications
  (energy, intensity, pulse width …)
- Specifications of facilities

2013 ~ 2018

R&D and Installation

- Spectrometer
- Detection system
- Beam line
- Apparatus for applied sciences

2018 ~ 2020

Day-1 experiments

Programmed Experiments

Upgrade and Extension

2013

Refinement

- Based on Realistic modification of specifications
- **PAC (Oct 2013)**
- **Expression of Interests (EoIs) (domestic + foreign)**

KOBRA

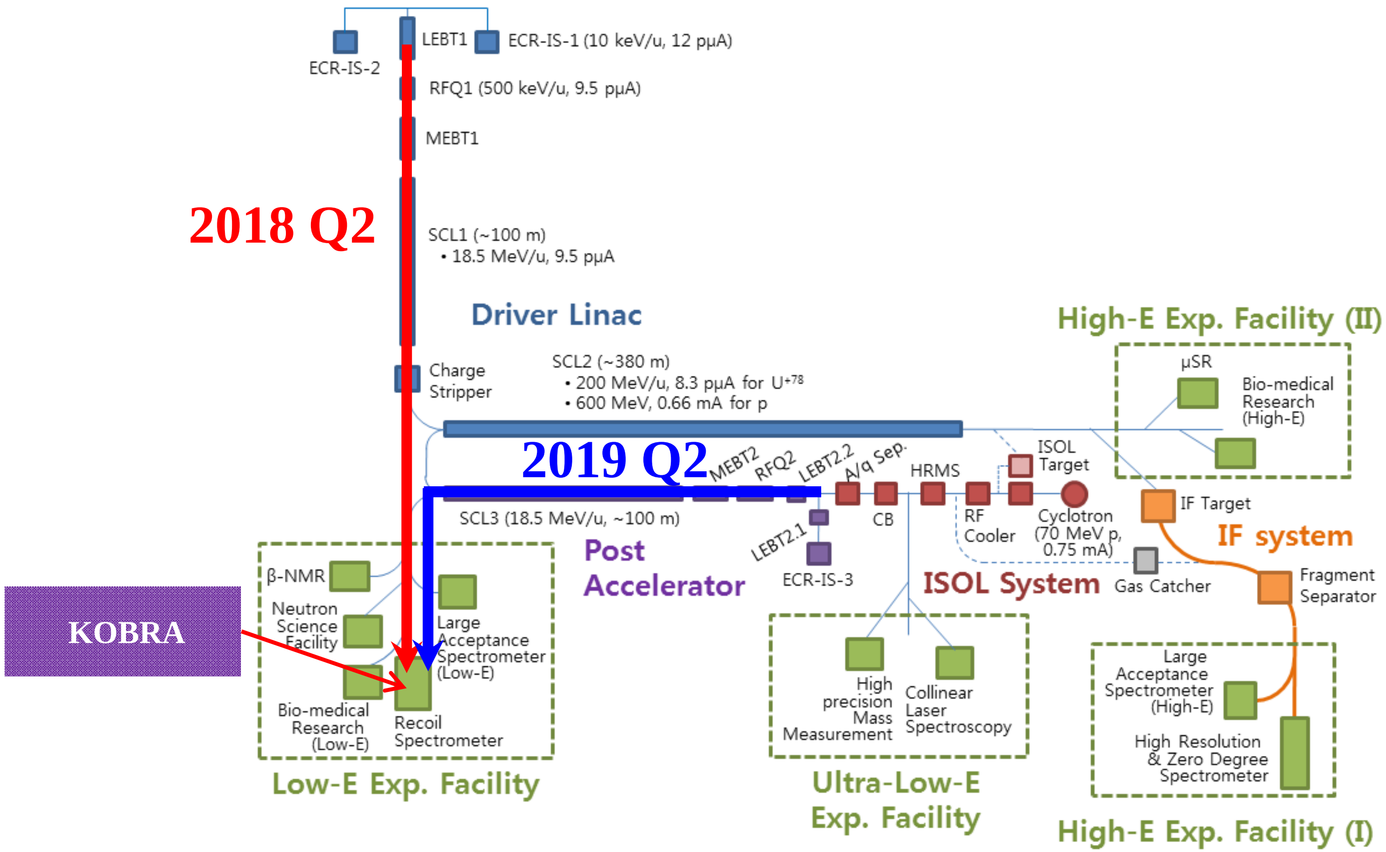
(KOrea Broad acceptance Recoil spectrometer and Apparatus)

Main facility for nuclear structure and nuclear astrophysics studies with low-energy stable and rare isotope beams

KOBRA
High performance spectrometer

@

RAON
High quality & Low Energy stable and radioactive ion beams

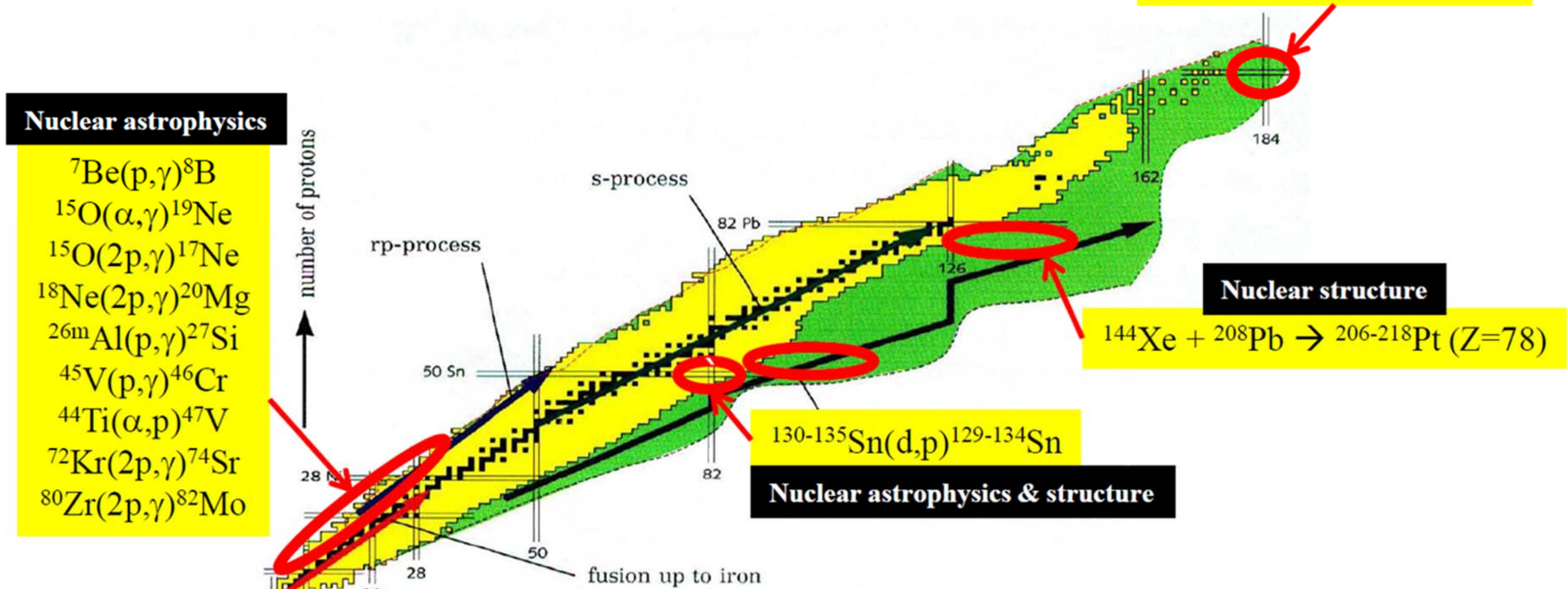


Science program at KOBRA

- **Main Research Subject**
  - Astrophysically important nuclear reactions
  - Rare event study
    - Super Heavy Element (SHE), New isotopes
  - Nuclear structure of exotic nuclei

SHE & Properties of very heavy nuclei

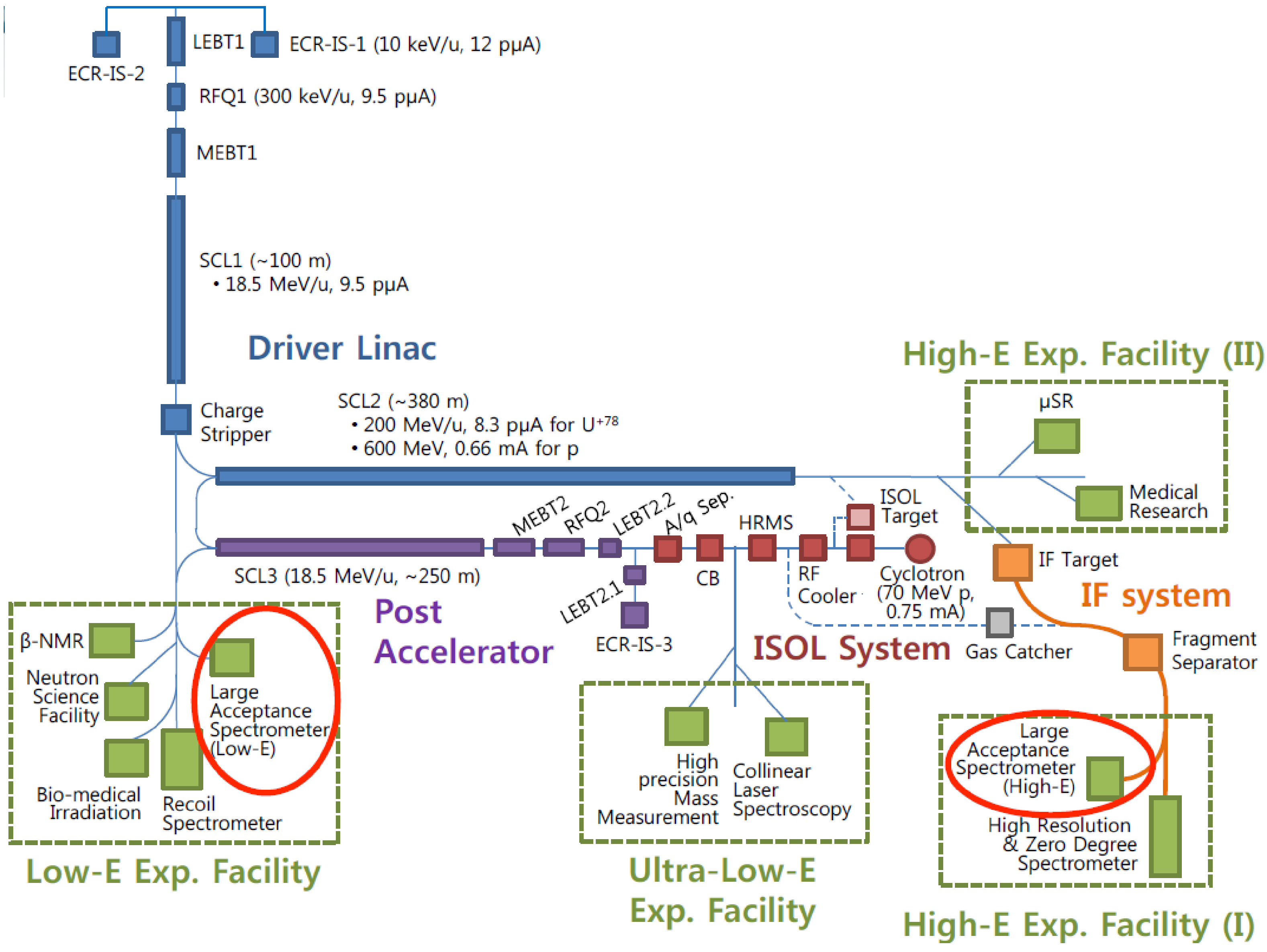
$^{54}Cr + ^{248}Cm \rightarrow ^{298,299}120$
$^{50}Ti + ^{249}Cf \rightarrow ^{295,296}120$
,with RI beams



<Candidates for Day-1 experiments at KOBRA>

LAMPS

(Large Acceptance Multi-Purpose Spectrometer)



Study of Nuclear Matter in Heavy-Ion Collision Experiment

Determining Equation of State (EOS) of the strongly interacting medium below and above the saturation density up to $\rho \sim 2\rho_0$

- Iso-spin dependence (symmetry energy)

Energy of nuclear matter

(density and isospin asymmetry dependence)

$$E(\rho,\delta)/A = E(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4) + \cdots$$

where $\rho = \rho_n + \rho_p$, $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$, $a_s \approx E_{sym}(0.6\rho_0)$

- Importance for astrophysics
  - To understand structure of neutron stars and supernovae
  - Nuclear synthesis and exotic nuclei near neutron drip lines

Key observables

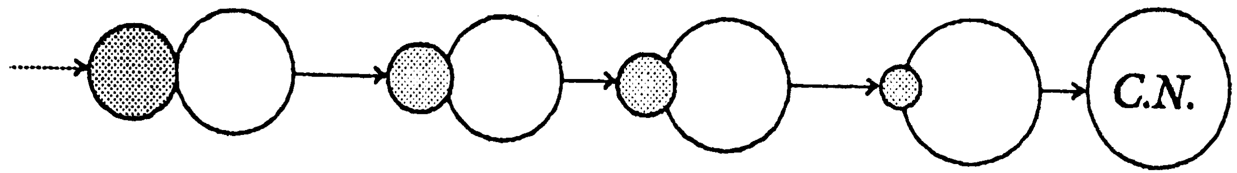
- **Pygmy and Giant dipole resonances**
- **Particle spectrum, yield, and ratio**
- **Collective flow**

Nuclear reactions at RISP: theoretical efforts

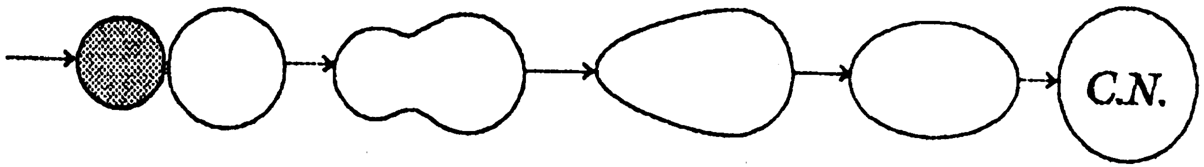
- ER cross sections for SHEs: **diabatic** (on-going), adiabatic (to come)
- Production rate of n-rich nuclei: **diabatic** (on-going), adiabatic (to come)
- Nuclear Reactions for Nuclear Astrophysics (to come)
- …

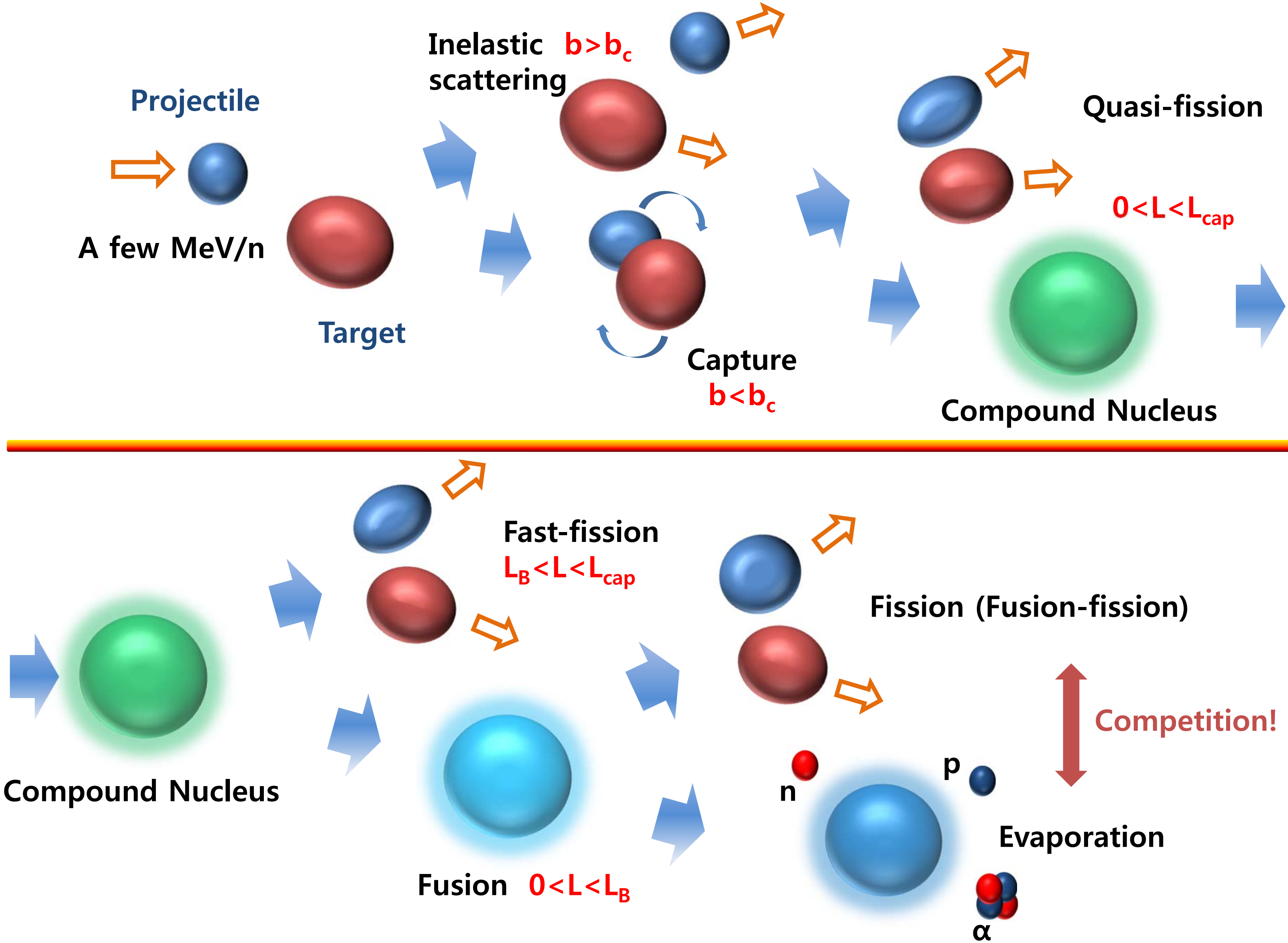
Two distinct ways

<Diabatic way>



<Adiabatic way>





Inelastic scattering
b>b$_c$
Projectile
A few MeV/n
Target
Capture
b<b$_c$
Quasi-fission
0<L<L$_{cap}$
Compound Nucleus
Fast-fission
L$_B$<L<L$_{cap}$
Fission (Fusion-fission)
Competition!
Compound Nucleus
Fusion 0<L<L$_B$
n
p
Evaporation
α

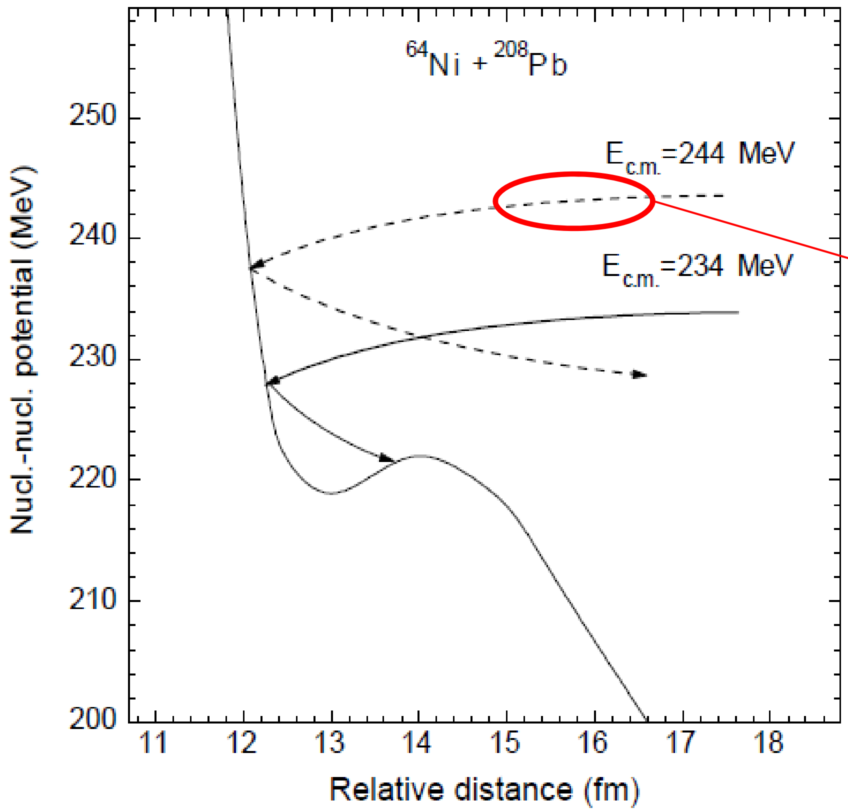
DNS (dinuclear system)

A configuration of two touching nuclei which keep their individuality. In this framework, the compound nucleus is formed by a series of transfers of nucleons from the light nucleus to the heavy one. Important degrees of freedom are the mass asymmetry η , the relative inter-nuclear distance **R**, deformation (rotation) of the fragments, etc .

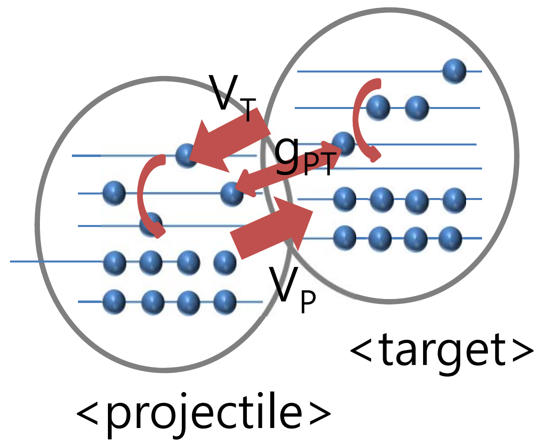
$$\eta = (A_1 - A_2)/(A_1 + A_2)$$

The dynamics of the DNS is considered as a combined diffusion in the degrees of freedom of the mass asymmetry η and of the relative distance describing the formation of the compound nucleus and the quasi-fission process (decay of the DNS), respectively.

Capture or inelastic scattering in DNS



kinetic energy dissipation by friction:



$$V(\mathbf{R}) = V_C(\mathbf{R}) + V_{nucl}(\mathbf{R}) + V_{rot}(\mathbf{R})$$

<Coulomb part>

$$
\begin{aligned}
V_C(R) =& \frac{Z_1 Z_2}{R} e^2 \\
&+ \frac{Z_1 Z_2}{R^3} e^2 \left\{ \left(\frac{9}{20\pi} \right)^{1/2} \sum_{i=1}^{2} R_{0i}^2 \beta_2^{(i)} \mathcal{P}_2(\cos\alpha_i') + \frac{3}{7\pi} \sum_{i=1}^{2} R_{0i}^2 \left[\mathcal{P}_2(\cos\alpha_i') \right]^2 \right\},
\end{aligned}
$$

<Rotation part>

$$
V_{rot}(R) = \hbar^2 \frac{l(l+1)}{2\mu R^2},
$$

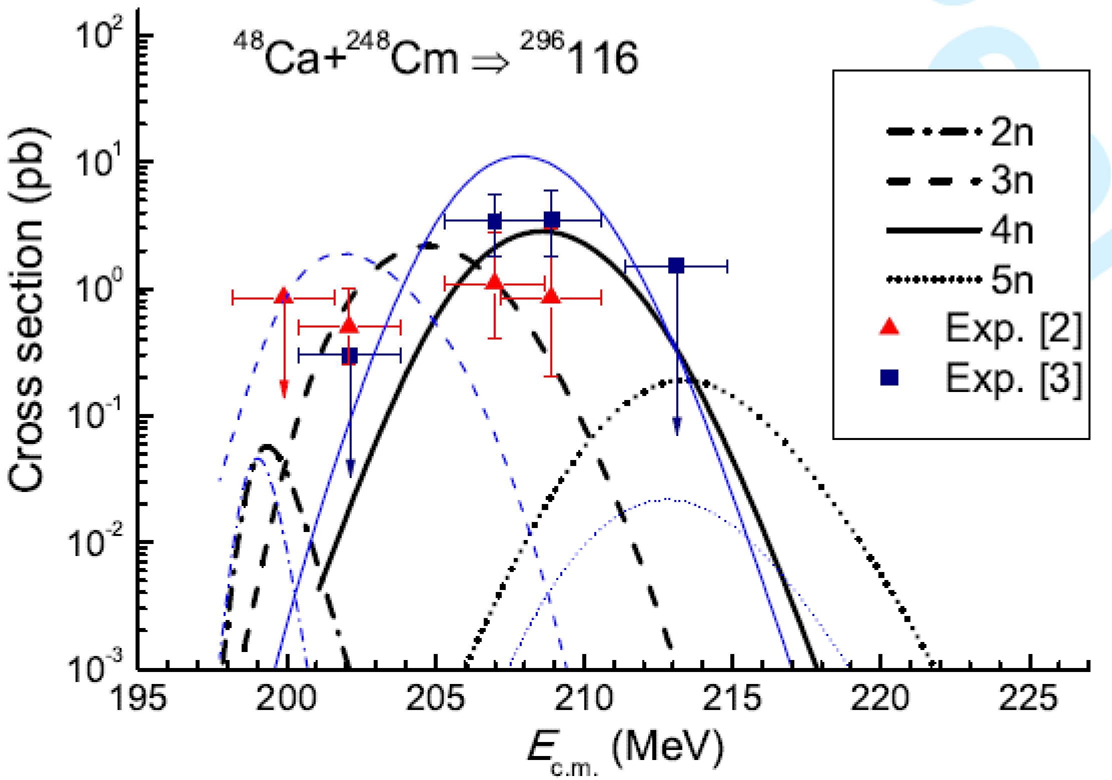
<Nuclear force part>

$$
V_{nucl}(R) = \int \rho_1(\mathbf{r_1}) \rho_2(\mathbf{R} - \mathbf{r_2}) \mathcal{F}(\mathbf{r_1} - \mathbf{r_2}) d\mathbf{r_1} d\mathbf{r_2}
$$

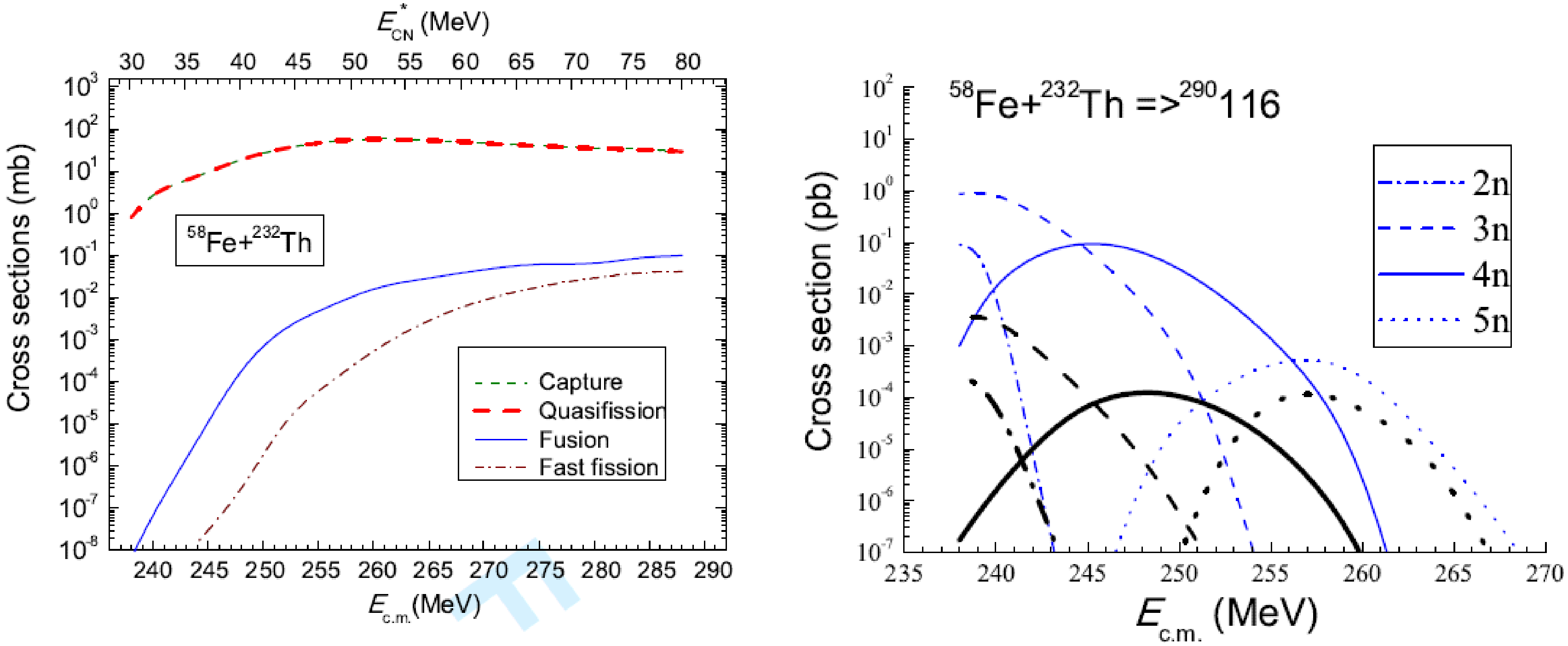
$$
\begin{aligned}
\mathcal{F}(\mathbf{r_1} - \mathbf{r_2}) =& C_0 \left(F_{in} \frac{\rho_0(\mathbf{r_1})}{\rho_{00}} + F_{ex} \left(1 - \frac{\rho_0(\mathbf{r_1})}{\rho_{00}} \right) \right) \delta(\mathbf{r_1} - \mathbf{r_2}), \\
\rho_i(\mathbf{r}) =& \frac{\rho_{00}}{1 + \exp((r - R_i(\theta_i', \phi_i'))/a_{0i})} \\
R_i(\theta_i', \phi_i') =& R_{0i}(1 + \beta_i Y_{20}(\theta_i', \phi_i'))
\end{aligned}
$$

Synthesis of SHE

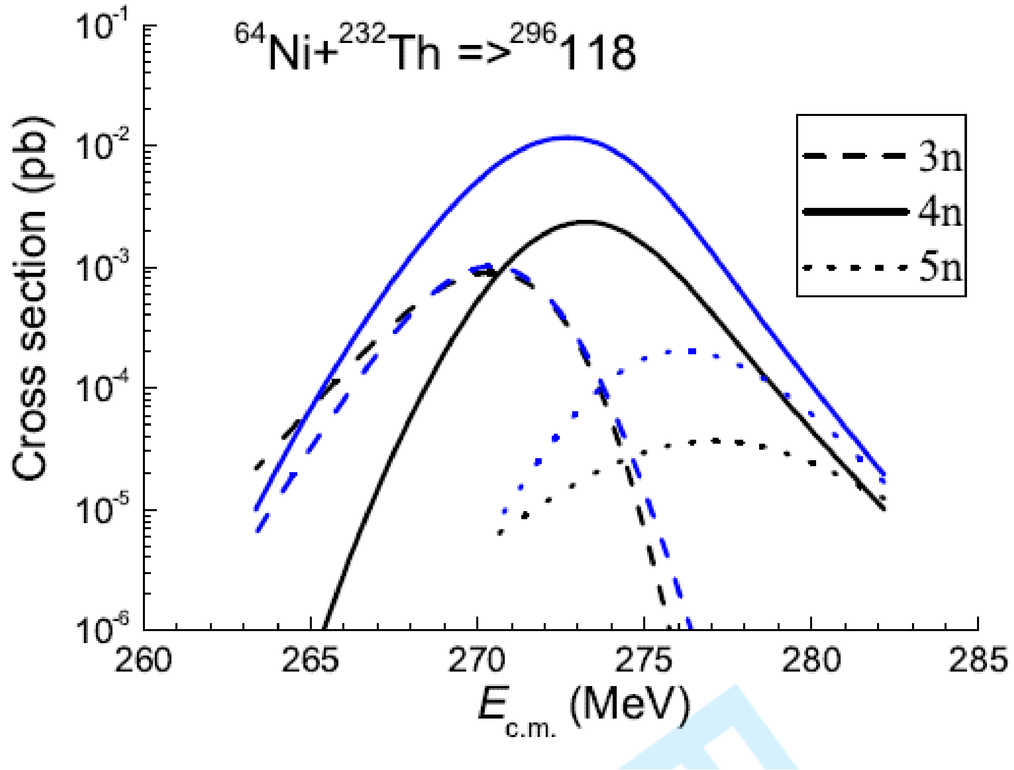
$^{58}Fe+^{232}Th => ^{290}116$



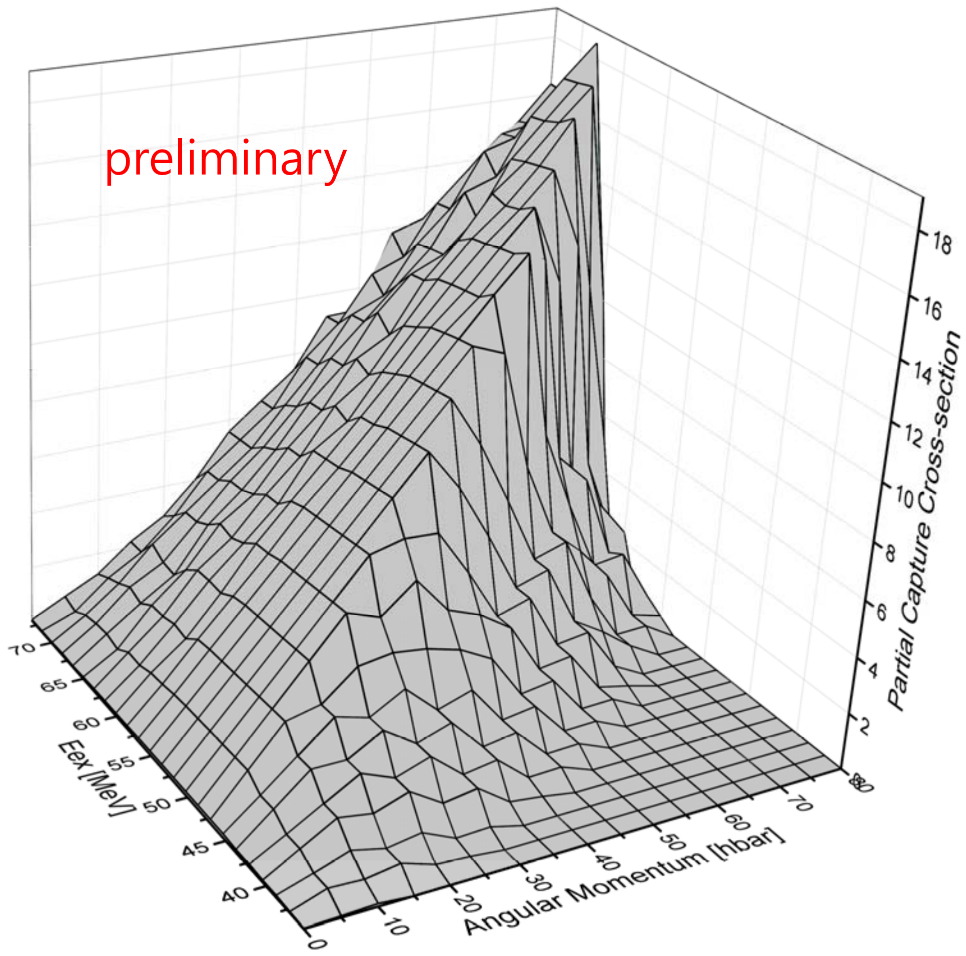
mass tables of Möller and Nix (thin lines)   Warsaw group (thick lines)



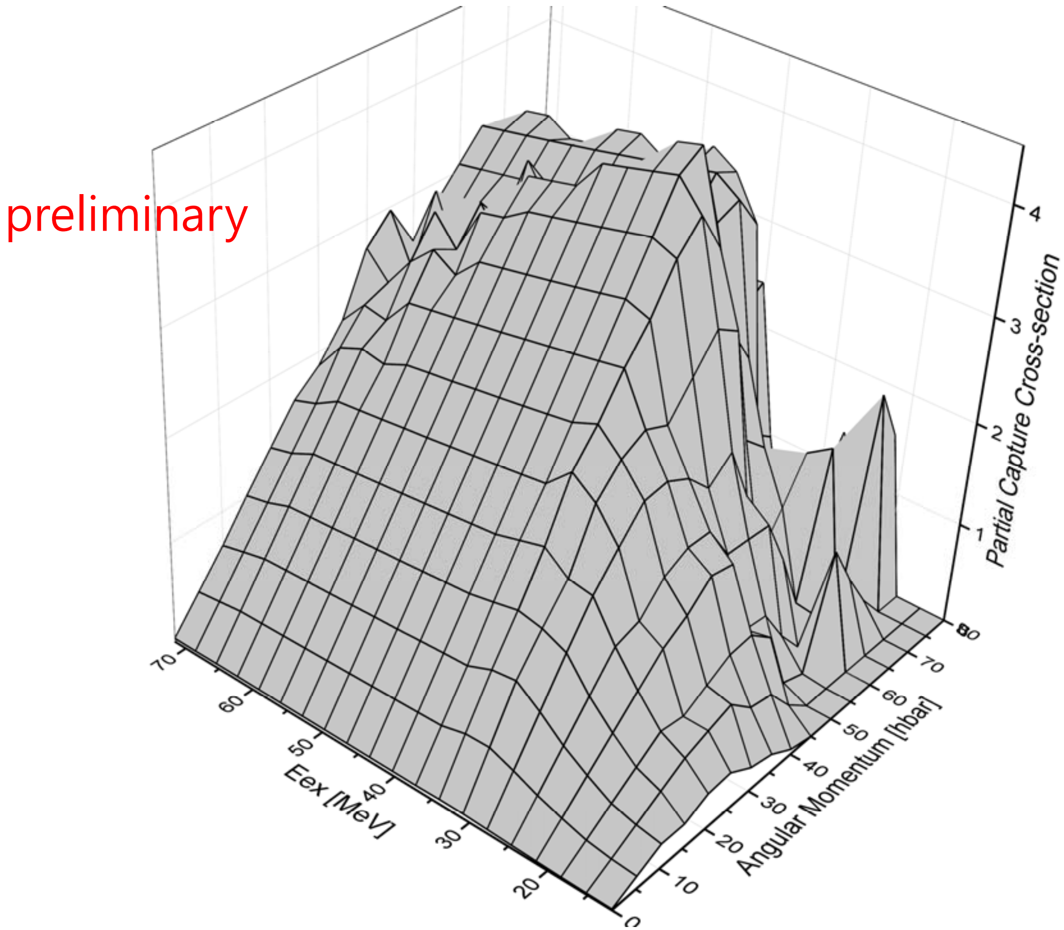
E^*_{CN} (MeV)
Cross sections (mb)
^{58}Fe+^{232}Th
Capture
Quasifission
Fusion
Fast fission
$E_{c.m.}$(MeV)
^{58}Fe+^{232}Th =>^{290}116
Cross section (pb)
2n
3n
4n
5n
$E_{c.m.}$ (MeV)



A Nasirov, Kyungil Kim, G. Mandaglio, G. Giardina, A. Muminov, YK, Eur.Phys.J. A49 (2013) 147

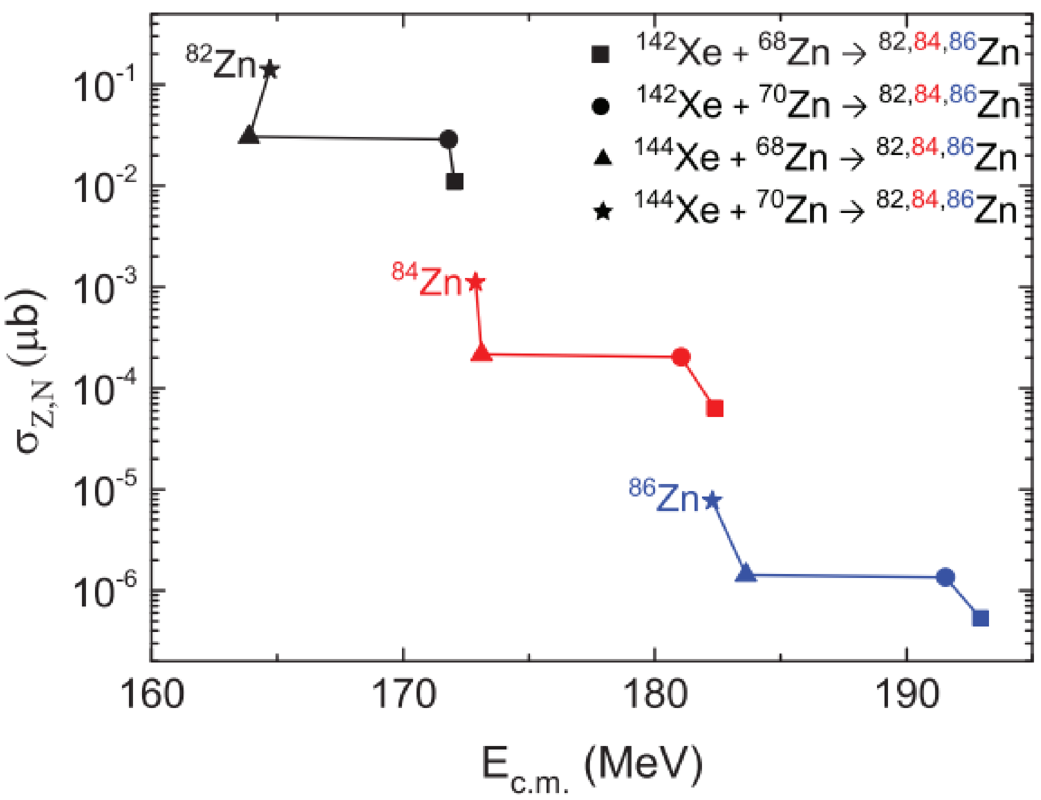


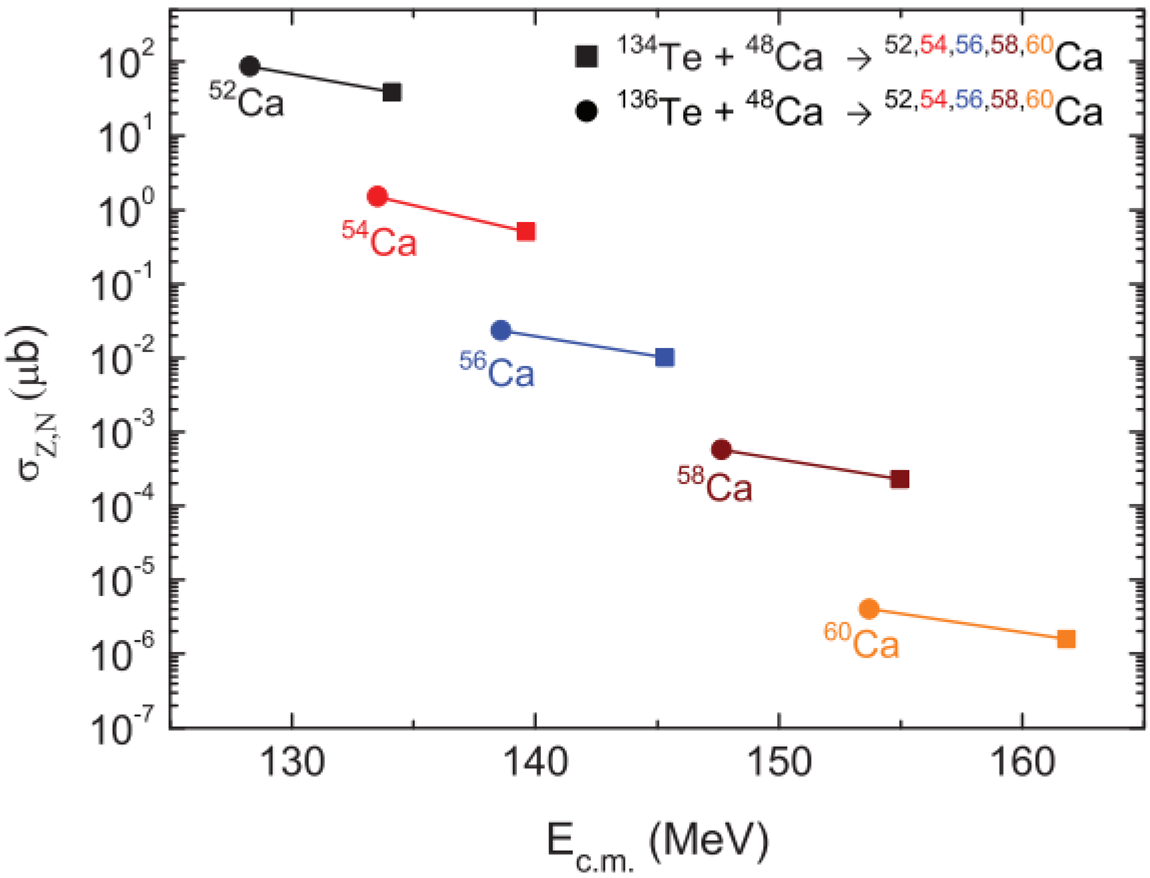
$^{40}Ar + ^{180}Hf \rightarrow ^{220}Th$



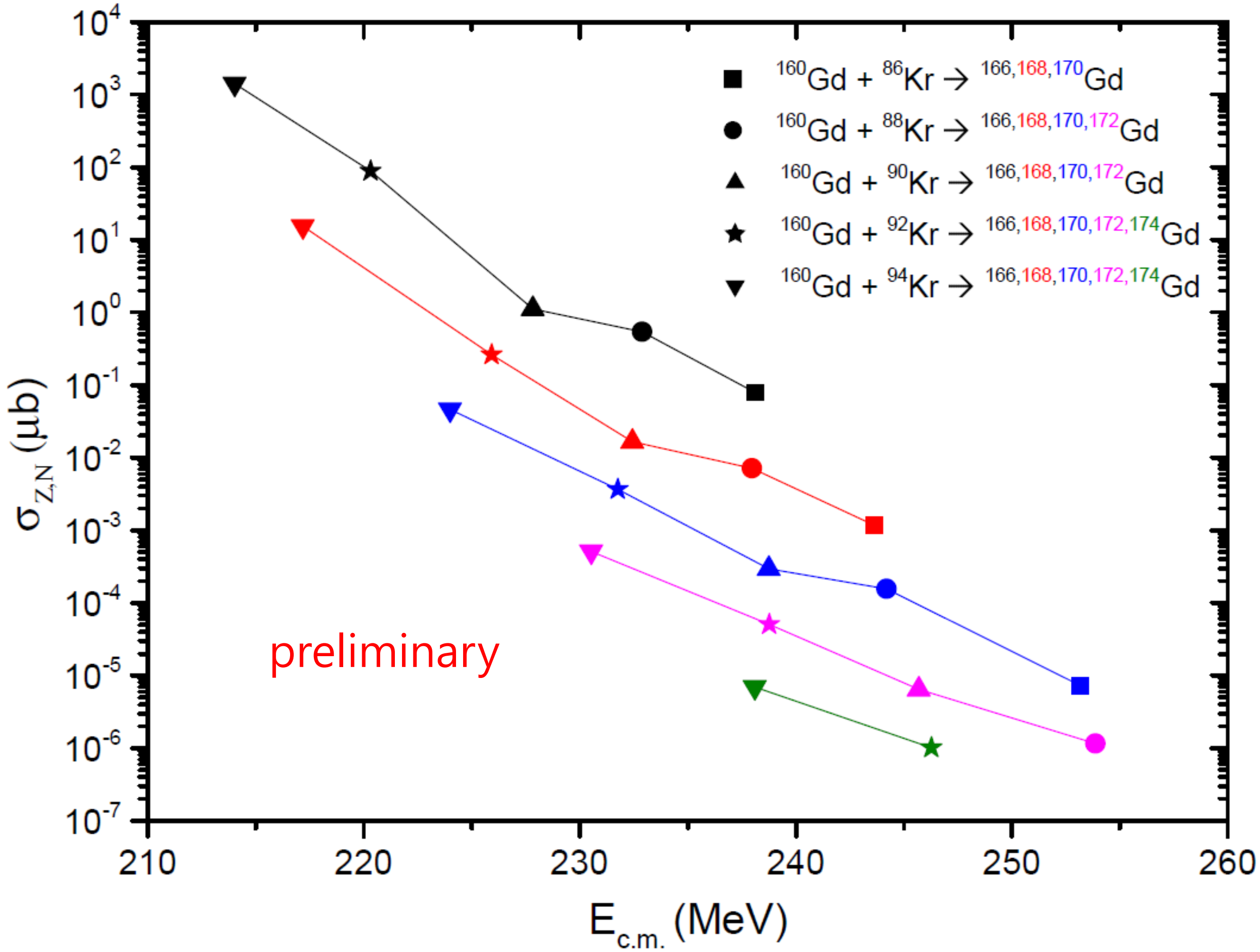
$^{82}Se + ^{138}Ba \rightarrow ^{220}Th$

N-rich isotope production with radioactive and stable beams

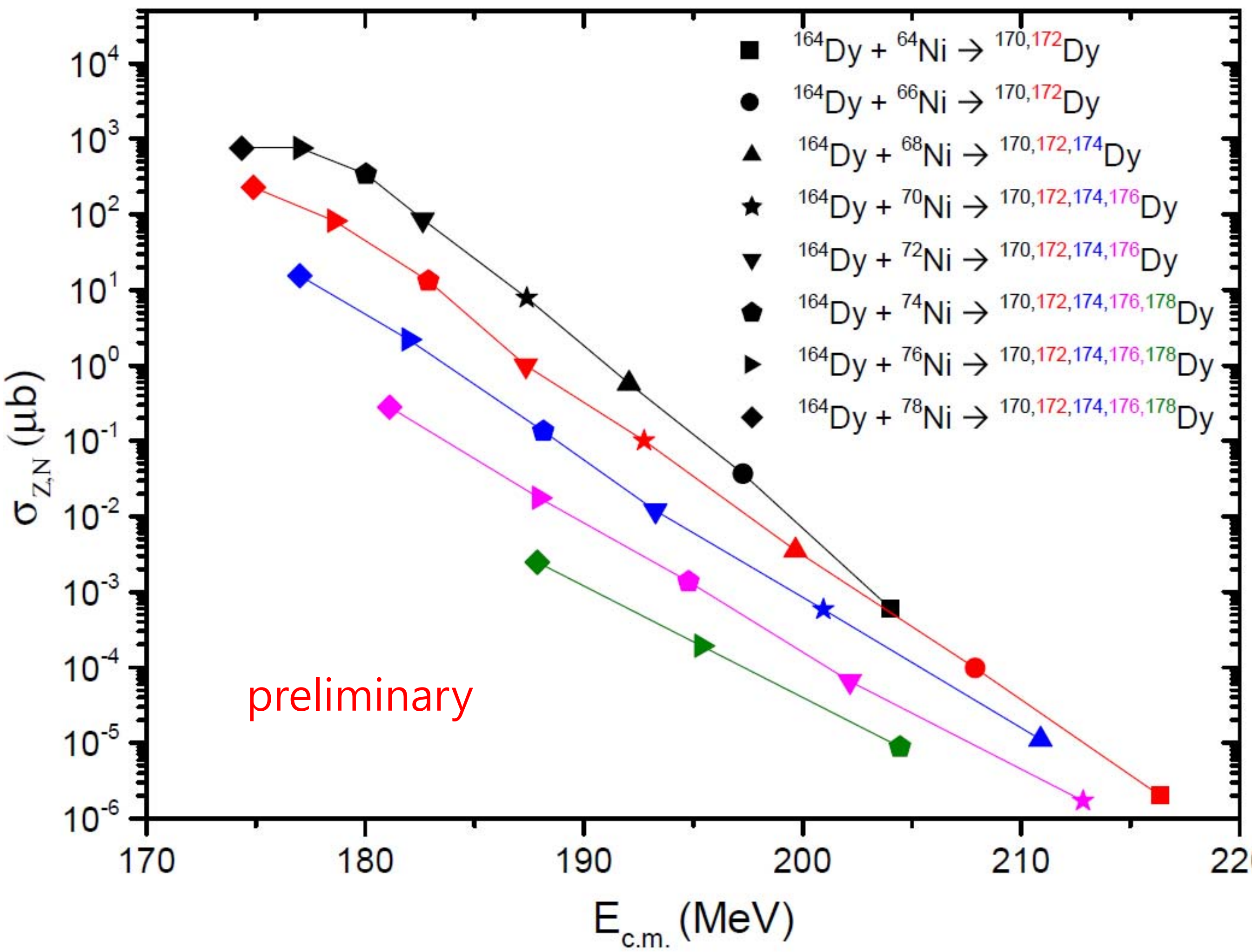




Myeong-Hwan Mun, G. G. Adamian, N. V. Antonenko, Y. Oh, and YK, Phys.Rev. C89 (2014) 034622



$^{160}Gd + ^{86}Kr \rightarrow ^{166,168,170}Gd$
$^{160}Gd + ^{88}Kr \rightarrow ^{166,168,170,172}Gd$
$^{160}Gd + ^{90}Kr \rightarrow ^{166,168,170,172}Gd$
$^{160}Gd + ^{92}Kr \rightarrow ^{166,168,170,172,174}Gd$
$^{160}Gd + ^{94}Kr \rightarrow ^{166,168,170,172,174}Gd$
preliminary
$\sigma_{Z,N}$ (μb)
$E_{c.m.}$ (MeV)



^{164}Dy + ^{64}Ni → ^{170,172}Dy
^{164}Dy + ^{66}Ni → ^{170,172}Dy
^{164}Dy + ^{68}Ni → ^{170,172,174}Dy
^{164}Dy + ^{70}Ni → ^{170,172,174,176}Dy
^{164}Dy + ^{72}Ni → ^{170,172,174,176}Dy
^{164}Dy + ^{74}Ni → ^{170,172,174,176,178}Dy
^{164}Dy + ^{76}Ni → ^{170,172,174,176,178}Dy
^{164}Dy + ^{78}Ni → ^{170,172,174,176,178}Dy
preliminary
$\sigma_{Z,N}$ (μb)
$E_{c.m.}$ (MeV)

Summary

- RAON will do many exciting things from 2018
- So far, nuclear reactions at RISP focused on the SHE synthesis and n-rich isotope productions.
- Nuclear theory at RISP will be well equipped with machinery for nuclear reactions in astrophysics very soon.