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Direct reaction and r-process nucleosynthesis

Nobu Imai
今井伸明
CNS, University of Tokyo

Contents

- 1st lecture
  - Brief introduction of *r*-process
  - Waiting point approximation
  - Two mechanism of the neutron capture reaction
- 2nd lecture
  - Direct radiative capture reaction channel
  - DWBA
  - Inverse kinematics
- 3rd lecture
  - Compound reaction channel
  - Surrogate reaction
  - Recent highlights at OEDO/RIBF

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Origin of the elements in the Universe

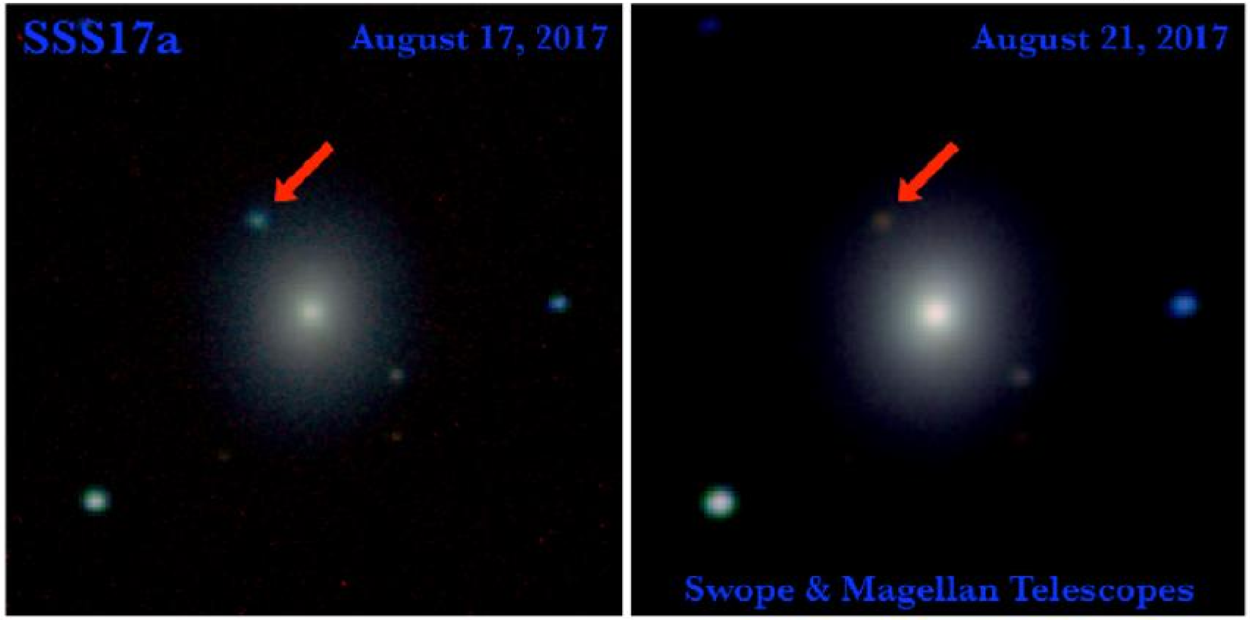
- Where do we come from?

- How are the heavier elements synthesized?

Third of 11 unanswered questions in 2002

https://www.discovermagazine.com/the-sciences/the-11-greatest-unanswered-questions-of-physics

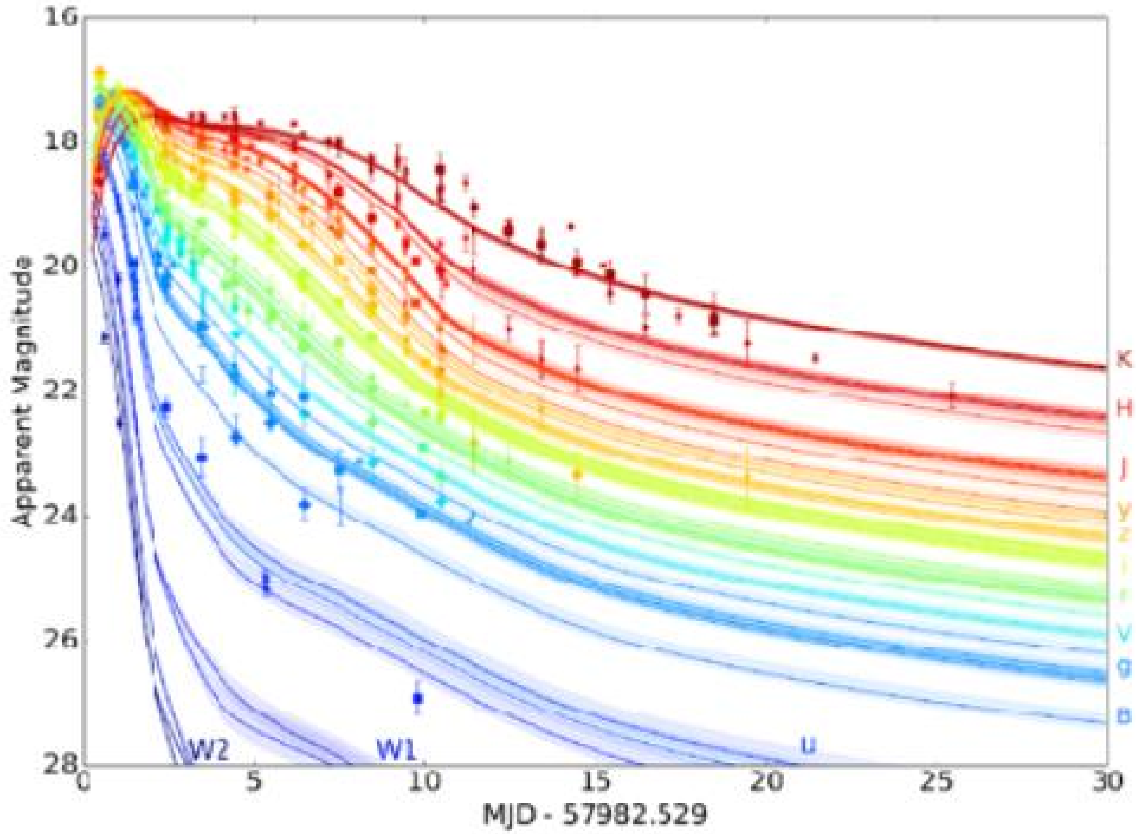
Neutron-star Merger



Discovery of the gravitational wave on 2017.8.17

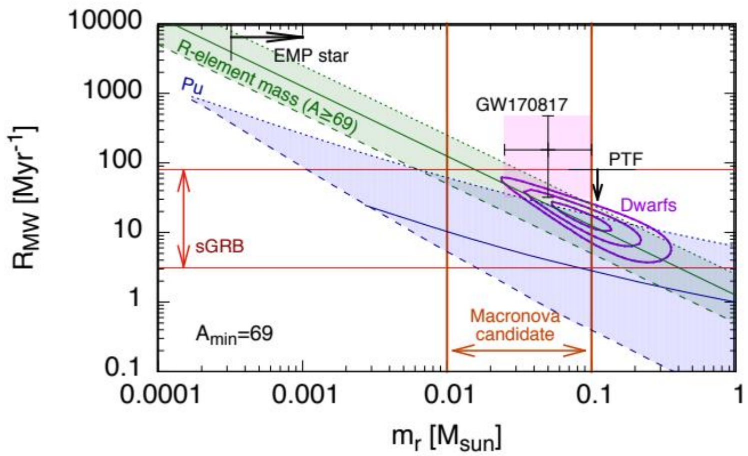
M.R. Drout et al., Science 358, 1750 (2017)

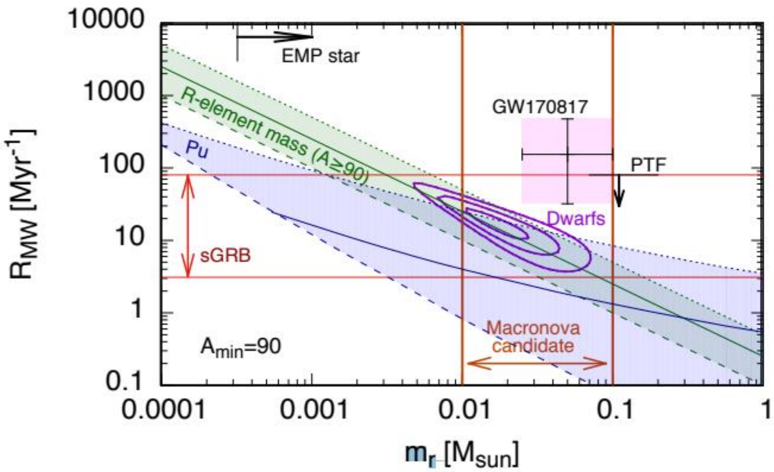
Time-evolution of the light-curve



V.A. Villar et al., ApJL 851 L21 (2017)

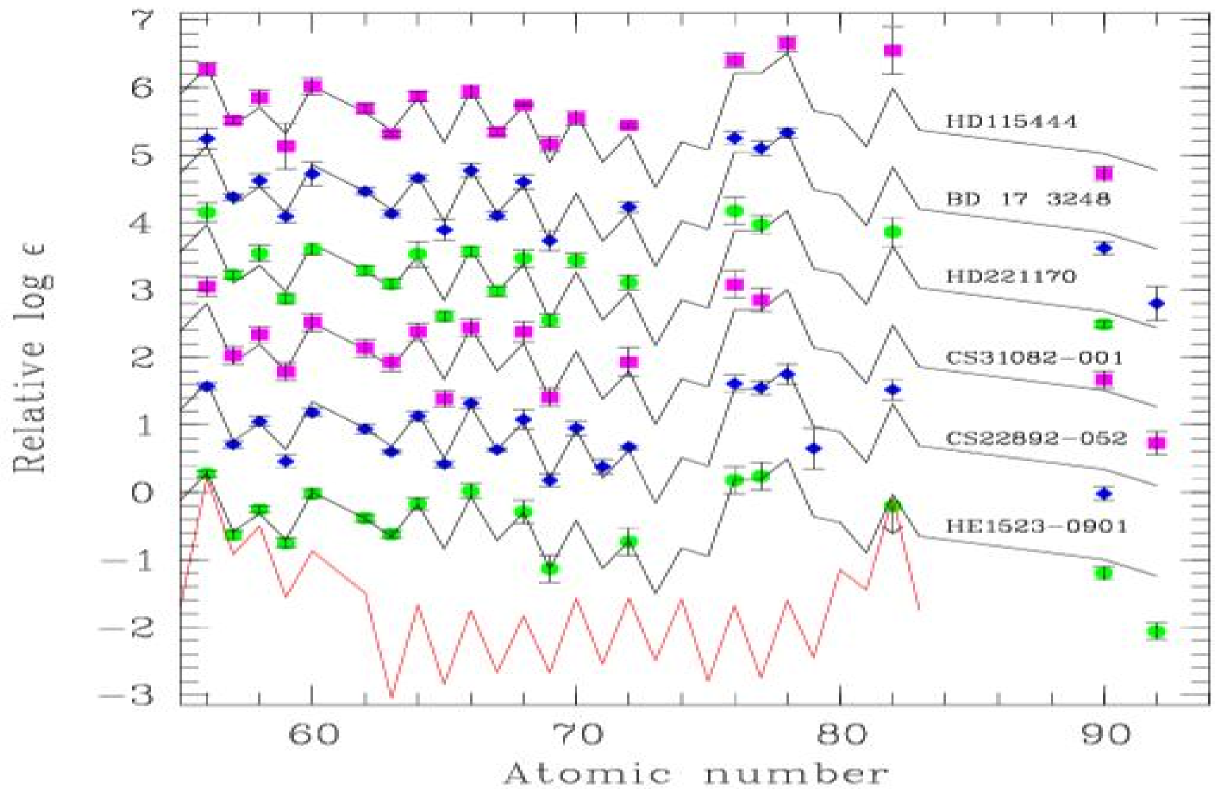
NS merger is enough ?





K. Hotokezak et al., arXiv:1801.01141

Universality of *r*-process abundance



A. Frebl (2008)

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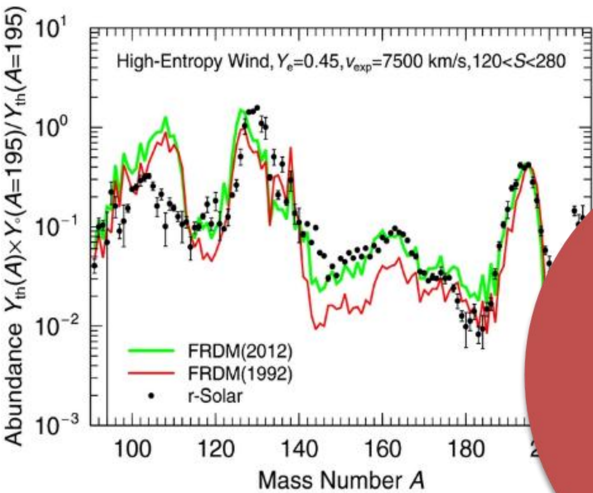
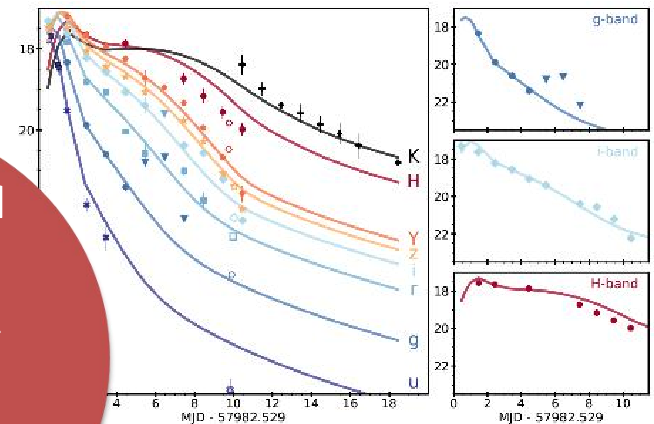
Study of *r*-process nucleosynthesis



r-process abundance peak



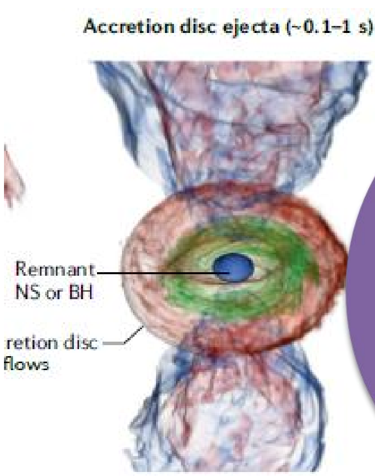
Light-curves@GW170817

Astronomical observation

Multi-messenger astronomy,

Meteolite

Origin of the element In the universe



Simulation

3D-hydrodinamical model

Nuclear Physics Param.

�decy, mass,

EOS,

neutroncapture

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Nuclear Physics Param. for nucleosynthesis

2016

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journal homepage: www.elsevier.com/locate/ppnp

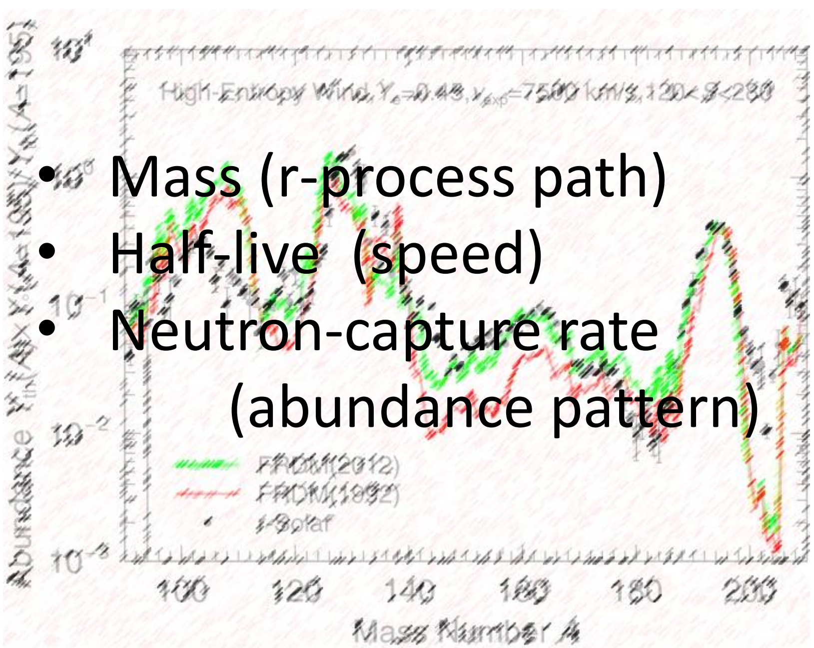
ELSEVIER

Review

The impact of individual nuclear properties on *r*-process nucleosynthesis

M.R. Mumpower[a], R. Surman[a,*], G.C. McLaughlin[b], A. Aprahamian[a]

[a] Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA
[b] Department of Physics, North Carolina State University, Raleigh, NC 27695, USA



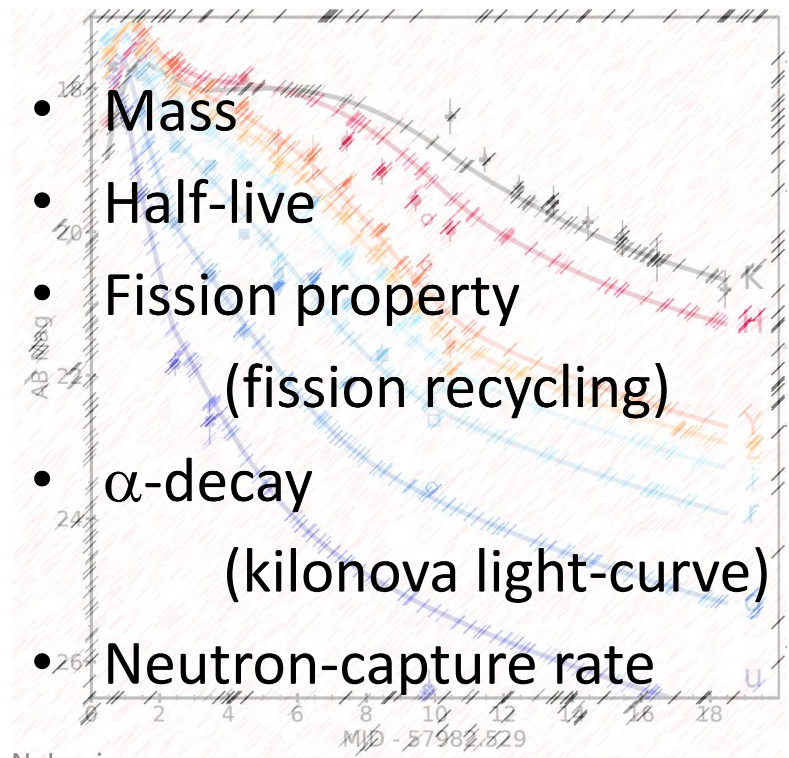
- Mass (r-process path)
- Half-live (speed)
- Neutron-capture rate
  (abundance pattern)

2021

REVIEWS OF MODERN PHYSICS, VOLUME 93, JANUARY–MARCH 2021

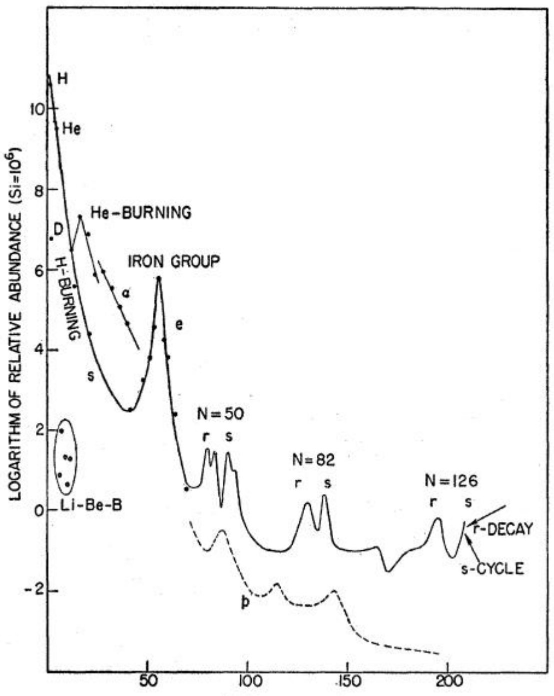
Origin of the heaviest elements: The rapid neutron-capture process

J. J. Cowen et al.,



- Mass
- Half-live
- Fission property
  (fission recycling)
- α-decay
  (kilonova light-curve)
- Neutron-capture rate

2 processes for heavier elements



The Nobel Prize in Physics 1983

Photo from the Nobel Foundation archive.
Subramanyan Chandrasekhar

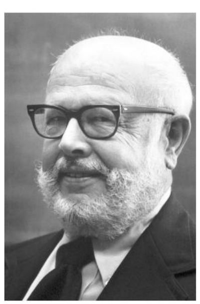


Photo from the Nobel Foundation archive.
William Alfred Fowler

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

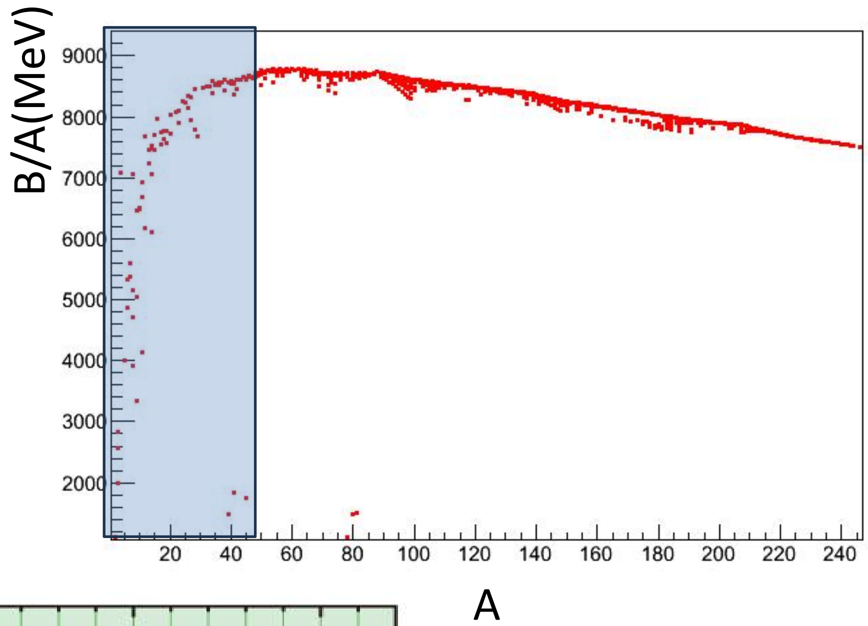
"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

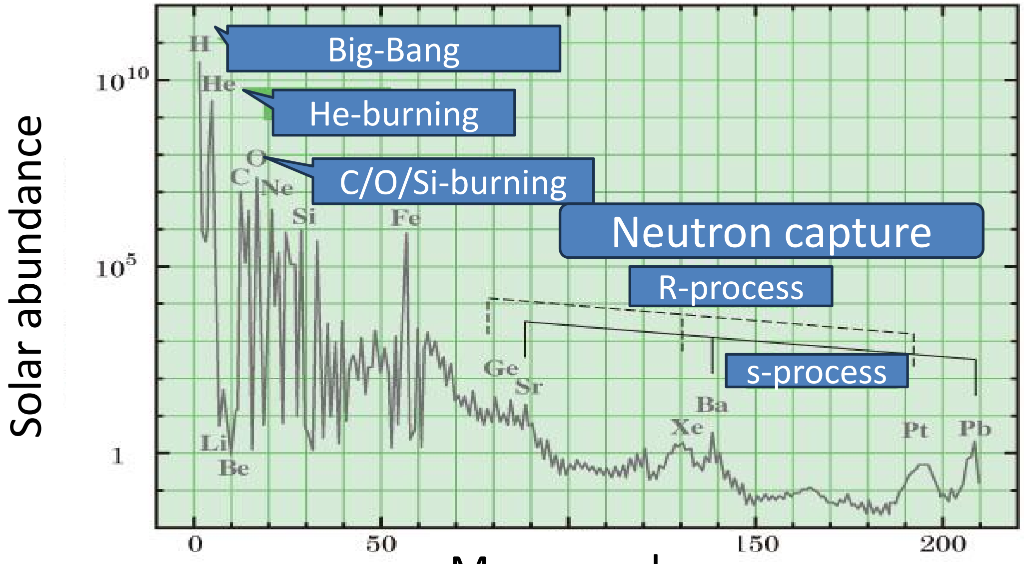
TABLE OF CONTENTS

https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.29.547

Solar abundance

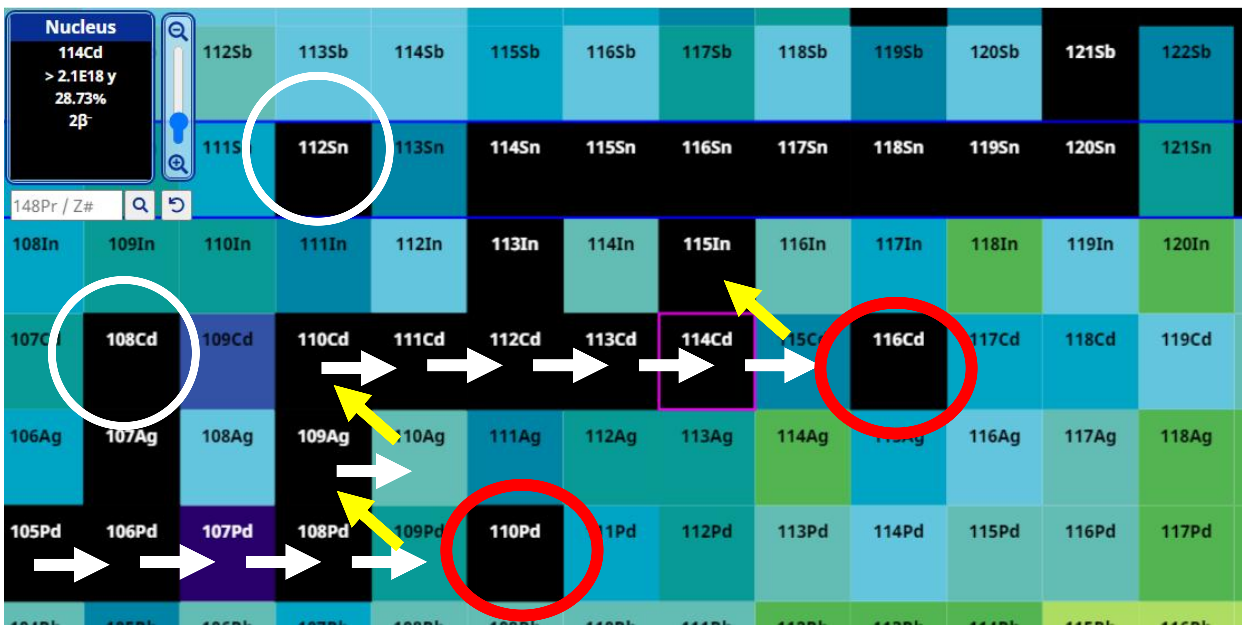
- Hydrogen burning
- Helium burning
- α process
- s-process
- r-pocess



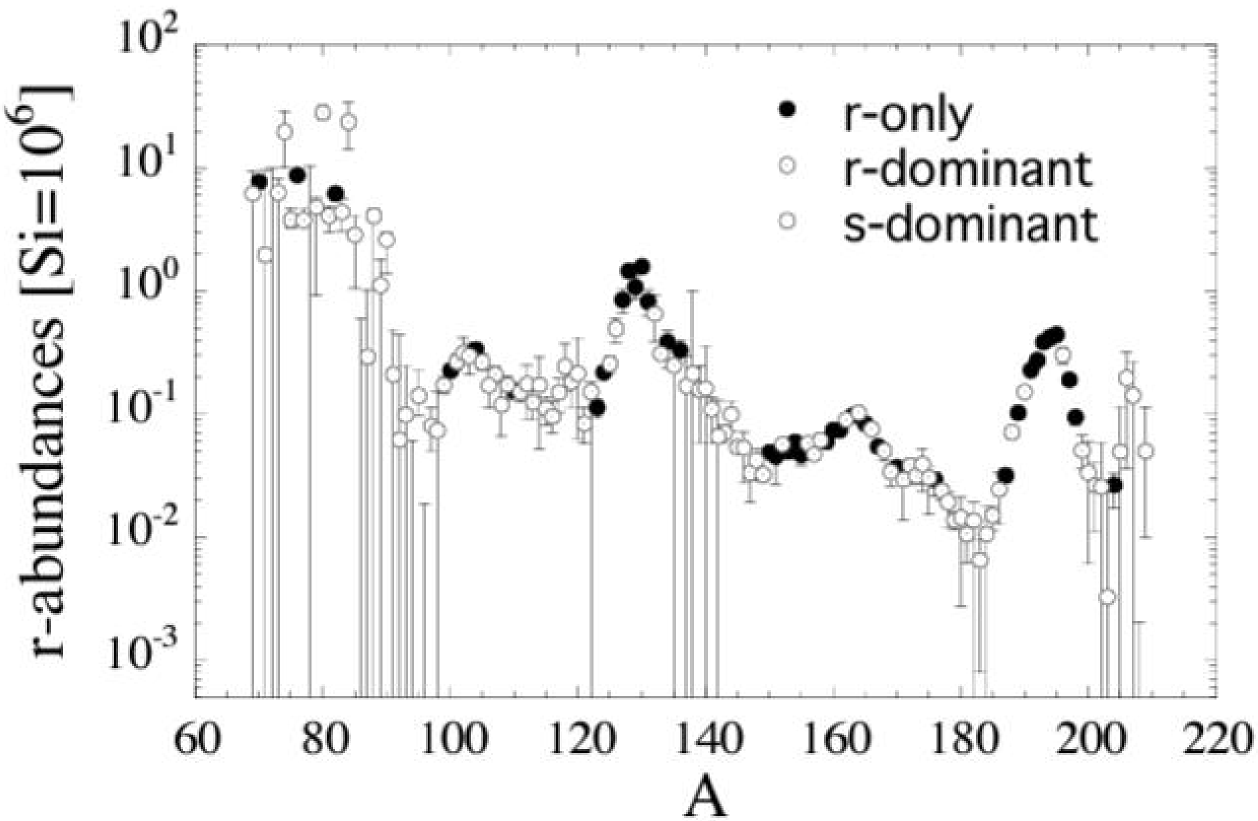


Scenarios of nuclear synthesis for A>60

- **S-process**: slow-neutron capture nucleosynthesis, e.g. AGB star,
$$N_n \sim 10^{11} \mathrm{m}^{-3}, \tau_{(n,\gamma)} \sim 10^5 \text{ year}$$
- **R-process**: rapid-neutron capture nucleosynthesis, e.g. supernovae, nsm
$$N_n \sim 10^{28} \mathrm{m}^{-3}, \tau_{(n,\gamma)} \sim 10^{-5} \text{ s}$$
- **Rp-process**: rapid-proton capture nucleosynthesis

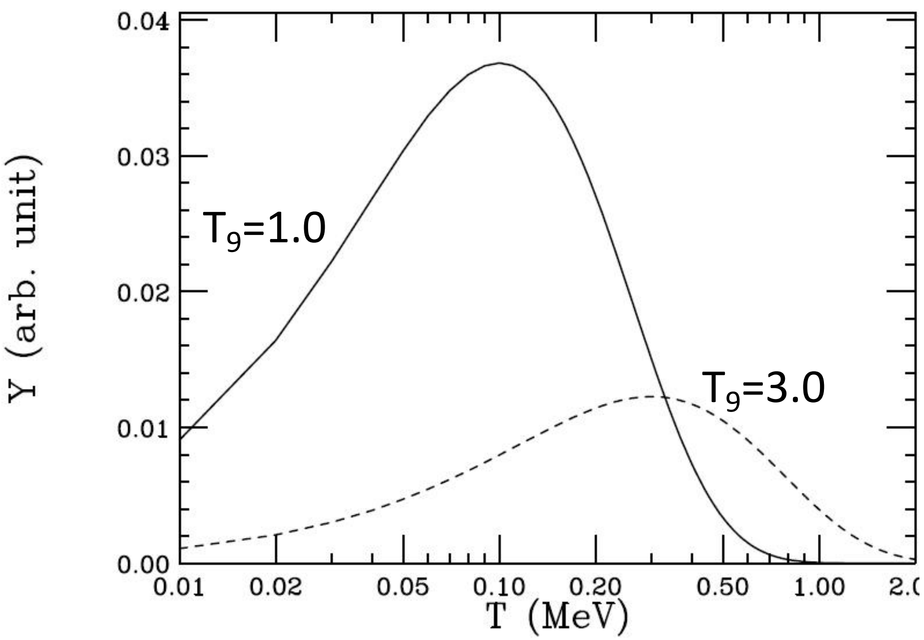


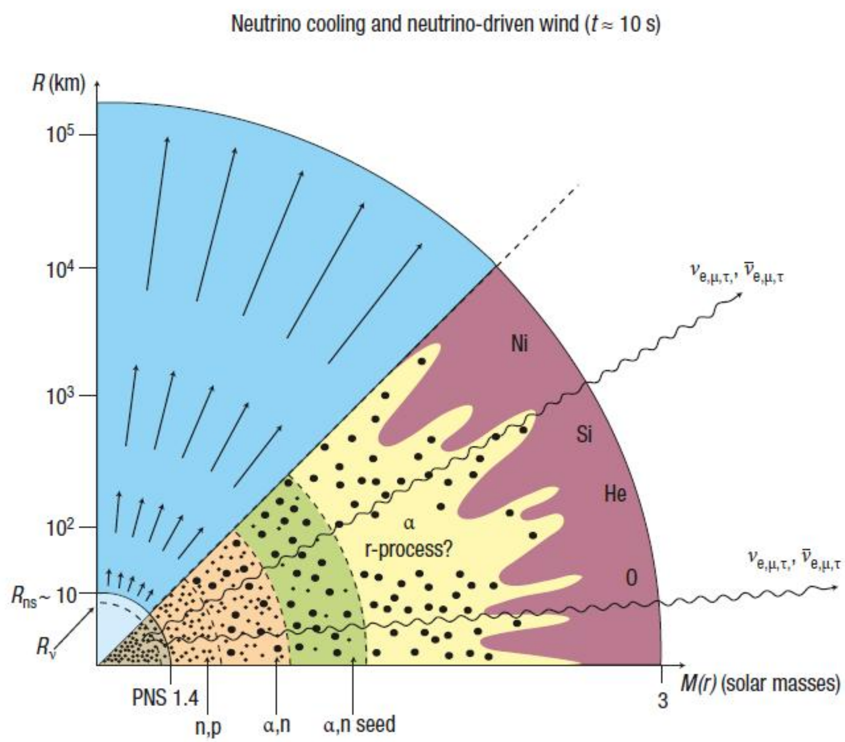
r-process abundance



$$rprocess = total\ - sprocess$$

Temperature in r-process



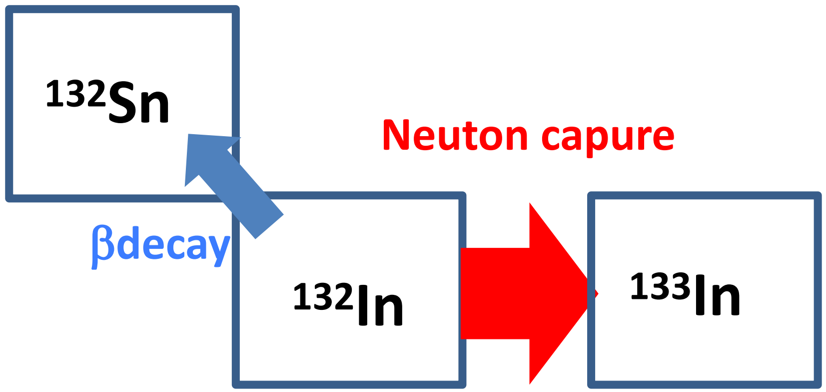


n-capture @$1<T_9<3$

S. Woosley and T. Janka,
Nature Physics 172, 147 (2005)

Elementary process of r-process

β decay and neutron-capture



β rate ω_β=1/t = **2.47 [s^{-1}]**

ω_n = N_n <σ>^{max} v

=10^{20} x0.1 mb 4.4x10^8 [cm/s]

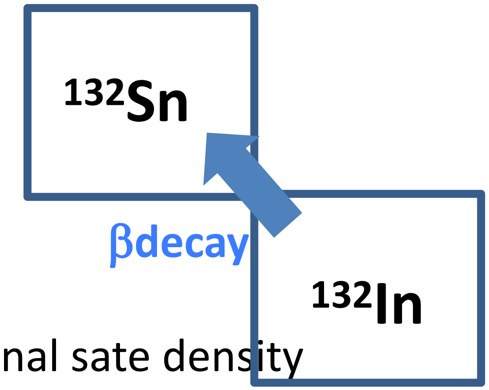
= 4.38 [s^{-1}]

(T^9=1 ~ 0.1 MeV)

Cross section would constrain the neutron density/temperature.

β Decay and neutron capture

- β decay
  - β⁻, $(\mathrm{Z,A}) \rightarrow (\mathrm{Z}+1,\mathrm{A}) + e^{-} + \bar{\nu}$



Outgoing channel

$$\frac{1}{\tau} = \frac{2\pi}{\hbar}\left|\langle\phi_f|O|\phi_i\rangle\right|^2 \rho_f$$

Final sate density

Entrance channel

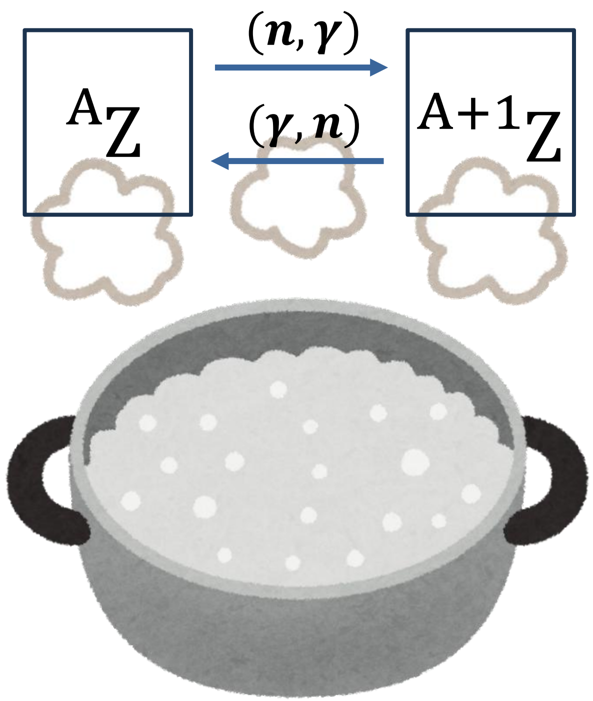
Interaction (G.T., Fermi, etc…)

- (Direct radiative) neutron capture reaction

$$\sigma_{\mathrm{n}\gamma} = \frac{16\pi}{9\hbar}\left(\frac{\varepsilon_\gamma}{\hbar c}\right)^3 \bar{e}^2 \left|\langle\varphi_f|\hat{T}^{E1}|\Psi_i\rangle\right|^2$$

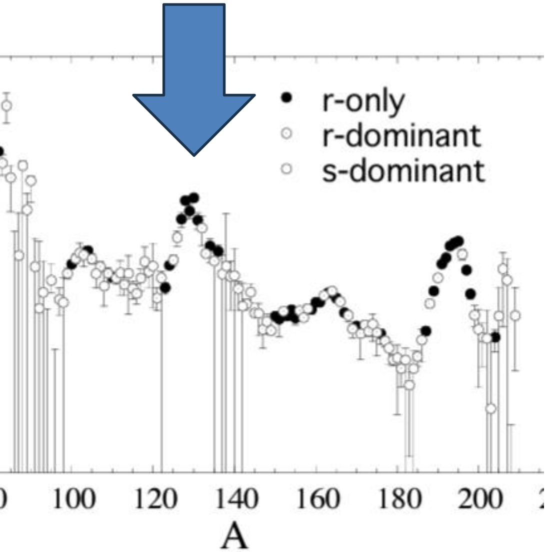
Photodisintegration

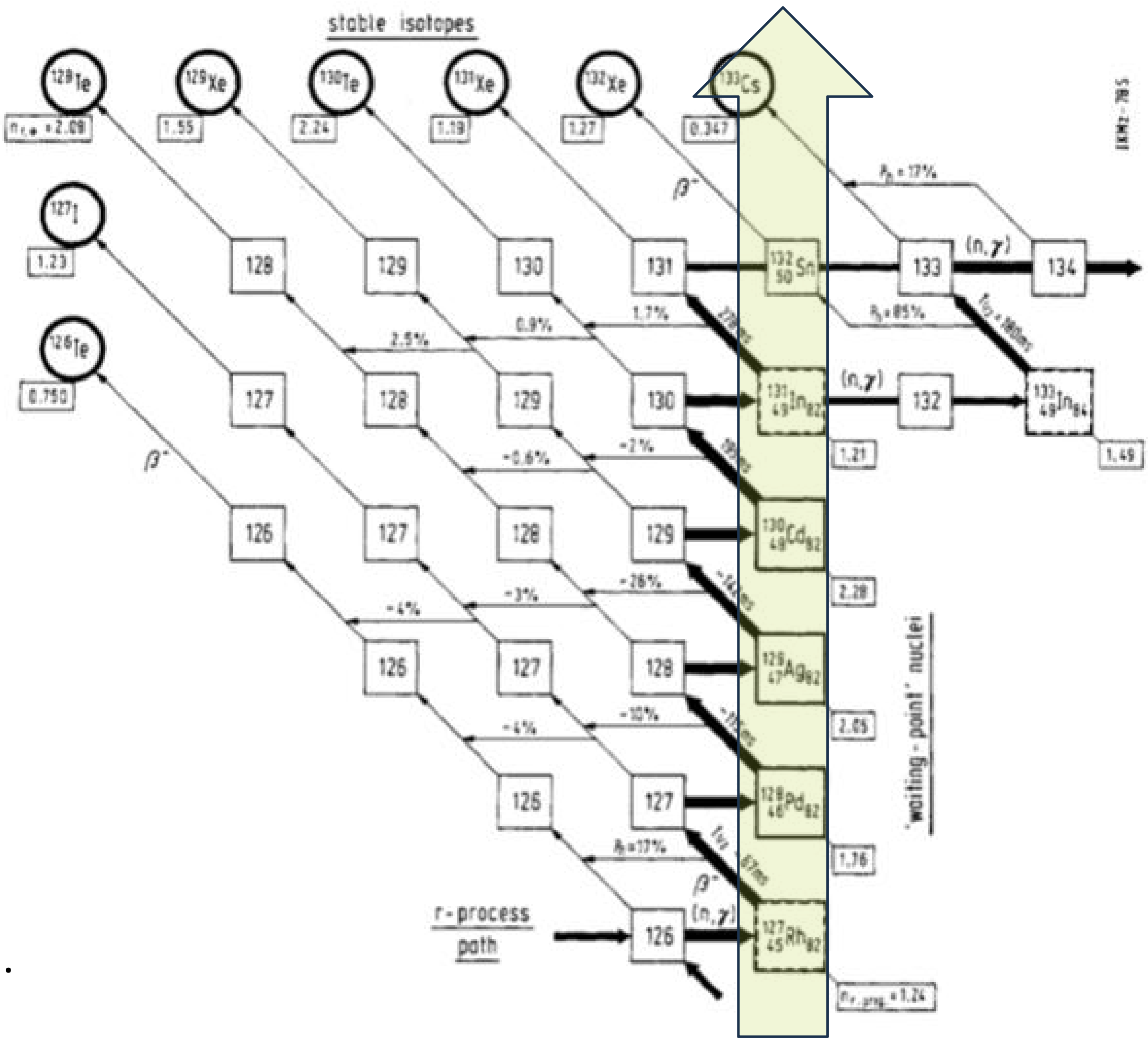
r-process happens in a hot bath



At the nucleus which has the magic number, the neutron capture rate drops, giving rise to the local equilibrium.

Origin of the second peak





K.L. Kratz, et al.,
JPG 14, S331 (1988).

Waiting-point approximation

- Neutron capture rate
  - $r_{n,\gamma}(A,Z) = \langle \sigma_{n,\gamma} v \rangle n_n N(A,Z)$

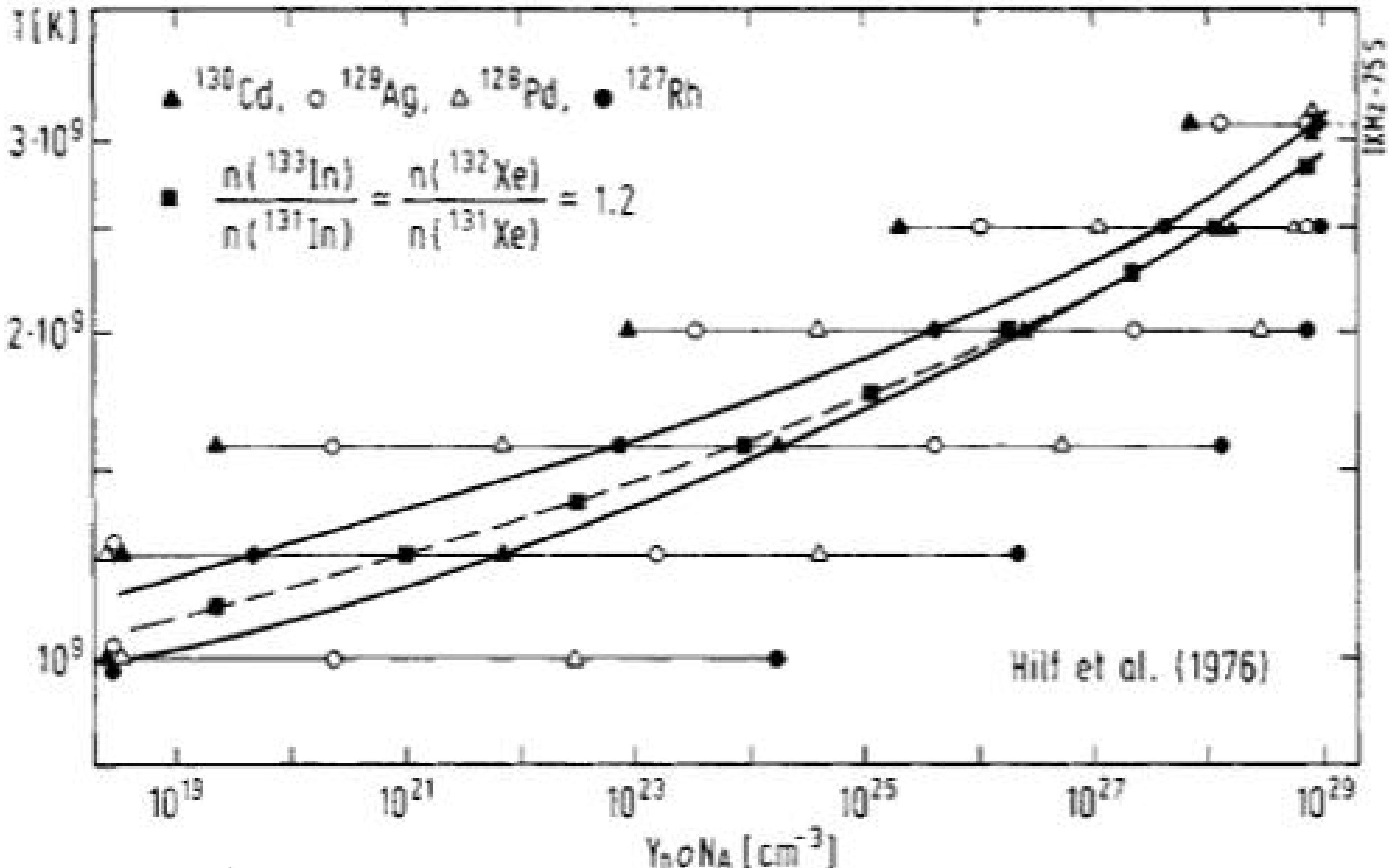
- Photodisintegration ; detailed balance
  - $r_{\gamma,n}(A+1,Z) = \frac{G(A,Z)G_n}{G(A+1,Z)} \left(\frac{A}{A+1}\right)^{3/2} \left(\frac{2\pi kT m_u}{h^2}\right)^{3/2} \langle \sigma_{n,\gamma} v \rangle N(A+1,Z) e^{-\frac{S_n}{kT}}$
  - G: partition function

- $(\gamma,n) \leftrightarrow (n,\gamma)$ equilibrium

  ➔ $r_{n,\gamma}(A,Z) = r_{\gamma,n}(A+1,Z)$

  - $\frac{N(A+1,Z)}{N(A,Z)} = n_n \frac{G(A+1,Z)G_n}{G(A,Z)} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{2\pi\hbar^2}{mkT}\right)^{3/2} \exp[S_n(Z,A)/kT]$

T-N_n for second peak



K.L. Kratz, et al.,
JPG 14, S331 (1988).

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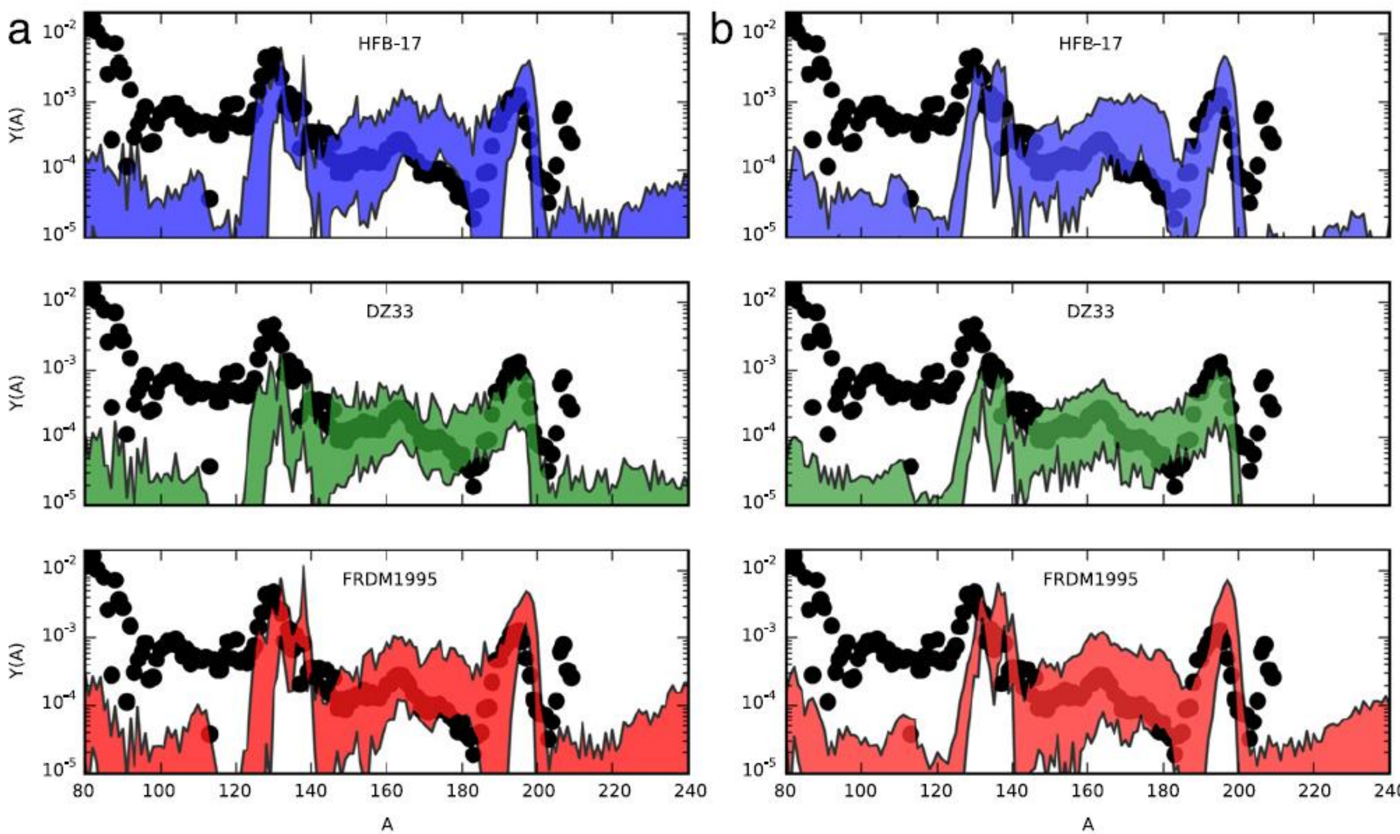
Influence to the final abundance

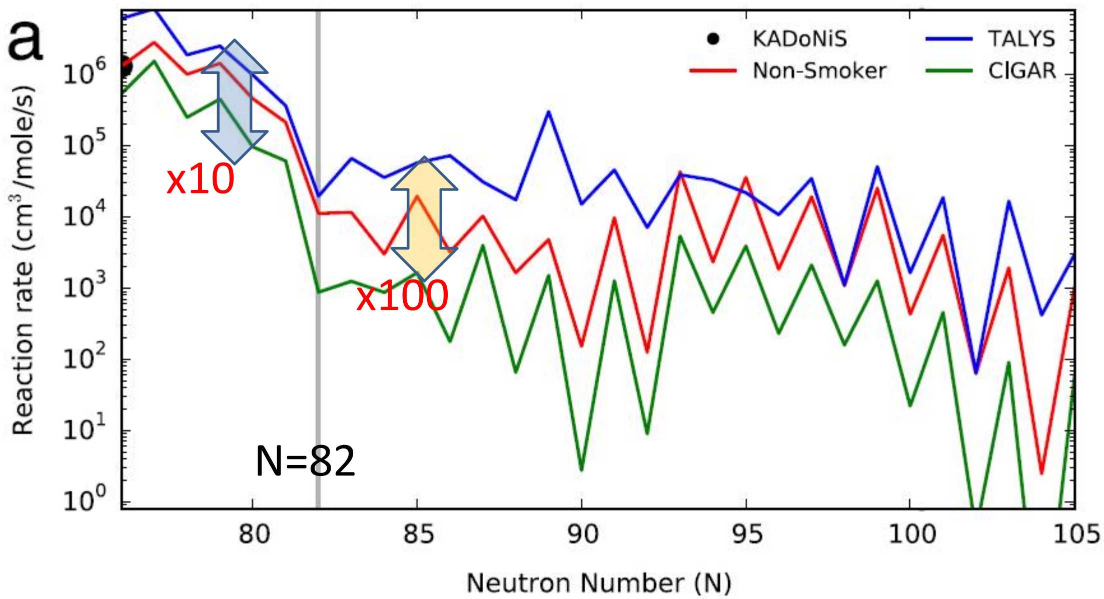


β-decay half-life
x0.1 ~ x10

σ_{ng} 1/10³~10³

M. Mumpower,
Prog. In Part. and Nucl. Phys. 86 (2016)86-126.

Uncertainties of theoretical $\sigma_{n\gamma}$



M. Mumpower,
Prog. In Part. and Nucl. Phys. 86 (2016)86-126.

Neutron capture cross section calculation code:
TALYS
NON-Smoker
CIGAR

^{A}Sn(n,γ)@T_9=1.0
Only Compound reaction is taken into account.

PRINCIPLE OF NEUTRON CAPTURE REACTION

Direct measurement ?

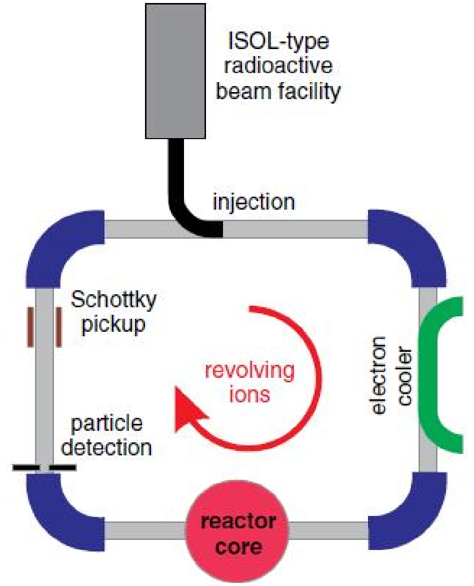
- Lifetime of neutron ~ 14 min.
- Target nucleus is also short-lived.

eg.) ^{130}Sn $T_{1/2}$= 3.7min

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 014701 (2014)

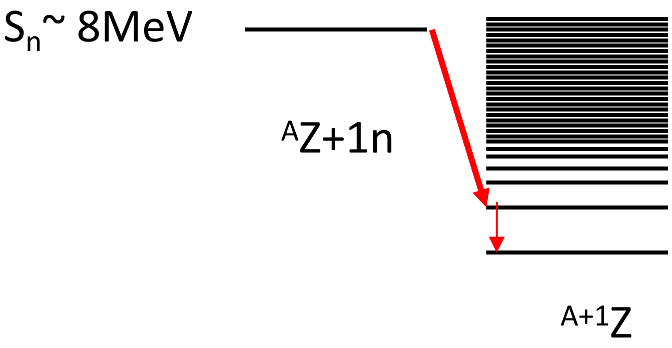
Measurements of neutron-induced reactions in inverse kinematics

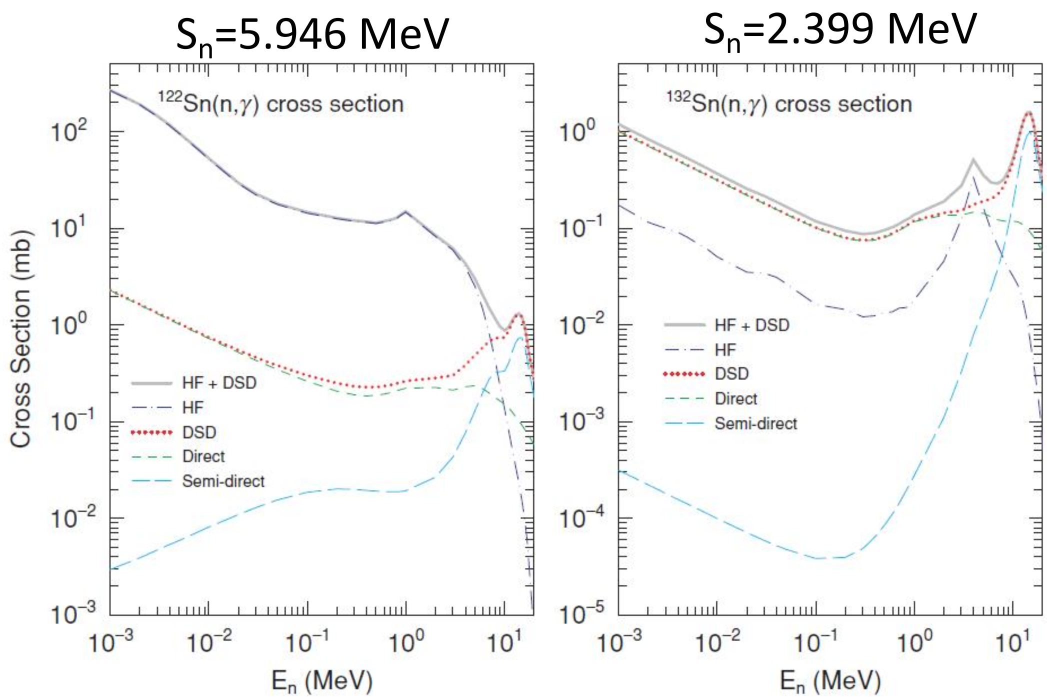
René Reifarth[1] and Yuri A. Litvinov[2,3]
[1] *Goethe-Universität Frankfurt am Main, Max-von-Laue-Str.1, 60438 Frankfurt am Main, Germany*
[2] *GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[3] *Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany*
(Received 17 September 2013; published 10 January 2014)



Two reaction mechanisms of (n,γ)

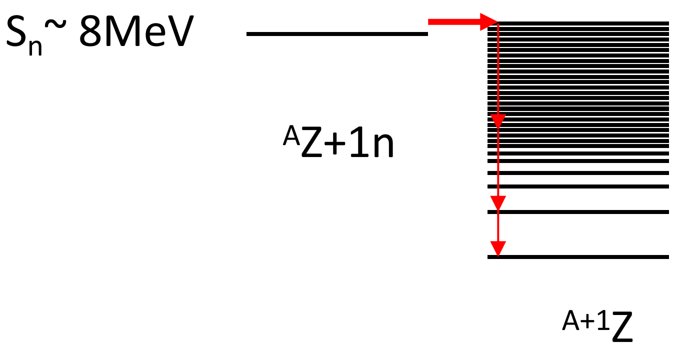
Direct/Semi-direct reaction (DRC)





S. Chiba et al., PRC77, 015809 ('08)

Compound reaction (CN)



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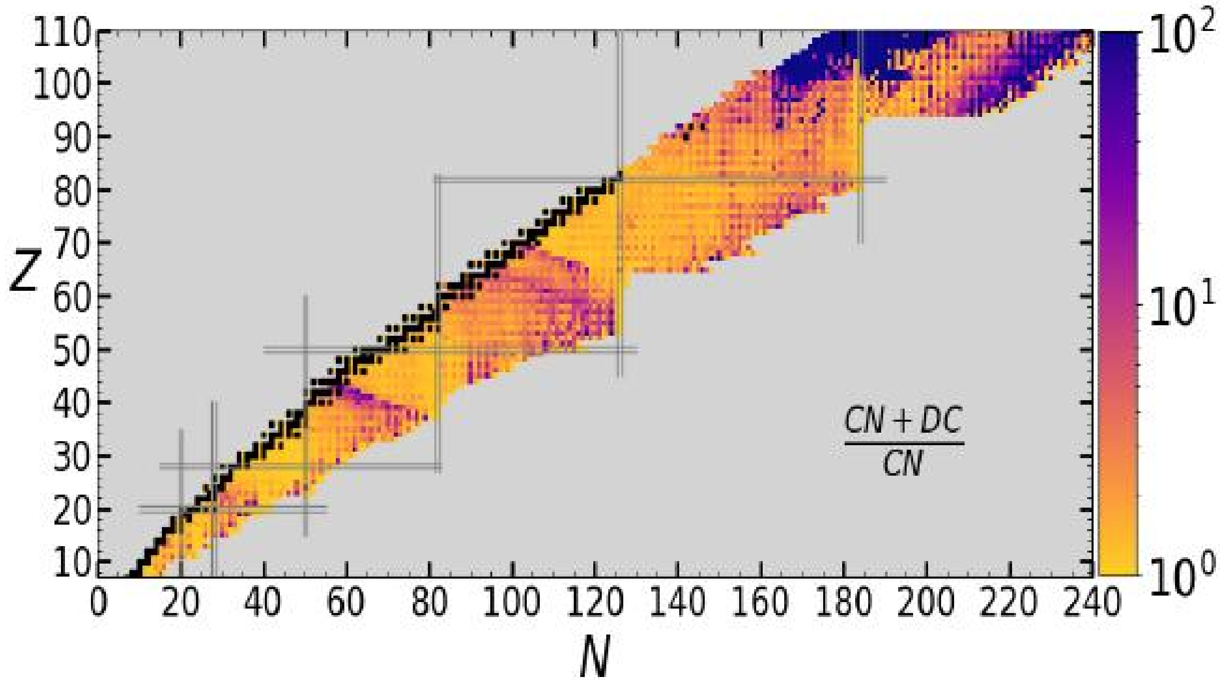
CN vs DC



I. Kullman, et al., (2023)

Summary 1

- Astrophysical site for r-process element is still mystery even after GW170817.
- Many nuclear physics parameters are needed.
- Neutron capture reaction is one of the missing parameters.
- To evaluate cross sections of short-lived nuclei, we need to use quantum mechanics.

DIRECT RADIATIVE CAPTURE REACTION CHANNEL

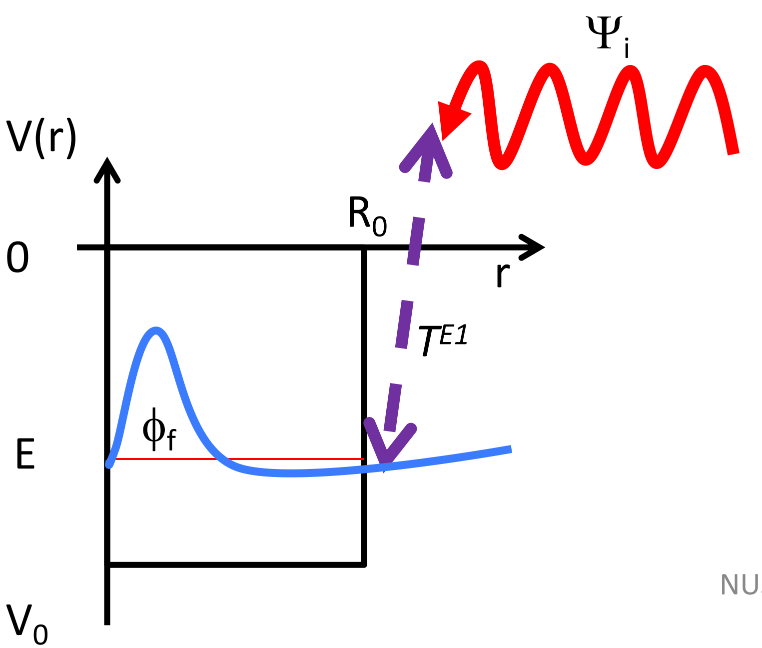
Direct/Semi-Direct reaction

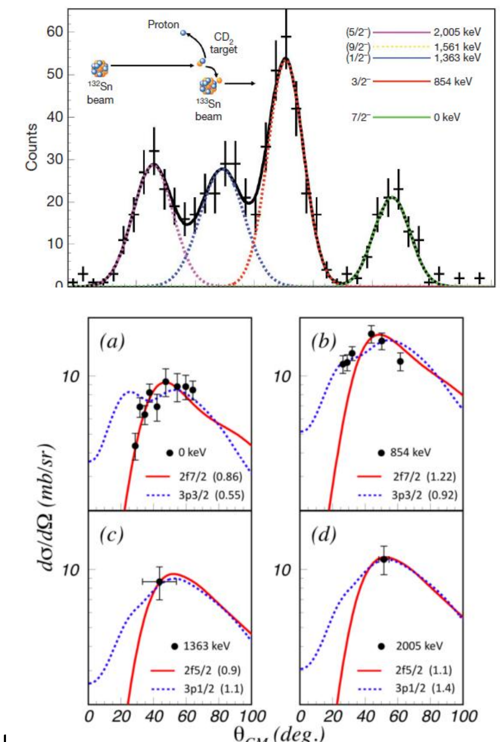
$$\sigma = \frac{16}{9}\pi \frac{\mu k_\gamma^3}{\hbar^2 k} \frac{1}{2I_i+1} \sum_{MM_iM_f} \left| \langle \Psi_f | \hat{O}^*_{1M}(\boldsymbol{r}) | \hat{\Psi}_i \rangle + \sum_s \frac{\langle \Psi_f | \hat{O}^*_{1M}(\boldsymbol{\rho}) | \Psi_s \rangle \langle \Psi_s | H' | \hat{\Psi}_i \rangle}{E - (E_r^s + \varepsilon_f) + i\frac{1}{2}\Gamma_r^s} \right|^2, \quad (7)$$

J.P. Boisson and S. Lang, NPA189, 334 (1972)

final bound sate wave function; J^π, strength

➔ (d,p) reactions etc.

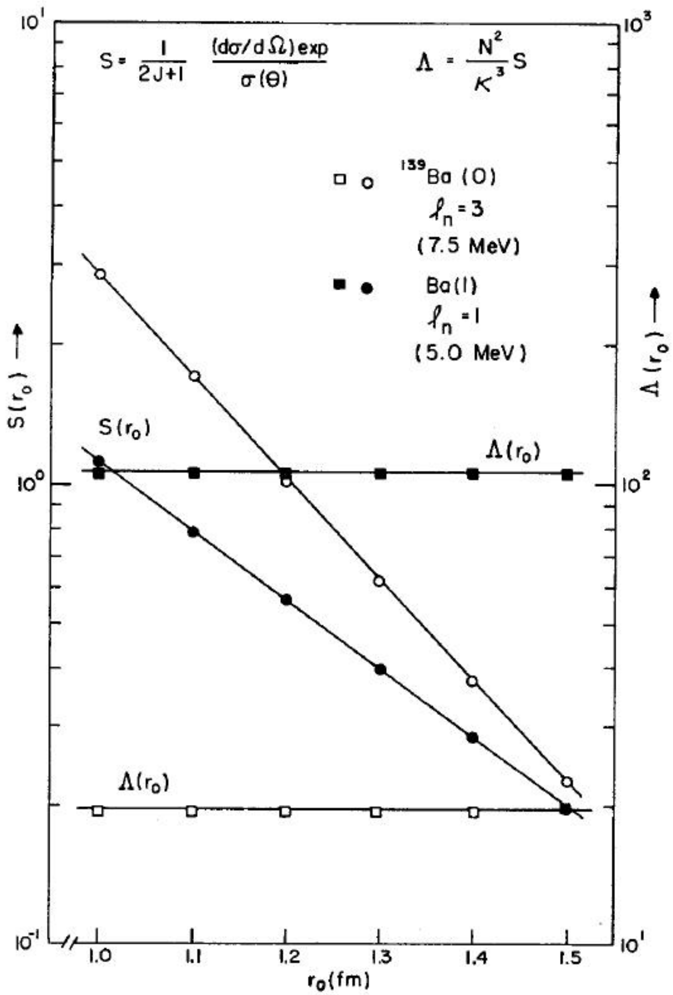




^{132}Sn(d,p)^{133}Sn.

K. Jones et al., Nature 465, 27 (2010)

reduced normalization constant



J. Raraport and A.K. Kerman, NPA119(1968)641.

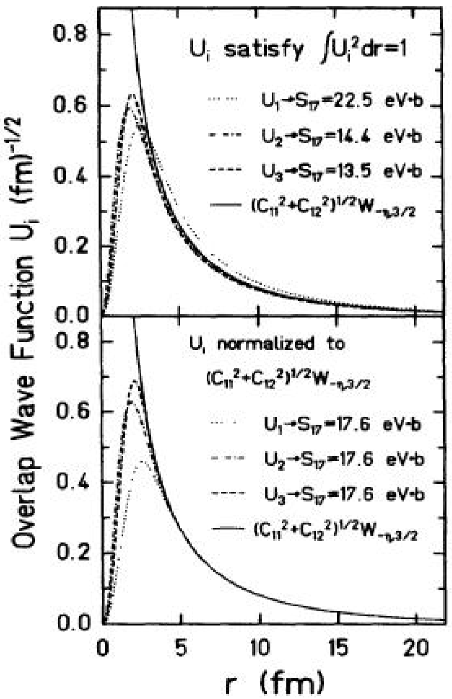
- *S* from DWBA strongly depends on the form factor.
- Reduced normalization constant $\Lambda = N^2/K^3 * S$ was found to be independent.
- "Though introducing reduced normalizations as spectroscopic quantities is somewhat disadvantageous because the single particle fractions of the states in question cannot be recognized directly, … "

B. Eteinmetz et al., PRC18, 71 ('74).

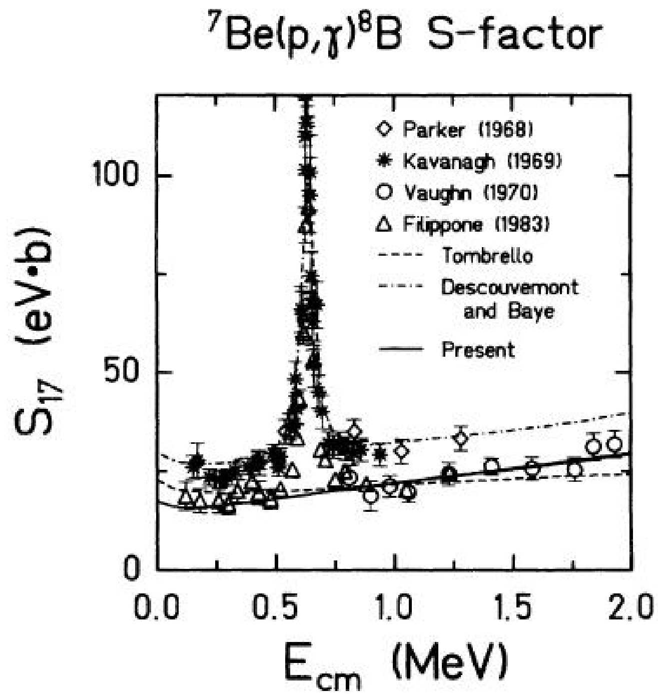
Asymptotic Normalization Constant

$$\left[-\frac{\hbar^2}{2m}\frac{1}{r}\left(\frac{d}{dr}\right)^2 r + \frac{Z_1 Z_2}{r} + \frac{l(l+1)}{2mr^2} - E\right]u_l(r) = 0$$

$u_l(r)$ → Whittaker function



H.M. Xu et al., PRL73,2027 (‘94)



$\sigma_{p\gamma}$ was deduced by integrating
the Whittaker function normalized with ANC
and $r > 5$ fm.

How about the case of *n*?

$$\sigma_{\mathrm{n}\gamma} = \frac{16\pi}{9\hbar}\left(\frac{\varepsilon_\gamma}{\hbar c}\right)^3 \bar{e}^2 \left|\left\langle \Psi_f \middle| \widehat{T}^{E1} \middle| \Psi_i \right\rangle\right|^2$$

$$= \frac{16\pi}{9\hbar}\left(\frac{\varepsilon_\gamma}{\hbar c}\right)^3 \bar{e}^2 \left|\sqrt{S} A_{if} \int_0^\infty u_{lf}(r) r w_{li}(r) dr\right|^2$$

S: spectroscopic factor

$w_{lj}(r)$; radial part of incoming wave function

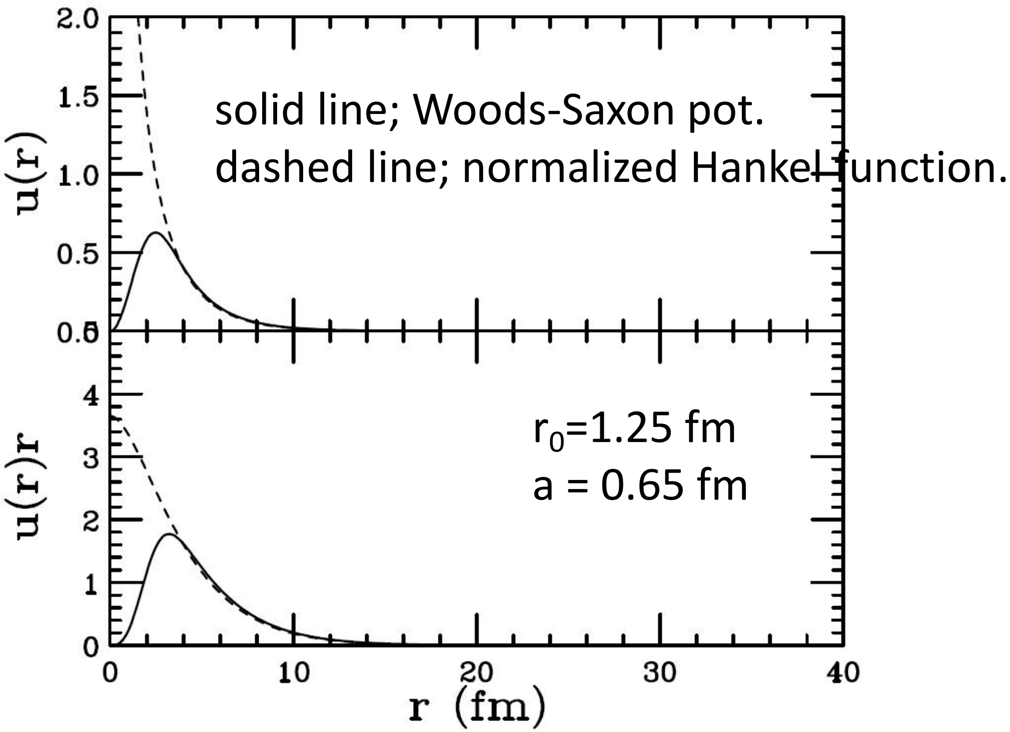
$u_{lf}(r)$; radial part of final bound state wave function

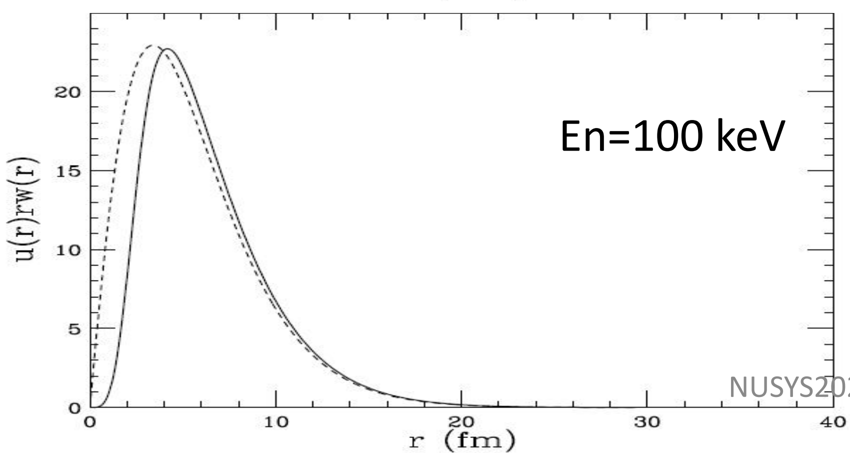
$$T^{E1} = rY^{(1)}(\theta, \varphi)$$

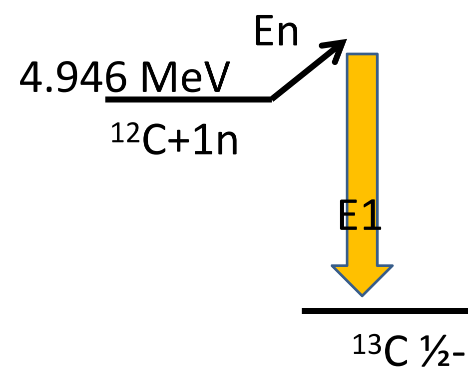
E1 operator magnifies the tail part of the wave function

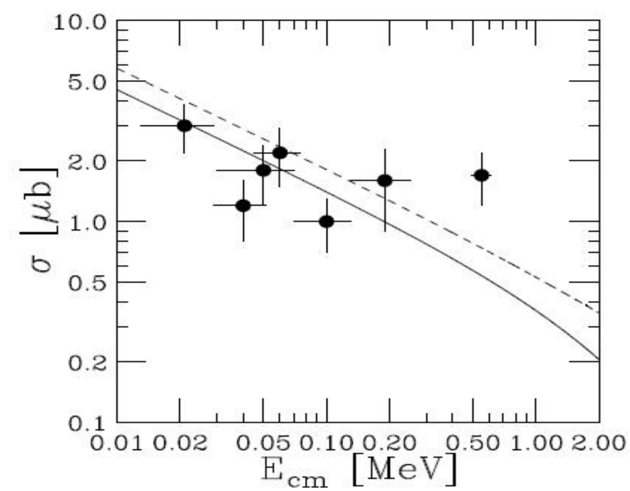
^{12}C(n,γ)^{13}C(1/2$^-$); s-wave n capture

$$0^+ + \frac{1}{2}^+ + \Delta L = E1 + 1/2^-$$





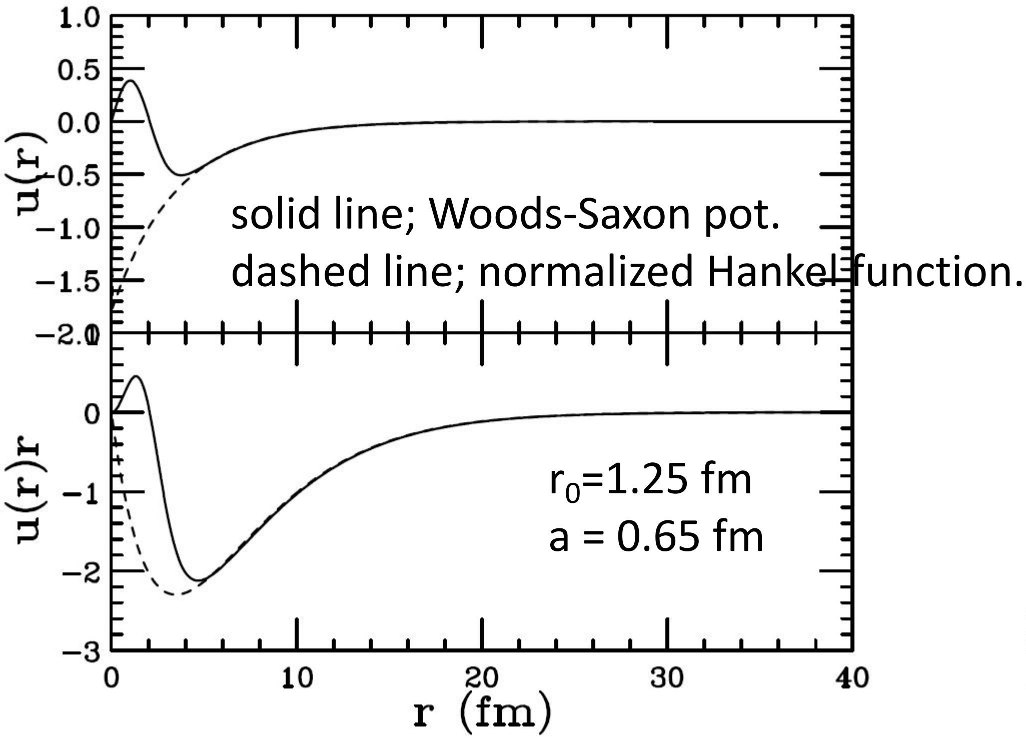


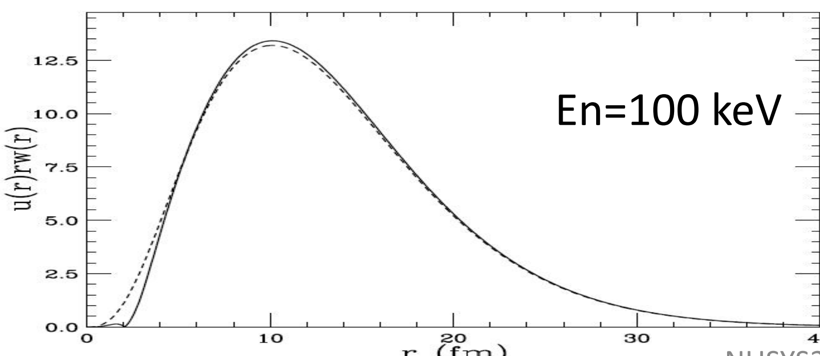


(n,γ)data; APJ 422, 912 (1994)

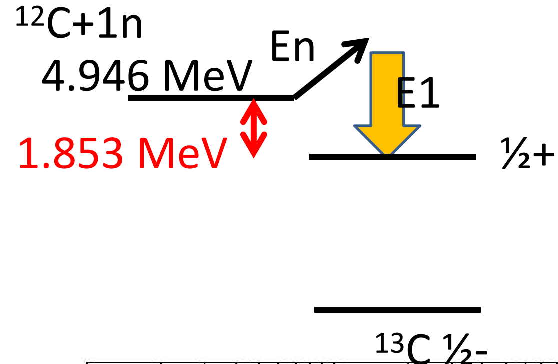
Hankel func. doesn't work well…

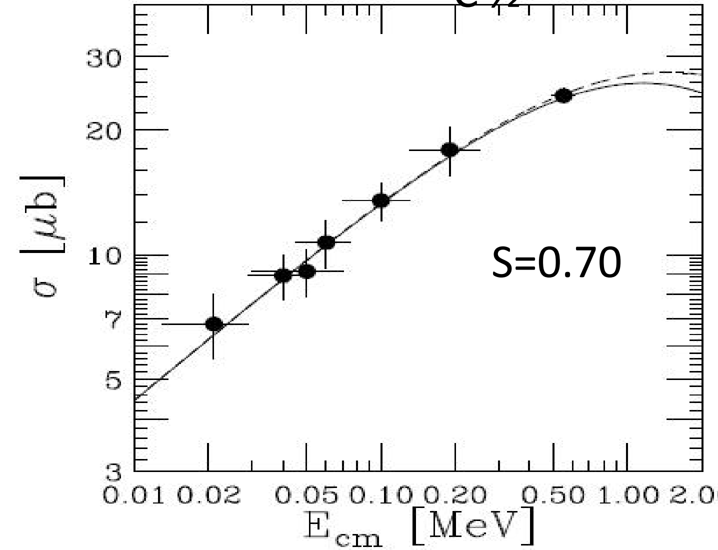
$^{12}C(n,\gamma)^{13}C(1/2^+)$; p-wave n capture





$$0^+ + \frac{1}{2}^+ + \Delta L = E1 + 1/2^+$$





(n,γ)data; APJ 422, 912 (1994)

Hankel func. works well !

Distorted Wave Born Approximation

$$T_{\beta\alpha} \cong \langle \Phi_\beta | V_\beta | \Phi_\alpha \rangle$$

$$\approx D_0 \frac{4\pi}{k_\alpha k_\beta} \frac{m_B}{m_A} \sum_{L_\alpha L_\beta} i^{L_\alpha - L_\beta - m}$$

post form zero range DWBA

$$\times \sqrt{(2L_\alpha + 1)(2l+1)} \langle L_\beta l 00 | L_\alpha 0 \rangle \langle L_\beta l - m m | L_\alpha 0 \rangle$$

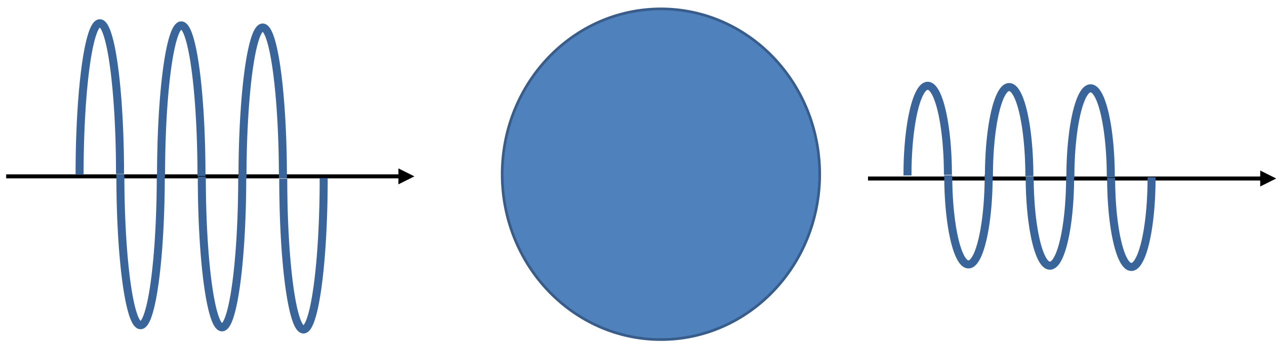
$$\times Y_{L_\beta}^m (\widehat{k}_\beta) \int \frac{u_l(r_\alpha)}{r_\alpha} \chi_{L_\beta}^\beta (k_\beta, \frac{m_A}{m_B} r_\alpha) \chi_{L_\alpha}^\alpha (k_\alpha, r_\alpha) dr_\alpha$$

$d\sigma/d\Omega$ of the transfer reaction → ANC
if the reaction takes place well outside the target nucleus.

radial distribution of the overlap integral;

$$I_{L_\beta}(r) \equiv \langle L_\beta 1 - m m | L_\alpha 0 \rangle Y_{L_\beta}^m (\widehat{k}_\beta) \frac{u_l(r_\alpha)}{r_\alpha} \chi_{L_\beta}^\beta (k_\beta, \frac{m_A}{m_B} r_\alpha) \chi_{L_\alpha}^\alpha (k_\alpha, r_\alpha)$$

Optical model potential



Quantum mechanical wave

Elastic scattering: only direction is changed.

Inelastic scattering: scattering into an exit channel different from the incident one.

Cloudy crystal ball

Elastic scattering: reflection of optical waves

Inelastic scattering: absorption due to the fact that crystal ball is cloudy

Smooth variations of the scattering cross section as a function of incident energy E and target nucleon number A.

Phenomenological OM potential

Optical model potential=

The average interaction between nucleons in the projectile with those in the target

$U_{opt}(\vec{r})$ follows closely the density distribution

$$f(r, r_0, a) = \frac{1}{1 + exp\{(r - r_0)/a\}}$$

In optical model studies, this is known as the Woods-Saxon form

$$U_{vol}(\vec{r}) = -\{V_0 f(r, r_v, a_v) + iW_0 f(r, r_w, a_w)\}$$

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DWBA codes

- DWUCK4,5;
  - https://github.com/padsley/DWUCK5
  - https://github.com/padsley/DWUCK4
- FRESCO;
  - https://www.fresco.org.uk/

Chat GPT?

Can you also let me know the input file for the 130Sn(d,p) reaction at 40 MeV for FRESCO DWBA code?

Certainly! Here is an example input file for the FRESCO DWBA code to calculate the 130Sn(d,p) reaction at 40 MeV. This is a simplified example, and you might need to adjust the parameters according to your specific experiment and requirements:

```
&input
  Title = "130Sn(d,p) Reaction at 40 MeV"
  Ener = 40.0        ! Incident energy in MeV
  React = "130Sn(d,p)131Sn"  ! Reaction description
  Elab = 45.0        ! Laboratory energy in MeV
  ElabStep = 0.5     ! Energy step in MeV
  ElabMax = 60.0     ! Maximum laboratory energy in MeV
  J_i = 0            ! Spin of the initial state (ground state)
  J_f = 1            ! Spin of the final state
/

&channel
  Proj = "130Sn"     ! Projectile
  Targ = "d"         ! Target
  Ex = 0.0           ! Excitation energy of the residual nucleus in MeV
/

&potential
  Type = "saxon"     ! Potential type
  V0 = -50.0         ! Central potential depth in MeV
  R0 = 1.25          ! Central potential radius in fm
  a0 = 0.65          ! Central potential diffuseness in fm
/

&output
  Dir = "output"     ! Output directory
  File = "results"   ! Output file name
  Plot = true        ! Generate plots
/

&options
  Coul = true        ! Include Coulomb interaction
```

```
56Fe(d,p)57Fe @ Ed=12 MeV;
NAMELIST
 &FRESCO hcm=0.1 rmatch=20.000
        rintp=0.20 hnl=0.100 rnl=4 centre=-0.45 jtmax=15
        thmin=1.00 thmax=180.00 thinc=1.00
        it0=1 iter=1
        chans=1 smats=2 xstabl=1
        elab= 12.0 /

 &PARTITION namep='deu'  massp=2.014 zp=1 namet='f56'   masst=55.934 zt=26 nex=1  /
 &STATES jp=1.0 bandp=1 ep=0.0 cpot=1 jt=1.0 bandt=1 et=0.0000  /

 &PARTITION namep='pro' massp=1.0078 zp=1 namet='f57'  masst=56.935 zt=26 qval=5.421 nex
 &STATES jp=0.5 bandp=1 ep=0.0  cpot=2 jt=0.5 bandt=-1 et=0.0000  /
 &partition /

 &POT kp=1 itt=F at=56 rc=1.15 /
 &POT kp=1 type=1 itt=F p1=90 p2=1.15 p3=0.81 /
 &POT kp=1 type=2 itt=F p4=21 p5=1.34 p6=0.68 /

 &POT kp=2 itt=F at=57 rc=1.15 /
 &POT kp=2 type=1 itt=F p1=47.9 p2=1.25 p3=0.65 /
 &POT kp=2 type=2 itt=F p4=11.5 p5=1.25 p6=0.47 /

 &POT kp=3 itt=F at=56 rc=1.00 /
 &POT kp=3 type=1 itt=F p1=65.0 p2=1.25 p3=0.65 /

 &POT kp=4 itt=F ap=1.0000 at=0.0000 rc=1.0000 /
 &POT kp=4 type=1 shape=2 itt=F p1=72.1500  p2=0.0000 p3=1.4840 /

 &POT kp=5 itt=F at=56 rc=1.15 /
 &POT kp=5 type=1 itt=F p1=47.9 p2=1.25 p3=0.65 /
 &POT kp=5 type=2 itt=F p4=11.5 p5=1.25 p6=0.47 /
 &pot /
```

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Sample input of DWUCK4

^{130}Sn(d,p)^{131}Sn* (Ex=3.9 MeV, J^{π}=3p$_{3/2}$)

```
1001000001000000000                                 130Sn(d,p)131Sn(Ex=3.9 p3)
 900.000  0.0000  0.1000
 40   1   1 3
  0.1000  0.0000 50.0000  0.0000  0.7000
 40.0000  2.0141  1.0000129.914  50.0000  1.3000  0.0000  0.0000  2.0000
   1.000 -91.941   1.150   0.810          -2.348  1.06    0.348
  -2.000   0.000   0.000   0.000   0.000  38.44   1.340   0.680
 -0.432   1.0000  1.0000 131.000 50.0000  1.2500  0.0000  0.0000  1.0000
   1.000 -58.419   1.110   0.570
   2.000   0.000   0.000   0.000   0.000 101.618   1.110   0.500
  -4.000 -11.000   1.110   0.570
 -1.7920  1.0000  1.0000 129.914 50.0000  1.3000  0.0000  0.0000  1.0000
   1.000  -1.000   1.250   0.600
  -4.000  -6.500   1.250   0.600
   2.0000  1.0000  3.0000  1.0000 36.0000
9999999999
```

Incoming wave

outgoing wave

Form factor
(single particle w.f.)
Of the final state

$$40\quad \underbrace{2.0141\quad 1.00}_{^{2}\mathrm{H}}\quad \underbrace{129.914\quad 50.0}_{^{130}\mathrm{Sn}}\quad 1.3\quad 0.0\quad 0.0\quad \underbrace{2.0}_{2J}$$

2 1 3 1 36

# of nodes

L

2 x J

2 x S

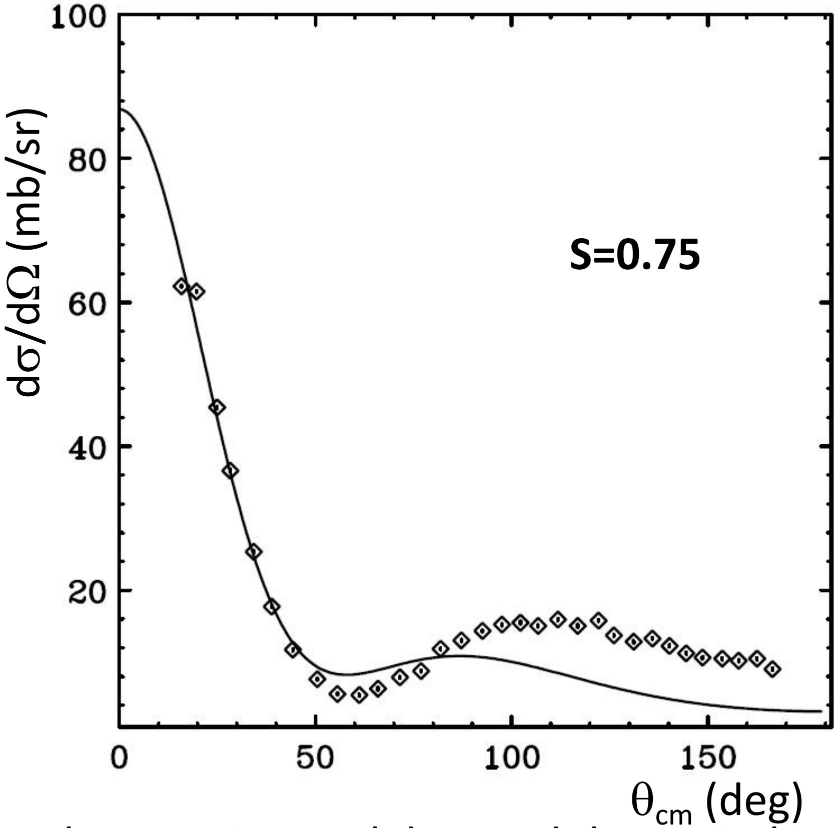
40 1 1 3 transfer to populate $p3/2$

$2\times\Delta J$: angular momentum transfer

Δl : angular momentum transfer

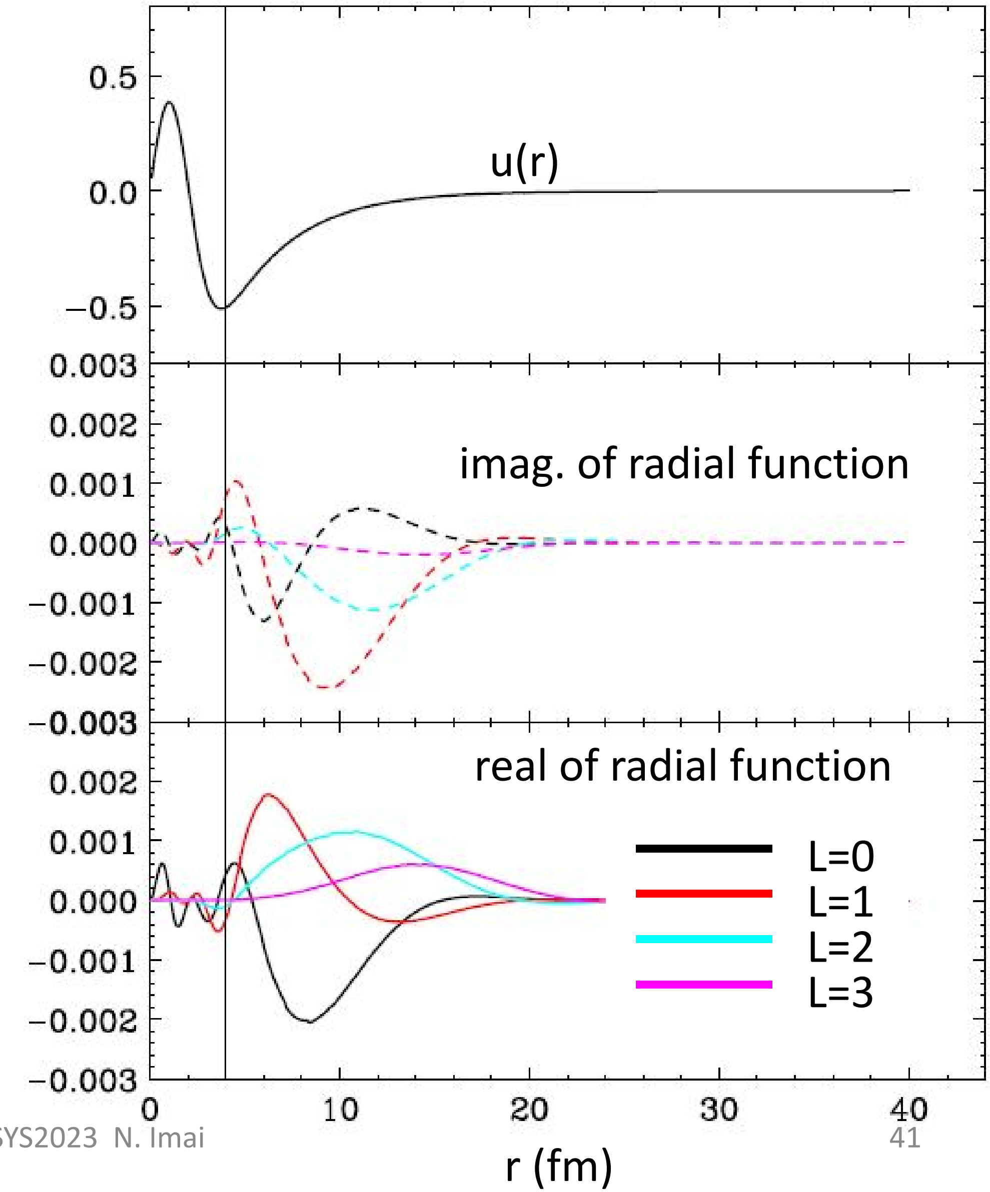
# of angular momentum transfer

$^{12}C(d,p)^{13}C^{*}(1/2^{+})$ @ 2.033 MeV

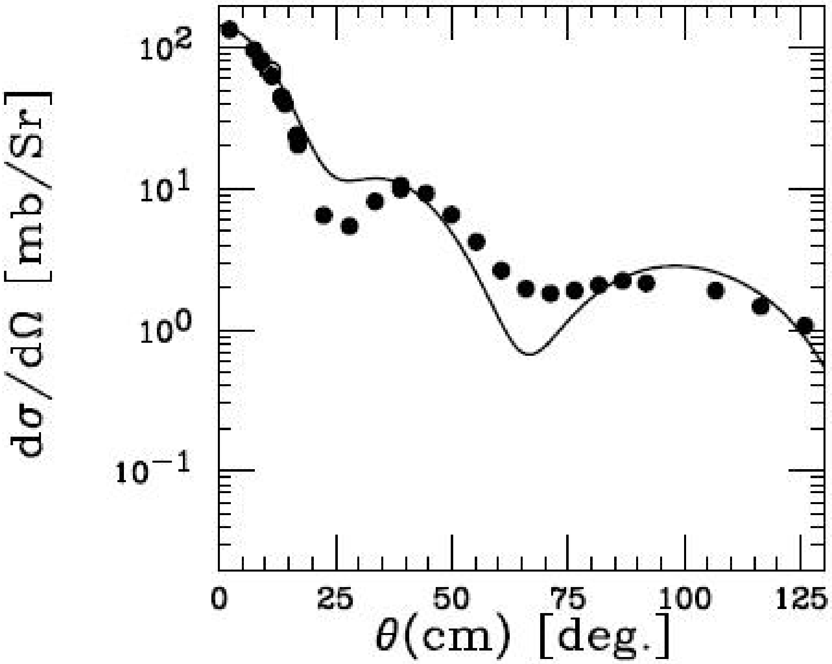


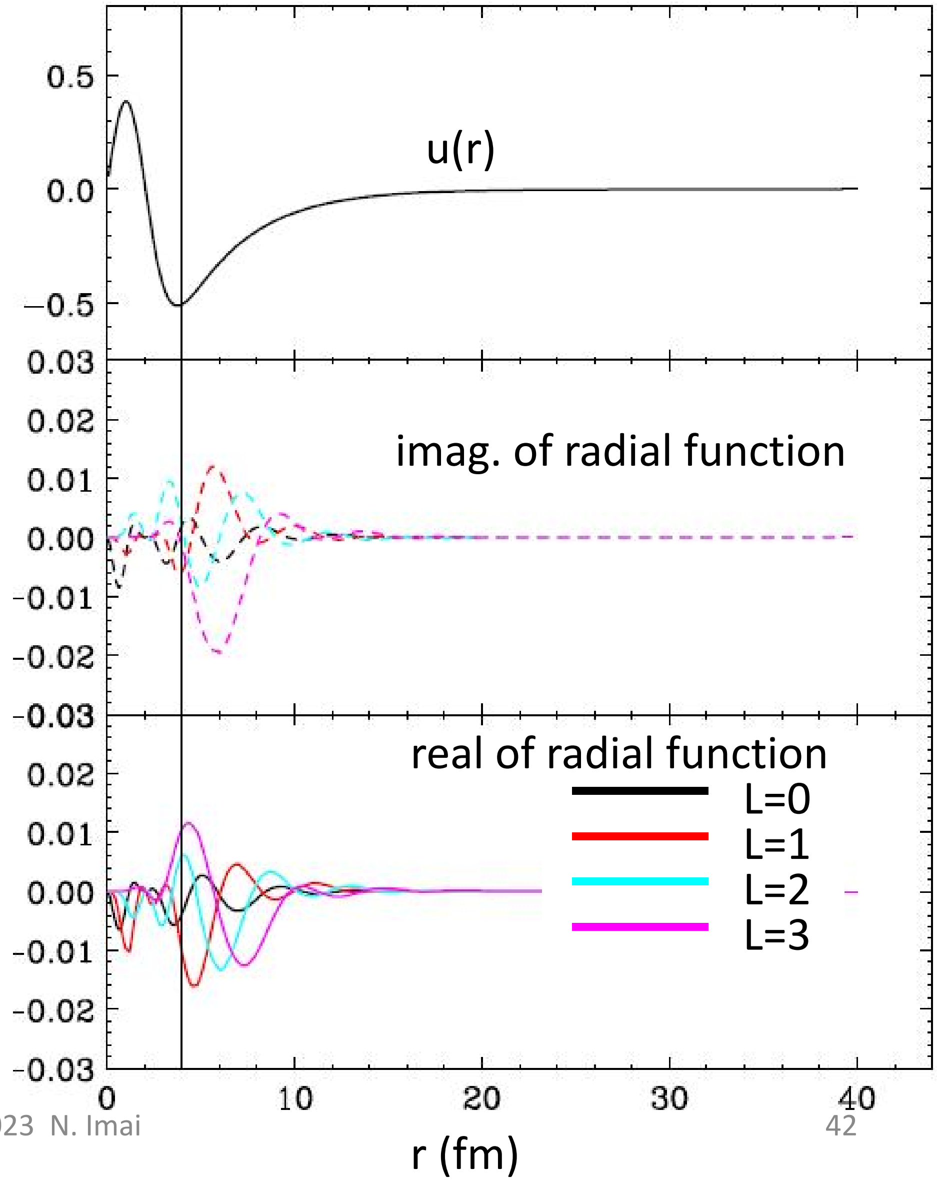
The experimental data and the optical model parameters are taken from NPA92(1967)91-122.

$$\frac{d\sigma/d\Omega_{\mathrm{rcutoff}=0\mathrm{fm}}}{d\sigma/d\Omega_{\mathrm{rcutoff}=4\mathrm{fm}}} = 99\%$$



$^{12}C(d,p)^{13}C^*(1/2^+)$ at 11.8 MeV



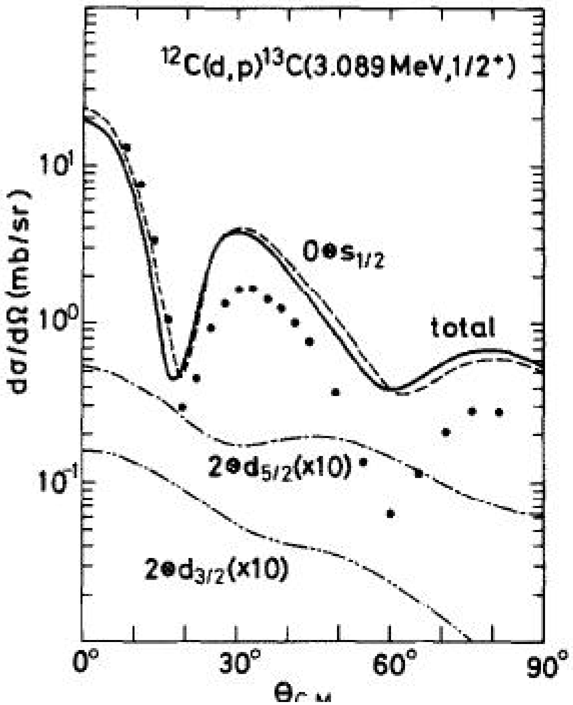


N. Imai et al, NPA 688, 281c (2001)

up to $d\sigma/d\Omega(\theta=2)$ was measured

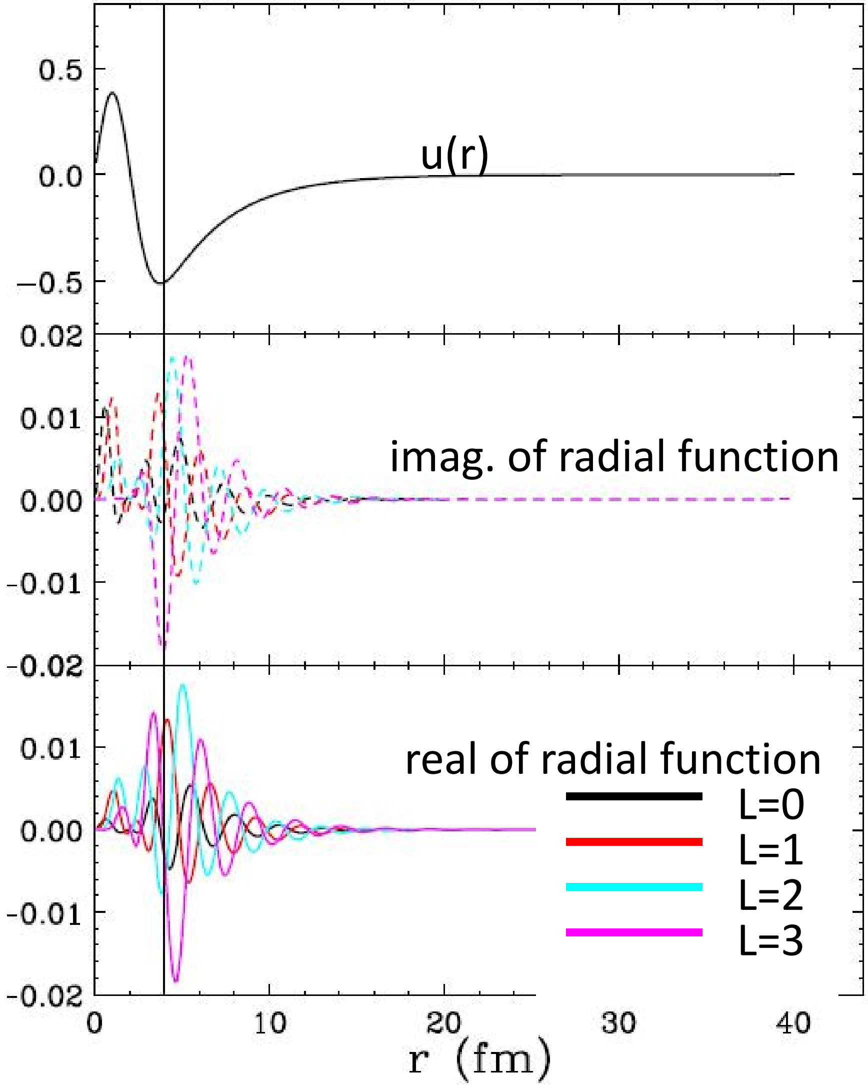
$$\frac{d\sigma/d\Omega_{\mathrm{rcutoff}=0\mathrm{fm}}}{d\sigma/d\Omega_{\mathrm{rcutoff}=4\mathrm{fm}}} = 79\%$$

$^{12}C(d,p)^{13}C^*(1/2^+)$ at 30 MeV



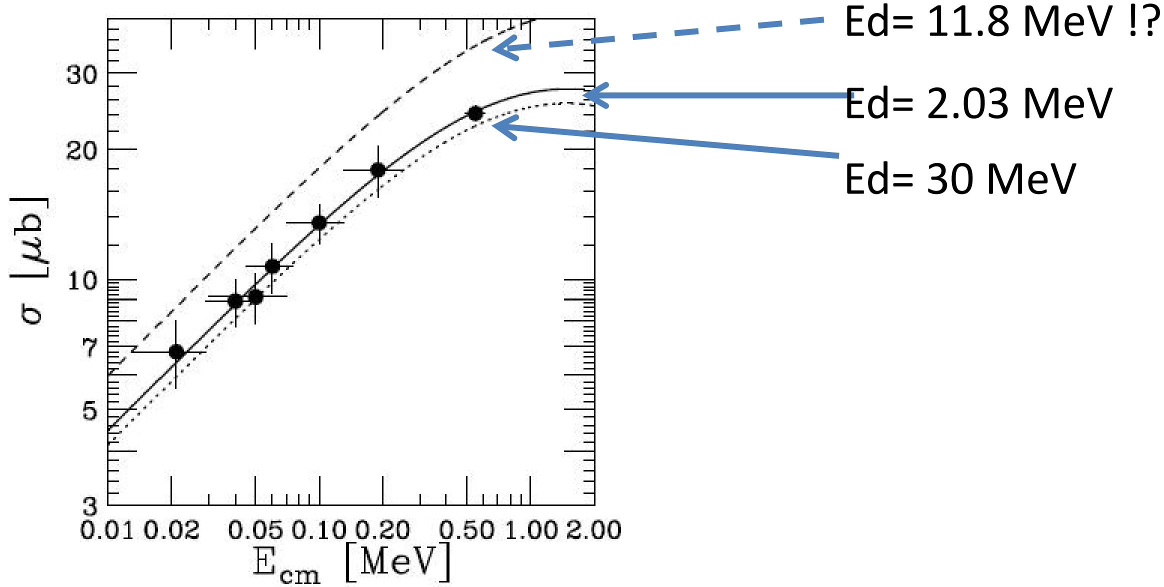
H. Ohnuma et al., NPA 448 ('85)205

$$\frac{d\sigma/d\Omega_{\mathrm{rcutoff}=0\mathrm{fm}}}{d\sigma/d\Omega_{\mathrm{rcutoff}=4\mathrm{fm}}}=66\%$$



σ(n,γ) with ANC

	E_d=2.03 MeV	E_d=11.8 MeV	E_d=30 MeV
S	0.75 (11)	0.94 (8)	0.65
ANC (fm^{-1}) (b^2*S)	2.6 (4)	3.6(4)	2.4



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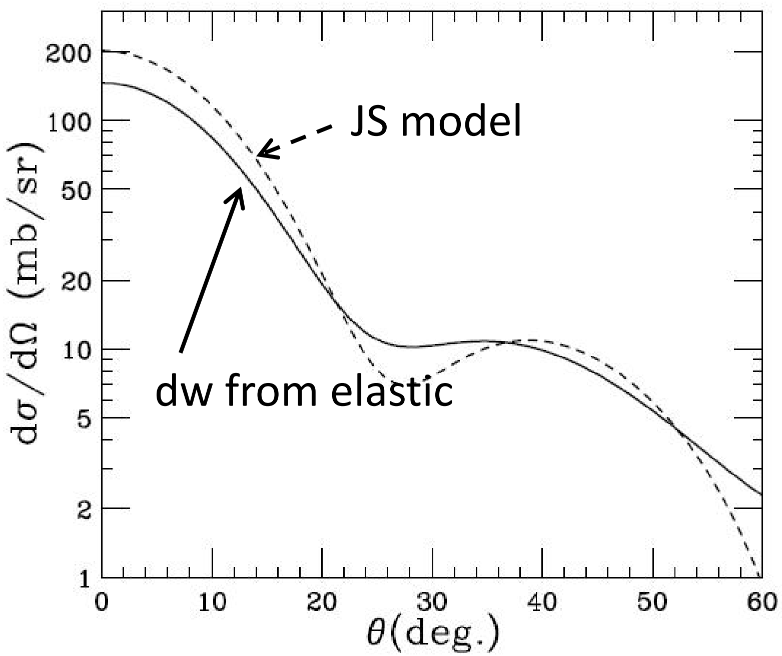
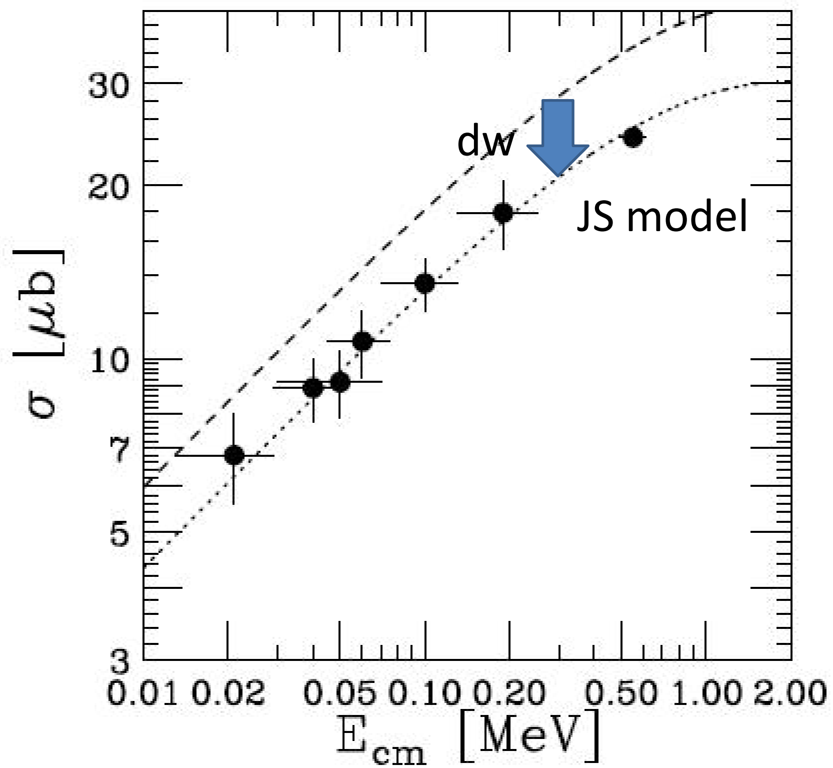
d breakup effect; ADBA





Adiabatic breakup model;

R.C. Johnson and P.J.R. Soper, PRC1, 976 ('70)

Prescription;

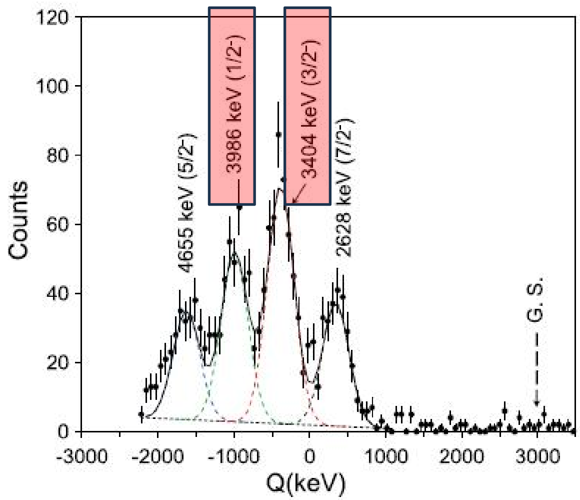
$V_{JS}=V^p+V^n$, $W_{JS}=(W^p+W^n)a/a_{JS}$, $r_{JS}=r$, $a_{JS}=a+0.04$

J.D. Harvey and R.C. Johnson, PRC 3, 636 ('71)

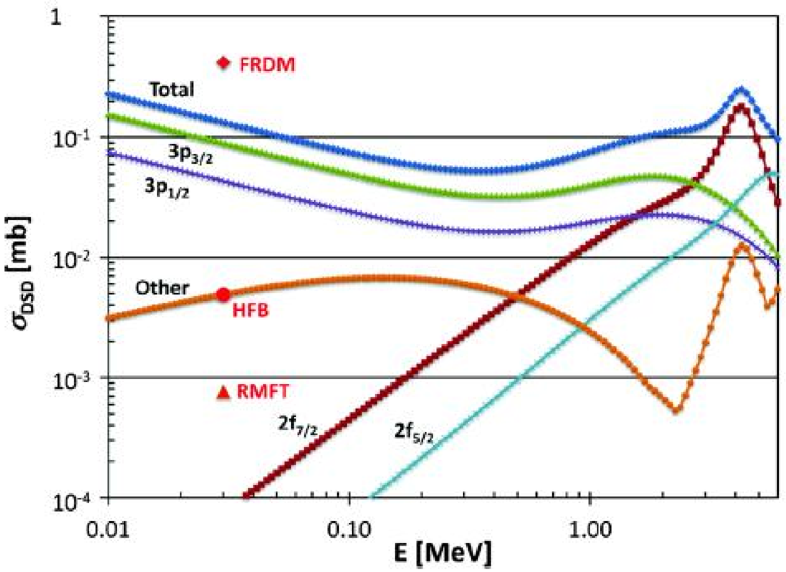
	DW	JS
S	0.94 (8)	0.68 (6)
ANC	3.6(4)	2.6(3)

DRC in ^{130}Sn

- low-energy neutron $L \sim 0$
- E1 transition is dominant.
- For the even-odd nuclei, bound states which have $L \sim 1$ are important.



d(^{130}Sn,p)



PRL109 172501 ('12)

Inverse reactions with RIBs

RIBF; world-leading RIB facility

Any RIB can be produced by the fission of ^{238}U of β=0.7

https://www.nishina.riken.jp/facility/SRC.html

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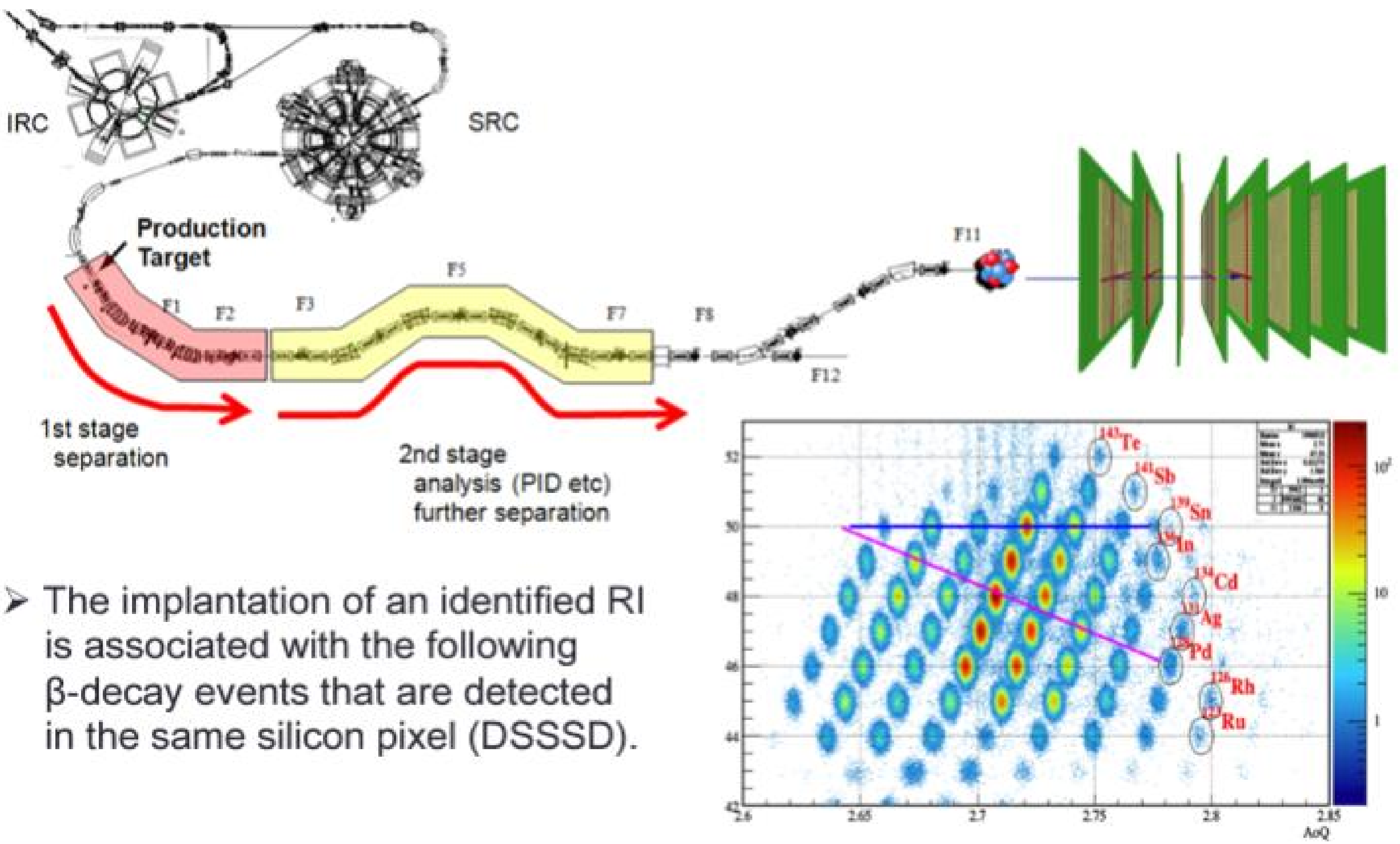
Beam production

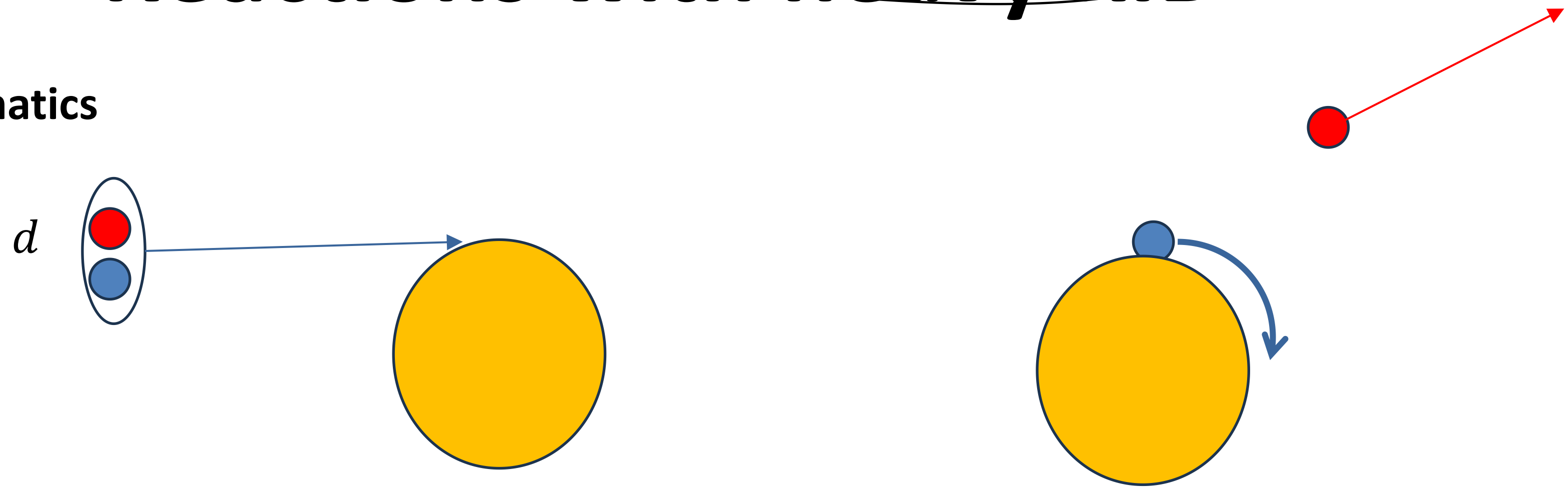


- The implantation of an identified RI is associated with the following β-decay events that are detected in the same silicon pixel (DSSSD).

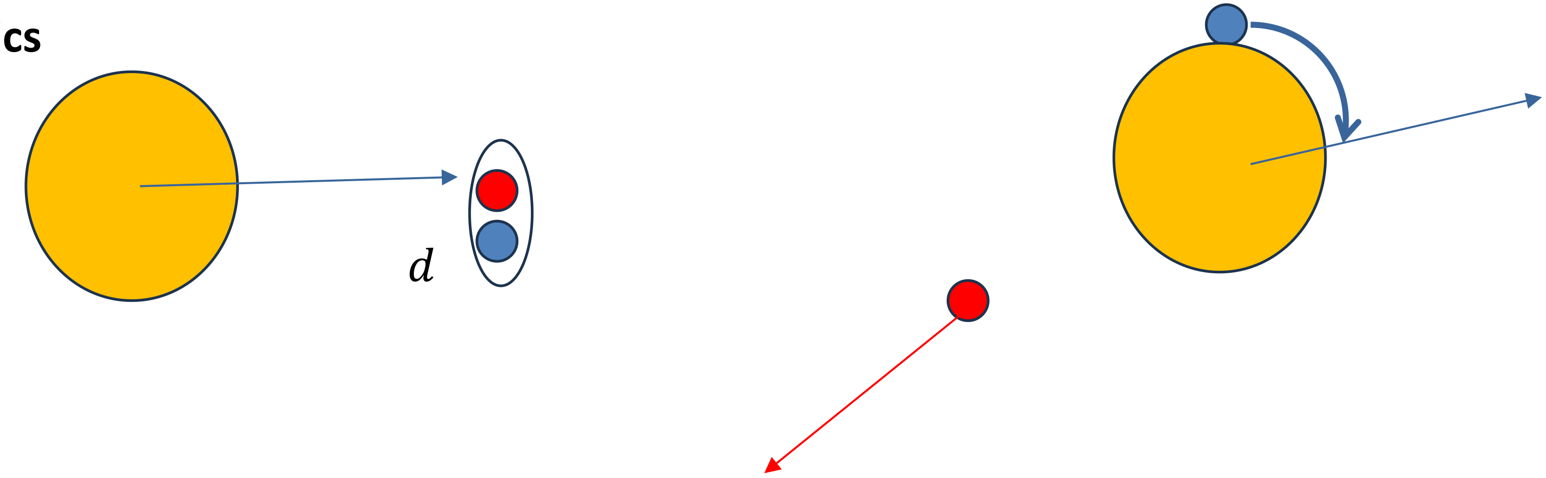
Courtesy of S. Nishimura

Reactions with heavy RIB

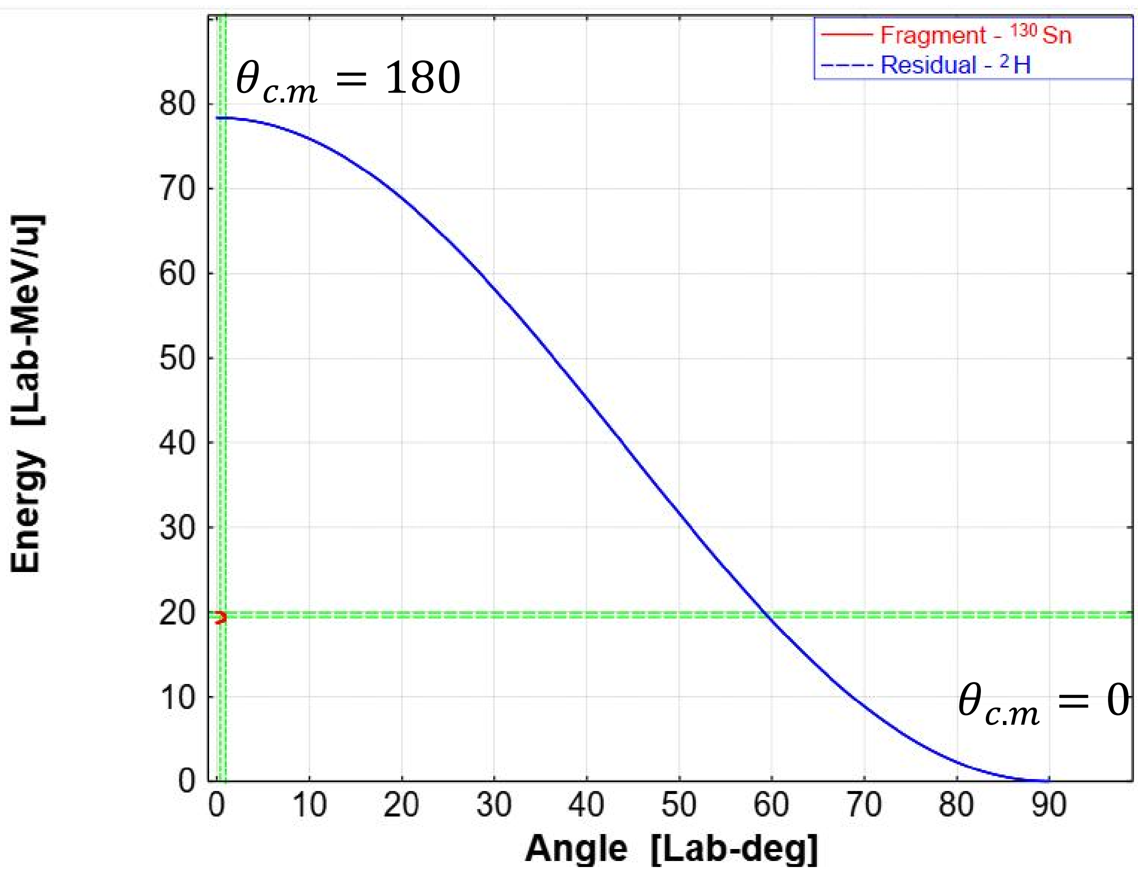
Normal kinematics



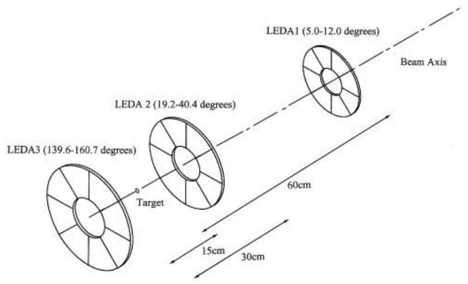
Inverse kinematics



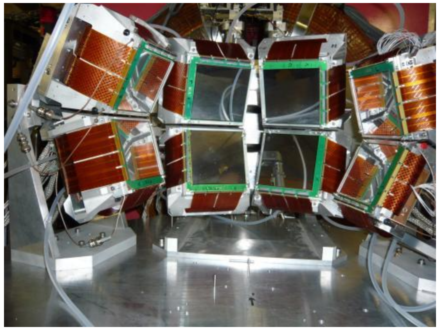
p(^{130}Sn,p)@20 MeV/nucleon



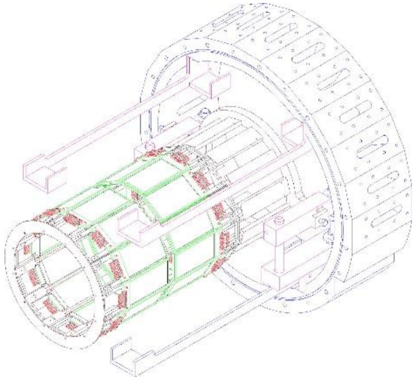
Recoil particle detector array in the world



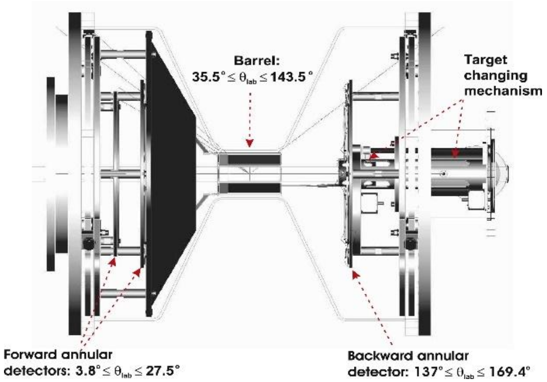
LEDA @ Leuven/Edinburg
T. Davidson, et al., NIMA 454, 350 (2000).



MUST/MUST2 @ France
Y. Blumenfeld et al., NIMA 421, 471(1999)



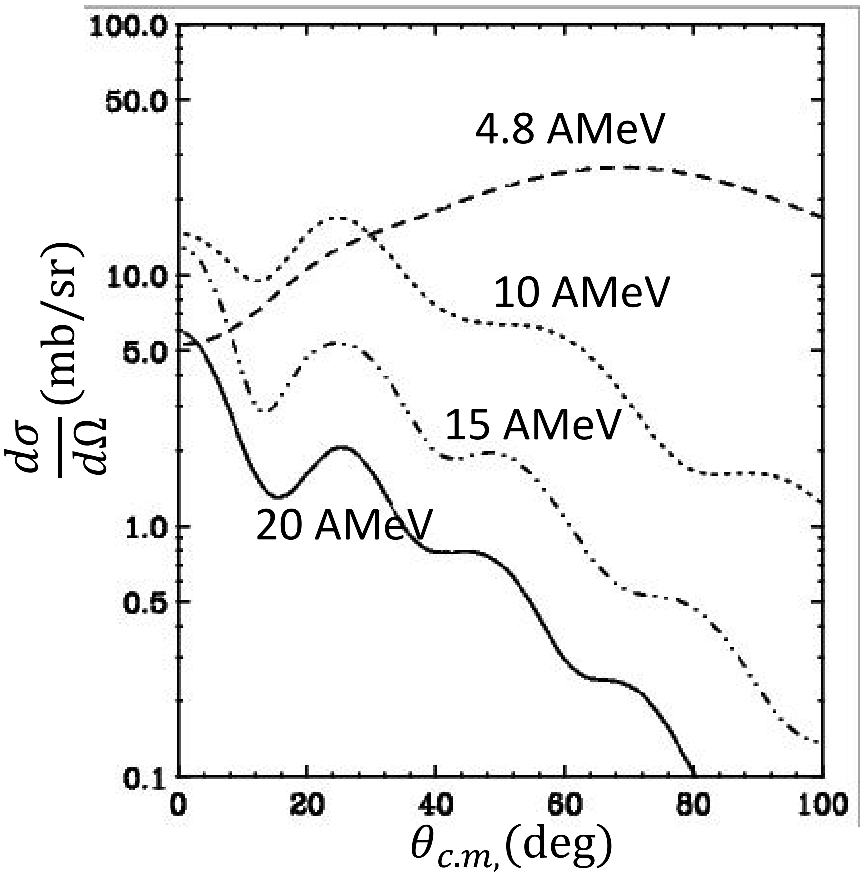
ORRUBA @ Oak Ridge
S.D. Pain, et al., NIMB 261, 1122-1125 (2007)

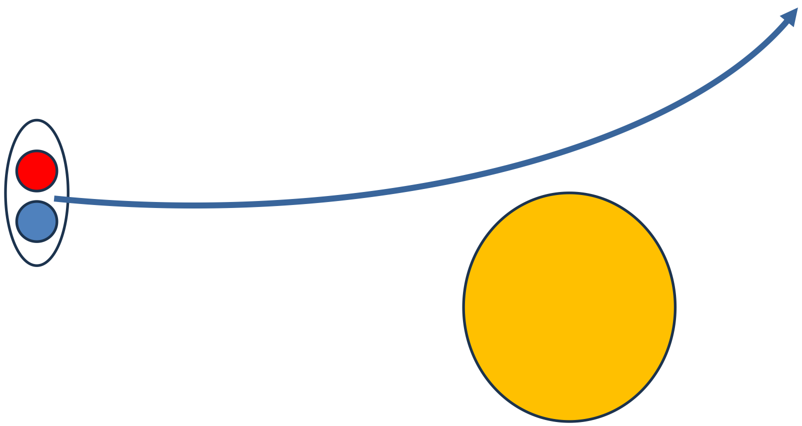


TIARA @ UK
M. Labiche, W.N. Catford, et al., NIMA 614, 439-448 (2010)

Energy dependence of Angular distribution

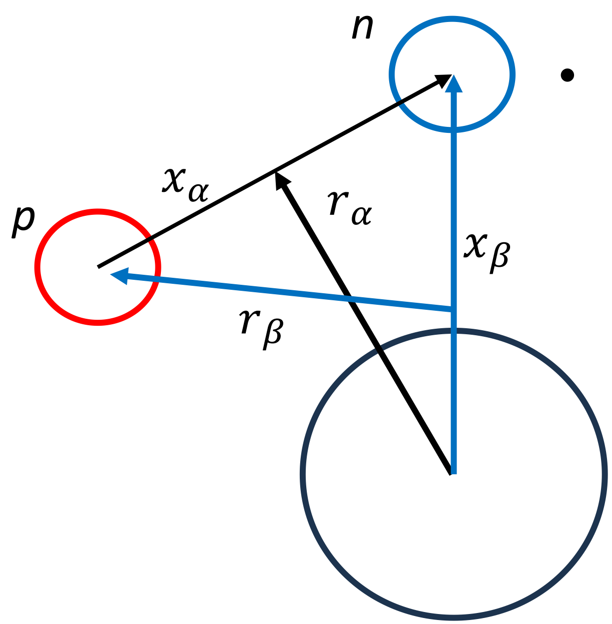
$^{130}\mathrm{Sn}(d,p)^{131}\mathrm{Sn}\ (3/2^-\ ,\ Ex = 3.404\ \mathrm{MeV})$





- Coulomb barrier ~ 6.8 MeV
- E < V_{Coul}; less diffraction

Hamiltonian of (*d*,*p*) reaction



- $$H = \underbrace{-\frac{\hbar^2}{2\mu_{dA}}\frac{\partial^2}{\partial\vec{r}_\alpha{}^2}}_{K_\alpha} \underbrace{-\frac{\hbar^2}{2\mu_{pn}}\frac{\partial^2}{\partial\vec{x}_\alpha{}^2} + V_{pn}}_{H_\alpha} + \underbrace{V_{nA} + V_{pA}}_{V_\alpha}$$

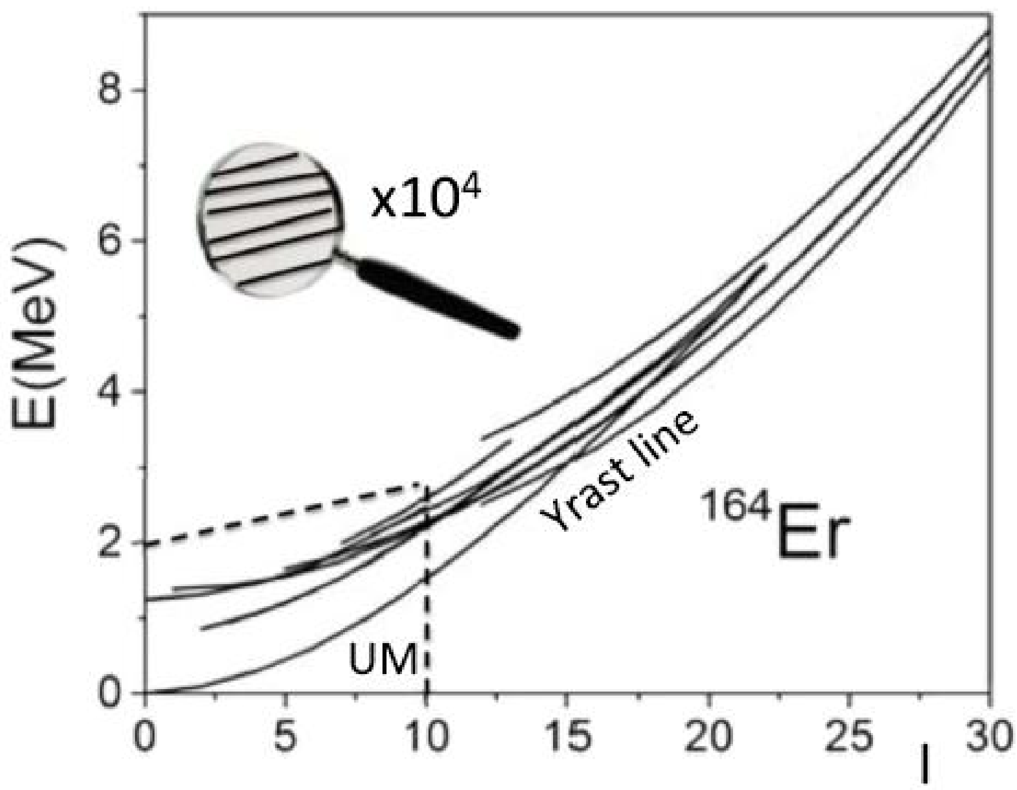
$$= \underbrace{-\frac{\hbar^2}{2\mu_{pA}}\frac{\partial^2}{\partial\vec{r}_\beta{}^2}}_{K_\beta} \underbrace{-\frac{\hbar^2}{2\mu_{nA}}\frac{\partial^2}{\partial\vec{x}_\beta{}^2} + V_{nA}}_{H_\beta} + \underbrace{V_{pA} + V_{pn}}_{V_\beta}$$

Summary (2)

- DRC of neutron can be determined by the final state bound state wave function.
- DWBA can help to determine the ANC.
- ChatGPT still needs trainings.
- Reaction in inverse kinematics, the conversion of the coordinate system looks tricky.

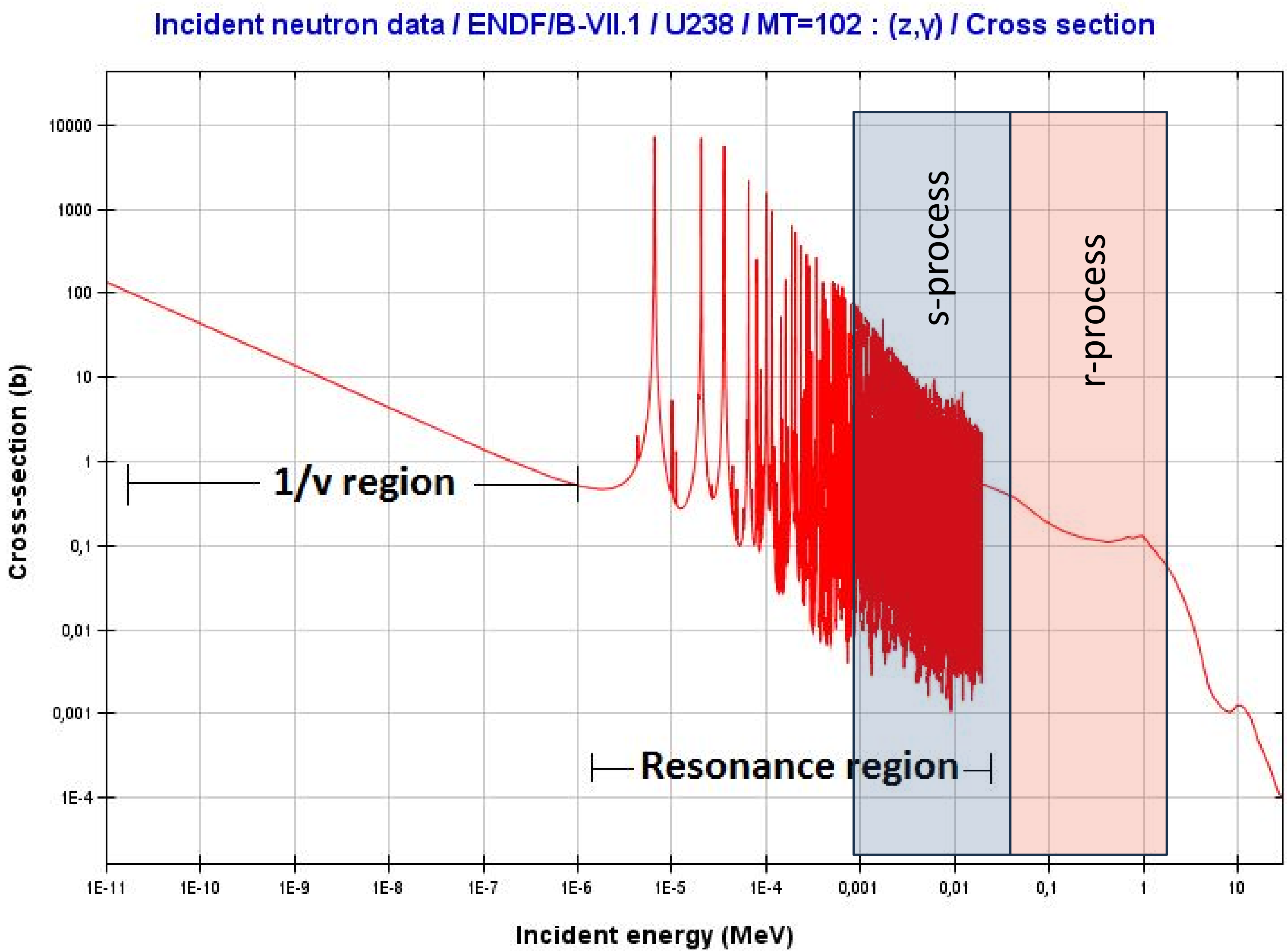
COMPOUND REACTION CHANNEL

Quantum Chaos above S_n



S. Frauendorf, Phys. Scr. 93 (2018) 043003

Neutron resonance



Compound reaction

Hauser-Feshbach theory

$$\sigma_{n\gamma}(E) = \frac{\pi}{k^2(2J_i+1)(2J_n+1)} \sum_{J^\pi} (2J+1) \frac{T_n(J^\pi) T_\gamma(J^\pi)}{T_{tot}(J^\pi)}$$

- ***T_n*: neutron transmission coeff.**
  ← optical model potential
- ***T_γ*: photon transmission coeff.**
  ← level density (cf. @^{131}Sn ρ= 40 MeV^{-1}), gamma strength function (γSF)

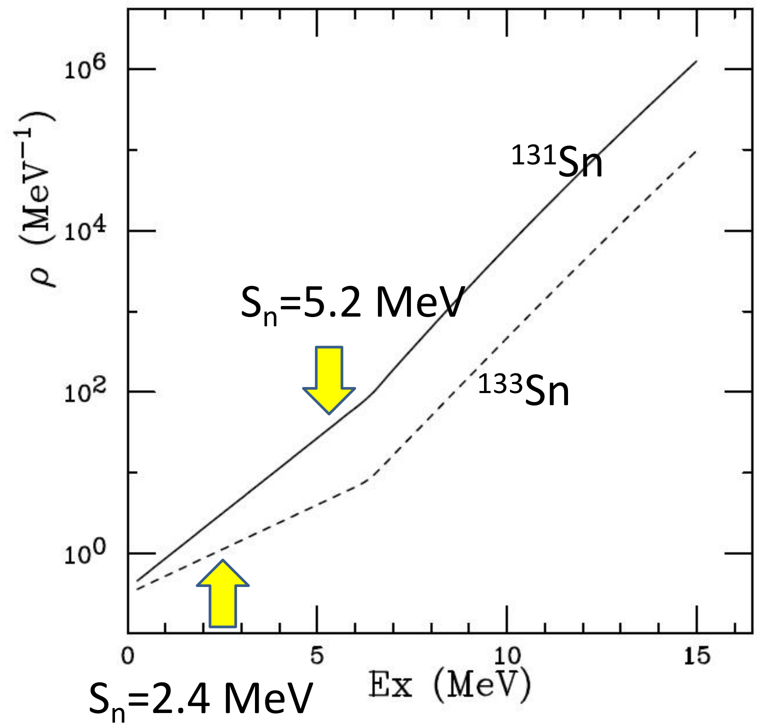
Cf.) Breit-Wigner

$$\sigma_{\beta\alpha} = \frac{\pi}{k^2} \frac{\Gamma_\beta \Gamma_\alpha}{(E-E_c)^2 + \left(\frac{\Gamma}{2}\right)^2}$$

$$(4.186) \quad \Gamma_{\alpha'}(E^{tot}, J, \Pi \longrightarrow E_x, I', \Pi_f) = \frac{1}{2\pi\rho(E^{tot}, J, \Pi)} \sum_{j'=|J-I'|}^{J+I'} \sum_{l'=|j'-s'|}^{j'+s'} \delta_\pi(\alpha') \left\langle T^J_{\alpha' l' j'}(E'_{a'}) \right\rangle$$

$$T_{(E1)}(E_\gamma) = 2\pi E_\gamma \frac{\sigma_{GDR}\Gamma_{\mathrm{GDR}}}{3\pi^2\hbar^2c^2} \left[\frac{E_\gamma \Gamma_{(E_\gamma)}}{\left(E_\gamma^2 - E_{GDR}^2\right)^2 + E_\gamma^2 \Gamma(E_\gamma)^2} + \frac{0.7\Gamma_{GDR} 4\pi^2 T^2}{E_{GDR}^5} \right]$$

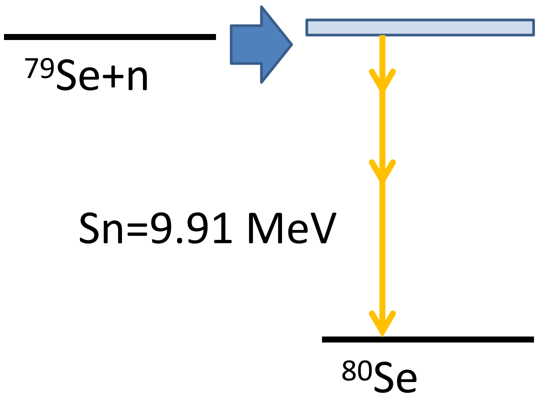
level density around ^{132}Sn

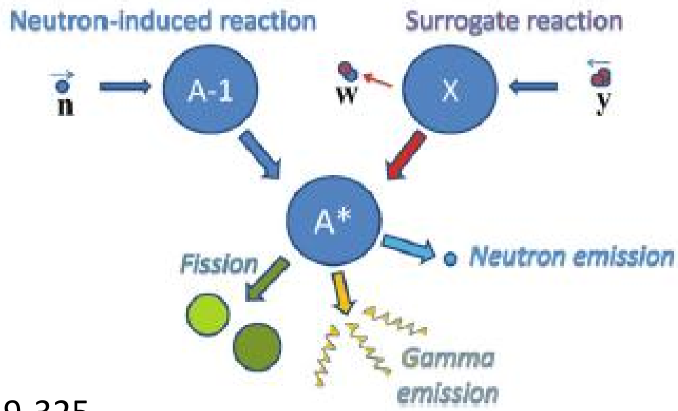


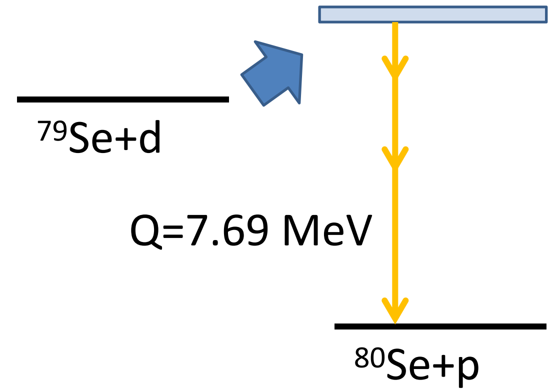
$$\rho_F(E_x, J, \Pi) = \frac{1}{2}\frac{2J+1}{2\sqrt{2\pi}\sigma^3} exp\left[-\frac{(J+1/2)^2}{2\sigma^2}\right]\frac{\sqrt{\pi}}{12}\frac{exp\left[2\sqrt{aU}\right]}{a^{1/4}U^{5/4}}$$

Fermi-gas model

Surrogate reaction: (n,γ) vs. (d,p)







G. Boutoux et al., PLB 712, (2012) 319-325.

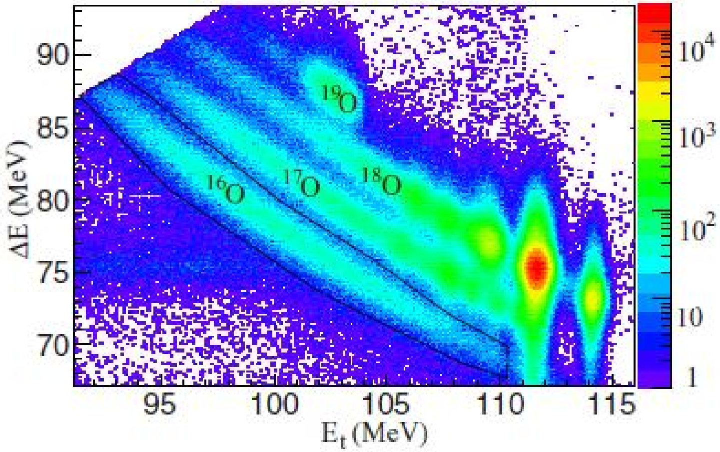
$$\sigma_{^{79}\mathrm{Se(n,\gamma)}^{80}\mathrm{Se}}(E_n) = \boxed{\sigma^{CN}_{^{80}\mathrm{Se}}(E_n)} P^{decay}_{^{80}Se^{*}\rightarrow\gamma+^{79}Se}(E^{*})$$

determined by
the optical model potential

Surrogate ratio method

$$\sigma^{(n,\gamma)}_{^{79}\mathrm{Se}}(E) = \sigma^{(n,\gamma)}_{^{77}\mathrm{Se}}(E) \times \frac{\sigma^{CN}(^{80}\mathrm{Se})}{\sigma^{CN}(^{78}\mathrm{Se})} \times \frac{P_{\gamma}^{^{80}\mathrm{Se}}(E)}{P_{\gamma}^{^{78}\mathrm{Se}}(E)}. \qquad (1)$$

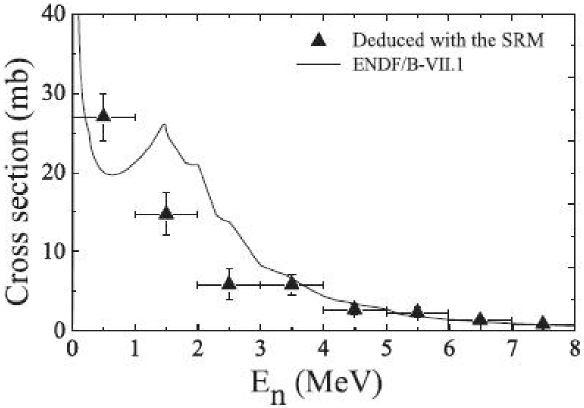
Example @JAEA



PRC94.015804('16)

$^{90}Zr(^{18}O,^{16}O)^{92}Zr^*$
$^{92}Zr(^{18}O,^{16}O)^{94}Zr^*$

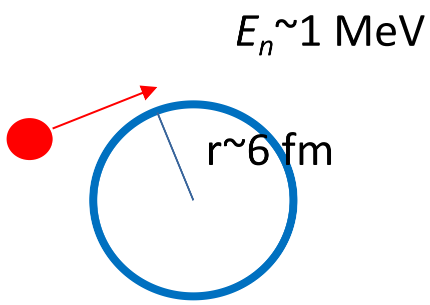
➔ $^{93}Zr(n,\gamma)^{94}Zr$



Spin distribution difference ?

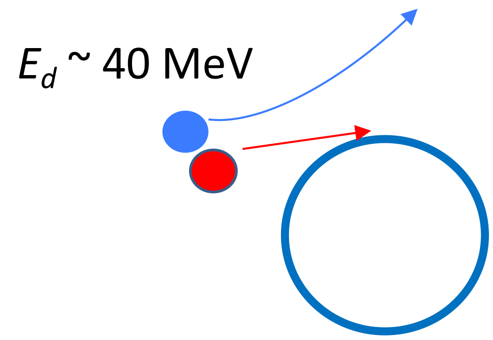
^{79}Se(n,γ) reaction vs ^{79}Se(d,p) reaction

Neutron capture



$\Delta L = p \times r \sim 1\,\hbar$

Stripping reaction



$\vartheta = 30$ deg. Ex= 10 MeV
Δp = 364 MeV/c

$\Delta L = \Delta p \times r \sim 12\,\hbar$

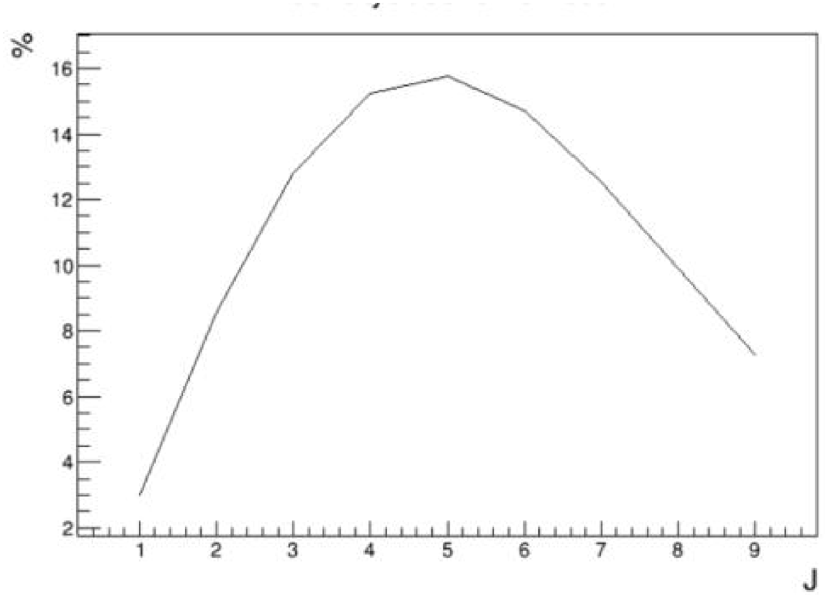
Level density distribution

Fermi-gas model

$$\rho_F(E_x, J, \Pi) = \frac{1}{2}\frac{2J+1}{2\sqrt{2\pi}\sigma^3}\exp\left[-\frac{(J+\frac{1}{2})^2}{2\sigma^2}\right]\frac{\sqrt{\pi}}{12}\frac{\exp\left[2\sqrt{aU}\right]}{a^{1/4}U^{5/4}}, \tag{4.236}$$

From TALYS manual

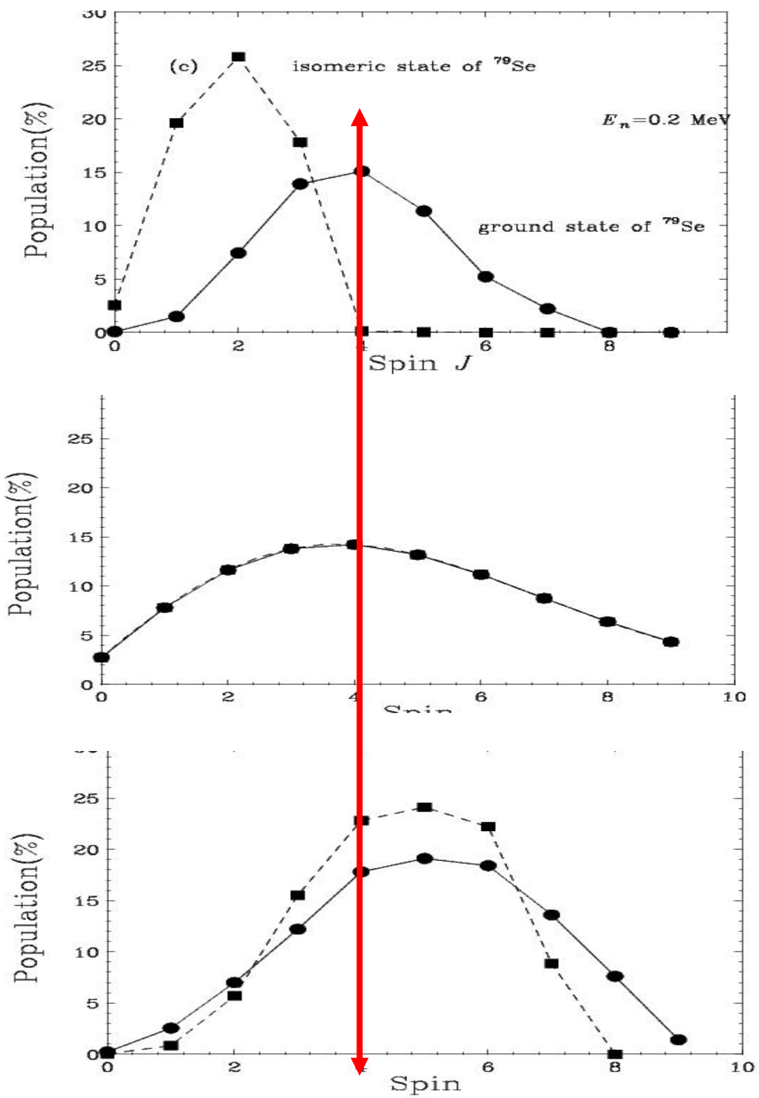
Assumption: The projection of the angular momentum are randomly coupled.



$^{80}Se^*$ at 10 MeV

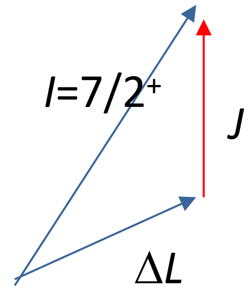
ρ ~ 2x10^5 MeV^{-1}

Calculated spin distribution for ^{79}Se



^{79}Se g.s. $I^{\pi} = 7/2^{+}$

iso @96 keV $I^{\pi} = 1/2^{-}$



Talys spin distribution at 10 MeV
By ^{79}Se(d,p) reaction @ 40 MeV
(complete compound reaction is assumed.)

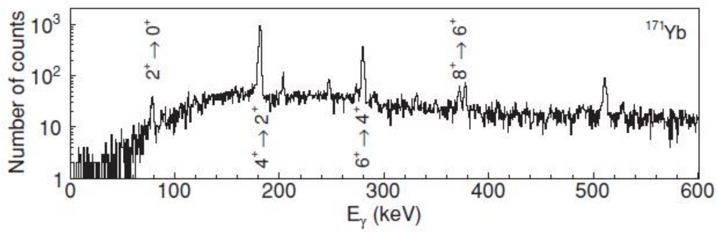
DWBA calc. $\Delta J = \frac{1}{2} \sim \frac{13}{2}$, S=1.0,
weighted with the level density

Surrogate reaction w/o γ-ray measurement

Typical setup for surrogate reaction exp.

= Recoil particle detectors

+ γ-ray detector array



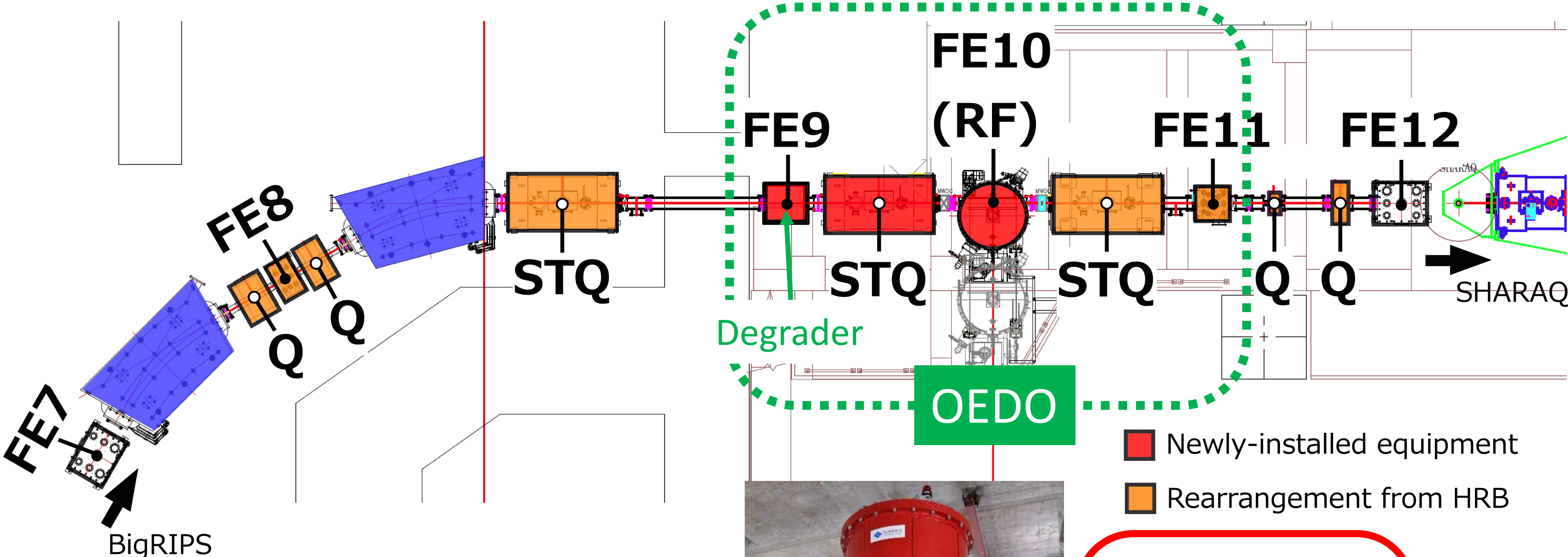
^{171}Yb(d,pγ) → ^{172}Yb(n,γ)

R. Hatarik et al.,
PRC81, 011602 (R) (2010)

Aha!
Gamma emission means that the nucleus doesn't change N and Z number!

Pγ was determined by identifying the outgoing residue nucleus.

Optimized Energy Degrading Optics for RI beams at RIBF



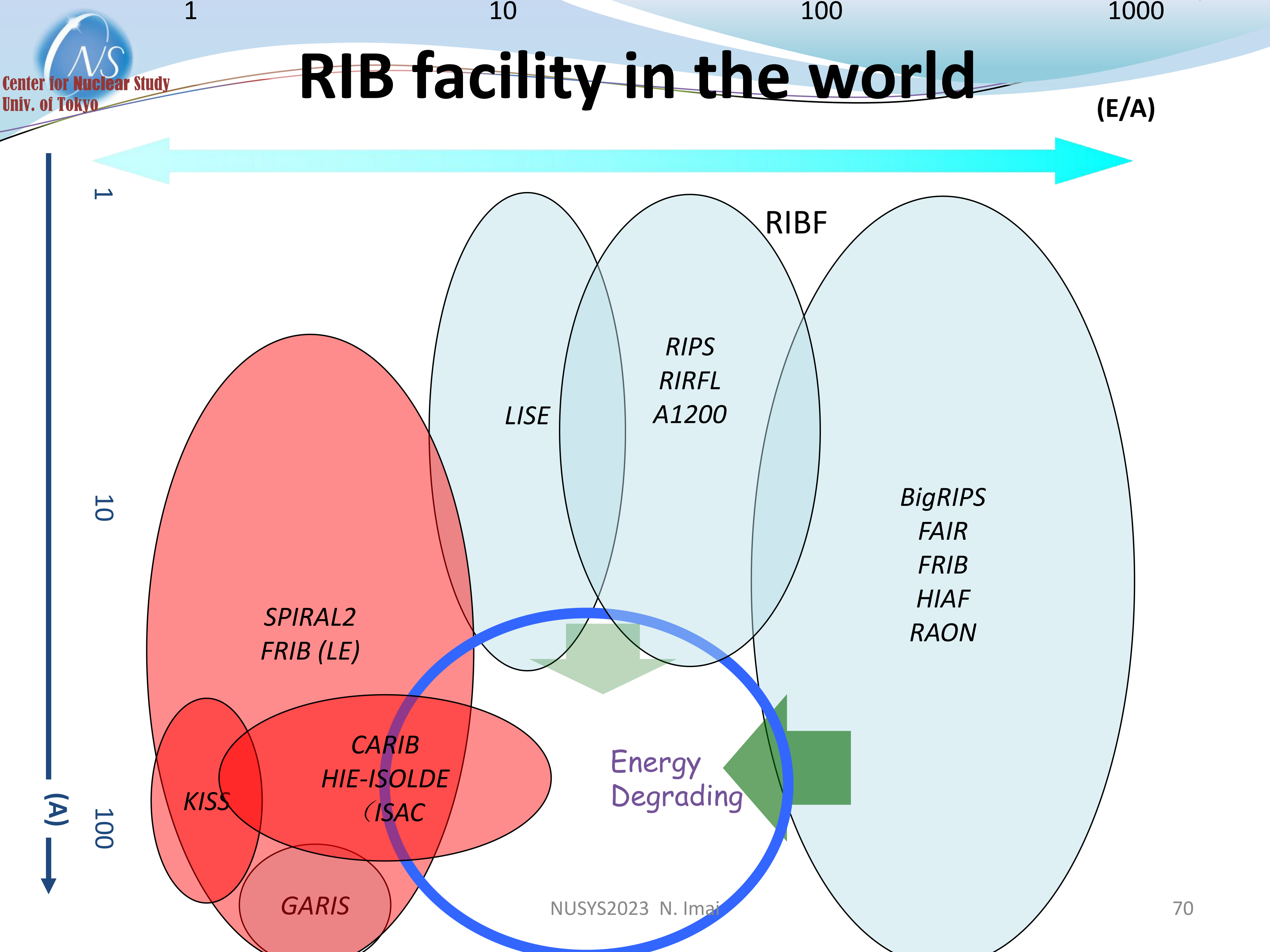
OEDO RFD

f_{RF} = 18.25 MHz
V_{max} = 350 kV
Gap(H) = 200 mm
L (Z) = 1200 mm
W(V) = 400 mm

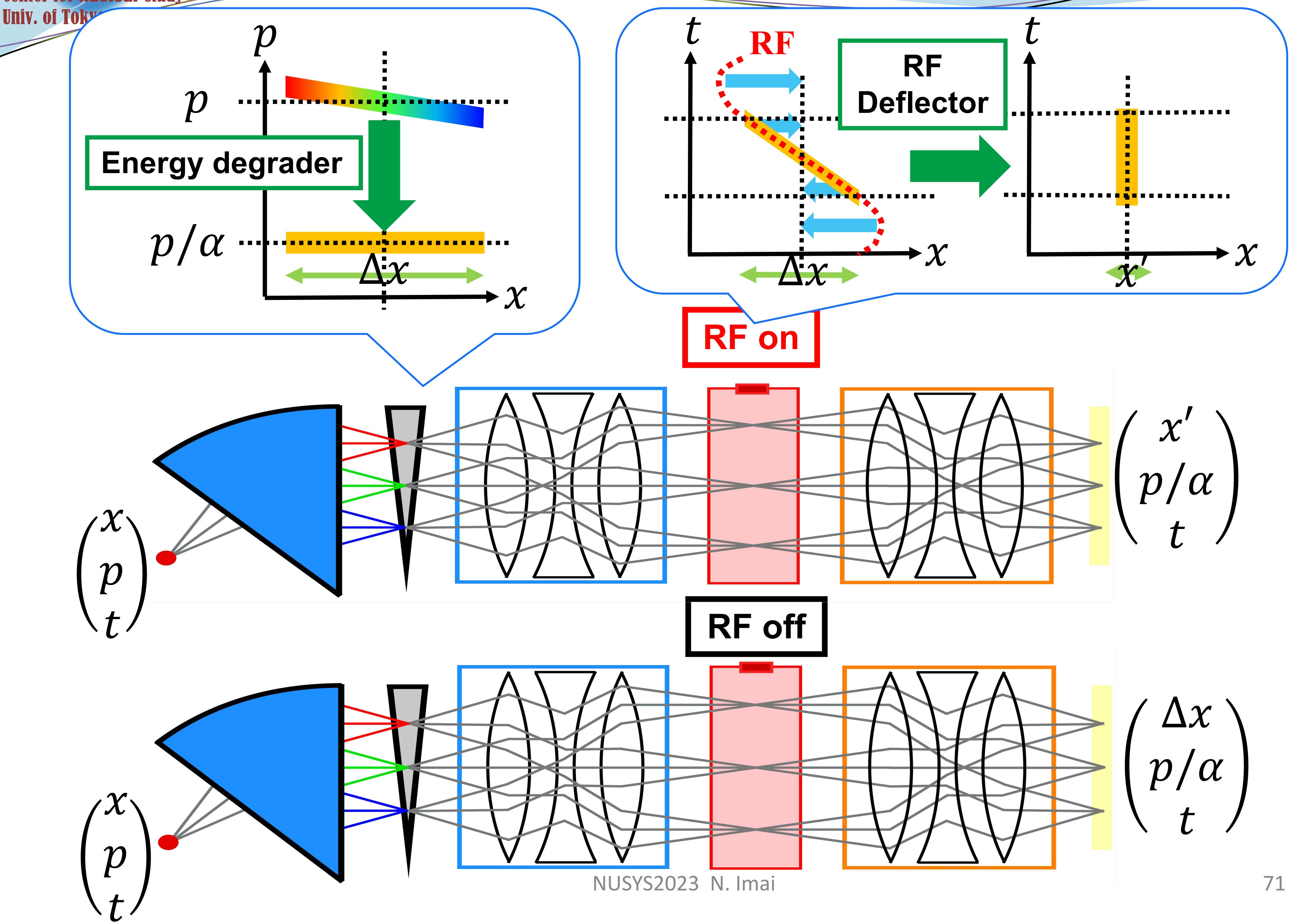
Installed in Mar. 2017.

RF deflector

RIB facility in the world



Principle of OEDO



Squeezing the beam spot

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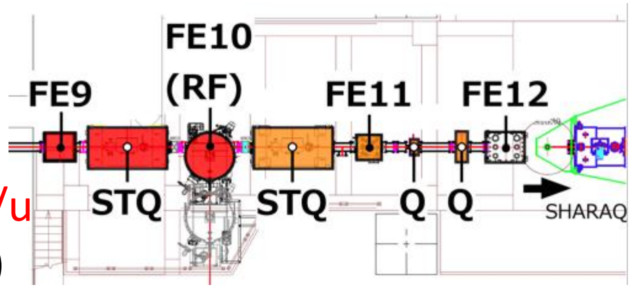
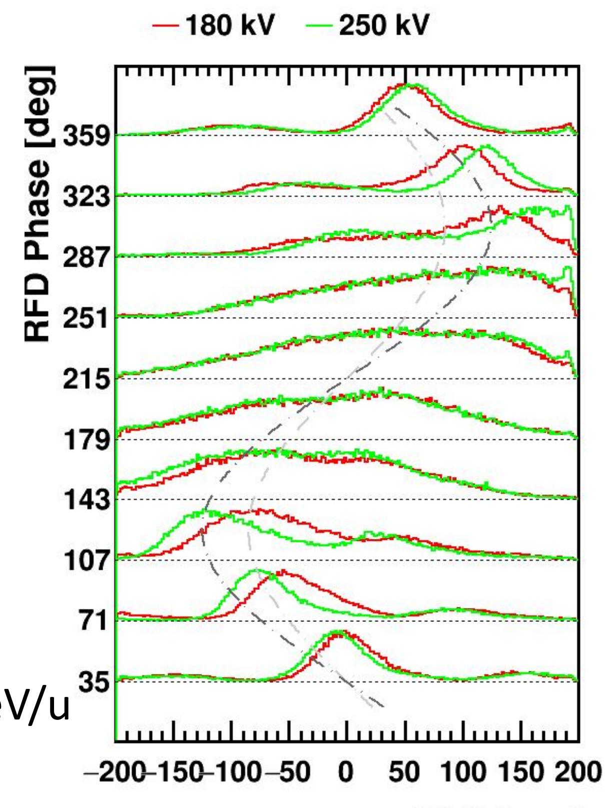
^{107}Pd, ^{93}Zr at ~30 MeV/u
(BigRIPS production)



^{107}Pd at 30MeV/u
(FE12)

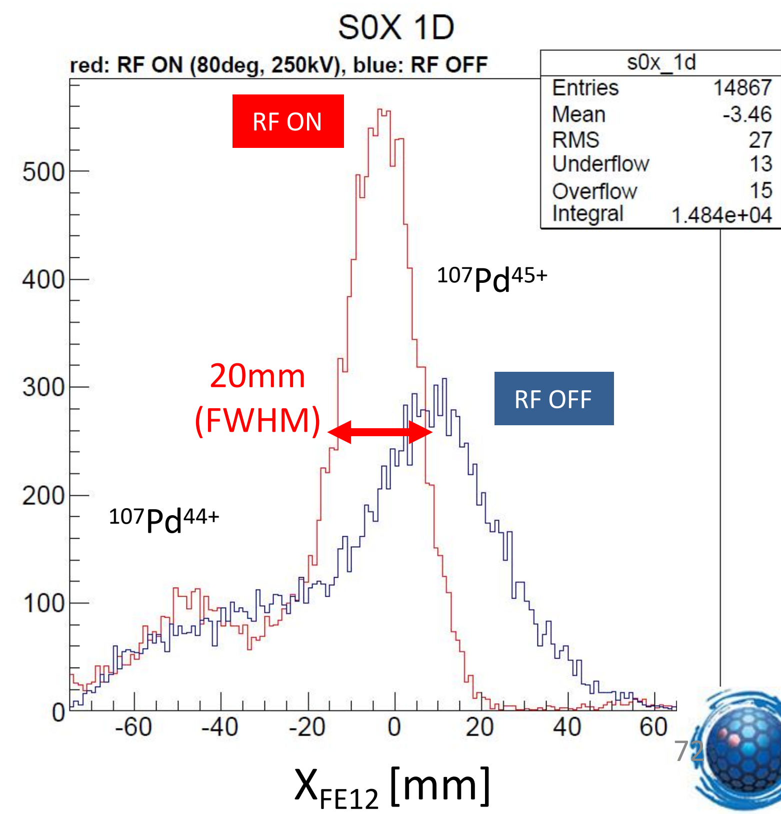
RF HV: 250kV
Phase: 80 deg.

Effects of RF Deflector



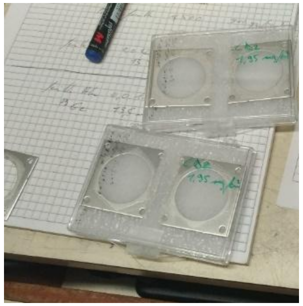
^{93}Zr
30 MeV/u

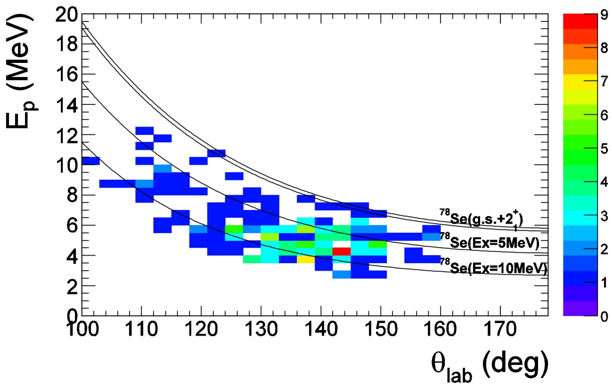
Focusing (FE12)

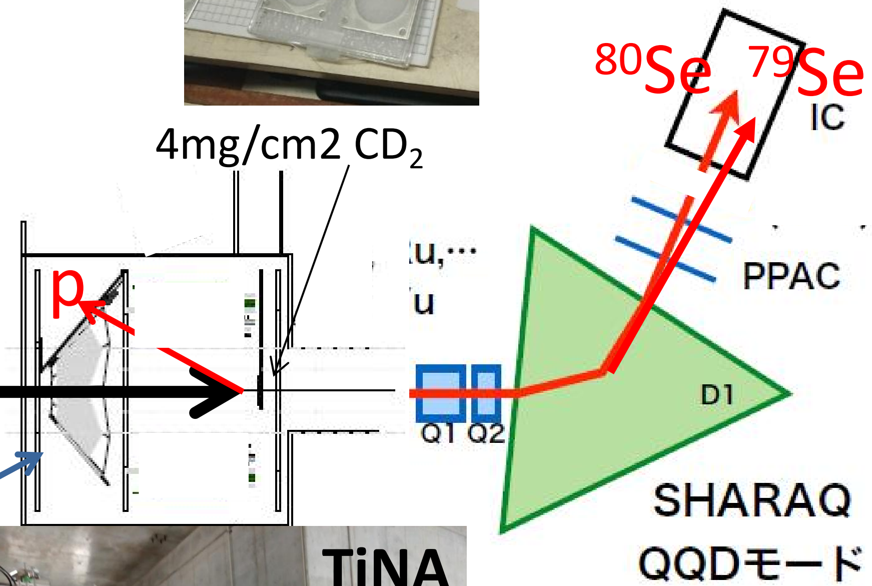


Experimental Setup for ImPACT17-02-02

Recoil particles: TiNA, SSD-CsI (CNS/RCNP/RIKEN)
reaction products: detectors at final focal plane
target: CD_2 4mg/cm^2
Beam int~ 10^4 pps at on CD_2

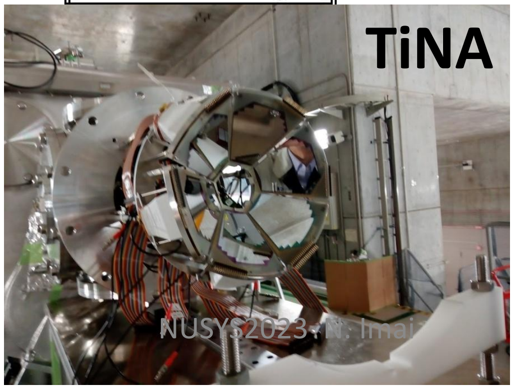






^{79}Se
(~20 MeV/u)

6x (SSD(YY1 16ch)+
CsI)



coincidence measurement of
recoil particles + outgoing particles.

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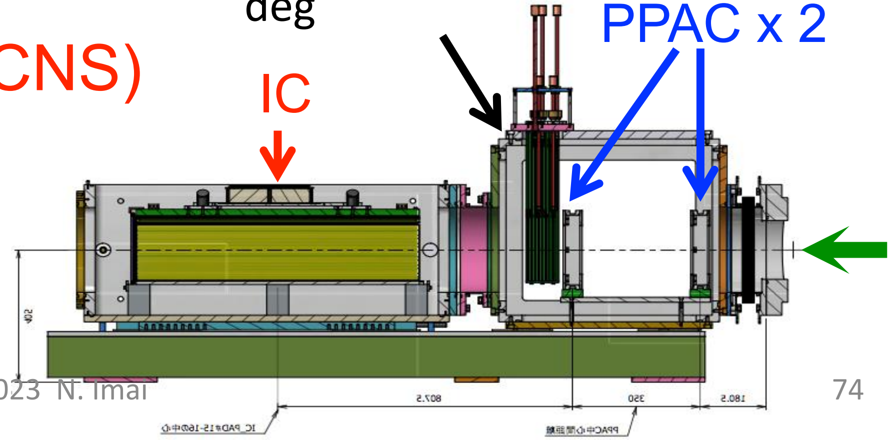
S1 Focal plane detector

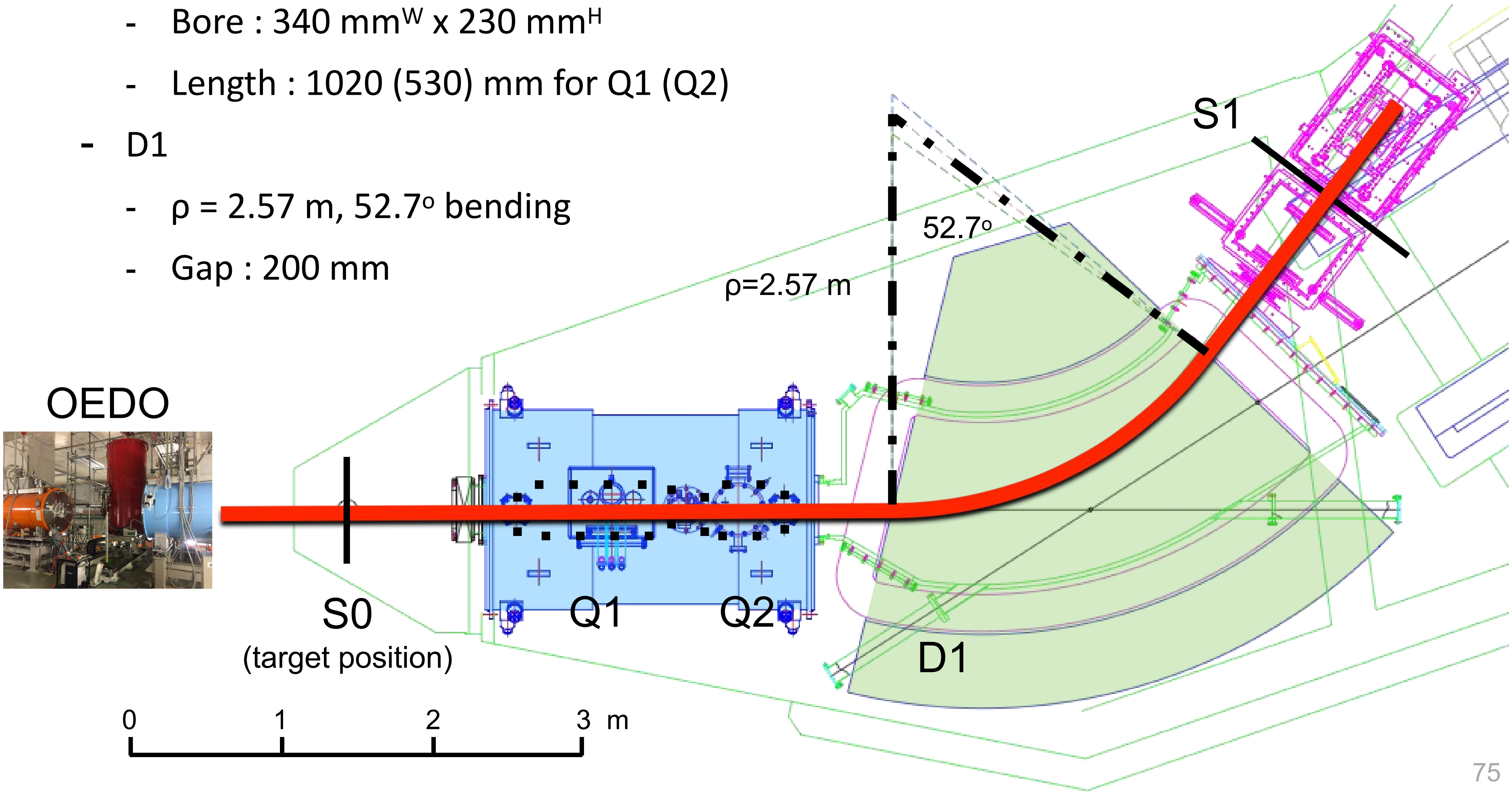
- PPAC :position, time of flight
  - Single(X-A-Y), Delay-line readout
  - 240 mm^W x 150 mm^H
- Ionization chamber : ΔE, Range
  - 30 pads
  - 280 mm^W x 150 mm^H
  - Total depth 757.5 mm
  - CF_4 110 torr
- Degrader to tune the range
- Kapton foil of 75 um

by Chiga(RIBF) and Dozono (CNS)

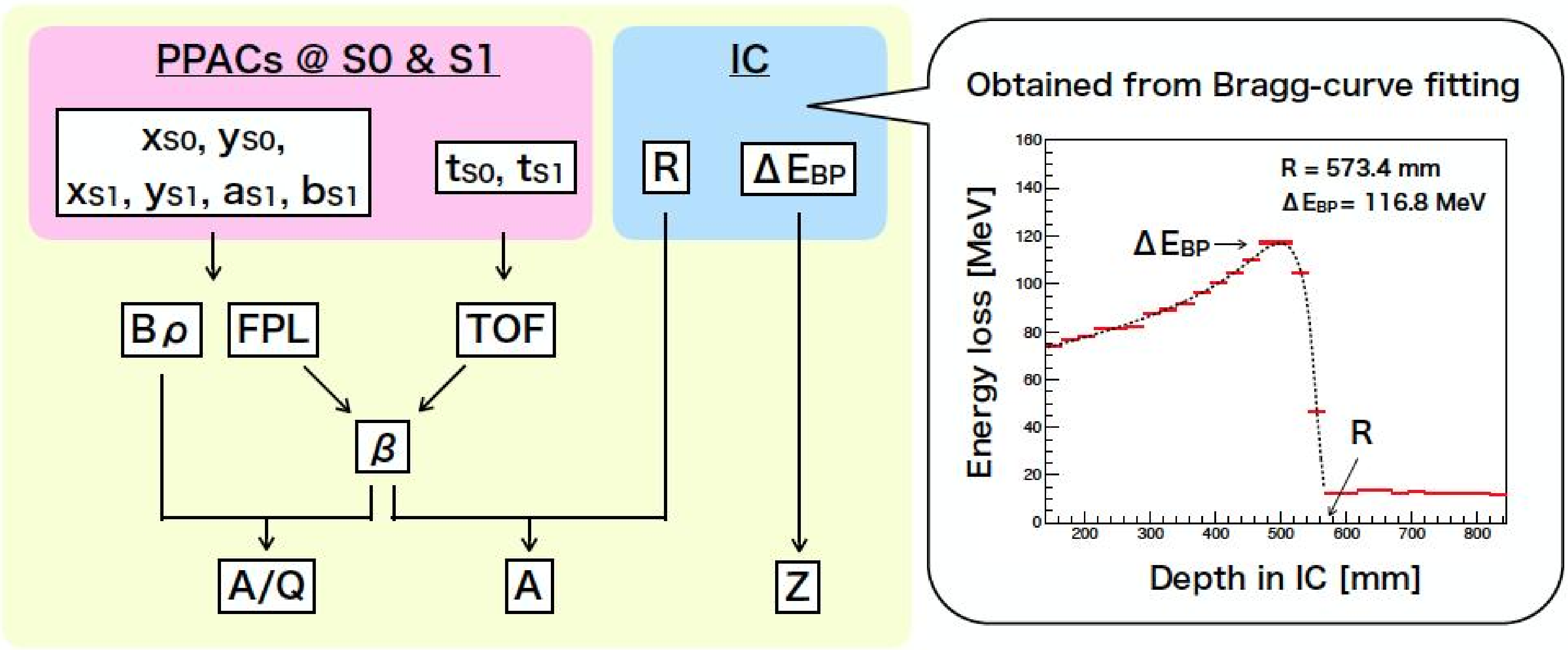


SHARAQ spectrometer

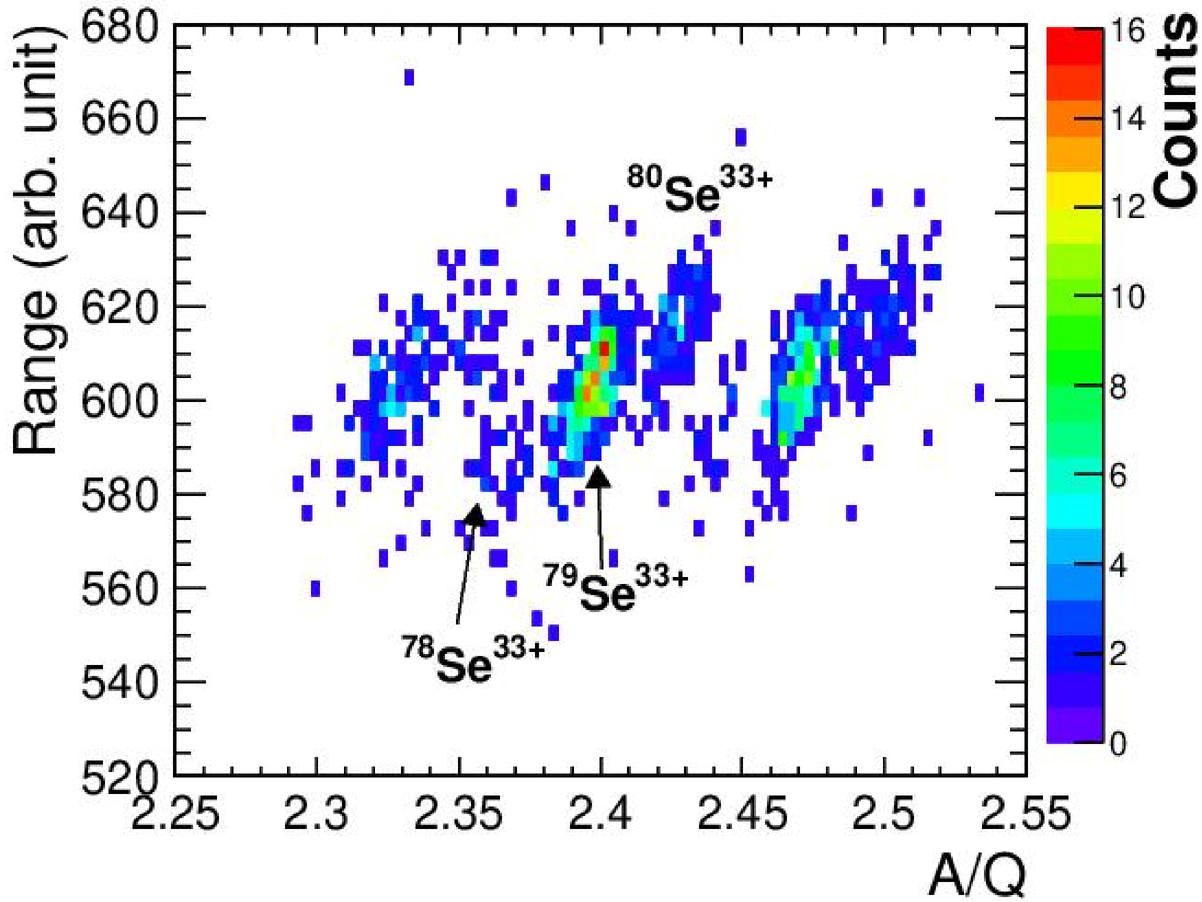
- Q-Q-D magnet configuration (First-half part of SHARAQ spectrometer)
  - Q1, Q2 (Superconducting)
    - Bore : 340 mm^W x 230 mm^H
    - Length : 1020 (530) mm for Q1 (Q2)
  - D1
    - ρ = 2.57 m, 52.7^o bending
    - Gap : 200 mm



PID of outgoing residue



PID of outgoing residues



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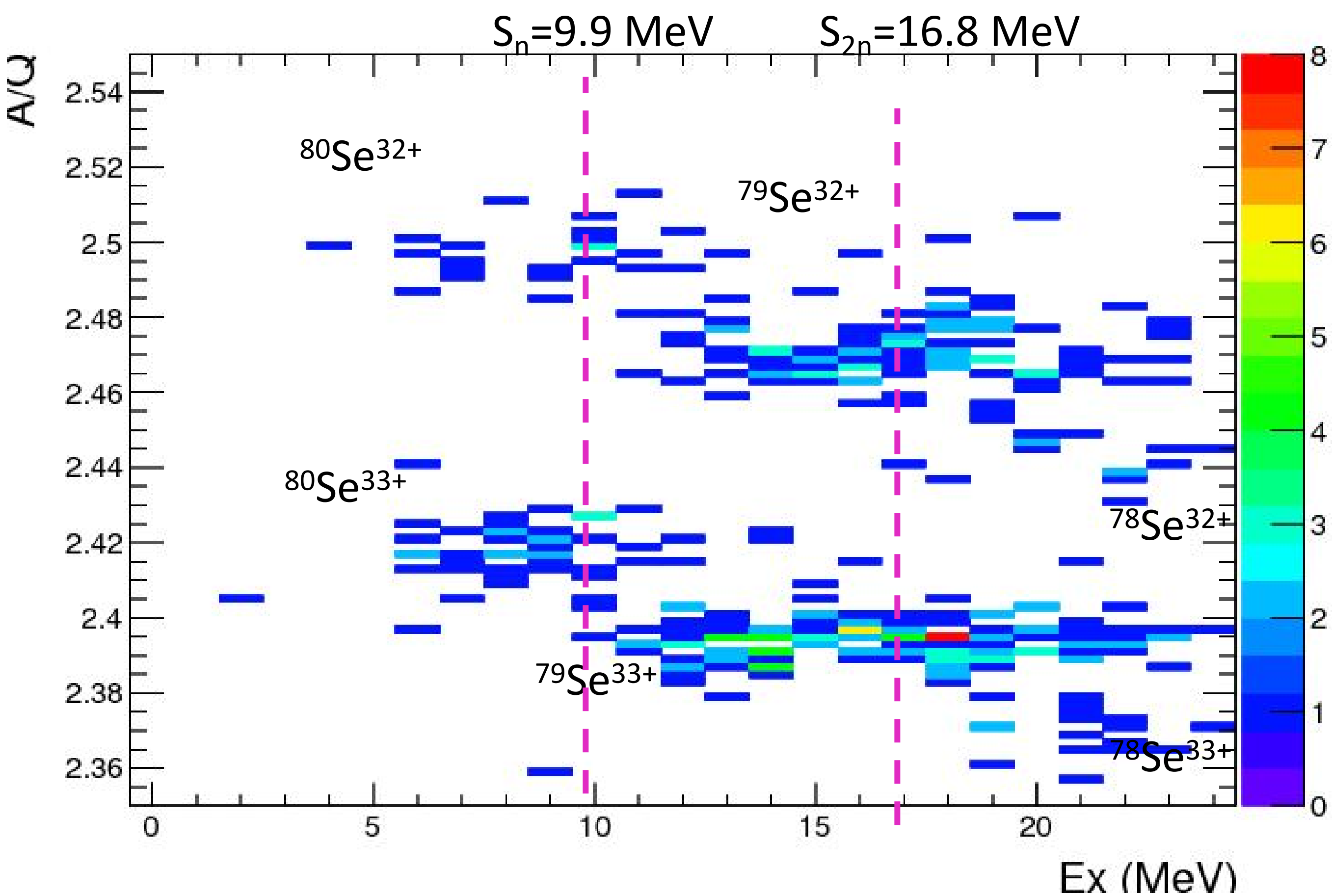
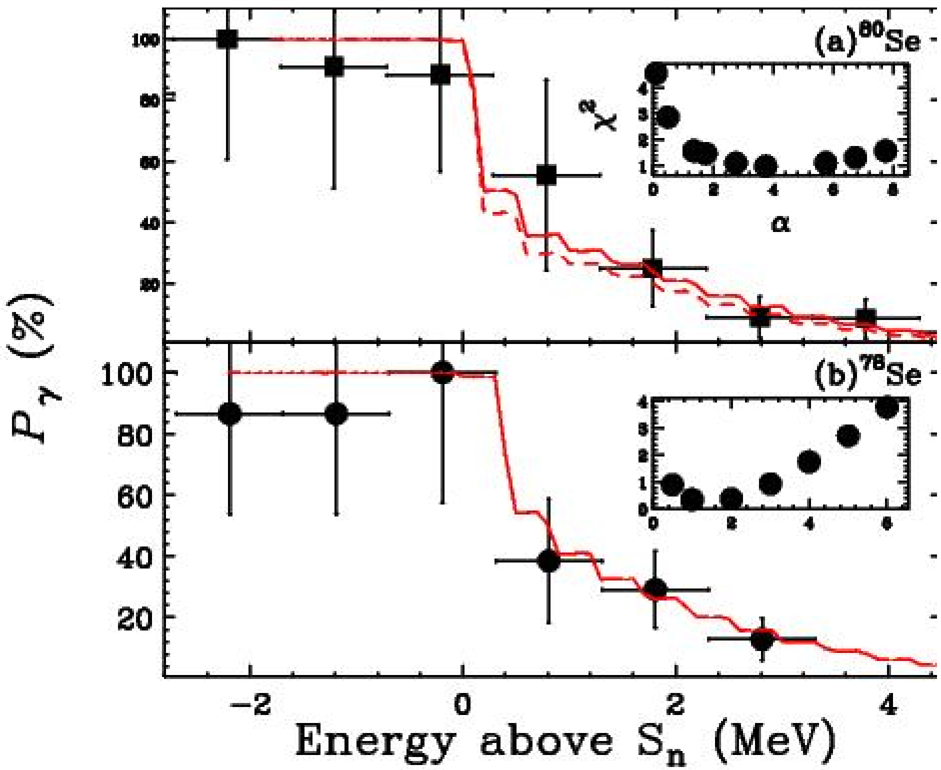
Residual nuclei vs Excitation energy



P_γ in ^{77,79}Se(d,p) reaction

$$P_\gamma(E) = \sum G_{decay}(J^\pi,\ E) F^{dp}(J^\pi,\ E)$$



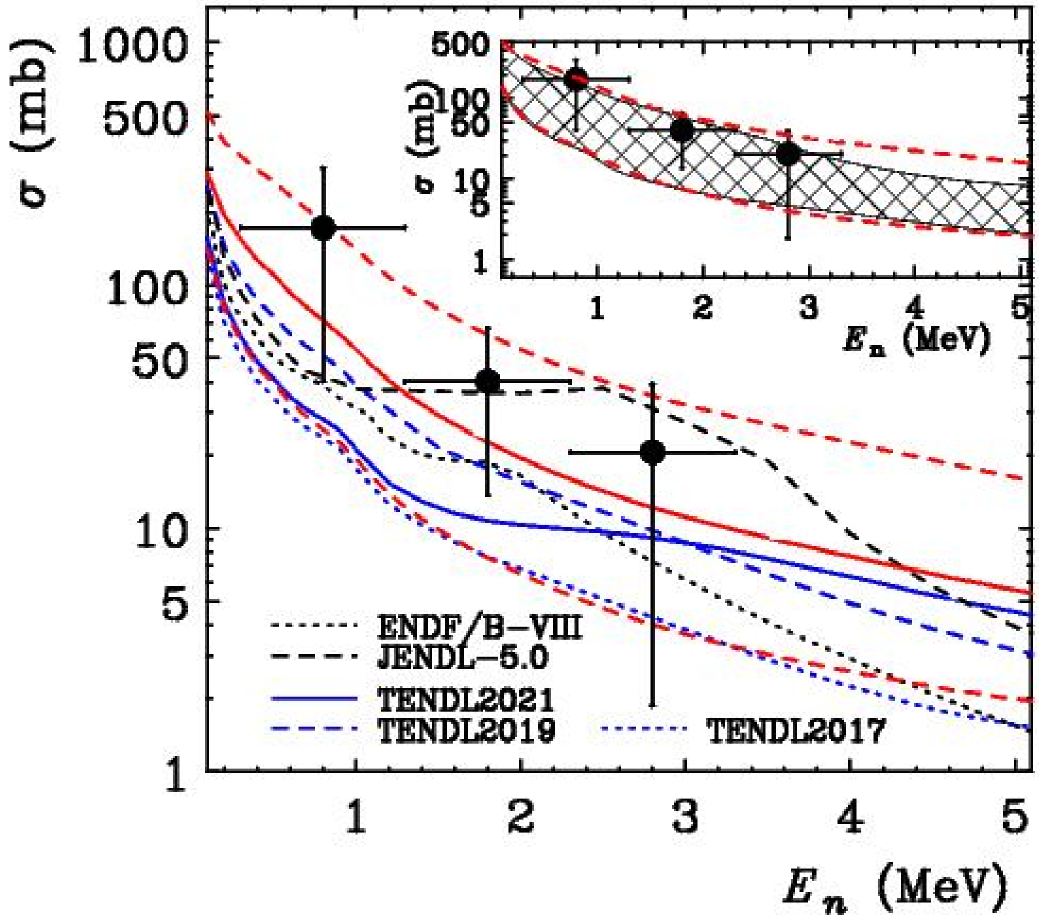
N. Imai et al., submitted to PLB

TENDL2021 recommendation
Normalization $\Gamma_\gamma \equiv \alpha$ = 1.75 (dashed)

Best fitting: α=3.75 (solid)

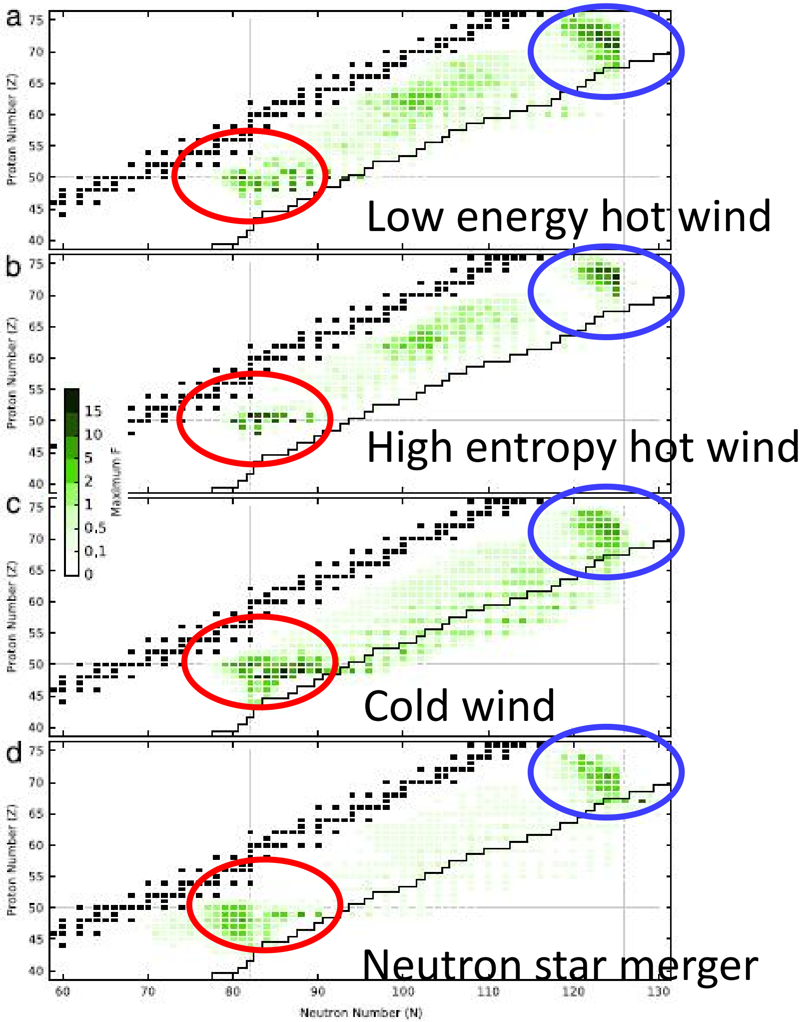
TENDL2021 recommendation
α=1.00
To reproduce Titech data (Igashira et al.,)

$^{79}Se(n,\gamma)$ cross sesction



EXPERIMENTAL STUDY OF NEUTRON CAPTURE RATE IN R-PROCESS

Which nuclear data are sensitive to the abundance?



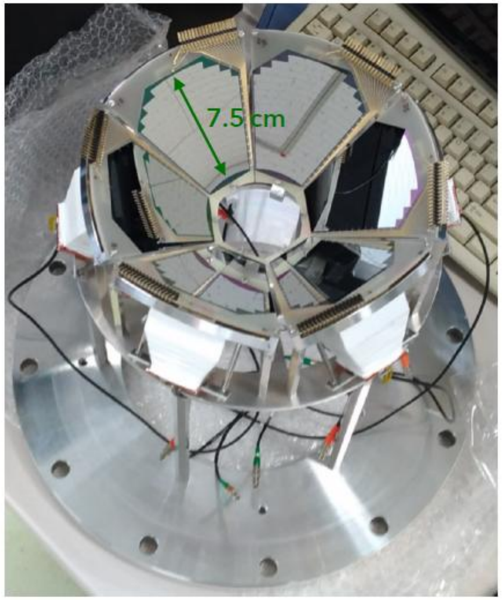
M. Mumpower, Prog. In Part. and Nucl. Phys. 86 (2016)86-126.

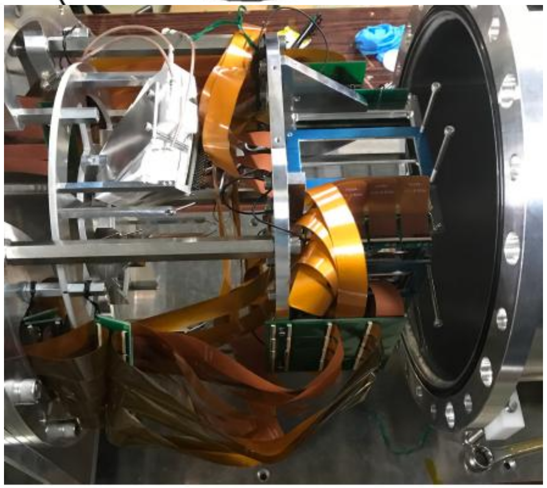
σ alters by 100 randomly.

$$F = 100 \sum_{A} |X(A) - X_b(A)|$$

South-west of ^{132}Sn is more sensitive To abundance

Upgrade of the recoil-particle detector TiNA





Drawbacks:
- Poor angular resolution (0.7°–2.4°)
- Minimal angle covered θ_{lab}= 21.8°

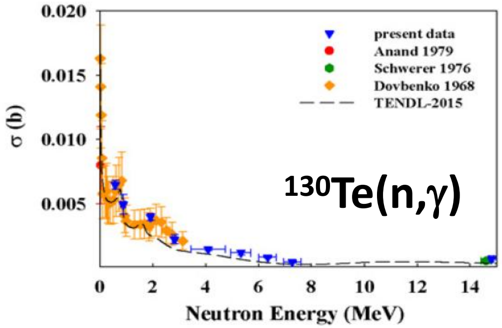
Angular resolution < 1 deg
Angular coverage ~70 deg.

SAKURA01

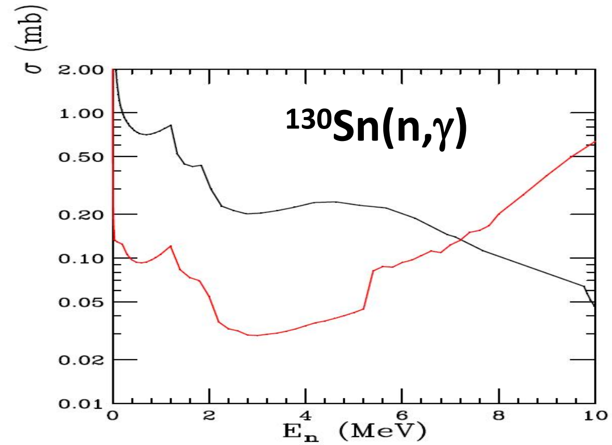
$^{130}Sn(d,p)^{131}Sn \rightarrow P_\gamma^1(E)$

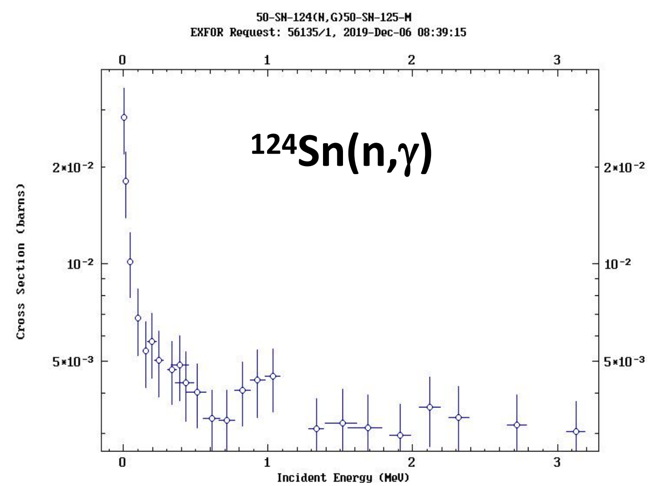
$^{130}Te(d,p)^{131}Te \rightarrow P_\gamma^2(E)$

$^{130}Te(n,\gamma)^{131}Te$

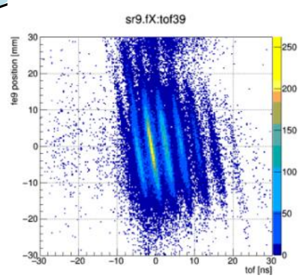


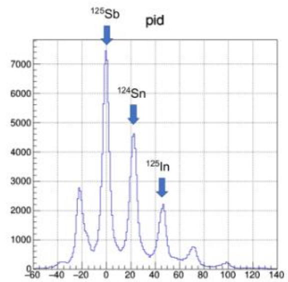
$^{124}Sn(d,p)^{125}Sn \rightarrow P_\gamma^3(E)$





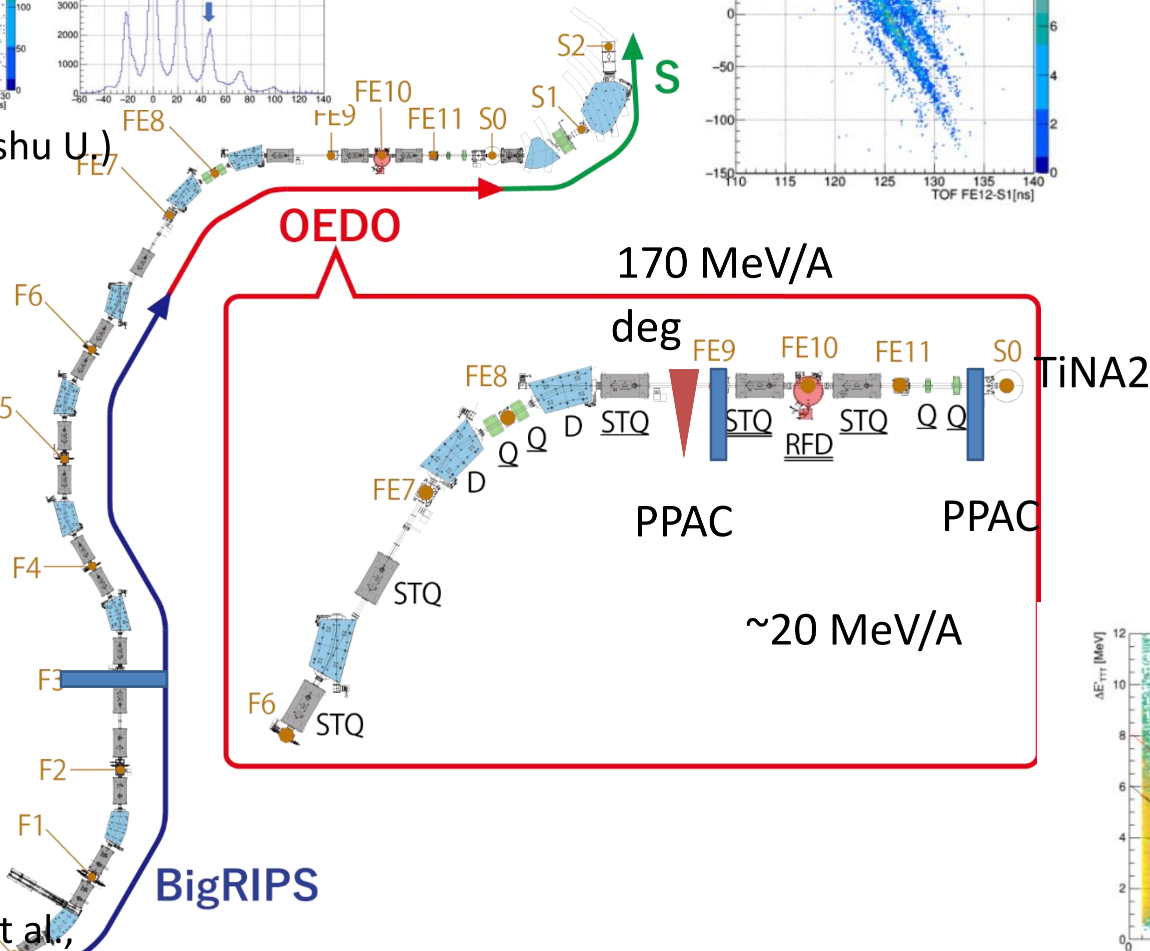
BigRIPS-OEDO beam line

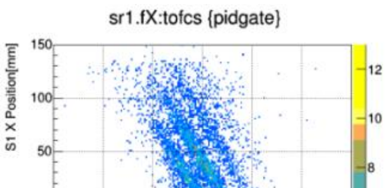


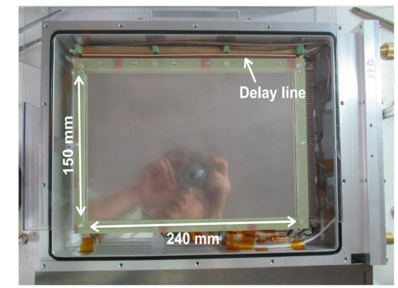


H. Tanaka (Kyushu U.)

170 MeV/A

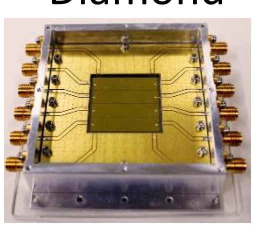




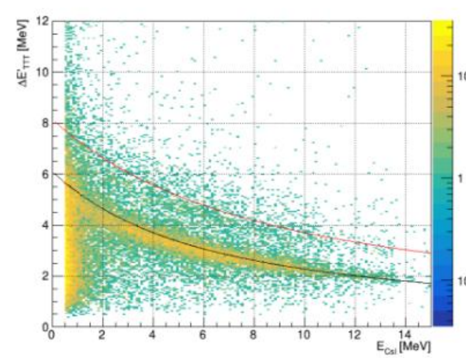


S. Hanai, S. Ota et al.,
NIMB541(2023)194-196.

500 kHz
Diamond

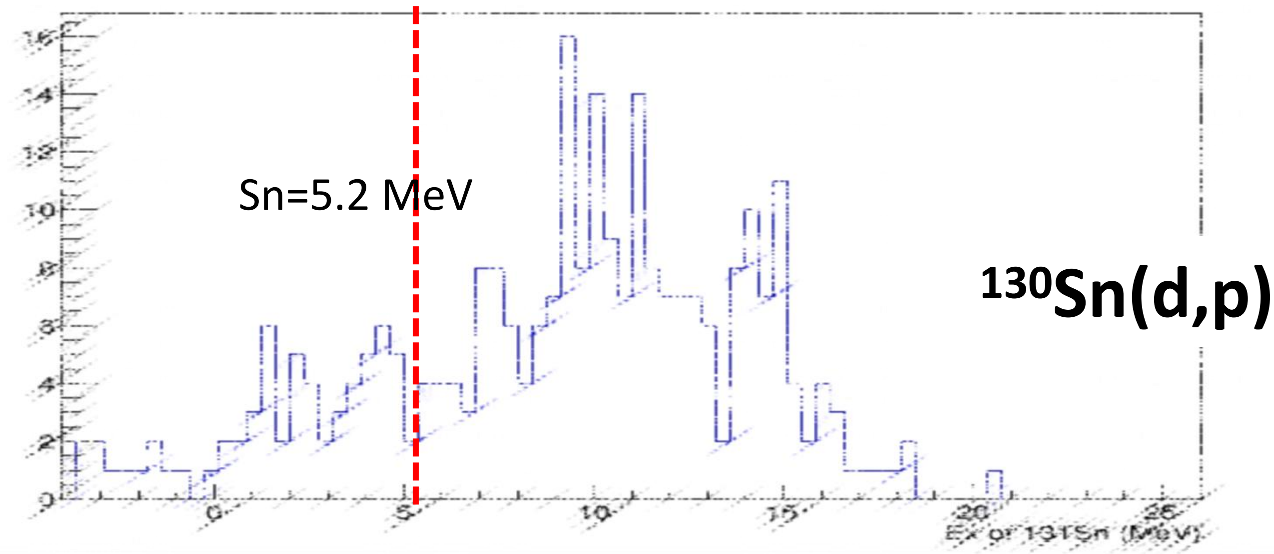


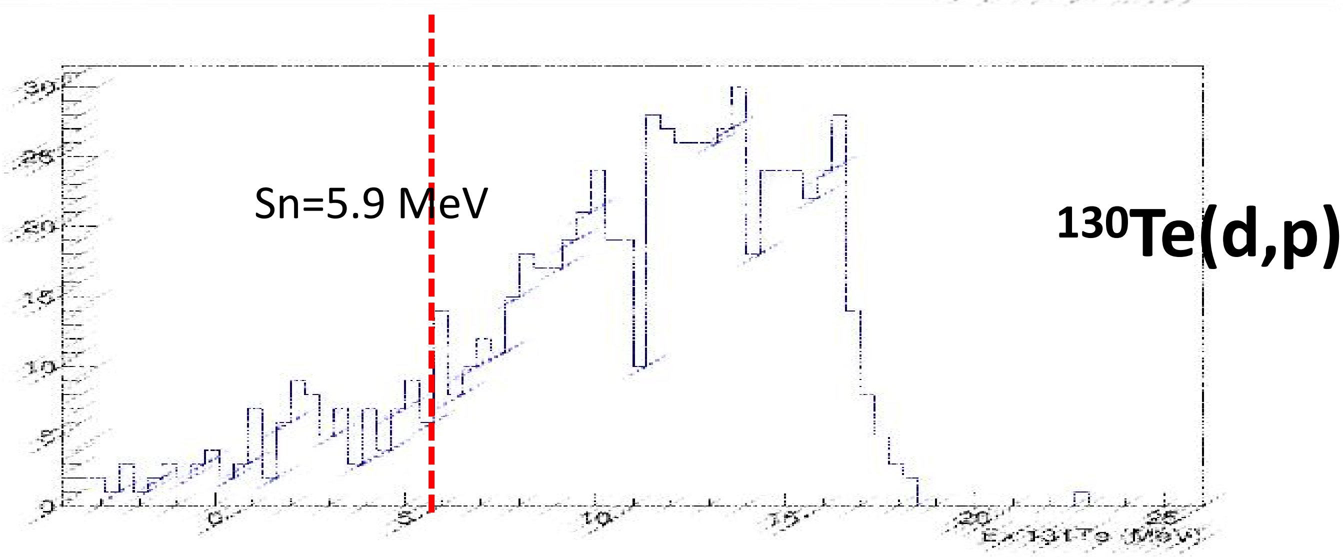
S. Michimasa et al.,
NIMB317,710 (2013)



T. Haginouchi (Tohoku U.)

Mass spectra





Summary

- The astrophysical site of r-process nucleosynthesis is still mystery.
- The kilo-nova after GW170817 boosts the research this field.
- Many RIB facilities are running for the r-process study.
- Neutron capture reaction and the direct nuclear reaction is governed by the quantum physics.
- OEDO/RIBF starts the astrophysical reaction rates with the surrogate idea