Center for Nuclear Study
Univ. of Tokyo

代理反応法を用いた不安定核中性子捕獲反応の研究

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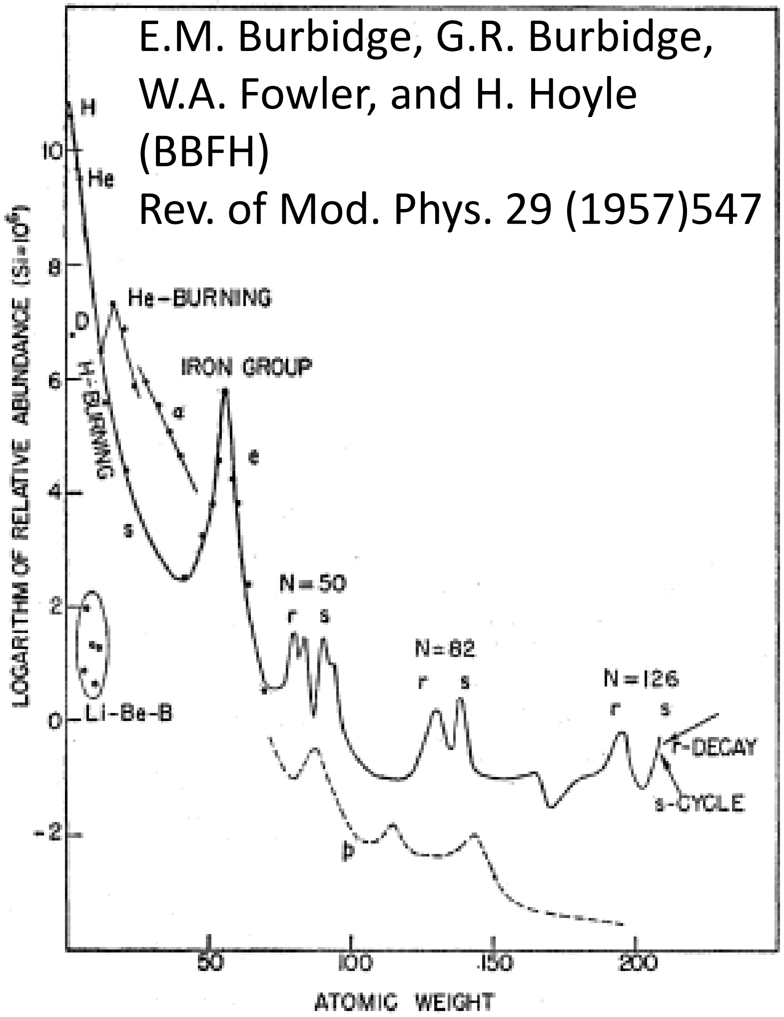
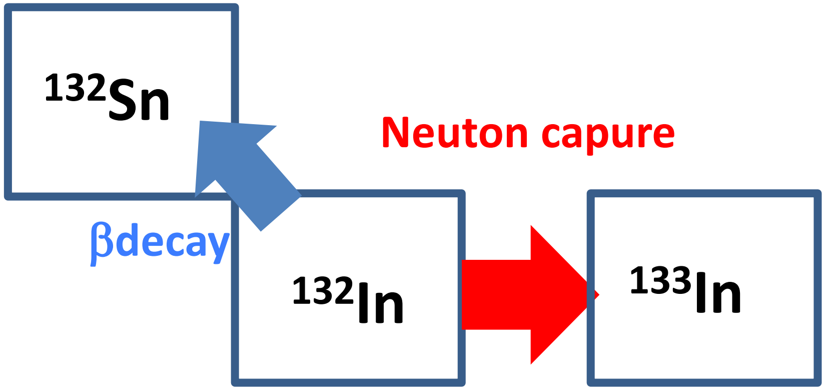
Nucleosynthesis in the star



E.M. Burbidge, G.R. Burbidge,
W.A. Fowler, and H. Hoyle
(BBFH)
Rev. of Mod. Phys. 29 (1957)547



^{132}Sn

βdecay

^{132}In

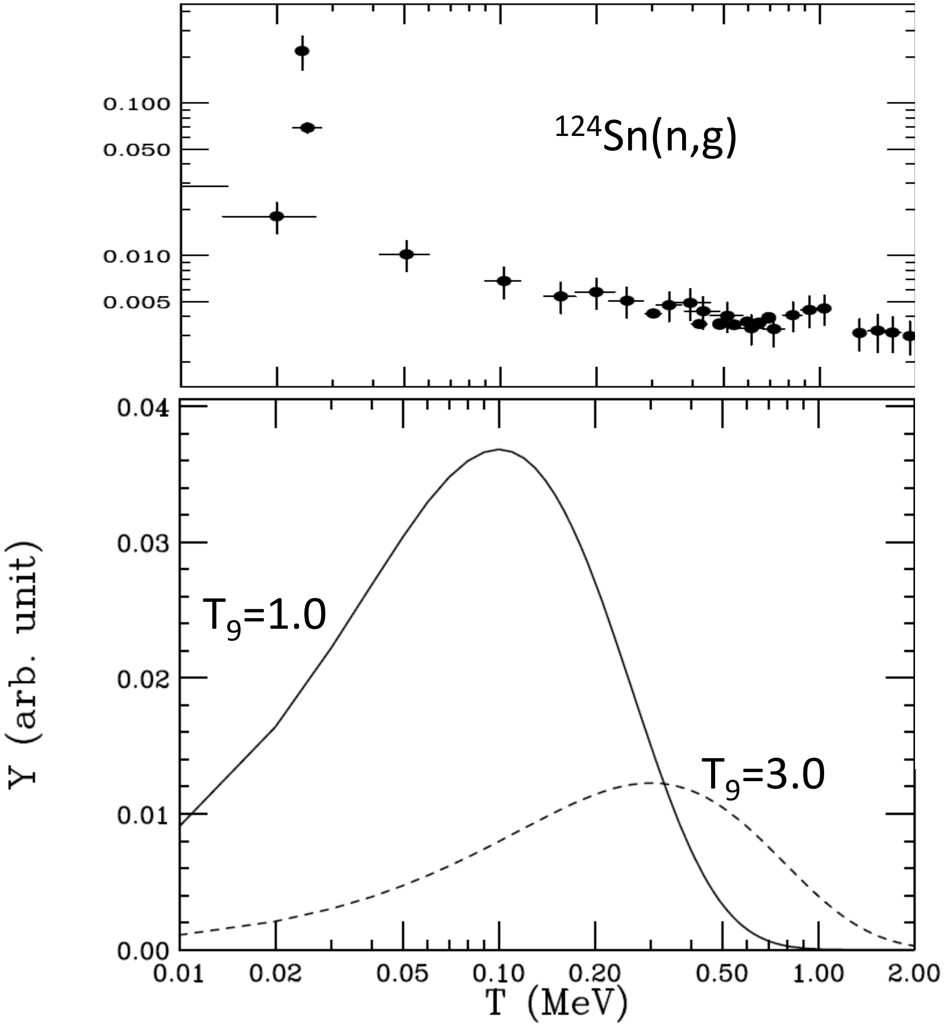
Neuton capure

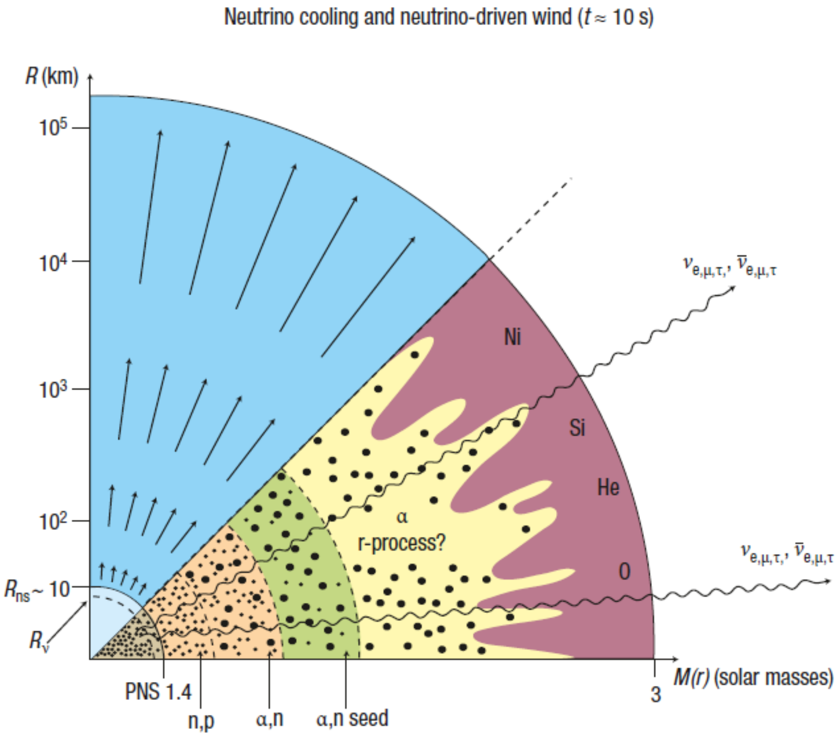
^{133}In

β rate ω_β=1/t = **2.47 [s^{-1}]**

ω_n = N_n $<\sigma>^{max}$ v
=10^{20} x0.1 mb $4.4\mathrm{x}10^8$ [cm/s]
= 4.38 [s^{-1}]
(T^9=1 ~ 0.1 MeV)

Neutron energy in r-process



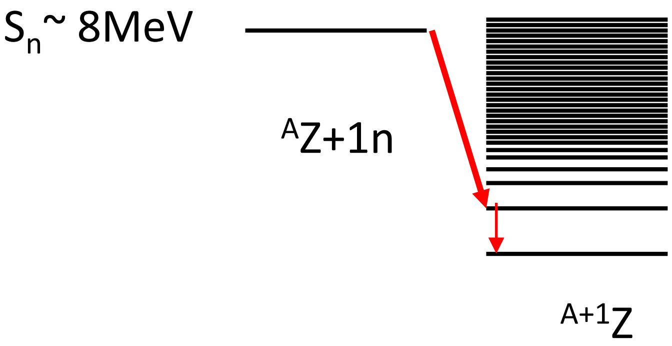


n-capture @$1<T_9<3$

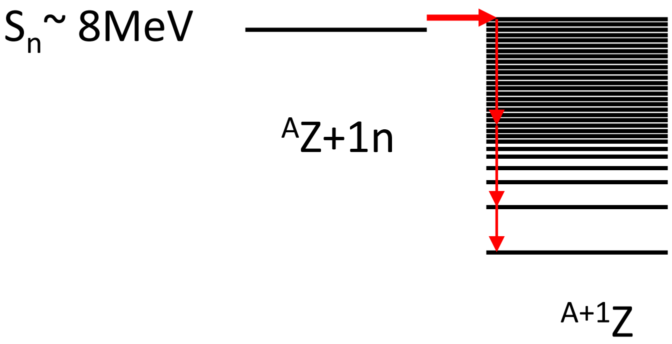
S. Woosley and T. Janka,
Nature Physics 172, 147 (2005)

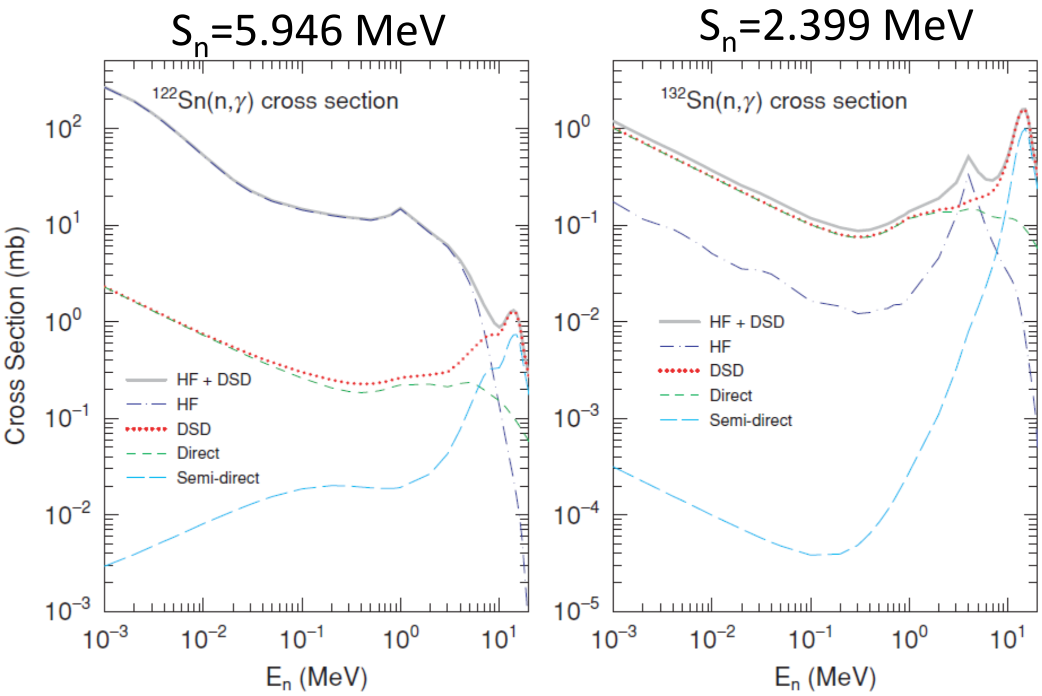
Two reaction mechanisms of (n,γ)

Direct/Semi-direct reaction (DRC)



Compound reaction (CN)





S. Chiba et al., PRC77, 015809 (‘08)

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.**

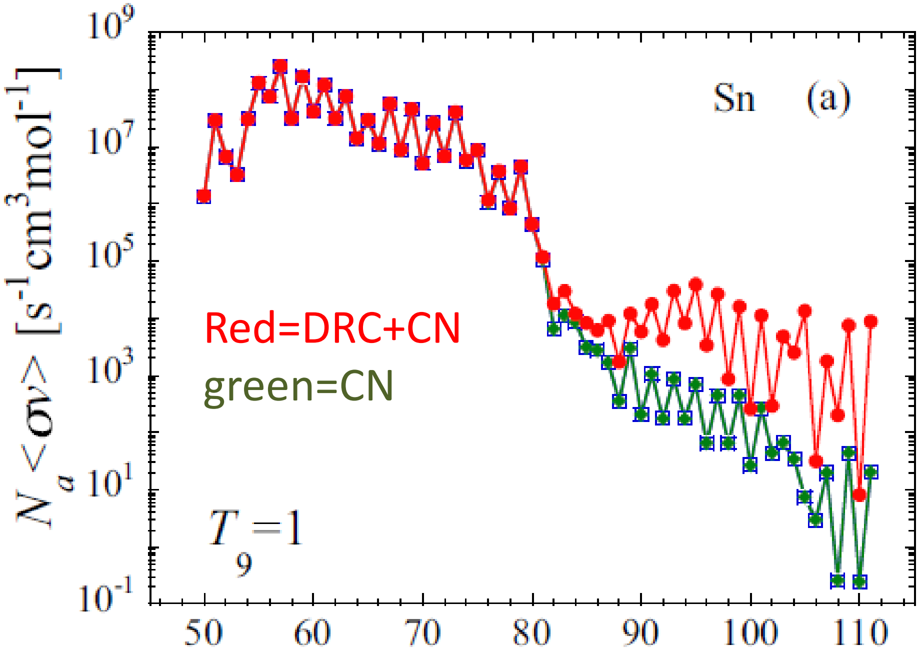
  ← level density (cf. @^{131}Sn ρ= 40 MeV^{-1}),

  gamma strength function (γSF)

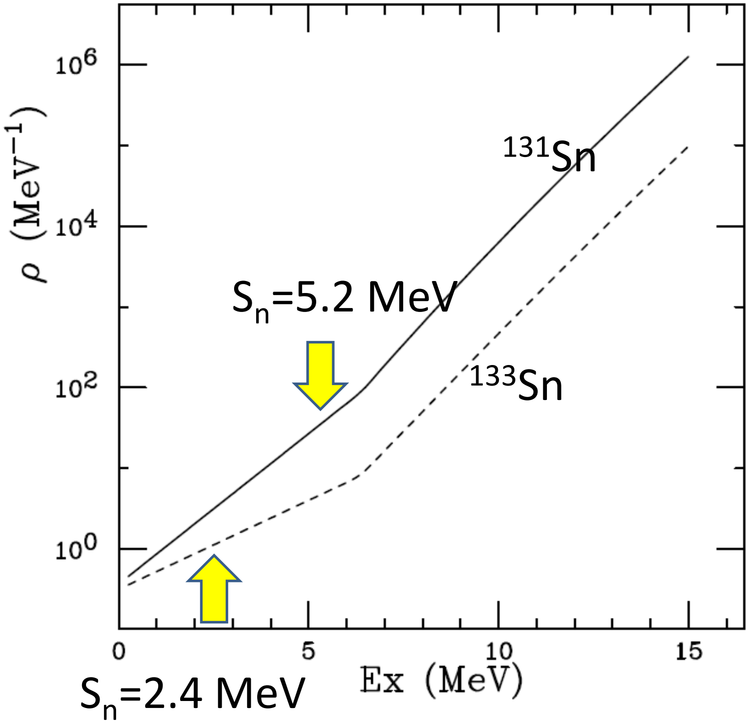
$$(4.186) \quad \Gamma_{\alpha'}(E^{tot}, J, \Pi \longrightarrow E_x, I', \Pi_f) = \frac{1}{2\pi\rho(E^{tot}, J, \Pi)} \sum_{j'=|J-I'|}^{J+I'} \sum_{l'=|j'-s'|}^{j'+s'} \delta_\pi(\alpha') \langle T^J_{\alpha' l' j'}(E'_{a'}) \rangle$$

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

DRC/CN and level density

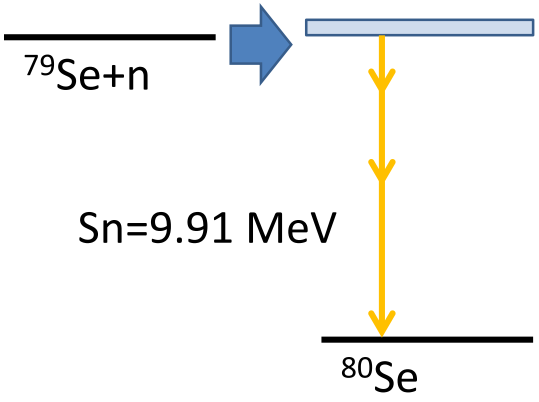


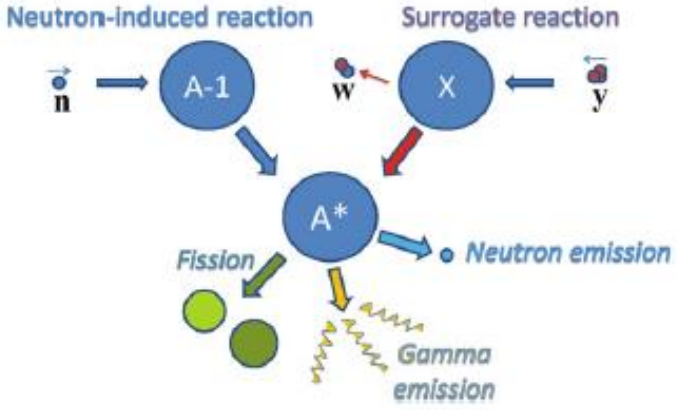
Y. Xu, S. Goriely et al., PRC90, 024604 ('14)



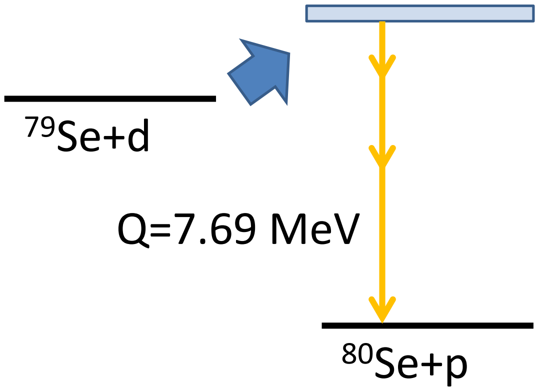
Evaluation of T_γ is important

Surrogate reaction: (n,γ) vs. (d,p)





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



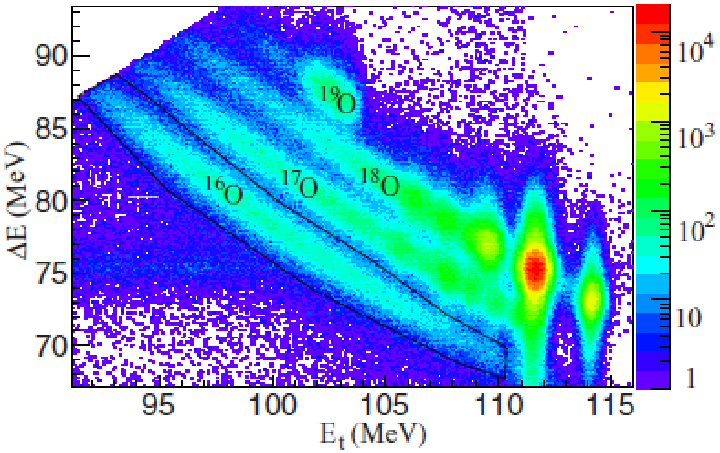
$$\sigma_{^{79}\mathrm{Se(n,}\gamma)^{80}\mathrm{Se}}(E_n) = \boxed{\sigma^{CN}_{^{80}\mathrm{Se}}(E_n)}P^{decay}_{^{80}Se^* \rightarrow \gamma + ^{79}Se}(E^*)$$

determined by
the optical model potential

Surrogate ratio method

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

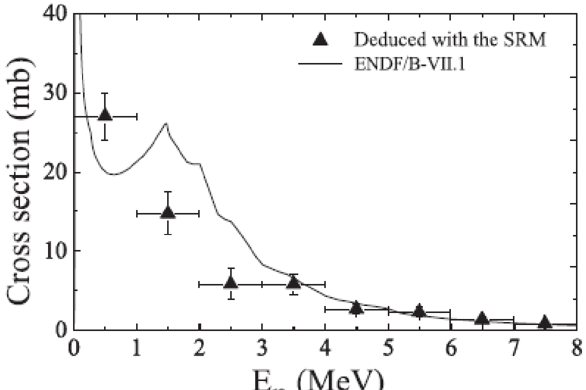
Example @JAEA



PRC94.015804('16)

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

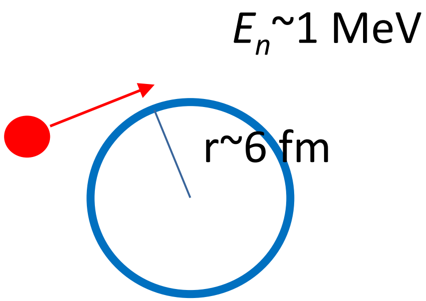
➔ ^{93}Zr(n,γ)^{94}Zr



Spin distribution difference ?

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

Neutron capture

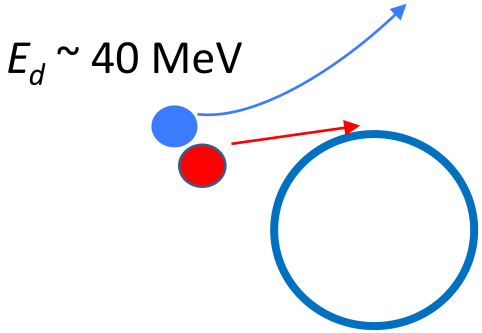


E_n~1 MeV

r~6 fm

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

Stripping reaction



E_d ~ 40 MeV

$\vartheta = 30$ deg. Ex= 10 MeV

Δp = 364 MeV/c

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

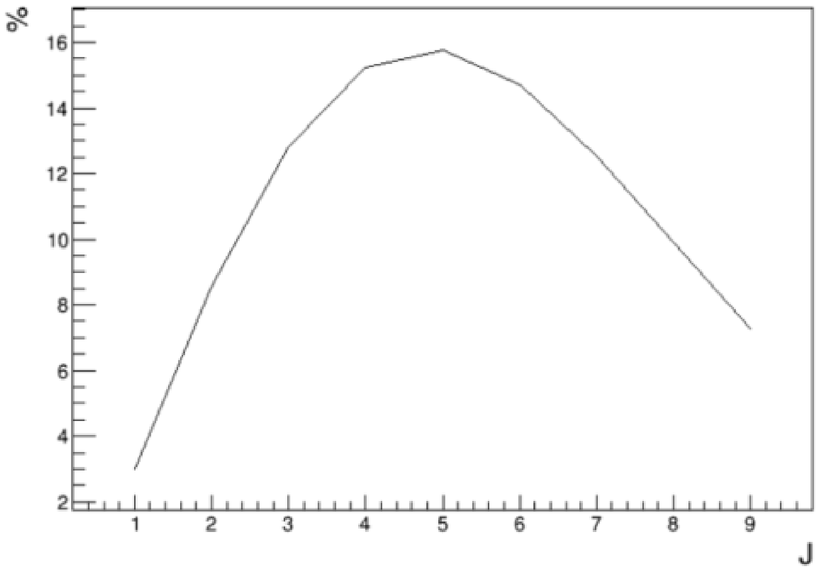
Level density distribution

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

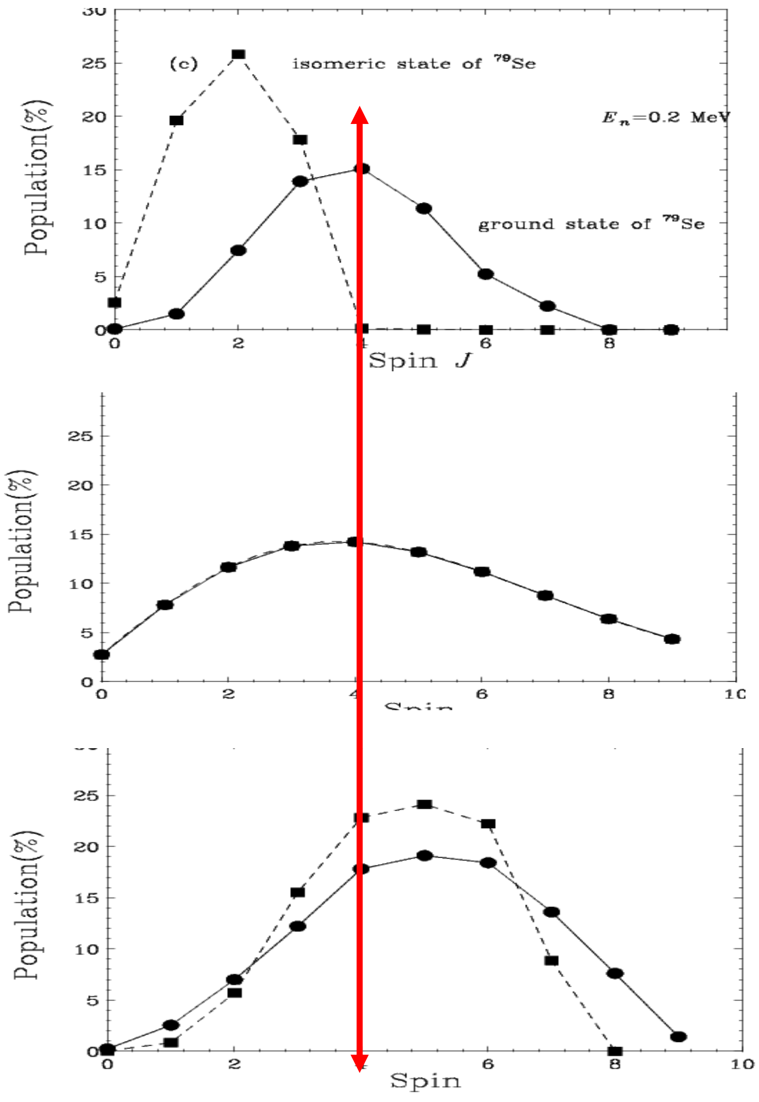
Assumption: The projection of the angular momentum are randomly coupled.



^{80}Se* at 10 MeV

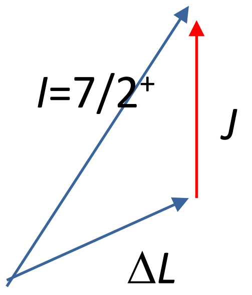
ρ ~ 2x10^5 MeV^{-1}

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

First exp of Surrogate reaction at OEDO/RIBF

- ^{79}Se(n,γ) “stellar thermometer”
- One of Long-lived fission products
- No direct experimental data about σ(n,γ)

E (MeV)	J^p	T1/2	Decay modes
0.0	$7/2^+$	$3.2\mathrm{x}10^5$ y	β^- 100%
0.0958	$1/2^-$	3.92m	IT:99.94% β^- 0.06%

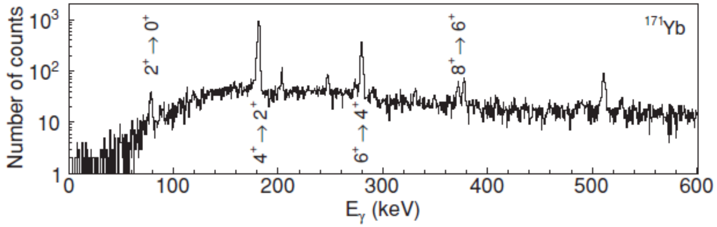
Surrogate ratio method/ Evaluation of **T_γ** from (d,p)

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)

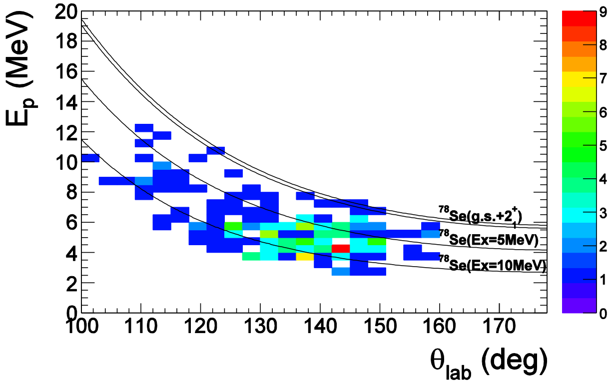
R. Hatarik et al.,
PRC81, 011602 (R) (2010)

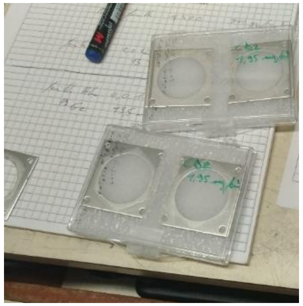
Aha!
Gamma emission means that the nucleus doesn't change N and Z number!

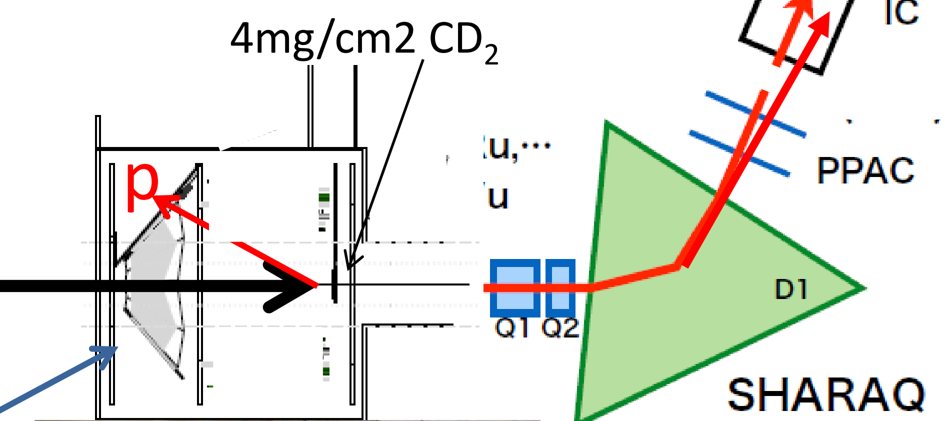
Pγ was determined by identifying the outgoing residue nucleus.

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



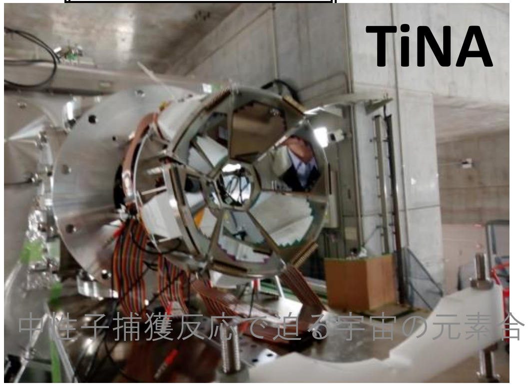




^{79}Se
(~20 MeV/u)

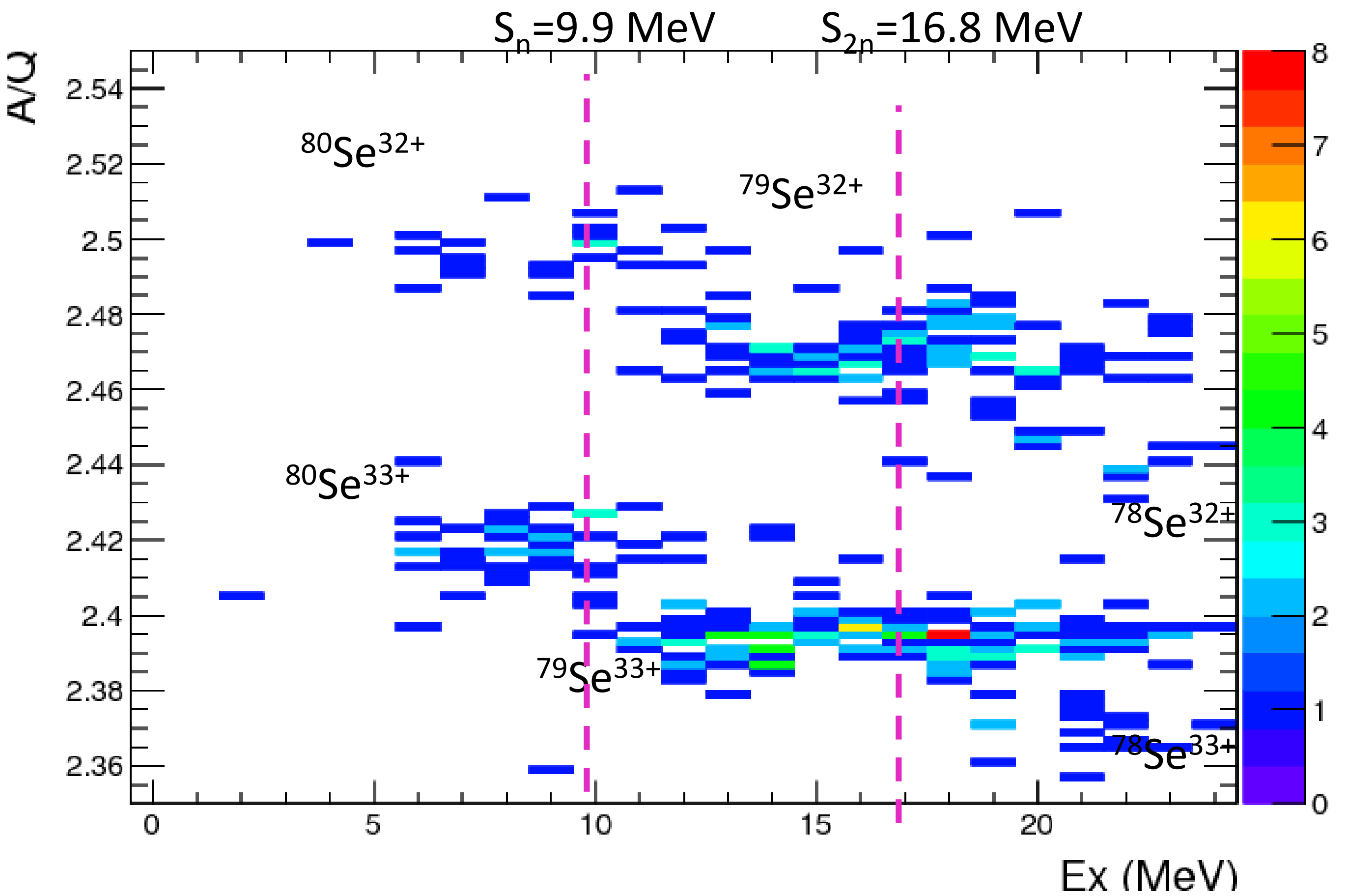
SHARAQ
QQDモード

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



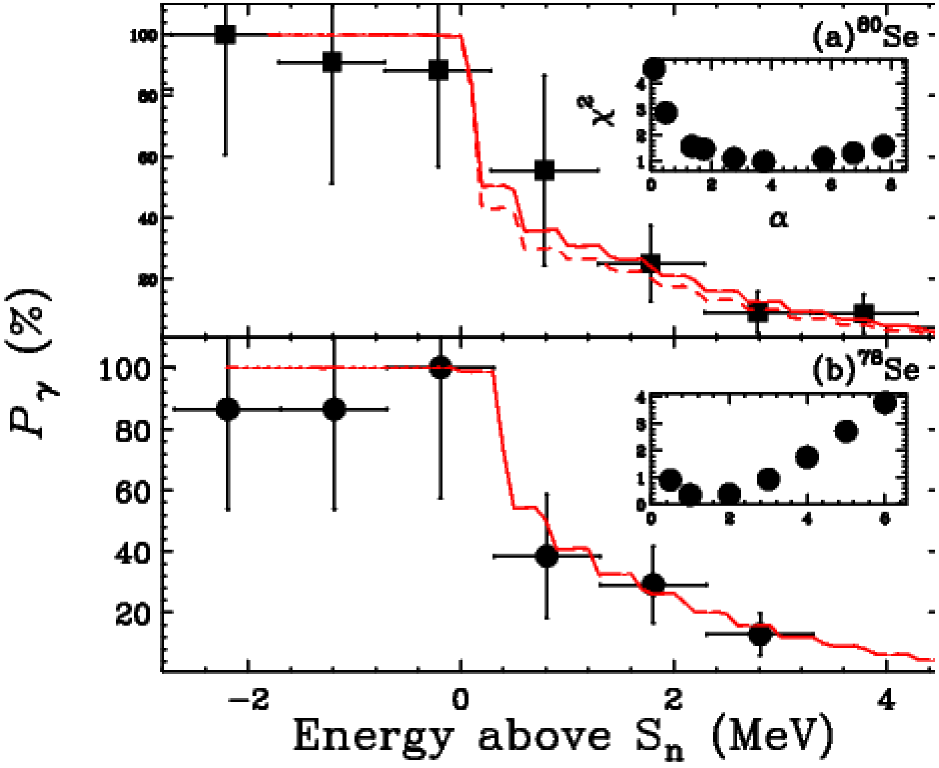
coincidence measurement of
recoil particles + outgoing particles.

Residual nuclei vs Excitation energy



P_γ in ^{77,79}Se(*d*,*p*) reaction

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



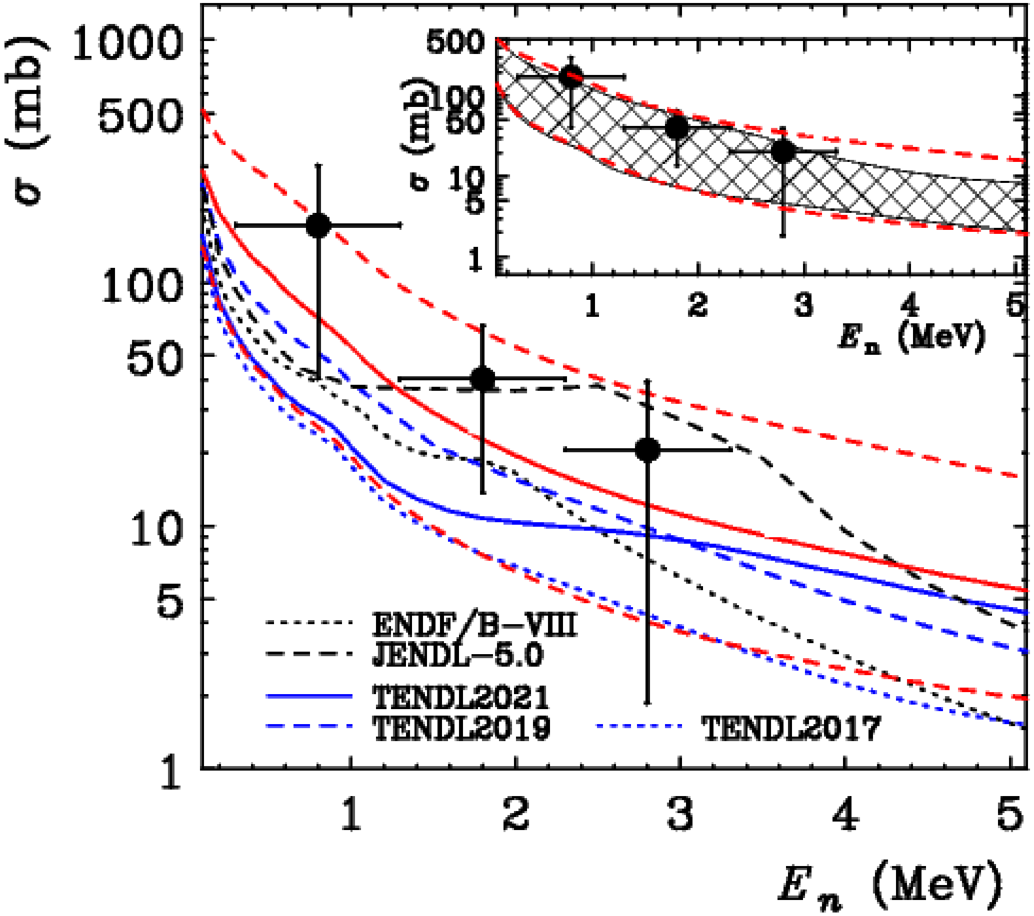
TENDL2021 recommendation
Normalization $\Gamma_\gamma \equiv \alpha$ = 1.75 (dashed)

Best fitting: α=3.75 (solid)

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

N. Imai et al., submitted to PLB

^{79}Se(n,γ) cross sesction



Summary

- Surrogate reaction **without** γ-ray measurement was employed with OEDO/SHARAQ.
  - – Spin distribution matching
  - – Odd nuclei may be better for (d,p) reaction
  - – Small energy step below 1 MeV is important
- σ of ^{79}Se(n,γ)^{80}Se were evaluated at E_n<6 MeV.
- We applied this method to medium heavy unstable nuclei ^{130}Sn and ^{56}Ni.

Collaborators of ImPACT-17

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