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R-process核の中性子捕獲反応実験について

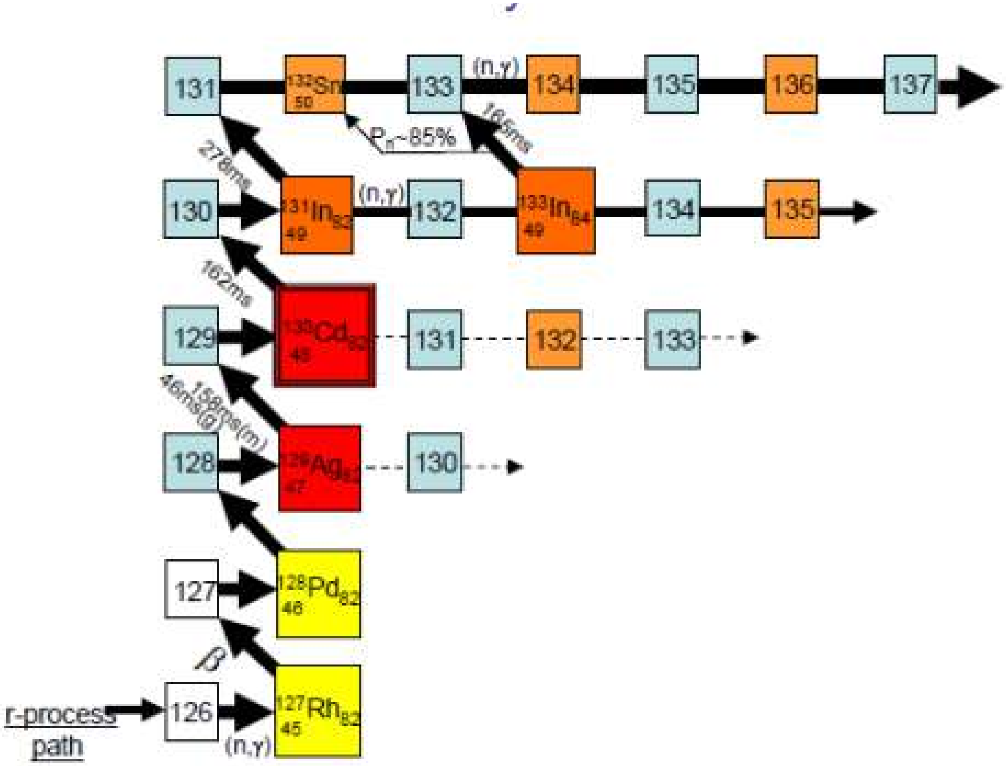
今井伸明
東京大学
原子核科学研究センター

Contents

- Astrophysical importance of n-capture rate
- Reaction mechanism of neutron capture reaction
- Example: experiment of $^{79}Se(n,\gamma)$
- Next experiment
- Summary

Astrophysical importance

r-process path around the 2nd peak



K.-L. Kratz (Revs. Mod. Astr. 1; 1988)

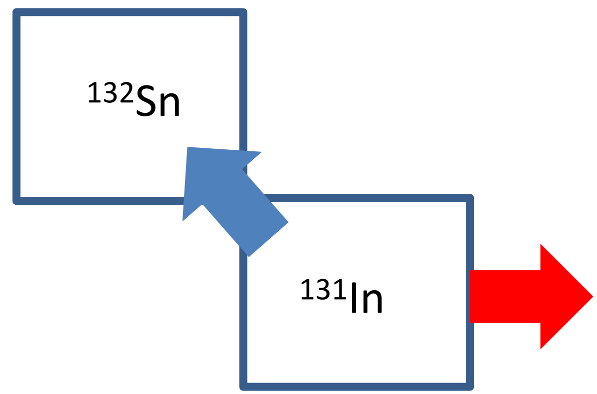
climb up the N= 82 ladder ...

A ≅ 130 "bottle neck"

⇨ **total r-process duration τ_r**

ior

β decay and neutron capture reaction



β rate ω_β=1/t = **2.47 [s^{-1}]**

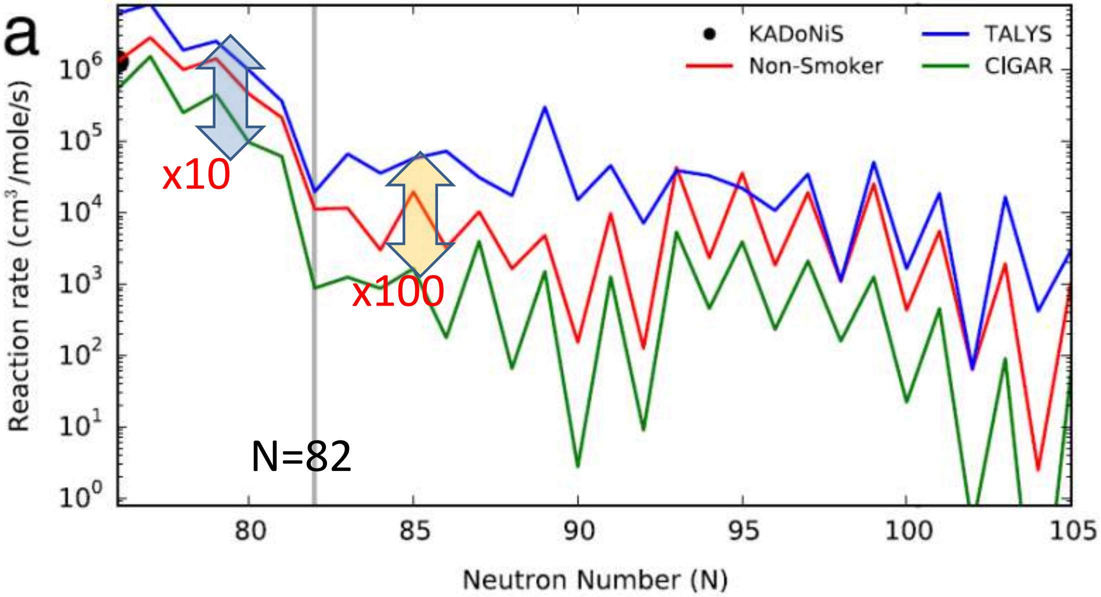
ω_n = N_n <σ>^{max}v

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

= 4.38 [s^{-1}]

(T^9=1 ~ 0.1 MeV)

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

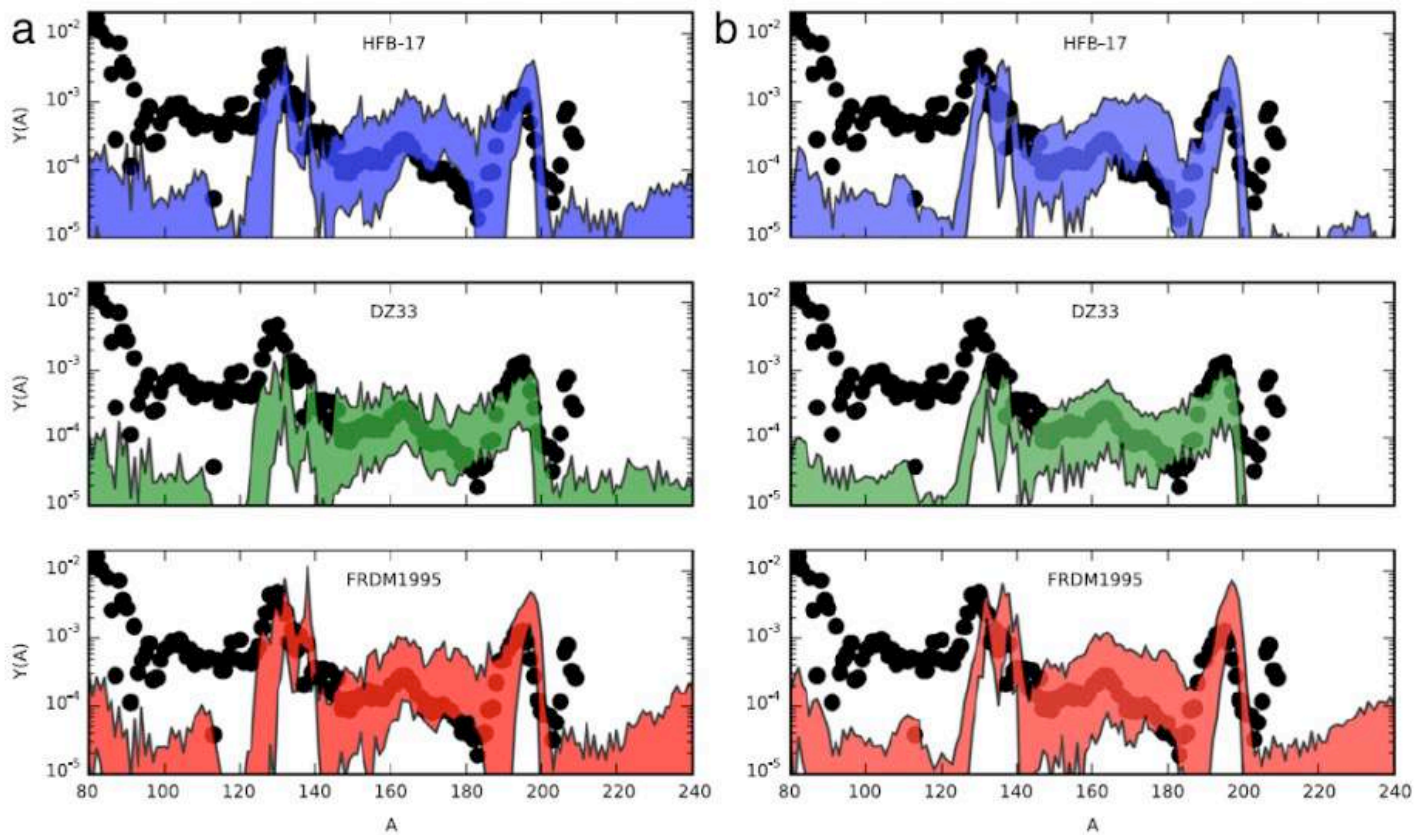


M. Mumpower,
Prog. In Part. and Nucl. Phys. 86 (2016)86-126.

$^{A}Sn(n,\gamma)@T_9=1.0$

Only Compound reaction is taken into account.

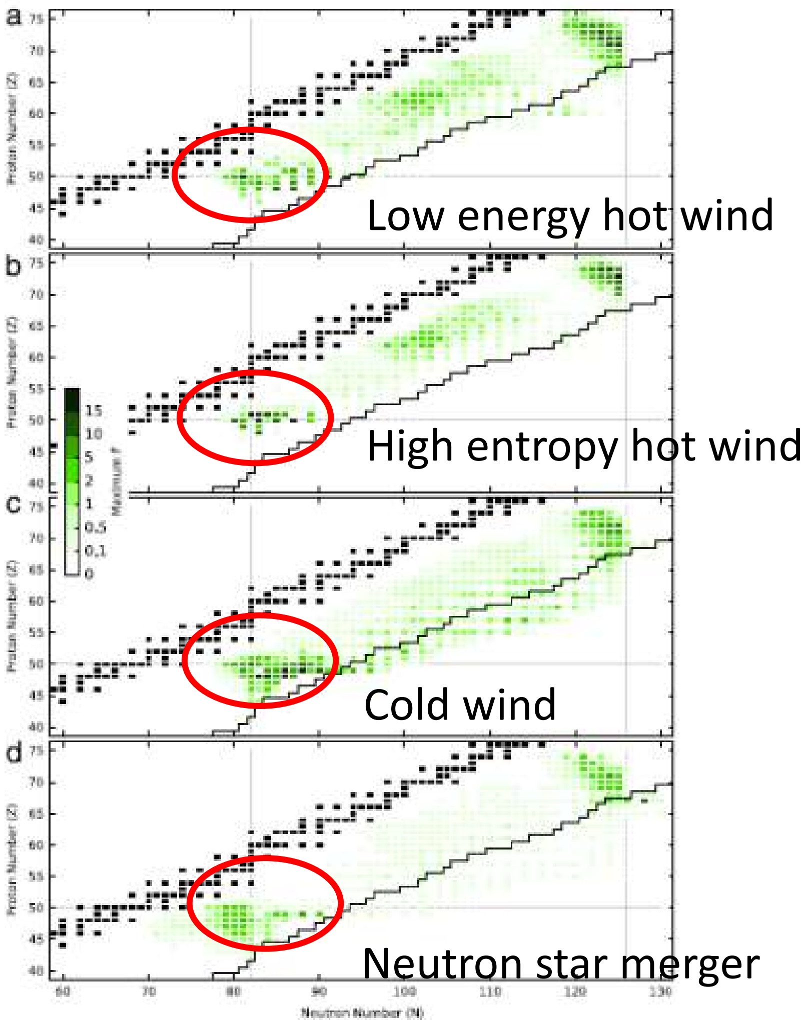
Influence to the final abundance



β-decay half-life
σ=2

σ_{ng} σ=10

Sensitivity test



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

断面積理論値を100倍にした時に
最終的なアバンダンスが変化する量。

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

^{132}Snの南西安定核側のデータがより重要。

中性子捕獲反応直接測定？

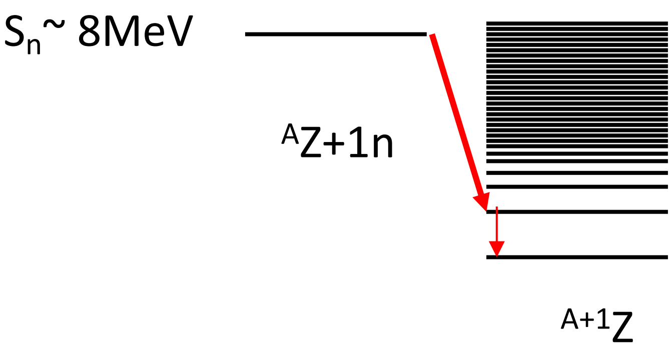
直接測定するのは(現在は)ほぼ不可能。。。

- T = 886.7 +/- 1.9 s
- 超冷中性子 ~ 2000 UCN/cm^3　(Ec=250 enV)

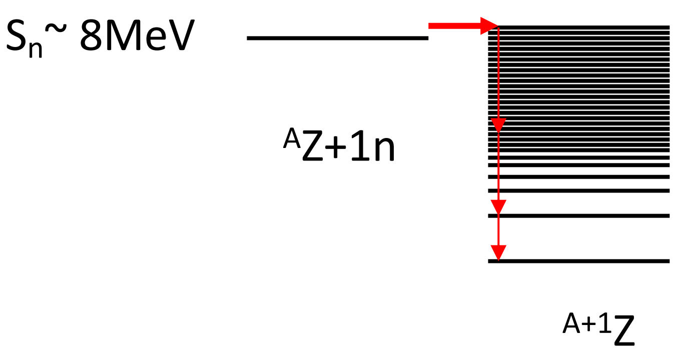
間接的な方法での断面積の評価が不可欠

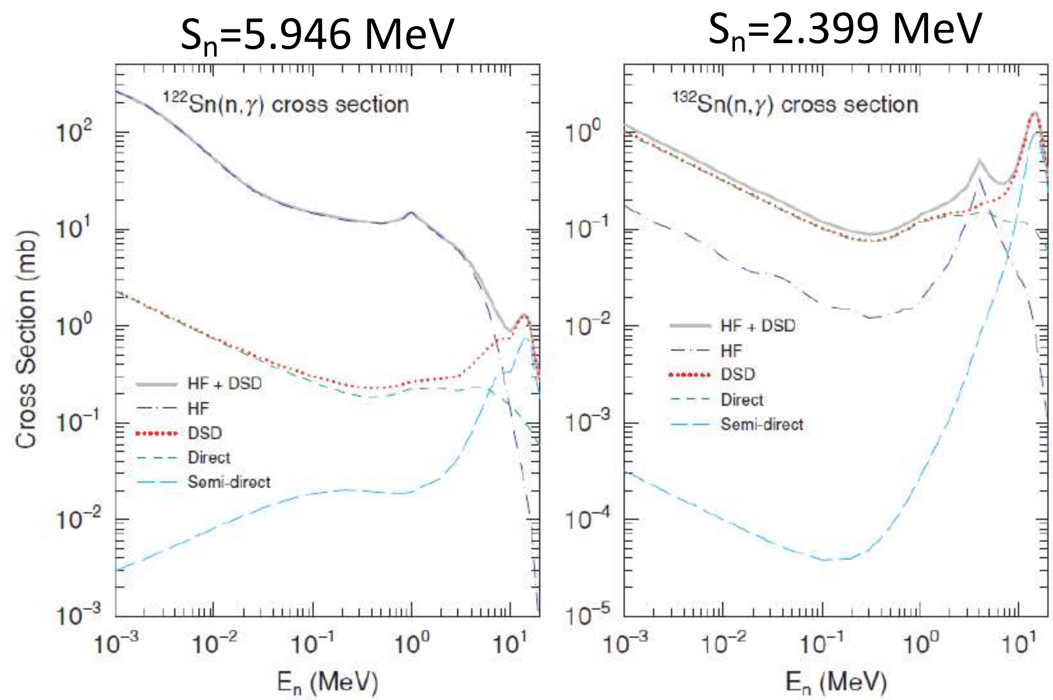
Two reaction mechanisms of (n,γ)

Direct/Semi-direct reaction (DRC)



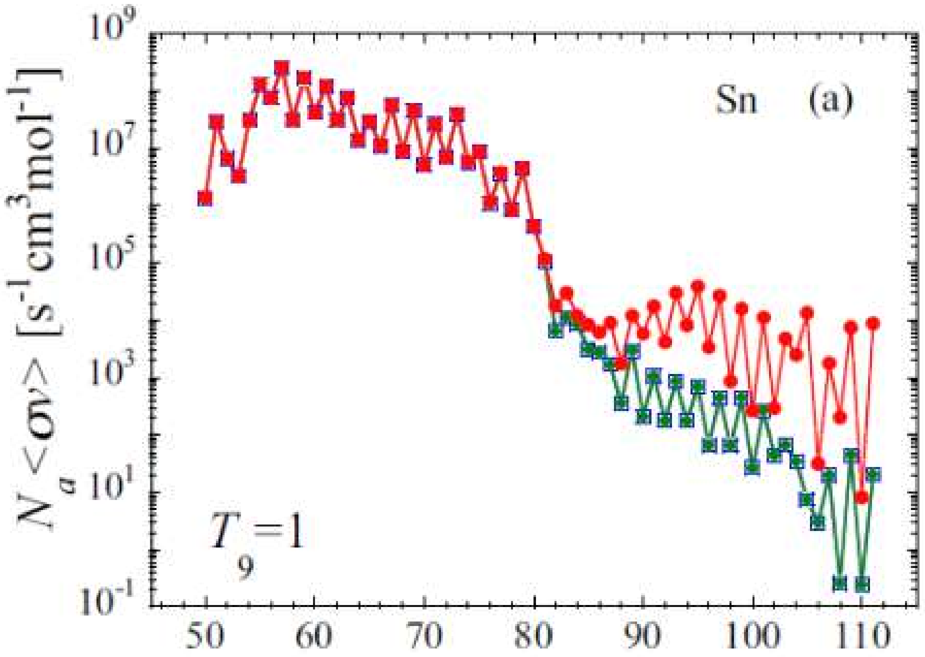
Compound reaction (CN)





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

DRC vs CN



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

赤=全チャンネル
緑=全チャンネル-DRC

N>82ではDRCが主成分

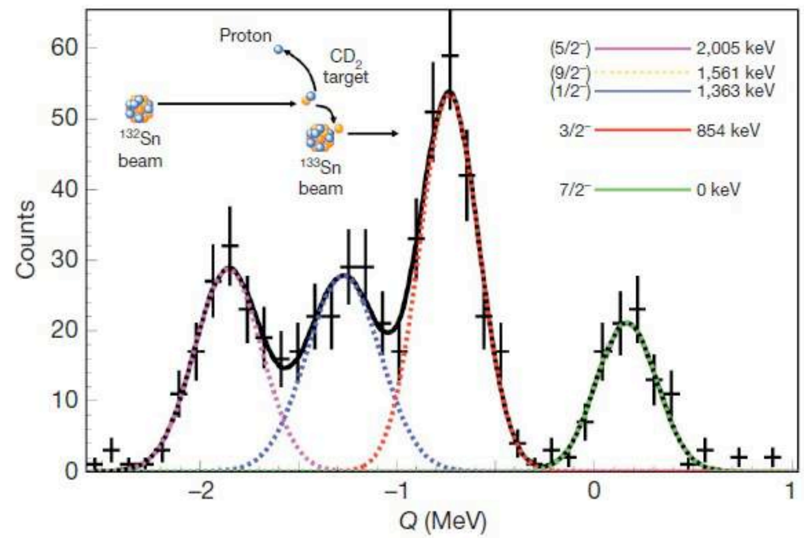
Direct/Semi-Direct reaction

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

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

始状態と終状態の波動関数

➔ (d,p)反応 etc.



^{132}Sn(d,p)^{133}Sn
K. Jones et al., Nature 465, 27 (2010)

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. ~^{133}Sn ρ= 10^3 MeV^{-1}),
  - gamma strength function (γSF)

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

Experimental challenge to T_γ

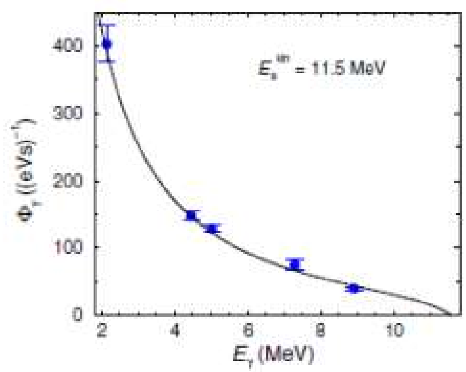
reverse reaction

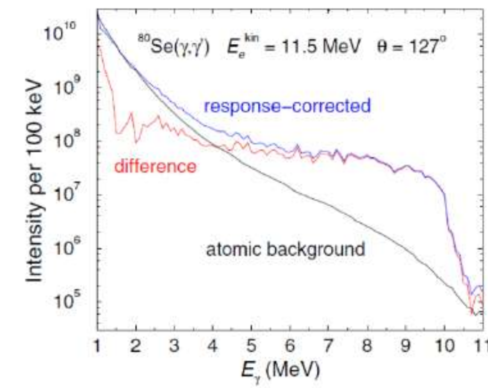
- γSFを導出する。
  - Real photon

    $\sigma_{\gamma\gamma'}$ ➔ γSF

    e.g. A. Makinaga et al.,

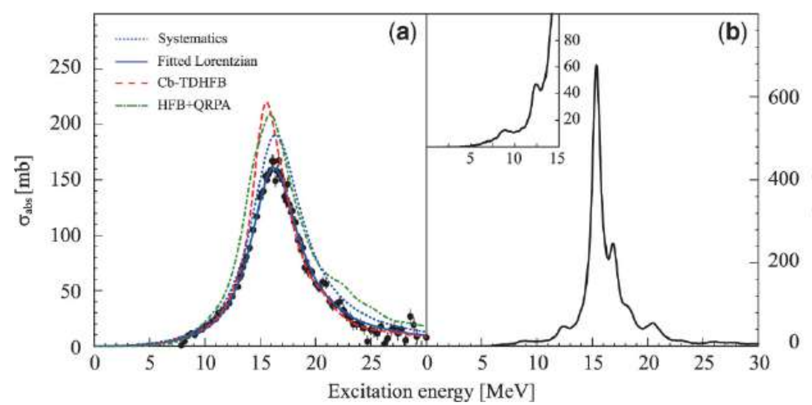
    PRC94, 044304 ’16





  - Virtual photon

    e.g. S. Takeuchi et al.PTEP013D02, ‘19



^{93,94}Zr Coulomb breakup

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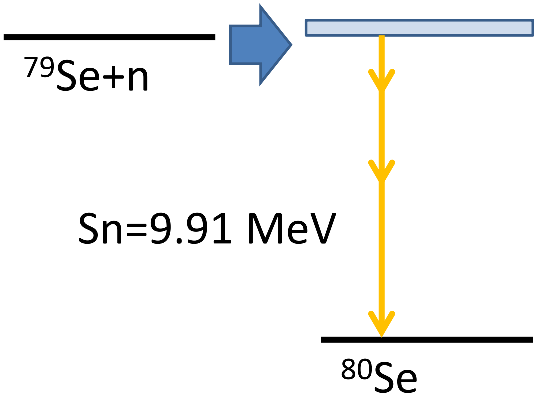
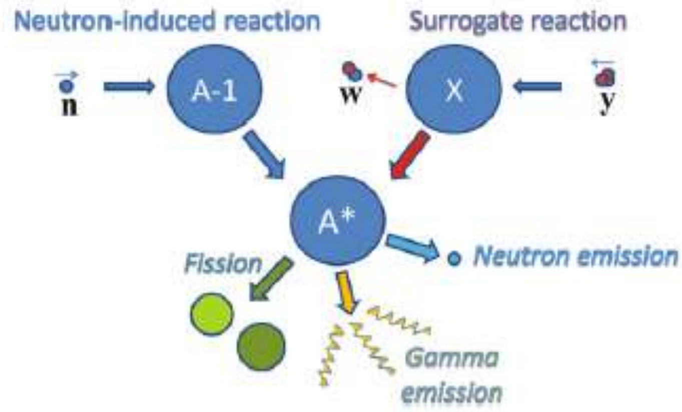
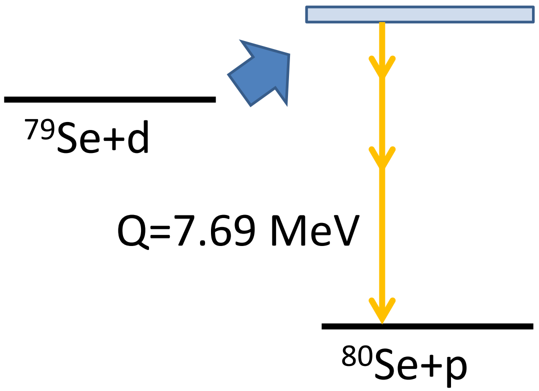
Experimental challenge to T_γ

Surrogate reactions (n,γ) vs. (d,p)







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

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

determined by
the optical model potential

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$P_\gamma(J^\pi,E)$

- high excited state of ^{80}Se was populated by $^{79}Se(d,p)^{80}Se$ reaction.
- branch of the γ decay from the compound nucleus was determined.

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

determined by (d,p)

$$P^{decay}_{n\gamma}(E^*) = \sum F_{n\gamma}(E^*, J^\pi) G_{decay}(E^*, J^\pi)$$

$$P^{decay}_{dp}(E^*) = \sum F_{dp}(E^*, J^\pi) G_{decay}(E^*, J^\pi)$$

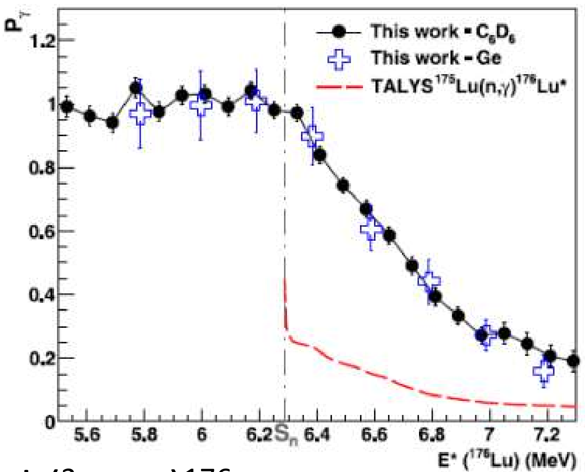
Assumption 1; $F_{ng}(E^*, J^\pi) \approx F_{dp}(E^*, J^\pi)$

Assumption 2; $G_{decay}(E^*, J^\pi) = G_{decay}(E^*)$

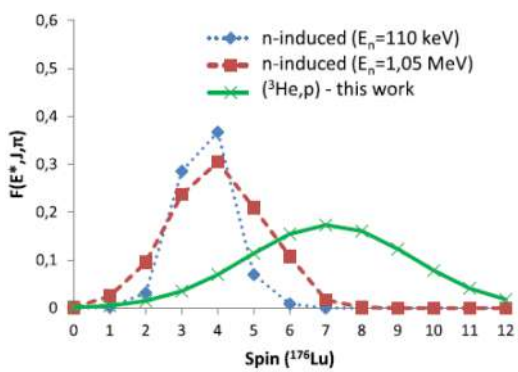
Weisskopf-Ewing approximation
V. Weisskopf, DH. Ewing, Phys. Rev. 57, 472('40)

Example: experiment of $^{79}Se(n,\gamma)$

Calculated spin distribution

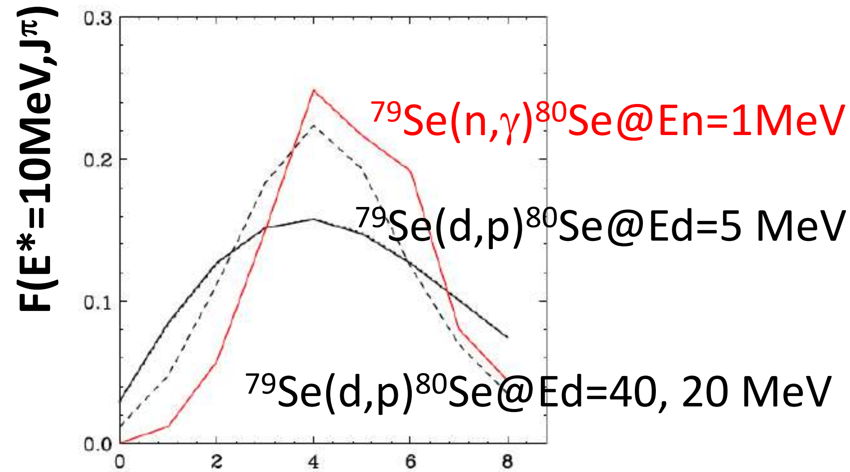


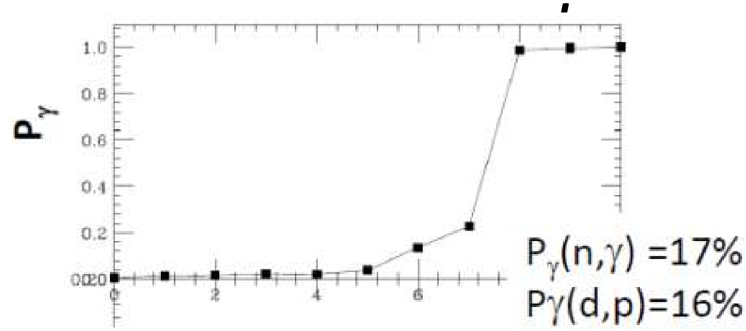
^{174}Yb(^{3}He,p)^{176}Lu



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

The different population of ***J***





ΔL ~ 0 transfer for (n,γ)

Different probability of emission of γ ?

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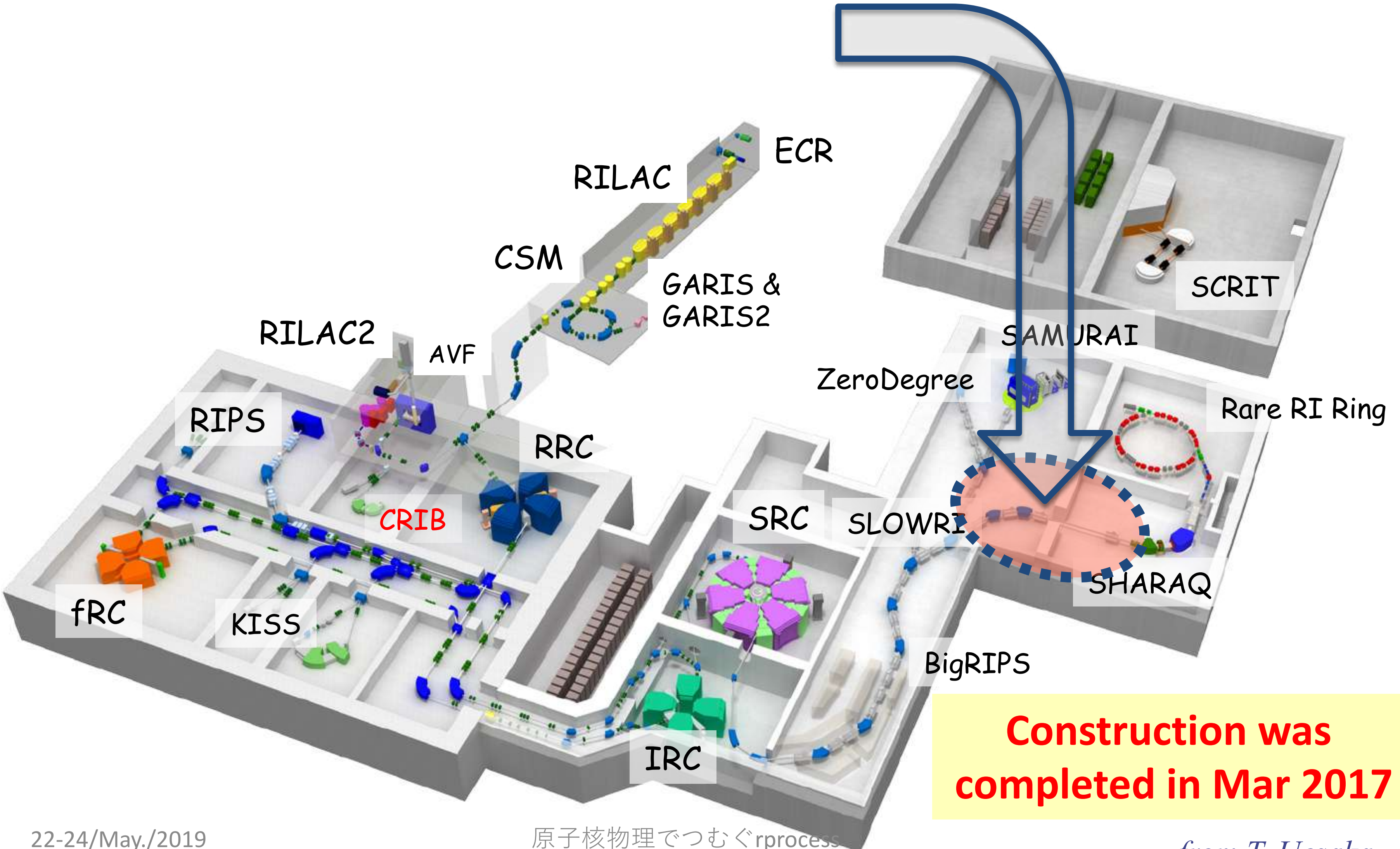
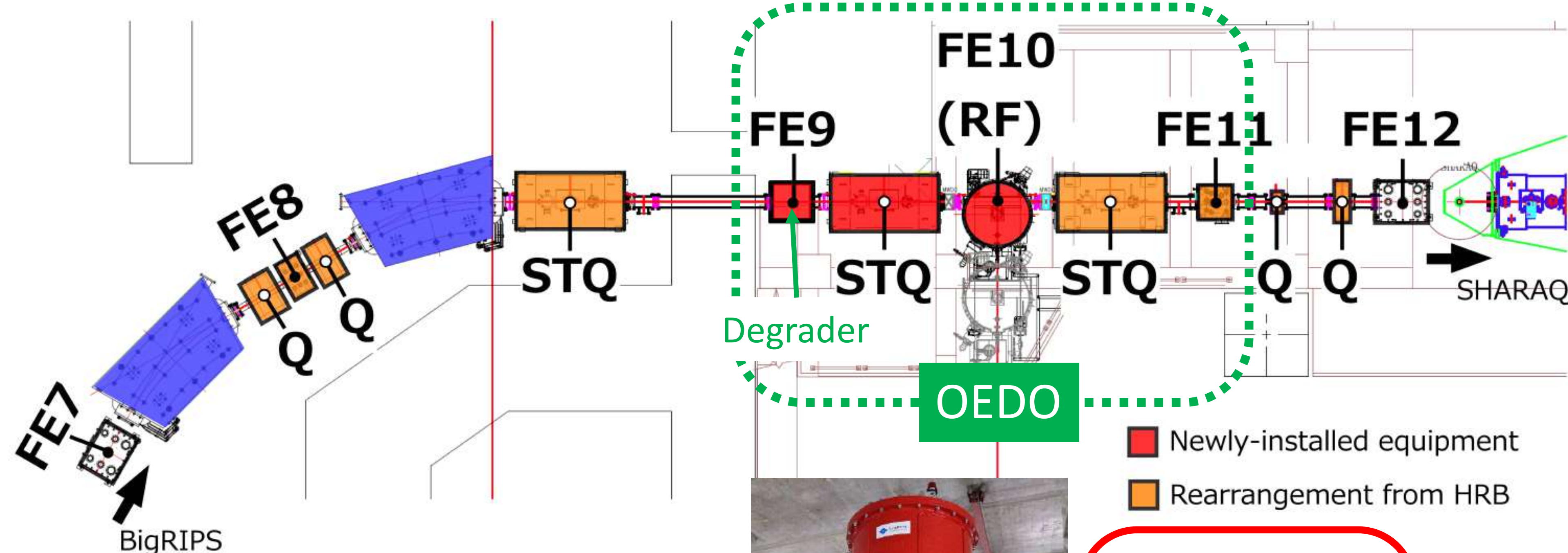
OEDO Beamline (Construction Site)



Construction was completed in Mar 2017

from T. Uesaka

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.

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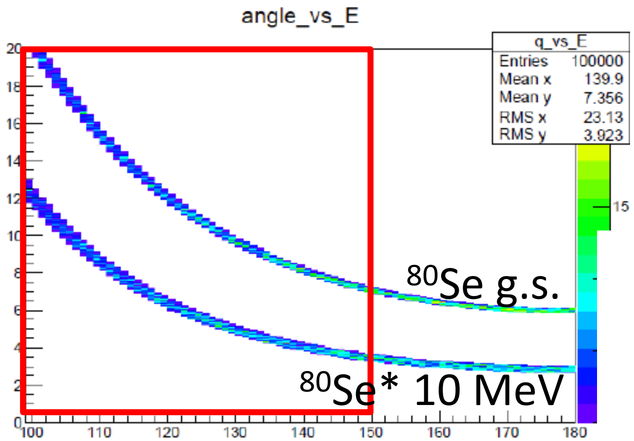
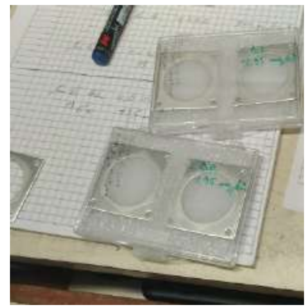
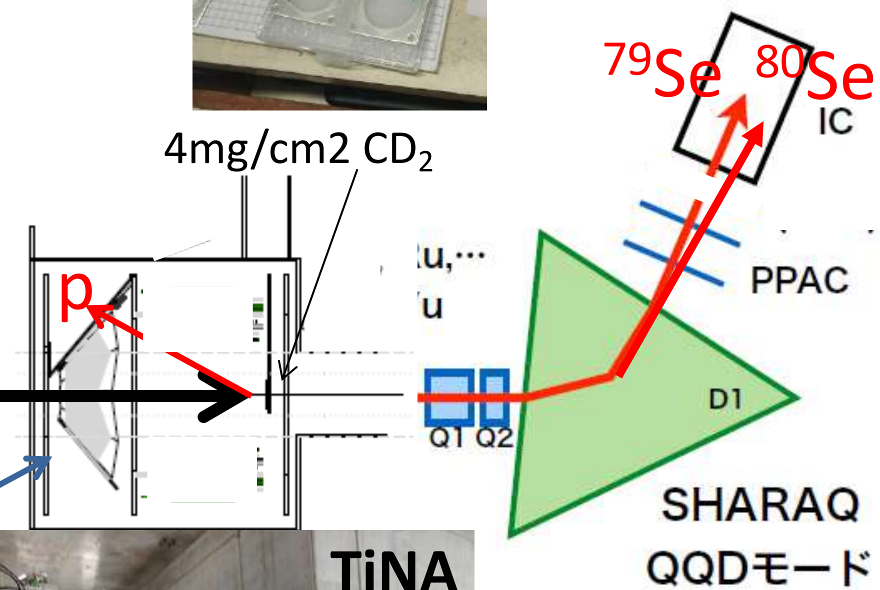
Experimental Setup around 2ndary target

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

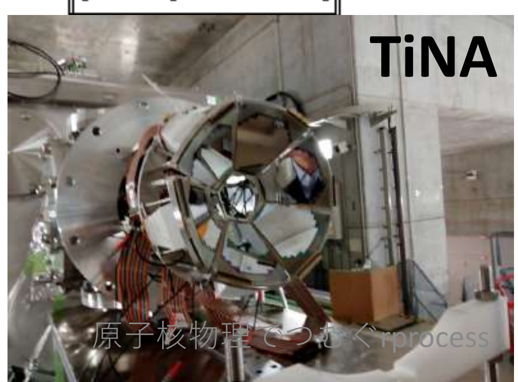






^{79}Se
(~20 MeV/u)

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



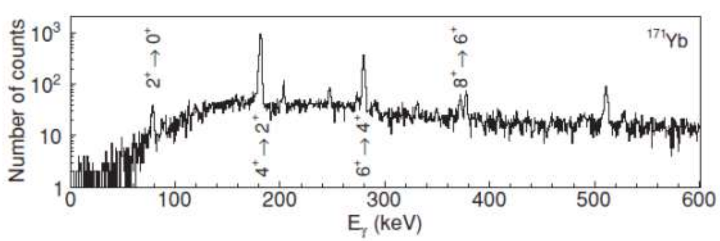
coincidence measurement of recoil particles + outgoing particles.

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.

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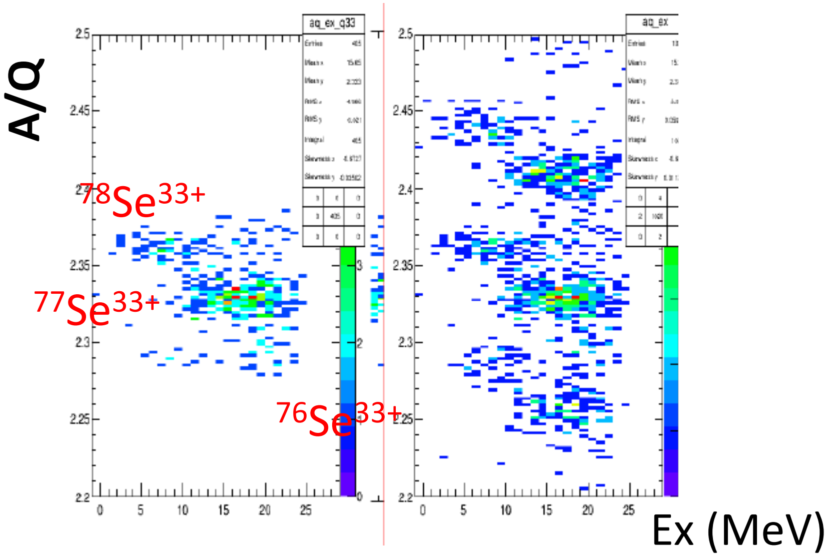
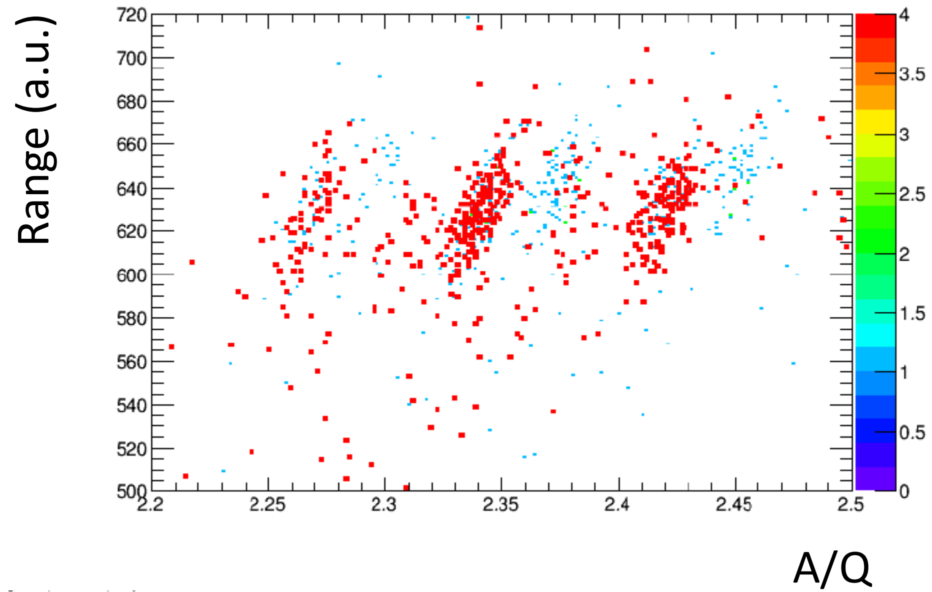
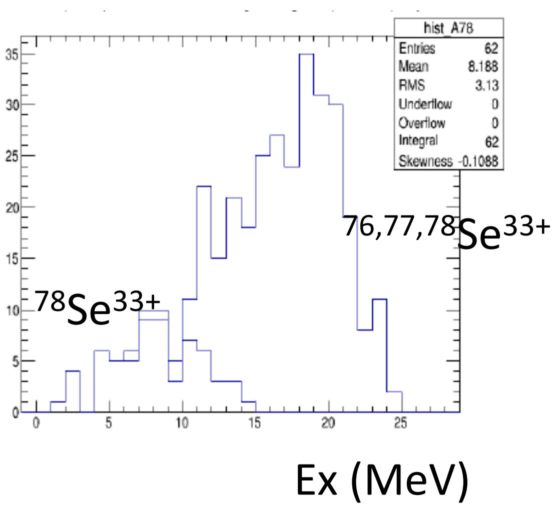
PI map of $^{77}Se(d,p)X$

$^{77}Se(d,p)^{78}Se$







PI map of $^{79}Se(d,p)X$

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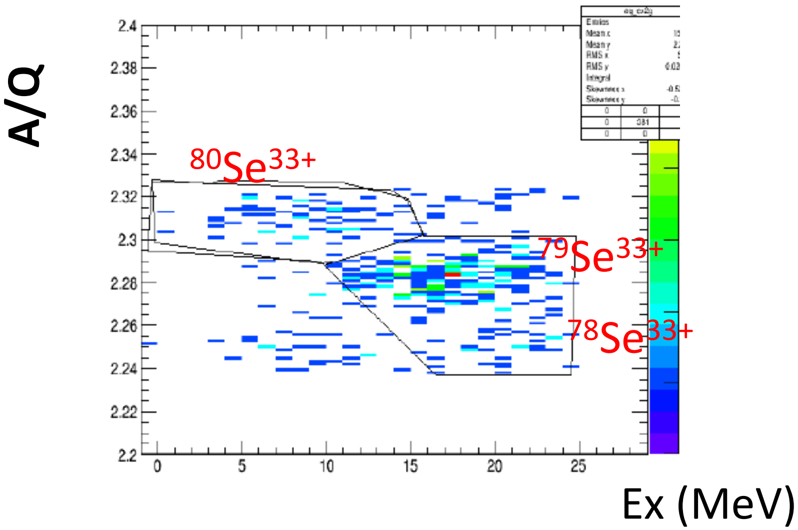
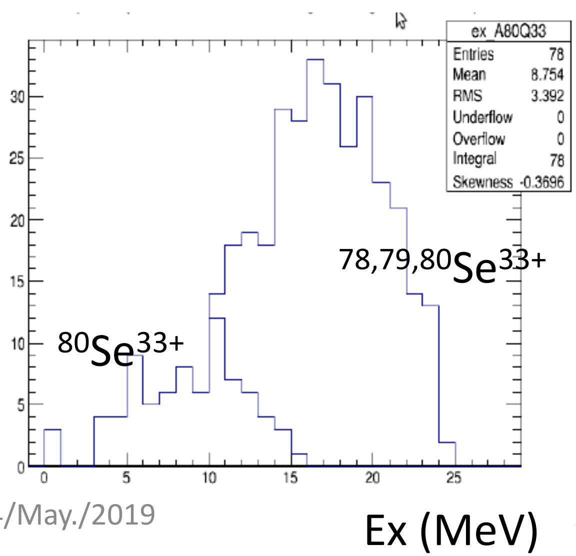
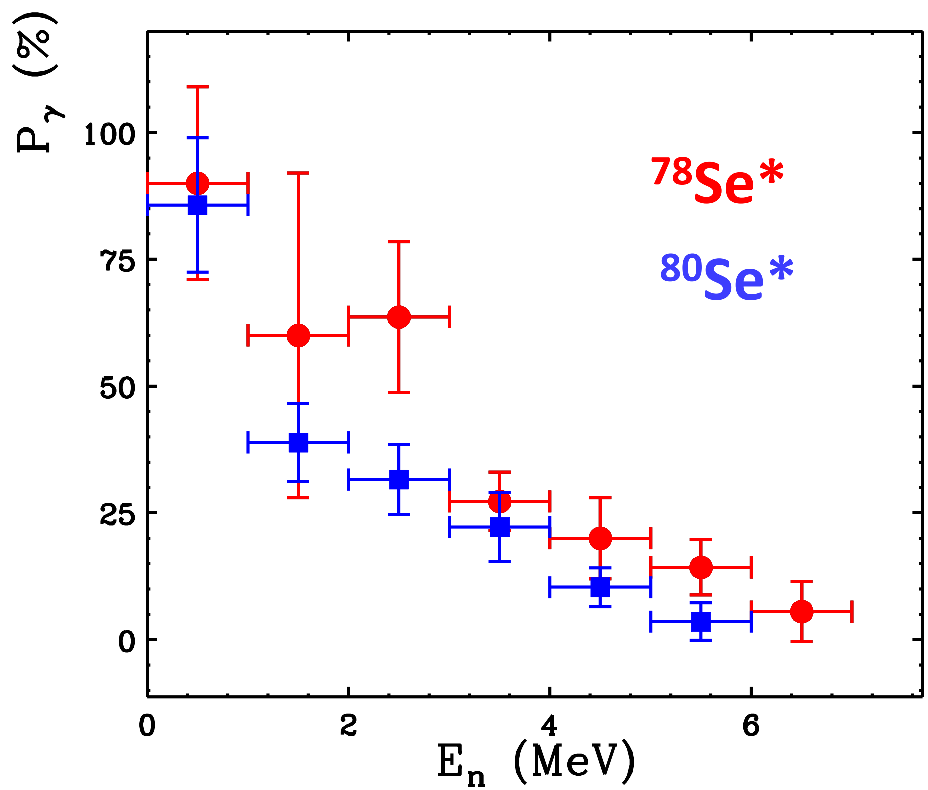
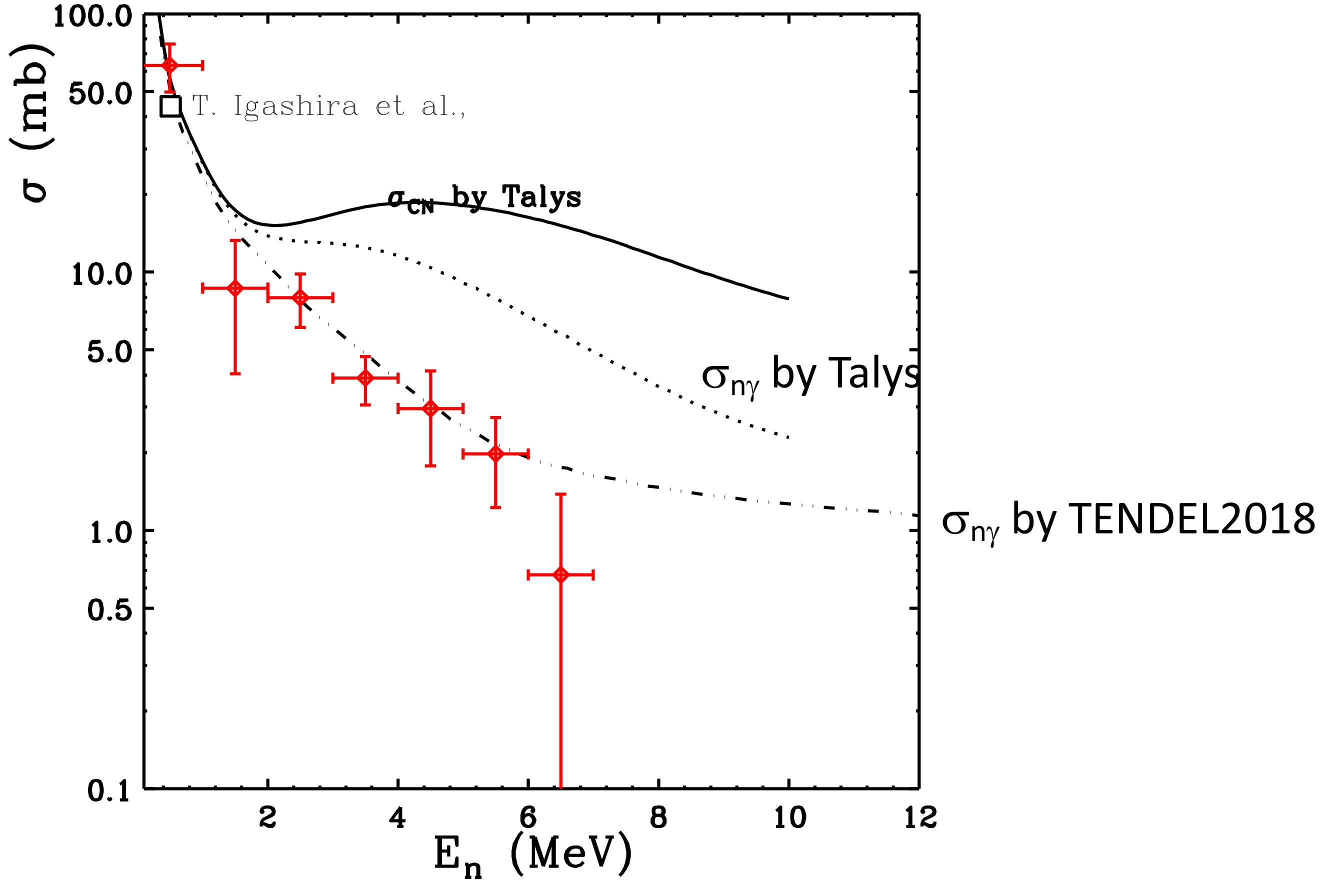
$^{79}Se(d,p)^{80}Se$



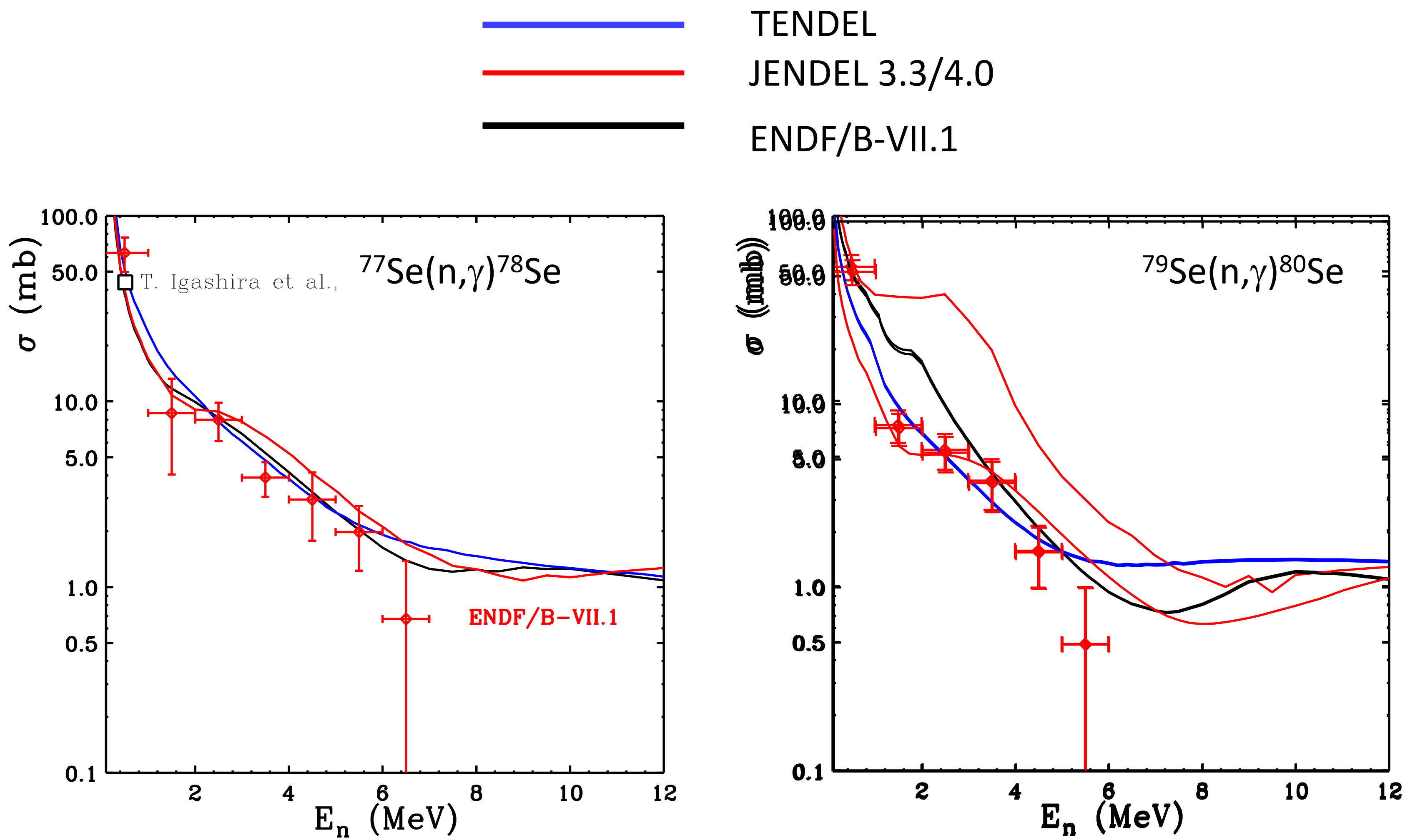




Evaluated $\sigma_{n\gamma}$ vs Talys



Comparison with evaluated nuclear data for $^{77,79}Se(n,\gamma)$

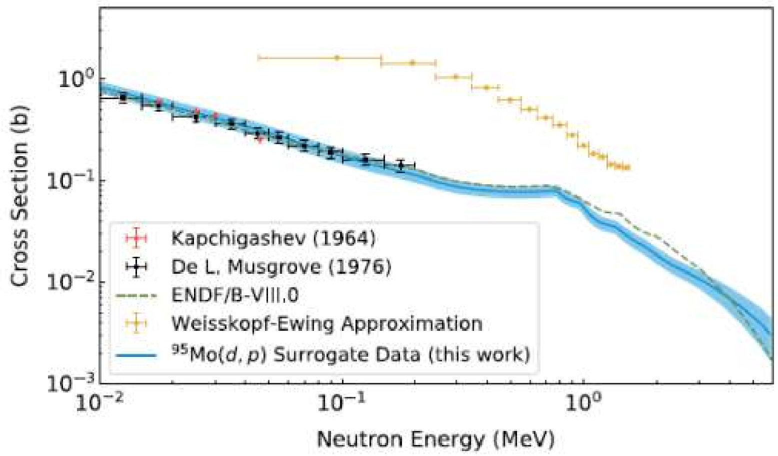


One step further...

^{95}Mo(d,pγ) → ^{95}Mo(n,γ)

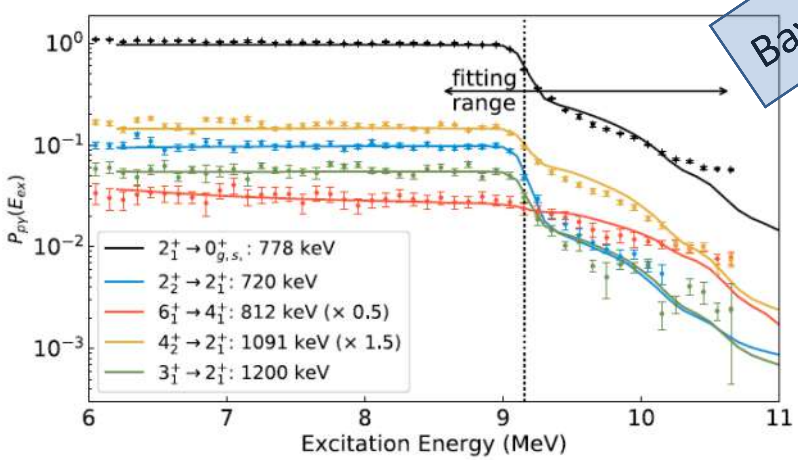
coincidence of p, γ

A. Ratkiewicz, et al.,
PRL 122 052502

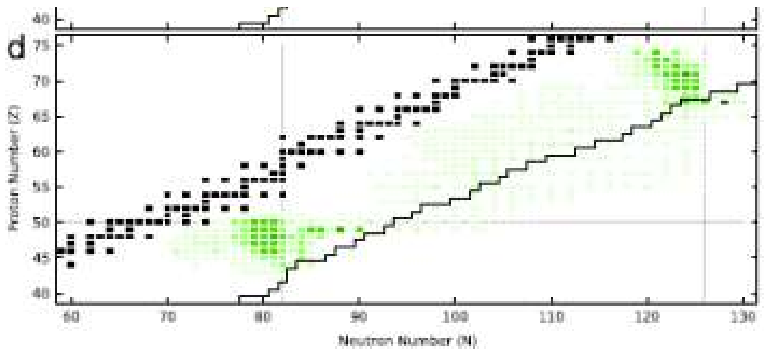


Bayesian fitting

γ-strength func
level density



Future experiment at OEDO



Neutron star merger

^{a}Low energy hot wind

^{b}High entropy hot wind

^{c}Cold wind

^{d}Neutron star merger

^{131}Cd(n,γ) 2x10^{4} pps/10pnA; F^{a}=9.47, F^{b}=14.75, F^{c}=15.62 F^{d}=1.95
^{130}Sn(n,γ) 4x10^{5} pps/10pnA; F^{a}=20.92, F^{b}=6.02, F^{c}=9.46, F^{d}=3.28

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Summary

- Neutron capture reaction is one of the key parameters which governs the synthesis.
- Surrogate reaction **without** γ-ray measurement was employed to evaluate the compound reaction cross section.
- σ of $^{77}Se(n,\gamma)^{78}Se$ is in good agreement with the past experimental data and the evaluation.
- σ of $^{79}Se(n,\gamma)^{80}Se$ were also determined at En<6 MeV for the first time.
- $^{131}Cd(n,g)$, $^{130}Sn(n,g)$ will be measured.

Collaborators of ImPACT-17

N.Imai, S.Michimasa, M.Dozono, S.Ota, M.Takaki, J.Hwang, C.Iwamoto, S.Masuoka, N.Kitamura, K.Kawata, H.Simizu, R. Tsunoda, S.Hayakawa, P.Schrock, O.Beliuskina, L.Yei, H.Yamaguchi, K.Yako, K.Wimmer,
T.Sumikama, H.Otsu, H.Wang, S.Takeuchi, S.Kawase, N.Chiga, X.Sun,
S.Naimi, D.Nagae, S.Omika, K.Chikaato, T.Teranishi, K.Iribe, K.Yoshida,
E.Ideguchi, Y.Fan, Y.Watanabe, K.Nakano, H.Miyatake, Y.X.Watanabe, T.Nakamura,
K.Yoshida, N.Fukuda, Y.Shimizu,
H.Suzuki, H.Takeda, D.S.Ahn,
Y.Yanagisawa, K.Kusaka, T.Ohtake,
H.Sakurai, and S.Shimoura