γ-ray spectroscopy in nuclear astrophysics

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Outline

1. p-process nucleosynthesis
2. Solving an unveiled mystery of 180Ta
3. p-process chaser detector
4. Timeline
5. Summary

Nuclear Astrophysics Experiments with HIAF, IMP Huizhou, China, 3-5 Sept. 2025

Project Team

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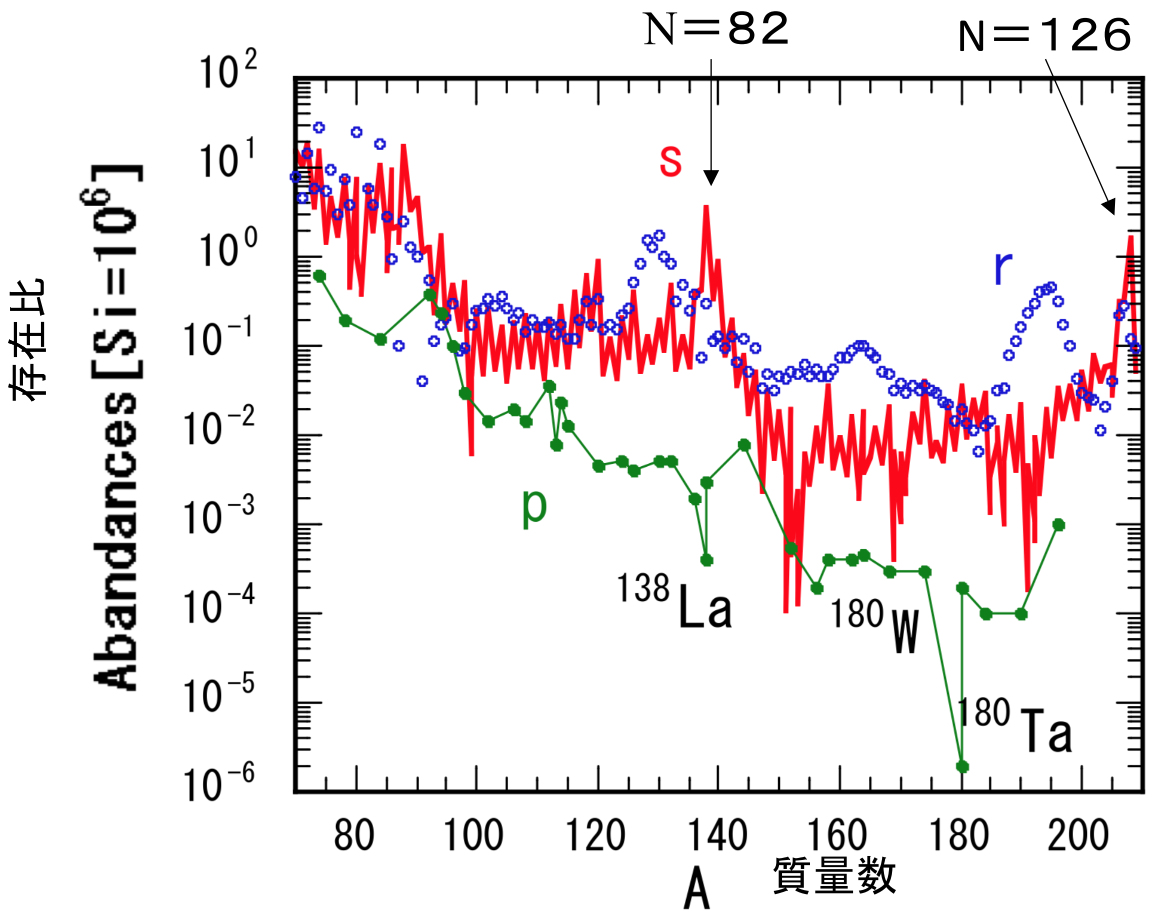
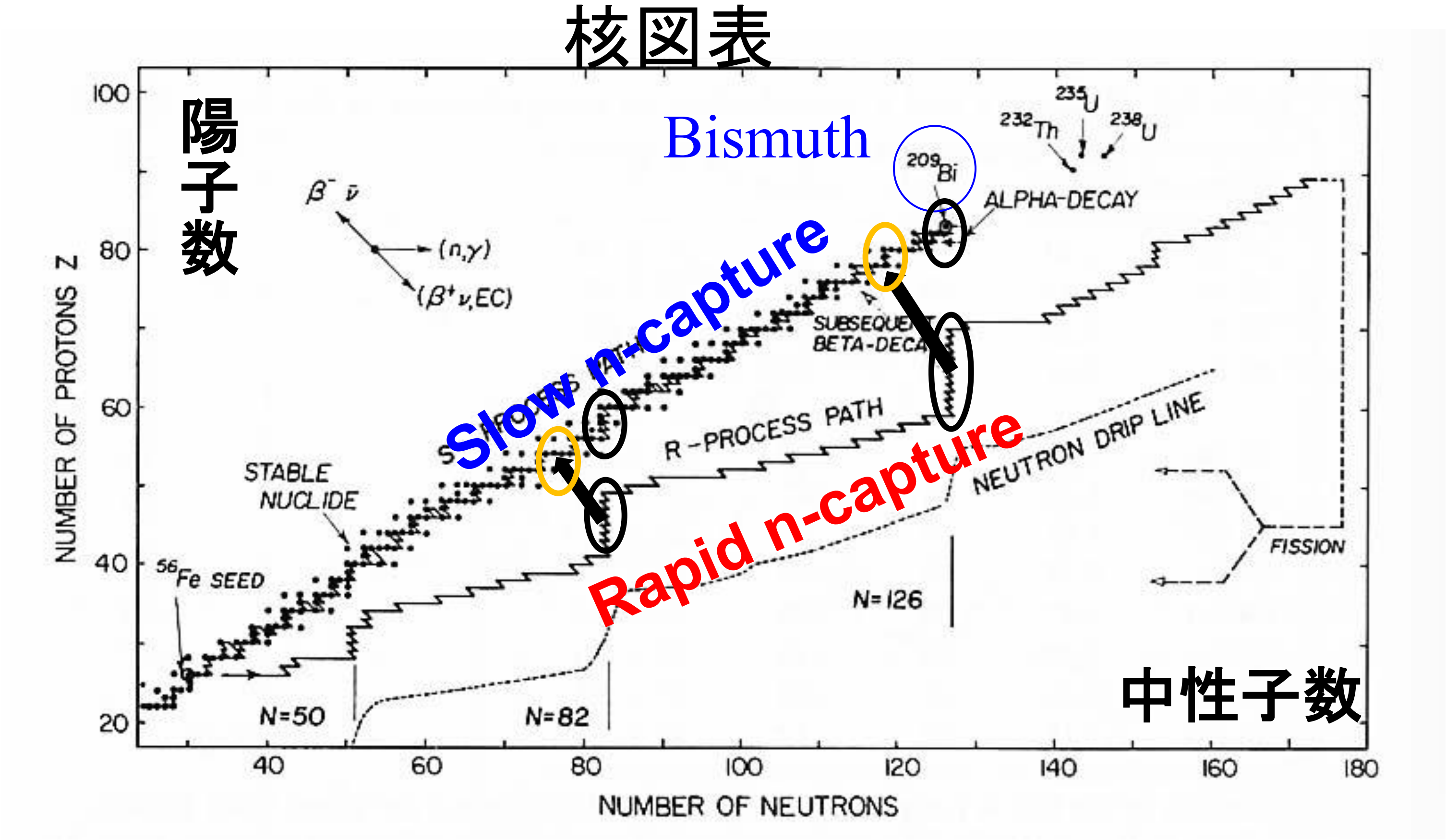
Abundances of heavy elements s-process, r-process and p-process



s-process and r-process nucleosynthesis

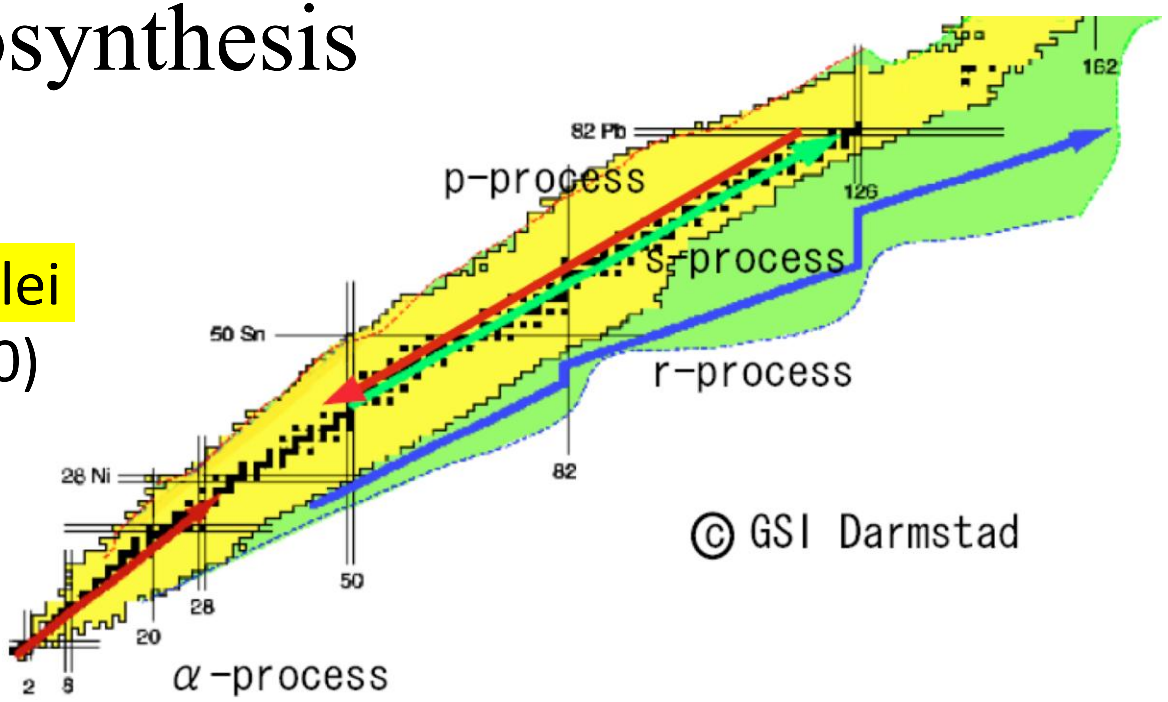
(n,γ) reactions

s-process: slow neutron capture process
r-process: rapid neutron capture process

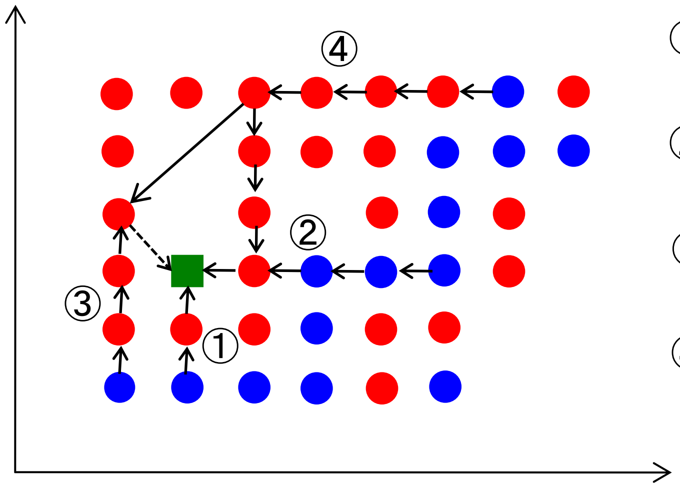


p-process nucleosynthesis

35 neutron-deficient nuclei
from Se(Z=34) to Hg(Z=80)



- Pre-existing nuclei produced by s- and r-processes



① (p,γ)

② (γ,n)

③ $(p,\gamma)+\beta-decay$

④ $(\gamma,n)+(\gamma,p)$

$(\gamma,n)+(\gamma,\alpha)+\beta-decay$

What does p stand for?

List of p-nuclei

35 neutron-deficient isotopes from Se to Hg

180Ta →

Nucleus	Natural abundance (%)	Abundance (10^6 Si) Anders&Grevesse
74Se	0.89	0.55
78Kr	0.35	0.153
84Sr	0.56	0.132
92Mo	14.84	0.378
94Mo	9.25	0.236
96Ru	5.54	0.103
98Ru	1.87	0.035
102Pd	1.02	0.0142
106Cd	1.25	0.0201
108Cd	0.89	0.0143
113In	4.29	0.0079
112Sn	0.97	0.0372
114Sn	0.66	0.0252
115Sn	0.34	0.0129
120Te	0.09	0.0043
124Xe	0.09	0.00571
126Xe	0.09	0.00509
130Ba	0.106	0.00476
132Ba	0.101	0.00453
138La	0.09	0.000409
136Ce	0.185	0.00216
138Ce	0.251	0.00284
144Sm	3.07	0.0008
152Gd	0.2	0.00066
156Dy	0.06	0.000221
158Dy	0.1	0.000378
162Er	0.14	0.000351
164Er	1.61	0.00404
168Yb	0.13	0.000322
174Hf	0.16	0.000249
180Ta	0.012	2.48E-06
180W	0.12	0.000173
184Os	0.02	0.000122
190Pt	0.014	0.00017
196Hg	0.15	0.00048

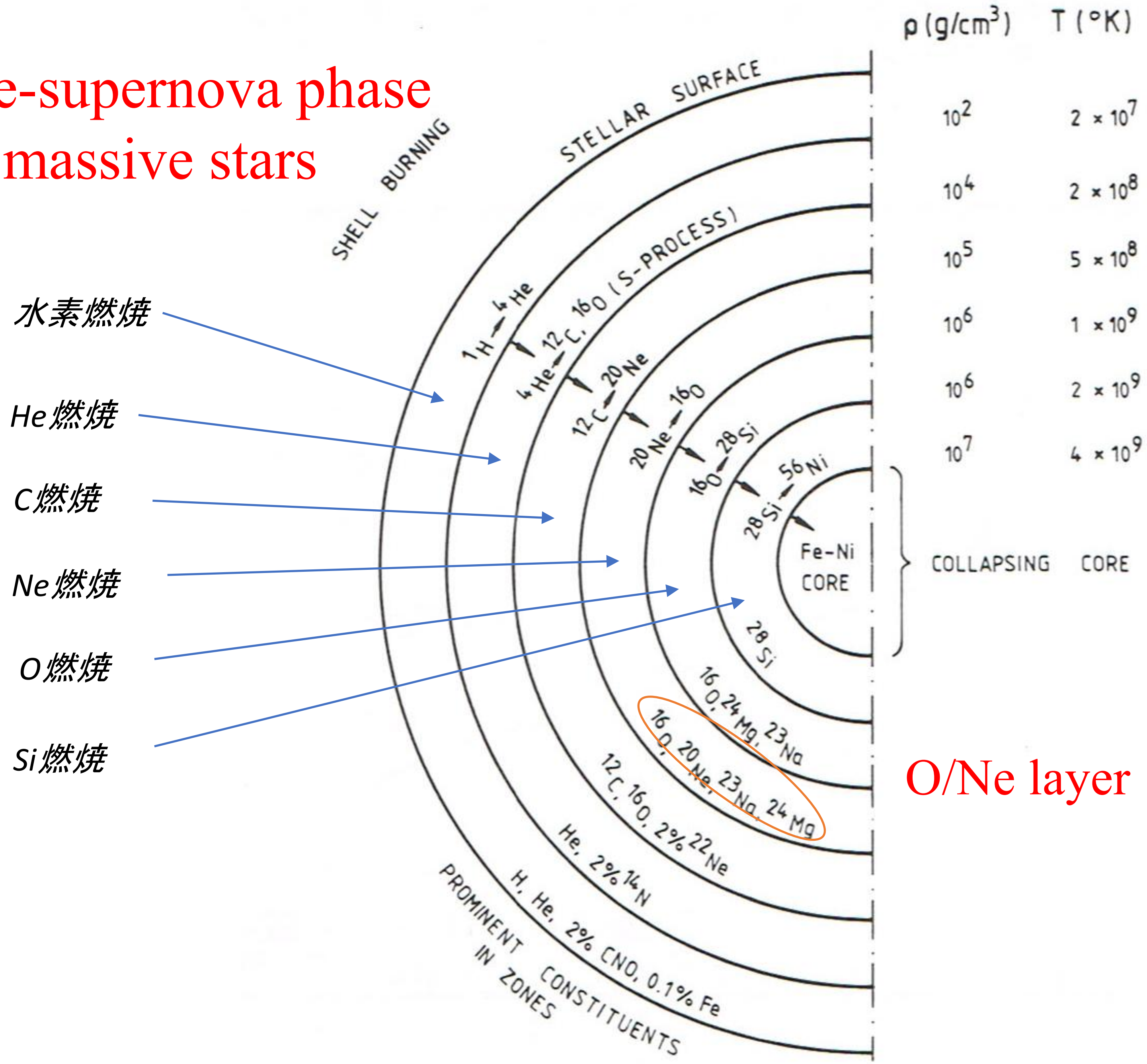
Astrophysical site of p-process

1. *Temperature: high enough for photoreaction*
2. *Temperature: not too high to prevent photoerosion of all elements to iron-group nuclei*
3. *Photoreaction is frozen in a short time scale*

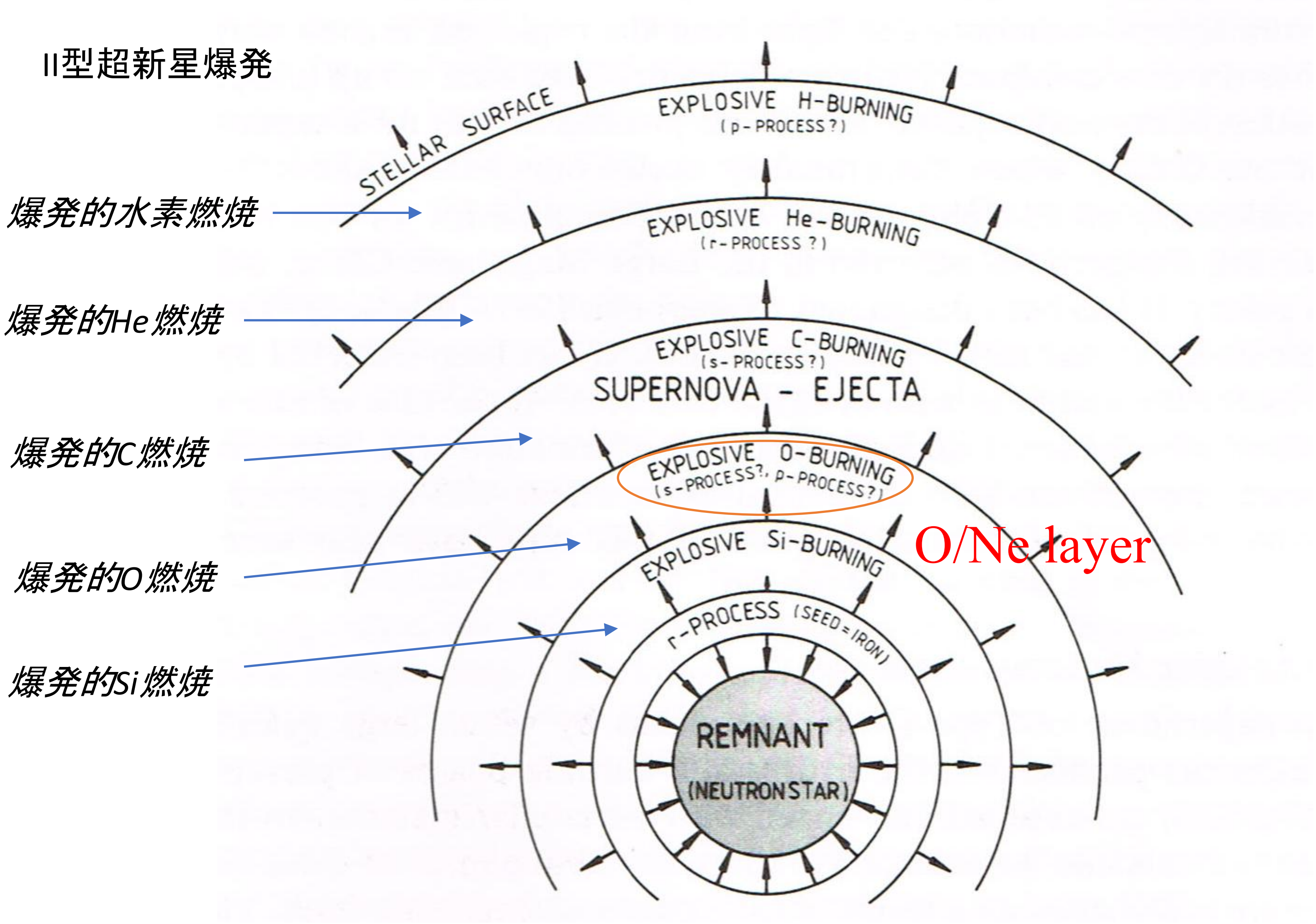
The O/Ne layers
in the pre-supernova phase of massive stars or
during the explosions of massive stars as type-Ⅱ supernovae
Temperature : $1.8 \leqq T[10^9 K] \leqq 3.0$
Peak photon energy : 200[keV]

Type Ia supernovae: disruption of a white dwarf after having accreted material above the Chandrasekhar limit from its companion in a binary system
[Type Ia Supernova - NASA Science]

Pre-supernova phase of massive stars



During the explosions of massive stars as type-II supernovae



^{180}Ta

Naturally occurring isomer
Rarest element

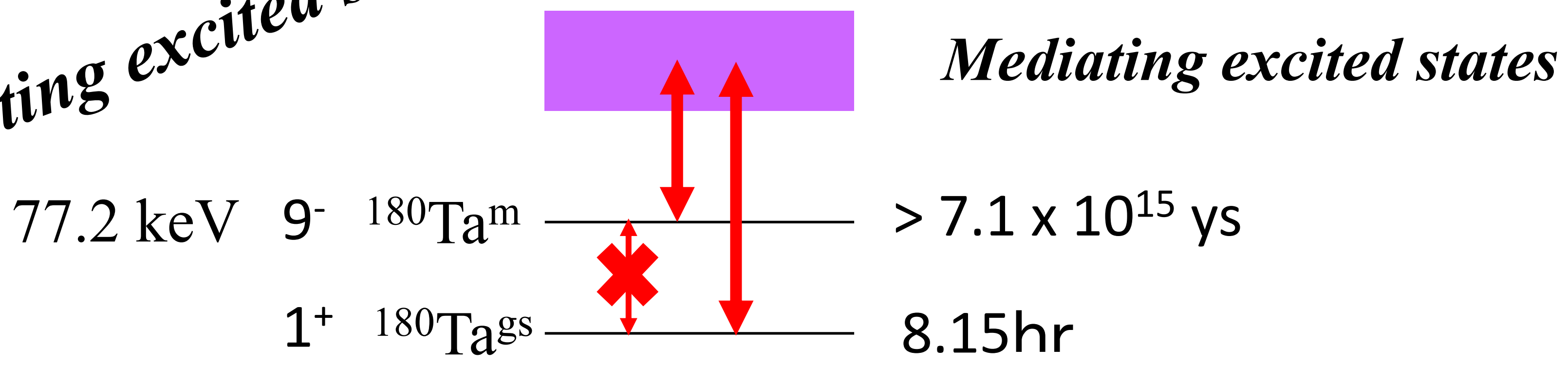
Mediating excited states are unidentified – an unveiled mystery

Nucleosynthesis of ^{180}Ta

s-process : Yokoi and Takahashi, Nature (Lon… (1983).

ν-process : Woosley et al., Astrophys… (1990).

p-process : Prantzos et al. …phys. 238, 455 (1990).



Search for mediating states in γ-ray spectroscopy

Dracoulis et al., PRC58, 1444 (1998)   Saitoh et al., NPA660, 121 (1999).

176Yb(11B,α3n)180Ta

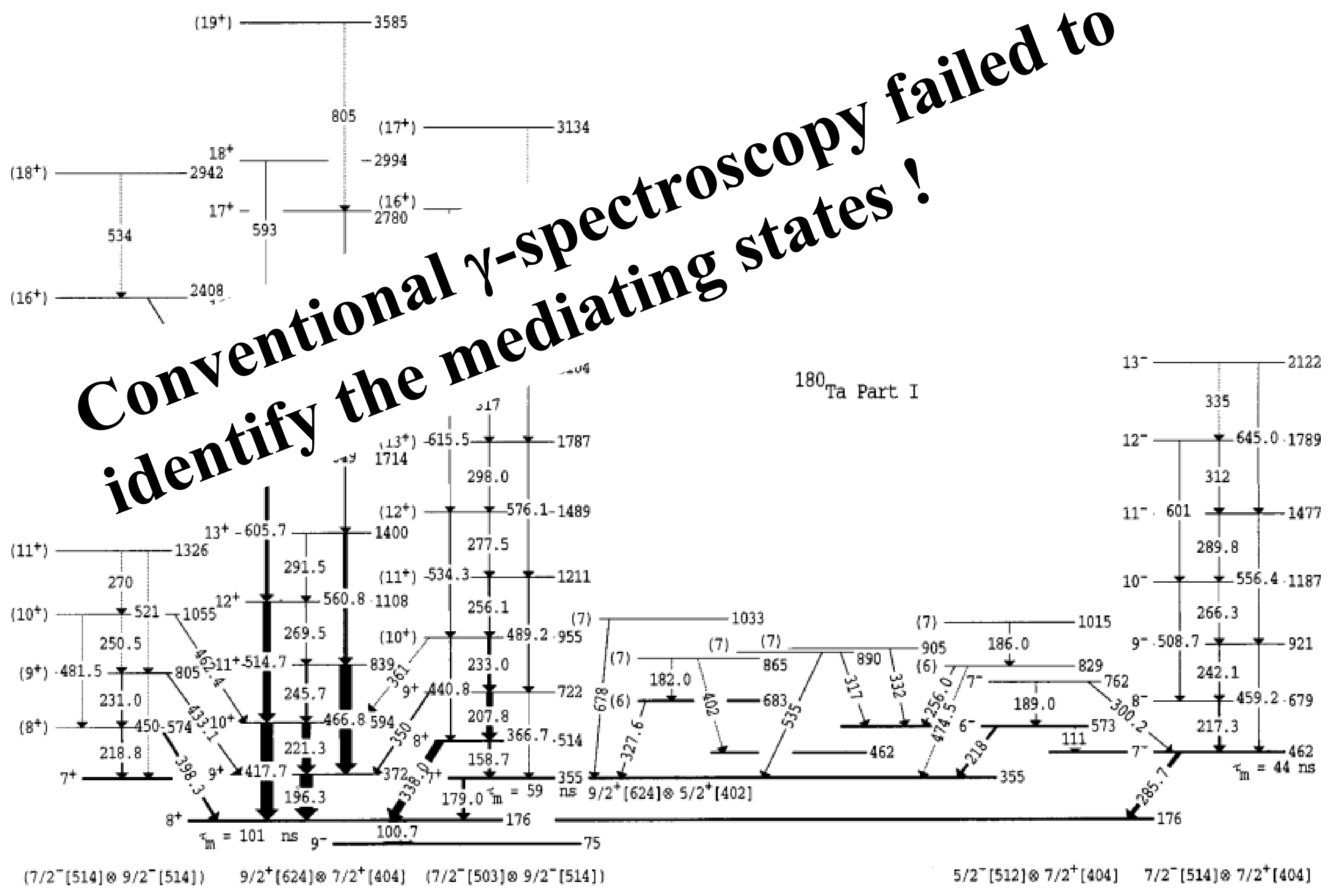
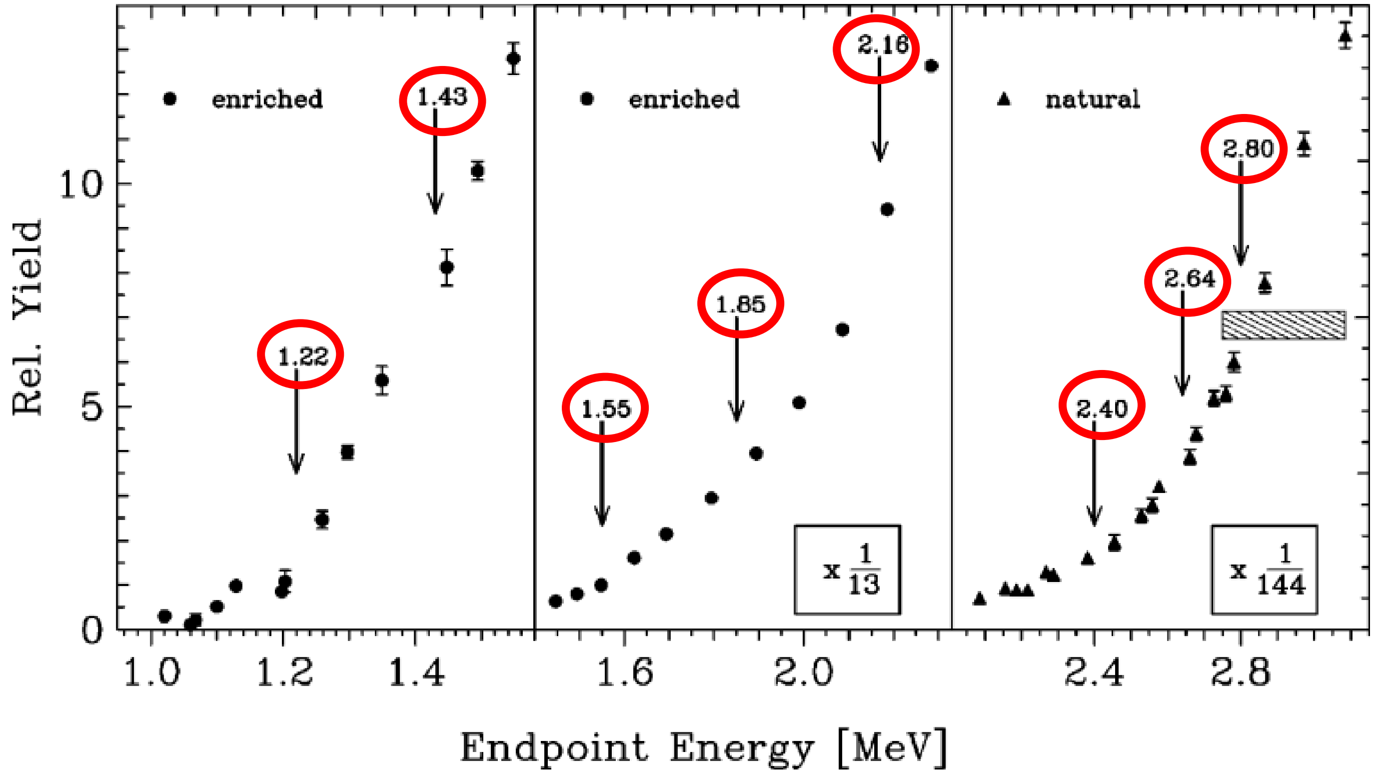


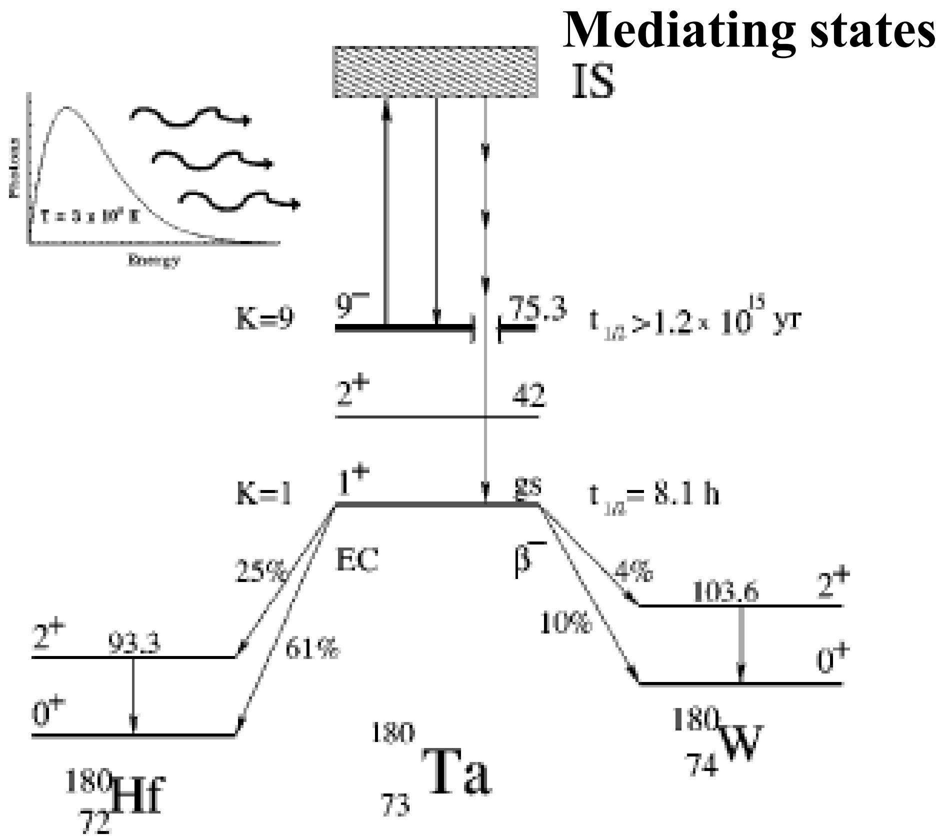
FIG. 2. Part I of the ^{180}Ta level scheme; transitions feeding to the 9^- state through the 8^+ isomer.

Photodestruction experiment of $^{180}Ta^m$ with bremsstrahlung

Beric et al., PRL83, 5242 (1999); PRC 65, 035801 (2002).

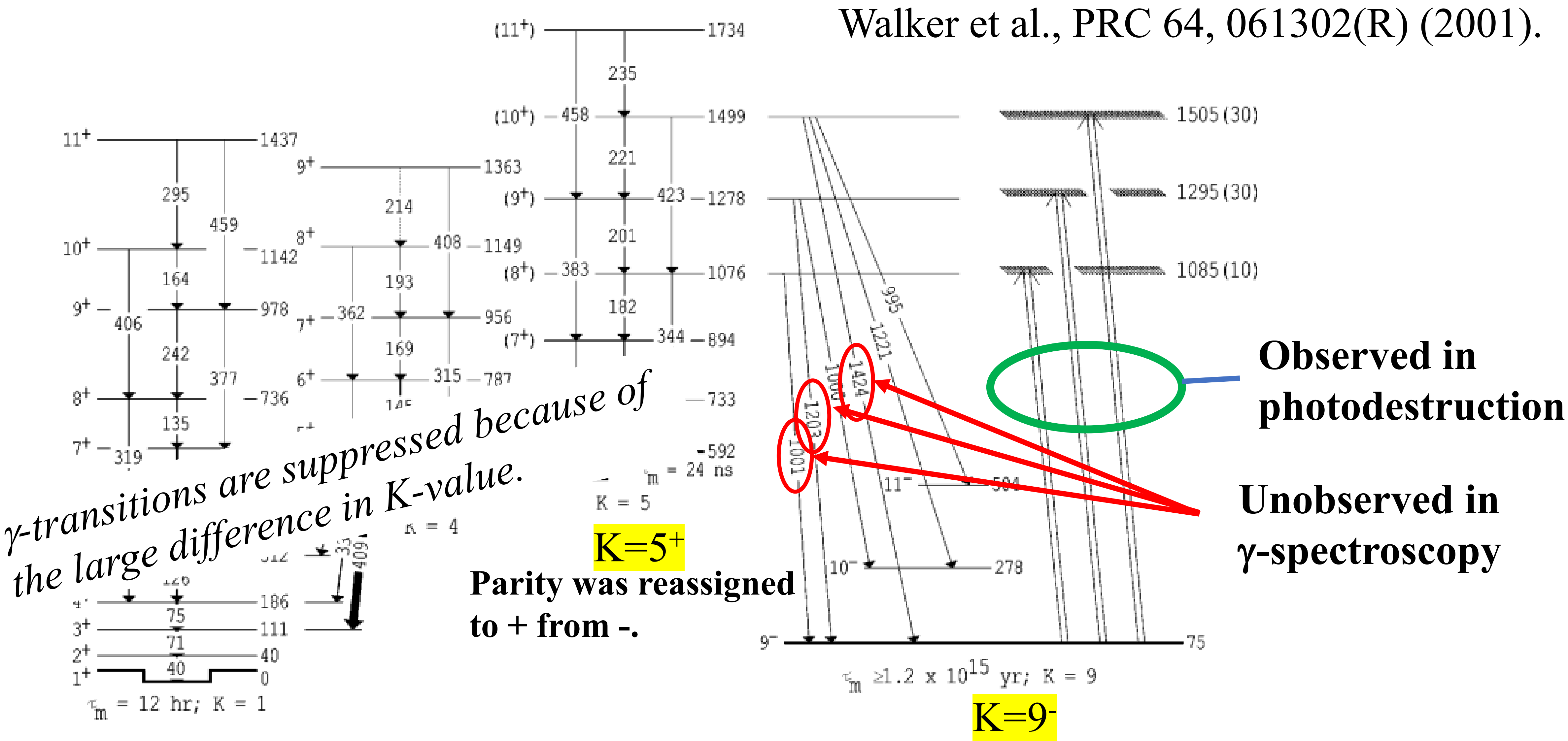
^{180}Ta target enriched to 5.45%. (Natural abundance: 0.012%)

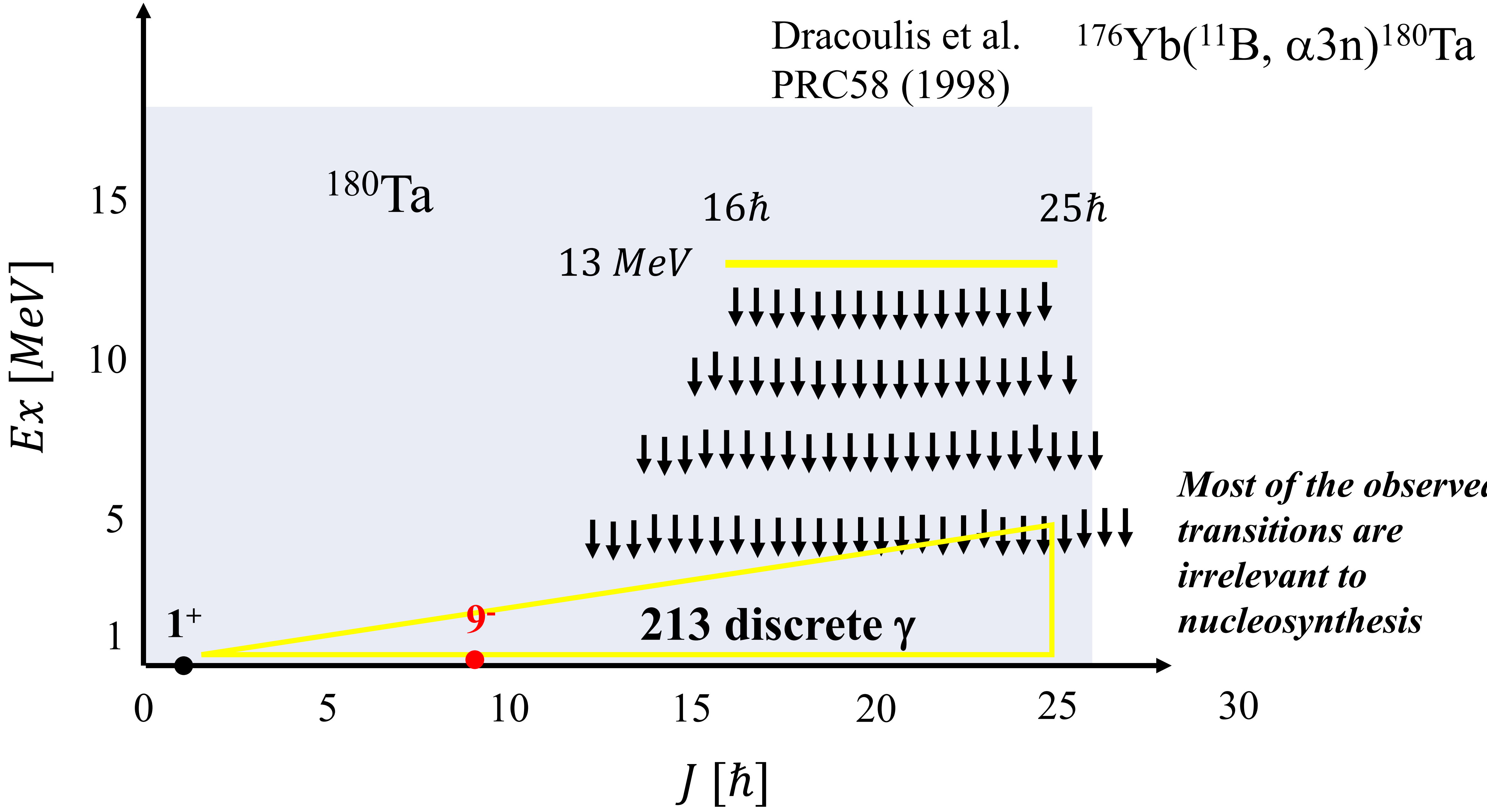




γ-spectroscopic interpretation of the photodestruction data

Walker et al., PRC 64, 061302(R) (2001).





Most of the observed transitions are irrelevant to nucleosynthesis

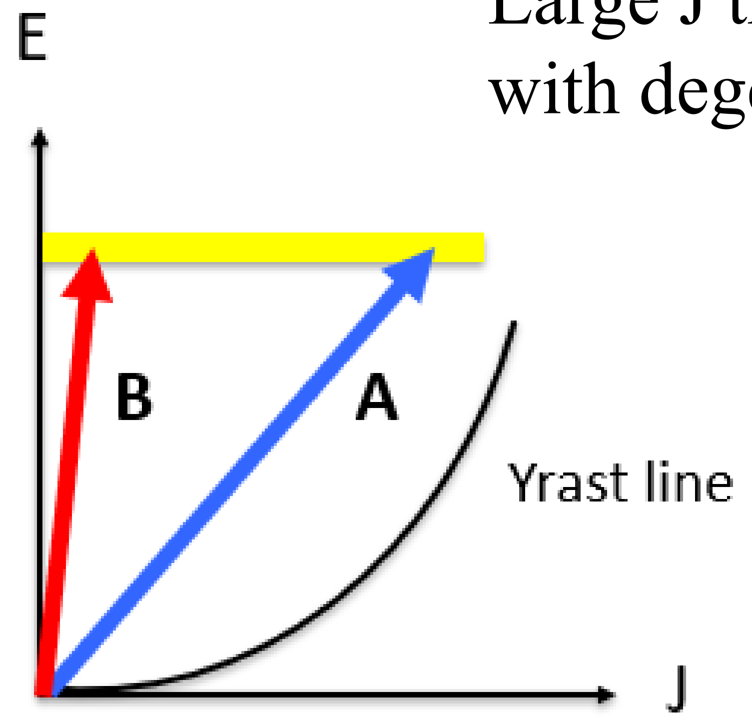
Photoreaction vs Heavy-ion reaction

B: photoreaction

E1 excitation
$\Delta J=1$

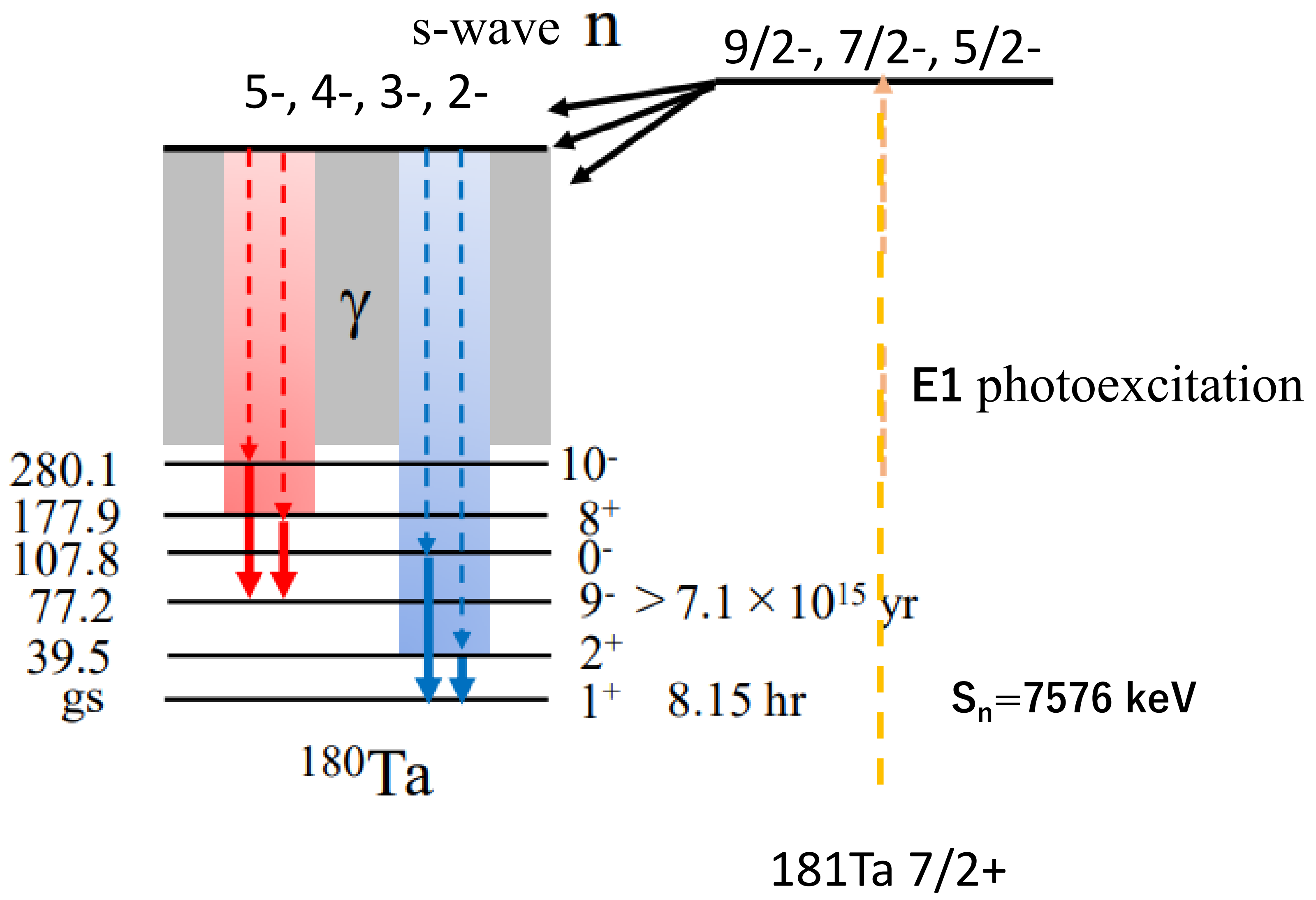
A: heavy-ion reaction

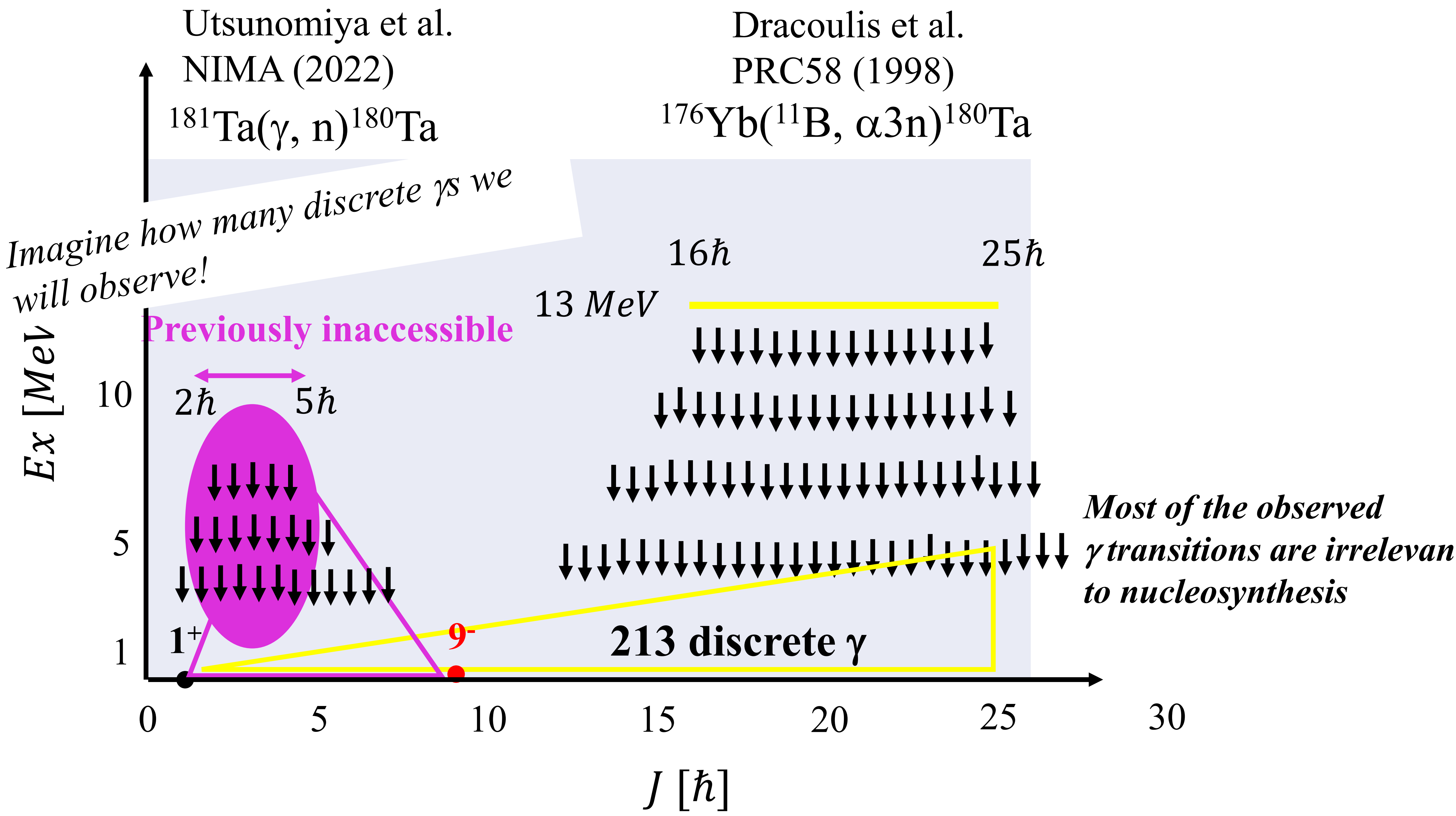
Large J transfer is emphasized with degeneracy $2J+1$



Let's chase the p-process nucleosynthesis

$^{181}Ta(\gamma,n)^{180}Ta$





Utsunomiya et al.
NIMA (2022)
^{181}Ta(γ, n)^{180}Ta
Dracoulis et al.
PRC58 (1998)
^{176}Yb(^{11}B, α3n)^{180}Ta
Imagine how many discrete γs we will observe!
16ℏ
25ℏ
13 MeV
Previously inaccessible
2ℏ
5ℏ
Most of the observed γ transitions are irrelevan to nucleosynthesis
1^+
9^-
213 discrete γ
Ex [MeV]
J [ℏ]
10
5
1
0
5
10
15
20
25
30

p-process nucleosynthesis

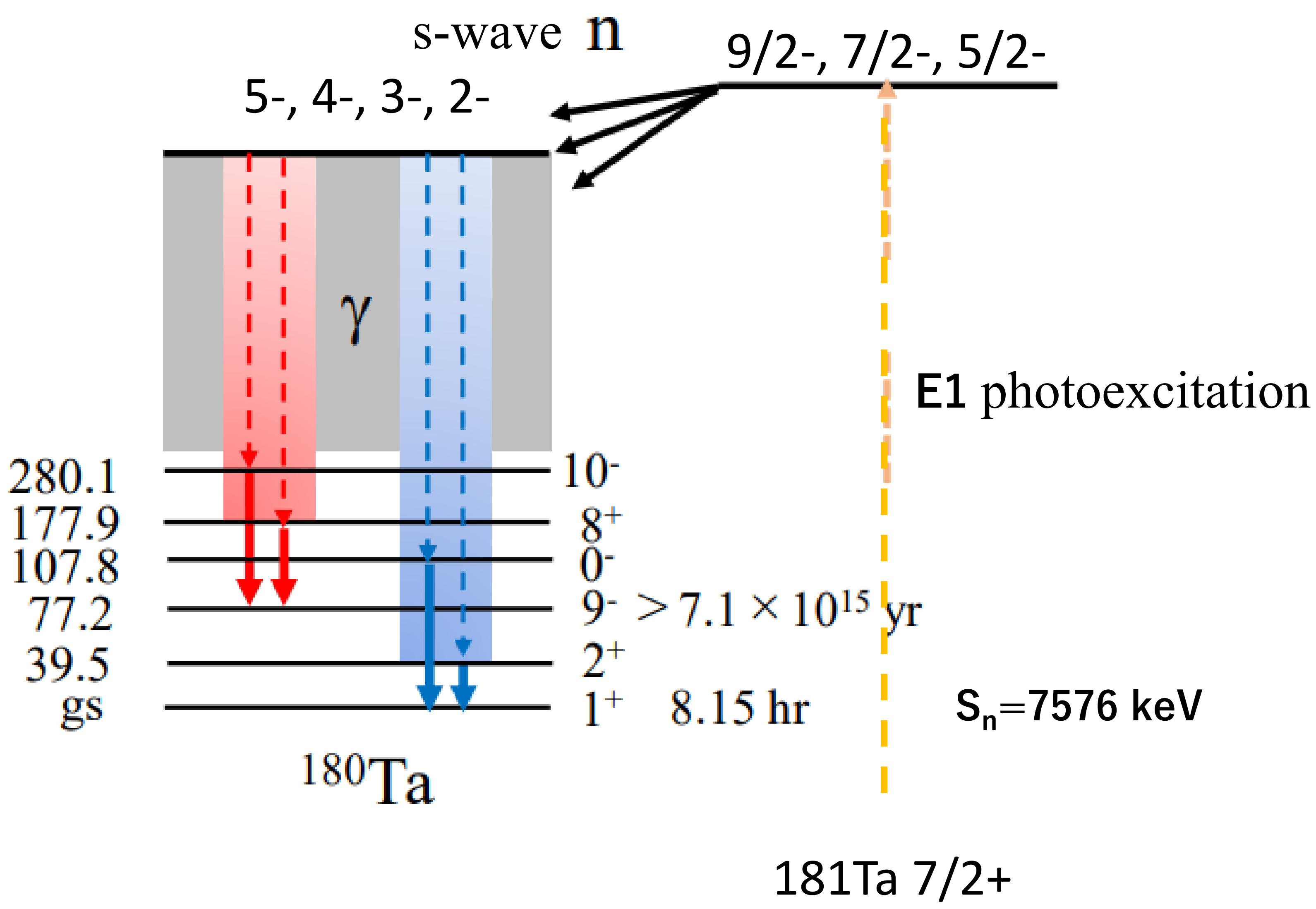
Total cross sections

$^{181}Ta(\gamma,n)^{180}Ta$

Partial cross sections

$^{181}Ta(\gamma,n)^{180}Ta^{gs}$

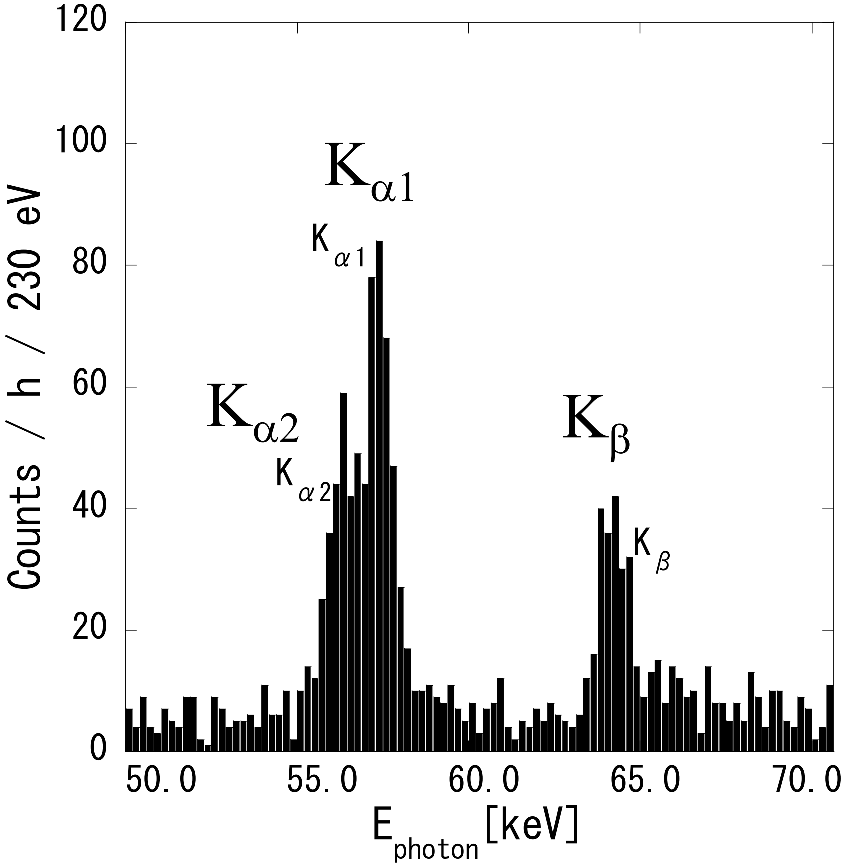
$^{181}Ta(\gamma,n)^{180}Ta^{m}$



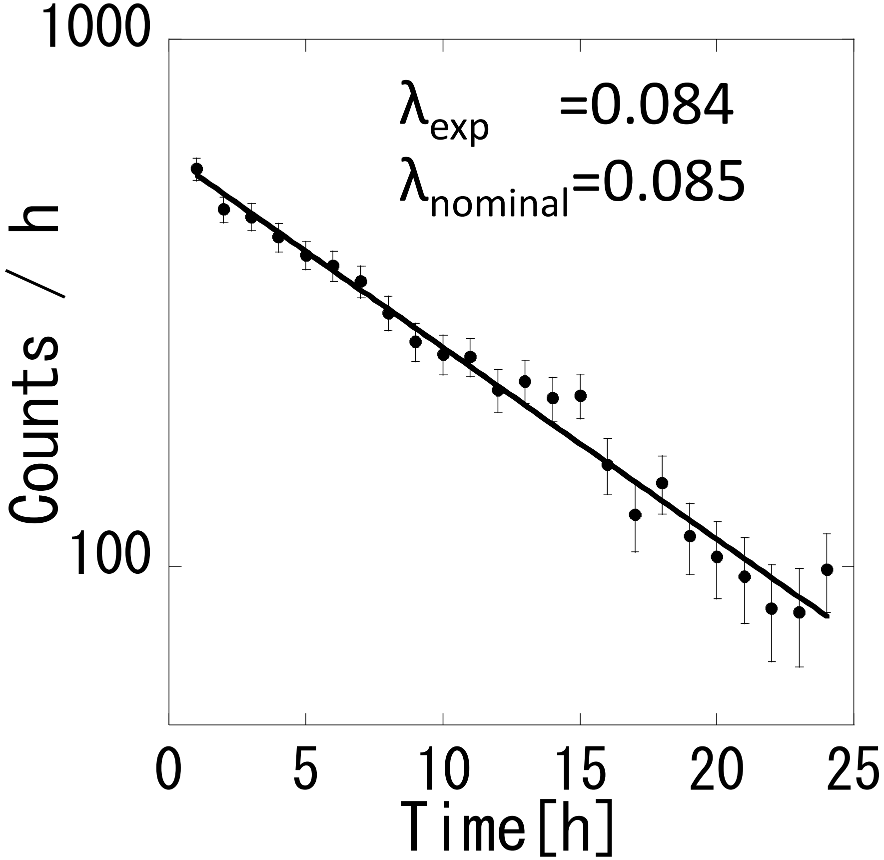
$^{180}Ta^{gs} \rightarrow {}^{180}Hf$: Electron Capture

Goko et al. Phys. Rev. Lett. 96, 192501 (2006)

Hf characteristic X rays

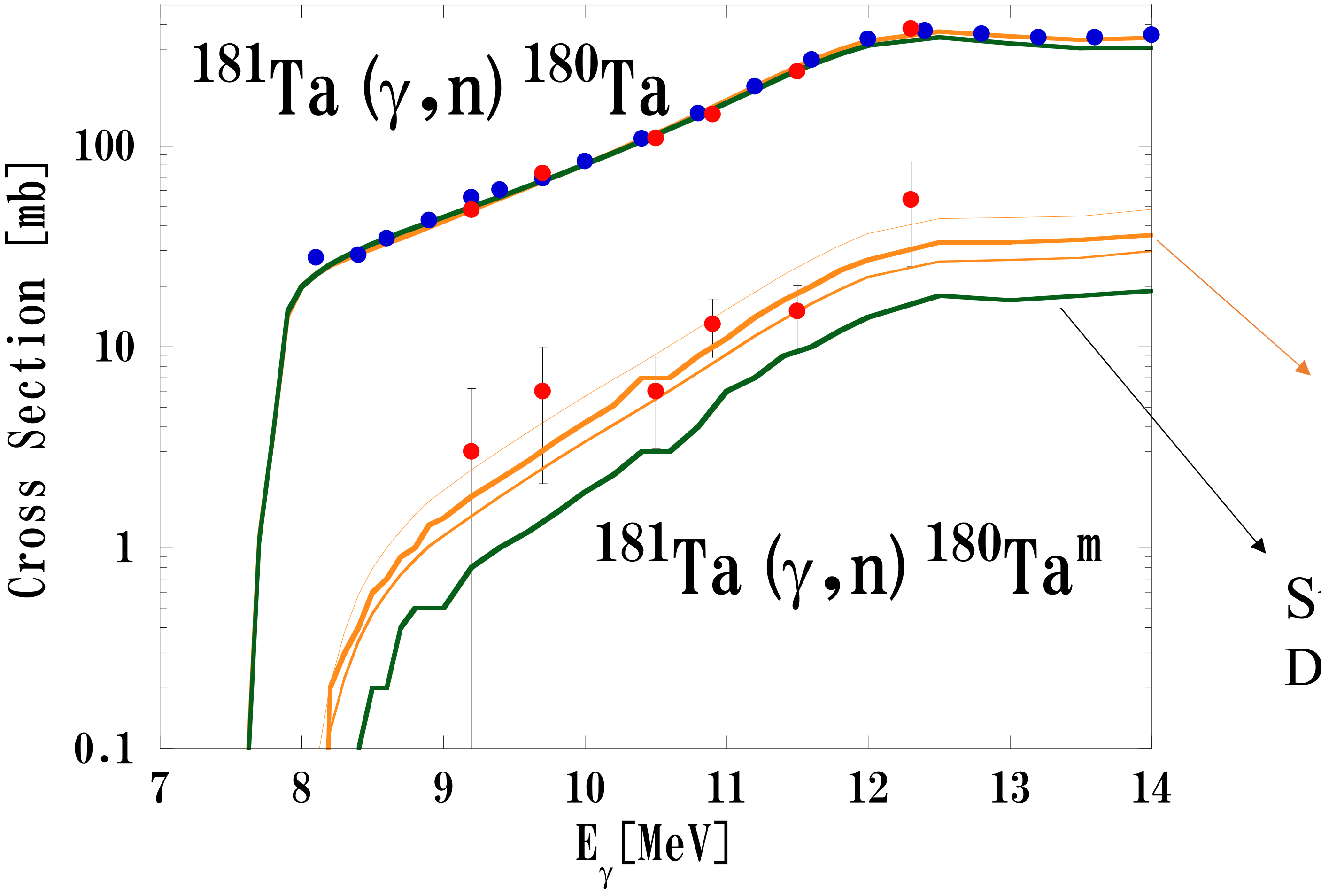


Life time measurement



Partial cross sections

Goko et al. Phys. Rev. Lett. 96, 192501 (2006)



σ_m/σ_{total}

~1/10 @ E_γ=12 MeV

~1/20 @ E_γ=10 MeV

HFB combinatorial NLD

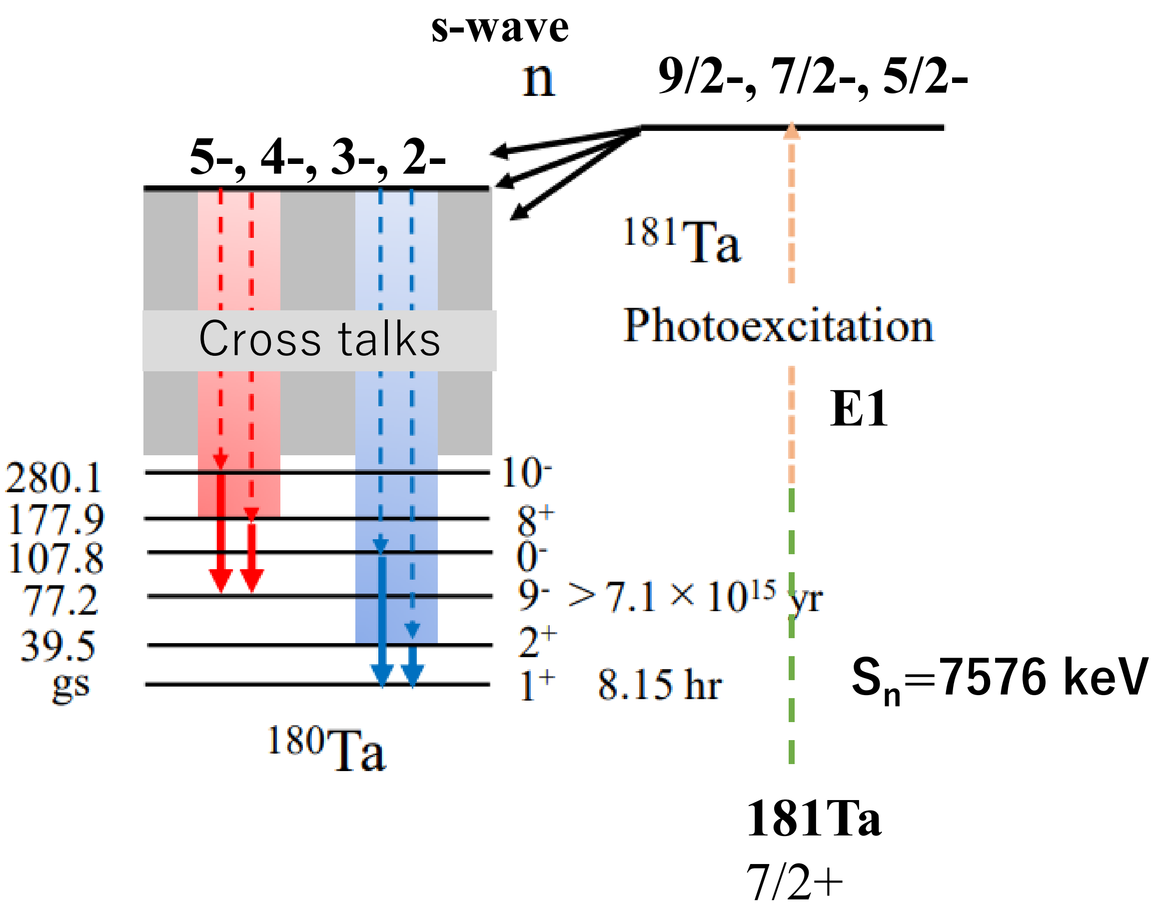
Hilaire & Goriely, NPA779 (2006)

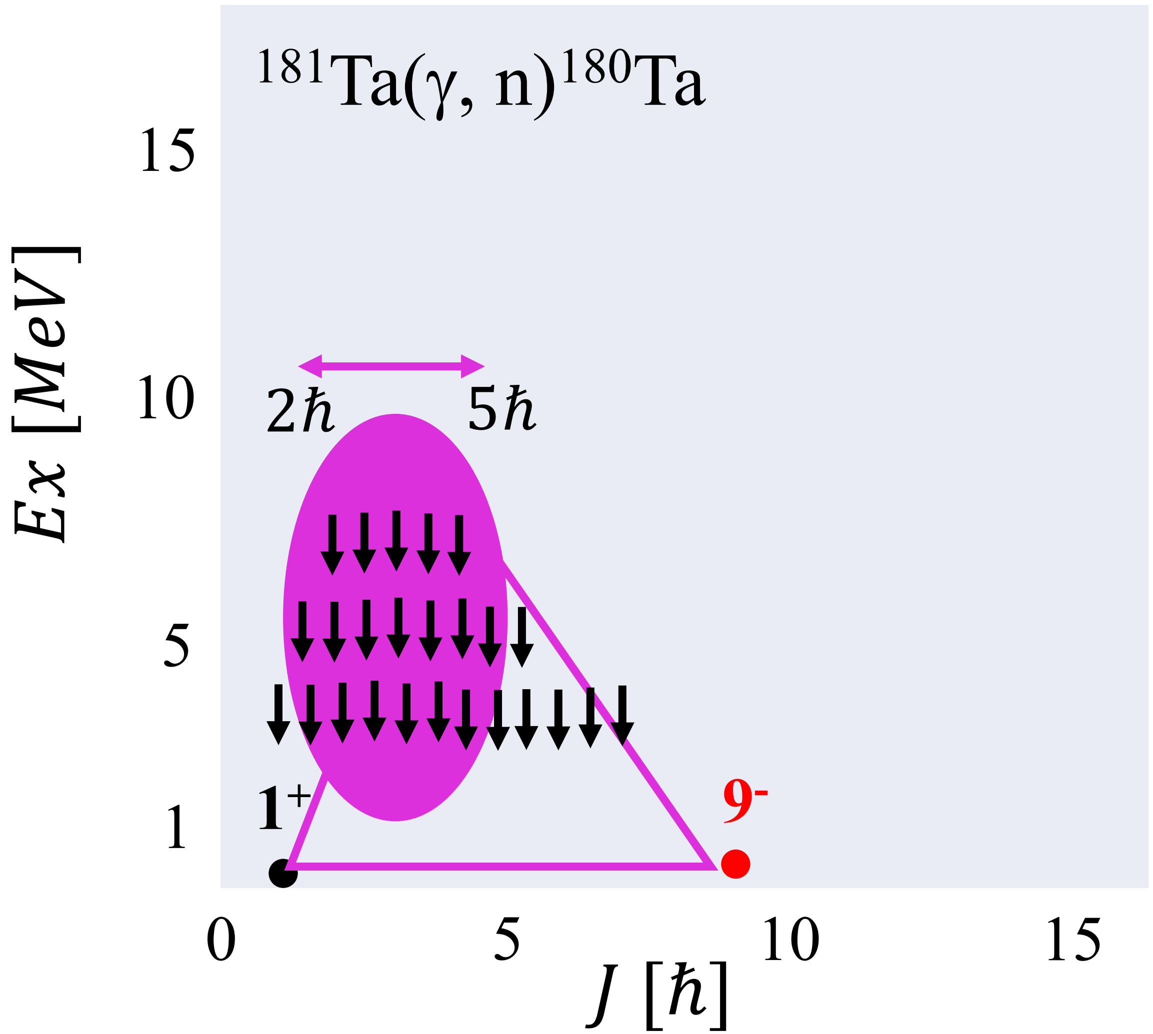
Statistical NLD

Demetriou & Goriely, NPA695 (2001)

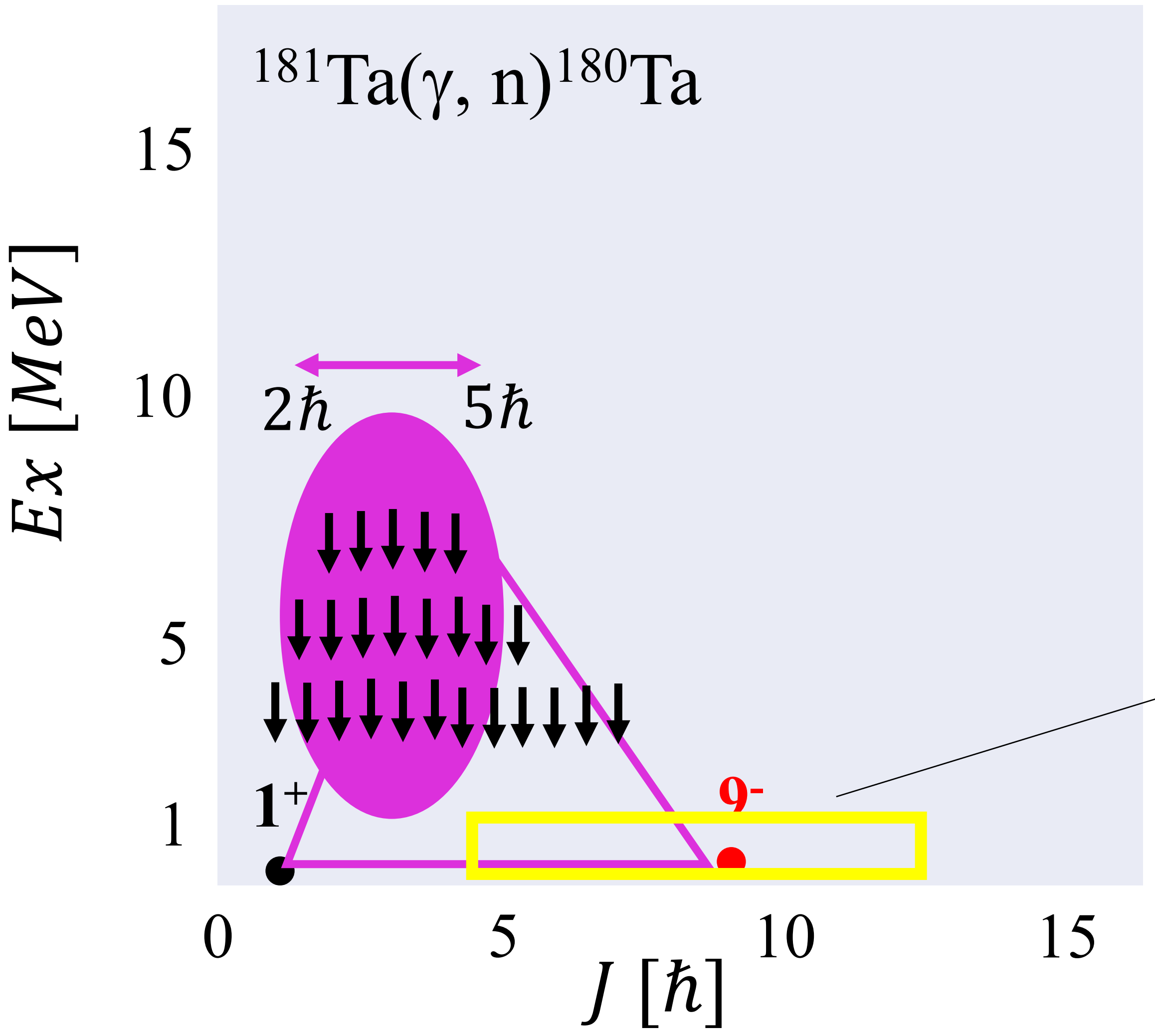
We perform n-γ_1-γ_2 triple coincidence measurements by chasing the p-process.

H. Utsunomiya et al., NIMA 1034 (2022) 166819

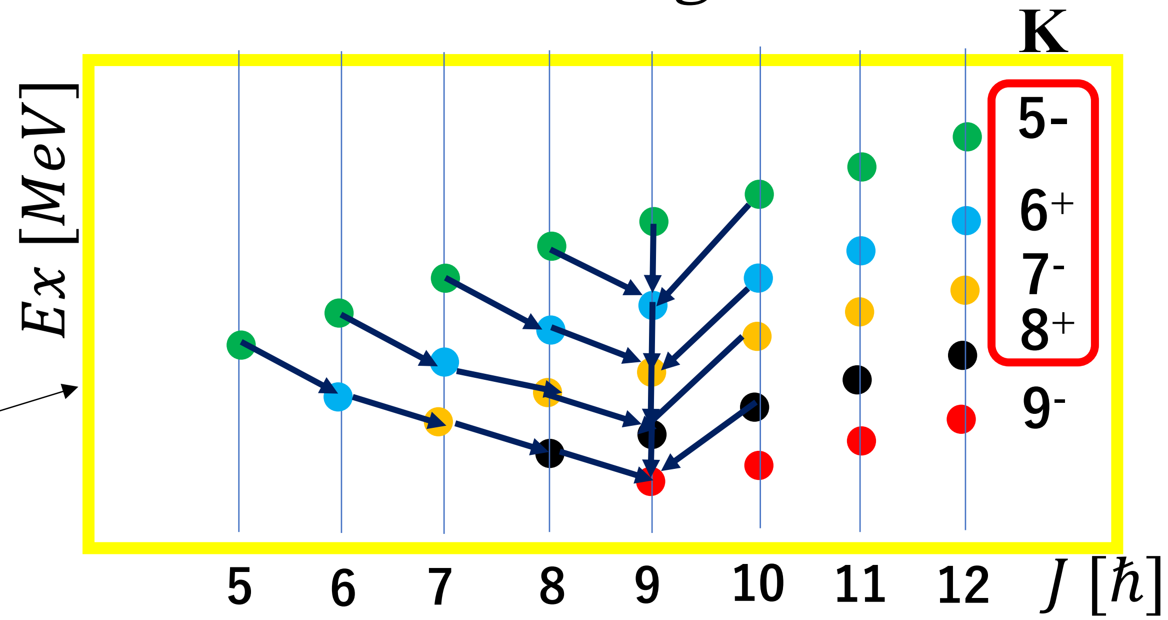




What would be observed?



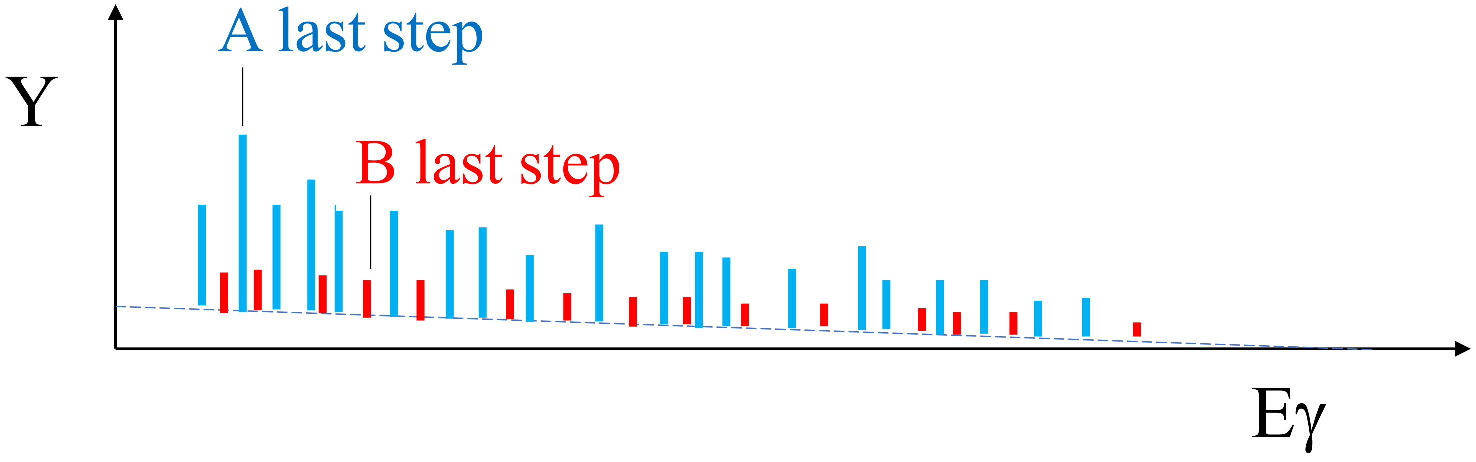
World of imagination!

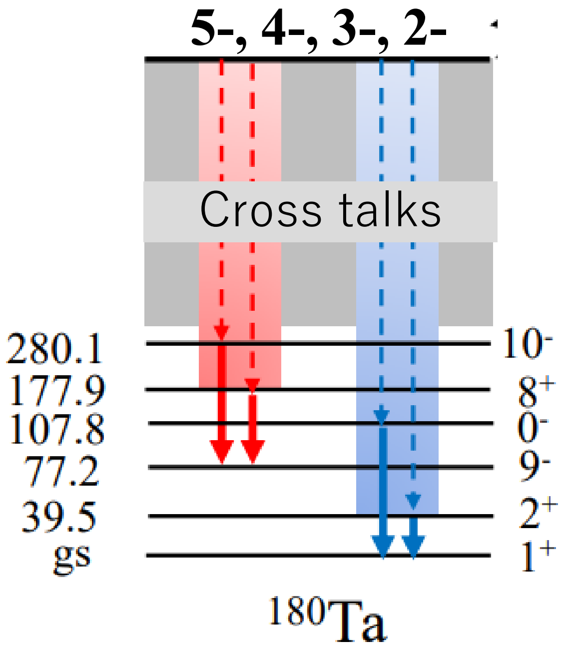


Experimental evidence for the presence of mediating states

γ–γ coin. spectrum

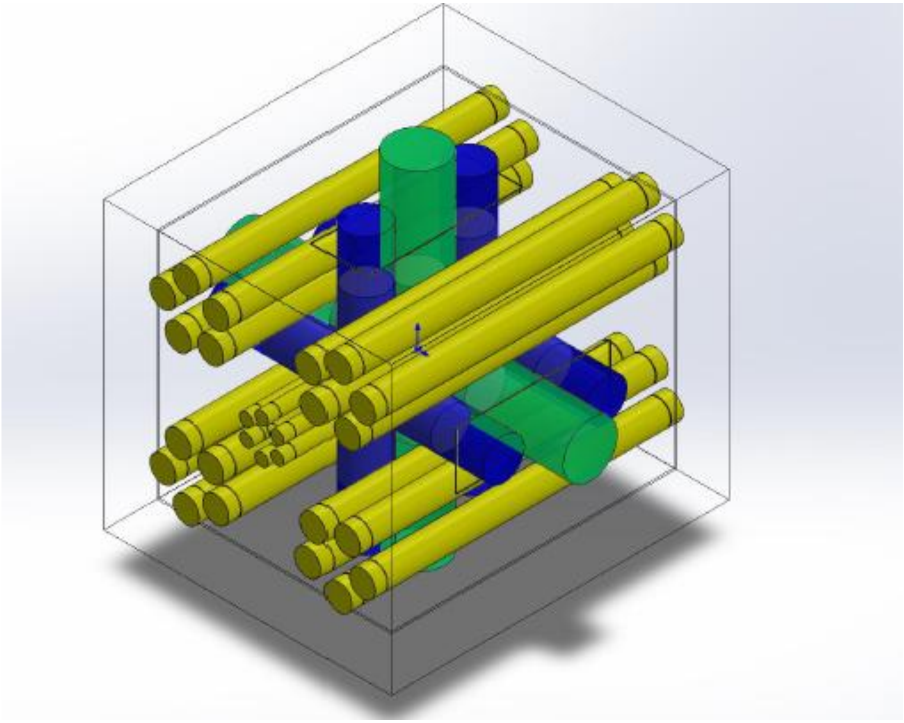
GS γ-transition Isomer γ-transition

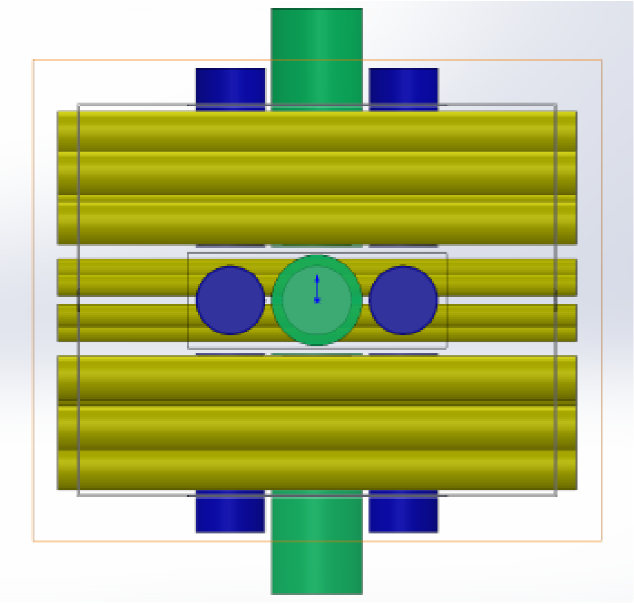




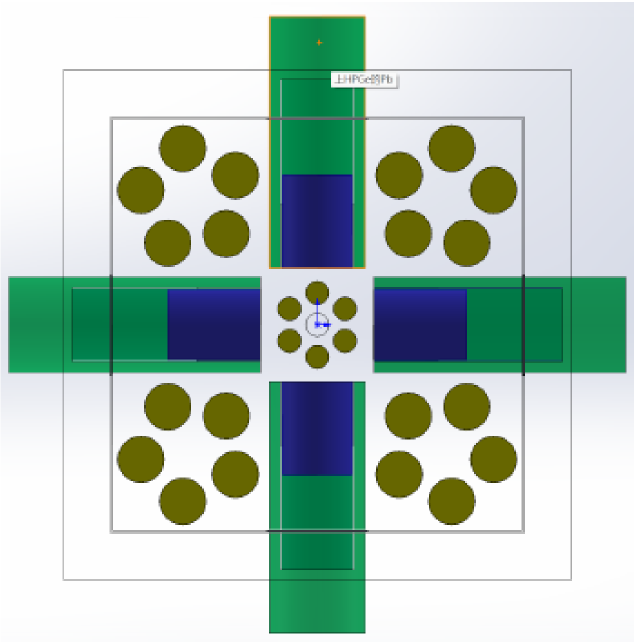
Upgraded p-process chaser detector Type-I

Yifan Liu





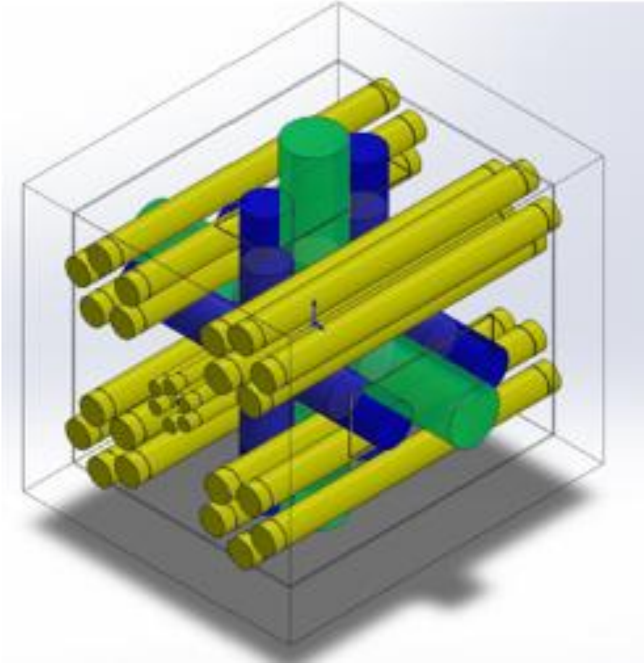
Left view

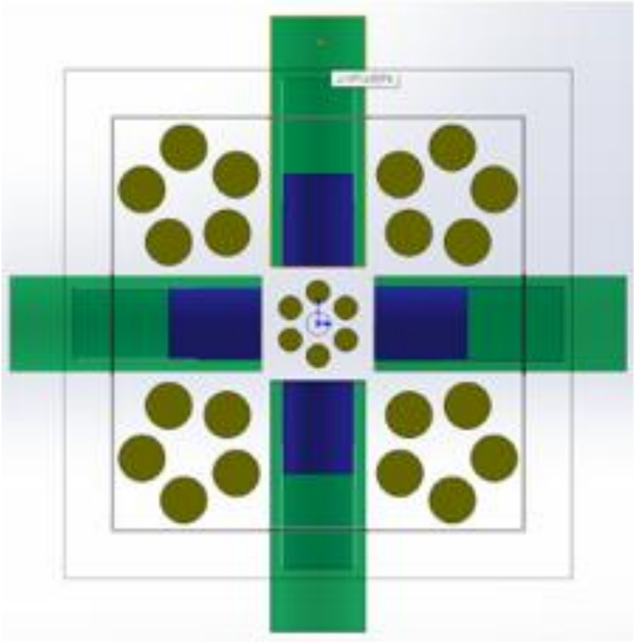


Front view

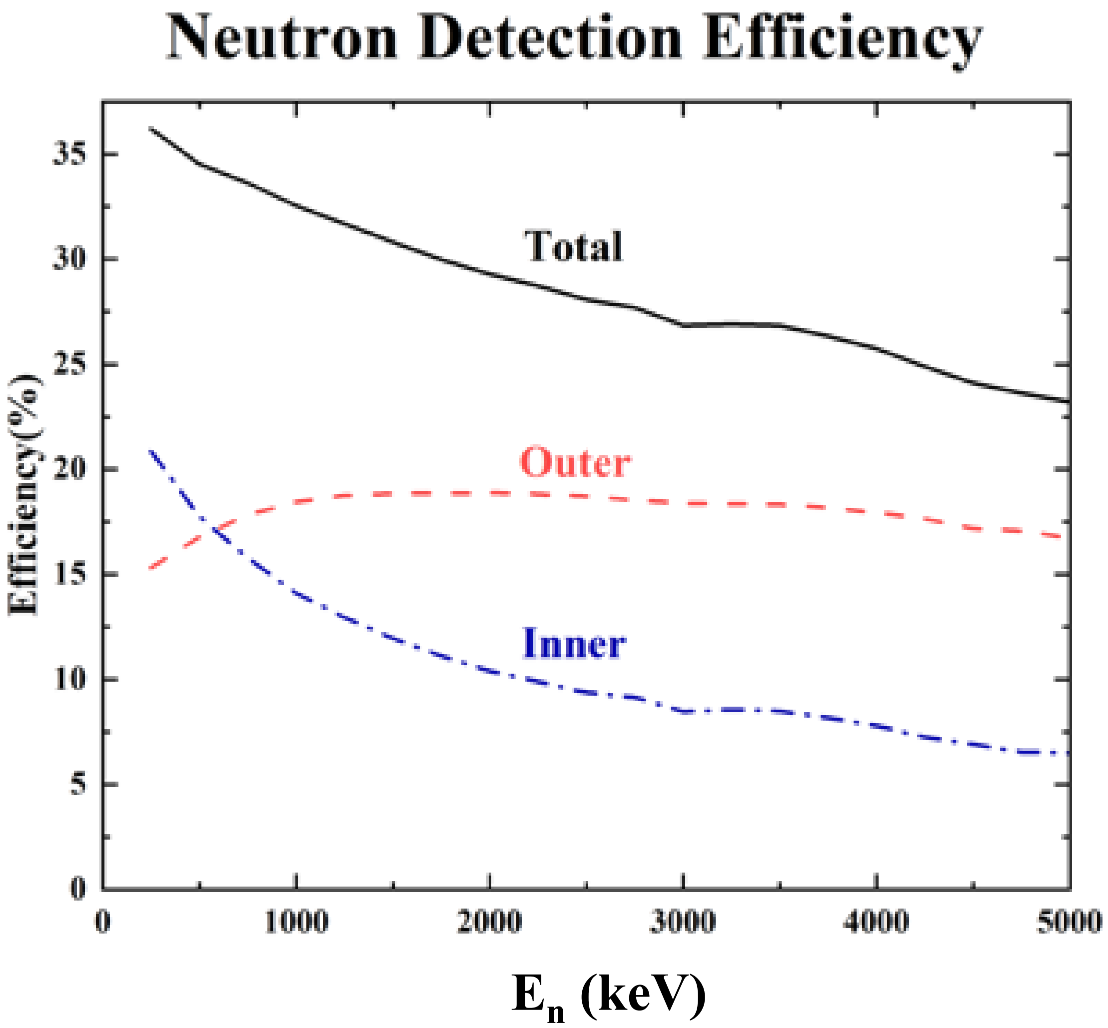
- 26 ^{3}He counters (6 x 1”ϕ + 20 x 2” ϕ)
- 4 HPGe (2 x [80mm ϕ x 70mm] + 2 x [73mm ϕ x73mm])
- 8 $LaBr_3$(Ce) (8 x [3”ϕ x 4”])

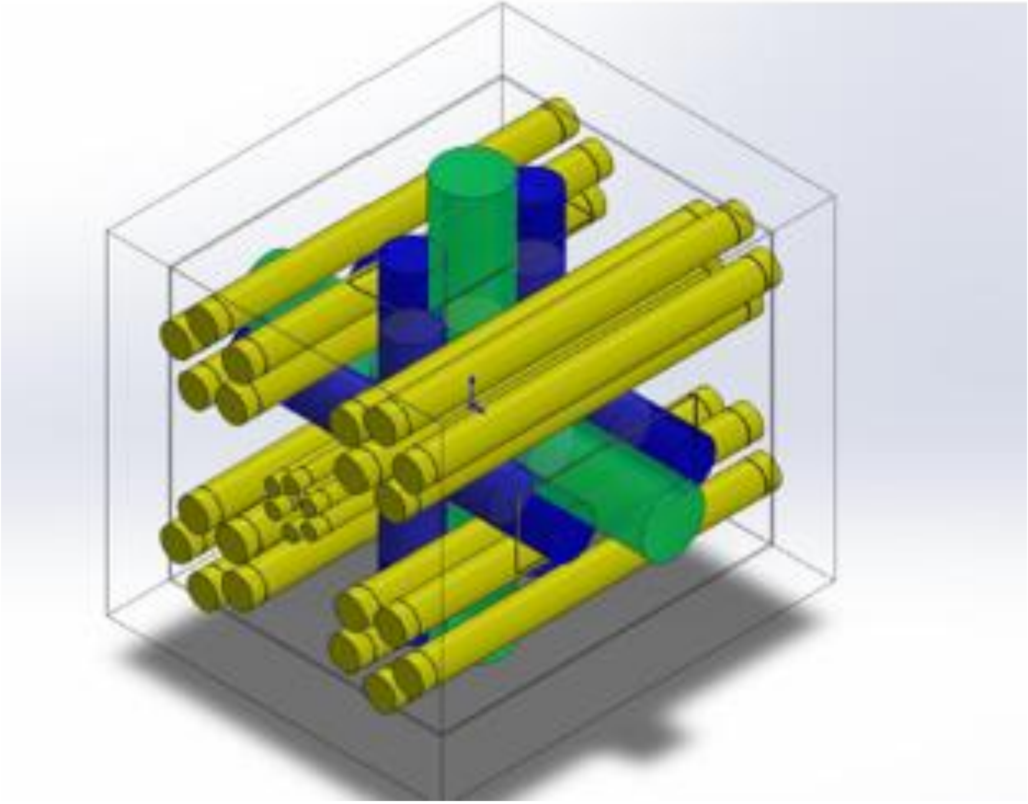
Moderator
479mm x 479mm x 568mm



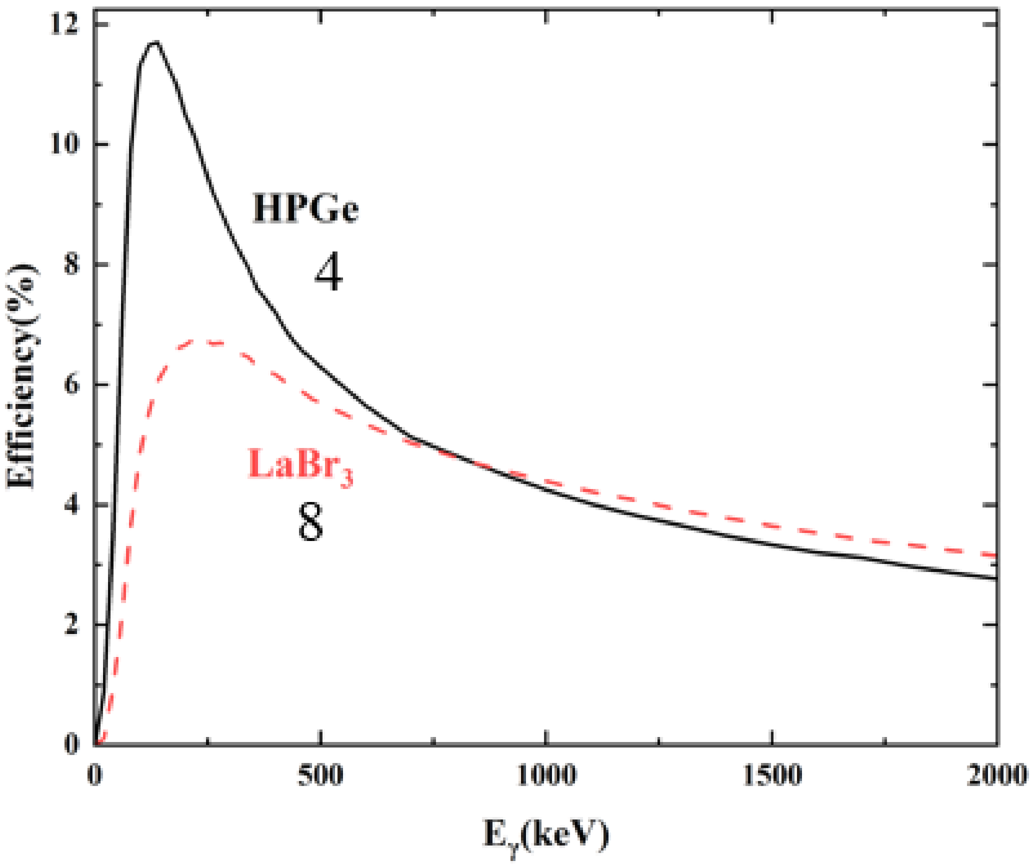


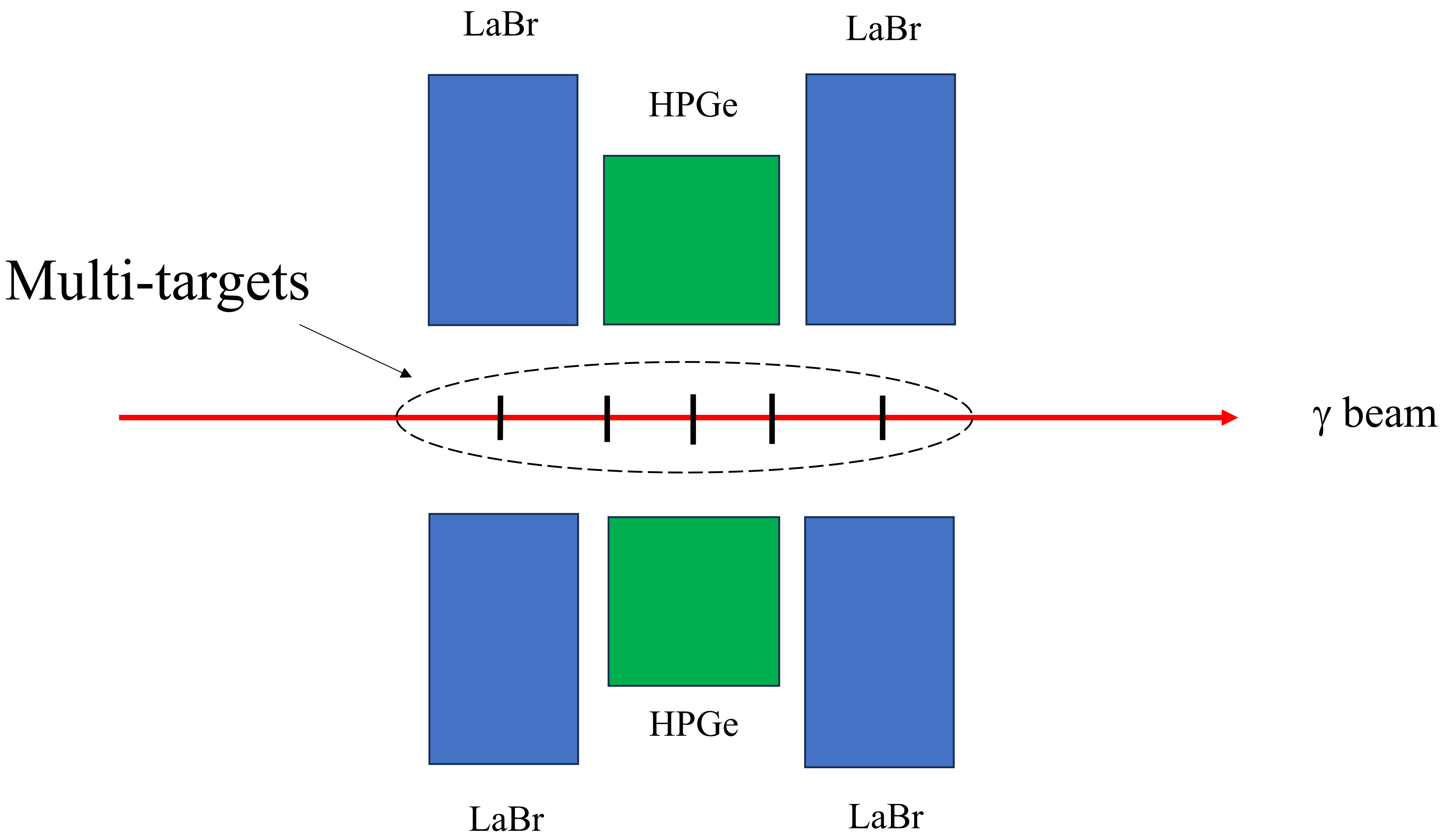
Front view


Neutron Detection Efficiency
Efficiency(%)
35
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
E_n (keV)
Total
Outer
Inner



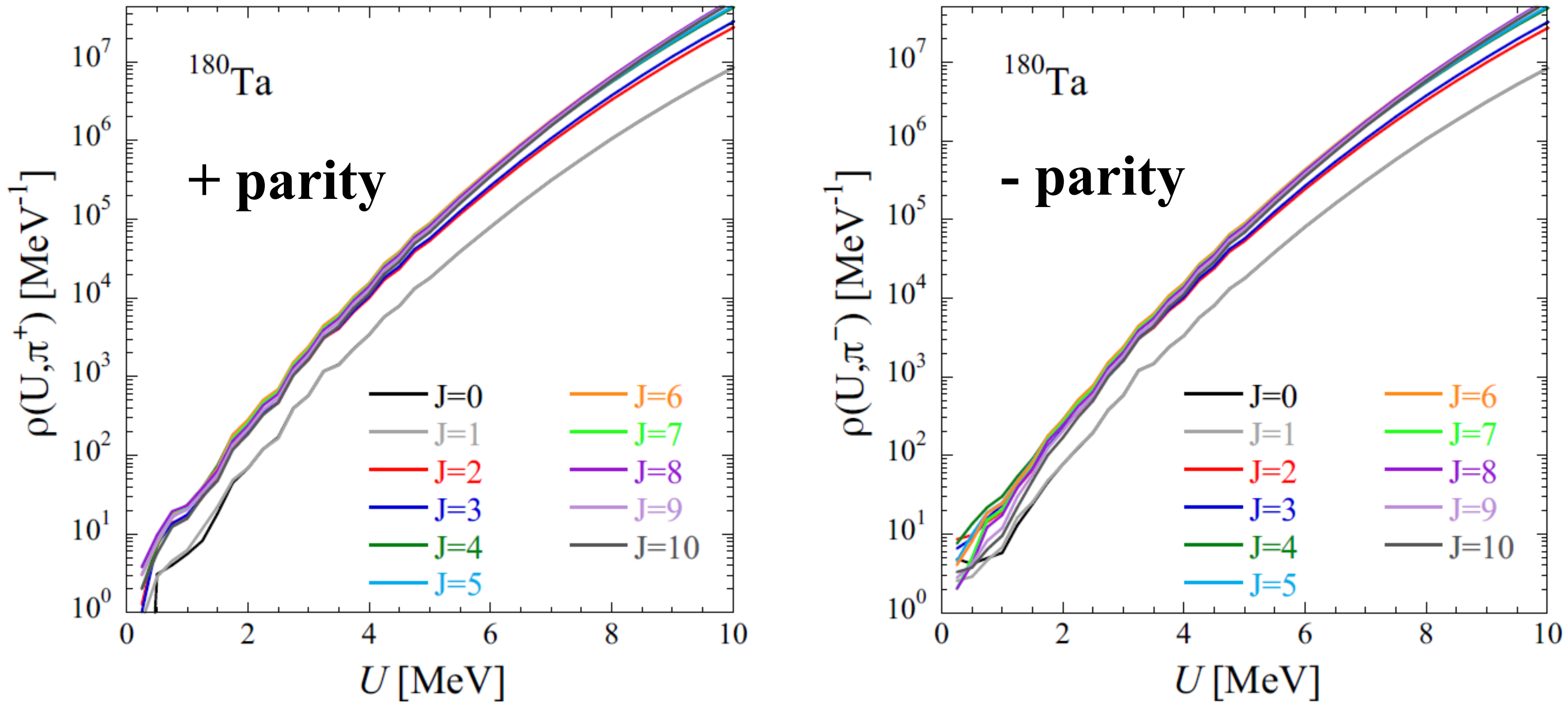
Sum Photopeak efficiency




LaBr
LaBr
HPGe
Multi-targets
γ beam
HPGe
LaBr
LaBr

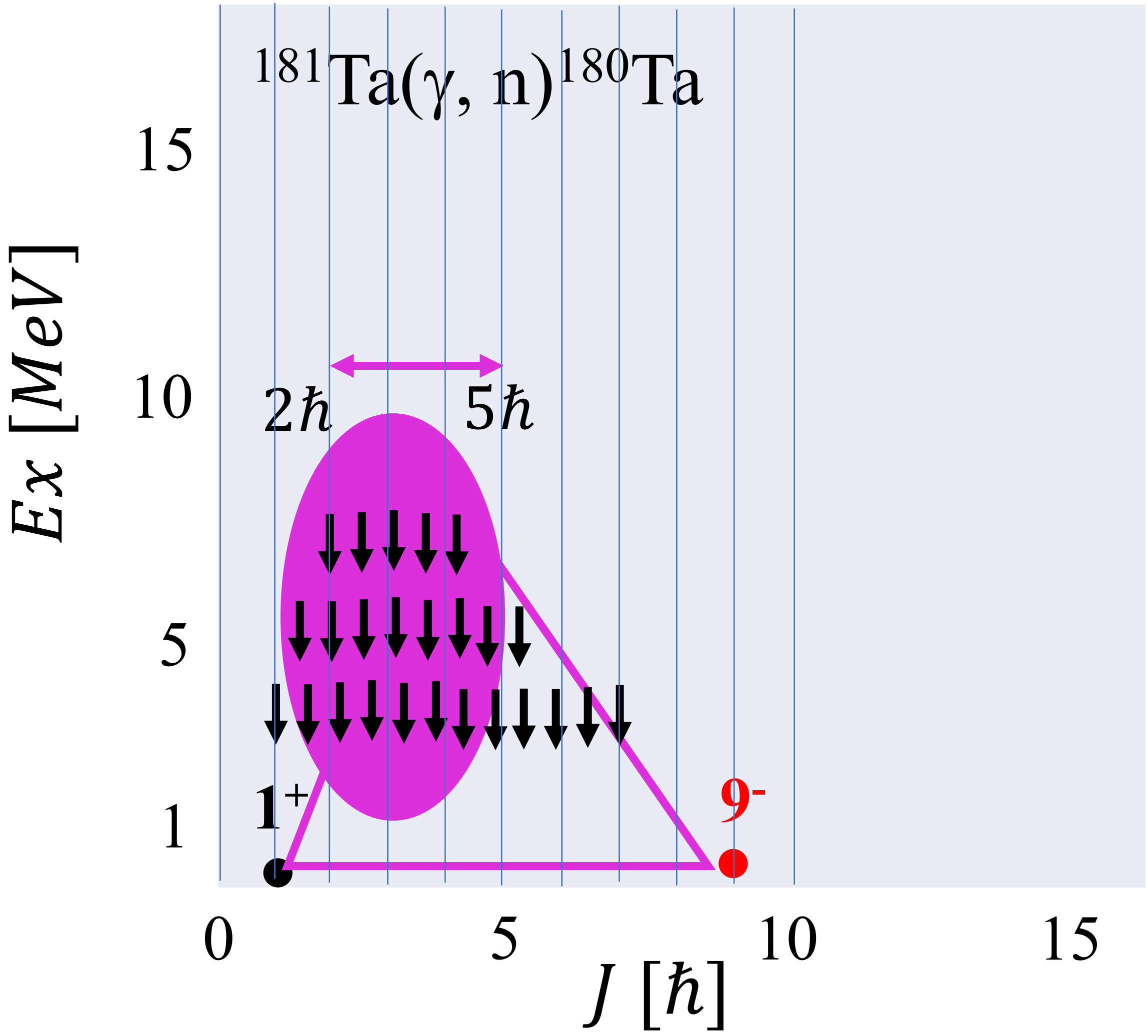
Unresolved states in ^{180}Ta

S. Goriely   HFB Combinatorial NLD, Phys. Rev. C78 (2008) 064307



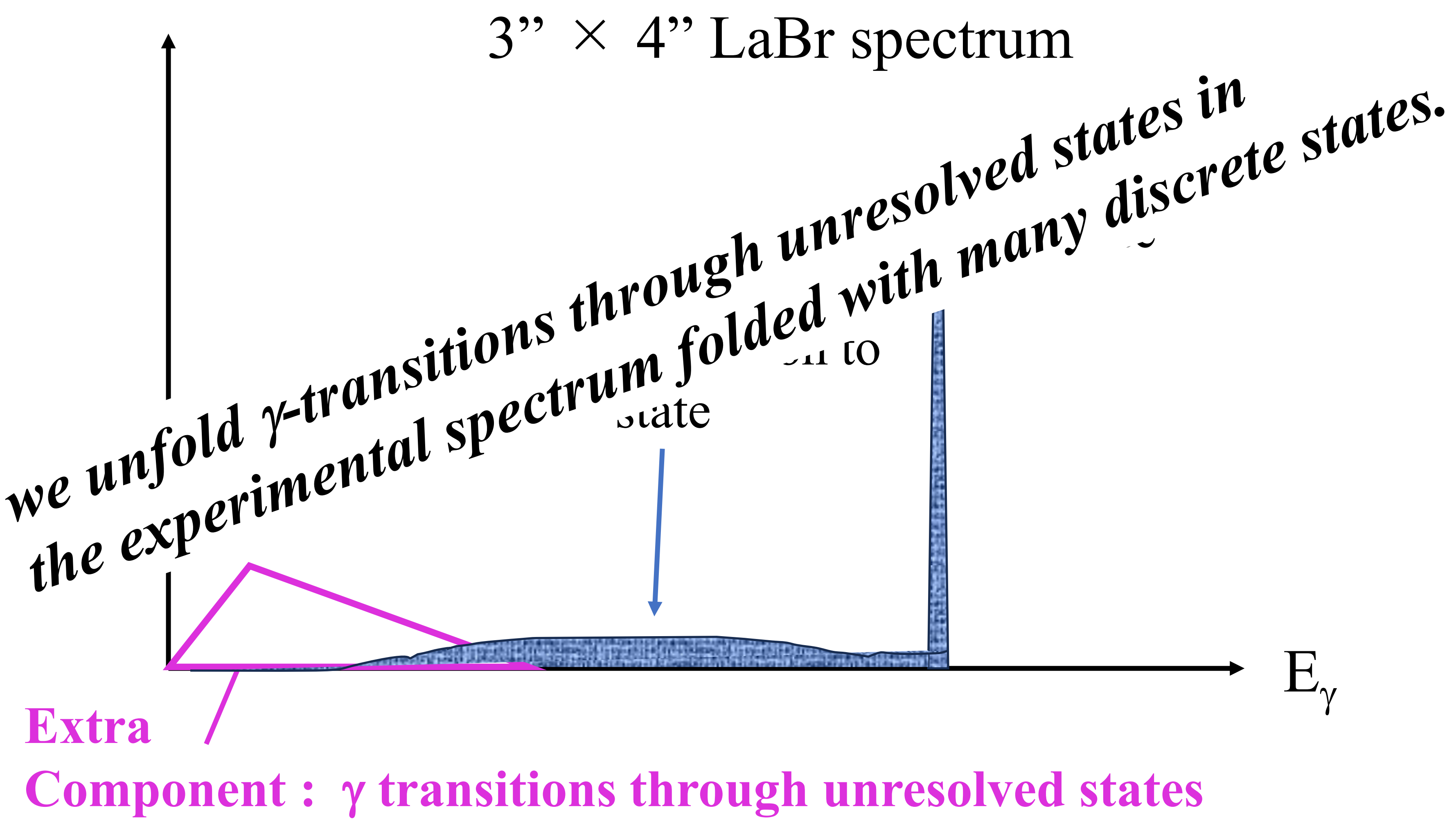
Unresolved states

γ transitions can occur through unresolved states.

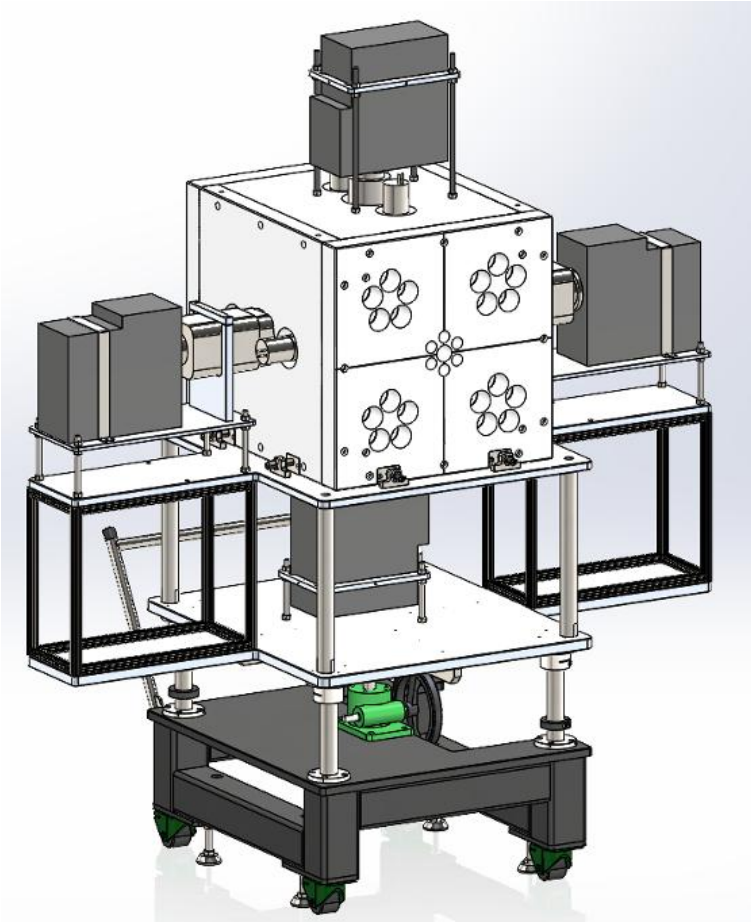


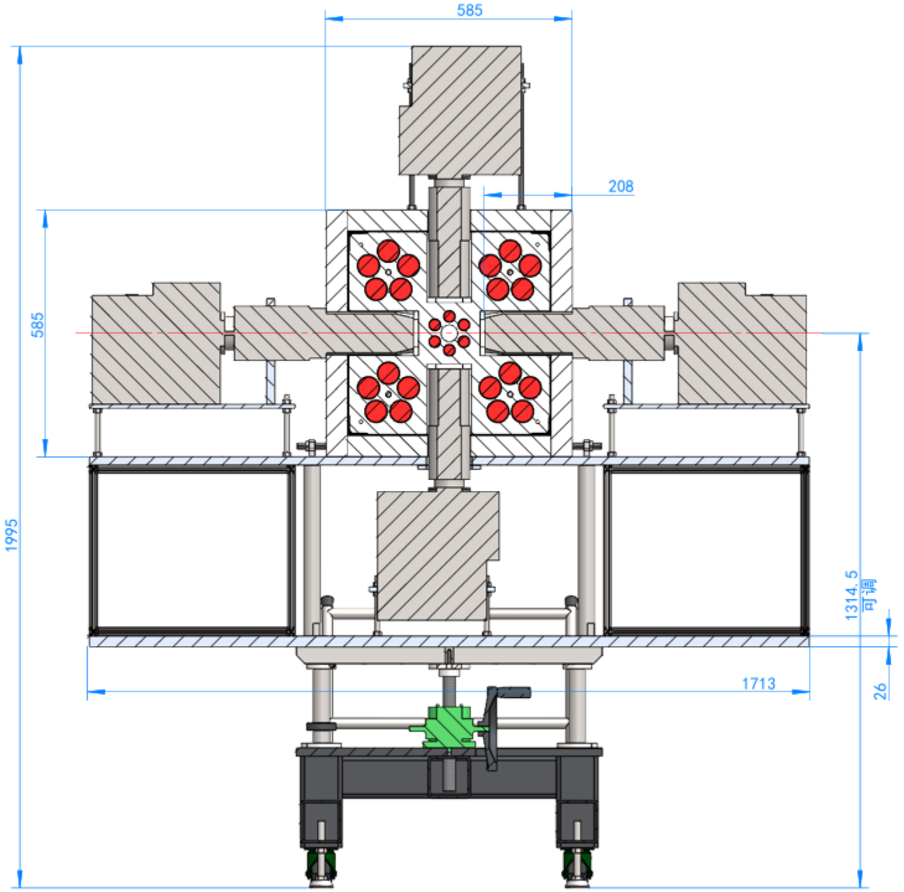
How do we single out γ transitions through unresolved states?

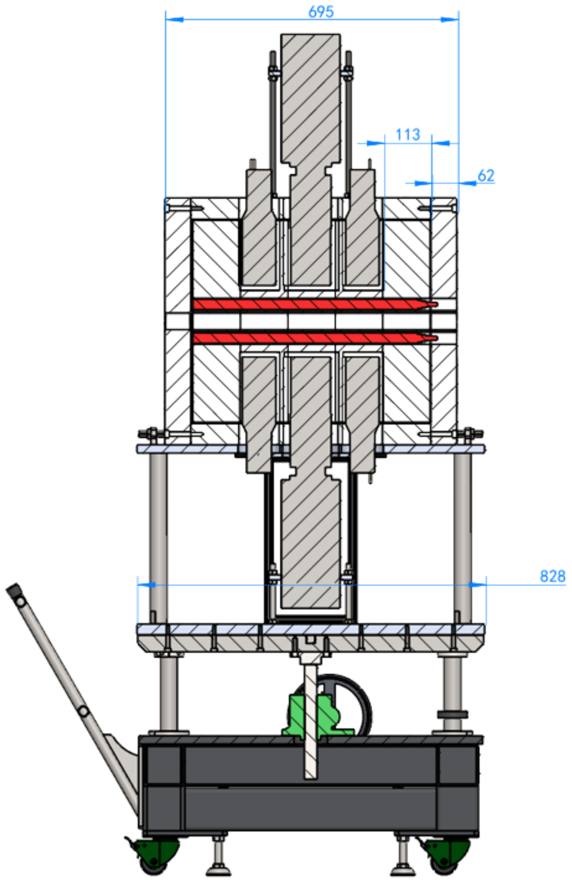
Concept of methodology: One discrete case



New moderator and detector support

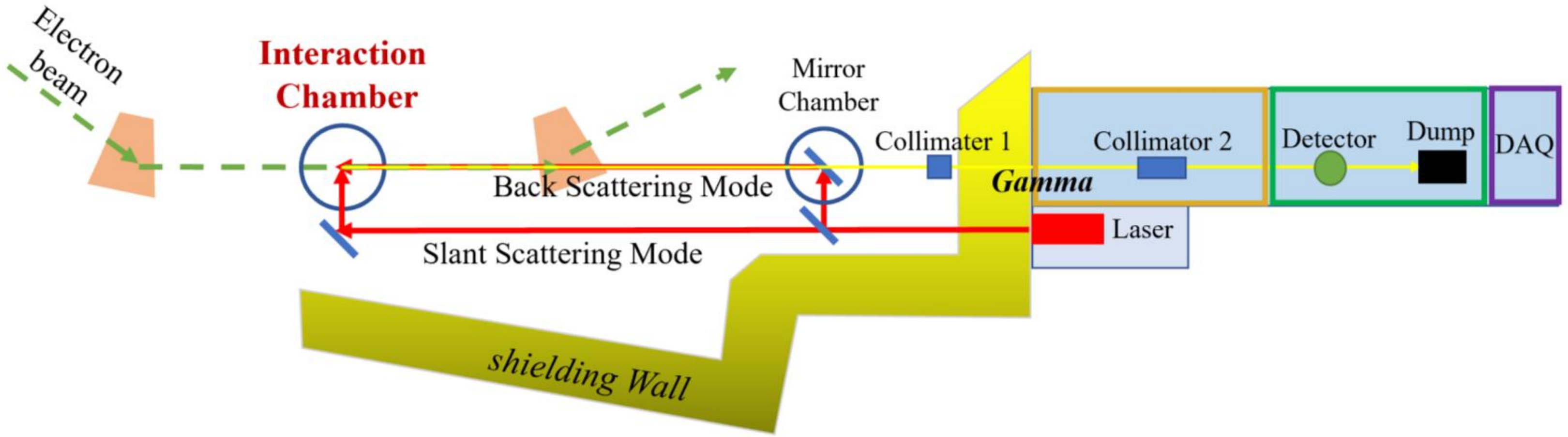






Timeline

1. Polyethylene moderator and mechanical support
   August-September 2025
2. Assembly of the detector system and offline tuning with the standard neutron and gamma sources
   January 2026
3. Online test measurements with gamma-ray beams
   February-March 2026
4. Experiment at SLEGS
   March-April 2026



Summary

1. We have devised a new γ-spectroscopy to identify mediating excited states between $^{180}Ta^{m}$ and $^{180}Ta^{gs}$.

2. A new γ-spectroscopy detector called p-process chaser detector is under construction toward an experiment in 2026.

3. The γ-spectroscopy based on photonuclear reactions plays a complementary role to the one based on heavy-ion reactions.