Production Cross Section Measurements Of ^{111}Ag With The Reaction $^{nat}Pd(\alpha,x)$

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[1] K. M. El-Azony *et al. NUCL SCI TECH*, vol. 33, no. 2, p. 14, Feb. 2022
[2] S. Chattopadhyay *et al*, *Applied Radiation and Isotopes*, vol. 66, no. 3, pp. 334-339, Mar. 2008
[3] C. Blackadar *et al.*, *ACS Appl. Mater. Interfaces*, vol. 14, no. 23, pp. 26382–26393, Jun. 2022

^{111}Ag as a therapeutic agent for β^- Targeted Radionuclide Therapy

$T_{1/2}$	Decay	γ-rays (intensity)	β^- energy
7.42 d	β^- (100 %)	342 keV (6.7 %) 245 keV (1.24 %)	E_{mean} = 350 keV E_{max} = 1037 keV

Suits the biological $t_{1/2}$ of antibodies ⇒ radioimmunotherapy [1]

2 γ-rays suitable for **SPECT** imaging

Tissue penetration depth of up to **4.8 mm** [2] ⇒ suitable for tumors and large clusters of cells

- Dose assessment and biodistribution monitoring with **SPECT imaging**
- Study of its use for **radiosynovectomy** (treatment for arthritis) of joint inflammation [2]
- Useful for the study of silver-based **antimicrobials** [3]

Production routes of ^{111}Ag

^{105}In 5.07 min ε β^+ = 100 %	^{106}In 6.23 min ε β^+ = 100 %	^{107}In 32.4 min ε β^+ = 100 %	^{108}In 58 min ε β^+ = 100 %	^{109}In 4.154 h ε β^+ = 100 %	^{110}In 4.9 h ε β^+ = 100 %	^{111}In 2.80 d ε β^+ = 100 %	^{112}In 14.88 m ε β^+ = 62 % β^- = 38 %	^{113}In STABLE 4.281 %	^{114}In 71.9 s β^- = 99.5 % ε β^+ = 0.5 %	^{115}In 4.41e14 y 95.719% β^- = 100 %
^{104}Cd 57.8 min ε β^+ = 100 %	^{105}Cd 55.4 min ε β^+ = 100 %	^{106}Cd STABLE 1.245 %	^{107}Cd 6.52 h ε β^+ = 100 %	^{108}Cd STABLE 0.888 %	^{109}Cd 461.98 d ε = 100 %	^{110}Cd STABLE 12.47 %	^{111}Cd STABLE 12.795 %	^{112}Cd STABLE 24.109 %	^{113}Cd 8.04e15 y 12.227 % β^- = 100 %	^{114}Cd STABLE 28.754 %
^{103}Ag 65.8 min ε β^+ = 100 %	^{104}Ag 69.3 min ε β^+ = 100 %	^{105}Ag 41.29 d ε β^+ = 100 %	^{106}Ag 23.96 m ε β^+ > 99 % β^- < 1 %	^{107}Ag STABLE 51.83 %	^{108}Ag 2.39 m β^- = 97.15 % ε β^+ = 2.85 %	^{109}Ag STABLE 48.161 %	^{110}Ag 24.56 s β^- = 100 %	^{111}Ag 7.421 d β^- = 100 %	^{112}Ag 3.15 h β^- = 100 %	^{113}Ag 5.37 h β^- = 100 %
^{102}Pd STABLE 1.02 %	^{103}Pd 17 d ε β^+ = 100 %	^{104}Pd STABLE 11.14 %	^{105}Pd STABLE 22.33 %	^{106}Pd STABLE 27.33 %	^{107}Pd 6.50e6 y β^- = 100 %	^{108}Pd STABLE 26.46 %	^{109}Pd 13.437 h β^- = 38.5 %	^{110}Pd STABLE 30.85 %	^{111}Pd 23.6 min β^- = 100 %	^{112}Pd 21.027 h β^- = 100 %

Light-charged particle routes :

- ^{232}Th(p,f)^{111}Ag
- UC_x(p,f)^{111}Ag
- ^{nat}Pd(d,x)^{111}Ag, ^{110}Pd(d,x)^{111}Ag
- ^{nat}Pd(α,x)^{111}Ag, ^{110}Pd(α,x)^{111}Ag, ^{108}Pd(α,x)^{111}Ag

Neutron and photonuclear routes :

- $^{110}Pd(n,\gamma)^{111m,g}Pd \xrightarrow{\beta^-} {}^{111}Ag$
- ^{nat}In(γ,x)^{111}Ag
- ^{nat}Cd(γ,x)^{111}Ag

[1] M. Aikawa *et al.*, '*Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 449, pp. 99–104, Jun. 2019

[2] A. Hermanne *et al.*, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 229, no. 3, pp. 321–332, Apr. 2005

α production route of ^{111}Ag with a natural palladium target

Several contribution to the production of ^{111}Ag :

- Direct production : ^{108}Pd(α,p) and ^{110}Pd(α,x) reactions
- Indirect production : decay of ^{111m}Pd, ^{111g}Pd and ^{111m}Ag

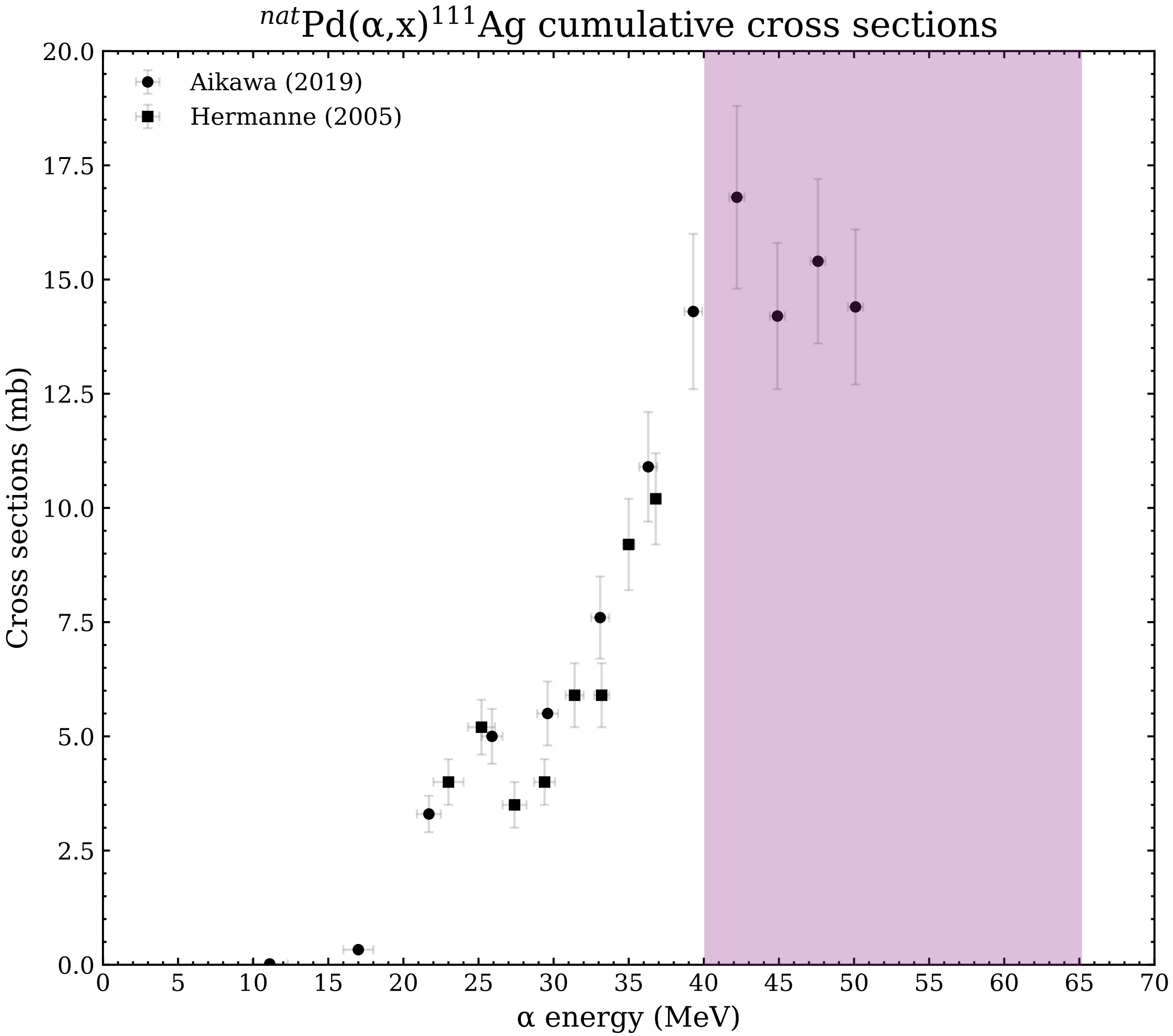
↳ study the **cumulative** production cross sections of ^{111}Ag

Only two experimental datasets for ^{nat}Pd(α,x)^{111}Ag.

↳ Extend the excitation function at higher energies

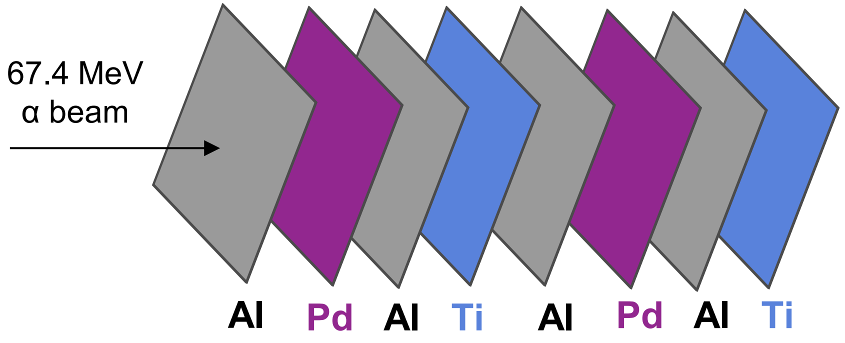
↳ Define the maximum cross section region

↳ Study the production of the long-lived silver contaminants

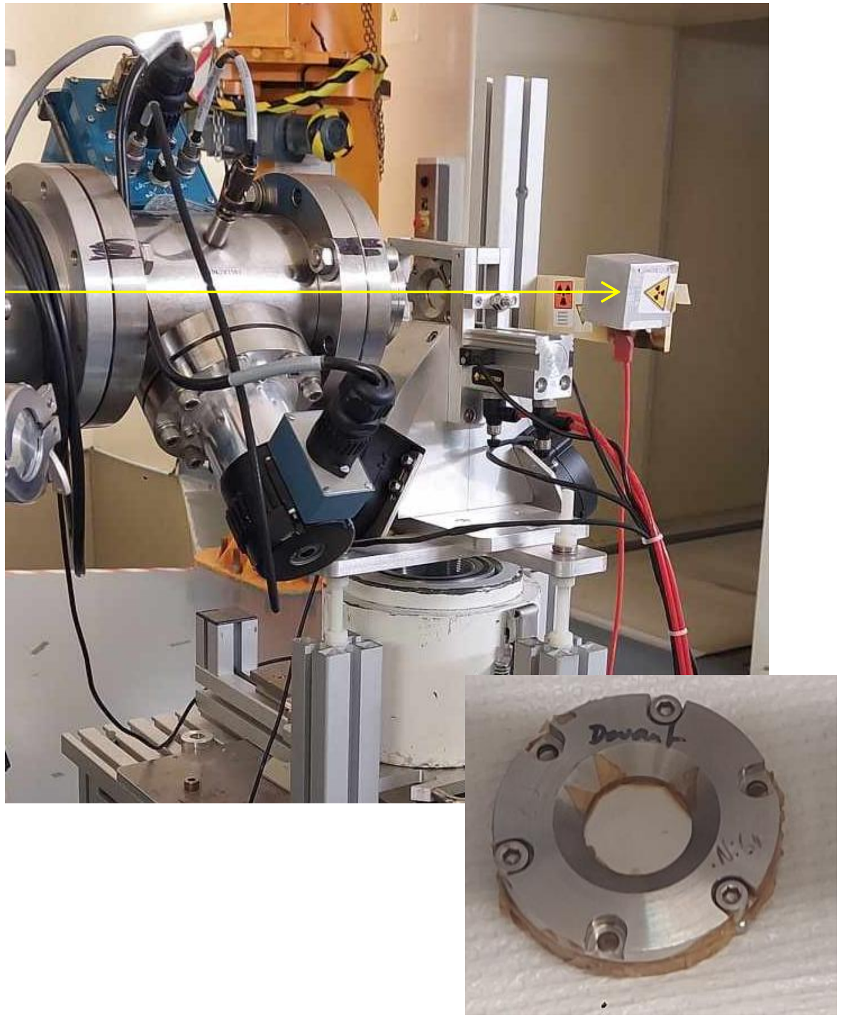


Cross section measurements with the stacked foils technique

5 campaigns of measurements performed at **GIP ARRONAX**:



- Characteristics of the irradiations : 2 hours at 150 nA
- Beam intensity measurements : monitor reaction $^{27}Al(\alpha,x)^{22}Na$
- Gamma spectrometry measurements performed at least three days after the irradiation for ^{111}Ag and the long-lived contaminants

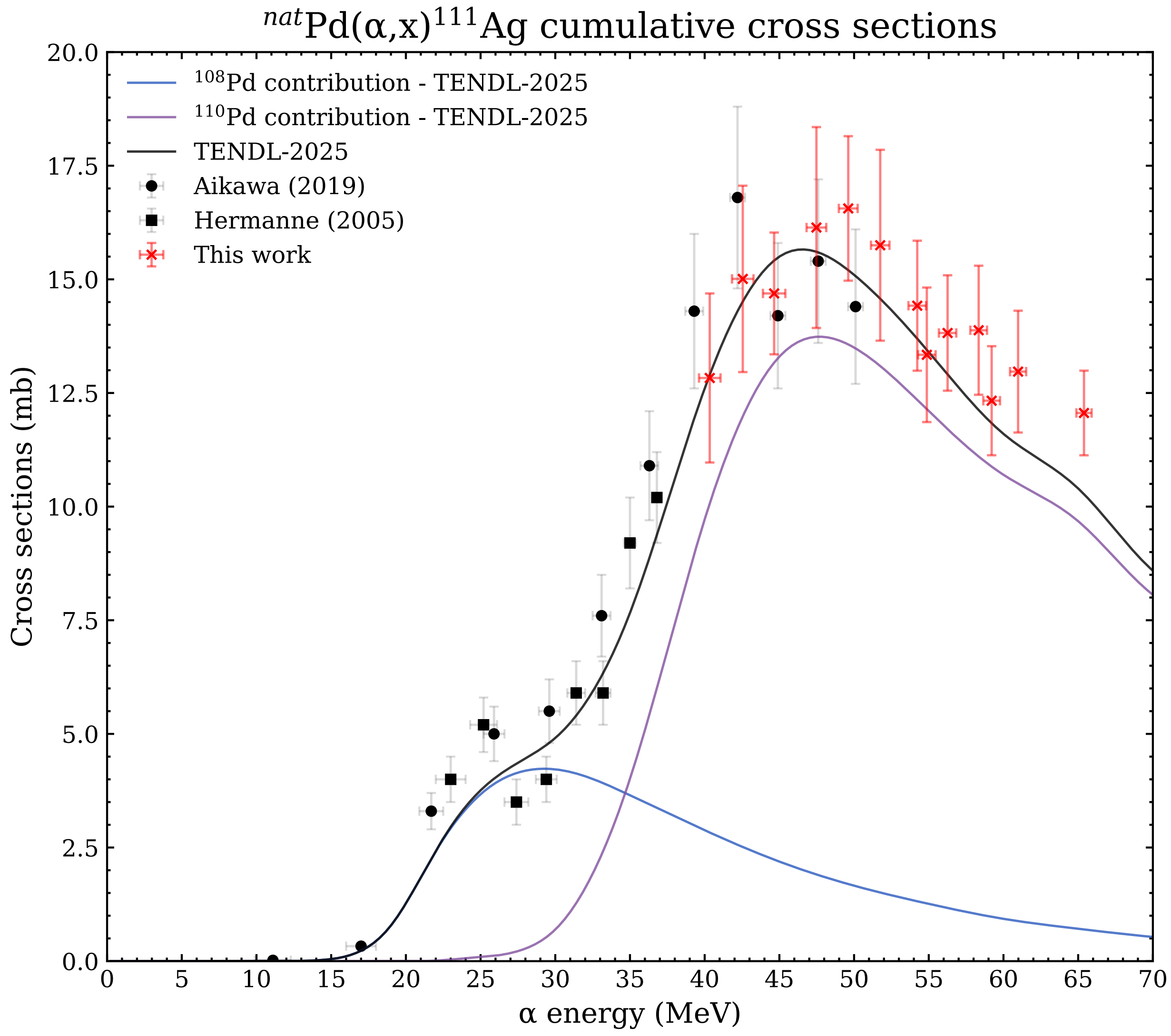


Results for $^{nat}Pd(\alpha,x)^{111}Ag$

- Additional measurements up to **65.4 MeV** in 5 experiments ⇒ good concordance between the different series.
- The maximum cross section is reached around 50 MeV with 16 mb.

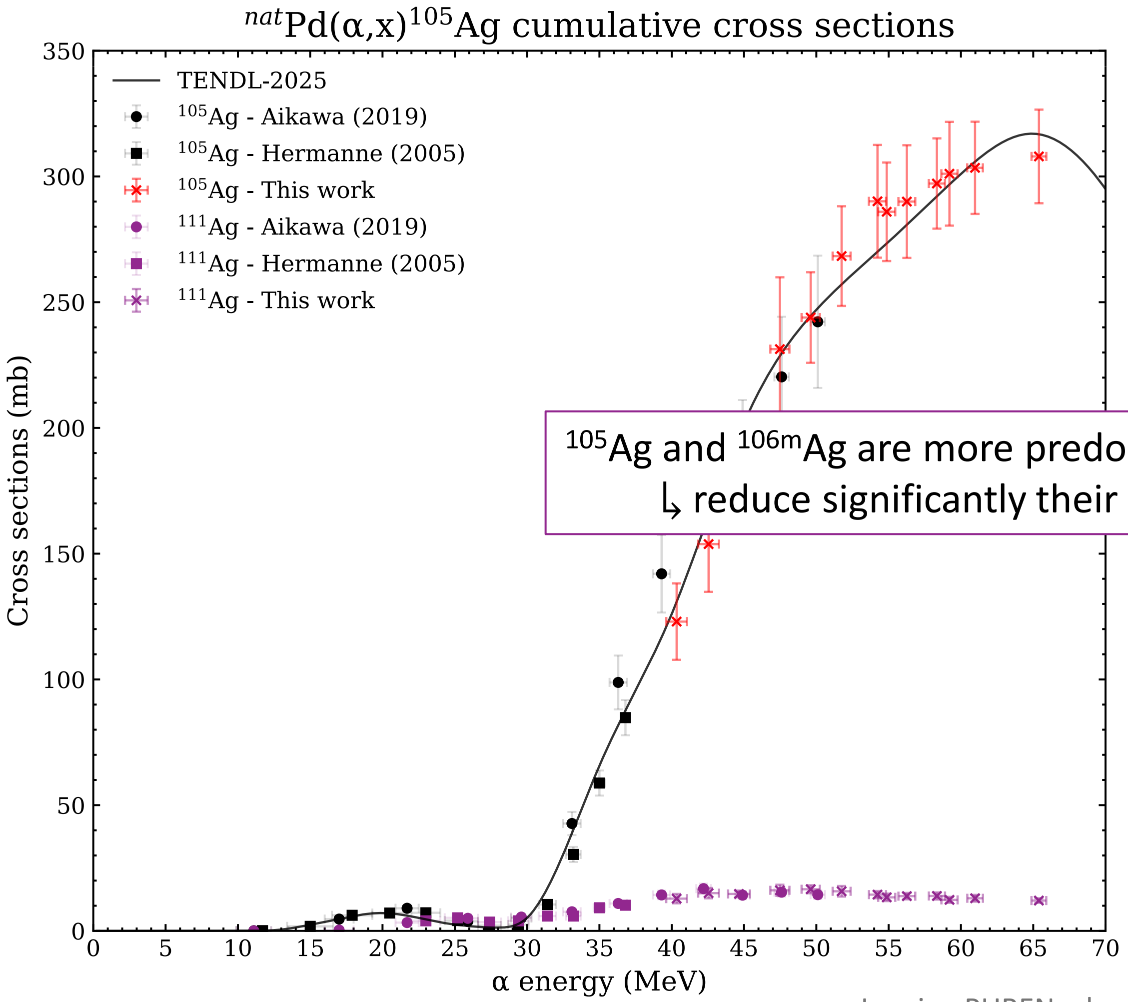
- Overall good agreement with the experimental values of Aikawa *et al.*
- The predicted cross sections by TENDL-2025 agree with the experimental data.

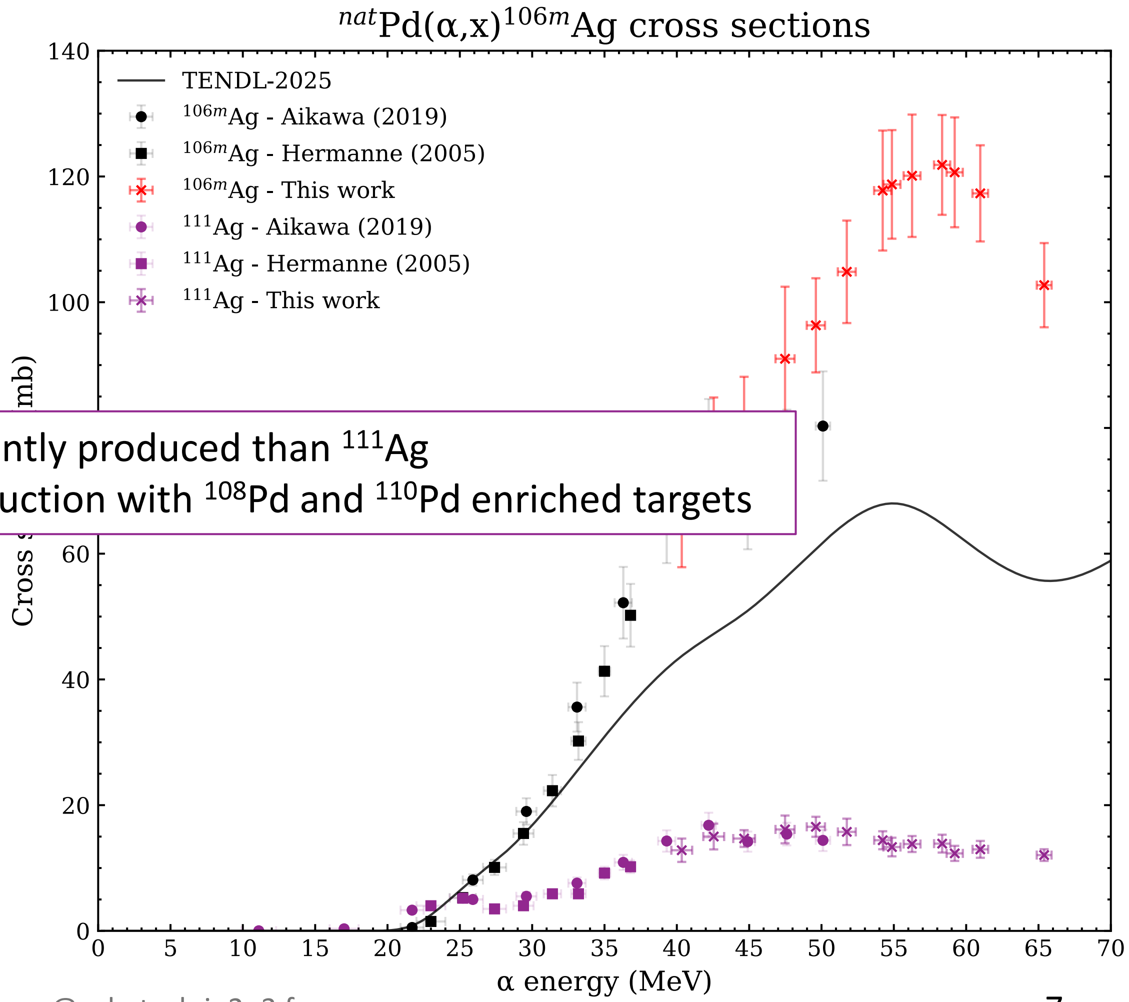
^{111}Ag is mostly produced by the alpha induced reaction on ^{110}Pd



Co-produced long-lived silver isotopes

Production of silver isotopes in the same energy range as ^{111}Ag: **^{105}Ag** ($t_{1/2}$ = 41.29 d), **^{106m}Ag** ($t_{1/2}$ = 8.28 d) and **^{110m}Ag** ($t_{1/2}$ = 249.83 d).





^{105}Ag and ^{106m}Ag are more predominantly produced than ^{111}Ag
↳ reduce significantly their production with ^{108}Pd and ^{110}Pd enriched targets

Co-produced long-lived silver isotopes

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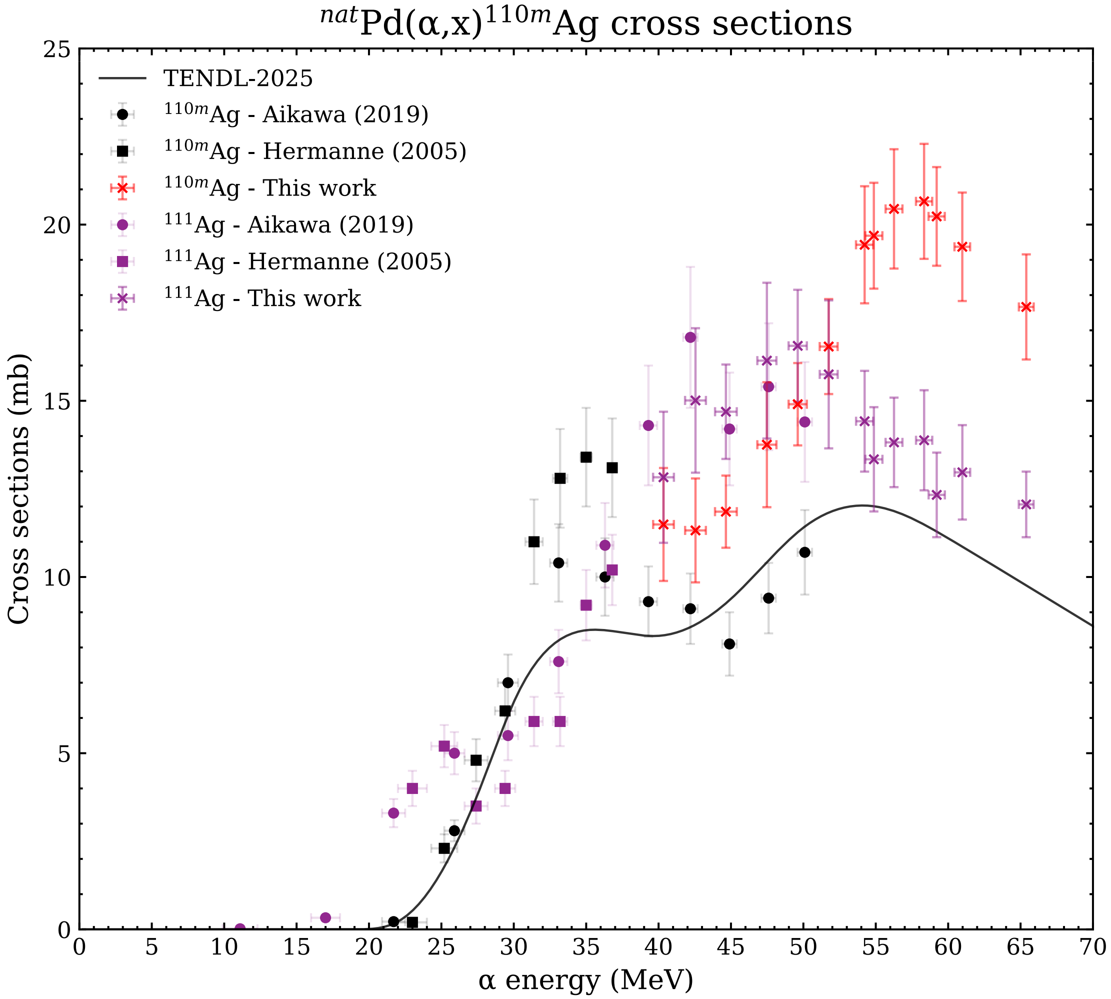

Even with an enriched target (^{108}Pd or ^{110}Pd), ^{110m}Ag will still be produced alongside ^{111}Ag.

Not suitable for medical applications

K. M. El-Azony, *et al., NUCL SCI TECH*, vol. 33, no. 2, p. 14, Feb. 2022
M. Ballan *et al.*, *Applied Radiation and Isotopes*, vol. 164, p. 109258, Oct. 2020
M. Tosato *et al.*, *Pharmaceuticals*, vol. 16, no. 7, p. 929, Jun. 2023

Comparison with the other production routes

Production route	Characteristics of the irradiation	Estimated production (EOB)	Long-lived silver isotopes	Specific activity
^{110}Pd(α,x)	E = 60 MeV Target thickness ≈ 255 µm	2 MBq/µAh (calculated from experimental cross sections)	^{110m}Ag	low
^{232}Th(p,f)	E_p = 90 MeV, m_t= 100 g (full-scale production of ^{225}Ac)	115 MBq/µAh	Small amount of ^{110m}Ag	medium
UC_x(p,f)	E_p = 40 MeV	4 MBq/µAh (FLUKA)	None with mass separation	High with mass separation
^{110}Pd(d,x)	E_d = 20 MeV Target thickness ≈ 416 µm	15 MBq/µAh (calculated from experimental cross sections)	^{110m}Ag	low
^{nat}Pd(n, x)	$\phi_n = 3 \times 10^{13}$ n cm^{-2} s^{-1} $t_{irradiation}$: 26 h m_t = 100 mg	5 MBq/h	None	Limited
^{110}Pd(n, γ)	$\phi_n = 1.7 \times 10^{13}$ n cm^{-2} s^{-1} $t_{irradiation}$: 1 h m_t = 62.7 mg	4.5 MBq/h	None	High
^{nat}In(γ,x)	$\phi_{10\ MeV < E\gamma < 24\ MeV} = 5.7 \times 10^{13}$ n cm^{-2} s^{-1} t_{irr} = 12 days	2.8 MBq/g.h	None	medium
^{nat}Cd(γ,x)	/	/	^{105,110m}Ag	low

Conclusion

New production cross section measurements of the reaction $^{nat}Pd(\alpha,x)^{111}Ag$ have been performed at GIP ARRONAX up to 65.4 MeV:

⟶ Good agreement with the data of Aikawa *et al.*

⟶ The maximum cross section is reached around 50 MeV with 16 mb.

⟶ The predicted cross sections of TENDL-2025 agree on overall with the experimental data.

⟶ Co-production of long-lived silver isotopes, $^{105,106m,110m}Ag$, that renders the reaction not suitable for the production of ^{111}Ag.

The indirect route $^{110}Pd(n,x)$ and the $UC_x(p,f)$ reaction coupled with mass separation seem to be the most promising routes to both avoid the co-production of long-lived silver isotopes and to achieve high specific activity


Thank you for your attention
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