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## PRODUCTION CROSS SECTION MEASUREMENTS OF THE $^{nat}\text{Pd}(\alpha, x)^{111}\text{Ag}$ REACTION



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### Medical interest of $^{111}\text{Ag}$

Promising **theranostic** (therapy + diagnostic) radionuclide.

- **Therapeutic use** in internal vectorized radiotherapy.
  - ↳ Its  $\beta^-$  particles are suitable for tumours and large clusters of cells (4.8 mm tissue penetration [1])
  - ↳ Suits the biological  $t_{1/2}$  of antibodies  $\Rightarrow$  radioimmunotherapy [2]
- $\gamma$ -ray at 342 keV (6.7 %) might be suitable for **SPECT imaging**.

$T_{1/2}$	Decay mode	$\gamma$ -ray energy (intensity)	$\beta^-$ energy (intensity)
7.421 d	$\beta^-$ (100 %)	342.13 keV (6.7 %)	$E_{\text{mean}} = 360.4$ keV $E_{\text{max}} = 1036.8$ keV (92 %)
		245.4 keV (1.24 %)	$E_{\text{mean}} = 223.5$ keV $E_{\text{max}} = 694.7$ keV (7.1 %)

Table 1: Decay characteristics of  $^{111}\text{Ag}$  (Nudat 3.0)

### Production routes of $^{111}\text{Ag}$

- **Neutron & photonuclear route** :  $^{110}\text{Pd}(n, x)^{111}\text{Pd} \xrightarrow{\beta^+} ^{111}\text{Ag}$ ,  $^{nat}\text{Cd}(\gamma, x)^{111}\text{Ag}$ ,  $^{nat}\text{In}(\gamma, x)^{111}\text{Ag}$ ,
- **Isotope Separation On-Line technique (ISOL)** : uranium carbide target impinged with a proton beam [3]
- **Light-charged particles route** :  $^{232}\text{Th}(p, f)^{111}\text{Ag}$ ,  $^{nat}\text{Pd}, ^{110}\text{Pd}(d, x)^{111}\text{Ag}$ ,  $^{110}\text{Pd}, ^{nat}\text{Pd}(\alpha, x)^{111}\text{Ag}$

Only two experimental datasets [4,5]

Measure the production cross sections of  $^{111}\text{Ag}$  via the reaction  $^{nat}\text{Pd}(\alpha, x)$  at high energy to better define the peak region. Compare this production route with the other ones.

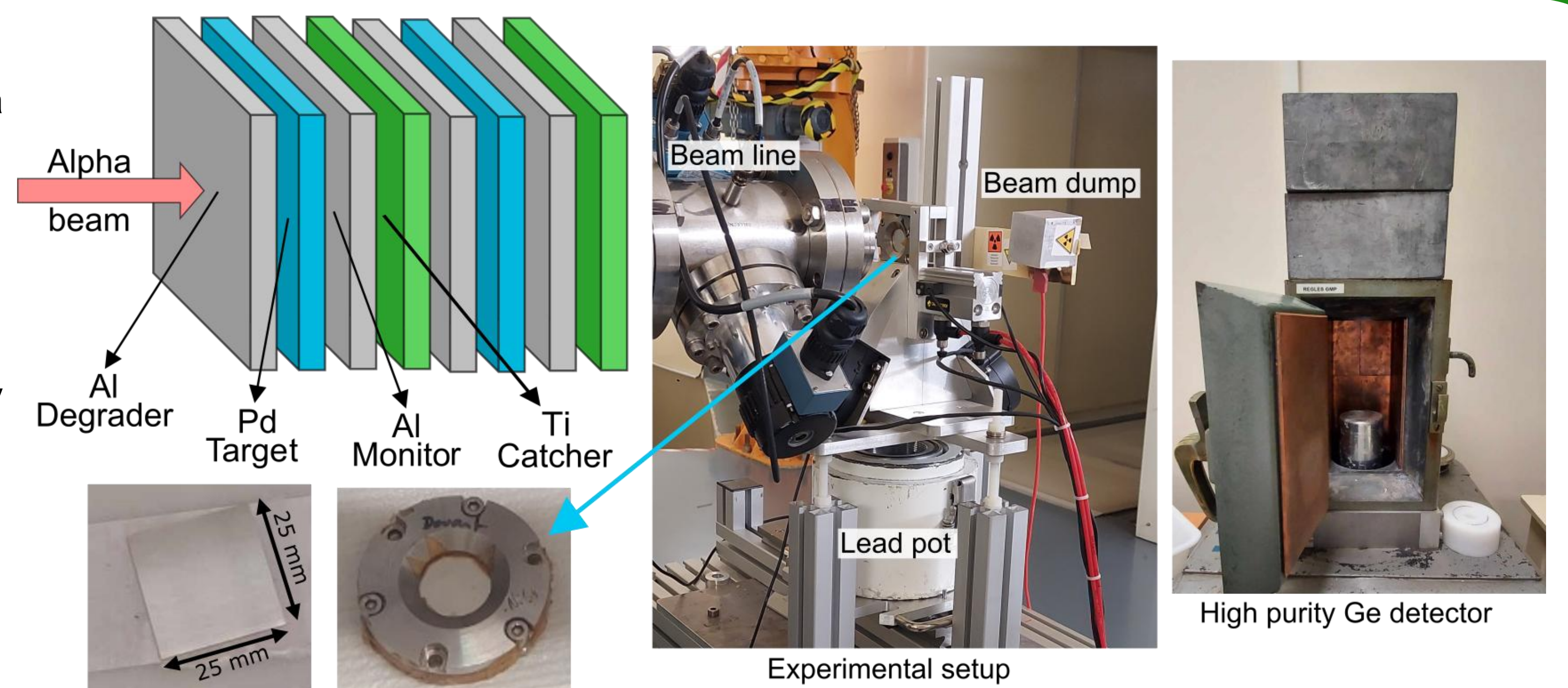
### Stacked foils technique

With this technique, several cross section measurements can be done with a single irradiation of thin stacked foils.

- Degraded: adjusts the beam energy.
- Target: where the reaction  $^{nat}\text{Pd}(\alpha, x)^{111}\text{Ag}$  takes place.
- Monitor: beam intensity measured via the monitor reaction  $^{27}\text{Al}(\alpha, x)^{22}\text{Na}$  [6].

Measurement of the activity produced after irradiation in each foils performed by gamma spectrometry with HPGe detectors.

3 campaigns accomplished at the ARRONAX cyclotron with an alpha beam of 67.4 MeV and 100-150 nA intensity



### $^{nat}\text{Pd}(\alpha, x)$ cross sections

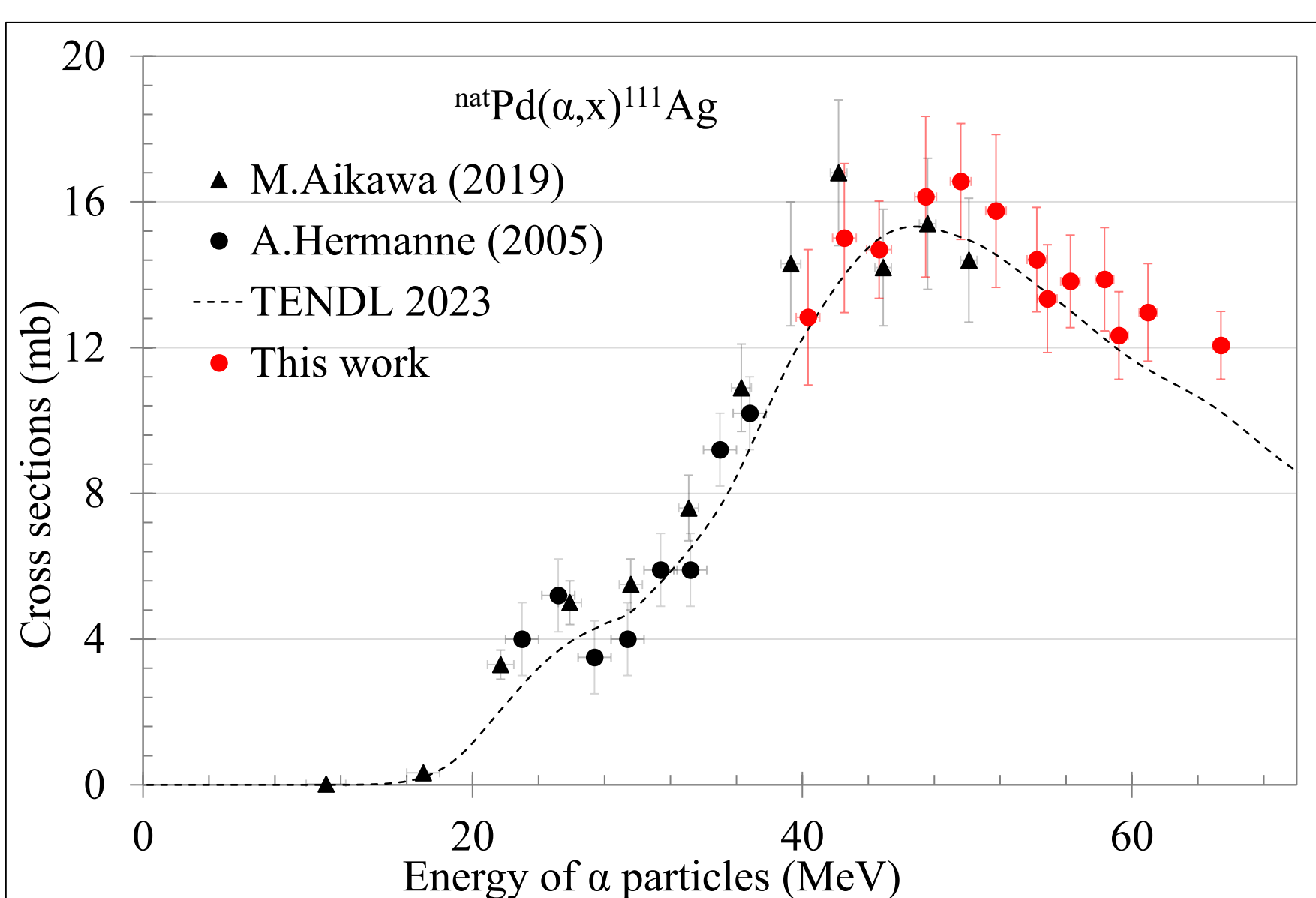


Figure 1: Production cross sections of  $^{nat}\text{Pd}(\alpha, x)^{111}\text{Ag}$

- Production of long-lived silver isotopes in the same energy range as  $^{111}\text{Ag}$ :  $^{105}\text{Ag}$  ( $t_{1/2} = 41.29$  d),  $^{106m}\text{Ag}$  ( $t_{1/2} = 8.28$  d) and  $^{110m}\text{Ag}$  ( $t_{1/2} = 249.83$  d).
- Their production cross sections are more significant than for  $^{111}\text{Ag}$ .
- Even with an enriched target ( $^{108}\text{Pd}$  or  $^{110}\text{Pd}$ )  $^{110m}\text{Ag}$  is still produced alongside  $^{111}\text{Ag}$ .

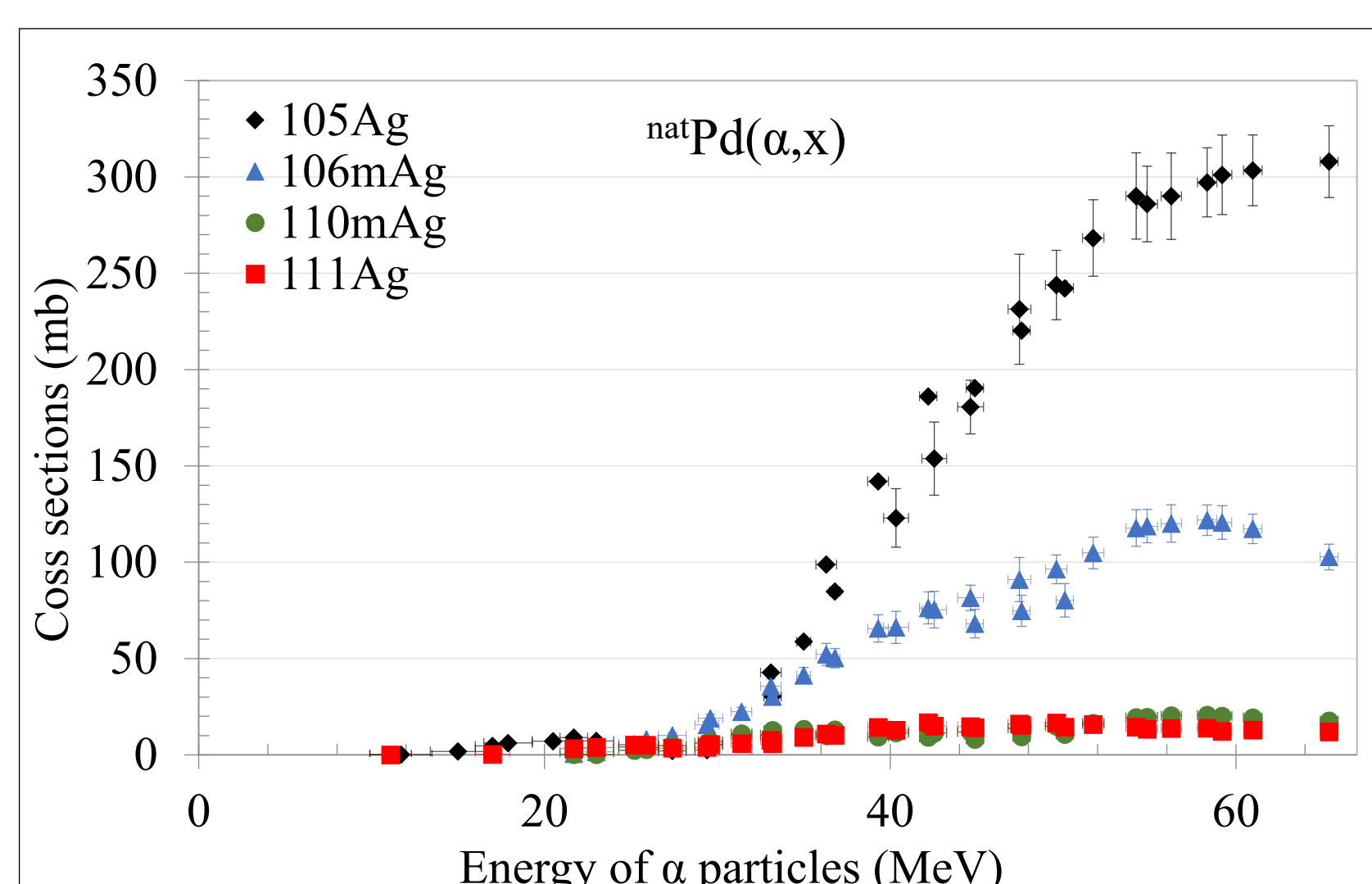


Figure 2: Production cross sections of  $^{nat}\text{Pd}(\alpha, x)^{105, 106m, 110m, 111}\text{Ag}$

- Additional measurements up to 65.4 MeV.
- 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-2023 agree with the experimental data.

### Yield

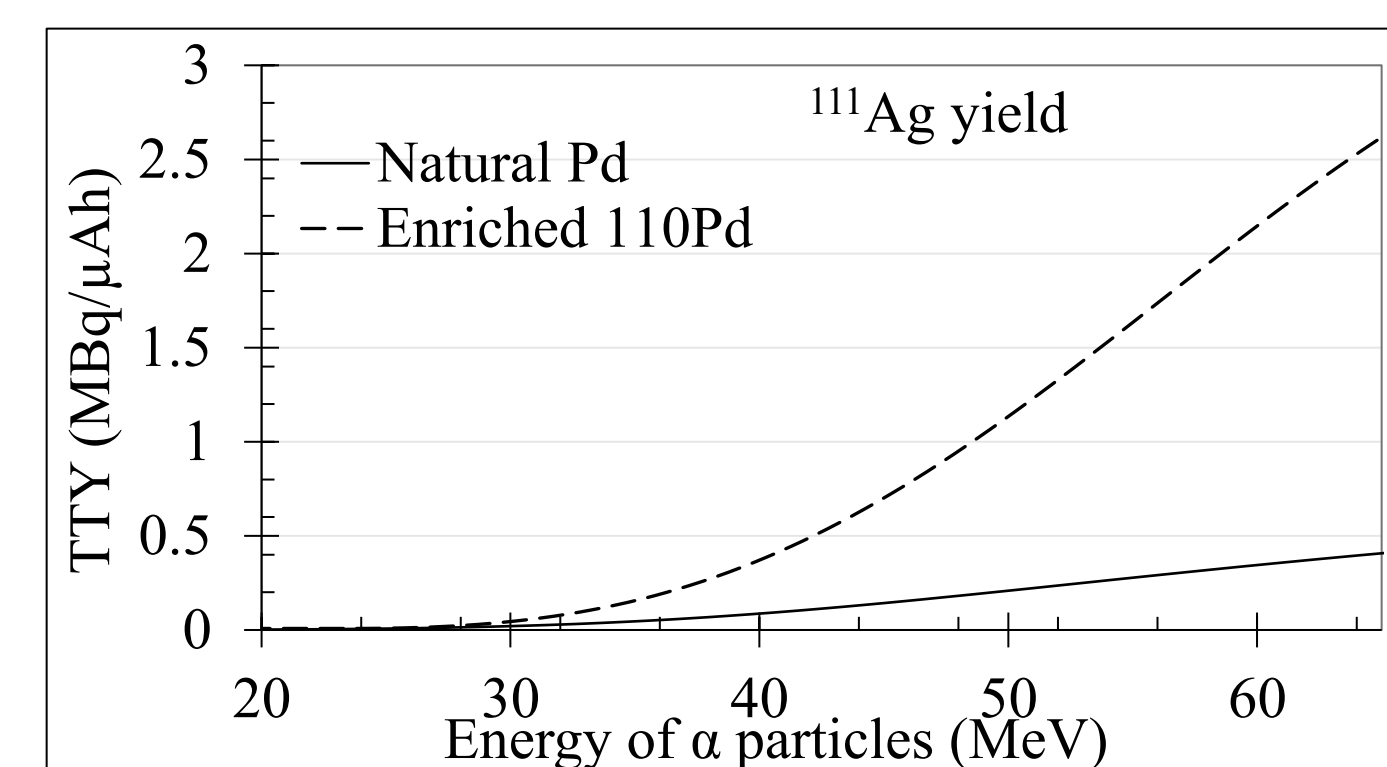


Figure 3: Thick Target Yield for the production of  $^{111}\text{Ag}$

- With an energy range of 60-35 MeV, equivalent to a target thickness of 250  $\mu\text{m}$ :
  - Yield of about 300 kBq/ $\mu\text{Ah}$  for  $^{nat}\text{Pd}$ .
  - Yield of about 2.0 MBq/ $\mu\text{Ah}$  for  $^{110}\text{Pd}$ .
  - ↳ but an estimated production of  $^{110m}\text{Ag}$  of 1.2 MBq/ $\mu\text{Ah}$

### Comparison with the other production routes

- **Neutron route**: An estimated production of around 3.85 MBq/h depending on the flux of neutron is achieved [7]. There are only short-lived silver isotopes that are produced, and a high specific activity is achieved.
- **Fission route**: Around 2.59 GBq/ $\mu\text{A}$  can be obtained during a full-scale production of  $^{225}\text{Ac}$ . However, small amounts of  $^{110m}\text{Ag}$  are produced alongside.
- **Deuteron route**: A TTY of 15 MBq/ $\mu\text{Ah}$  can be achieved with an enriched  $^{110}\text{Pd}$  target but there is a significant co-production of  $^{110m}\text{Ag}$  [7].
- **Photonuclear route**: Co-production of several silver isotopes might be possible with the  $^{nat}\text{Cd}(\gamma, n)$  route. The  $^{nat}\text{In}(\gamma, \alpha)$  might be better suited as there might only be the production of stable  $^{109}\text{Ag}$ . A good specific activity could be achieved [2,6].
- **ISOL route**: a predicted TTY was obtained with the Monte-Carlo code FLUKA of about 4 MBq/ $\mu\text{Ah}$ . This route will lead to high purity and specific activity. [3]
- **Alpha route**: With a  $^{110}\text{Pd}$  enriched target, an estimated TTY of 2.0 MBq/ $\mu\text{Ah}$  can be reached. However, there is at the same time a significant co-production of  $^{110m}\text{Ag}$ .

### Conclusion

- New measurements of the production cross sections of  $^{nat}\text{Pd}(\alpha, x)^{105, 106m, 110m, 111}\text{Ag}$  have been performed at GIP ARRONAX. The peak is now defined and our values agree with Aikawa *et al.*
- The alpha production route has too many drawbacks, even with enriched targets: significant co-production of long-lived  $^{110m}\text{Ag}$  and small TTY.
- The most promising route seems to be the neutron route: it does not lead to the co-production of long-lived silver isotopes.

### References

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