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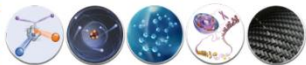
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PRISMA



Physics of Radiation InteractionS with Matter and Applications



Production cross section measurements of the $^{nat}\text{Pd}(\alpha, x)^{111}\text{Ag}$ reaction

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❑ Low toxicity of silver in humans \Rightarrow already used in several pharmaceuticals [1]

❑ ^{111}Ag can be used for β^- therapy:

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

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

2 γ suitable for SPECT imaging

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

❑ The appeal for ^{111}Ag :

- Dose assessment and biodistribution monitoring with SPECT imaging
- Radiosynovectomy : treatment for arthritis. [2]

[1] K. M. El-Azony *et al.*, 'Advantages and disadvantages of nuclear reactions used in reactors or cyclotrons, in addition to a theoretical study based on photodisintegration on natural indium for ^{111}Ag production' Feb. 2022

[2] S. Chattopadhyay *et al.*, 'Preparation and evaluation of a new radiopharmaceutical for radiosynovectomy, ^{111}Ag -labelled hydroxyapatite (HA) particles', Mar. 2008

Context and motivations

Production routes of ^{111}Ag :


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

Neutron and photonuclear routes :

- $^{110}\text{Pd}(n,\gamma)^{111}\text{Pd} (\beta^-) \rightarrow ^{111}\text{Ag}$
- Isotope Separation On-Line technique (ISOL)
- $^{\text{nat}}\text{In}(\gamma,x)^{111}\text{Ag}$
- $^{\text{nat}}\text{Cd}(\gamma,x)^{111}\text{Ag}$

Light-charged particle routes :

- $^{232}\text{Th}(p,f)^{111}\text{Ag}$ (fission product)
- $^{\text{nat}}\text{Pd}(d,x)^{111}\text{Ag}$, $^{110}\text{Pd}(d,x)^{111}\text{Ag}$
- $^{\text{nat}}\text{Pd}(\alpha,x)^{111}\text{Ag}$, $^{110}\text{Pd}(\alpha,x)^{111}\text{Ag}$, $^{108}\text{Pd}(\alpha,x)^{111}\text{Ag}$


 Few experimental data available

□ α production routes of ^{111}Ag :

- Only two experimental datasets for $^{\text{nat}}\text{Pd}(\alpha, x)^{111}\text{Ag}$.
- Lack of data at high energy.
 - ↳ add data in the region of the peak and investigate what's happening after it.

□ Motivations

1. New measurements at high energy of $^{\text{nat}}\text{Pd}(\alpha, x)^{111}\text{Ag}$.
2. Comparison with the literature.
3. Comparison with the other production routes.

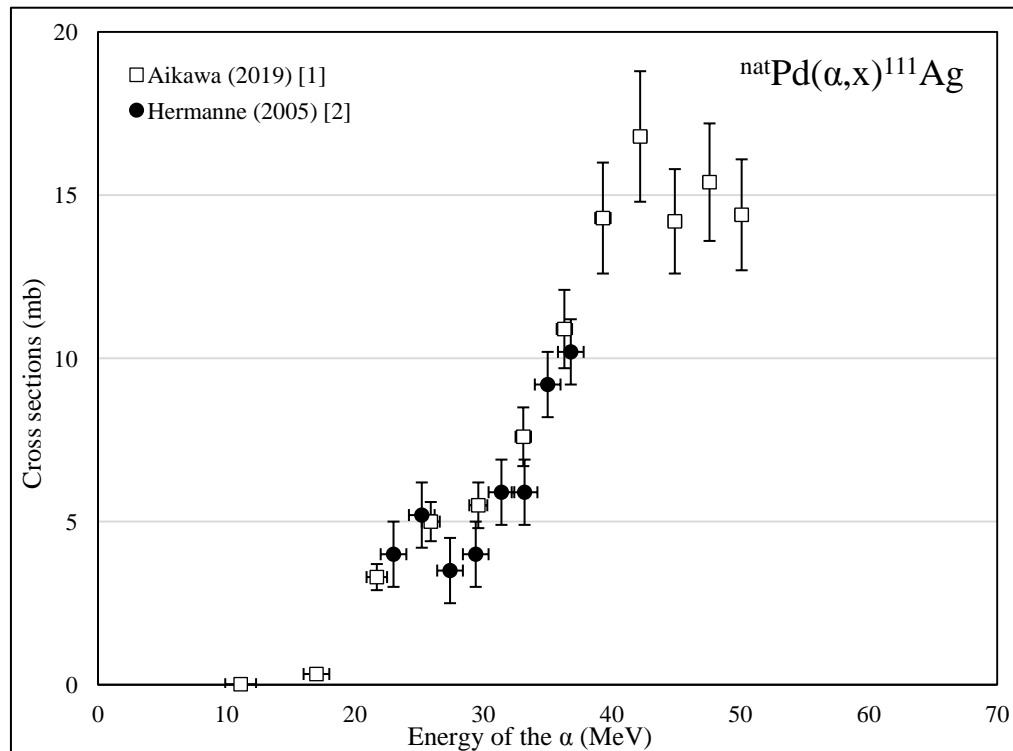


Figure 1 : Cross section measurements of the $^{\text{nat}}\text{Pd}(\alpha, x)^{111}\text{Ag}$ reaction

[1] M. Aikawa *et al.*, 'Activation cross sections of alpha-particle induced nuclear reactions on natural palladium', Jun. 2019

[2] A. Hermanne *et al.*, 'Experimental determination of cross section of alpha-induced reactions on $^{\text{nat}}\text{Pd}$ ', Apr. 2005

Method: Stacked-foils technique

- ❑ **Stacked-foils technique:** in one irradiation, **several production cross sections** can be measured.

↳ One pattern composed : degrader, target, monitor + catcher

- ❑ 3 campaigns of measurements accomplished at the **GIP Arronax**:
 - Alpha beam of 67.4 MeV
 - Monitor reactions : $^{27}\text{Al}(\alpha,x)^{24}\text{Na}$, $^{27}\text{Al}(\alpha,x)^{22}\text{Na}$

	1 st exp	2 nd exp	3 rd exp
Time of irradiation	1 h 30	2 h	2 h
Intensity of the beam	100 nA	150 nA	150 nA

- ❑ Use of the γ -rays at 342 keV (6.7 %) and 245 keV (1.24 %) to extract ^{111}Ag activity with a **HPGe** detector.

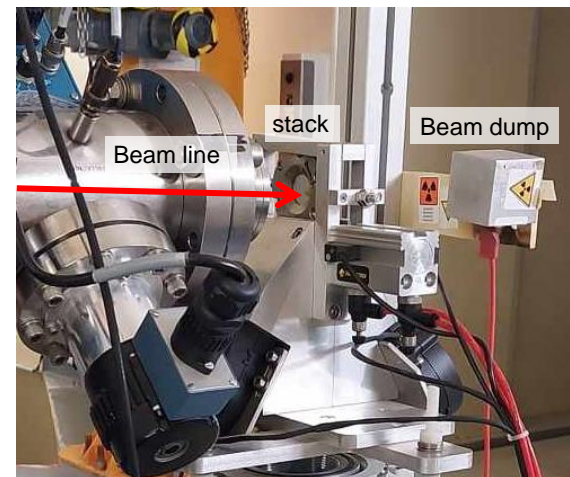
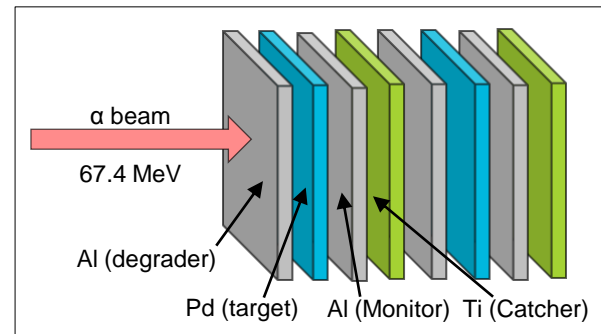


Figure 3: Schematical representation of the stack and setup of the experiment

☐ **Observations:**

- 8 measurements done in three different experiments: good consistency between the 1st and 3rd series.

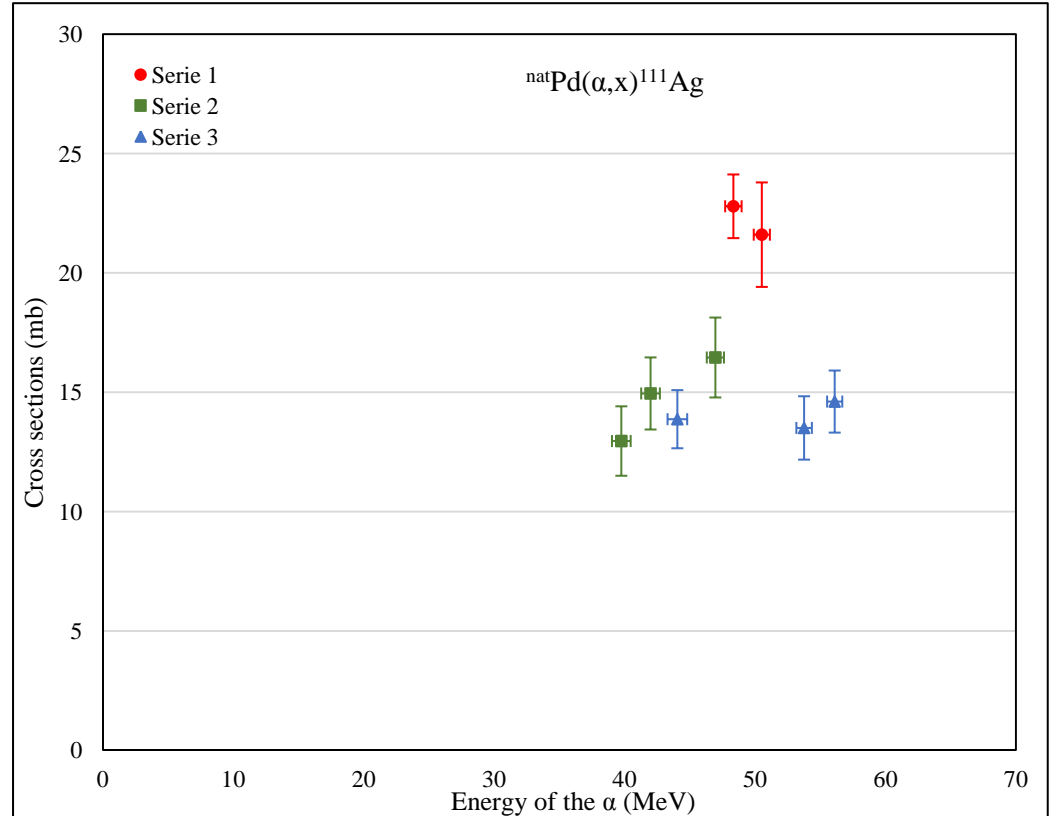


Figure 4: Cross section measurements of the $^{nat}\text{Pd}(\alpha, x)^{111}\text{Ag}$ reaction.

Observations:

- 8 measurements done in three different experiments: good consistency between the 1st and 3rd series.
- The maximum cross section seems to be around 50 MeV
- **Overall good agreement** with the experimental values of Aikawa *et al.*
 - ↳ the points at 48 and 50.5 MeV (*serie 1*) seem questionable.

Make new measurements in the area around the peak to define it better.

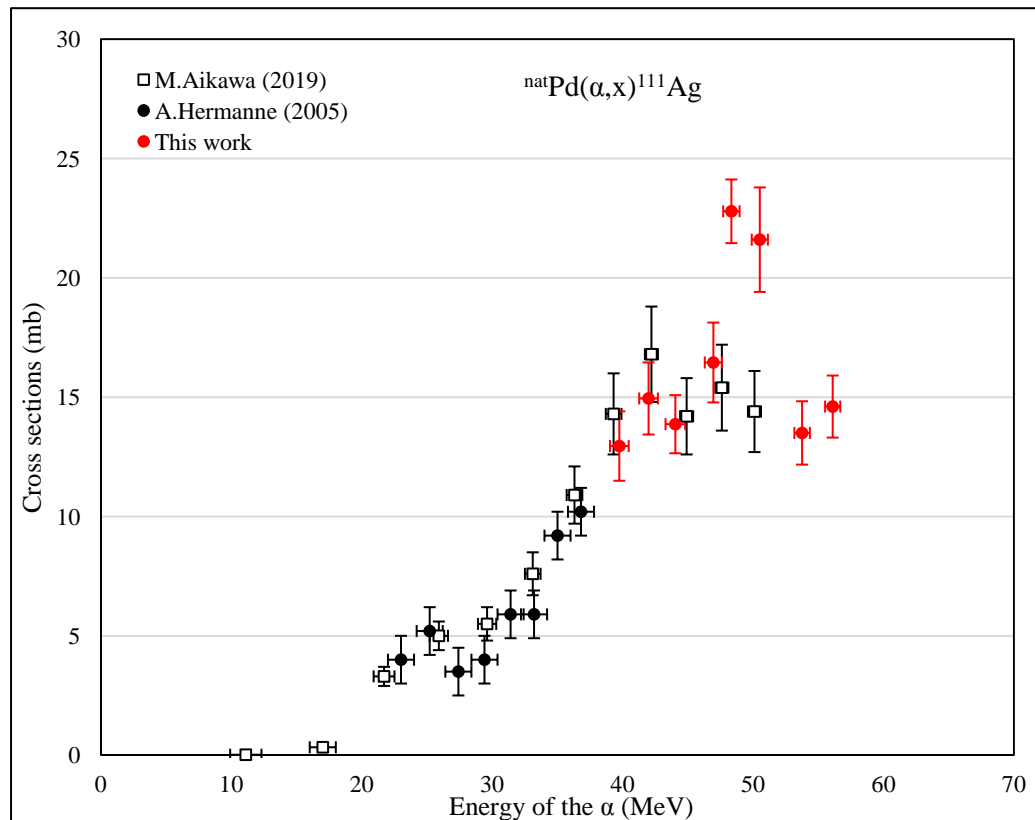


Figure 4: Cross section measurements of the $^{nat}\text{Pd}(\alpha, x)^{111}\text{Ag}$ reaction.

Results – Contaminants

- Production of other silver isotopes:

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 %

^{106m}Ag: t_{1/2} = 8.28 j

^{110m}Ag: t_{1/2} = 249.83 j

- Most of the contaminants produced are short-lived ⇒ a cooling time of **1-2 days** is enough for them to decay completely
 - ↳ Not the case for the longer-lived ¹⁰⁵Ag (t_{1/2} = 41.29 j), ^{106m}Ag (t_{1/2} = 8.28 j) and ^{110m}Ag (t_{1/2} = 249.83 j)



If possible, find an interval of energy where only ¹¹¹Ag is produced

Observations:

- ^{111}Ag and $^{110\text{m}}\text{Ag}$ have the lowest cross sections of all the long-lived silver isotopes.
 - ↳ more than **5 times** lower than for $^{106\text{m}}\text{Ag}$ and more than 10 times lower than ^{105}Ag .
- They are all produced in the same energy interval than ^{111}Ag .

↳ their production is **unavoidable**.



Use of an **enriched target** of ^{108}Pd or ^{110}Pd :

- Small production of ^{105}Ag and $^{106\text{m}}\text{Ag}$.
- ^{111}Ag is **still** produced alongside $^{110\text{m}}\text{Ag}$.

What about the other production routes ?

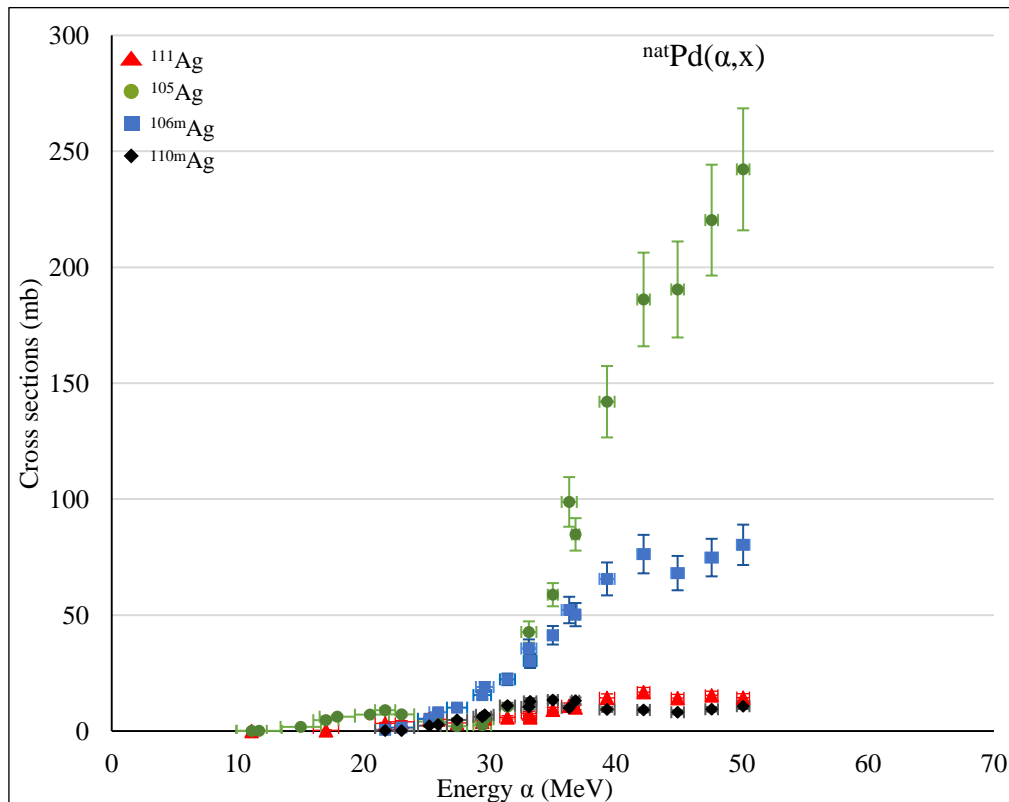


Figure 5: Cross section measurements of the $^{nat}\text{Pd}(\alpha,x)^{111}\text{Ag}, ^{105}\text{Ag}, ^{106\text{m}}\text{Ag}, ^{110\text{m}}\text{Ag}$ reaction.

□ Deuteron route :

- Maximum cross section of ${}^{\text{nat}}\text{Pd}(d,x){}^{111}\text{Ag}$ is at lower energy than with the alpha route : 10 MeV.
- The same contaminants : ${}^{105}, {}^{106\text{m}}, {}^{110\text{m}}\text{Ag}$
 - ↳ low purity and low specific activity
- A theoretical production could be between 16 and 6 MeV.
 - ↳ Target thickness : $\approx 225 \mu\text{m}$
 - ↳ Yield at EOB : $\approx 1.21 \text{ MBq}/\mu\text{Ah}$

□ Reactor route :

- Indirect production : ${}^{110}\text{Pd}(n,\gamma){}^{111}\text{Pd} (\beta^-) \rightarrow {}^{111}\text{Ag}$
- Contaminants : only short-lived silver isotopes
- High specific activity
- Production of 100 MBq of ${}^{111}\text{Ag}$ [1]:
 - ↳ neutron flux : $3 \times 10^{13} \text{ n cm}^{-2} \text{ s}^{-1}$
 - ↳ 26 h of irradiation

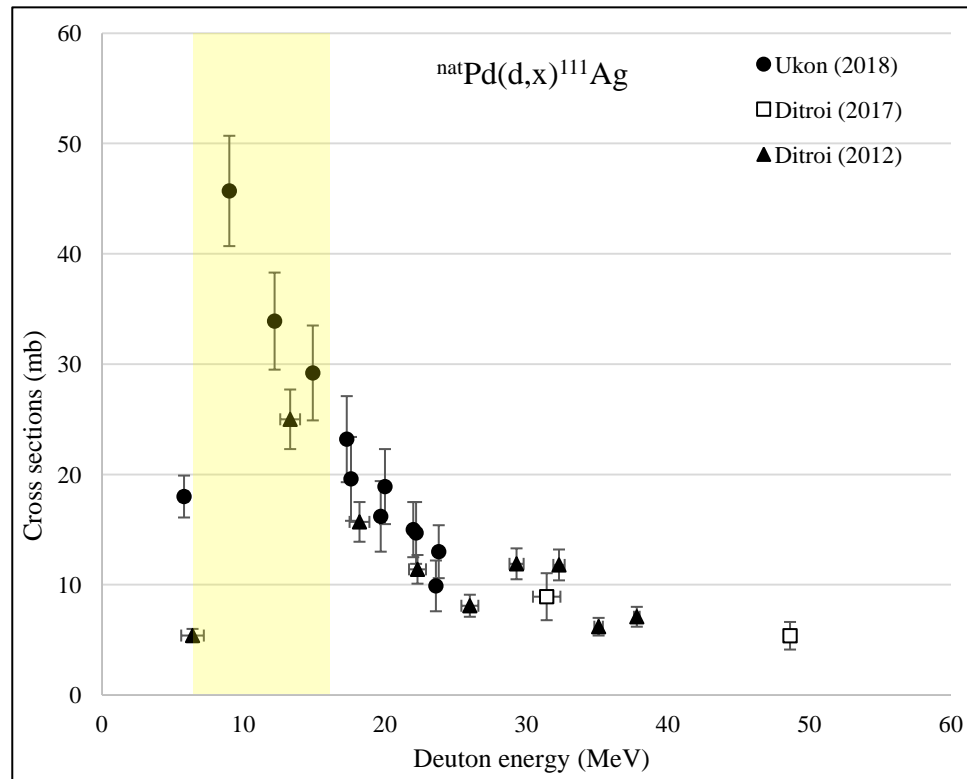


Figure 6: Cross section measurements of the ${}^{\text{nat}}\text{Pd}(d,x)$ reaction.

Results – Production routes

Production route	Characteristics of the irradiation	Estimated production (EOB)	Purity	Specific activity
$^{110}\text{Pd}(n, \gamma)^{111}\text{Pd}$ [1]	Flux : $3 \times 10^{13} \text{ n cm}^{-2} \text{ s}^{-1}$ $t_{\text{irradiation}}$: 26 h	3.85 MBq/h	Short-lived silver isotopes	High
$^{\text{nat}}\text{Pd}(d, x)$	E = 16 MeV Target thickness $\approx 225 \mu\text{m}$	1.21 MBq/ μAh	$^{105}, ^{106\text{m}}, ^{110\text{m}}\text{Ag}$	low
$^{\text{nat}}\text{Pd}(\alpha, x)$	E = 60 MeV Target thickness $\approx 255 \mu\text{m}$	0.29 MBq/ μAh	$^{105}, ^{106\text{m}}, ^{110\text{m}}\text{Ag}$	low

Less ^{111}Ag produced with the alpha route with a thicker target than with the deuteron route

Could be improved with a ^{110}Pd / ^{108}Pd enriched target

The most promising route seems to be the **neutron route.**

- ❑ New production cross section measurements of the reaction ${}^{\text{nat}}\text{Pd}(\alpha,x){}^{111}\text{Ag}$ have been performed at the GIP Arronax at high energy:
 - Good agreement with the data of Aikawa *et al.*, apart from the points of my first experiment.
 - The maximum cross section seem to be around 50 MeV

- ❑ Comparison with the most accessible production routes:
 - low purity and specific activity with the alpha and deuteron routes
 - Good purity and high specific activity with the neutron route ⇒ the most promising

- ❑ **Outlook:**
 - Measure again the peak area to understand the difference between the data from Aikawa my first experiment
 - Future experiments between 55 and 65 MeV to have experimental data after the peak
 - Extract the production cross sections of the silver contaminants (${}^{105}\text{Ag}$, ${}^{106\text{m}}\text{Ag}$ and ${}^{110\text{m}}\text{Ag}$)



THANK YOU FOR YOUR
ATTENTION



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