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Laurine Puren, Arnaud Guertin, Ferid Haddad, Vincent Métivier, Etienne
Nigron

► **To cite this version:**

Laurine Puren, Arnaud Guertin, Ferid Haddad, Vincent Métivier, Etienne Nigron. Production cross section measurements of the $\text{natNi}(d,x)\text{61Cu}$ reaction. 19th International Workshop on Targetry and Target Chemistry (WTCC19), Aug 2024, Heidelberg, Germany. hal-04771648

HAL Id: hal-04771648

<https://hal.science/hal-04771648v1>

Submitted on 7 Nov 2024

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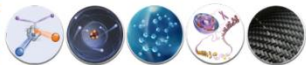
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PRISMA



Physics of Radiation InteractionS with Matter and Applications

WTTCC 19



Production cross section measurements of the ${}^{\text{nat}}\text{Ni}(d,x){}^{61}\text{Cu}$ reaction

L. Puren, A. Guertin, F. Haddad, V. Metivier, E. Nigron

Laurine PUREN

PhD Student
SUBATECH Laboratory (Nantes, France)

Context and motivations

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^{60}Cu 23.74 m $\epsilon \beta^+ = 100\%$	^{61}Cu 3.339 h $\epsilon \beta^+ = 100\%$	^{62}Cu 9.672 m $\epsilon \beta^+ = 100\%$	^{63}Cu STABLE 69.15 %	^{64}Cu 12.70 h $\epsilon \beta^+ = 61.5\%$ $\beta^- = 38.5\%$	^{65}Cu STABLE 30.85 %	^{66}Cu 5.09 min $\beta^- = 100\%$	^{67}Cu 61.81 h $\beta^- = 100\%$
Imaging			Imaging & Therapy		Therapy		

- ❑ ^{61}Cu can be used for PET applications:
 - ↳ Adequate half-life : $t_{1/2} = 3.339$ h
 - ↳ **β^+ decay** (61 %) : $E_{\text{moy}} = 524$ keV, $E_{\text{max}} = 1216$ keV
- ❑ Formation of true theranostic pairs : $^{61}\text{Cu} / ^{67}\text{Cu}$ and $^{64}\text{Cu} / ^{67}\text{Cu}$.
 - ^{61}Cu emits more positrons per decay than ^{64}Cu ($t_{1/2} = 12.701$ h, 17.9 % β^+).
 - ↳ Possibility to **reduce** the scanning time or possibility to **lessen** the dose delivered to the patients. [1]
 - Suitable to be linked with small molecules / peptides. [1]

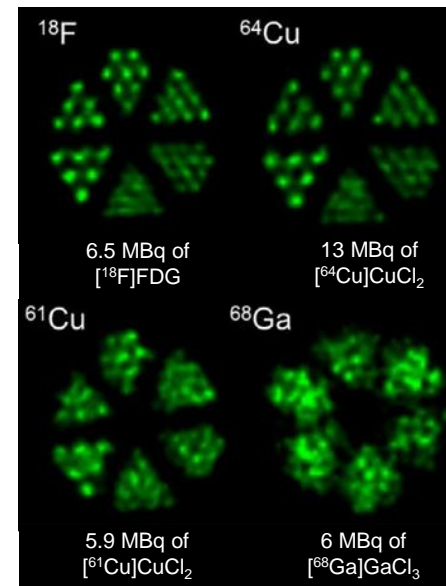


Figure 1: Visual comparison of different PET images of radionuclides using Jaszczak phantom (rods of 0.7 to 1.2 mm) obtained with a small-animal PET scanner within 30 minutes [1]

- Reassessment of the **relative intensity** of the γ -ray at **656.008 keV** to the one at **282.956 keV** of ^{61}Cu :

Gamma-ray (keV)	NDS (2015) [1] relative (<i>absolute</i>)	ENSDF (2020) [2] relative (<i>absolute</i>)	Bleuel et al. [3] relative (<i>absolute</i>)
282.956	100 % (12.2 ± 2.2 %)	100 % (12.7 ± 2.0 %)	100 % (12.2 ± 2.2 %)
373.050	17.6 ± 0.4 % (2.15 ± 0.05 %)	16.8 ± 0.4 % (2.14 ± 0.33 %)	16.87 ± 0.22 % (2.06 ± 0.03 %)
656.008	88.3 ± 1.5 % (10.77 ± 0.18 %)	82 ± 14 % (10.4 ± 1.6 %)	79.4 ± 1.0 % (9.69 ± 0.12 %)
1185.234	30.7 ± 0.6 % (3.75 ± 0.07 %)	28.6 ± 0.6 % (3.6 ± 0.6 %)	28.8 ± 0.4 % (3.51 ± 0.05 %)

Table 1: Absolute and relative intensities to the γ -ray at 282.956 keV of the main γ -rays of ^{61}Cu .

- $^{nat}\text{Ni}(d,x)^{61}\text{Cu}$ can be used as a monitor reaction [4] for **production cross section measurements** \Rightarrow impacts the determination of the production cross sections of other radioisotopes.



Evaluate the impact of this reassessment on the production cross section of $^{nat}\text{Ni}(d,x)^{61}\text{Cu}$

[1] K. Zuber *et al.*, 'Nuclear Data Sheets for A = 61', *Nuclear Data Sheets*, vol. 125, p. 1–200, Mar. 2015

[2] ENSDF document available from the National Nuclear Data Center ^{61}Cu EC Decay dataset

[3] D. L. Bleuel *et al.*, 'Precision measurement of relative γ -ray intensities from the decay of ^{61}Cu ', *Applied Radiation and Isotopes*, vol. 170, 109625, Apr. 2021

[4] A. Hermanne *et al.*, 'Reference Cross Sections for Charged-particle Monitor Reactions', *Nuclear Data Sheets*, vol. 148, p. 338–382, Feb. 2018

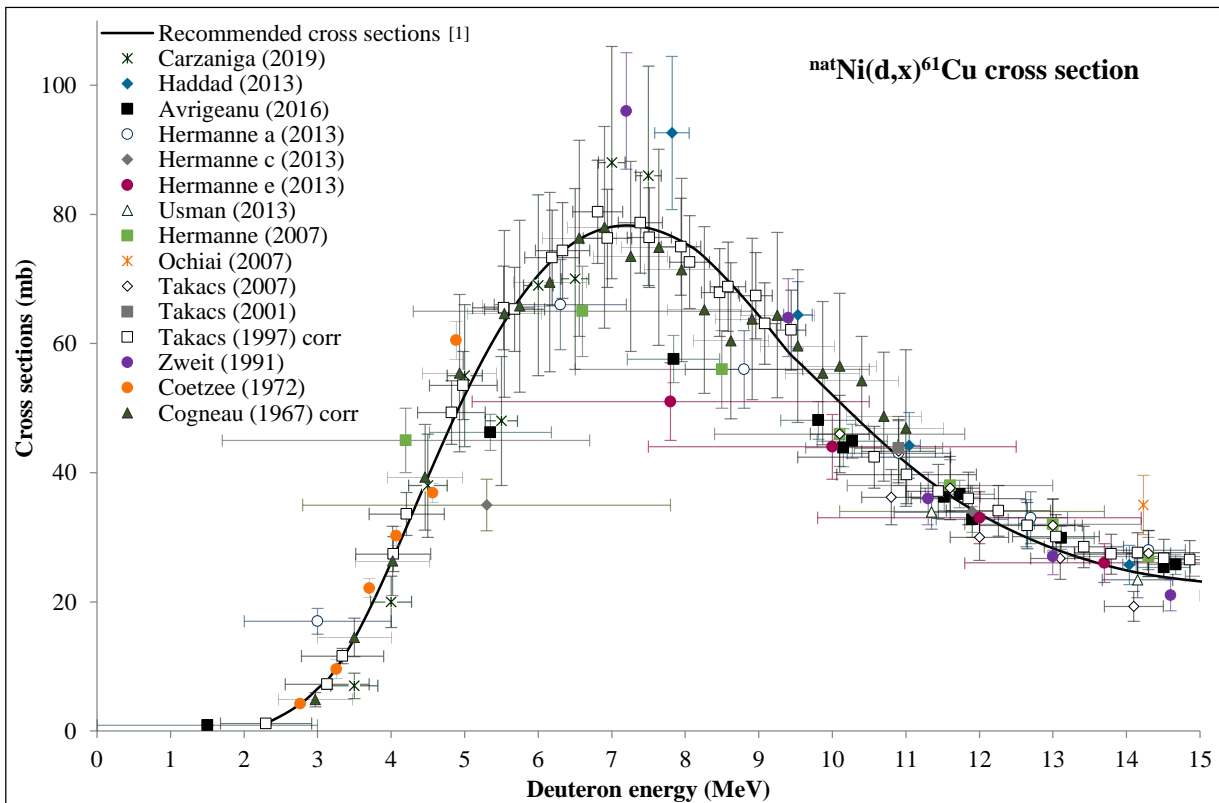


Figure 2: Experimental production cross sections of the ${}^{\text{nat}}\text{Ni}(d,x){}^{61}\text{Cu}$ reaction.

15 different data sets \Rightarrow significant disparities between the data.

\downarrow for example : the peak value varies between **51 mb** and **96 mb**.

Motivations :

1. New measurements at low energy of the ${}^{\text{nat}}\text{Ni}(d,x){}^{61}\text{Cu}$ cross sections.
2. Comparison of the experimental data with the literature and the recommended cross sections.
3. Assess the impact of the re-evaluation of the relative intensities of the γ -rays of ${}^{61}\text{Cu}$ on the measurements and the literature.

Method : Stacked-foils technique

- ❑ 3 campaigns of measurements accomplished at the **GIP Arronax**:
 - Deuteron beam of 16 MeV
 - 1 hour irradiation at 100 nA of intensity
 - Monitor reactions : ${}^{\text{nat}}\text{Ti}(d,x){}^{48}\text{V}$, ${}^{\text{nat}}\text{Ti}(d,x){}^{46}\text{Sc}$ (${}^{\text{nat}}\text{Ni}(d,x){}^{56}\text{Co}$, ${}^{\text{nat}}\text{Ni}(d,x){}^{58}\text{Co}$).
- ❑ γ -rays of ${}^{61}\text{Cu}$ used to extract its activity with a HPGe:

Gamma-ray (keV)	ENSDF 2020
282.956	$12.7 \pm 2 \%$
373.050	$2.14 \pm 0.33 \%$
588.605	$1.17 \pm 0.18 \%$
656.008	$10.4 \pm 1.6 \%$
908.631	$1.09 \pm 0.17 \%$
1185.234	$3.6 \pm 0.6 \%$

Table 2: Absolute intensity of the γ -rays of ${}^{61}\text{Cu}$

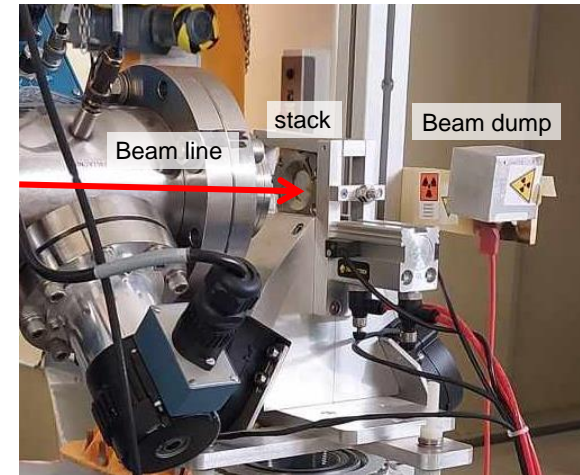
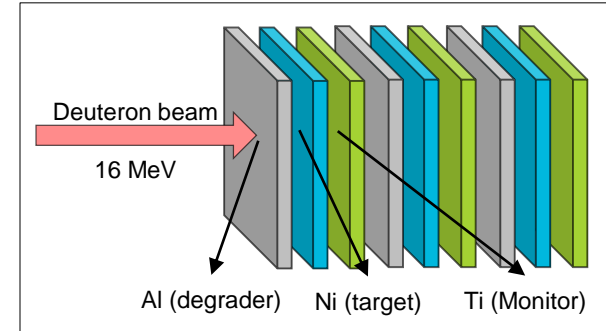


Figure 3: Schematical representation of the stack and setup of the experiment

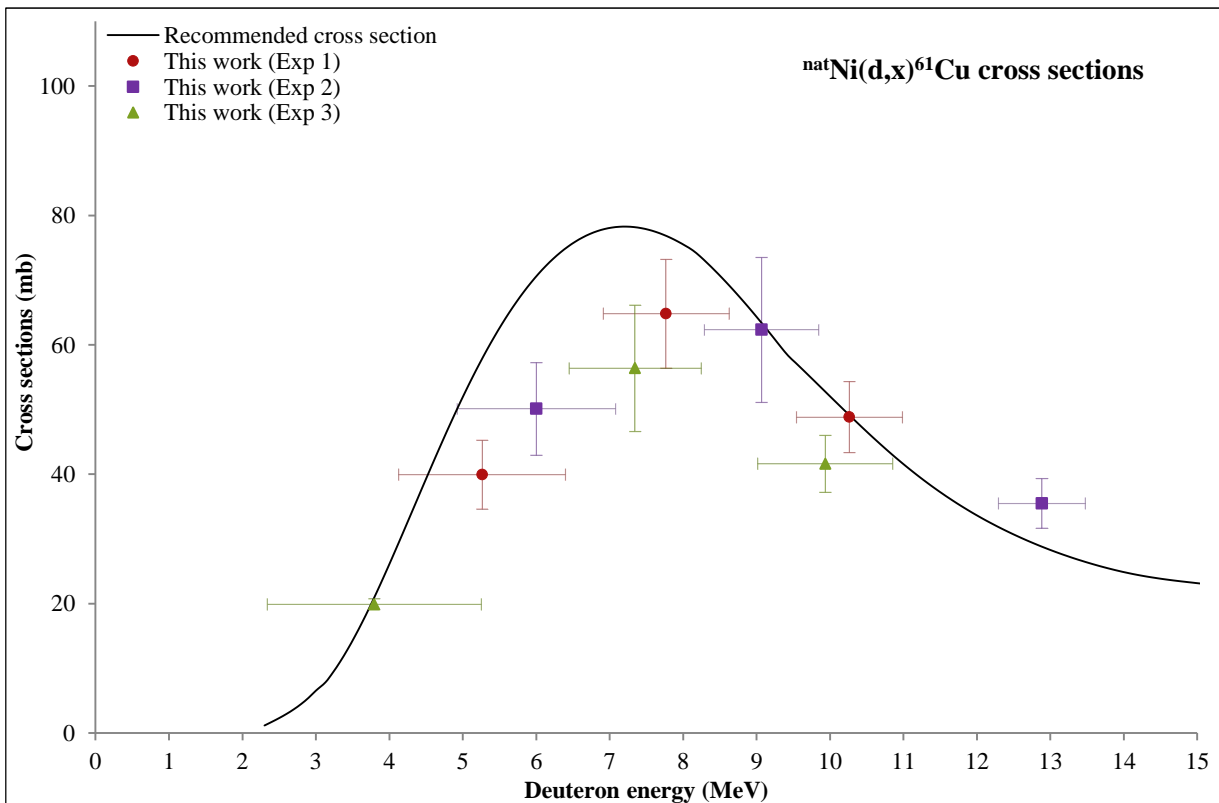


Figure 4: Experimental production cross sections of the $^{nat}\text{Ni}(d,x)^{61}\text{Cu}$ reaction.

Observations:

- 9 measurements done in 3 different experiments \Rightarrow consistency.
- The peak of the recommended cross sections is **20 % greater** than the one measured.
- the maximum we measure is slightly **shifted to higher energy** compared to the recommended curve.

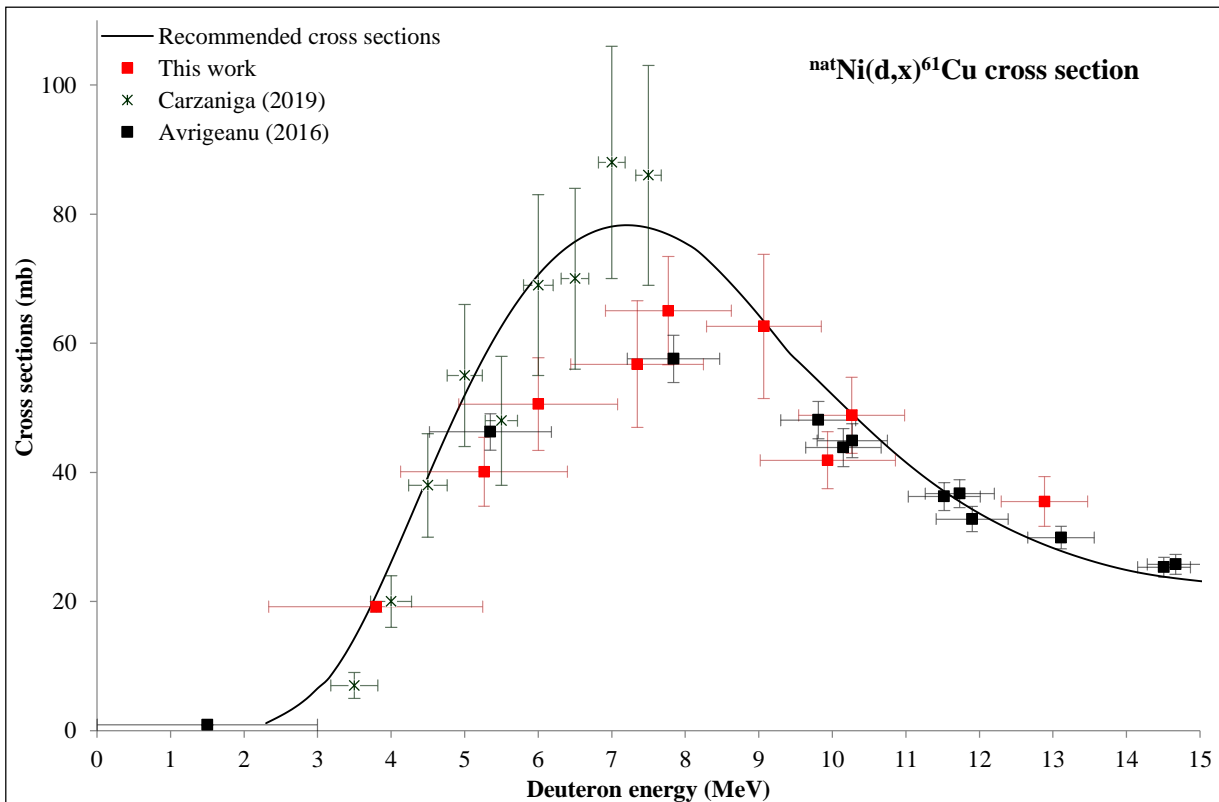


Figure 4: Experimental production cross sections of the ${}^{\text{nat}}\text{Ni}(d,x){}^{61}\text{Cu}$ reaction.

Observations:

- 9 measurements done in 3 different experiments \Rightarrow consistency.
- The peak of the recommended cross sections is **20 % greater** than the one measured.
- the maximum we measure is slightly **shifted to higher energy** compared to the recommended curve.
- Our data are consistent with the experimental data of Avrigeanu *et al.*
- With Carzaniga *et al.* \Rightarrow same observations as with the recommended cross sections

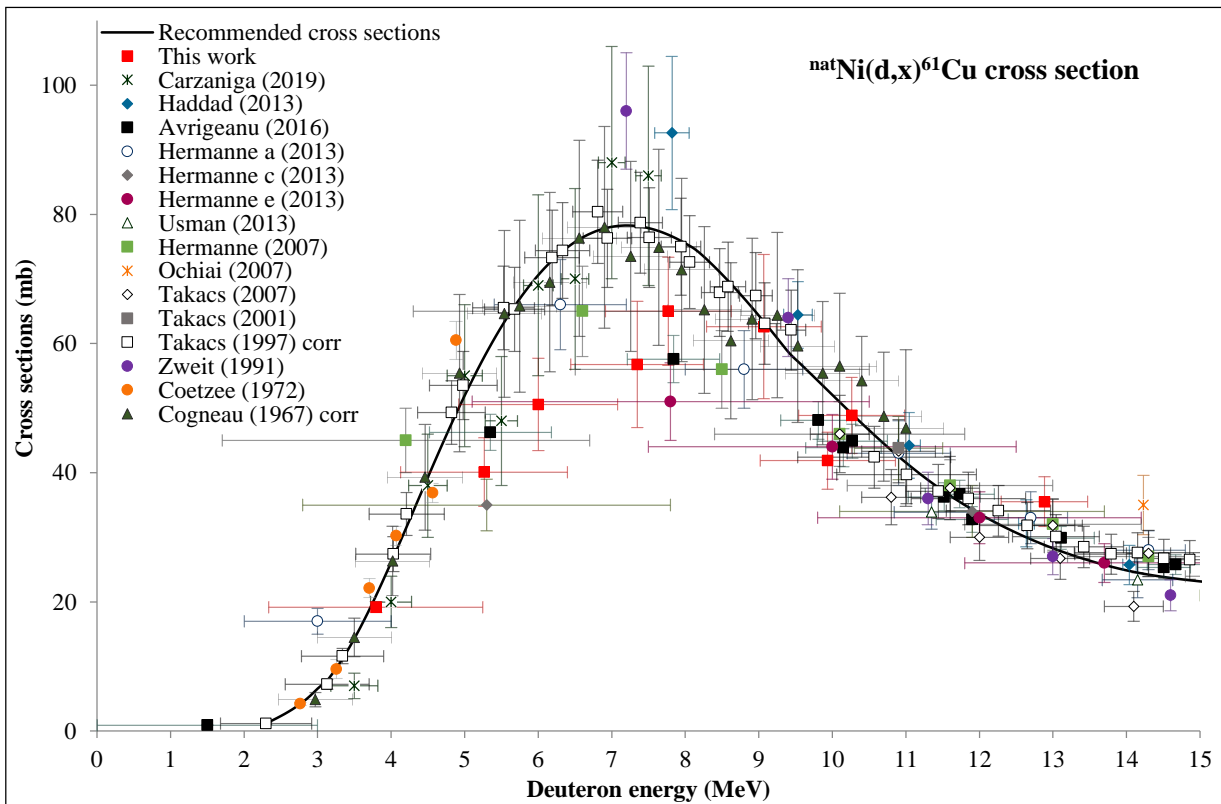


Figure 4: Experimental production cross sections of the $^{nat}\text{Ni}(d,x)^{61}\text{Cu}$ reaction.

Observations:

- The **low** and **high energy** parts are in agreement with existing data and with the recommended cross sections.
- Large discrepancy around the maximum from the 15 different data sets available.
 - ↳ Investigation will be pursued to figure out what is going on.

New measurements to be done with a farraday cup coupled with an electron repeller to lower the uncertainties.

Results – Impact of the reassessment

- 5 different databases have been used to get the ^{61}Cu γ -ray intensities:

	282.956 keV	656.008 keV	1185.234 keV	Authors
Table of Isotopes (1978)	?	?	?	Zweit (1991)
Table of Radioactive Isotopes (1986)	12.5 %	10.66 %	?	Takacs (2001), Takacs (1997)
LUND LBNL	12.2 ± 0.002 %	10.77 ± 0.009 %	3.75 ± 0.015 %	Avriganu (2016), Haddad (2013), Takacs (2007)
NDS (2015)	12.2 ± 2.2 %	10.77 ± 0.18 %	3.75 ± 0.07 %	Usman (2016), Hermanne a,c,e (2013) Hermanne (2007)
ENSDF (2020)	12.7 ± 2 %	10.4 ± 1.6 %	3.6 ± 0.6 %	My work

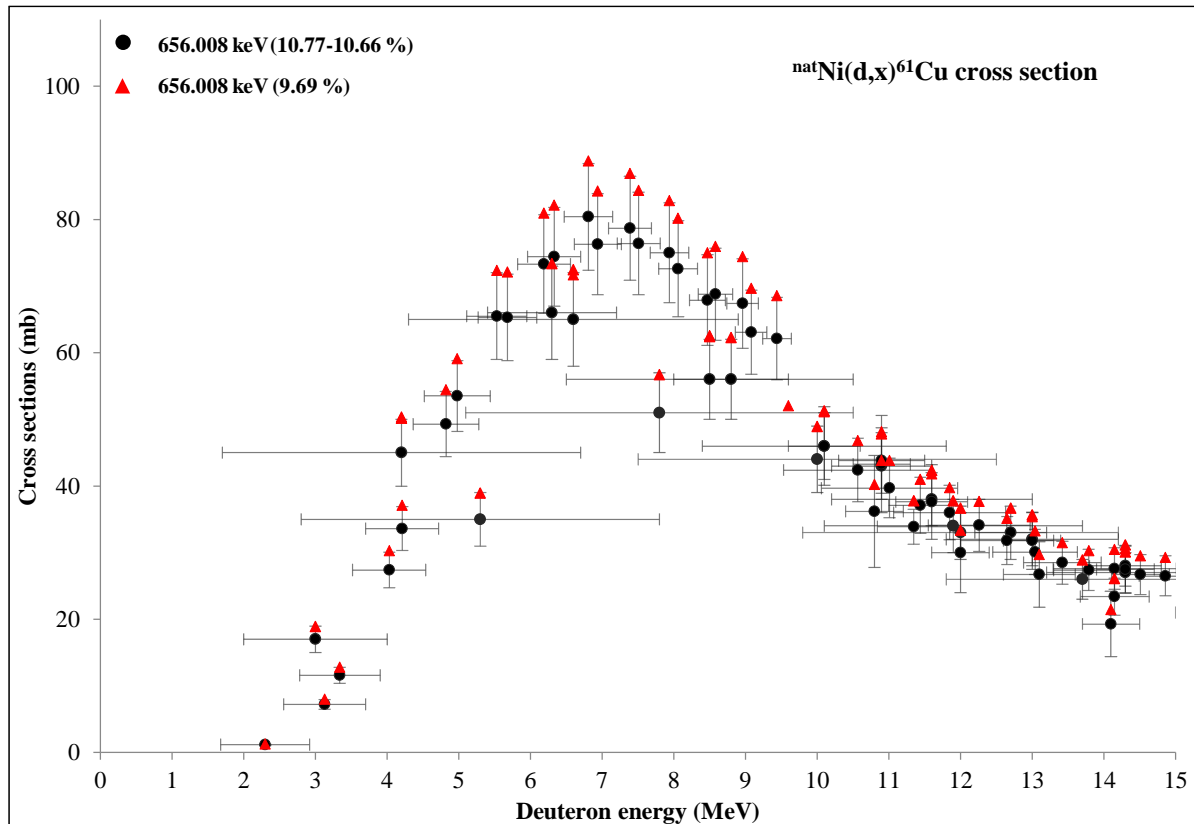
No database indicated for Carzaniga (2019), Ochiai (2007) and Coetzee (1972)

Table 3 : Intensity of the most intense gamma of ^{61}Cu depending on the database used.

- The data sets use **different γ -rays** to obtain the ^{61}Cu activities:
 - The γ -ray at 656 keV
 - The γ -ray at 283 keV
 - The γ -rays at 283 keV, 656 keV and 1185 keV

Results – Impact of the reassessment

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□ Half of the experimental data relies only on the **656 keV γ -ray** to extract the ${}^{61}\text{Cu}$ activities.

↳ around **10 %** of difference (NDS 2015, LUND LBNL etc.) \Rightarrow within the uncertainties

Figure 4 : Experimental data of the production cross sections of ${}^{nat}\text{Ni}(d,x){}^{61}\text{Cu}$ using the 656.008 keV γ -ray

Results – Impact of the reassessment

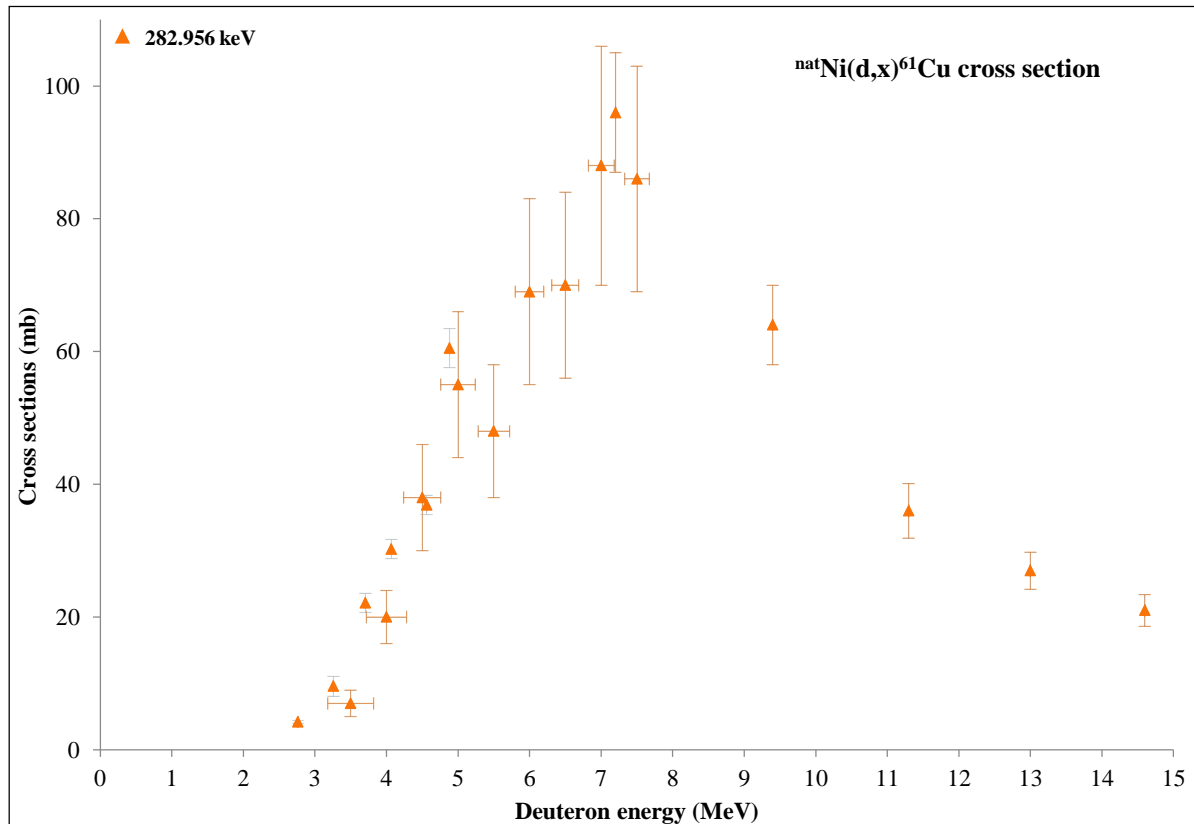


Figure 5 : Experimental data of the production cross sections of $^{nat}\text{Ni}(d,x)^{61}\text{Cu}$ using the 282.956 keV γ -ray

□ Half of the experimental data relies only on the **656 keV γ -ray** to extract the ^{61}Cu activities.

↳ around **10 %** of difference (NDS 2015, LUND LBNL etc.) \Rightarrow within the uncertainties

□ 3 data use the **283 keV γ -ray** : no database indicated for the intensity chosen.

→ No changes with NDS 2015, LUND LBNL

→ around **2 %** of difference (Table of Radioactive Isotopes)

RESULTS – Impact of the reassessment

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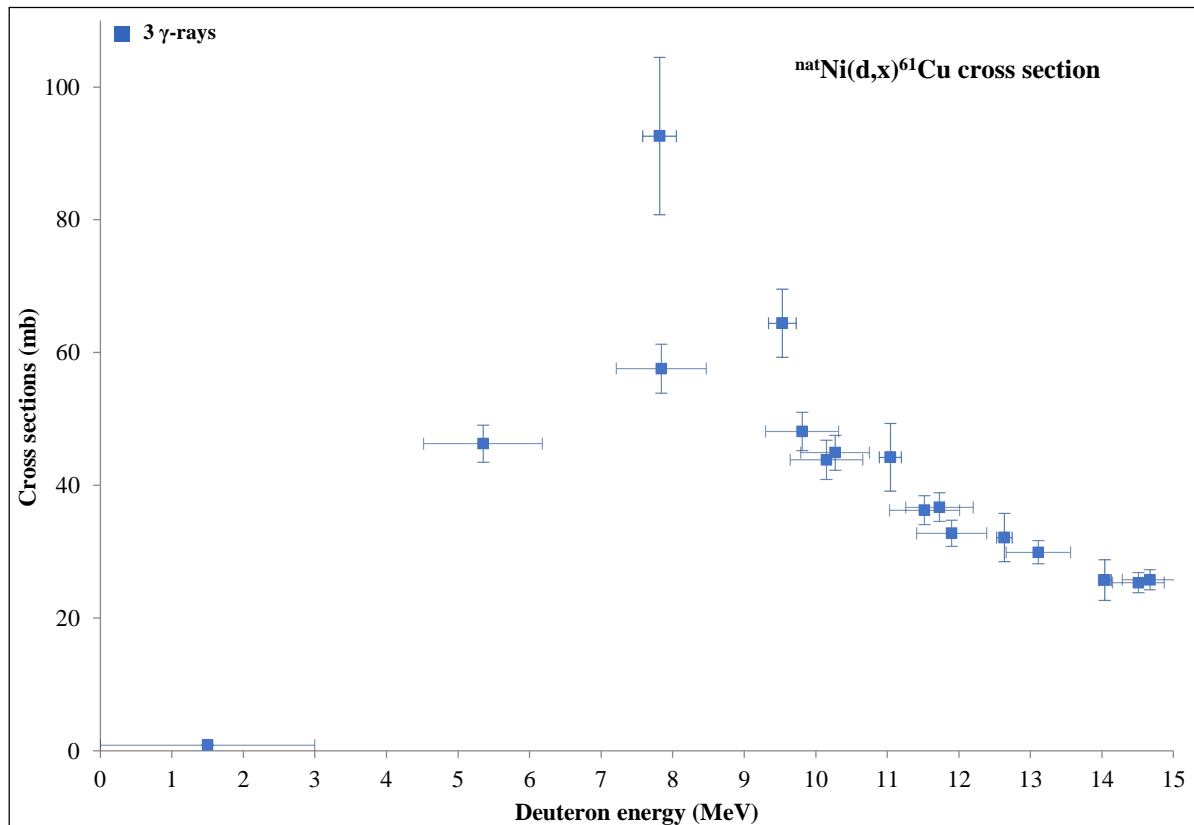


Figure 6 : Experimental data of the production cross sections of $^{nat}\text{Ni}(d,x)^{61}\text{Cu}$ using the 3 main γ -rays of ^{61}Cu .

- Half of the experimental data relies only on the **656 keV γ -ray** to extract the ^{61}Cu activities.
 - ↳ around **10 %** of difference (NDS 2015, LUND LBNL etc.) \Rightarrow within the uncertainties
- 3 data use the **283 keV γ -ray** : no database indicated for the intensity chosen.
 - \rightarrow No changes with NDS 2015, LUND LBNL
 - \rightarrow around **2 %** of difference (Table of Radioactive Isotopes)
- 2 data sets use **3 γ -rays** (283, 656, 1185) : not possible to evaluate.

RESULTS – Impact of the reassessment

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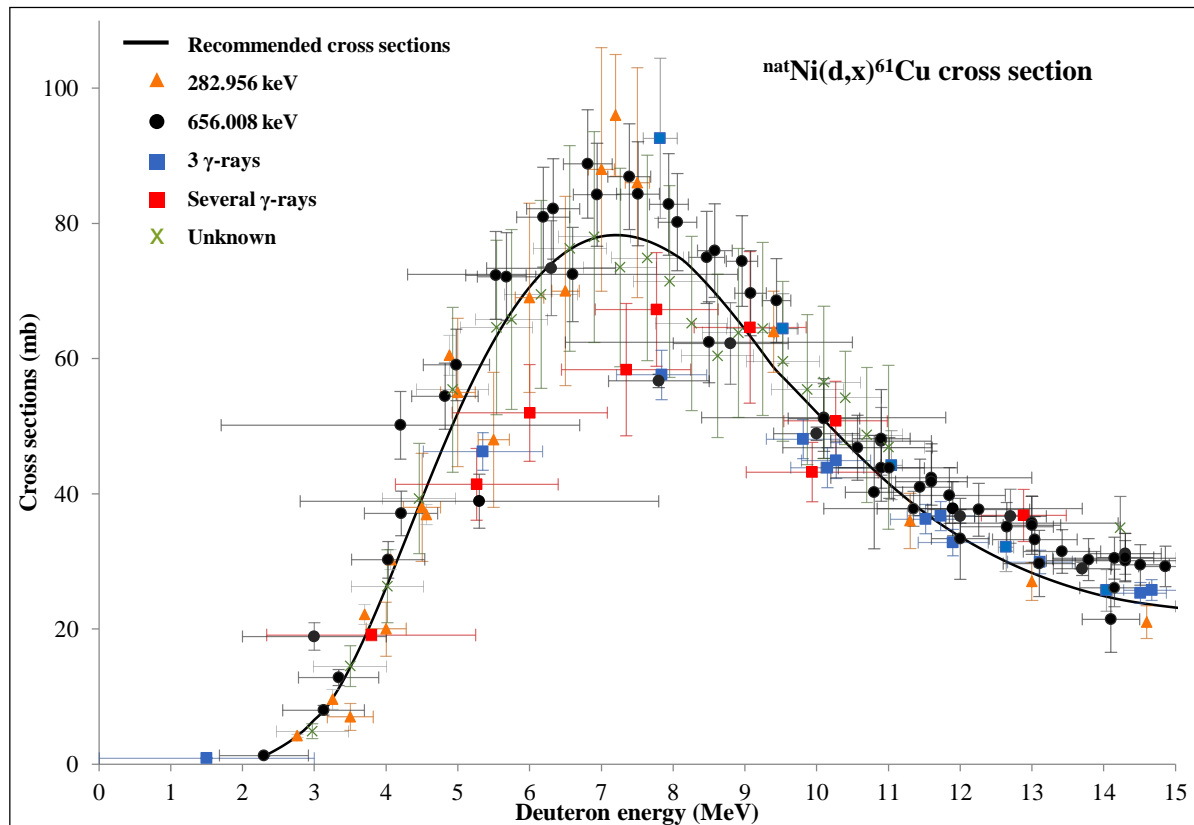


Figure 7 : Experimental production cross sections of the $^{nat}\text{Ni}(d,x)^{61}\text{Cu}$ reaction with the reassessed values.

- Half of the experimental data relies only on the **656 keV γ -ray** to extract the ^{61}Cu activities.

↳ around **10 %** of difference (NDS 2015, LUND LBNL etc.) \Rightarrow within the uncertainties

- 3 data use the **283 keV γ -ray** : no database indicated for the intensity chosen.

\rightarrow No changes with NDS 2015, LUND LBNL

\rightarrow around **2 %** of difference (Table of Radioactive Isotopes)

- 2 data sets use **3 γ -rays** (283, 656, 1185) : not possible to evaluate.

- Using **multiple γ -rays** : around **3.2 %** of difference in my case.

All of the corrections are within the uncertainties of each data sets

- ❑ New production cross section measurements of the reaction ${}^{\text{nat}}\text{Ni}(d,x){}^{61}\text{Cu}$ have been performed at the GIP Arronax at low energy :
 - Good agreement with the data of Avrigeanu *et al.* and at low and high energy with the literature and the recommended cross sections.
 - There's a **slight shift** in **energy** at the peak and its value is **20 % lower** than the recommended value.
 - Investigation to be pursued to figure out what is going on at the maximum.

- ❑ With the reassessment of the intensities of the γ -ray of ${}^{61}\text{Cu}$ proposed by Bleuel *et al.* \Rightarrow some **significant changes** in the experimental data from the literature using the **656 keV γ -ray** but they remain within the **uncertainties**.

Outlook : New measurements with a farraday cup coupled with an electron repeller to have an absolute measure of the flux of the beam.

**THANK YOU FOR YOUR
ATTENTION**

Laurine Puren