

Neutron inelastic cross section measurements for natural titanium

A. Olacel¹, F. Belloni.², C. Borcea¹, M. Boromiza^{1,3}, Ph. Dessagne⁴, G. Henning⁴,
M. Kerveno⁴, A. Negret¹, M. Nyman², E. Pirovano², A. J. M. Plompen²

¹Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH), Magurele, Romania

²European Commission, Joint Research Center, Geel, Belgium

³University of Bucharest, Faculty of Physics, Bucharest-Magurele, Romania

⁴Unistra, CNRS, IPHC, Strasbourg, France

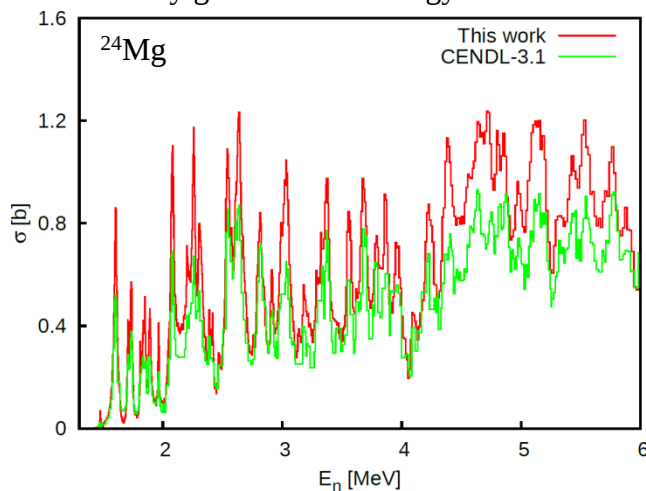
1. General motivation



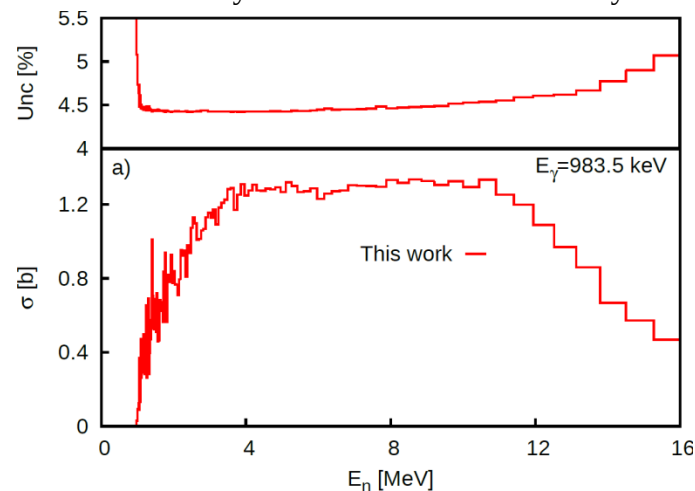
- Key data for the development of the new generation of nuclear reactors and other applications/fields of physics.
- Useful tool for a better understanding of nuclear reaction mechanisms.
- In particular, the first transition in ^{48}Ti ($E_\gamma=983.5$ keV) is investigated in order to establish a γ -ray reference cross section for neutron-induced reactions.

Quality of the results

- Very good neutron energy resolution



- Very low total relative uncertainty



2. Experimental setup



GELINA - Geel Electron LINear Accelerator

- Linear electron accelerator ($E_e \approx 70 - 140$ MeV, $\Delta t < 1$ ns)
- Neutrons produced in the U target by photon induced reactions
- Multiuser facility
- Flight paths from 8 m up to 400 m in length
- The inelastic scattering experiment was done at FP3, 200 m measurement station.



GAINS - Gamma Array for Inelastic Neutron Scattering

- 12 HPGe detectors @ 110° , 150° and 125°
- Relative efficiency: 100%
- FWHM ≈ 2.8 keV for the 1332 keV of ^{60}Co
- Fission chamber to monitor the neutron flux
- Digital acquisition
(12 bit amplitude resolution, 440 MS/s)
- Time of flight technique:
 - n time of flight $\rightarrow E_n$
 - pulse amplitude $\rightarrow E_\gamma$



Talk C. Borcea – I279 (Wednesday, 14:00, Fast Neutrons I)

1. Experimental particularities

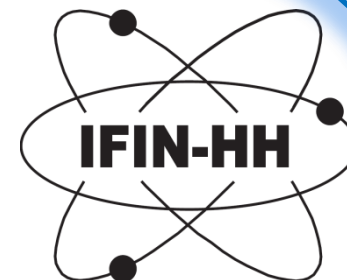


- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- E_n up to 20 MeV
- **Sample characteristics:**



- Natural sample with five stable isotopes;
- $\varnothing = 8.000$ cm;
- thickness: 0.45 cm.

1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- E_n up to 20 MeV
- **Sample characteristics:**



- Natural sample with five stable isotopes;
- $\varnothing = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- E_n up to 20 MeV
- **Sample characteristics:**



- Natural sample with five stable isotopes;
- $\varnothing = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- E_n up to 20 MeV
- **Sample characteristics:**



- Natural sample with five stable isotopes;
- $\varnothing = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm ²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

+

1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- **E_n up to 20 MeV**
- Sample characteristics:



- Natural sample with five stable isotopes;
- $\varnothing = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm ²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

+

Reaction	$^{47}\text{Ti}(n, 2n)^{46}\text{Ti}$	$^{48}\text{Ti}(n, 2n)^{47}\text{Ti}$	$^{49}\text{Ti}(n, 2n)^{48}\text{Ti}$	$^{50}\text{Ti}(n, 2n)^{49}\text{Ti}$
Q value (MeV)	9.0710(5)	11.8710(5)	8.3100(5)	11.1600(5)

1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- **E_n up to 20 MeV**
- Sample characteristics:



- Natural sample with five stable isotopes;
- $\varnothing = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm ²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

+

Reaction	$^{47}\text{Ti}(n, 2n)^{46}\text{Ti}$	$^{48}\text{Ti}(n, 2n)^{47}\text{Ti}$	$^{49}\text{Ti}(n, 2n)^{48}\text{Ti}$	$^{50}\text{Ti}(n, 2n)^{49}\text{Ti}$
Q value (MeV)	9.0710(5)	11.8710(5)	8.3100(5)	11.1600(5)



1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- **E_n up to 20 MeV**
- Sample characteristics:



- Natural sample with five stable isotopes;
- $\emptyset = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm ²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

+

Reaction	$^{47}\text{Ti}(n, 2n)^{46}\text{Ti}$	$^{48}\text{Ti}(n, 2n)^{47}\text{Ti}$	$^{49}\text{Ti}(n, 2n)^{48}\text{Ti}$	$^{50}\text{Ti}(n, 2n)^{49}\text{Ti}$
Q value (MeV)	9.0710(5)	11.8710(5)	8.3100(5)	11.1600(5)



(n, n') and $(n, 2n)$ reaction contributions in the identified peaks

1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- **E_n up to 20 MeV**
- Sample characteristics:



- Natural sample with five stable isotopes;
- $\emptyset = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm ²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

+

Reaction	$^{47}\text{Ti}(n, 2n)^{46}\text{Ti}$	$^{48}\text{Ti}(n, 2n)^{47}\text{Ti}$	$^{49}\text{Ti}(n, 2n)^{48}\text{Ti}$	$^{50}\text{Ti}(n, 2n)^{49}\text{Ti}$
Q value (MeV)	9.0710(5)	11.8710(5)	8.3100(5)	11.1600(5)



$$E_\gamma = 983.5 \text{ keV } (^{48}\text{Ti})$$

1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- **E_n up to 20 MeV**
- Sample characteristics:



- Natural sample with five stable isotopes;
- $\emptyset = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm ²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

+

Reaction	$^{47}\text{Ti}(n, 2n)^{46}\text{Ti}$	$^{48}\text{Ti}(n, 2n)^{47}\text{Ti}$	$^{49}\text{Ti}(n, 2n)^{48}\text{Ti}$	$^{50}\text{Ti}(n, 2n)^{49}\text{Ti}$
Q value (MeV)	9.0710(5)	11.8710(5)	8.3100(5)	11.1600(5)



$E_\gamma = 983.5$ keV (^{48}Ti)

Contributions



1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- **E_n up to 20 MeV**
- Sample characteristics:



- Natural sample with five stable isotopes;
- $\emptyset = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm ²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

+

Reaction	$^{47}\text{Ti}(n, 2n)^{46}\text{Ti}$	$^{48}\text{Ti}(n, 2n)^{47}\text{Ti}$	$^{49}\text{Ti}(n, 2n)^{48}\text{Ti}$	$^{50}\text{Ti}(n, 2n)^{49}\text{Ti}$
Q value (MeV)	9.0710(5)	11.8710(5)	8.3100(5)	11.1600(5)



$E_\gamma = 983.5$ keV (^{48}Ti)

Contributions

→ $^{48}_{22}\text{Ti}(n, n'\gamma)^{48}_{22}\text{Ti}$

1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- **E_n up to 20 MeV**
- Sample characteristics:



- Natural sample with five stable isotopes;
- $\emptyset = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm ²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

+

Reaction	$^{47}\text{Ti}(n, 2n)^{46}\text{Ti}$	$^{48}\text{Ti}(n, 2n)^{47}\text{Ti}$	$^{49}\text{Ti}(n, 2n)^{48}\text{Ti}$	$^{50}\text{Ti}(n, 2n)^{49}\text{Ti}$
Q value (MeV)	9.0710(5)	11.8710(5)	8.3100(5)	11.1600(5)



$E_\gamma = 983.5$ keV (^{48}Ti)
 Contributions
→
 $^{48}_{22}\text{Ti}(n, n'\gamma)^{48}_{22}\text{Ti}$ +

1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- **E_n up to 20 MeV**
- Sample characteristics:



- Natural sample with five stable isotopes;
- $\emptyset = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm ²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

+

Reaction	$^{47}\text{Ti}(n, 2n)^{46}\text{Ti}$	$^{48}\text{Ti}(n, 2n)^{47}\text{Ti}$	$^{49}\text{Ti}(n, 2n)^{48}\text{Ti}$	$^{50}\text{Ti}(n, 2n)^{49}\text{Ti}$
Q value (MeV)	9.0710(5)	11.8710(5)	8.3100(5)	11.1600(5)



$E_\gamma = 983.5$ keV (^{48}Ti)
 Contributions
→
 $^{48}_{22}\text{Ti}(n, n'\gamma)^{48}_{22}\text{Ti}$
+
 $^{49}_{22}\text{Ti}(n, 2n\gamma)^{48}_{22}\text{Ti}$

1. Experimental particularities



- GELINA running at 800 Hz;
- GAINS consisted of 10 HPGe detectors (4 x 110°, 4 x 150°, 2 x 125°);
- Reaction: $^{nat}\text{Ti}(n, n'\gamma)$
- **E_n up to 20 MeV**
- Sample characteristics:



- Natural sample with five stable isotopes;
- $\emptyset = 8.000$ cm;
- thickness: 0.45 cm.

The most important particularity!!!

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm ²)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

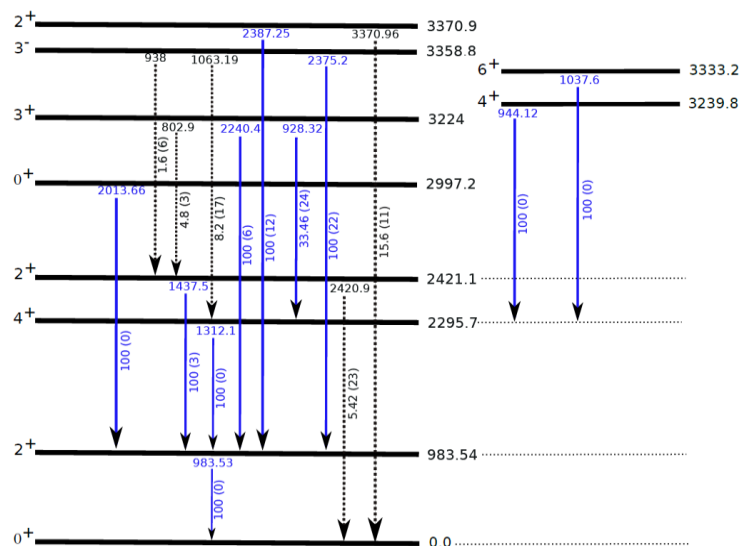
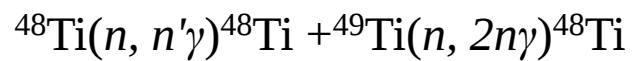
+

Reaction	$^{47}\text{Ti}(n, 2n)^{46}\text{Ti}$	$^{48}\text{Ti}(n, 2n)^{47}\text{Ti}$	$^{49}\text{Ti}(n, 2n)^{48}\text{Ti}$	$^{50}\text{Ti}(n, 2n)^{49}\text{Ti}$
Q value (MeV)	9.0710(5)	11.8710(5)	8.3100(5)	11.1600(5)

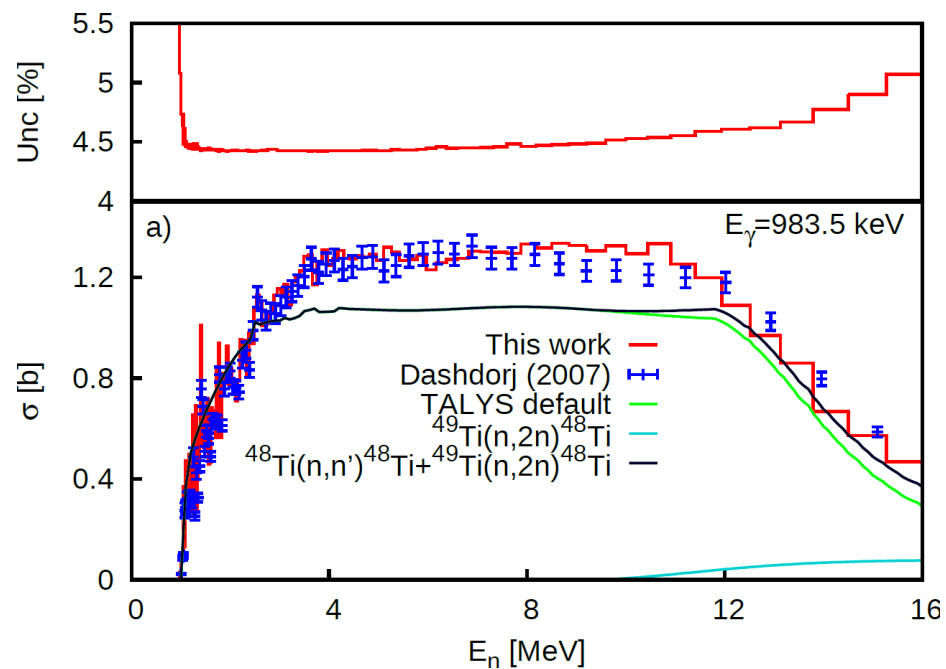
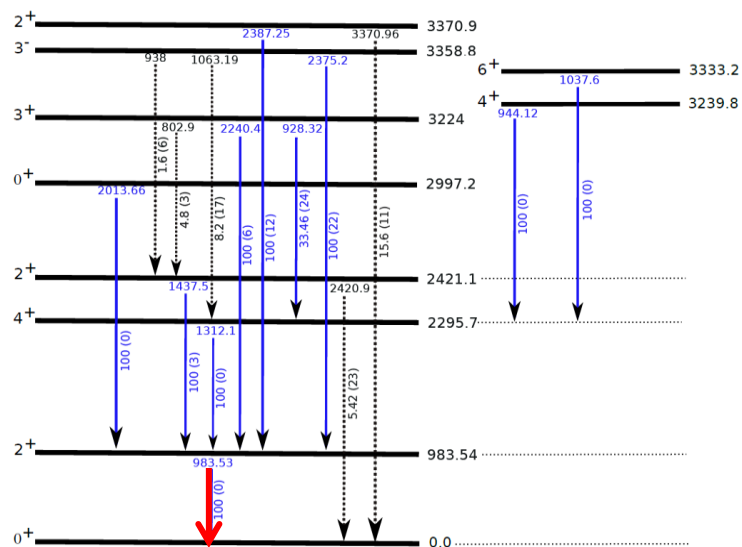
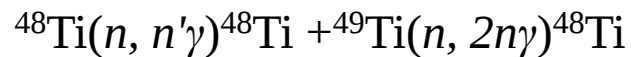


$$E_\gamma = 983.5 \text{ keV } (^{48}\text{Ti}) \xrightarrow{\text{Contributions}} \boxed{{}^{48}_{22}\text{Ti}(n, n'\gamma){}^{48}_{22}\text{Ti}} + {}^{49}_{22}\text{Ti}(n, 2n\gamma){}^{48}_{22}\text{Ti}$$

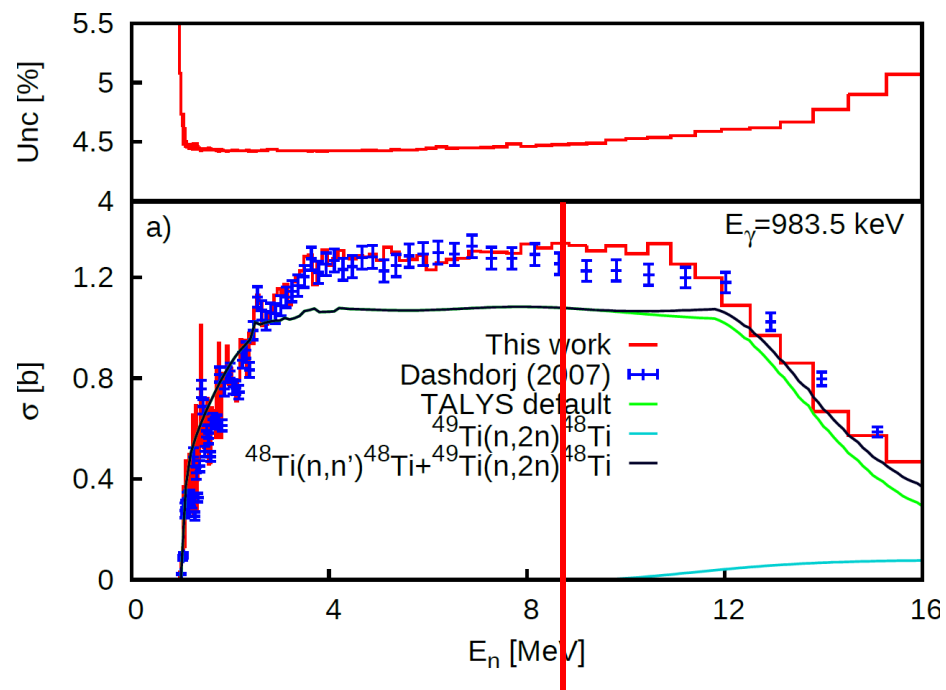
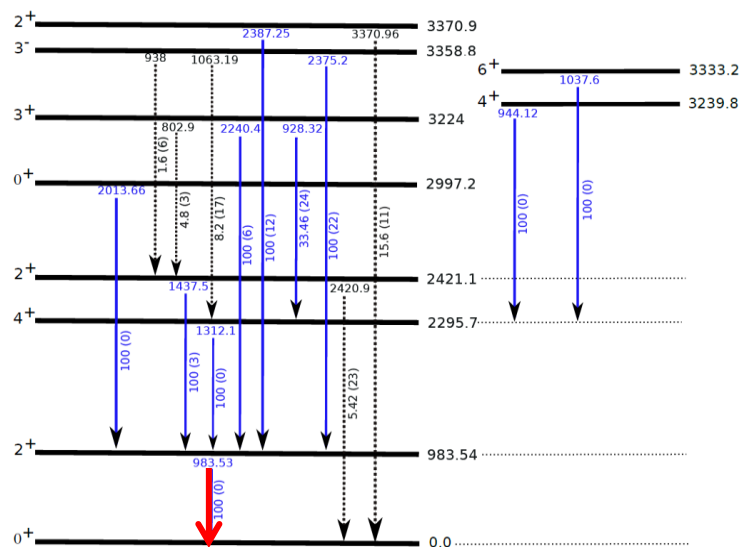
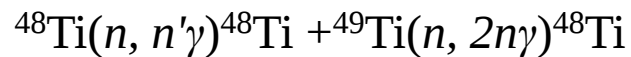
Results



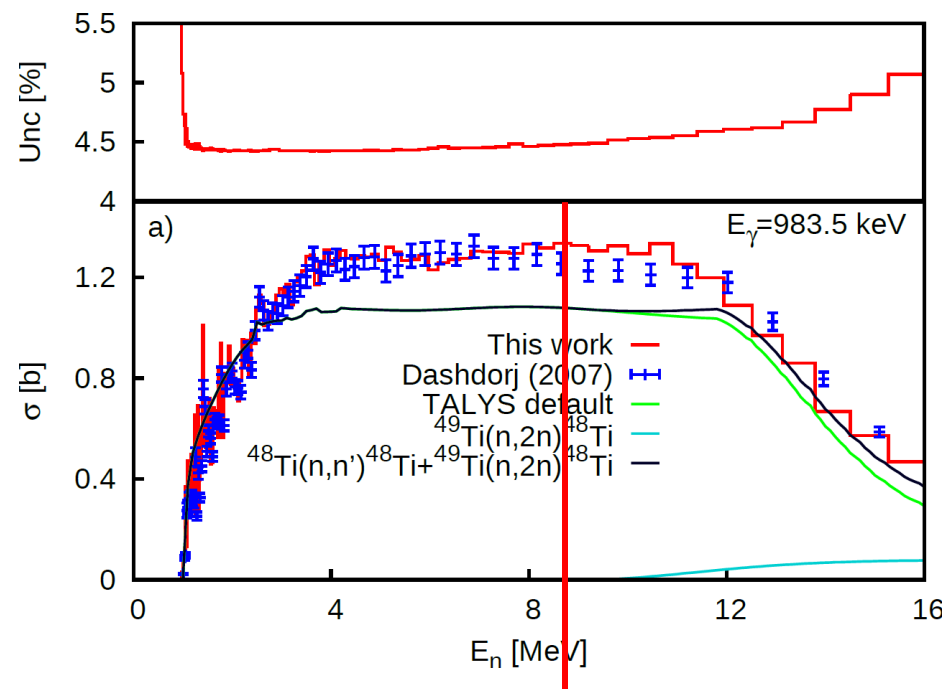
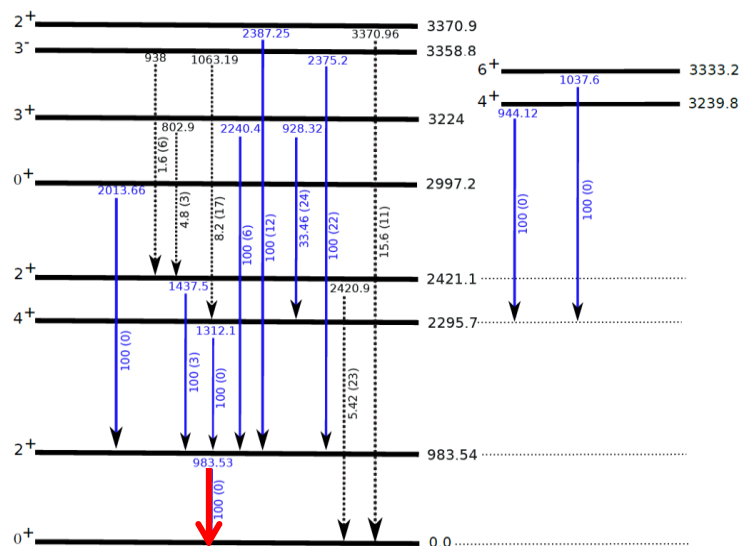
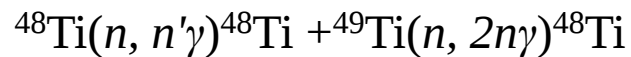
Results



Results

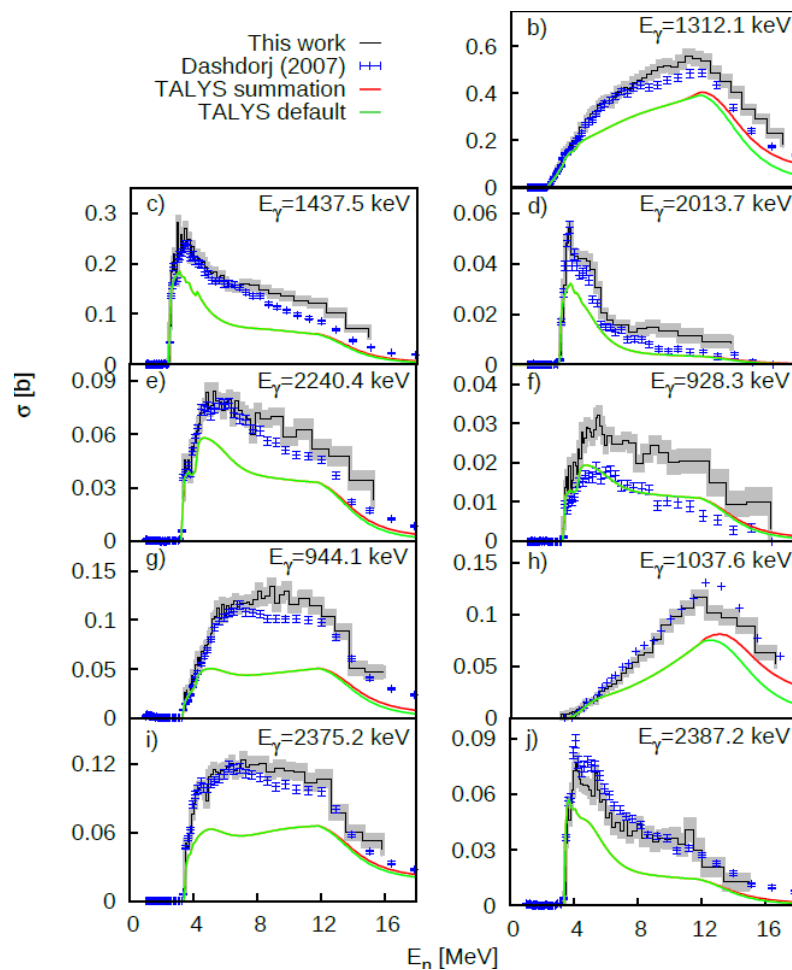
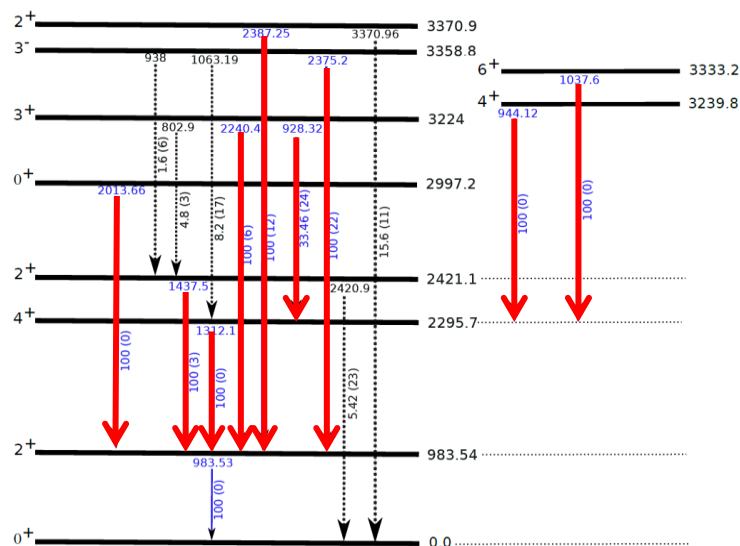
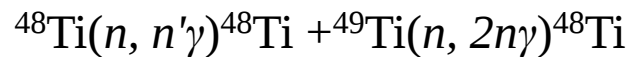


Results

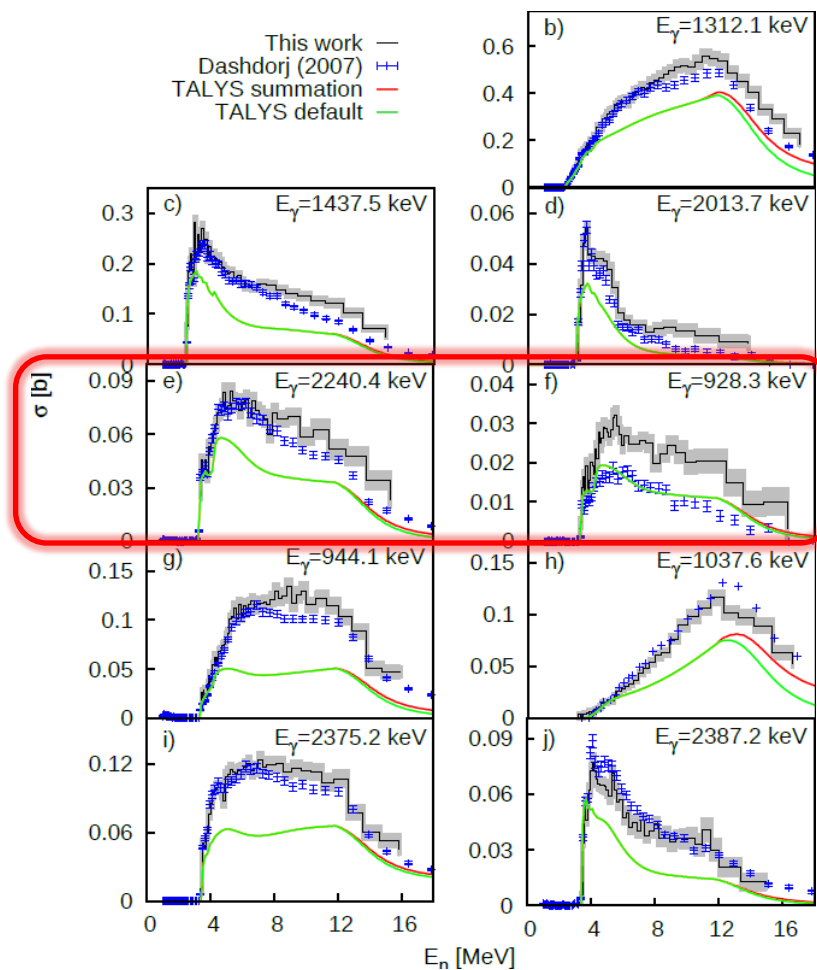
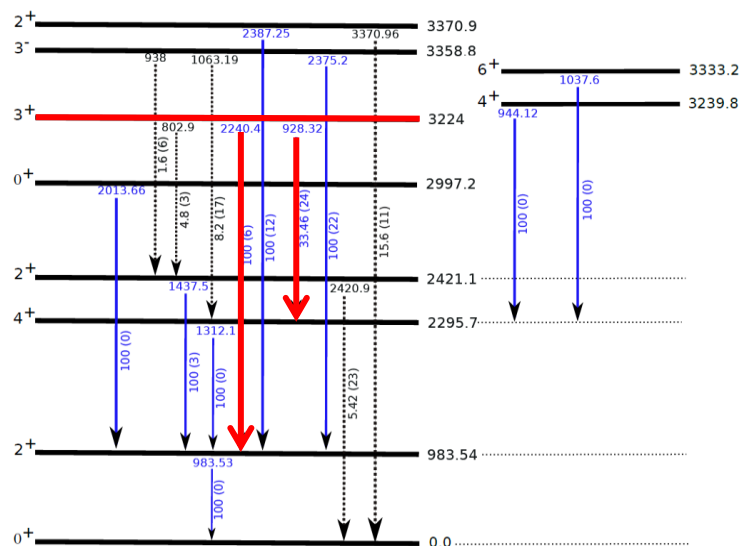
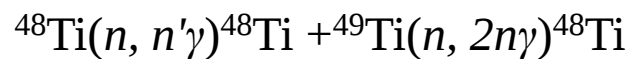


Q value $^{49}\text{Ti}(n, 2n)^{48}\text{Ti}$ reaction + $E_{\text{threshold}}$ (983.5 keV level) ≈ 9 MeV

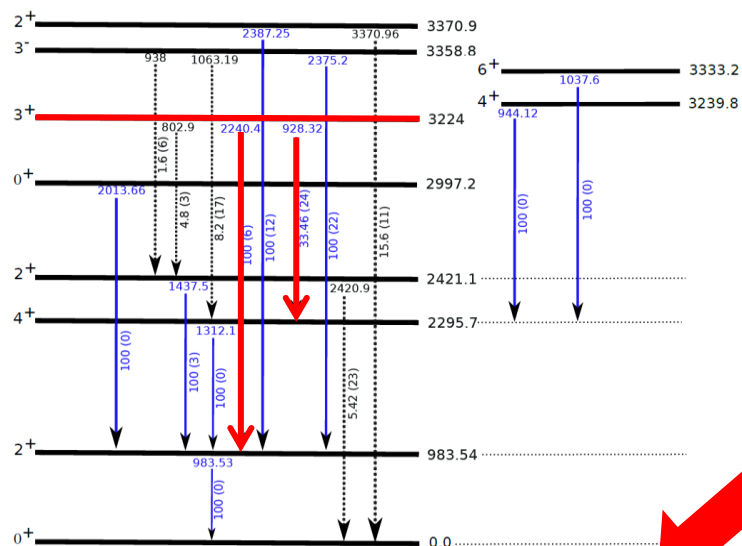
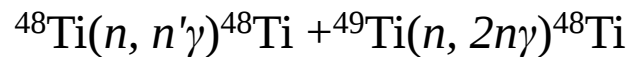
Results



Results

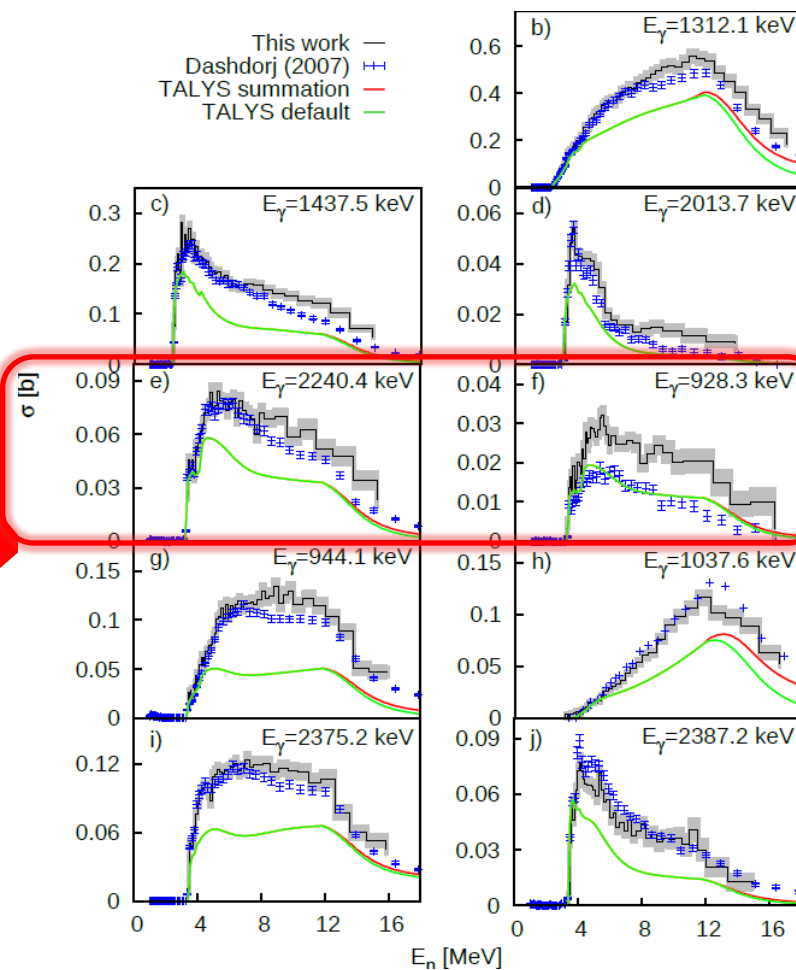


Results

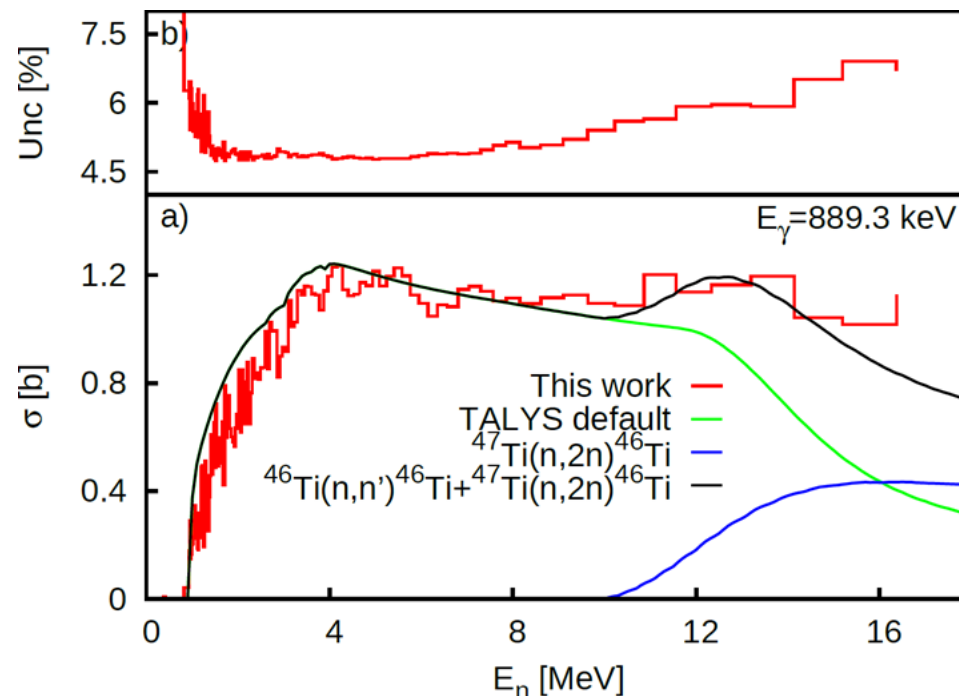
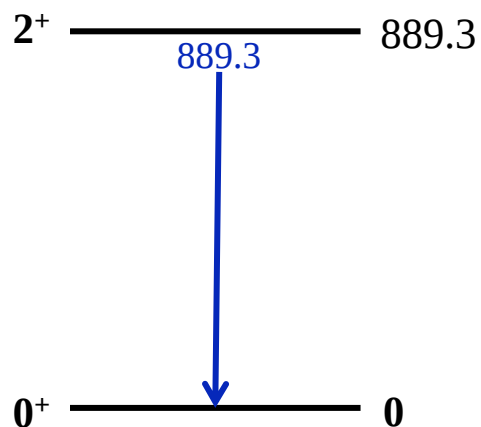
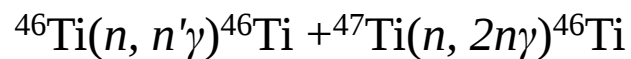


Branching ratio of $E_\gamma=928.3$ keV:

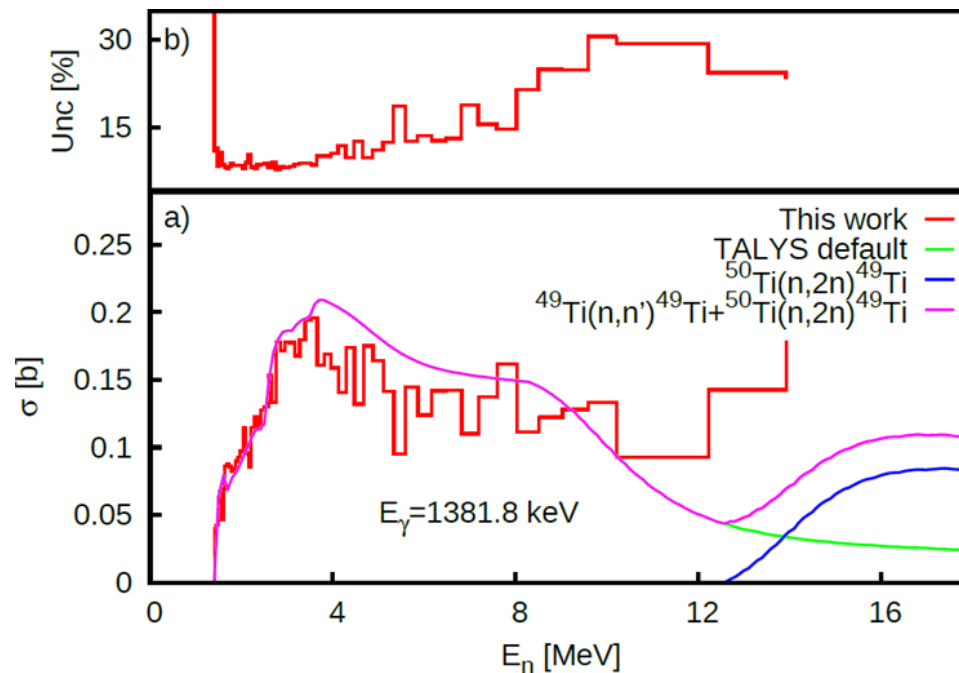
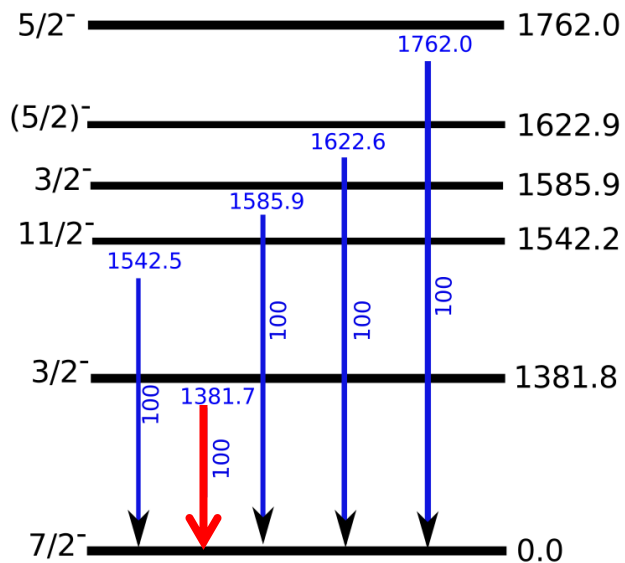
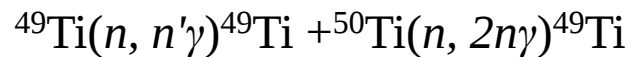
- Our result: 36.2(9)%;
- ENSDF: 33.46(24)%.



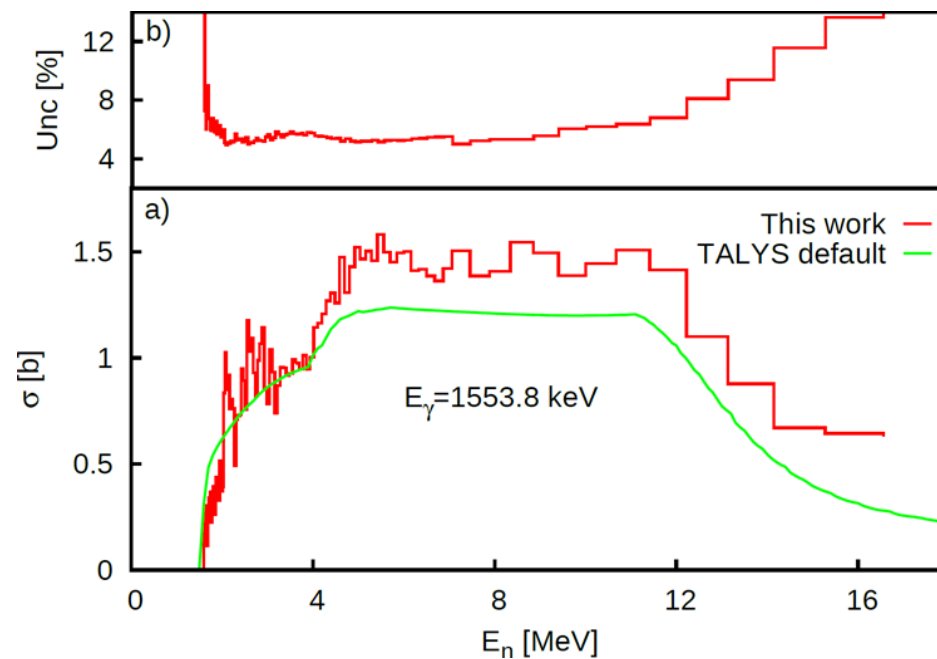
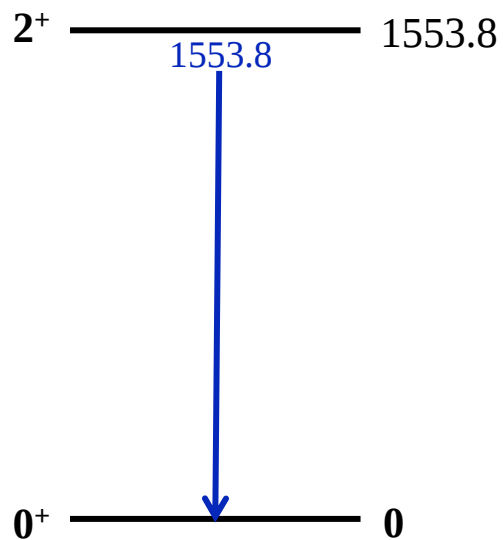
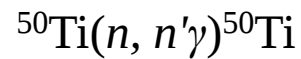
Results - minor isotopes



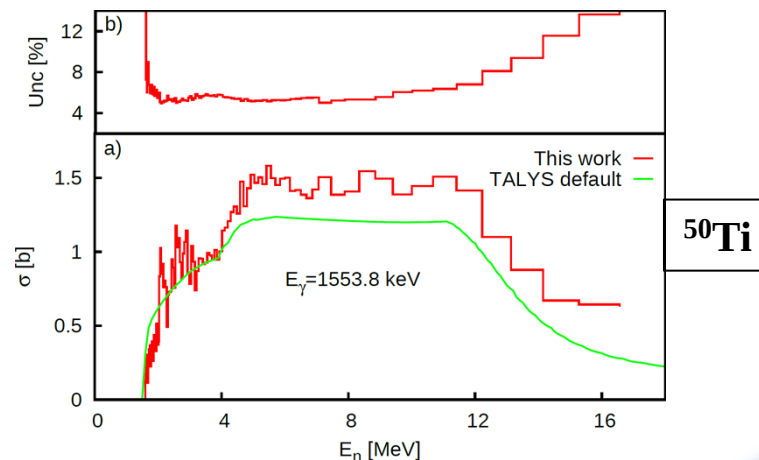
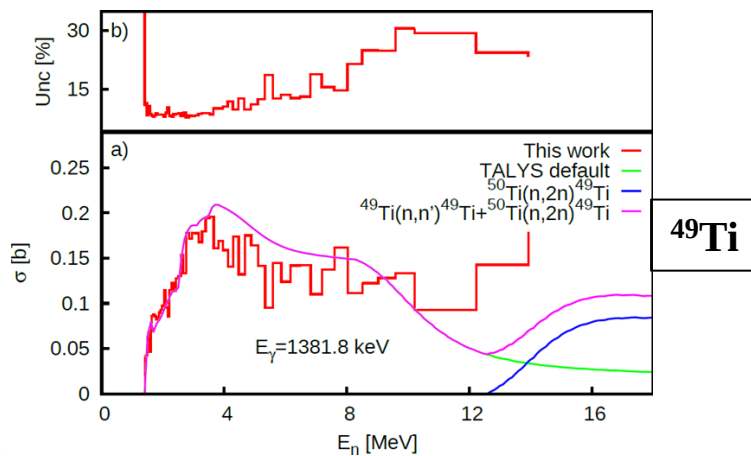
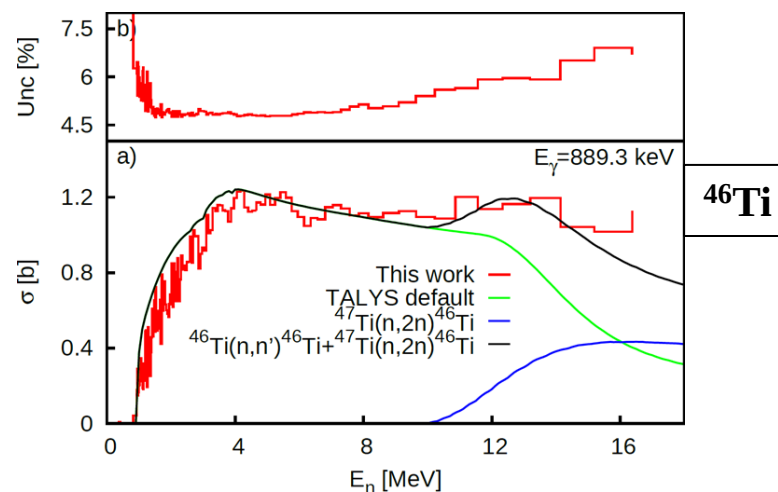
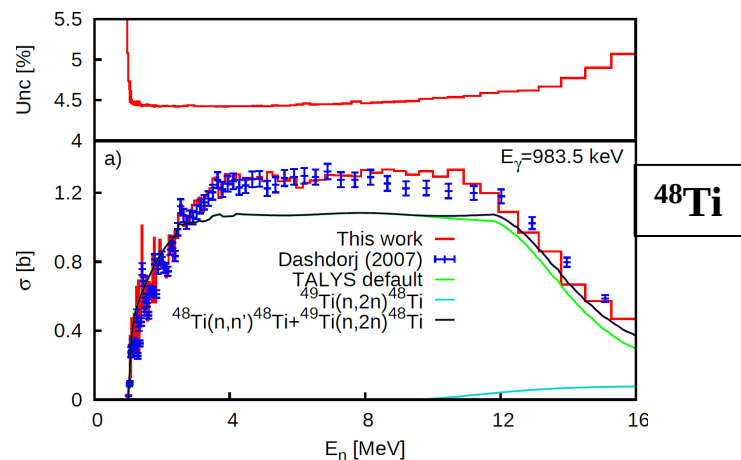
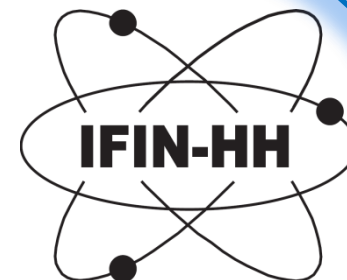
Results - minor isotopes



Results - minor isotopes



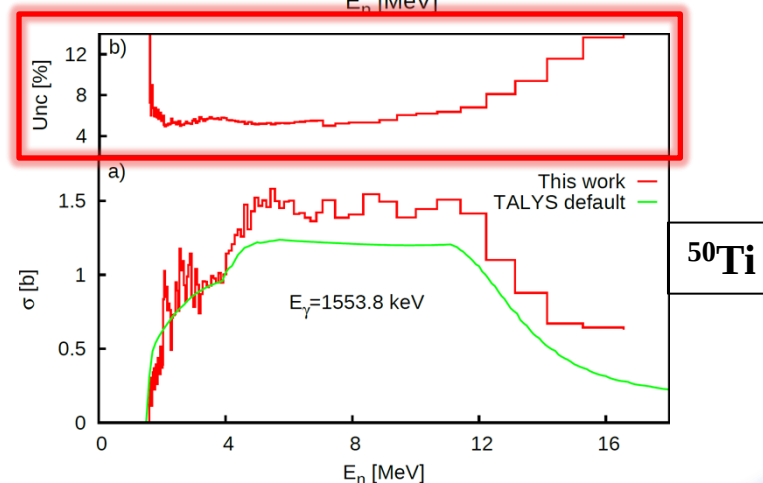
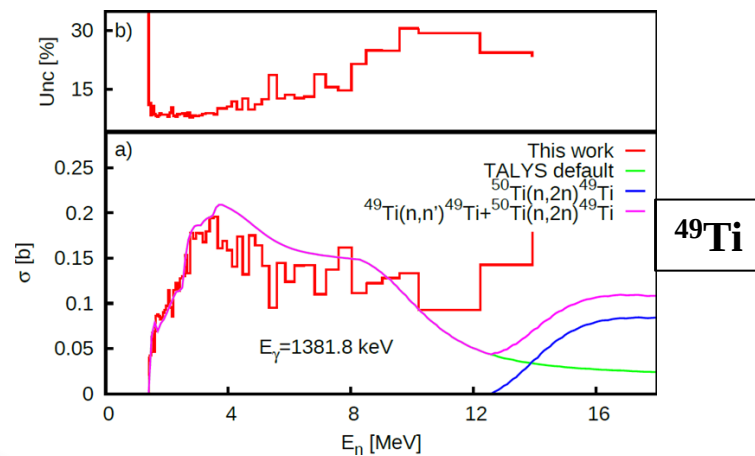
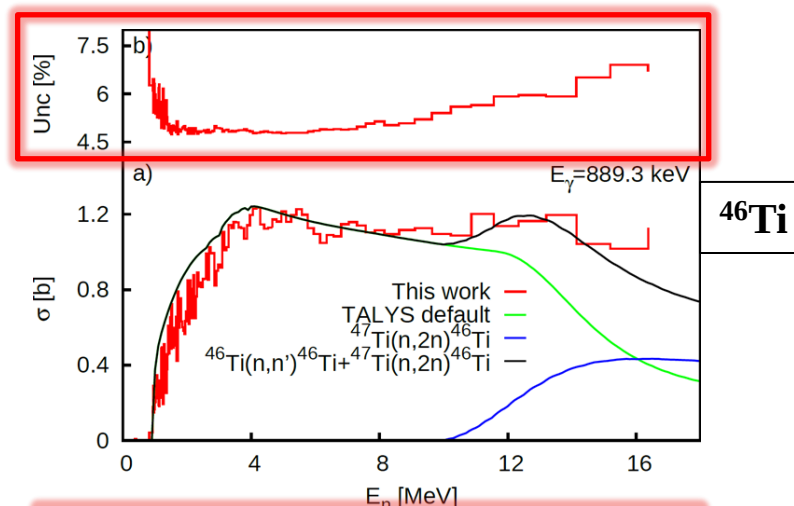
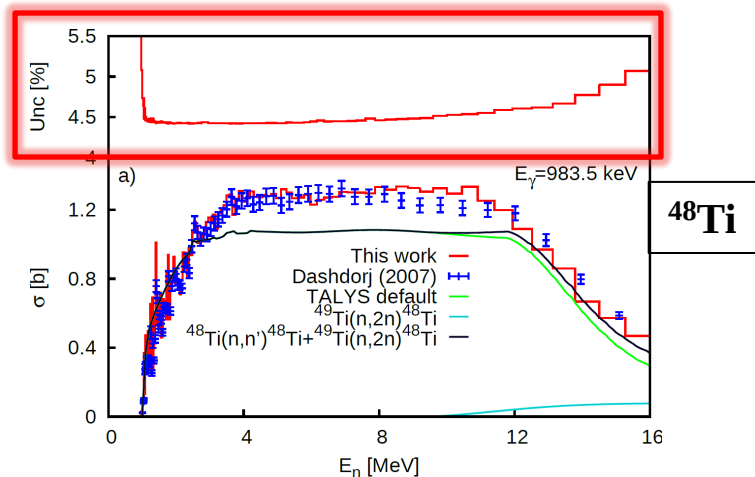
Results - Uncertainties



Results - Uncertainties



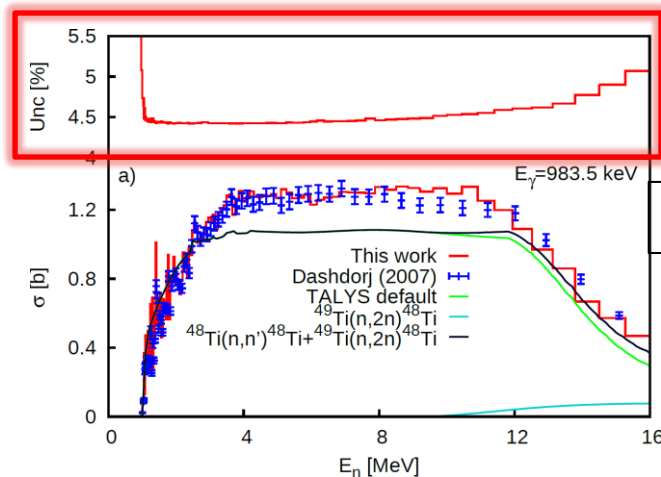
$\approx 5\%$



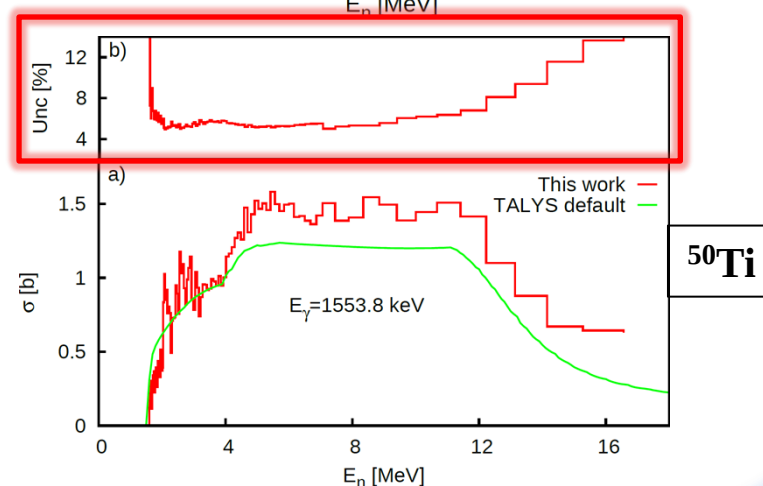
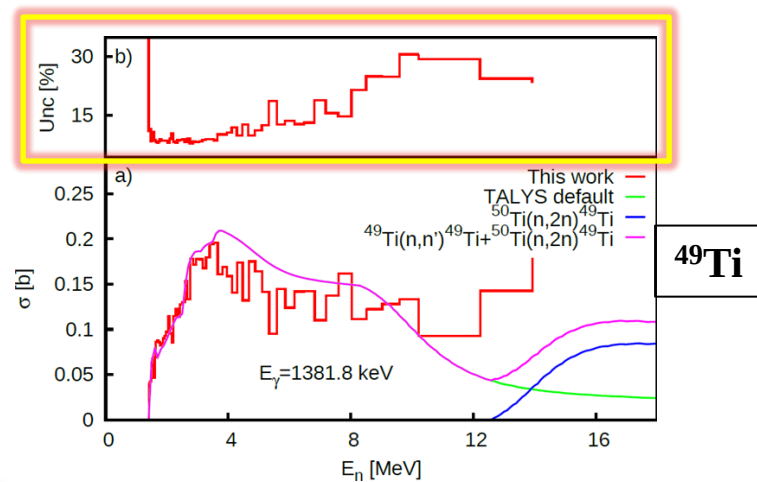
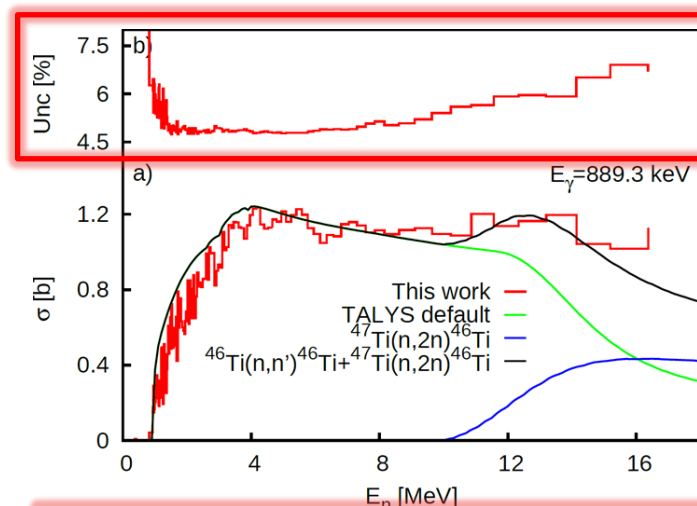
Results - Uncertainties



$\approx 5\%$



$\approx 10\%$



Conclusions



- The aim of this experiment was to provide high precision cross section data for the stable isotopes of natural titanium and it was accomplished by reporting data with an uncertainty around 5% for the strongest transitions.
- The results of the γ -production cross section for the first transition in ^{48}Ti were sent to be evaluated by the group in charge with the establishing of the standard γ -ray cross section.
- A full publication is in preparation.

Thank you!

