Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering

GAINS – Twenty Years After

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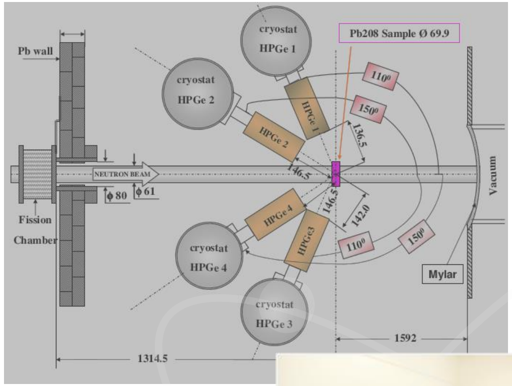

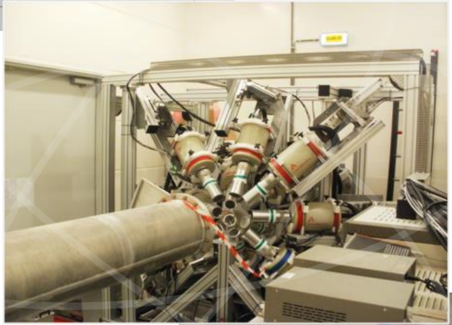

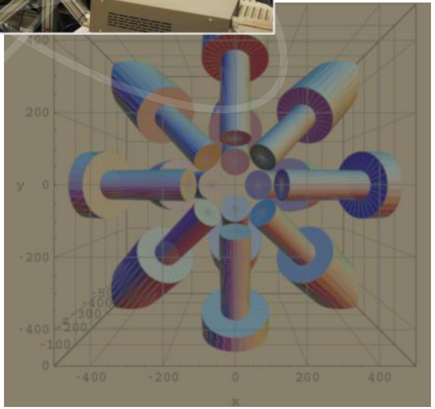

SANDA
Supplying Accurate Nuclear Data for energy and non-energy Applications
HORIZON2020
Accelerator and Research reactor Infrastructures for Education and Learning
ARIEL

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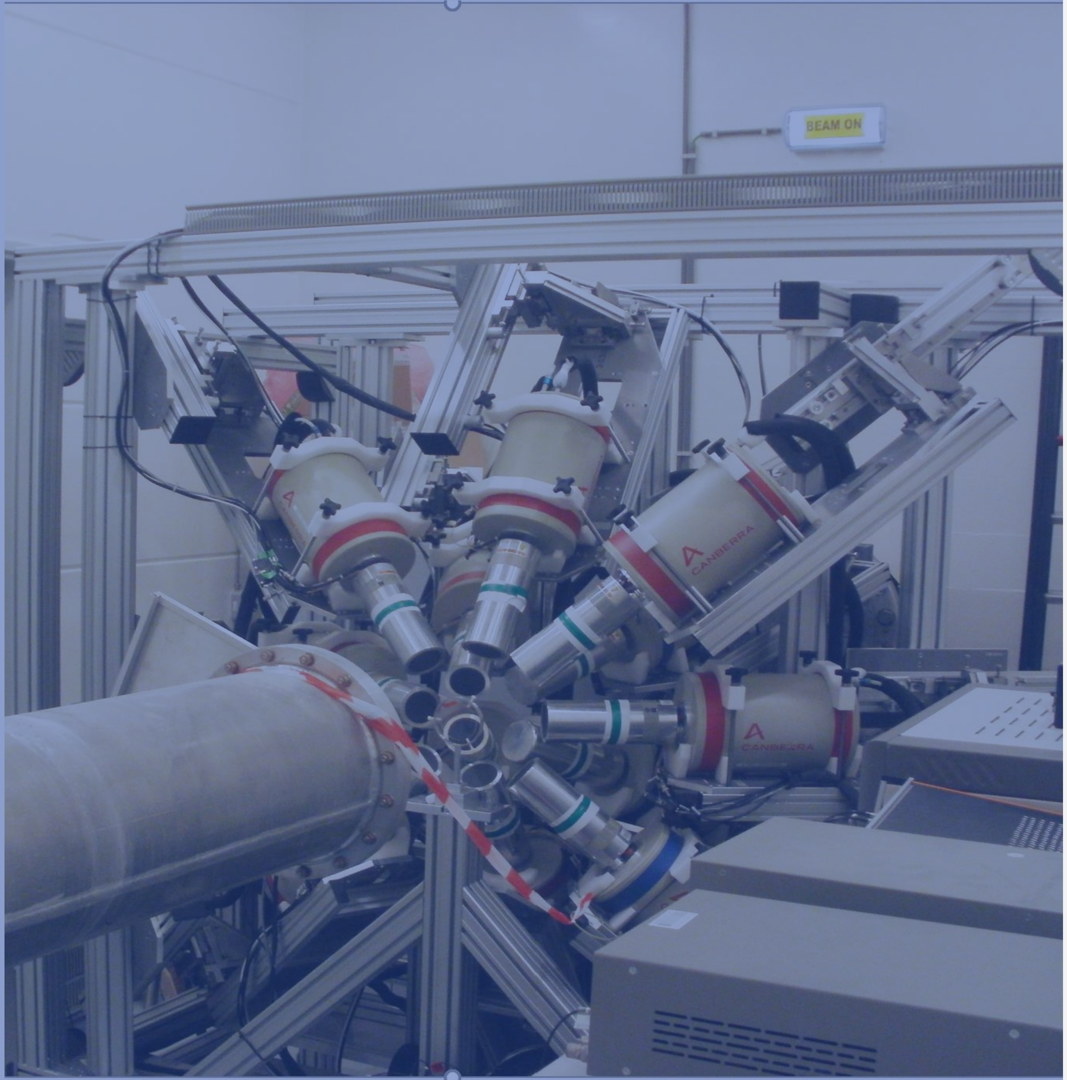

What is GAINS?

What is GAINS?

GAINS - Gamma Array for Inelastic Neutron Scattering

- provides important nuclear data (neutron inelastic cross sections) of interest for:
  - applications – addressing the nuclear data community needs for the development of the new generation of nuclear reactors
  - fundamental research – better understanding of the nuclear reaction mechanisms

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GELINA - Geel Electron LINear Accelerator

- EC-JRC Geel, Belgium

$E_e \approx 70$ - 140 MeV, $\Delta t \approx 2$ ns

Neutrons produced by photon induced reactions in U-Mo

Multiuser facility

Flight paths from 10 m up to 400 m in length

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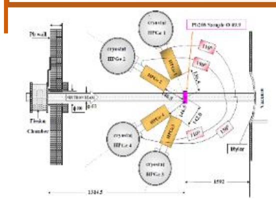
2000

2-4 HPGe detectors
Support: table
FP: 200 m
DAQ: conventional electronics



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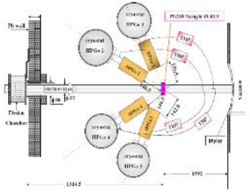

2005

4 HPGe detectors
Support: table
FP: 200 m
DAQ: **Acqiris digitizer**
420 MSPS
12 bits

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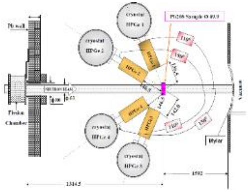
2000	2005	2006
2-4 HPGe detectors Support: table FP: 200 m DAQ: conventional electronics	4 HPGe detectors Support: table FP: 200 m DAQ: **Acqiris digitizer** **420 MSPS** **12 bits**	4 HPGe detectors Support: **1st frame** FP: 200 m DAQ: Acqiris digitizer 420 MSPS 12 bits



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2000

2-4 HPGe detectors
Support: table
FP: 200 m
DAQ: conventional electronics

2005

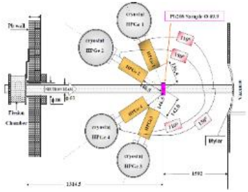
4 HPGe detectors
Support: table
FP: 200 m
DAQ: **Acqiris digitizer**
420 MSPS
12 bits

2006

4 HPGe detectors
Support: **1st frame**
FP: 200 m
DAQ: Acqiris digitizer
420 MSPS
12 bits

2008

12 HPGe detectors
Support: 1st frame
FP: 200 m
DAQ: Acqiris digitizer
420 MSPS
12 bits



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GAINS - Gamma Array for Inelastic Neutron Scattering

- provides important nuclear data (neutron inelastic cross sections) of interest for:
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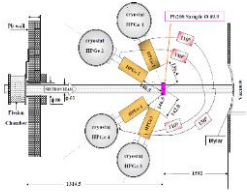
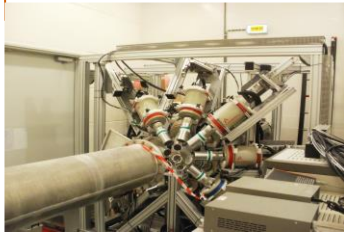
2000	2005	2006	2008	2015
2-4 HPGe detectors Support: table FP: 200 m DAQ: conventional electronics	4 HPGe detectors Support: table FP: 200 m DAQ: **Acqiris digitizer** **420 MSPS** **12 bits**	4 HPGe detectors Support: **1st frame** FP: 200 m DAQ: Acqiris digitizer 420 MSPS 12 bits	**12 HPGe detectors** Support: 1st frame FP: 200 m DAQ: Acqiris digitizer 420 MSPS 12 bits	12 HPGe detectors Support: **2nd frame** FP: **100 m** DAQ: Acqiris digitizer 420 MSPS 12 bits





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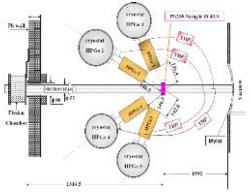
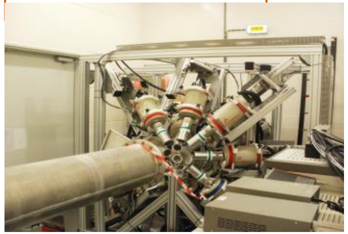
2002	2005	2006	2008	2015	2022	
2-4 HPGe detectors Support: table FP: 200 m DAQ: conventional electronics	4 HPGe detectors Support: table FP: 200 m DAQ: **Acqiris digitizer** **420 MSPS** **12 bits**	4 HPGe detectors Support: **1st frame** FP: 200 m DAQ: Acqiris digitizer 420 MSPS 12 bits	**12 HPGe detectors** Support: 1st frame FP: 200 m DAQ: Acqiris digitizer 420 MSPS 12 bits	12 HPGe detectors Support: **2nd frame** FP: **100 m** DAQ: Acqiris digitizer 420 MSPS 12 bits	10 HPGe detectors 2 LaBr2 detectors Support: 2nd frame FP: 100 DAQ: **new digitizers**	Ongoing project University of Groningen



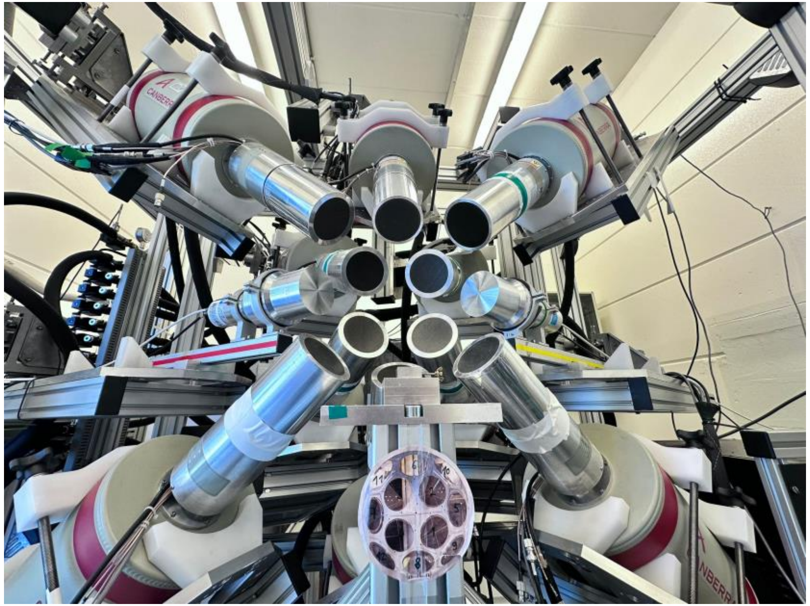


GAINS nowadays

- 10 HPGe detectors:
  - 4 @ 110°
  - 4 @ 150°
  - 2 @ 125°
- 2 $LaBr_3$ detectors @ 125°
- ^{235}U Fission chamber for beam monitoring
- Neutron energy range: E_{th} – 20 MeV
- 100 m - Neutron energy resolution:

  3 keV @ 1MeV

  80 keV @ 10 MeV



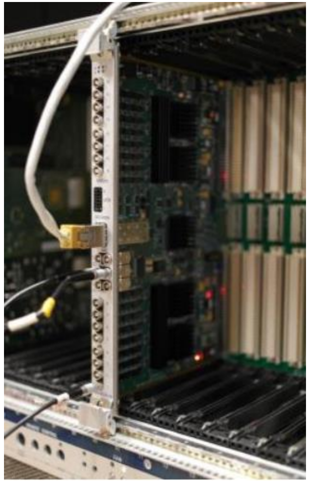
GAINS nowadays

Acqiris DC440:

2 input channels/card
1 common external trigger
12 bits
420 MHz sampling

Struck SIS3316-250-14 SADC:

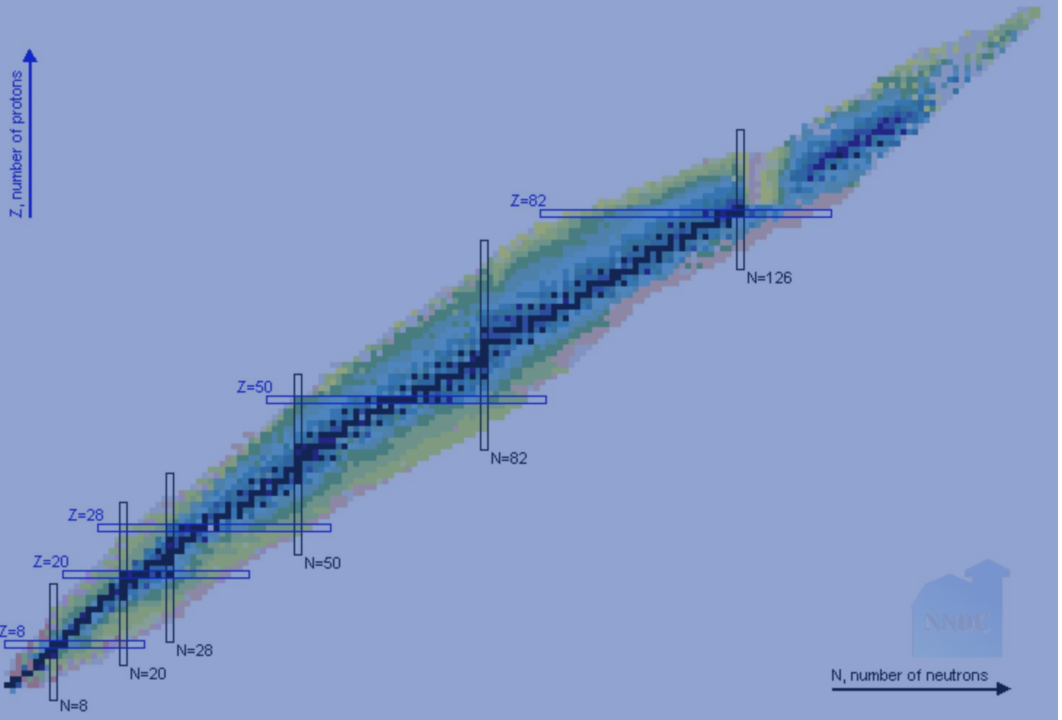
16 input channels/card
internal triggering with external gate
14 bits
250 MHz sampling



What is GAINS?

GAINS is all of these people which during the years contributed to the program:

A. Plompen – leader of the project at JRC-Geel,
L. Olah – made the first attempts to measure (n,n'g) with HPGe detectors at GELINA,
C. Mihailescu – PhD student, first successfully finalized measurements, commissioned the digitizers,
C. Borcea – National expert, supervisor of L. Olah and C. Mihailescu
A. Negret – Postdoc in Geel, commissioned the first version of GAINS, wrote the DAQ
– Senior scientist at IFIN-HH (Bucharest), performed numerous experiments using GAINS
N. Nankov – Postdoc in Geel, performed measurements at GAINS
C. Rouki – Postdoc in Geel, performed measurements at GAINS
M. Nyman – Postdoc in Geel, performed measurements at GAINS
A. Olacel – PhD student, then postdoc at IFIN-HH, Bucharest, performs measurements at GAINS
M. Boromiza – PhD student, then postdoc at IFIN-HH, Bucharest, performs measurements at GAINS
A. Oprea – Postdoc in Geel, performs measurements at GAINS.



What do we measure?

What do we measure?

Neutron inelastic scattering reaction

$$n + {}^{A}_{Z}X_{N} \longrightarrow {}^{A+1}_{Z}X_{N+1}{}^{*} \longrightarrow {}^{A}_{Z}X_{N}{}^{*} + n$$

$E_n = E_{th} \div \sim 20$ MeV

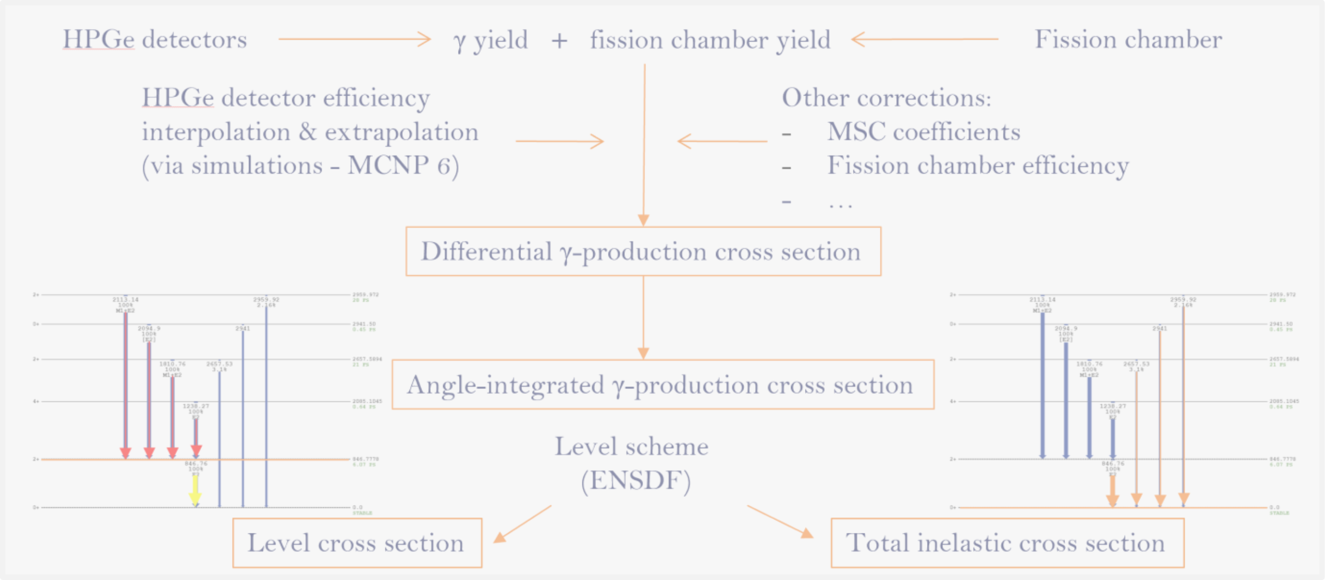
$$E^{*} \approx E_n - E_n'$$

$$\downarrow$$

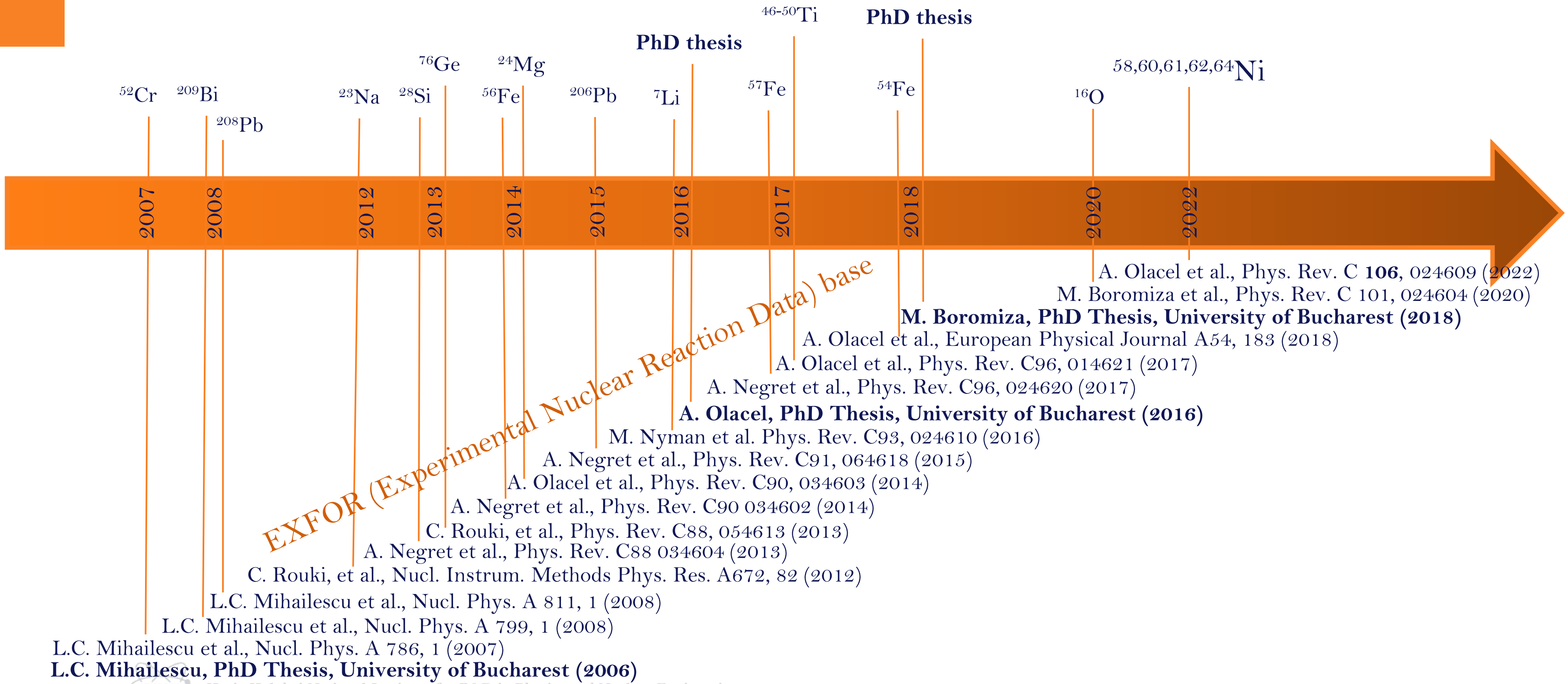
$$ {}^{A}_{Z}X_{N} + \gamma$$

- In order to study the inelastic scattering one could detect
  neutrons or gammas.

- γ-spectroscopy measurements coupled with time of flight method
- we extract angle-integrated γ production cross sections normalized to the very well known ^{235}U(n, fission) cross section



GAINS: Nuclear data factory



GAINS: Nuclear data factory

PhD thesis

$^{46-50}$Ti

PhD thesis

^{76}Ge ^{24}Mg

^{52}Cr ^{209}Bi ^{208}Pb ^{23}Na ^{28}Si ^{56}Fe

2007 2008 2012 2013 2014

PHYSICAL REVIEW C **90**, 034603 (2014)

Neutron inelastic cross-section measurements for ^{24}Mg

A. Olacel,[1,2,*] C. Borcea,[1] P. Dessagne,[3] M. Kerveno,[3] A. Negret,[1] and A. J. M. Plompen[4]
[1]*Horia Hulubei National Institute for Physics and Nuclear Engineering, Reactorului 30, 077125 Bucharest-Măgurele, Romania*
[2]*University of Bucharest, Faculty of Physics, Atomistilor 405, 077125, Bucharest-Măgurele, Romania*
[3]*CNRS, Université de Strasbourg, UMR7178, IPHC, 23 rue du Loess 67037 Strasbourg, France*
[4]*European Commission, Joint Research Center, Institute for Reference Materials and Measurements, B-2440 Geel, Belgium*
(Received 24 June 2014; published 8 September 2014)

The γ production cross sections from neutron inelastic scattering on ^{24}Mg were measured for neutron energies up to 18 MeV at GELINA (the Geel Linear Accelerator), the neutron source operated by EC-JRC-IRMM, Belgium. The level cross section and the total inelastic cross section were determined. We used the GAINS (Gamma Array for Inelastic Neutron Scattering) spectrometer with seven large-volume high-purity germanium (HPGe) detectors placed at 110° and 150° with respect to the beam direction. The neutron flux was determined with a ^{235}U fission chamber. The results are compared with calculations performed with the TALYS 1.6 code using the default settings.

DOI: 10.1103/PhysRevC.90.034603 PACS number(s): 25.40.Fq, 27.30.+t, 29.30.Kv

Rev. C **106**, 024609 (2022)
Rev. C 101, 024604 (2020)
Bucharest (2018)
2018)

EXFOR (Experimental N

A. Negret et al., Phys. Rev. C91, 064618 (2015)
A. Olacel et al., Phys. Rev. C90, 034603 (2014)
A. Negret et al., Phys. Rev. C90 034602 (2014)
C. Rouki, et al., Phys. Rev. C88, 054613 (2013)
A. Negret et al., Phys. Rev. C88 034604 (2013)
C. Rouki, et al., Nucl. Instrum. Methods Phys. Res. A672, 82 (2012)
L.C. Mihailescu et al., Nucl. Phys. A 811, 1 (2008)
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L.C. Mihailescu et al., Nucl. Phys. A 786, 1 (2007)
L.C. Mihailescu, PhD Thesis, University of Bucharest (2006)

^{24}Mg(n, n'γ)^{24}Mg @ 200 m

Magnesium is a structural material in nuclear reactors.

Useful tool for a better understanding of nuclear reaction mechanisms.

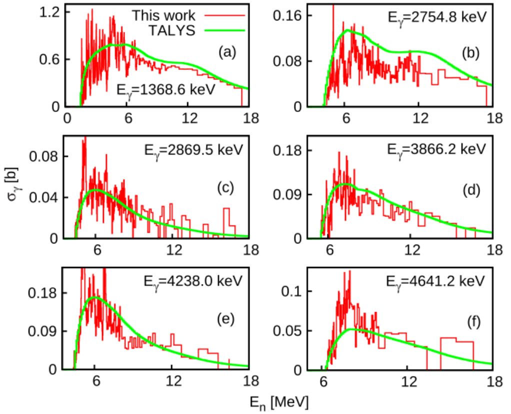


FIG. 4. (Color online) Integrated γ production cross section for each observed transition. The red line represents the results of the present experiment while the green line displays the results of the TALYS 1.6 theoretical calculations using the default input parameters.

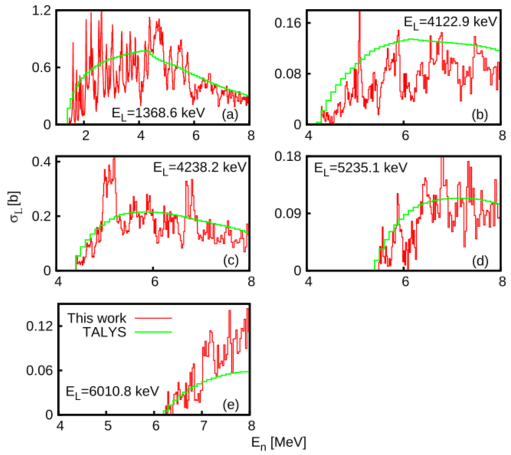


FIG. 5. (Color online) The production cross section for the first five excited levels compared with the TALYS 1.6 default calculations.

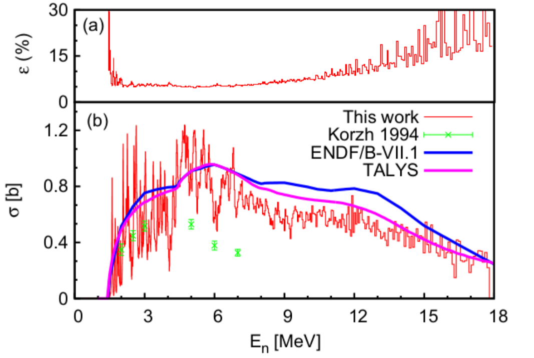
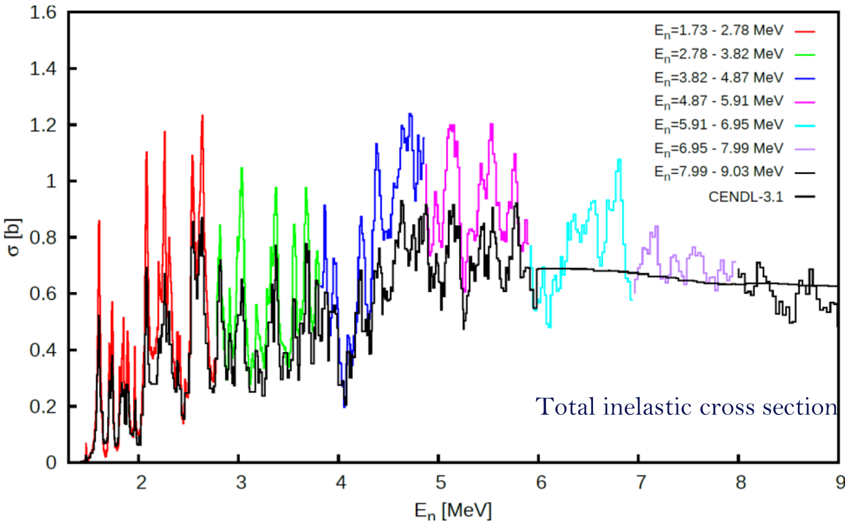


FIG. 6. (Color online) (b) Total inelastic cross section for the ^{24}Mg$(n,n'\gamma)^{24}$Mg reaction. The red line represents the result of our experiment, the green dots the results from the previous experiment of Korzh *et al.* (1994) [8], the dark blue line displays the evaluated values from ENDF/B-VII.1 [35], while the magenta line represents the TALYS 1.6 calculations. (a) The relative total uncertainties.

^{24}Mg(n, n'γ)^{24}Mg @ 200 m

Neutron energy resolution -1 keV @ 1MeV & 35 keV @ 10 MeV

How high can we resolve individual resonances in the CN 25Mg?



Simple estimates:

- Calculate which J$^\pi$ are populated in the CN (^{25}Mg)
- Calculate level density for each J$^\pi$ and excitation energy using BSFG model
- Counting the resonances from the total inelastic cross section

E_n range (MeV)	Average E_n (MeV)	$E^*(^{25}$Mg) (MeV)	$J(^{25}$Mg) (TALYS)	Theoretical level density (MeV^{-1}) (BSFG)	Experimental level density (MeV^{-1})
1.73–2.78	2.26	9.5	1/2–5/2	19	18
2.78–3.82	3.30	10.5	1/2–7/2	36	18
3.82–4.87	4.34	11.5	1/2–7/2	53	10
4.87–5.91	5.39	12.5	1/2–7/2	79	13
5.91–6.95	6.43	13.5	1/2–9/2	132	11
6.95–7.99	7.47	14.5	1/2–9/2	191	10
7.99–9.03	8.51	15.5	1/2–9/2	275	8

GAINS: Nuclear data factory

PHYSICAL REVIEW C **96**, 014621 (2017)

Neutron inelastic scattering measurements on the stable isotopes of titanium

A. Olacel,[1,*] F. Belloni,[2] C. Borcea,[1] M. Boromiza,[1,3] P. Dessagne,[4] G. Henning,[4] M. Kerveno,[4] A. Negret,[1] M. Nyman,[2] E. Pirovano,[2] and A. J. M. Plompen[2]

[1] *Horia Hulubei National Institute for Physics and Nuclear Engineering, Reactorului 30, 077125 Bucharest-Măgurele, Romania*
[2] *European Commission, Joint Research Centre, Retieseweg 111, B-2440 Geel, Belgium*
[3] *University of Bucharest, Faculty of Physics, Atomistilor 405, 077125, Bucharest-Măgurele, Romania*
[4] *Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*

(Received 24 May 2017; published 31 July 2017)

The results of a neutron inelastic scattering experiment performed at the Geel Electron Linear Accelerator pulsed white neutron source of the European Commission Joint Research Centre are reported. The neutrons with energies up to 18 MeV interacted with a ^{nat}Ti sample and the γ rays resulting from inelastic scattering reactions on the stable isotopes were detected using the Gamma Array for Inelastic Neutron Scattering (GAINS) spectrometer. We were able to measure the γ-production cross sections for 21 transitions in the five stable Ti isotopes. From these, the level cross sections and the total inelastic cross sections were determined. Our experimental results are compared with theoretical calculations performed using the TALYS 1.8 code, evaluated nuclear data libraries, and also with previously reported results.

DOI: 10.1103/PhysRevC.96.014621

$^{46\text{-}50}$Ti

PhD thesis

Fe

^{54}Fe

^{16}O

^{58,60,61,62,64}Ni

2017

2018

2020

2022

EXFOR (Experimental Nuclear Data) base

A. Olacel et al., Phys. Rev. C **106**, 024609 (2022)
M. Boromiza et al., Phys. Rev. C 101, 024604 (2020)
M. Boromiza, PhD Thesis, University of Bucharest (2018)
A. Olacel et al., European Physical Journal A54, 183 (2018)
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M. Nyman et al. Phys. Rev. C93, 024610 (2016)
A. Negret et al., Phys. Rev. C91, 064618 (2015)
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L.C. Mihailescu, PhD Thesis, University of Bucharest (2006)

^{nat}Ti(n, n'γ)^{nat}Ti @ 200 m

Titanium is a structural material in nuclear reactors.

Useful tool for a better understanding of nuclear reaction mechanisms.

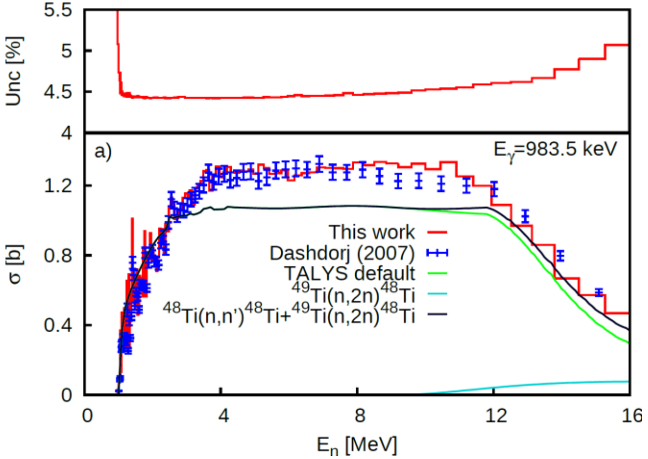
The first transition in ^{48}Ti (E_{γ}=983.5 keV) is under investigation to estabilish a γ-ray reference cross section for neutron-induced reactions.

^{48}Ti(n,n'γ) gamma production cross section as a candidate for a reference cross section

S.P. Simakov[1], V.G. Pronyaev[2], R. Capote[1] and R.O. Nelson[3]
1) Nuclear Data Section, IAEA, Wagramer Strasse 5, A-1400 Vienna, Austria
2) Institute of Physics and Power Engineering, Bondarenko Sq. 1, Obninsk, Russian Federation
3) LANSCE-NS, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract
The yield of 984 keV γ-rays from ^{48}Ti(n,n') reaction has been evaluated from threshold up to 20 MeV. For this purpose all currently available measured discrete gamma production and neutron inelastic cross sections were thoroughly analysed and renormalised to the updated standards when possible. The TALYS and EMPIRE nuclear reaction codes were used to get an optimal description of these cross sections for natural Titanium and its main isotope ^{48}Ti. The final evaluation of the 984 keV γ-ray yield from ^{48}Ti(n,n') reaction and covariance matrix was performed on the basis of collected experimental data and optimised model calculations employing the least squares code GMA.

A. Olacel et al., PHYSICAL REVIEW C 96, 014621 (2017)



A. D. Carlson et al., A new evaluation of the neutron data standards, EPJ Web of Conferences. 146. 02025. 10.1051/epjconf/201714602025

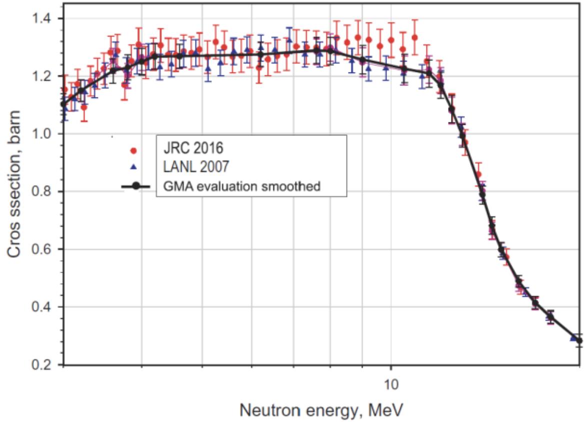


Figure 10. Recent measurements of the ^{48}Ti(n,n'γ) cross section (E = 0.984 MeV) compared with the GMA evaluation.

GAINS: Nuclear data factory

^{52}Cr ^{209}Bi ^{208}Pb ^{23}Na **^{28}Si** ^{76}Ge **^{24}Mg** **^{56}Fe** **^{206}Pb** ^{7}Li PhD thesis ^{57}Fe $^{46-50}$Ti ^{54}Fe PhD thesis ^{16}O ^{58,60,61,62,64}Ni

2007 2008 2022

PHYSICAL REVIEW C **88**, 027601 (2013)

Neutron inelastic scattering measurements for background assessment in neutrinoless double β decay experiments

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[1] *"Horia Hulubei" National Institute for Physics and Nuclear Engineering, 077125 Bucharest-Măgurele, Romania*
[2] *European Commission, Joint Research Center, Institute for Reference Materials and Measurements, B-2440 Geel, Belgium*

(Received 28 June 2013; revised manuscript received 24 July 2013; published 13 August 2013)

The inelastic scattering of neutrons on structural materials constitutes a major concern for the design of neutrinoless double β decay experiments. We explore our neutron inelastic scattering data on ^{206}Pb, ^{56}Fe, ^{28}Si, ^{24}Mg, and ^{12}C, searching for possible contributors to the background in the energy region where neutrinoless double β decay signals would be produced.

DOI: 10.1103/PhysRevC.88.027601 PACS number(s): 23.40.−s, 25.40.Fq

Olacel et al., Phys. Rev. C **106**, 024609 (2022)
…omiza et al., Phys. Rev. C 101, 024604 (2020)
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…Journal A54, 183 (2018)
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C. Rouki, et al., Phys. Rev. C88, 054613 (2013)

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C. Rouki, et al., Nucl. Instrum. Methods Phys. Res. A672, 82 (2012)
L.C. Mihailescu et al., Nucl. Phys. A 811, 1 (2008)
L.C. Mihailescu et al., Nucl. Phys. A 799, 1 (2008)
L.C. Mihailescu et al., Nucl. Phys. A 786, 1 (2007)
L.C. Mihailescu, PhD Thesis, University of Bucharest (2006)

$\beta\beta(0\nu)$: sources of background

GAINS is the perfect tool to check two things:

1. If the neutrons produce γ's with $E_\gamma=Q^{\beta\beta}$ on the isotopes of interest (^{76}Ge, ^{130}Te, etc.)
   For ^{76}Ge, see C. Rouki et al., Phys. Rev. C88, 054613 (2013).

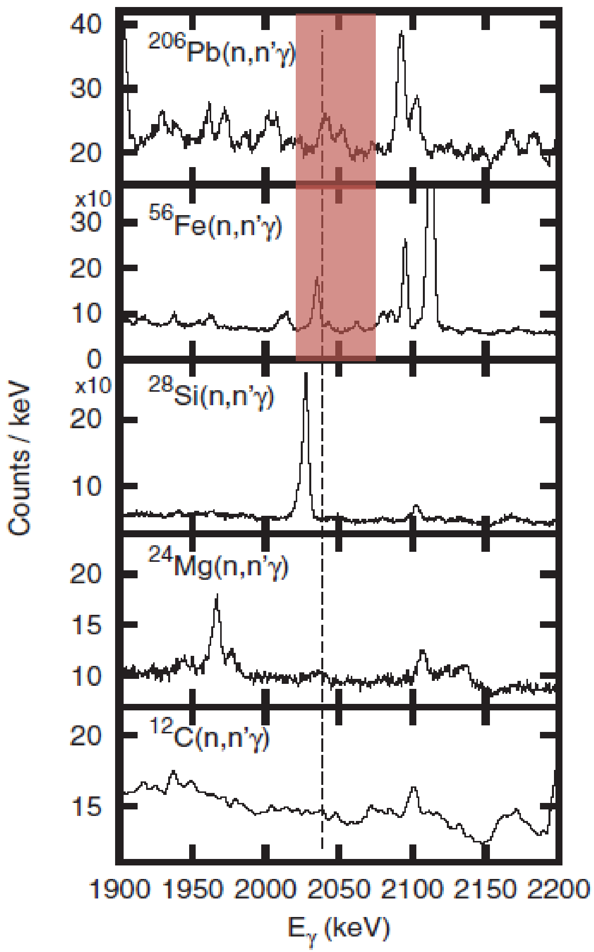
2. If the neutrons produce γ's with $E_\gamma=Q^{\beta\beta}$ on other structural materials: ^{206}Pb, ^{56}Fe, ^{28}Si, ^{24}Mg, ^{12}C.

$Q^{\beta\beta}$ (^{76}Ge) = 2039.06 keV

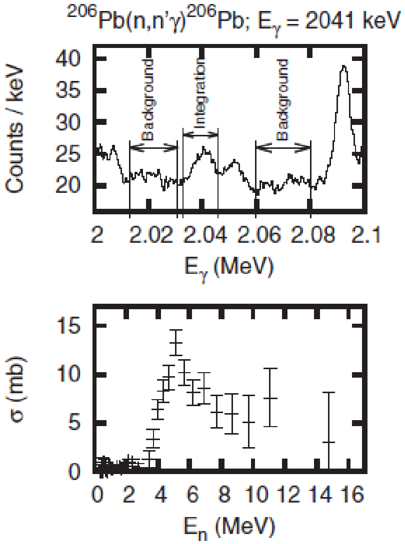
Possible contaminants:

- ^{206}Pb: E_γ=2041 keV
  (E_L=3743.7 keV, $J^\pi=1^-$)

- ^{56}Fe: E_γ=2034.7 keV
  (E_L=4119.9 keV, $J^\pi=3^+$)



ββ(0ν): sources of background



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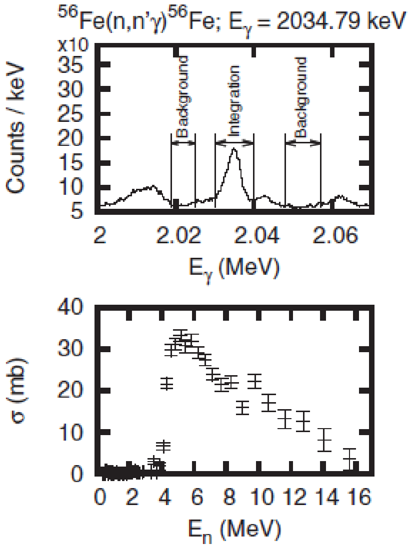
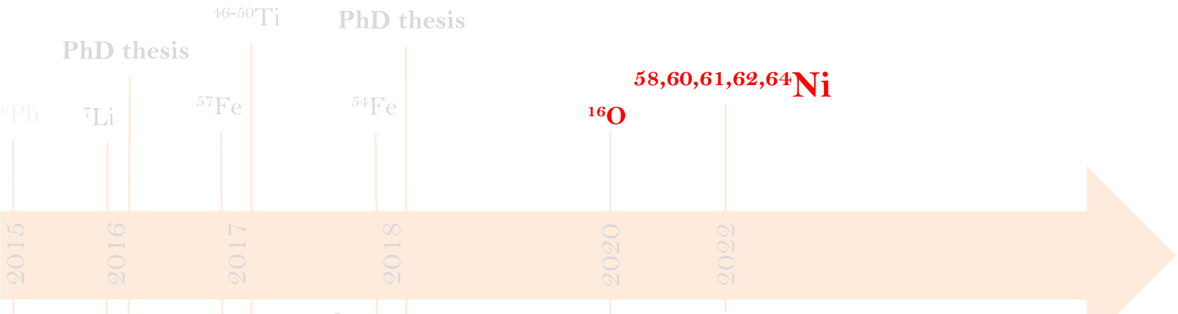


Threshold does not confirm E_L
σ_{max}=13±1 mb

Threshold OK
σ_{max} = 33±2 mb

GAINS: Nuclear data factory



A. Olacel et al., Phys. Rev. C 106, 024609 (2022)
M. Boromiza et al., Phys. Rev. C 101, 024604 (2020)

PHYSICAL REVIEW C **106**, 024609 (2022)

Nucleon-induced inelastic cross sections on ^{nat}Ni

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(Received 8 June 2022; accepted 26 July 2022; published 17 August 2022)

This paper reports on the results of $(n, n'\gamma)$ and $(p, p'\gamma)$ cross section measurements on nickel performed at the Geel Electron Linear Accelerator of the European Commission, Joint Research Centre (Geel) and at the 9-MV Tandem Accelerator of Horia Hulubei National Institute for Physics and Nuclear Engineering (Bucharest-Magurele), respectively. The main goal was to reliably measure with small uncertainty the most intense transitions arising from the inelastic channel. Comparisons are performed between the extracted results, nuclear reaction model calculations using default parameter values, and previously reported measurements, if available. The broader goal of this paper is related to our study on the possibility of inferring neutron inelastic cross sections from the proton-induced ones, in this case for ^{58}Ni. We show that—by making use of the Lane consistency of the nucleon optical model potential and of the constraints offered by the proton data—one can extract a neutron-target potential that better describes the experimental data, as compared to the calculation with default neutron parameters. We also discuss relevant issues and still open questions of our calculations along with future plans for mitigation.

DOI: 10.1103/PhysRevC.106.024609

PHYSICAL REVIEW C **101**, 024604 (2020)

Nucleon inelastic scattering cross sections on ^{16}O and ^{28}Si

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(Received 13 September 2019; revised manuscript received 25 November 2019; accepted 16 December 2019; published 10 February 2020)

This paper reports cross-section measurements of the (n, n') and (p, p') reactions on ^{16}O and ^{28}Si at Geel Electron Linear Accelerator and at the 9-MV Tandem Accelerator of Horia Hulubei National Institute for Physics and Nuclear Engineering, respectively. The main purpose was to measure the neutron- and proton-induced inelastic γ-production cross sections for all observed transitions in ^{16}O and ^{28}Si, followed by the calculation of the corresponding total inelastic cross section. The results are compared with theoretical calculations performed using the TALYS 1.9 code, evaluated nuclear data, and previously reported experimental data. The broader goal of this work is to study whether and to what extent the neutron-induced inelastic cross sections of these nuclei can be inferred from those obtained using suitable charged particle reactions. We show that, by making use of the formal similarities between the neutron- and the proton-target optical model potentials and isospin symmetry in mirror nuclei, one can develop a procedure that combines experimental proton-induced inelastic cross sections with theoretical calculations to infer neutron inelastic cross sections. For ^{16}O and ^{28}Si, the precision associated with this procedure is around 10–20% for most of the incident energy range.

DOI: 10.1103/PhysRevC.101.024604

(n, n'γ) vs (p,p'γ) measurements

Inferring the neutron inelastic channel from proton-induced cross sections

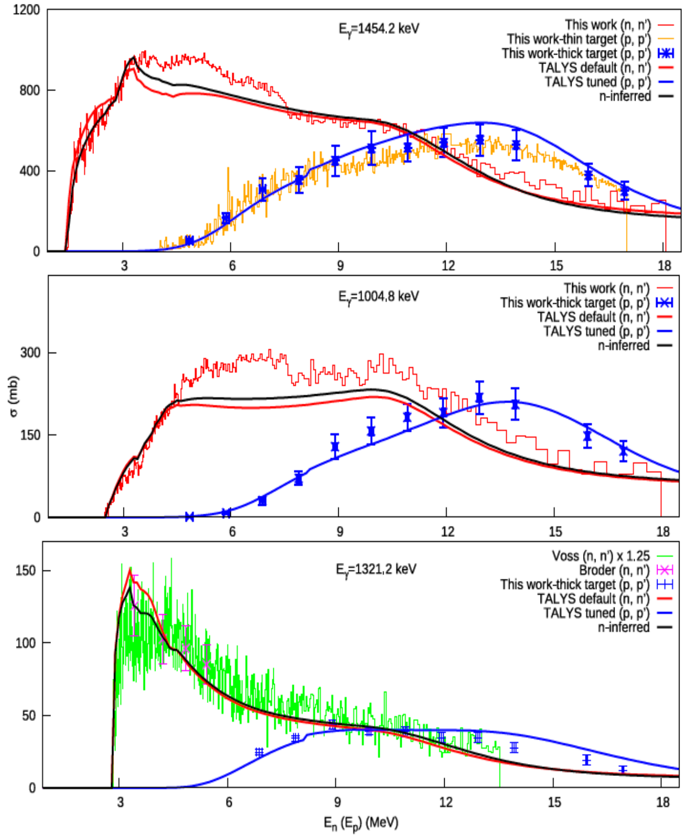
A combination of experiment & theory
Nuclei studied so far:
- ^{16}O & ^{28}Si: *M. Boromiza et al.*, Phys. Rev. C 101, 024604 (2020)
- ^{58}Ni: A. Olacel, *M. Boromiza* et al.*, Phys. Rev. C 106, 024609 (2022)

^{58}Ni(*n, n'g*) ^{58}Ni inferred from ^{58}Ni(*p, p'g*) ^{58}Ni

↓ **CN:** ^{59}Ni ↓ **CN:** ^{59}Cu

^{58}Ni: not a N=Z nucleus =>
=> non-zero Lane term

THE GENERAL IDEA: Starting from proton data, construct a neutron OMP => calculate neutron-induced inelastic cross sections => compare to the experimental data measured at GELINA

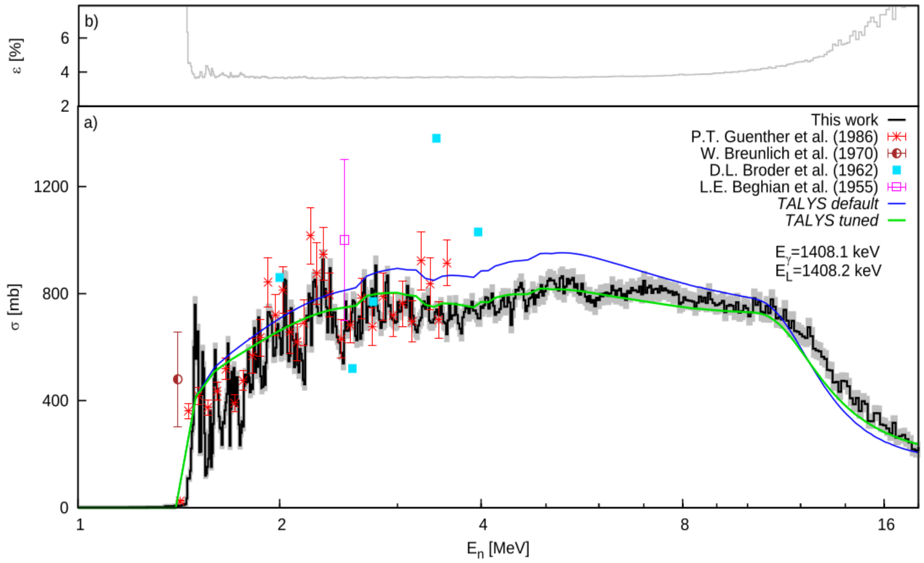


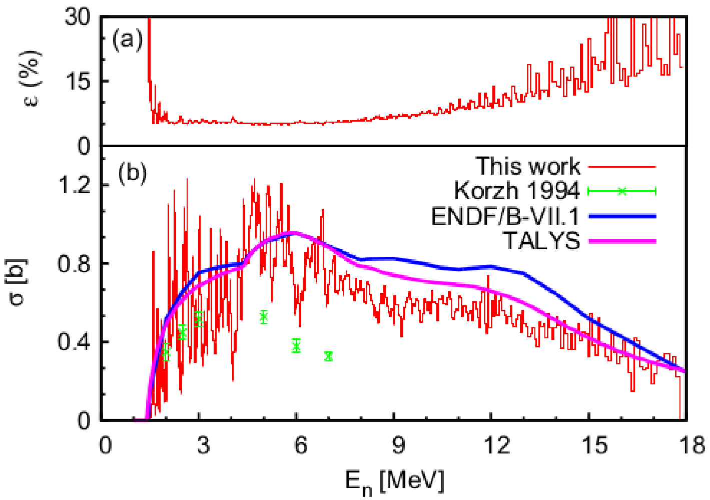
Why is GAINS important?

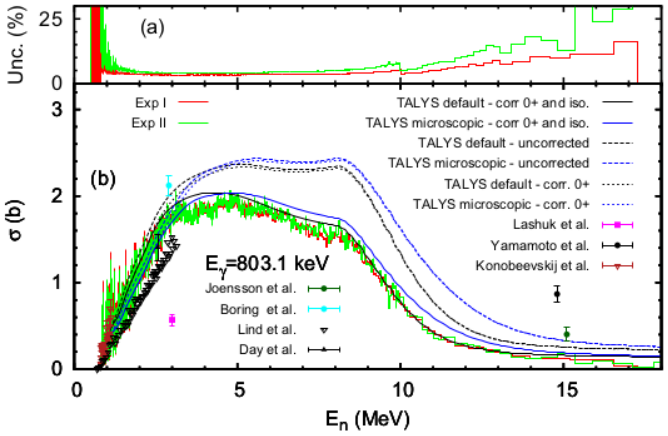
Why is GAINS important?

Very low total relative uncertainty - (5%) for the strongest transition.

Very good neutron energy resolution (≈2000 cross section points for the main transition).







Why is GAINS important?

Our results - highly relevant in the nuclear data community

Active involvement in:

European-funded nuclear data projects

2019 – 2023 - **SANDA** (**S**upplying **A**ccurate **N**uclear **D**ata for energy and non-energy **A**pplications) [H2020 – EURATOM]

2013 – 2018 - **CHANDA** (solving **CHA**llenges in **N**uclear **DA**ta) [FP7 - EURATOM – FISSION]

2010 – 2013 - **ANDES** (**A**ccurate **N**uclear **D**ata for nuclear **E**nergy **S**ustainability) [FP7 - EURATOM – FISSION]

Nationally (Romanian)-funded grants

2022 – 2024 - **IRON** (Inelastic Reactions on ^{56}Fe induced by nucleons) [PN-III-P4-PCE-2021-0490]

2022 – 2023 – Comparative study of the (n,n') and (p,p') reactions on 40Ca [PN-III-P1-1.1-PD-2021-0207]

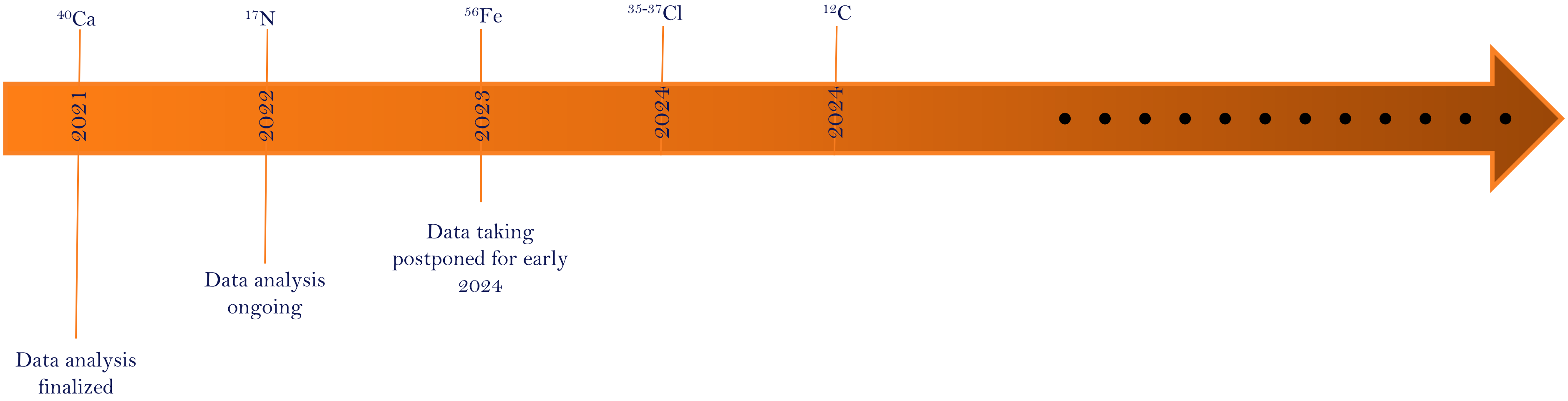
2017 – 2019 - **NP_INEL** (Precise neutron inelastic and charged particle reaction cross sections as a tool for a better understanding of nuclear reaction mechanisms) [PN-III-P4-ID-PCE-2016-0025]

Conclusions

Conclusions

GAINS – ambitious and very productive experimental program.

GAINS – continuous upgrade in order to respond to the nuclear data community needs.



Thanks

Do you have any questions?

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