Neutron inelastic cross-sections on ^{40}Ca

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The content of this presentation

- scientific motivation for performing the experiment
- experimental setup
- data analysis procedure
- experimental results

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Scientific motivation - I

ADDRESSING NUCLEAR DATA NEEDS ON ^{40}Ca:

- **Inelastic scattering is one of the main neutron energy loss mechanisms inside a reactor**
- **Main isotope: ^{40}Ca makes up 96.9% of natural calcium**
- **LiF-CaF_2 melt - promising candidate for GEN IV Molten Salt Reactors (MSRs)**
  - **fuel candidates for MSRs: fluorides of fissile (UF_4) and fertile (ThF_4) elements dissolved in carrier salts**
  - **very good online processing capabilities of the burned fuel (via electrochemical separation of both uranium and thorium and most of the fission products)**
- **Status of the experimental data prior to our experiment:**
  - **only 3 (angle-integrated) γ-production cross section points at 17 and 22 MeV for the main transition (3736 keV)**
  - **no angle-integrated data below 17 MeV**
  - **one data set of differential (measured at 90°) cross section values**
  - **one data set with level cross section values in the low neutron energy region (4-6 MeV)**

Scientific motivation - II

AIDING THE THEORY SIDE:

Providing reliable and very low uncertainty reaction observables for the continuous refinement of

reaction models → **reaction codes: TALYS, EMPIRE...**

The incident energy range of interest for our group: **few hundreds keV to 20 MeV** → mainly **inelastic channel**

Scientific motivation - III

EXPLORATORY STUDIES:

Not (really) covered in today's talk!!!

Scientific motivation - III

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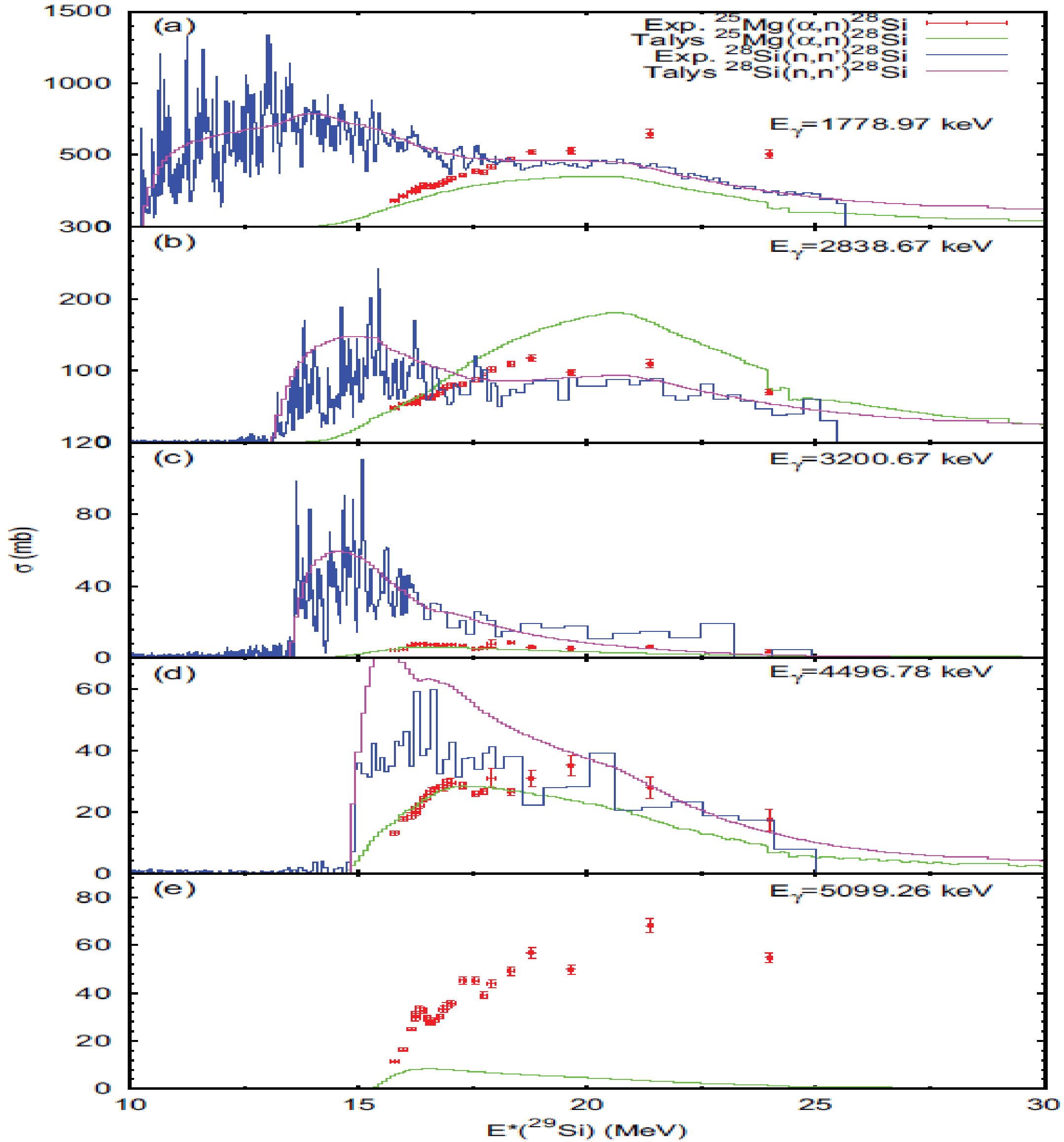
"Surrogate"-type approach for the inelastic channel: → **Inferring neutron cross sections from charged particles-induced reactions**

TRY NO. 1: ^{28}Si(n, $n'\gamma$)^{28}Si vs ^{25}Mg(α, $n\gamma$)^{28}Si A. Negret *et al.*, Phys. Rev. C **88**, 034604 (2013)

^{29}Si*

Bohr hypothesis for compound nucleus CN (which dominates at low incident energies)

Scientific motivation - III



TAKE AWAY MESSAGE:
The γ-production cross sections excited in the two reactions are indeed of the same order of magnitude, BUT an attempt to directly relate the (n,n') channel and its surrogate yields uncertainties of at least 50%.

FIG. 5 A. Negret, *et al.*, Phys. Rev. C 88, 034604 (2013)
Gamma production cross sections in the ^{28}Si(n, $n'\gamma$)^{28}Si and the ^{25}Mg(α, $n\gamma$)^{28}Si reactions as a function of the excitation energy in the compound nucleus ^{29}Si

Scientific motivation - III

Surrogate study for ^{95}Mo(n,γ)

A. Ratkiewicz, J. E. Escher, et al. PHYSICAL REVIEW LETTERS 122, 052502 (2019)

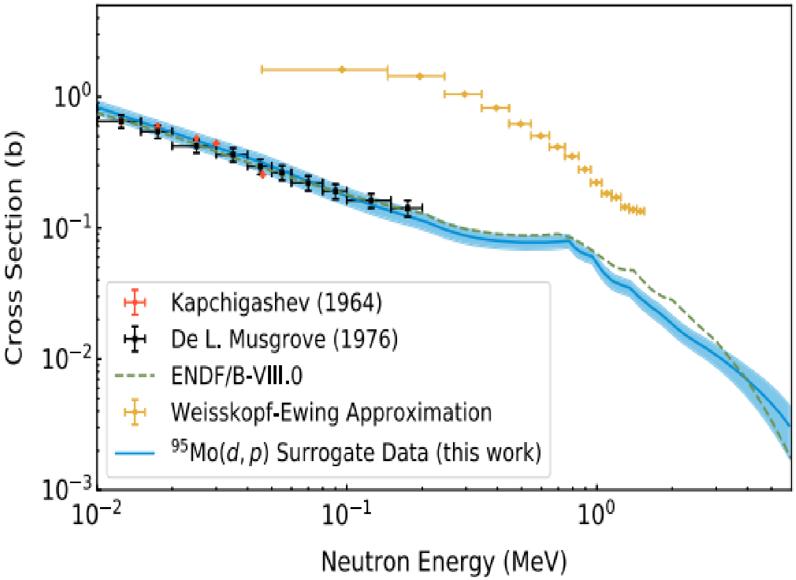


FIG. 5. Cross sections for the ^{95}Mo(n, γ) reaction. The (n, γ) cross section obtained from the SRM (solid blue curve) is in excellent agreement with direct measurements of the cross section [15,36] (red circles and black squares). The uncertainty due to experimental data and fitting error is indicated by the shaded band. The result obtained using the WE approximation is also shown (gold diamonds).

WHY IS THIS NOT WORKING FOR THE INELASTIC CHANNEL?

It seems that for both capture and inelastic channels one needs, <u>on a target-by-target basis</u>, a very detailed handling of the CN spin-parity population differences
NOT TRIVIAL!!!

↓

Oliver C. Gorton, J. E. Escher, PHYSICAL REVIEW C **107**, 044612 (2023)

Scientific motivation - III

“Surrogate”-type approach for the inelastic channel: ⇒ **Inferring neutron cross sections from proton-induced reactions**

TRY NO. 2:

Scientific motivation - III

“Surrogate”-type approach for the inelastic channel: ➡ **Inferring neutron cross sections from proton-induced reactions**

TRY NO. 2:

Minimize the OMP differences

Scientific motivation - III

"Surrogate"-type approach for the inelastic channel: → **Inferring neutron cross sections from proton-induced reactions**

TRY NO. 2:
Minimize the OMP differences

$^{16}O(n, n'\gamma)^{16}O$ versus $^{16}O(p, p'\gamma)^{16}O$

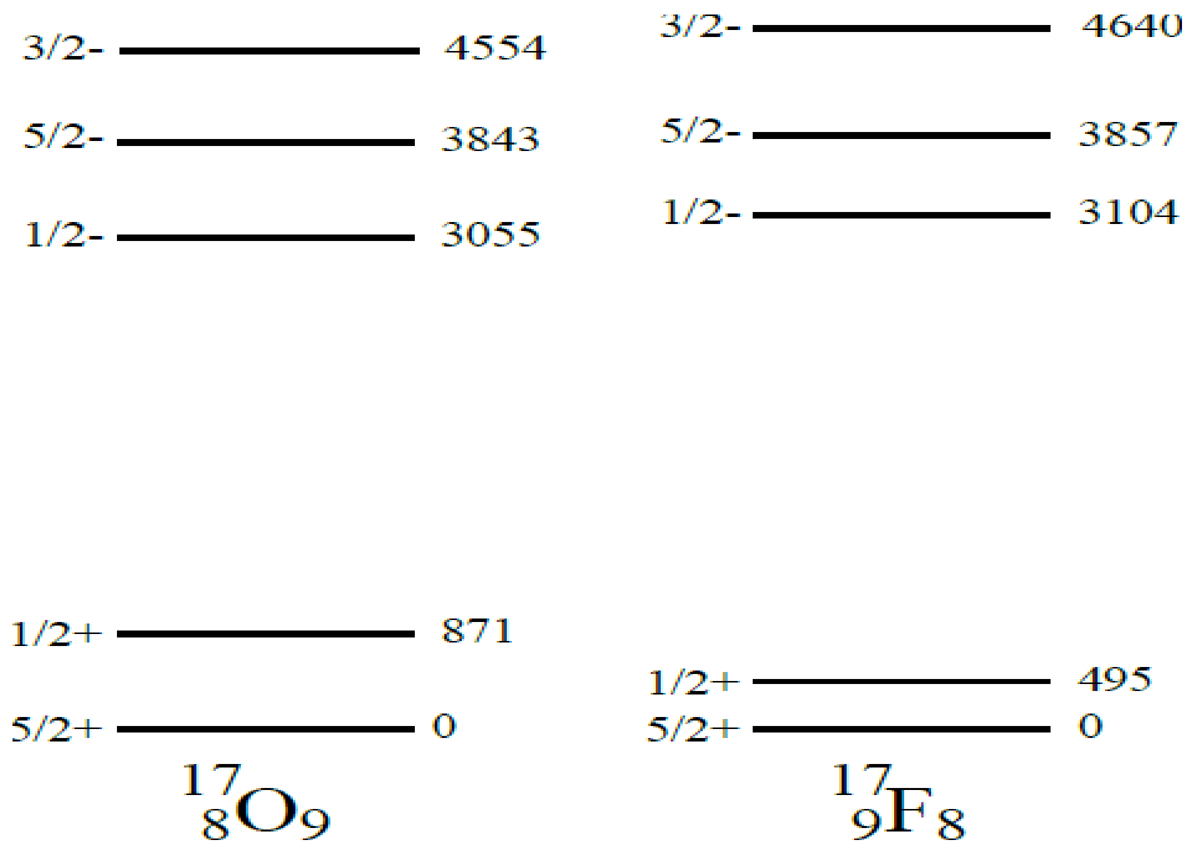
CN: ^{17}O **CN: ^{17}F**

Not the same compound nucleus (as in the above study)

Now we make use of the **isospin symmetry**

Scientific motivation - III

Partial level schemes of ^{17}O and ^{17}F mirror nuclei through which the two corresponding neutron and proton reactions on ^{16}O proceed



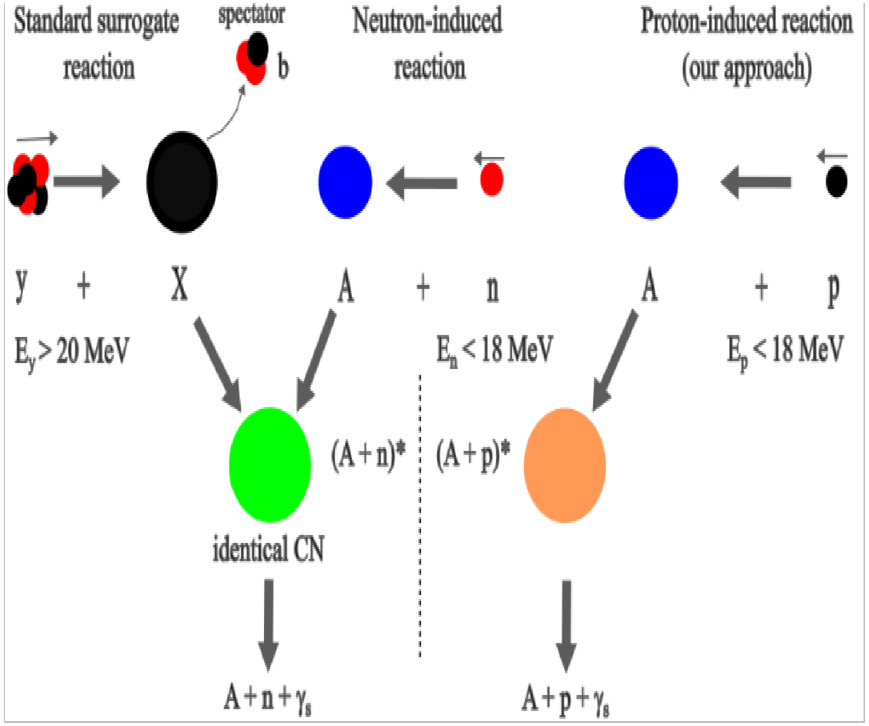
Scientific motivation - III

EXPLORATORY STUDIES:

"Surrogate"-type approach for the inelastic channel: ⇒ **Inferring neutron cross sections from charged particles-induced reactions**

TRY NO. 2: **NOT REALLY A SURROGATE!!!**

Scientific motivation - III

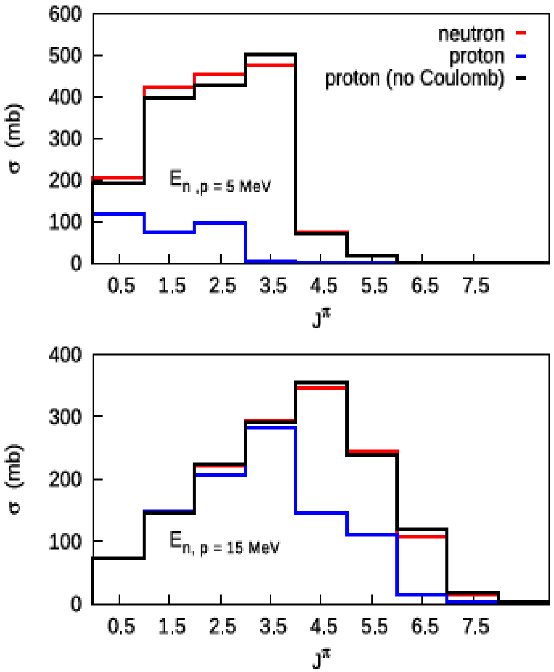


Complementary to "standard" surrogate!

- very <u>different</u> OMPs in the input channel
- <u>identical</u> residual/final nuclei
- Weisskopf-Ewing limit of CN reactions MUST hold

VERSUS

- <u>extremely similar</u> OMPs in the input channel
- <u>different</u> CN => nuclear structure-induced differences☹
- we do not really care about the Weisskopf-Ewing approximation☺

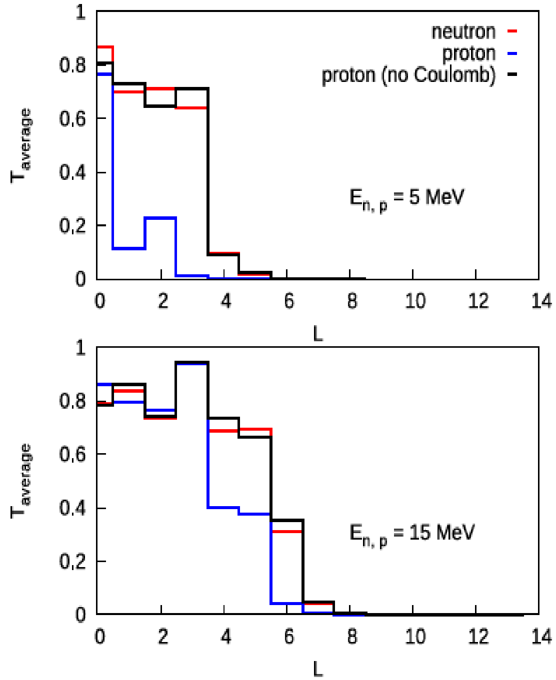


J populated in CN

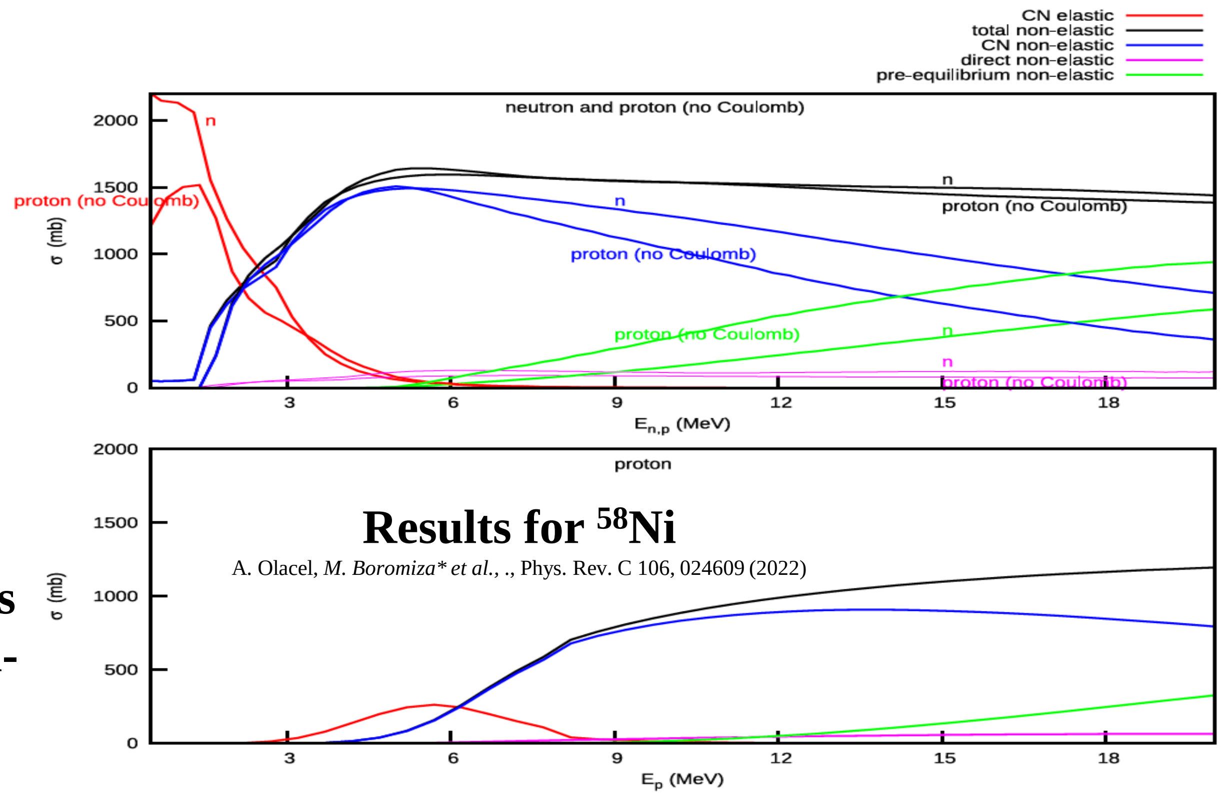
Results for ^{58}Ni

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

Different reaction observables for 3 projectiles: a neutron, a proton and a proton whose Coulomb term was removed from the proton-^{58}Ni OMP



Transmission coefficients populated in CN



Results for ^{58}Ni

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Different reaction contributions for 3 projectiles: a neutron, a proton and a proton whose Coulomb term was removed from the proton-^{58}Ni OMP

Scientific motivation - III

Inferring the neutron inelastic channel from proton-induced cross sections

- **Inspired by the surrogate reactions method**
- **A combination of experiment & theory**
- **Nuclei studied so far:**

Not (really) covered in today's talk!!!

- ^{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)
- **UP NEXT: ^{40}Ca!!!**

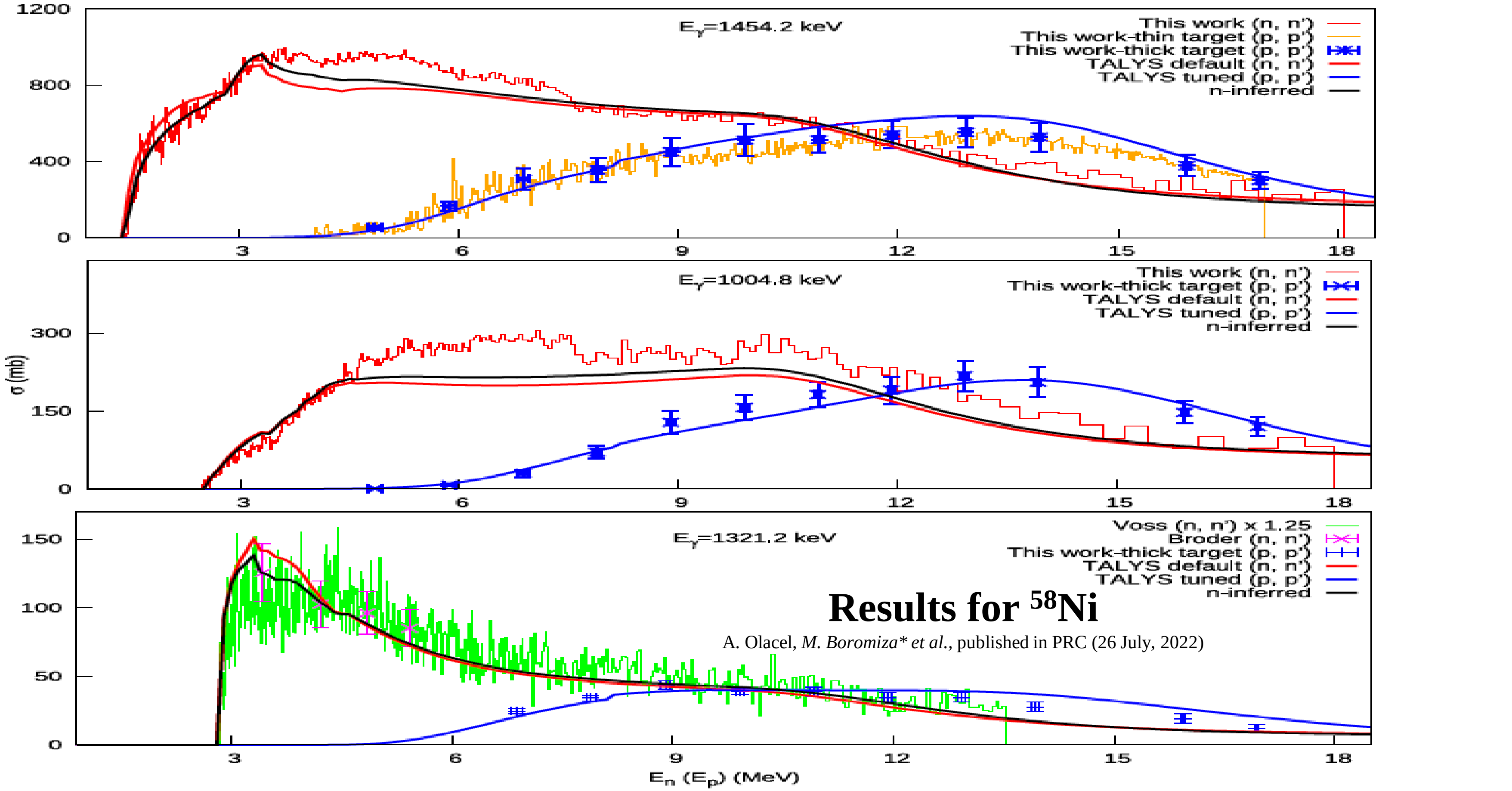
- **WHY?**

a) determining the neutron cross sections from a much **simpler-to-measure** reaction
b) extracting information about the **isospin-dependent term & Lane consistency** of the nucleon-target OMP

THE GENERAL IDEA:

- Starting from a Lane-consistent proton OMP, tune this potential on proton experimental data
- Construct/infer a Lane-consistent neutron-like OMP from the proton case above
  - drop its Coulomb term
  - invert the sign of its Lane term
  - …
- Calculate **proton-inferred** neutron-like inelastic cross sections
- Compare to the experimental data actually measured at GELINA

HOW WELL DOES THIS WORK?
thus far…



Results for ^{58}Ni

A. Olacel, *M. Boromiza* et al.*, published in PRC (26 July, 2022)

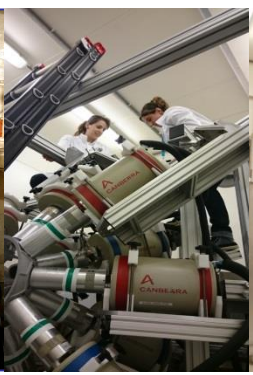
Experimental setup

- ❑ scientific motivation for performing the experiment
- ❑ **experimental setup**
- ❑ data analysis procedure
- ❑ experimental results

Experimental setup

→ *Neutron* inelastic scattering cross section measurements @ GELINA

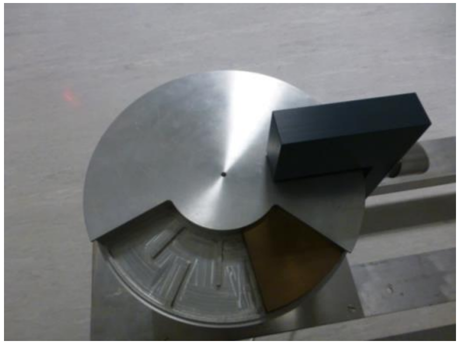


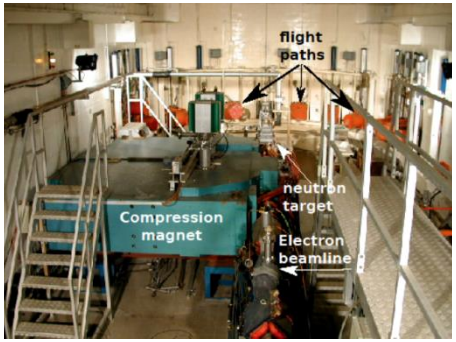



Experimental setup

GELINA
Geel Eelectron LiNear Accelerator

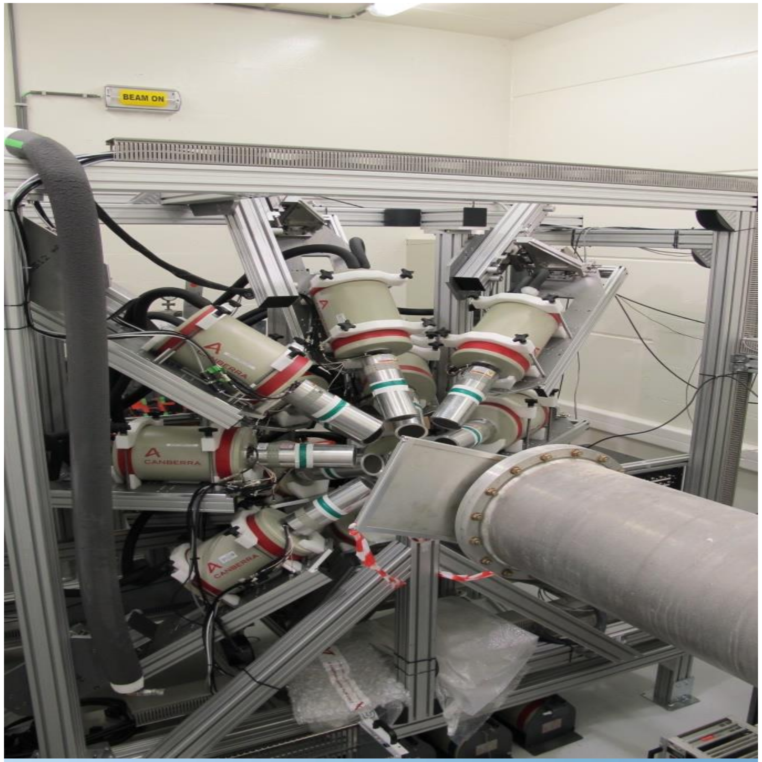
- Linear accelerator
  - $E_e \approx 70 – 140$ MeV
  - $\Delta t < 1\text{-}2$ ns
- Rotating depleted uranium target
- $0 < E_n < 20$ MeV
- Multi-user facility
- Flight paths and measurement cabins: 10 ÷ 400 m
- Time-of-Flight (ToF) technique
- High resolution measurements





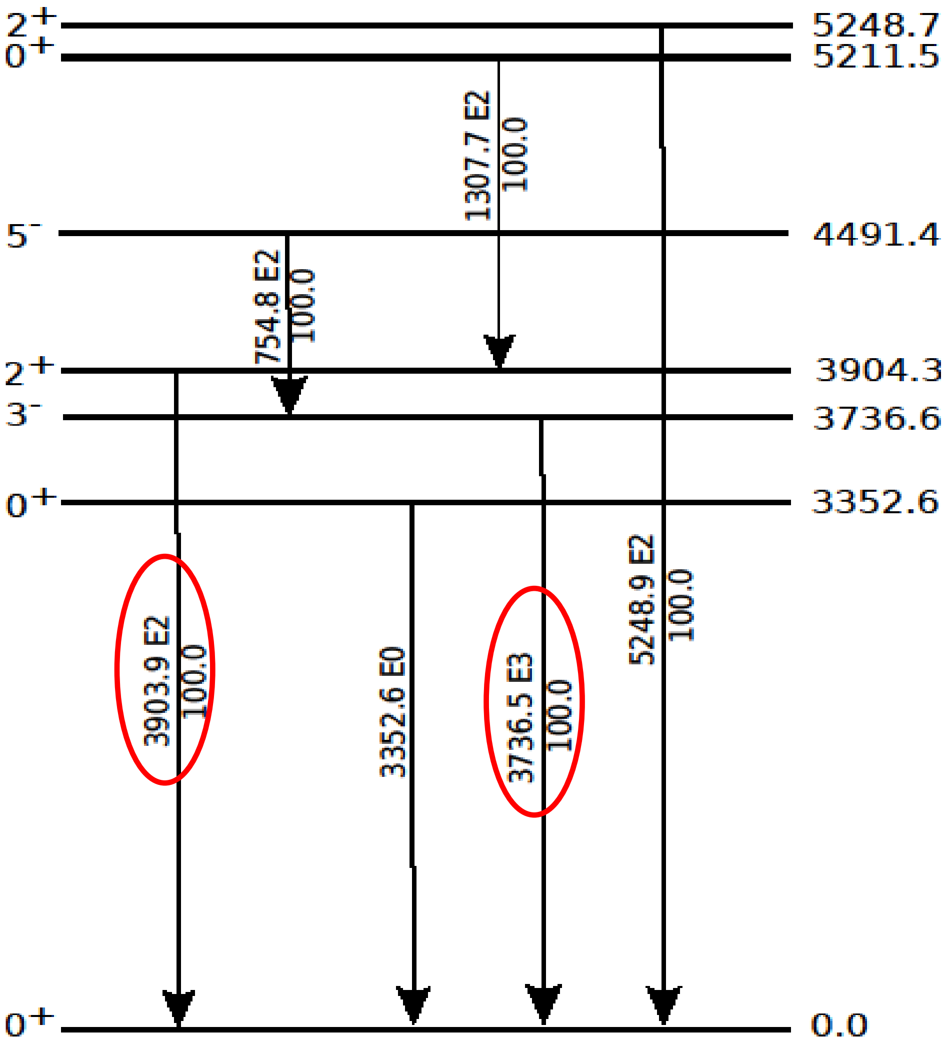
Experimental setup

GAINS
Gamma Array for Inelastic Neutron Scattering



- Flight path 3 @ 100 m
  - good neutron energy resolution
  - **@ 100 m**: 3 keV at 1 MeV, 80 keV at 10 MeV
- 12 HPGe detectors @ 110º, 150º and 125º, d=17 cm
- Large volume: relative efficiency 100%
- FWHM typically ≈ 3 keV @ 1332 keV (^{60}Co)
- Digital acquisition (ACQIRIS digitizers)
  - 12 bit amplitude resolution (4096 channels)
  - 420 MS/s (2.38 ns sampling period)
- **Target**: calcium fluoride compound (CaF_2)
- **Fission chamber (with ^{235}U deposits) to monitor the neutron flux - $^{235}U(n,f)$ normalization**
- **Time of Flight (ToF) & γ-spectroscopy techniques**:
  - n time of flight → E_n
  - pulse amplitude → E_γ

Preparing the experiment: main difficulties



- Target preparation: compound CaF_2 (as ^{40}Ca has a 96.9 % natural abundance):
  - Weak transitions: thick target
  - Keep the γ self-attenuation + MSC to reasonable values
  - 2 mm thickness and 76 mm diameter (beam: 61 mm)
- Very high energy γ rays: 3736 keV (3^-), 3903 keV (2^+) and 5248 keV (2^+):
  - large volume HPGe
  - tricky efficiency extrapolation up to 4 or even 5 MeV

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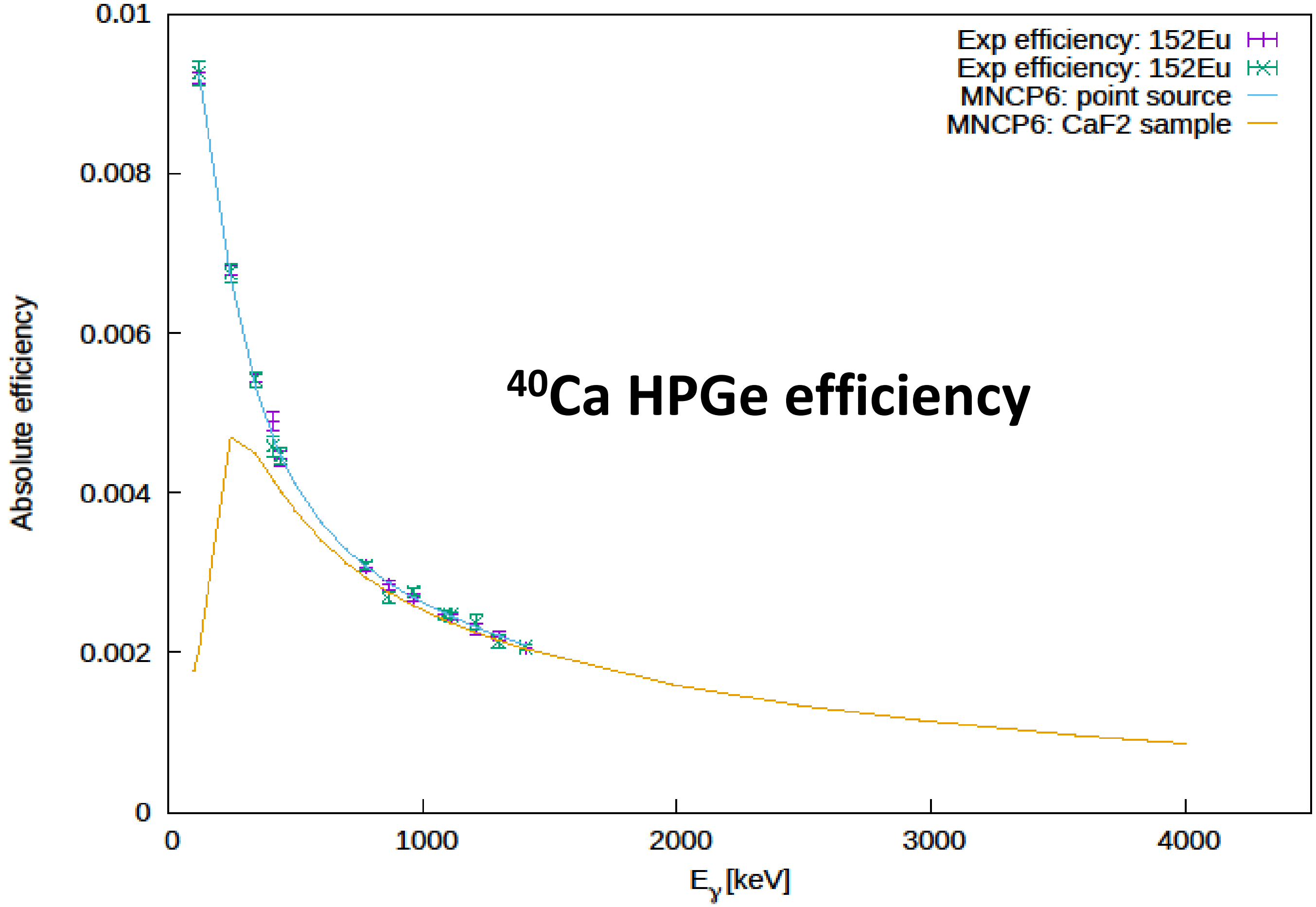

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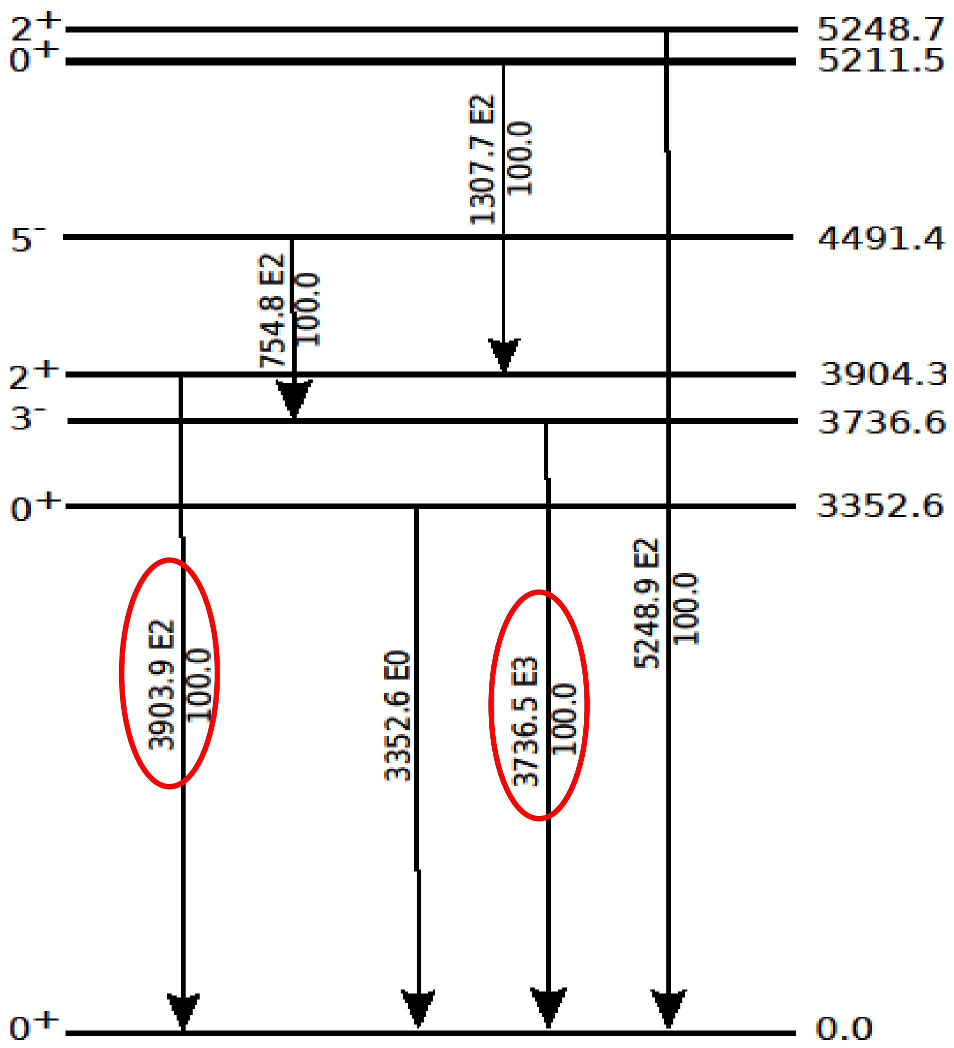

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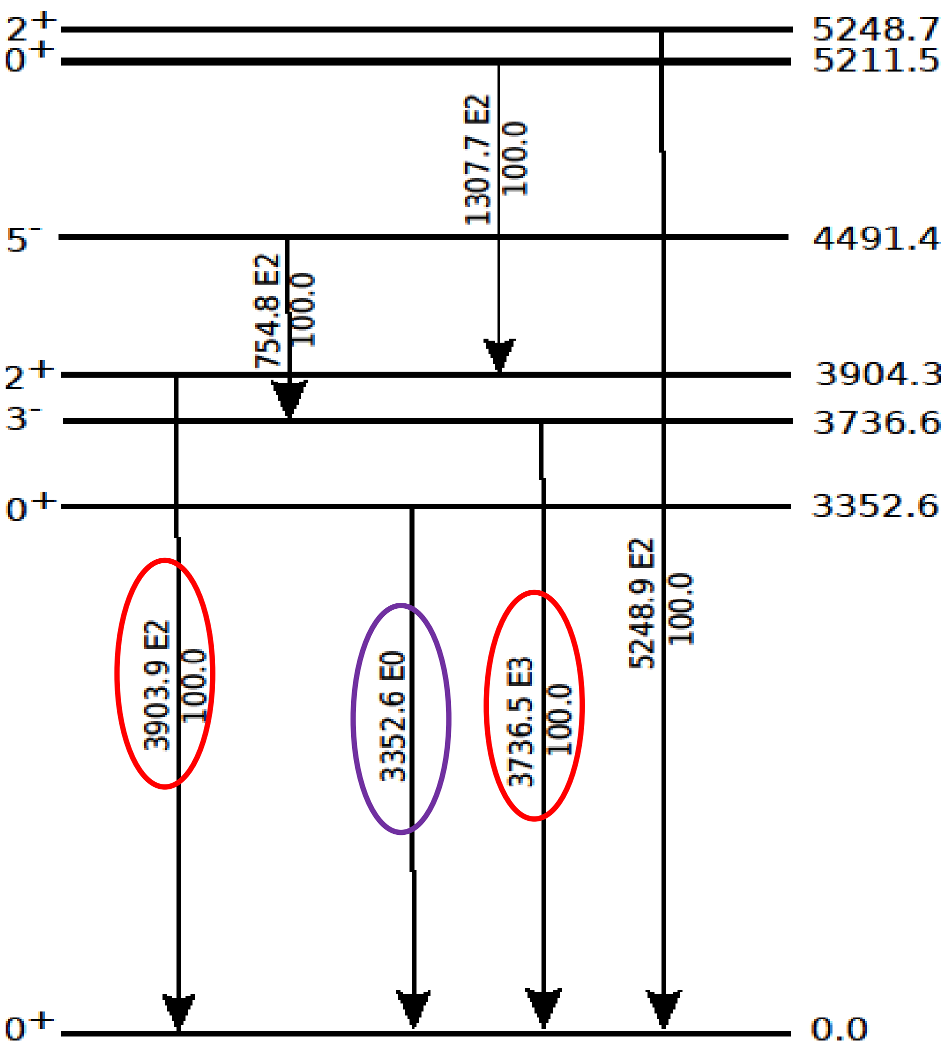

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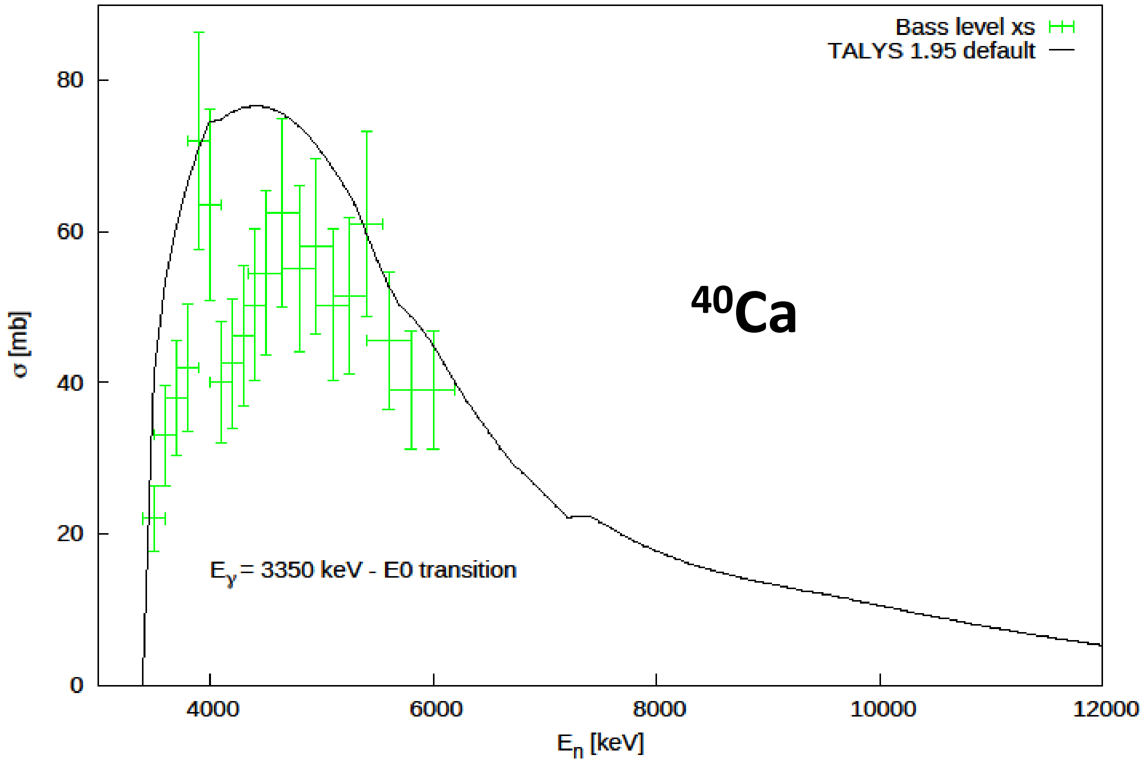

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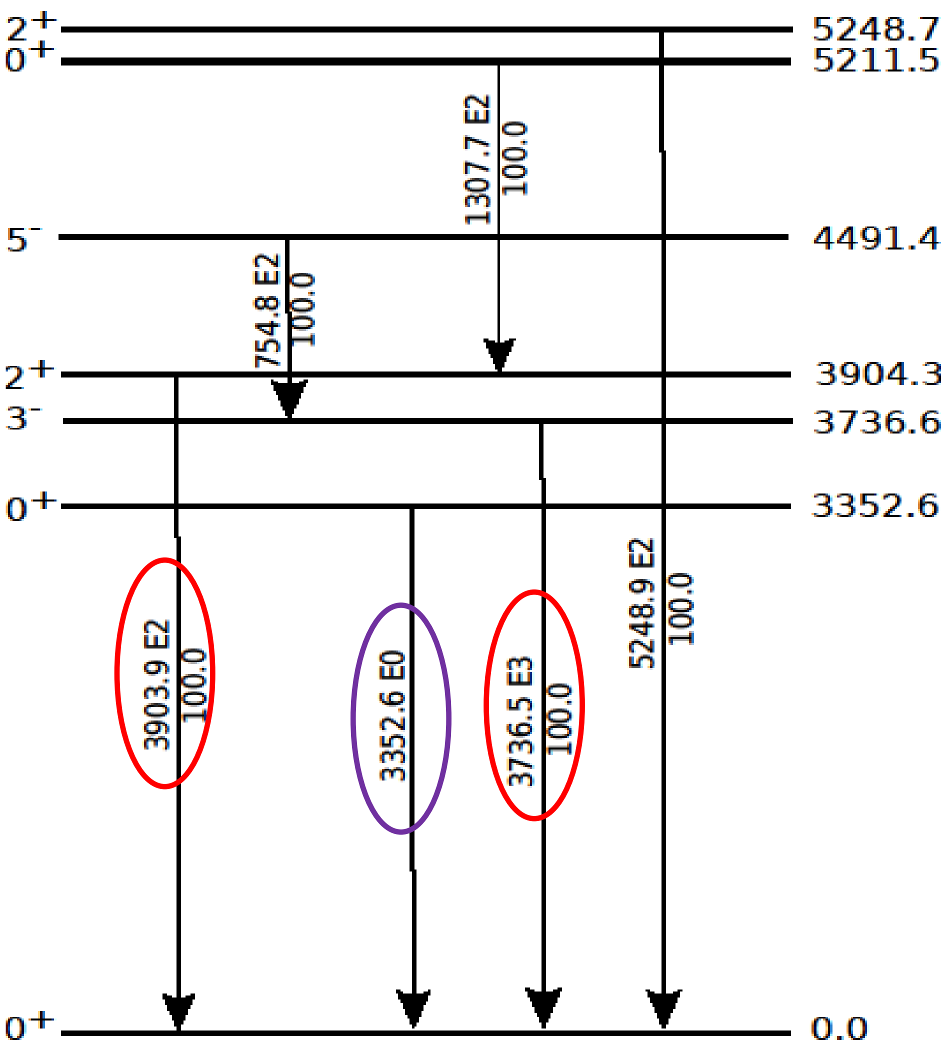

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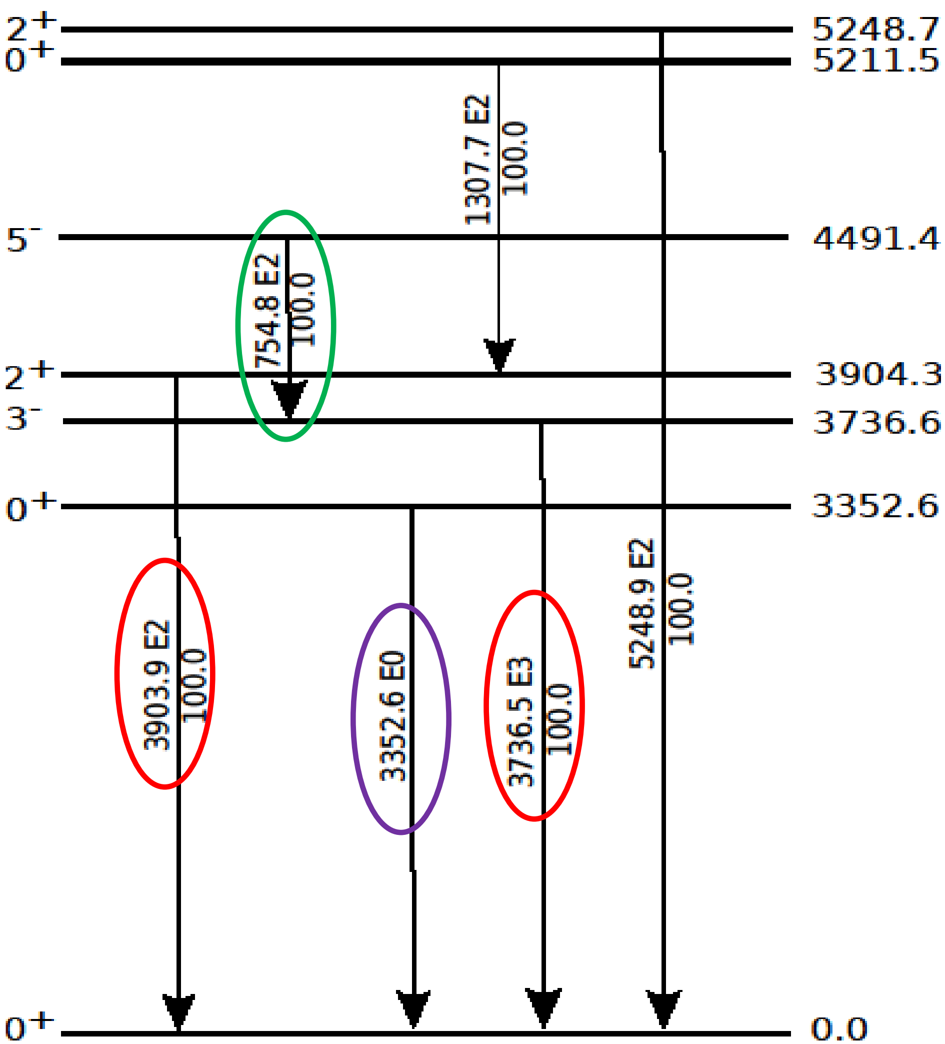

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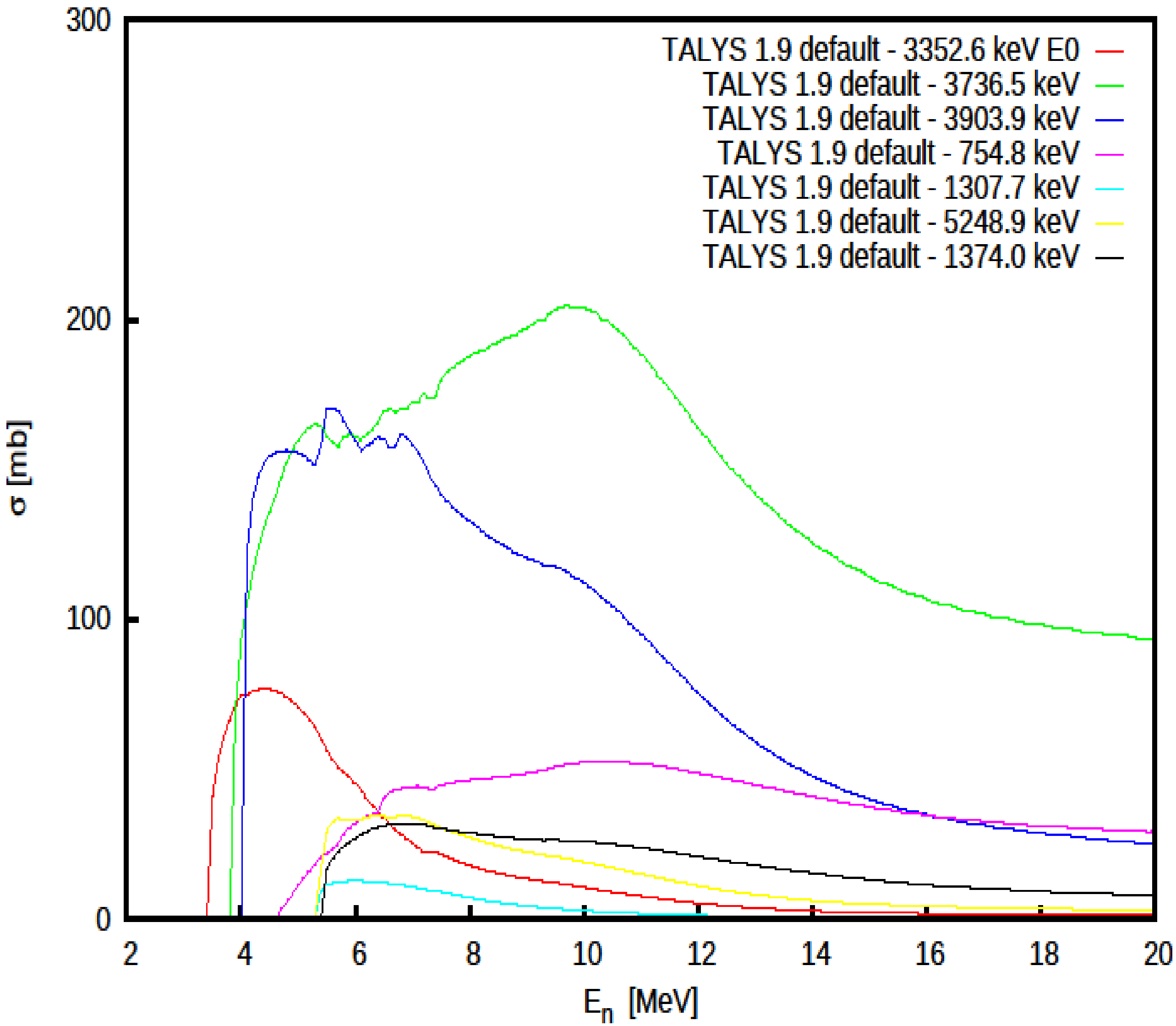

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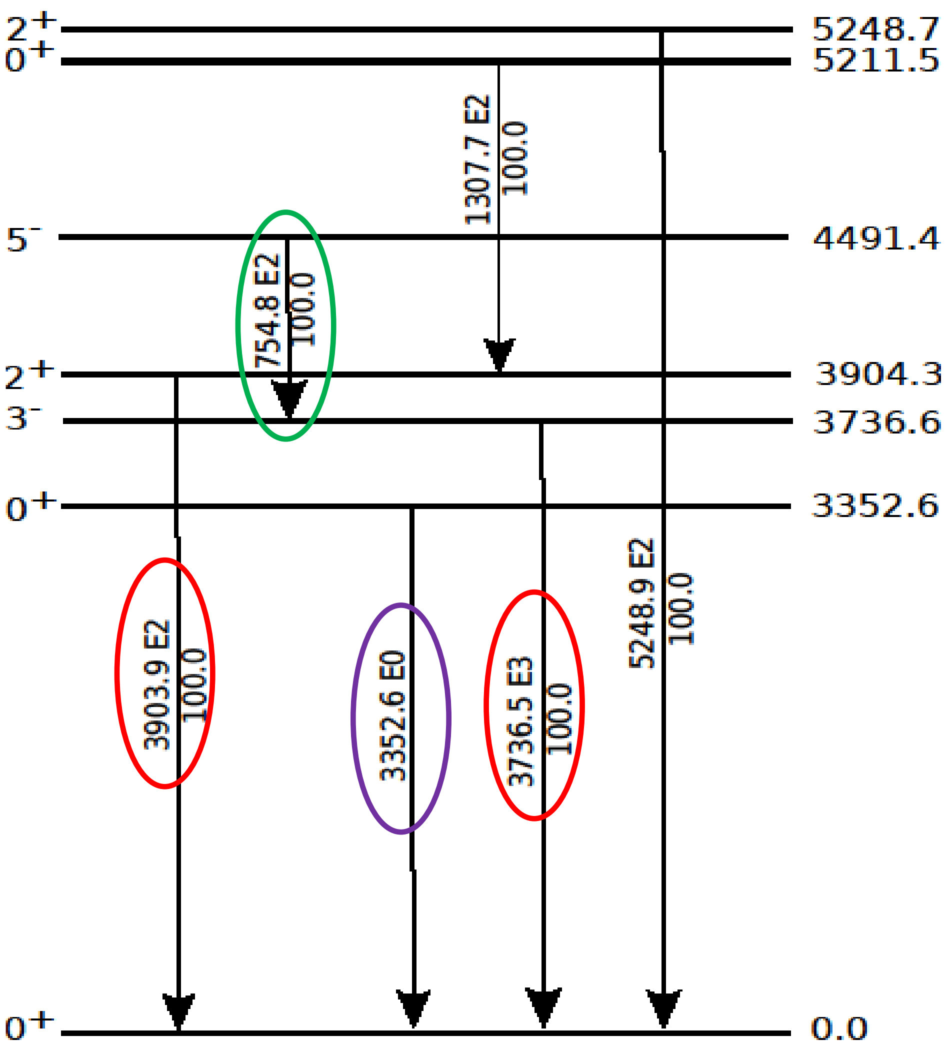

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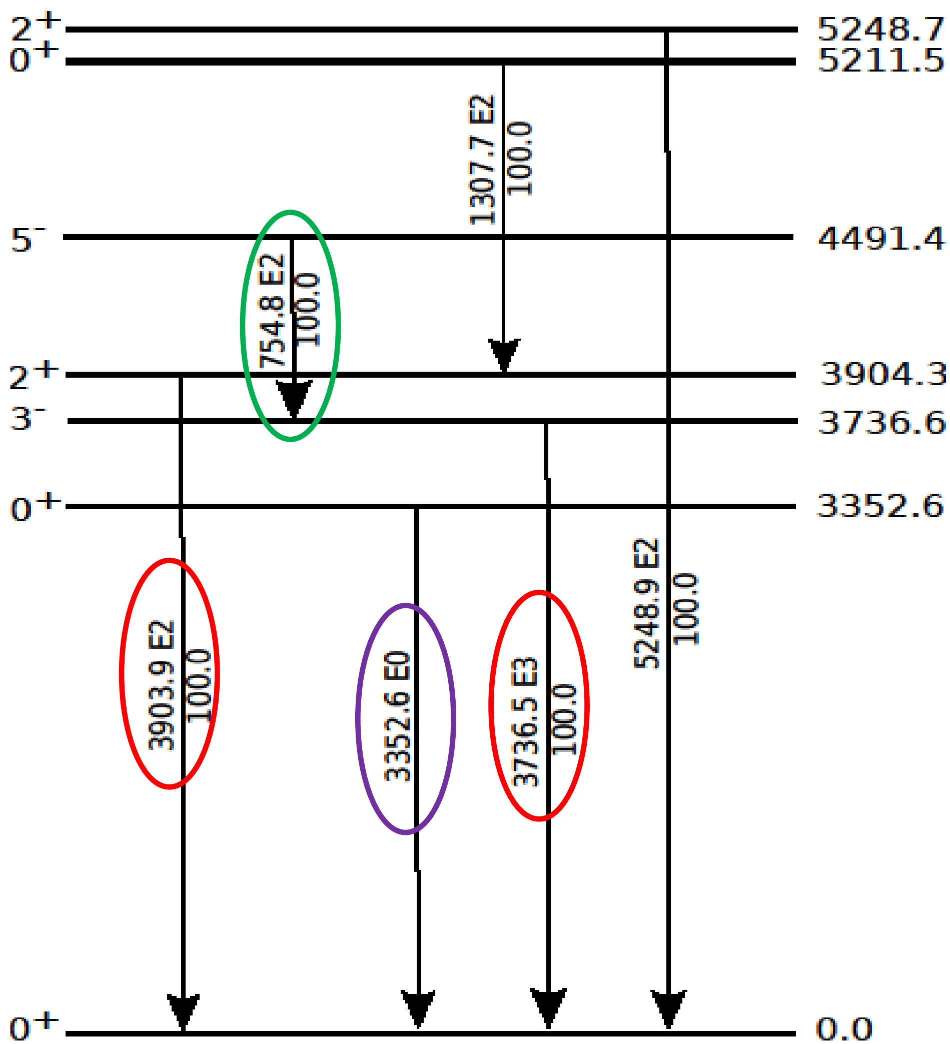

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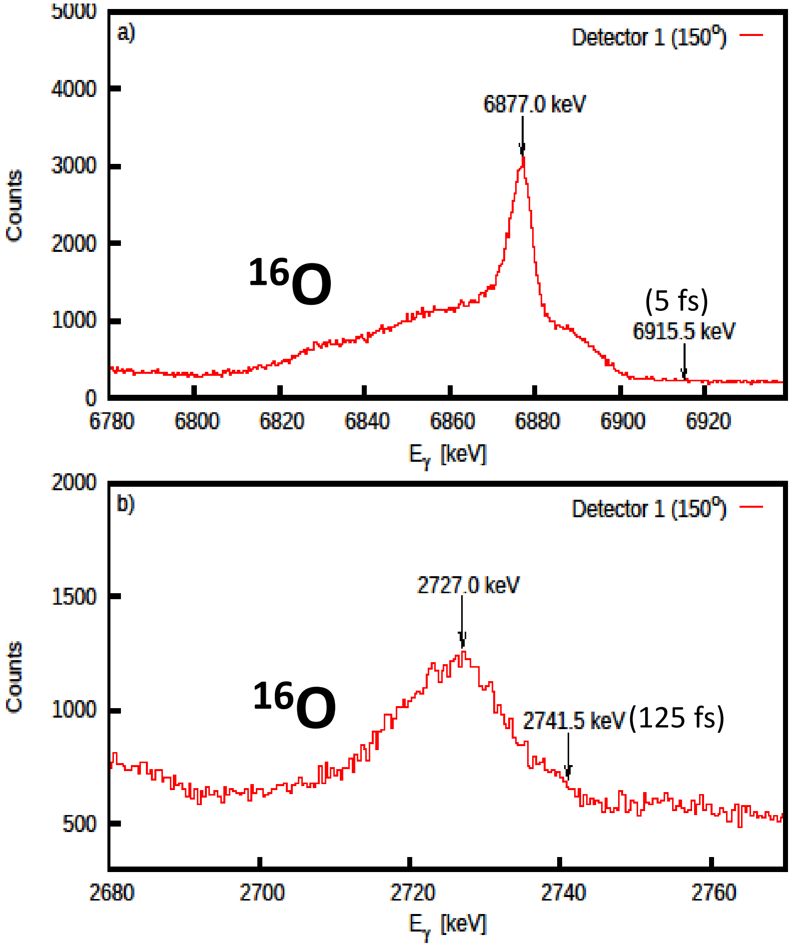
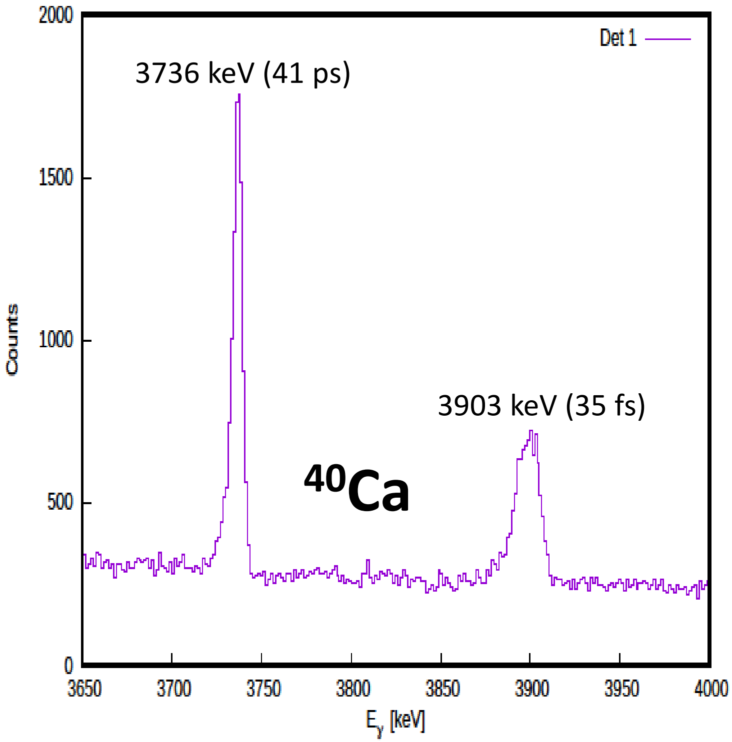
Preparing the experiment: main difficulties



SRIM stopping powers for ^{40}Ca:
-> yield around 0.5-1 ps stopping time



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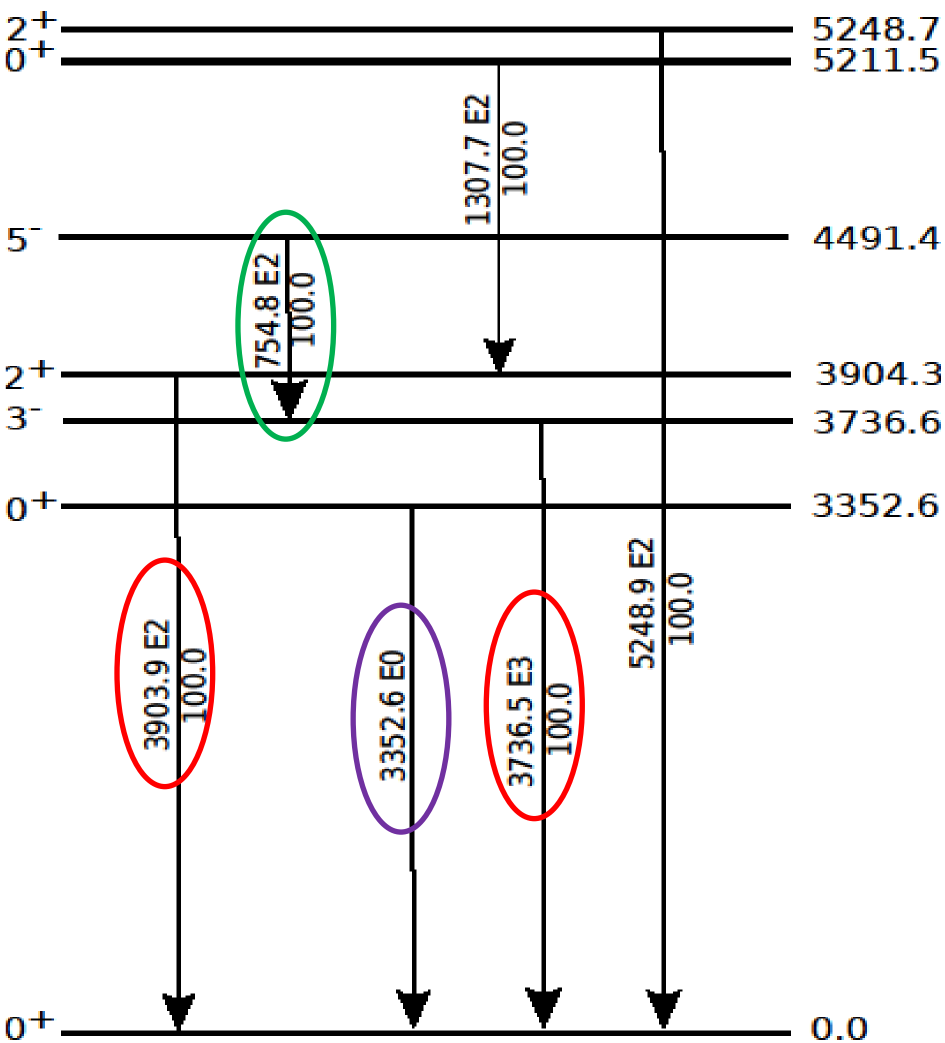

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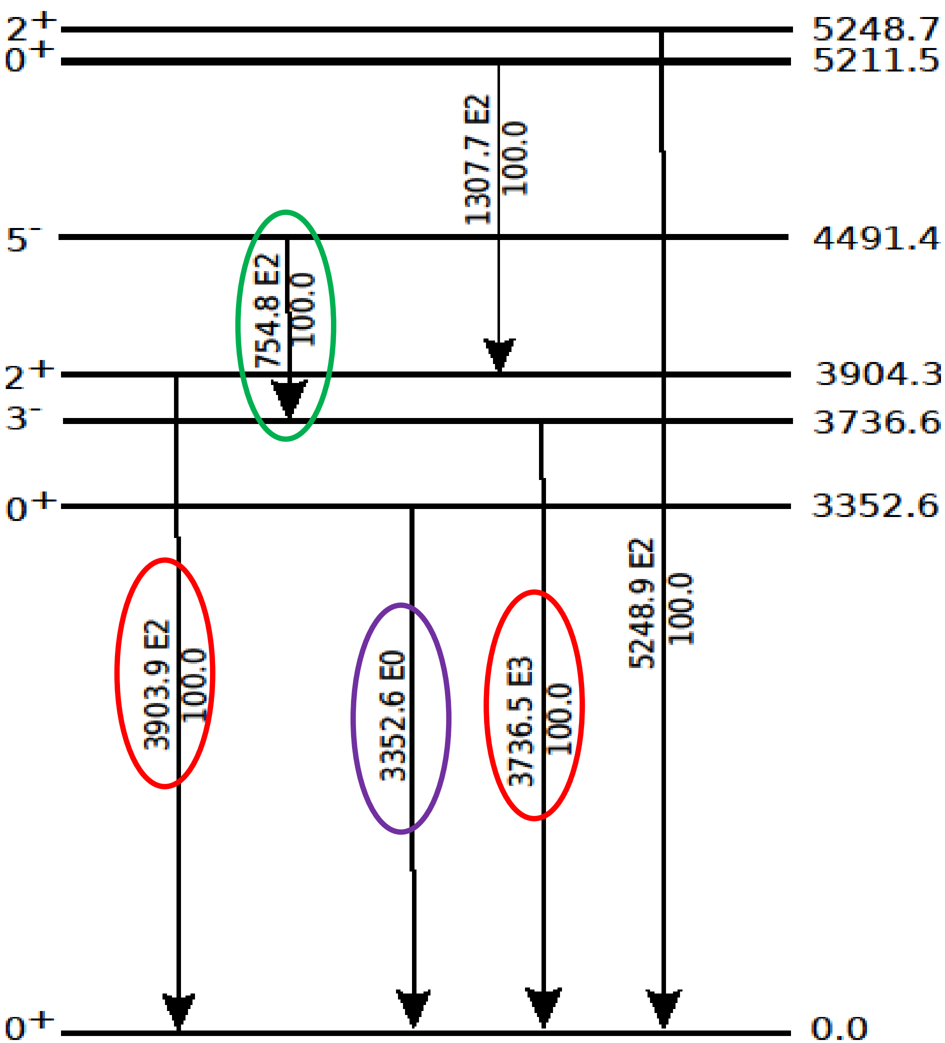

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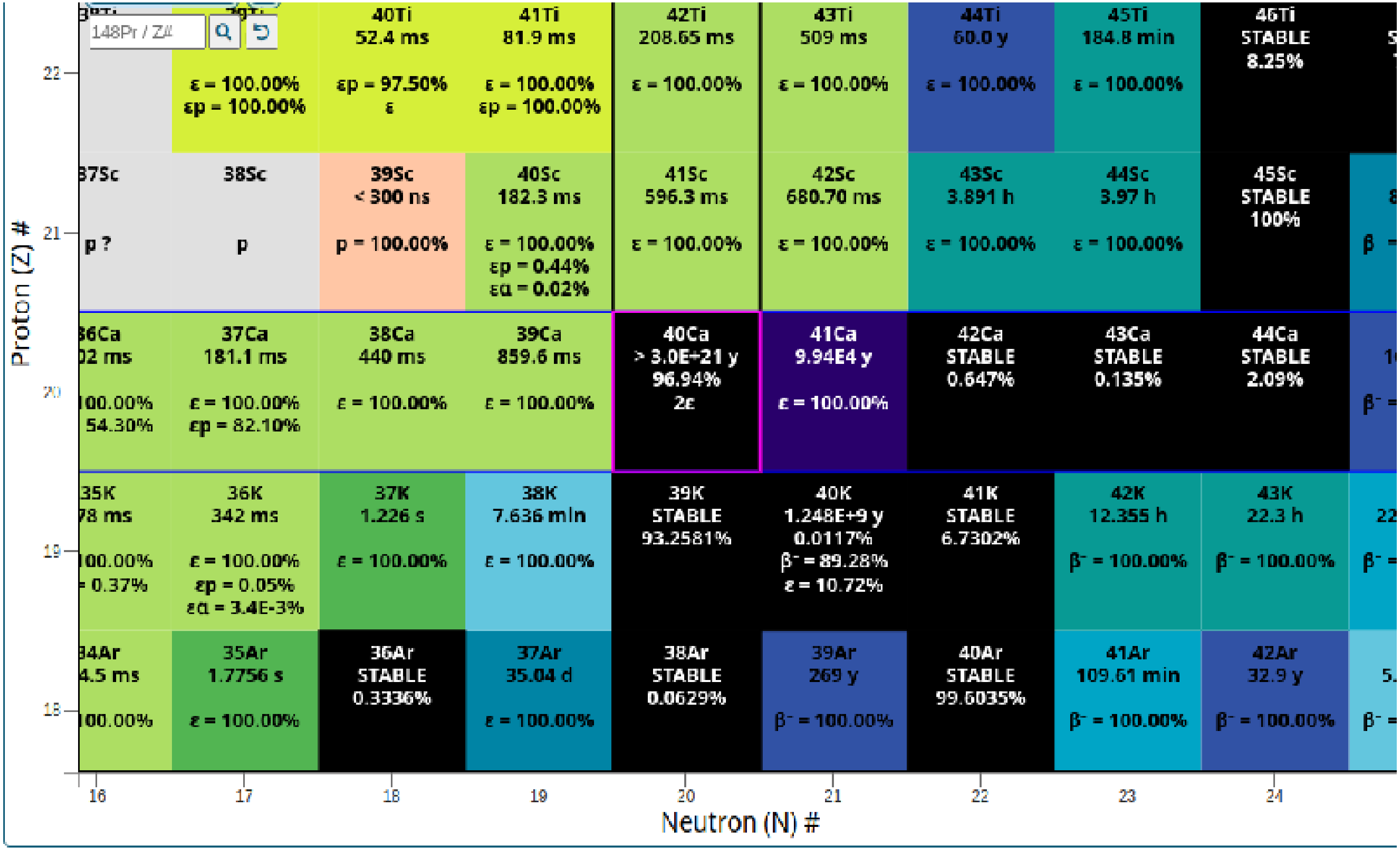
- Additional transitions? Maybe 754 keV…
- We expected **Doppler broadenings** of the peaks of interest: $T_{1/2}$ of 41 ps (3736 keV) and 35 fs (3903 keV)
- Possible contaminants from other reaction channels, mainly $^{40}Ca(n,p)^{40}K$

Preparing the experiment: main difficulties



Data analysis

- ❑ scientific motivation for performing the experiment
- ❑ experimental setup
- ❑ **data analysis procedure**
- ❑ experimental results

Detection technique: γ spectroscopy

IFIN-HH

Neutron inelastic scattering reaction:

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

CN

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

$E^* \approx E_n - E_n'$

$\downarrow$

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

Inelastic cross section: detect outgoing neutrons or gammas

neutrons → **Direct access to Level cross sections**

gammas → **γ-production cross sections** → **Indirect access to** → **Level cross section + Total inelastic cross section**

Data analysis

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

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HPGe detectors ➡

Data analysis

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HPGe detectors → γ yield

Data analysis

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HPGe detectors → γ yield ← Fission chamber

Data analysis

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HPGe detectors ⇒ γ yield + fission chamber yield ⇐ Fission chamber

Data analysis

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HPGe detectors → γ yield + fission chamber yield ← Fission chamber

HPGe detector efficiency interpolation & extrapolation (via simulations - MCNP 6) →

← Other corrections:

- MSC coefficients
- Fission chamber efficiency
- …

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Differential γ-production cross section

Data analysis

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↓

Differential γ-production cross section

↓

Angle-integrated γ-production cross section

Data analysis

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

HPGe detectors → γ yield + fission chamber yield ← Fission chamber

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← Other corrections:
- MSC coefficients
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↓

Differential γ-production cross section

↓

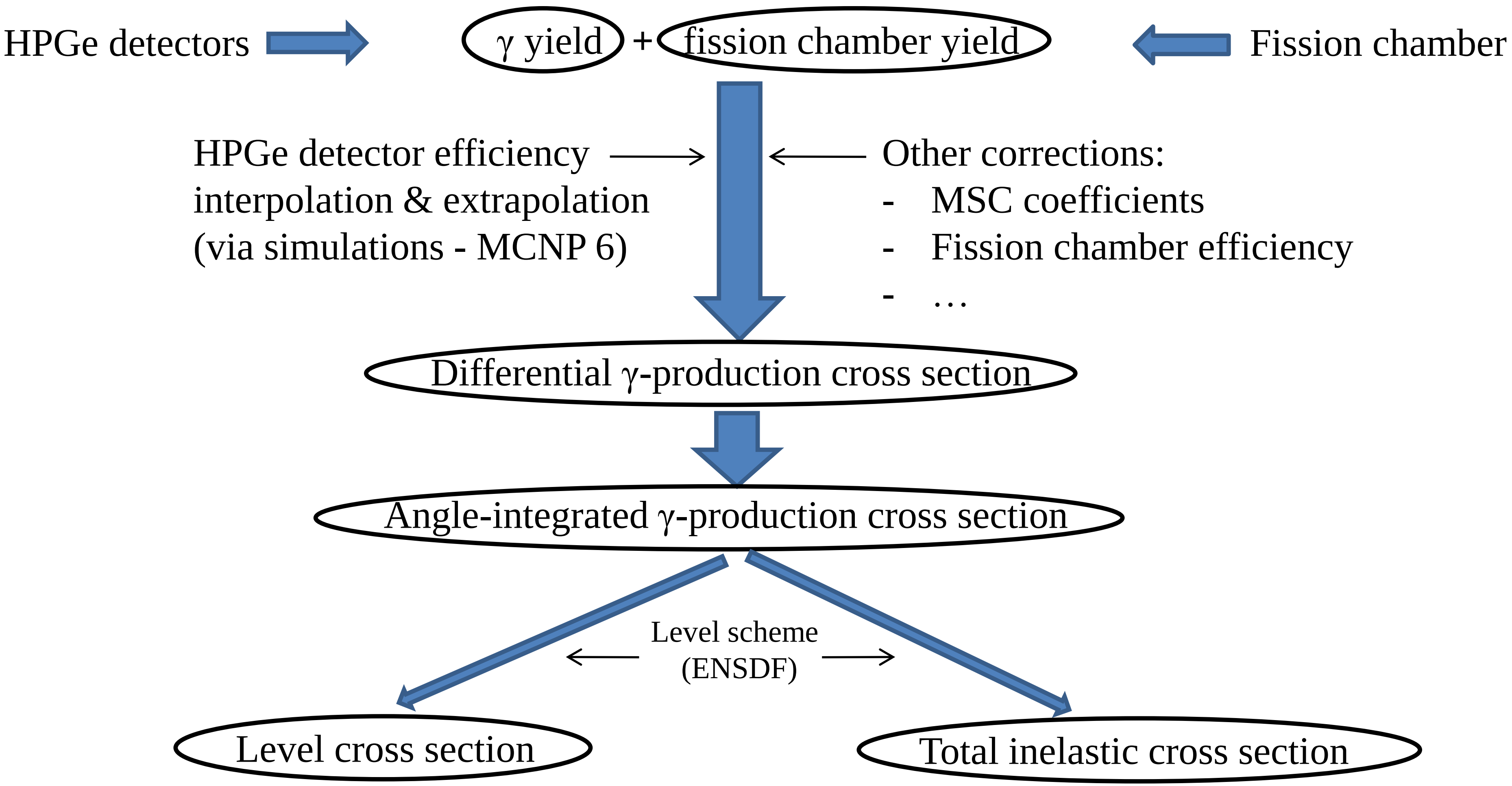
Angle-integrated γ-production cross section

↓ ← Level scheme (ENSDF)

Level cross section

Data analysis

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



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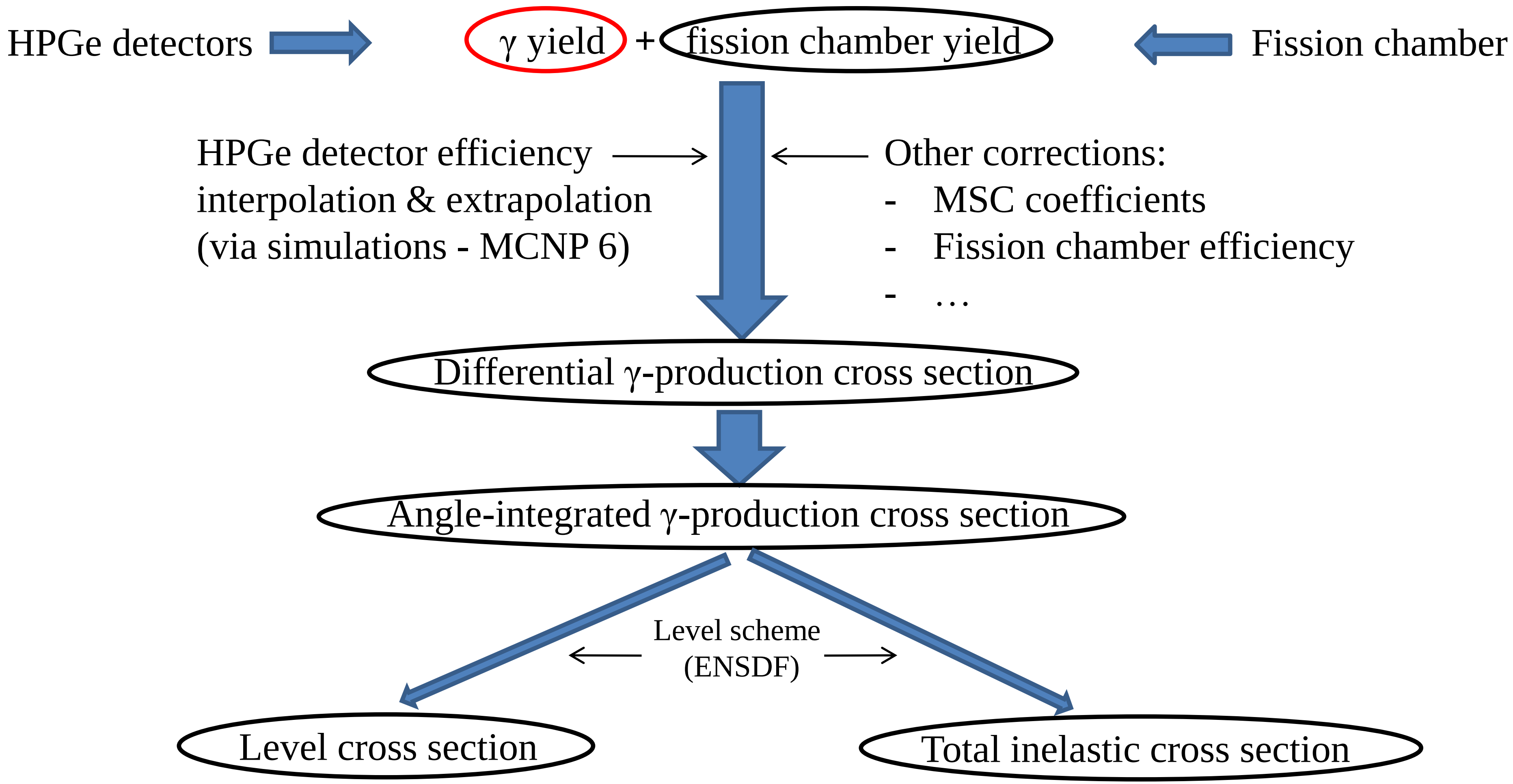
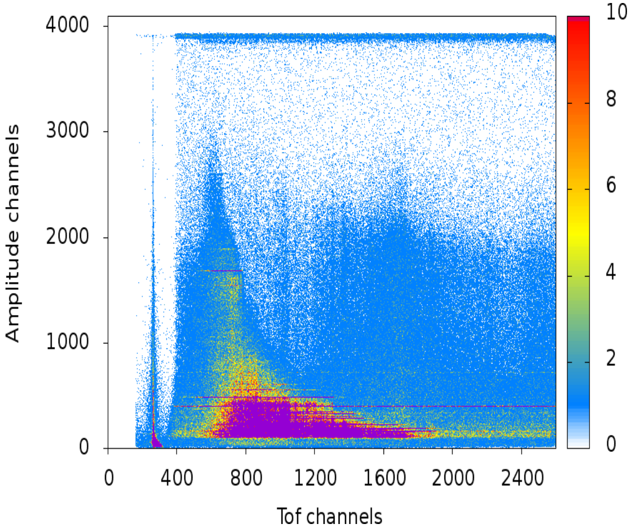
- γ–spectroscopy measurements coupled with time of flight method
- we extract cross sections normalized to the very well known ^{235}U(n, fission) cross section



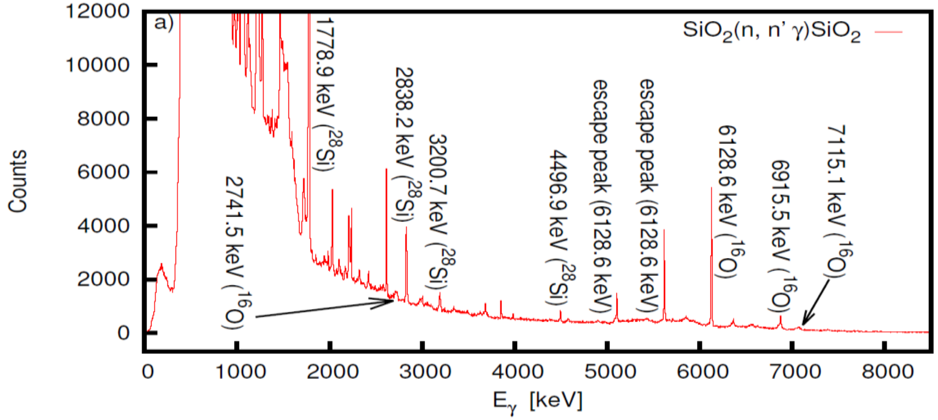
- **γ–spectroscopy measurements**

The time-amplitude matrix of one HPGe detector

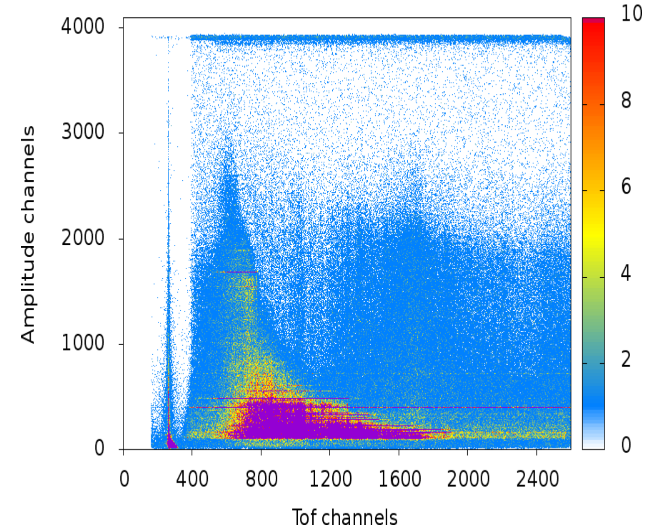


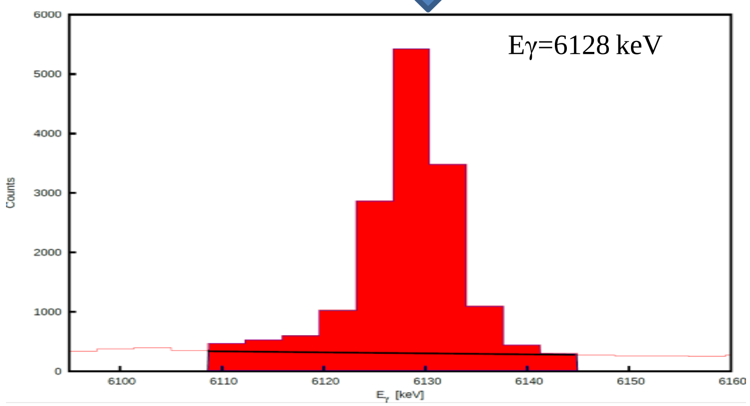
Data analysis

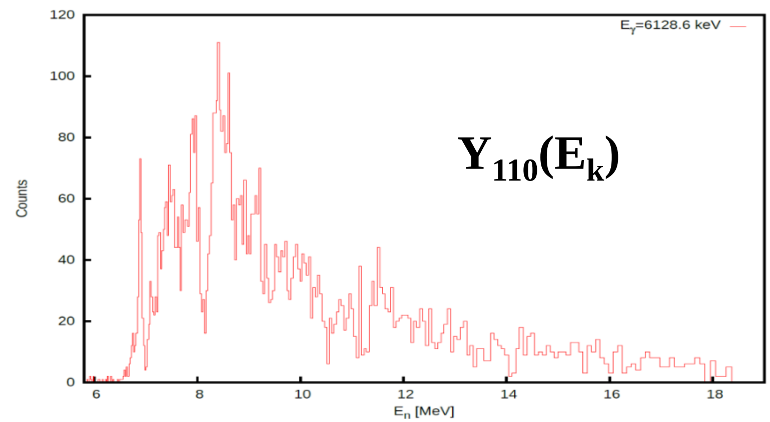
➢ γ–spectroscopy measurements



The time-amplitude matrix of one HPGe detector

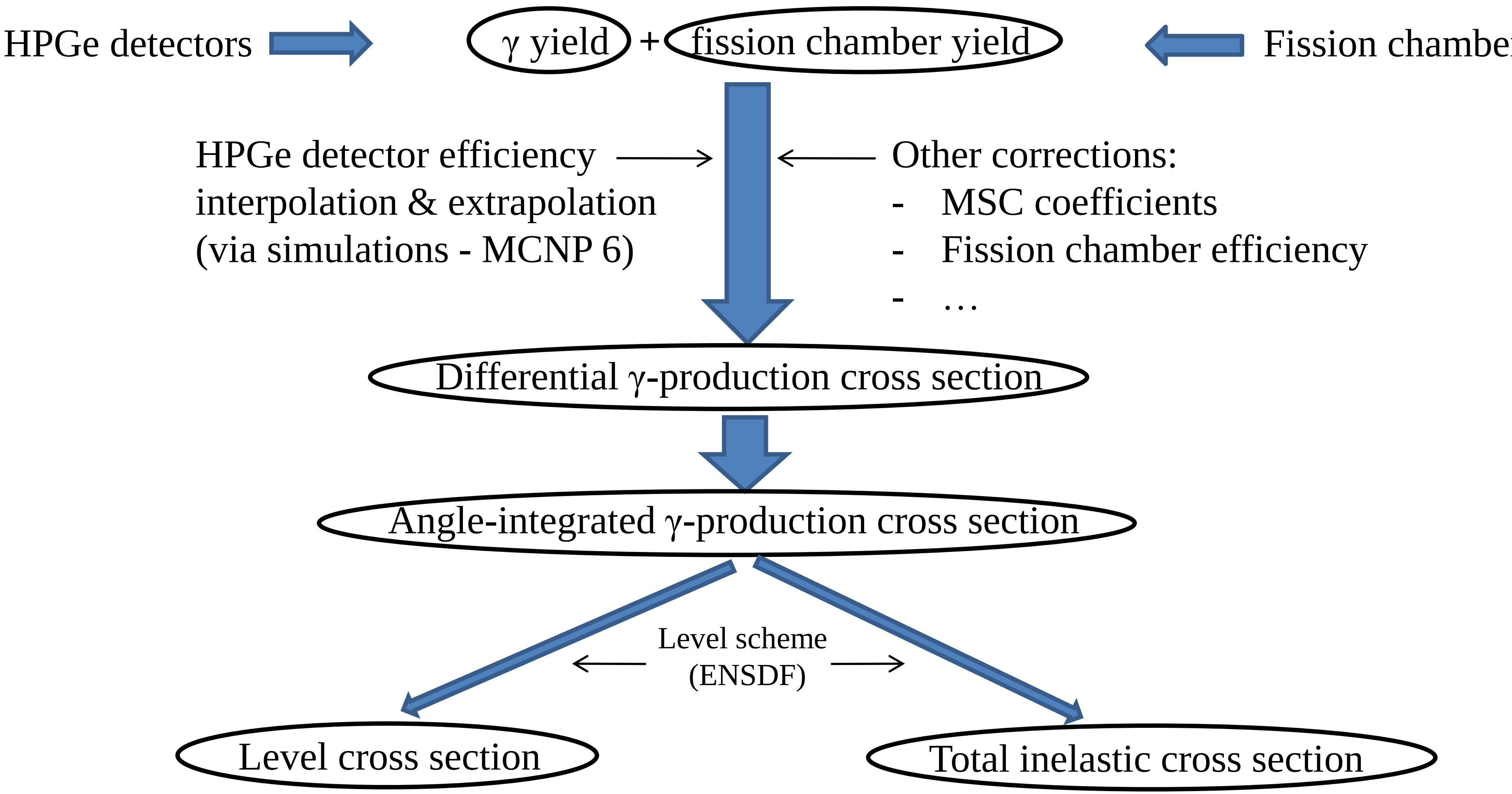






Data analysis

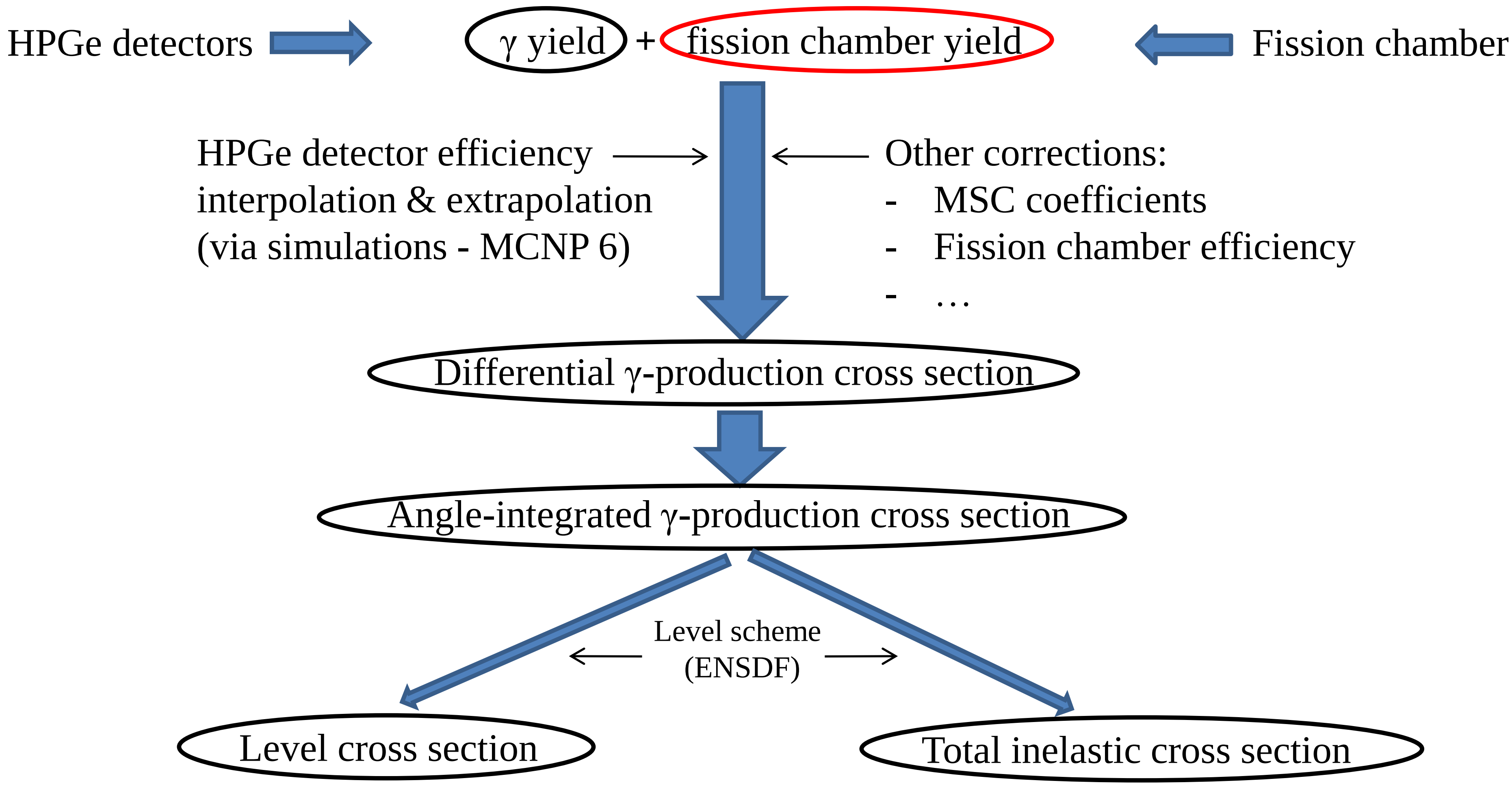
- γ–spectroscopy measurements coupled with time of flight method
- we extract cross sections normalized to the very well known ^{235}U(n, fission) cross section



Data analysis

IFIN-HH

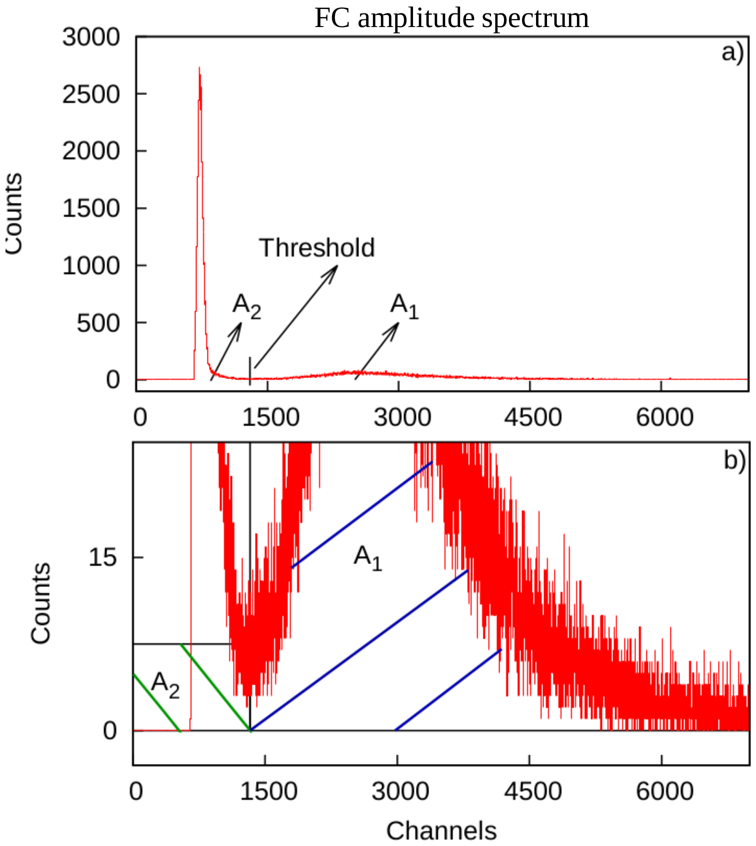
- γ–spectroscopy measurements coupled with time of flight method
- we extract cross sections normalized to the very well known ^{235}U(n, fission) cross section



Data analysis

- FC data analysis - very similar to HPGe detector's case:
  - FC time-amplitude matrix
  - FC Amplitude spectrum
  - FC ToF spectrum
  - ….

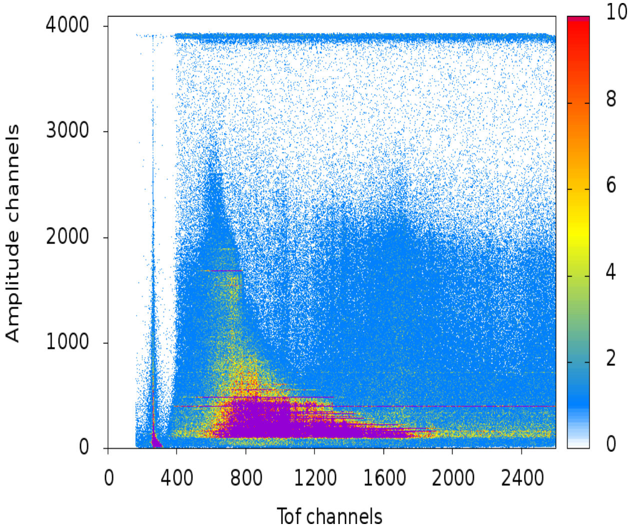
FC efficiency determination



Data analysis

- ToF technique or **calibration in time of flight**

The time-amplitude matrix of one HPGe detector



Data analysis

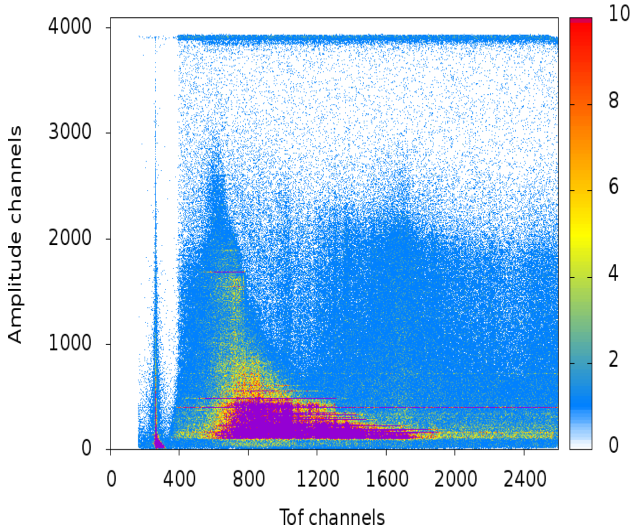
- ToF technique or **calibration in time of flight**

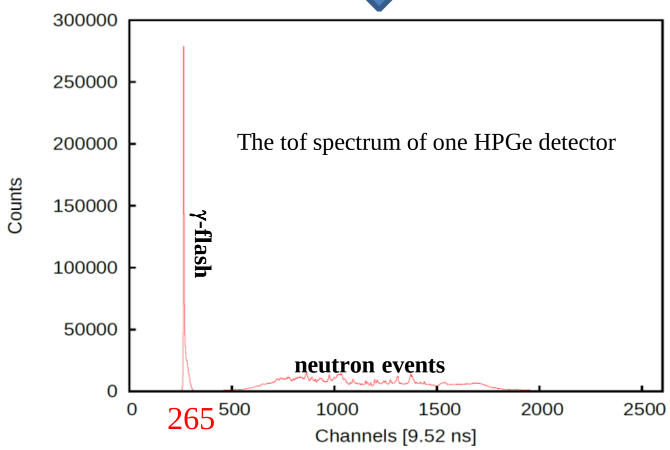
$$t_{\gamma-flash} = \frac{d_{flight\ path}}{c} = \frac{19868.4\ cm}{29.979\ cm/ns} = 662.743\ \text{ns}$$

$$E_n = m_0 c^2 \left[\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1 \right]$$

Figure out the neutron energy by using the γ-flash as a time reference!!!

The time-amplitude matrix of one HPGe detector

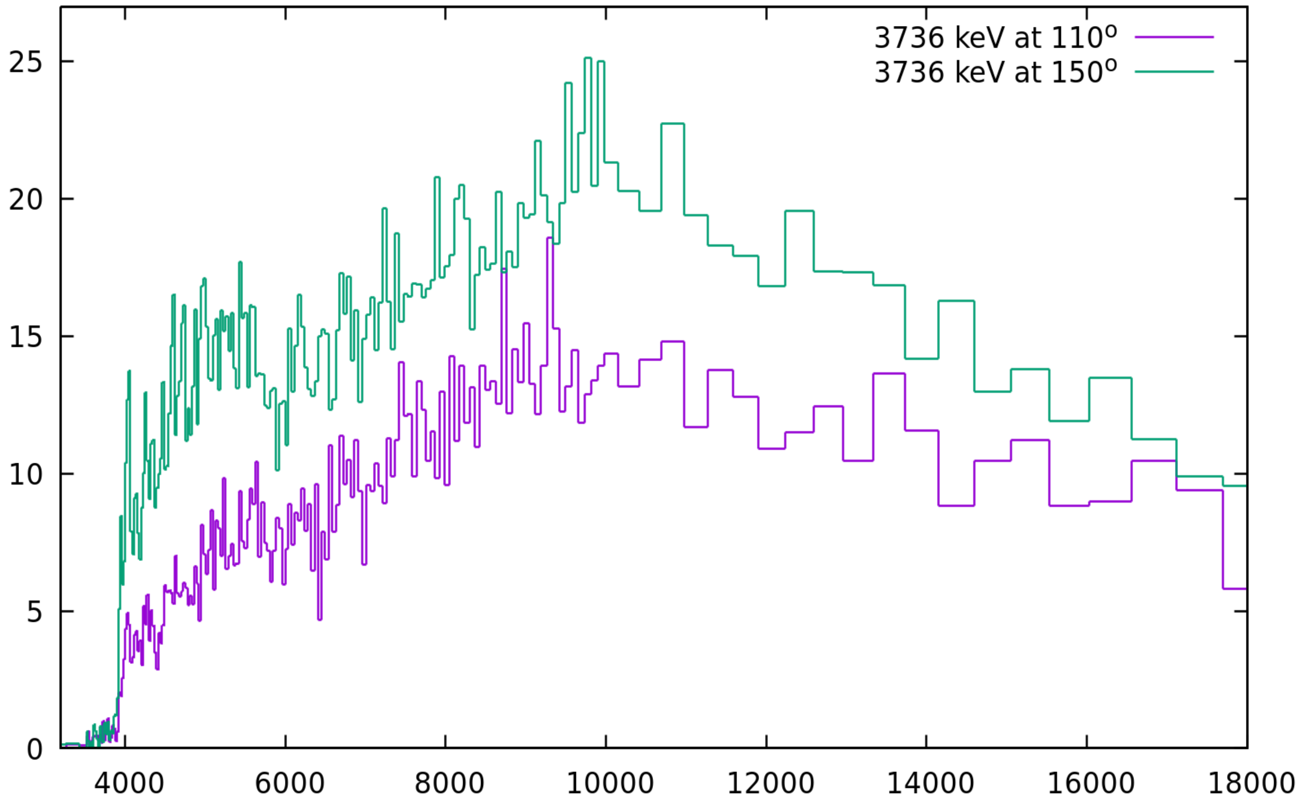




Data analysis

- **Differential** γ–production cross sections (**at 110º and 150º**)

$$\frac{d\sigma}{d\Omega}(\theta_i, E_k) = \frac{1}{4\pi}\frac{Y_j(E_k)}{Y_{FC}(E_k)}\frac{\varepsilon_{FC}\sigma_U(E_k)}{\varepsilon_j}\frac{t_U}{t_s}\frac{A_U}{A_s}\frac{1}{c_{ms}(E_k)}$$

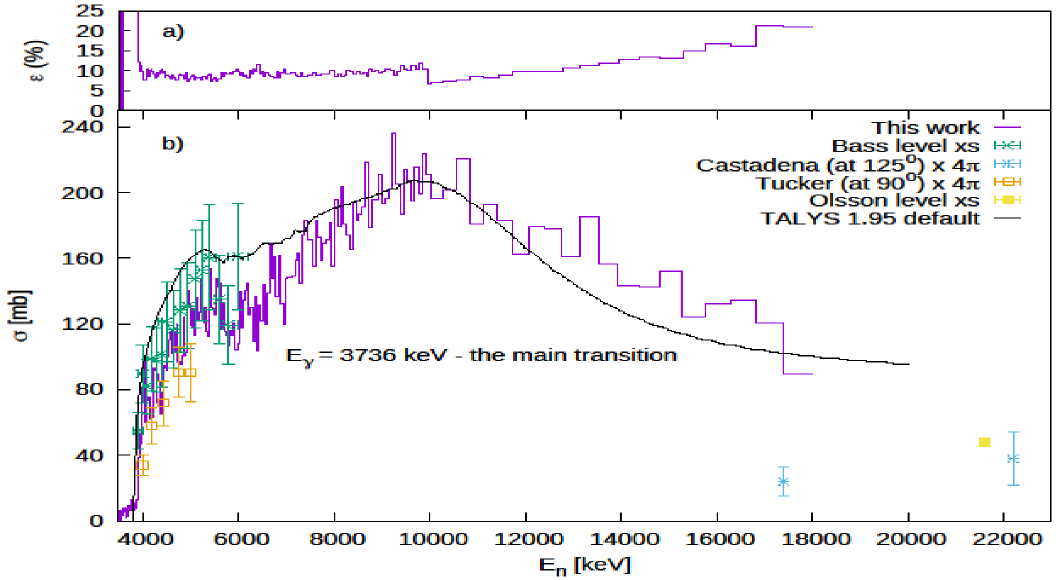


Nota Bene! 110º and 150º are nodes (zeroes) of the 4th order Legendre Polynomials

Data analysis

- **Angle-integrated** γ–production cross sections → our primary results

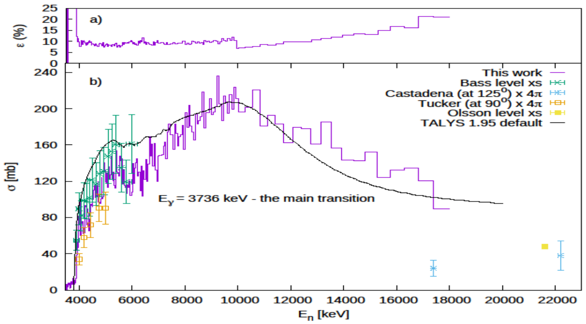
$$\sigma(E_k) = 2\pi[w_{110^o}\frac{d\sigma}{d\Omega}(110^o, E_k) + [w_{150^o}\frac{d\sigma}{d\Omega}(150^o, E_k)]$$

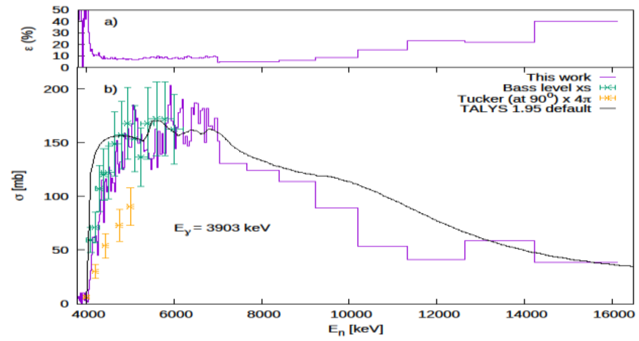


Angle integration based on Gaussian Quadrature Theorem
plus
Legendre Polynomials series expansion of the differential cross section

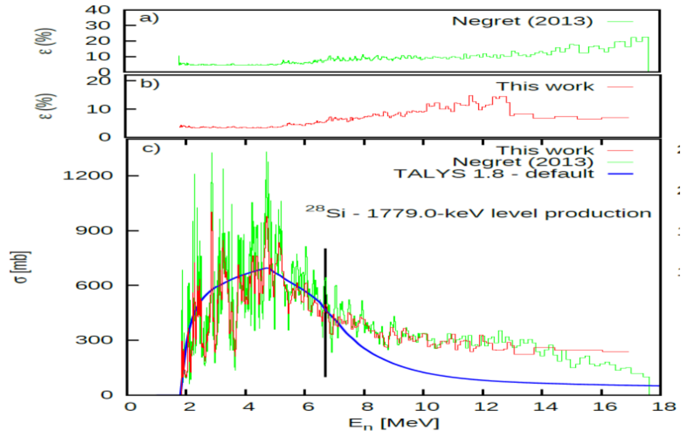
Data analysis

γ-production cross sections (primary results)

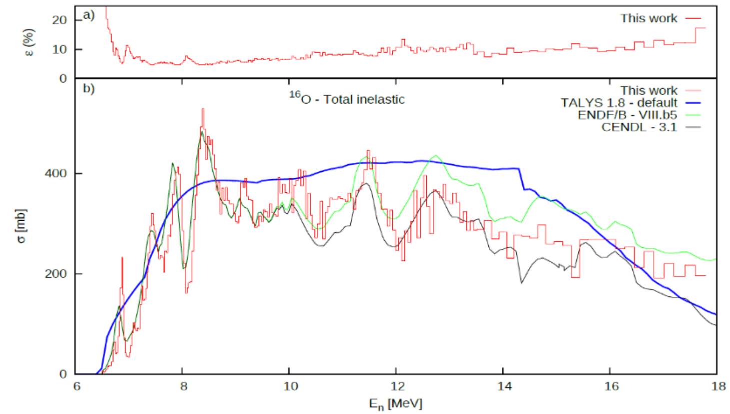




~~level cross section~~



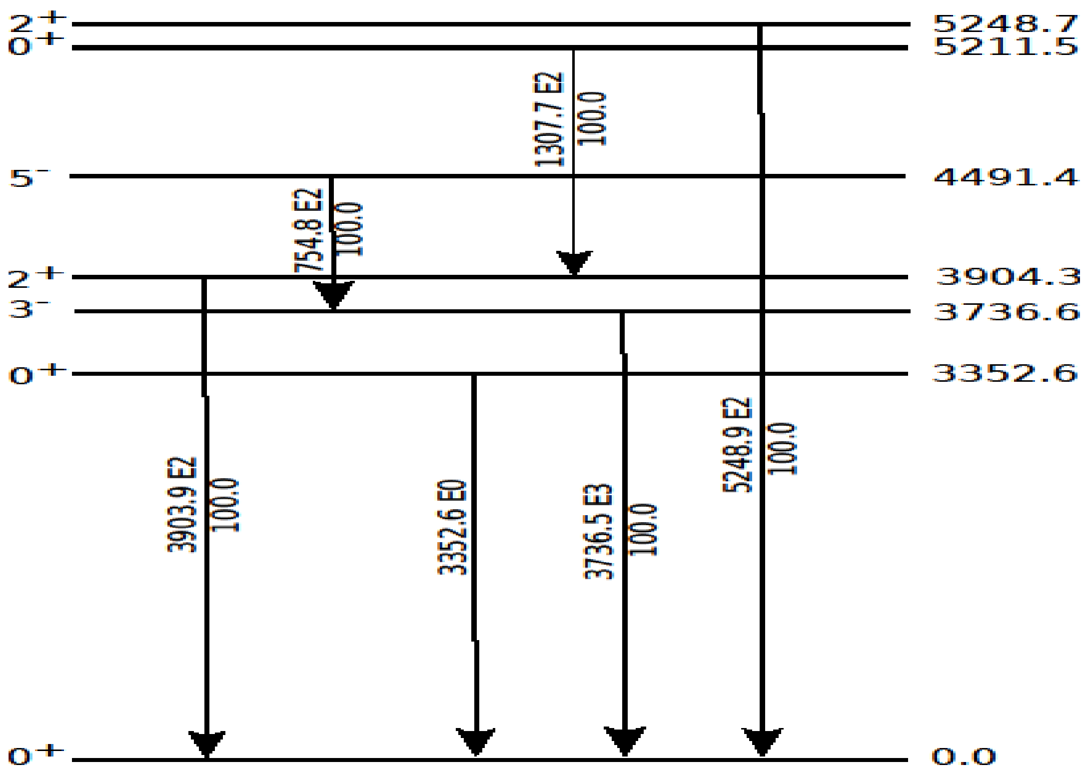
total inelastic cross section



Data analysis

- **Total inelastic cross sections**

- Calculated based on the feeding of the ground state using the production cross section of the observed transitions.



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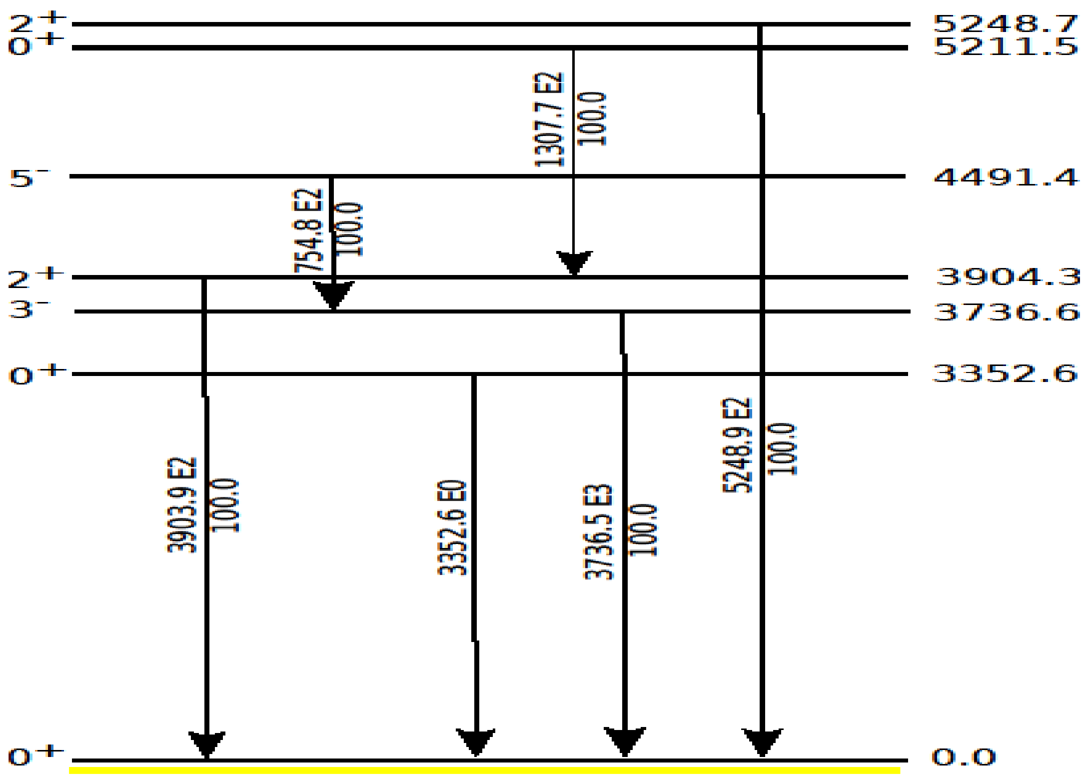

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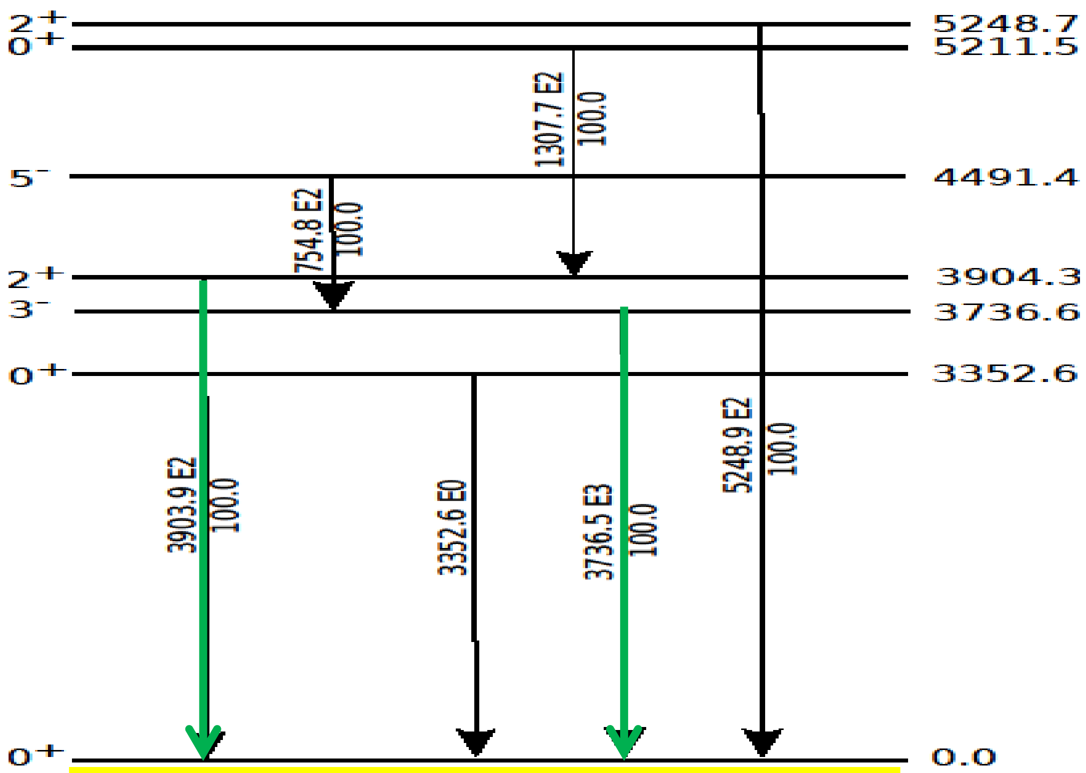

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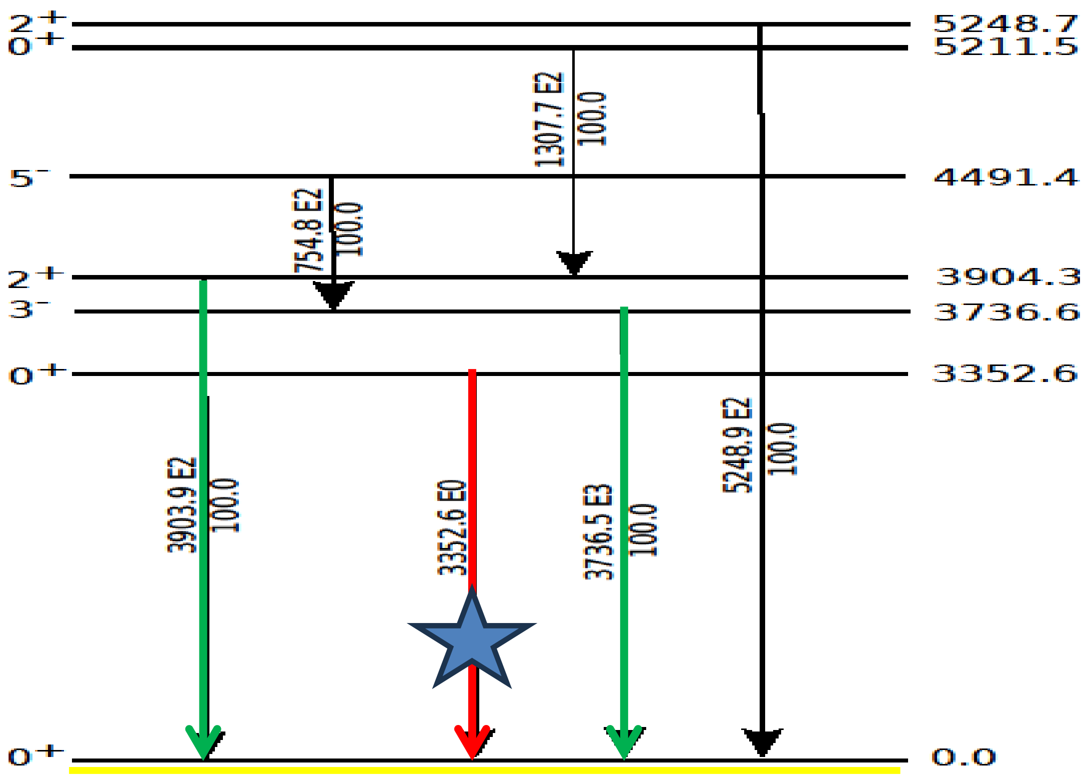

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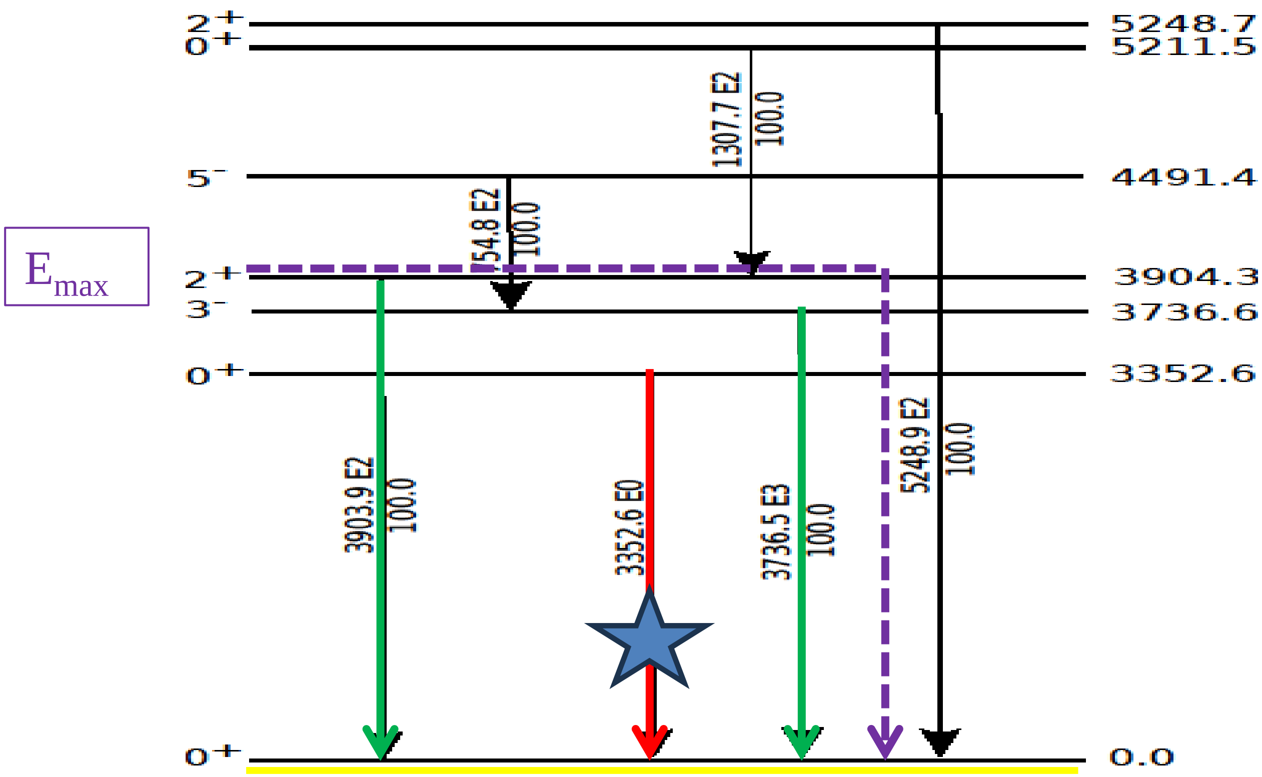
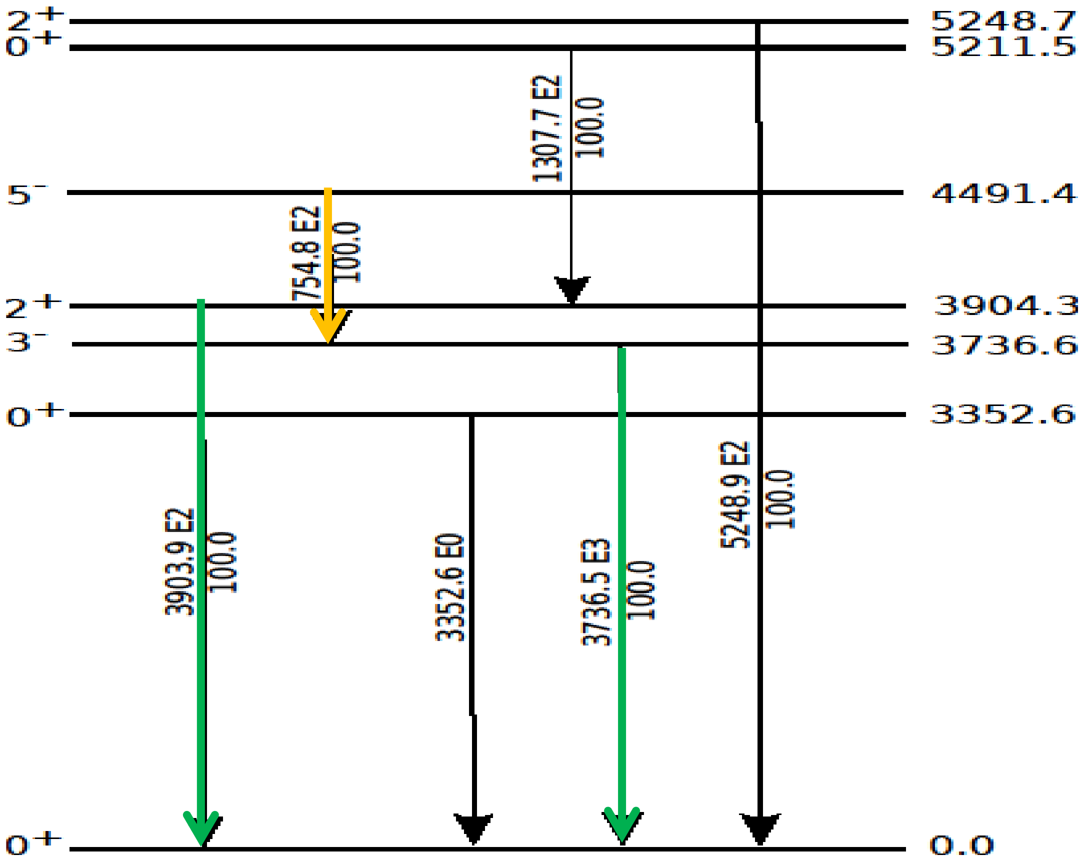


Experimental results

- ❑ scientific motivation for performing the experiment
- ❑ experimental setup
- ❑ data analysis procedure
- ❑ **experimental results**

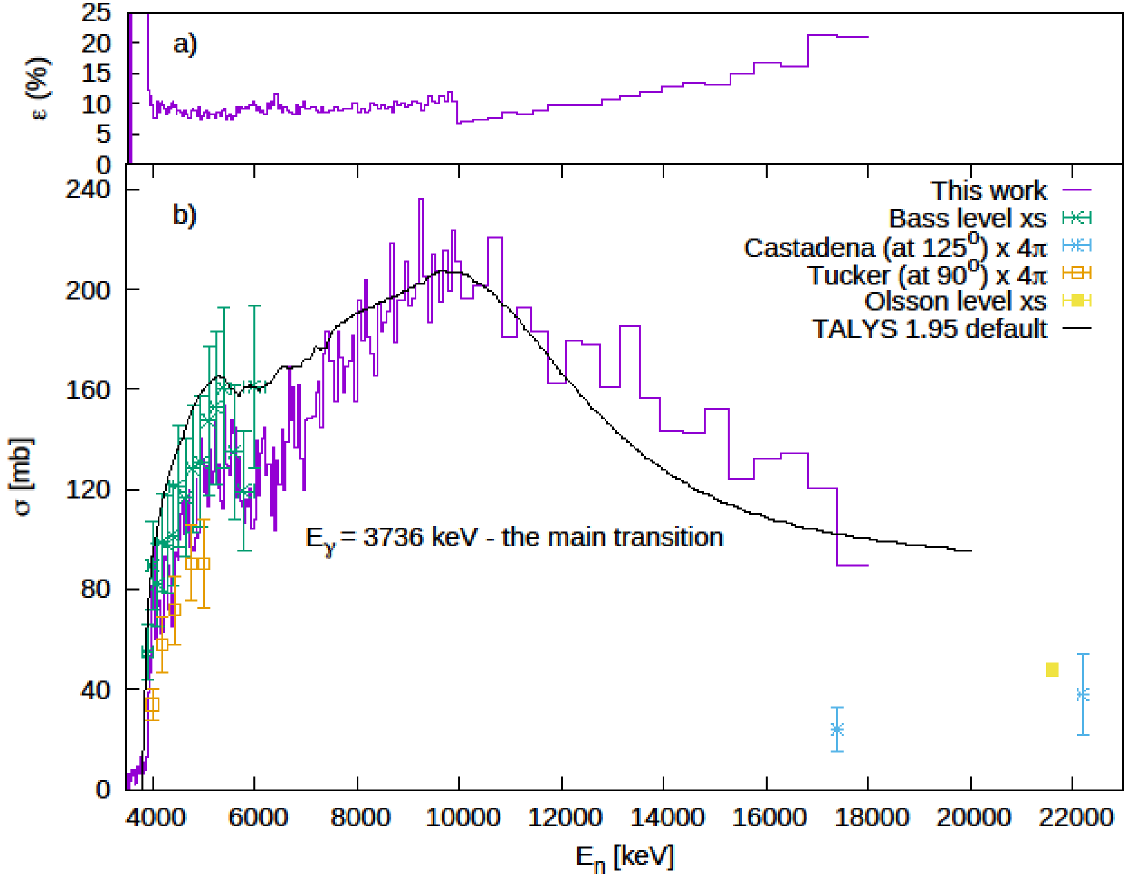


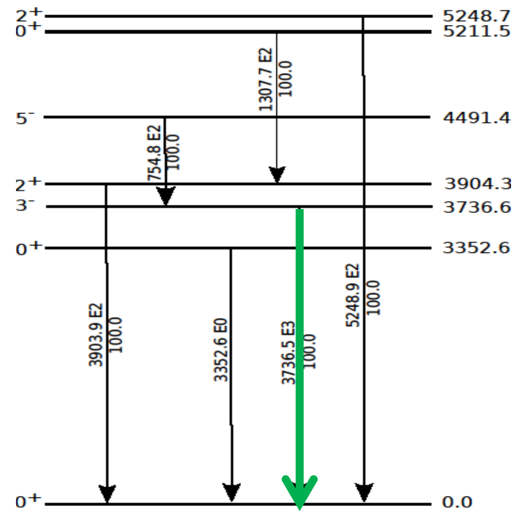
Two transitions in ^{40}Ca:

- **3736 keV (the main transition)**
- **3903 keV**
- **(maybe also 754 keV)**
- **Most probably also 109 keV and 197 keV from ^{19}F**

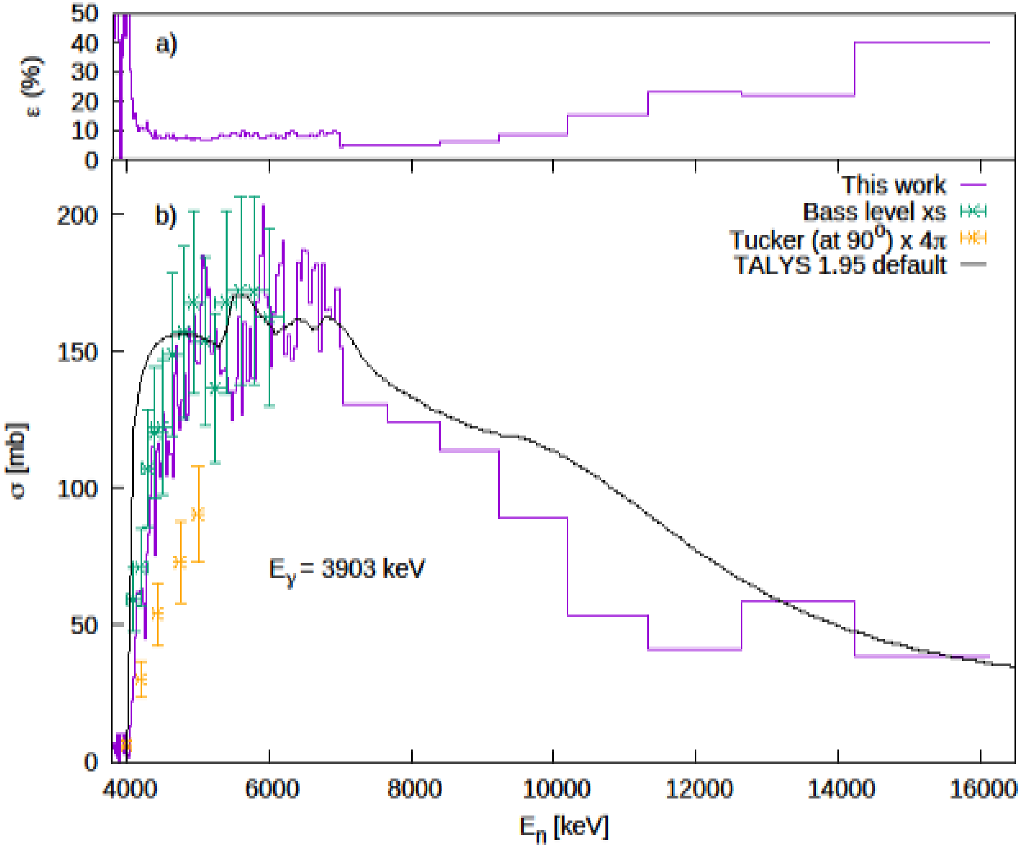
Experimental results

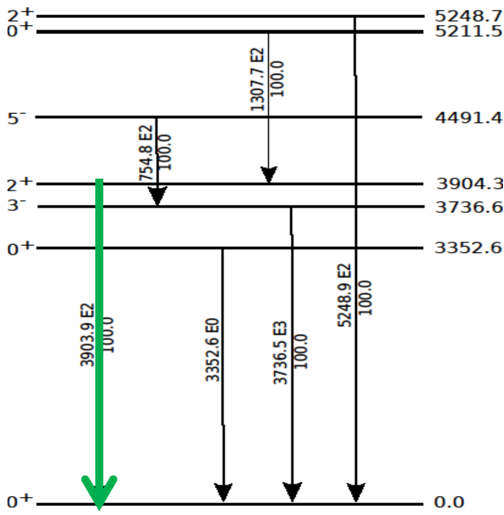
3736 keV: γ-production cross section





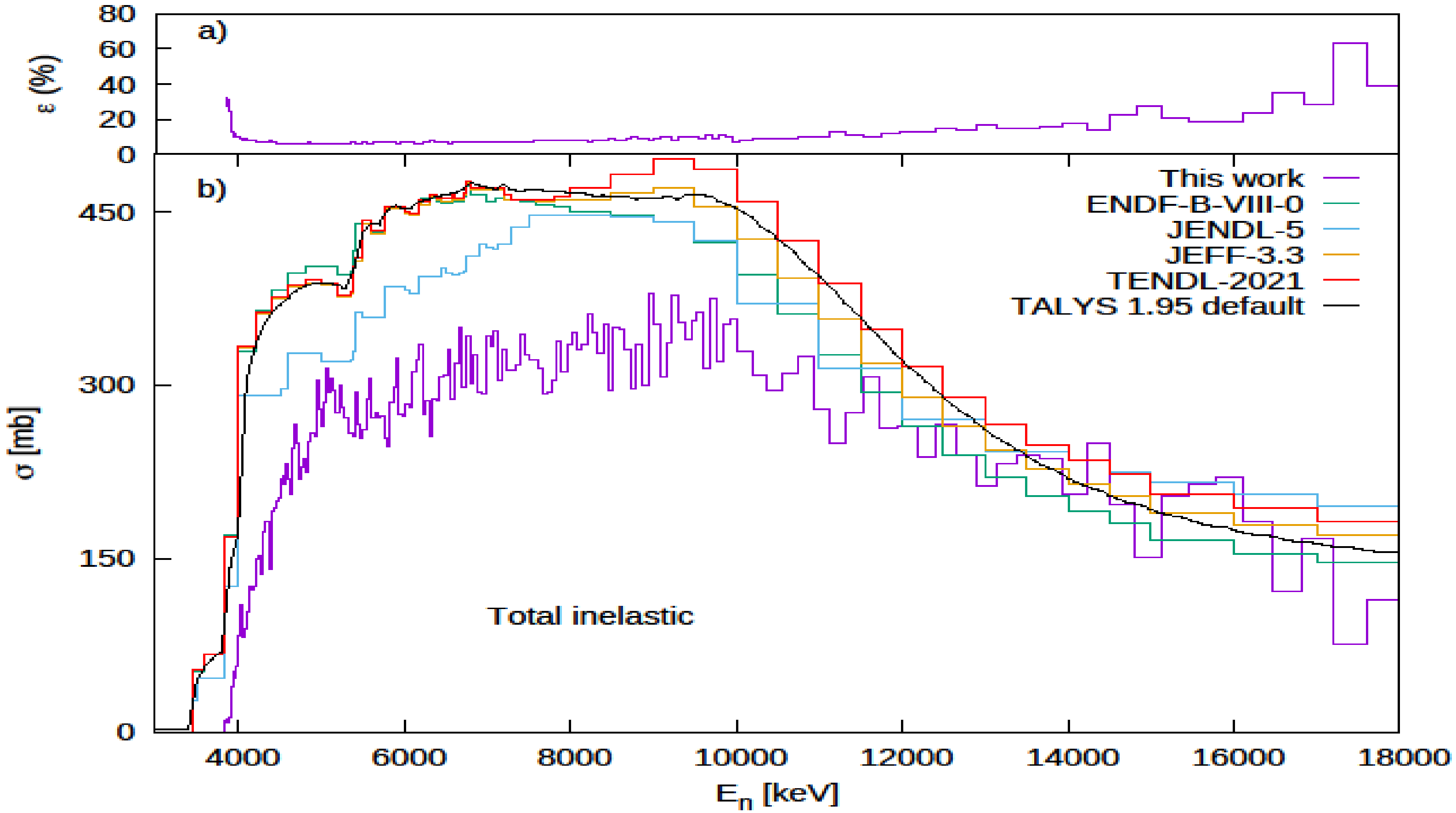
3903 keV: γ-production cross section





Experimental results

Total inelastic cross section on ^{40}Ca



Thank you for your attention!

BACKUP SLIDES

Data analysis

γ–ray emission anisotropy