Study of lifetimes of nuclear excited states near the N=20 island of inversion using the Doppler Shift Attenuation Method

R. Nicolás del Álamo, I. Zanon, D. Brugnara *et al.*

AGATA Collaboration Council
October 19th- 20th 2023

INFN
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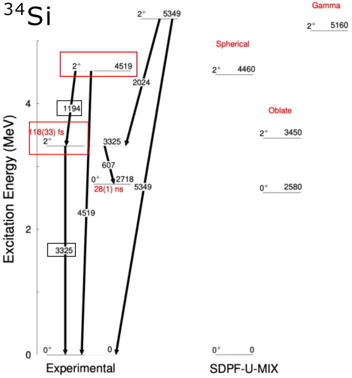
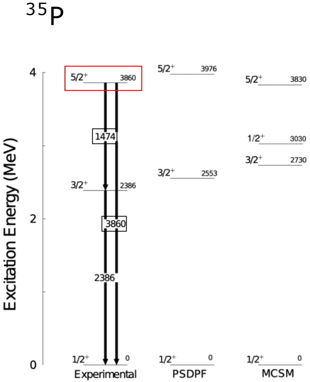
^{34}Si and ^{35}P are located in the boundary of the N=20 island of inversion.
The aim of the experiment is to measure the lifetimes (DSAM) of a set of states in both isotopes to determine whether they belong to an intruder band.

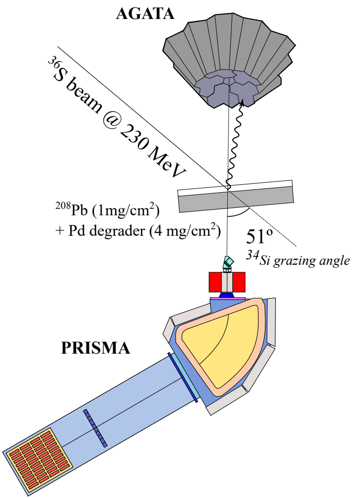




A. Poves (2022), R. Licâ et al. (2019)

T. Otsuka *et al.* (1998), Y. Utsuno *et al.* (1999)

Status of the experiment

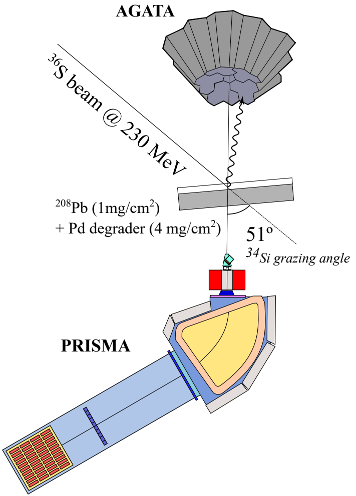


Experimental details:

- Multi-nucleon transfer reaction, ^{36}S on ^{208}Pb (1 mg/cm^2) @ 230 MeV.
- DSAM degrader: 4 mg/cm^2 Pd.
- Experiment performed in November 2022, during 8 days of beam time.
- TANDEM + ALPI accelerator complex.

Status of the analysis (AGATA raw data):

Status of the experiment



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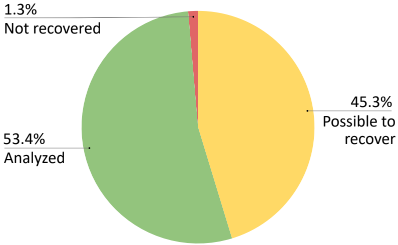
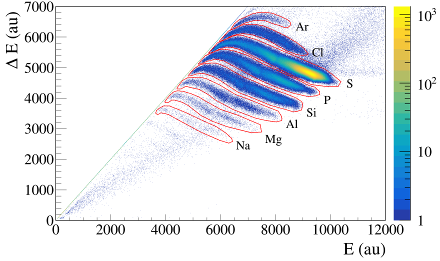
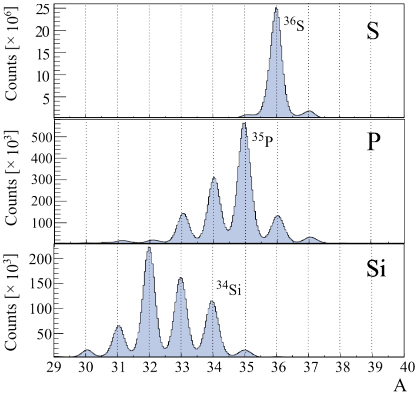


Experimental Z and mass distributions

This experiment: ^{36}S beam at 230 MeV on a 1 mg/cm^2 ^{208}Pb target + 4 mg/cm^2 Pd

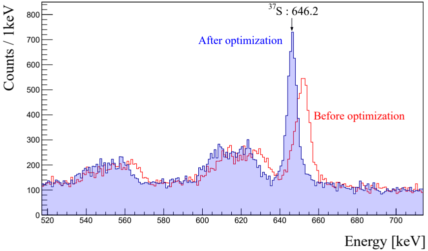




The distributions are compatible with R. Chapman *et al.* (2015), L. Grocutt *et al.* (2019), ^{36}S beam @ 215 MeV on 0.3 mg/cm^2 ^{208}Pb.

Doppler correction optimization:

- Based on the shape and position of the 646 keV peak of ^{37}S, $t_{1/2} = 133.8(28)$ ps.
- Focused on the optimization of the PRISMA TOF and the relative angles between AGATA and PRISMA.



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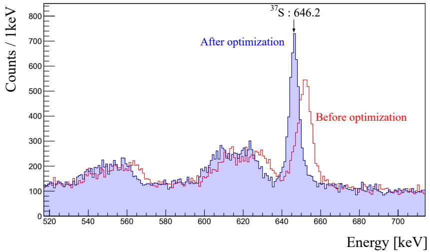
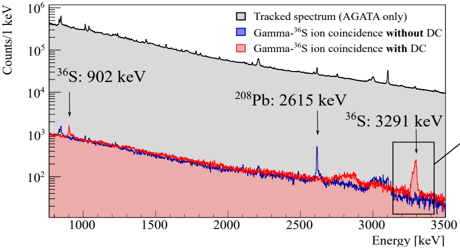
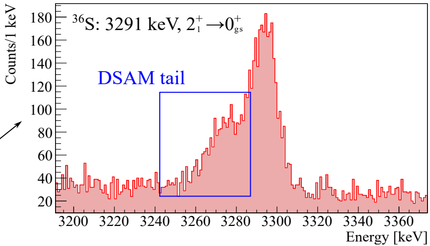




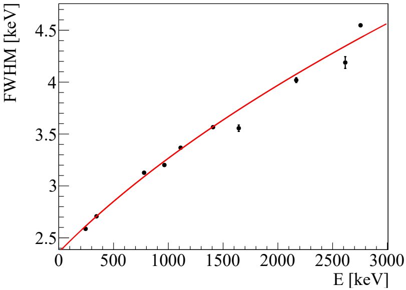


Simulation

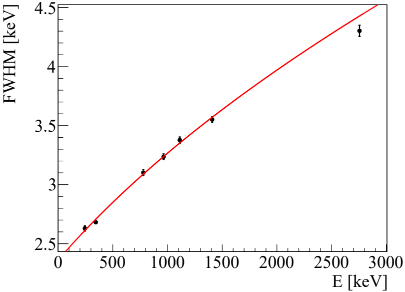
Adapted the AGATA simulation to reproduce the:

- Detector geometry (crystals present on the set-up and orientation)
- Beam, target and degrader features (energy, thickness)
- Detector resolutions (Energy spectra FWHM and PRISMA β resolution)

Example: energy-smearing with source data (^{152}Eu)

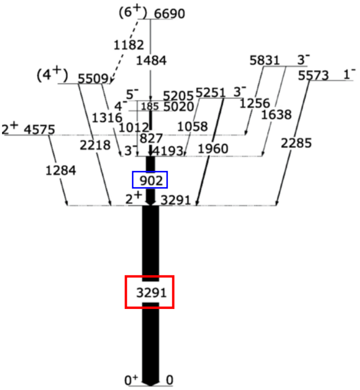


(a) Experimental data



(b) Simulated data

Validation through the re-measurement of the lifetime of the 2_1^+ state of ^{36}S, previously measured by K.-H. Speidel *et al.* (2008) (DSAM).



The feeding from the long-lived 3_1^- state was eliminated by setting thresholds in the Total Kinetic Energy Loss (TKEL) spectrum.

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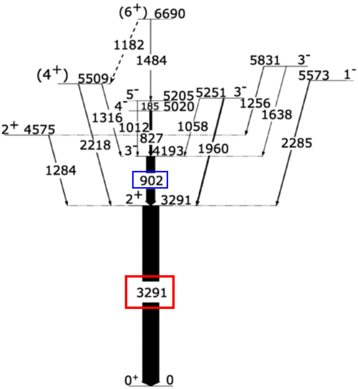
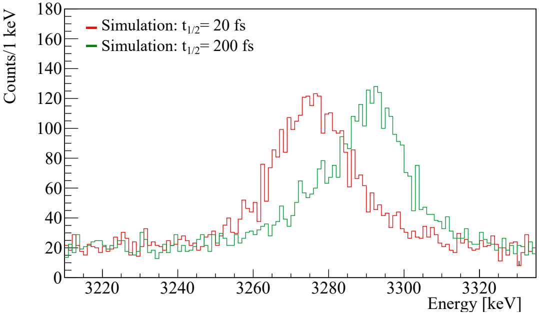
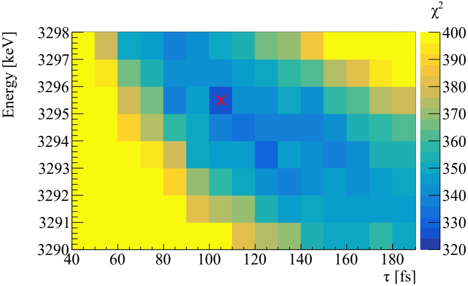


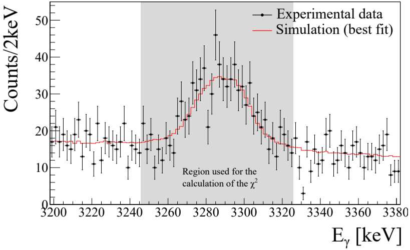


The feeding from the long-lived 3_1^- state was eliminated by setting thresholds in the Total Kinetic Energy Loss (TKEL) spectrum.

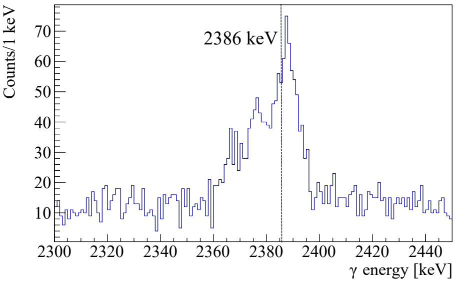
Lifetime of the 2_1^+ of ^{36}S

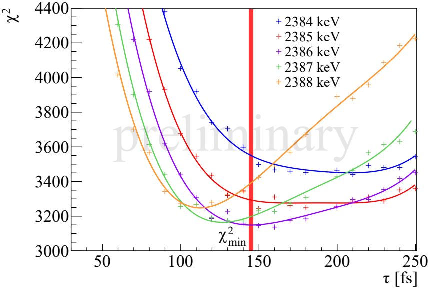
The estimated lifetime is 100(20) fs, which is compatible with the previous measurement by K.-H. Speidel *et al.* (2008) of $\tau = 120(10)$ fs.





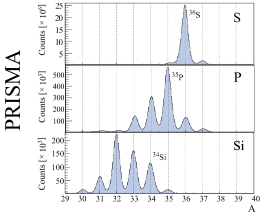
The peak corresponding to the $3/2_1^+ \rightarrow 1/2_{gs}^+$ transition of ^{35}P (2386 kev) shows a tail associated with the DSAM effect. Using the same method as for ^{36}S, a first estimation of $\tau \sim 145(5)$ fs was obtained.

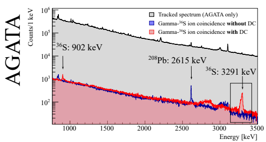




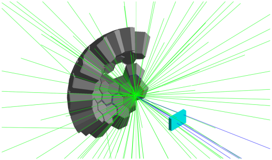
Summary and perspective

1. Data analysis:



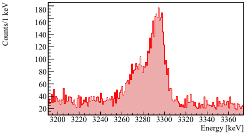


2. GEANT4 simulation:



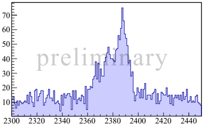
3. Lifetimes (via line-shape analysis):

^{36}S: 3291 keV, $2^+_1 \to 0^+_{gs}$



$\tau = 100(20)$ fs

^{35}P: 2386 keV, $3/2^+_1 \to 1/2^+_{gs}$



$\tau = 145(5)$ fs

Perspective:

- Further assessment of the feeding effects and measurement uncertainties
- New channel analysis: ^{35}P, ^{34}Si... analysis ongoing!

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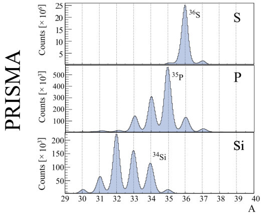

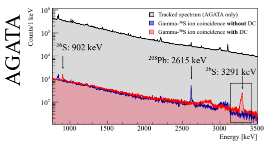

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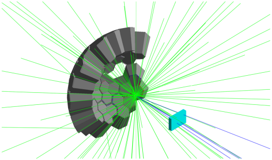

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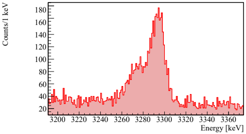

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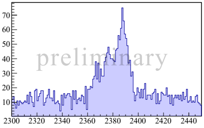

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Perspective:

Further assessment of the feeding effects and measurement uncertainties

New channel analysis: ^{35}P, ^{34}Si... analysis ongoing!

Thank you

On behalf of everyone participating to the experiment!

Lifetime measurements for the study of intruder states towards the island of inversion along the $N = 20$ shell closure
AGATA + PRISMA

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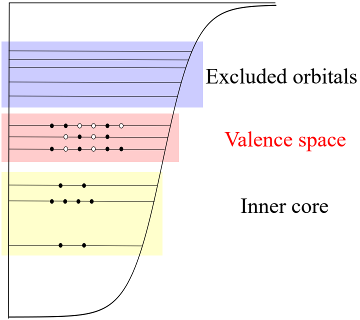
Back-up slides: Table of contents



The Nuclear Shell Model

$$\hat{H} = \hat{H}_0 + \hat{H}_{res} = \sum_{i=1}^{A} \hat{h}_i + \frac{1}{2}\sum_{ij} \hat{V}_{ij}$$

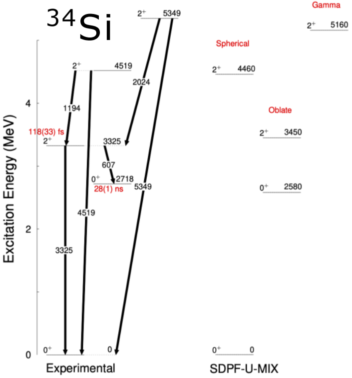
Diagonalize $\hat{H}$ adapted to the valence space:

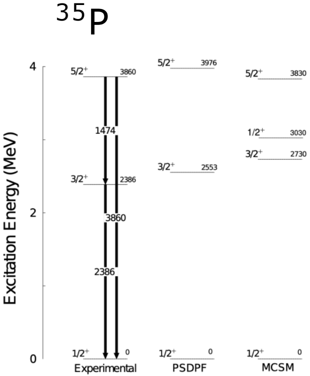
$$\hat{H}|\Psi_k\rangle = E_k|\Psi_k\rangle, \qquad |\Psi_k\rangle = \sum_j C_k^j|\Phi_j\rangle$$

$$\hat{H}_0|\Phi_k\rangle = E_k^{(0)}|\Phi_k\rangle$$

$|\Phi_k\rangle \equiv$ Antisymmetrized independent particle shell model eigenstates (Slater determinants)

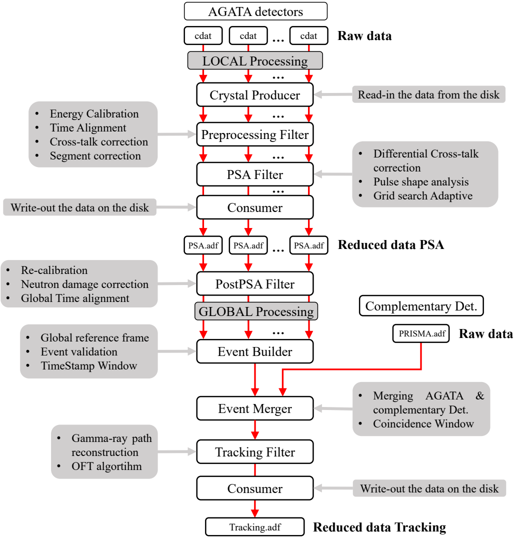
Residual interactions mix single particle states and can change the normal shell model ordering!





[1] A. Poves, private communication.
[2] R. Licâ et al., Phys. Rev. C 100, 034306 (2019).
[3] T. Otsuka et al., Phys. Rev. Lett. 81, 1588 (1998).
[4] Y. Utsuno et al., Phys. Rev. C 60, 054315 (1999).

AGATA data processing



Followed steps:

PostPSA processing

Neutron damage: ^{60}Co

Re-calibrations: ^{152}Eu

Time alignment

After merge with PRISMA

Ion-γ coincidence window

Doppler correction optimization

R.M. Pérez-Vidal, PhD thesis

AGATA: Neutron damage corrections

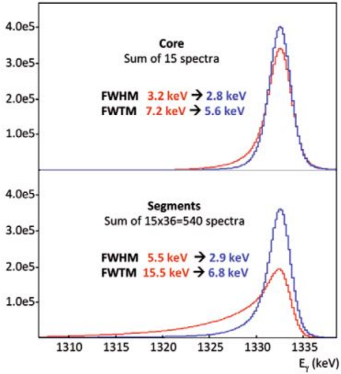
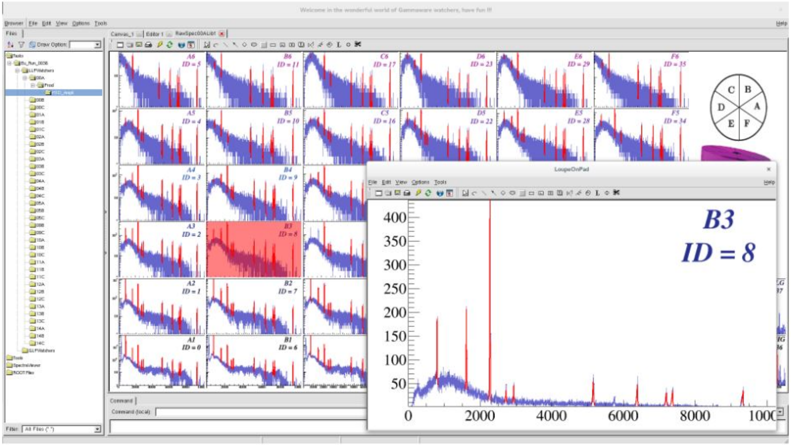


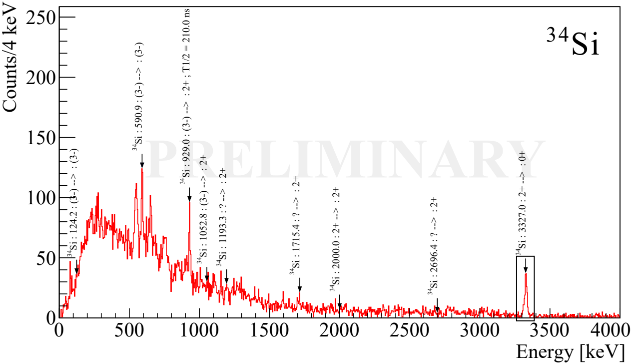
Fig. 7. The line shape of the summed core and segment energy spectra before (red) and after correction for trapping (blue). The spectra were taken at the end of the first AGATA beam campaign at Legnaro. The detectors were suffering heavily from neutron damage. Listed improvements need comparison with the summed resolution of undamaged detectors, which amounted to 2.5 keV FWHM and 4.8 keV FWTM.

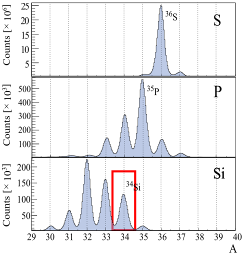
Calibrate the energy spectrum of each of the 36 segments for the 34 crystals used in the experiment.



Form AGATA local level processing guide.

Gating on the masses and Doppler correction (PRISMA):





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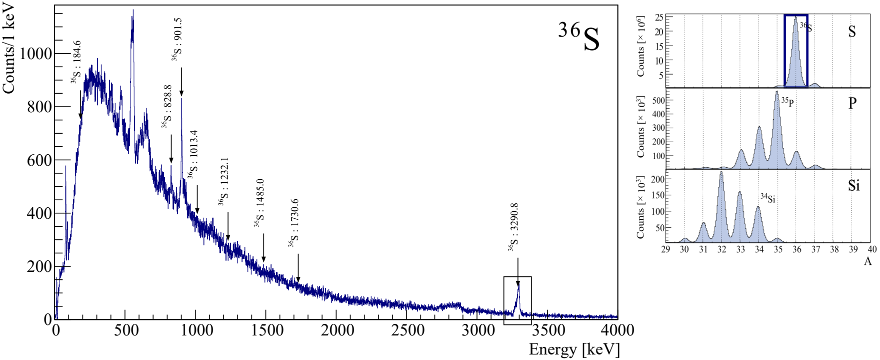
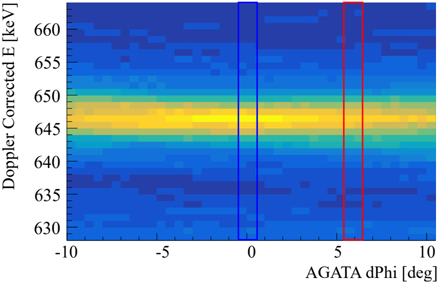
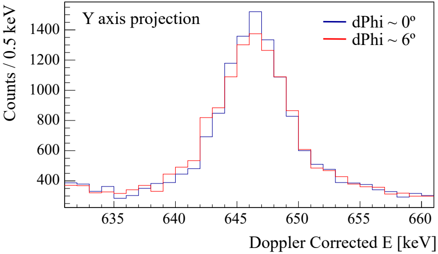


AGATA: Doppler-Shift correction optimization

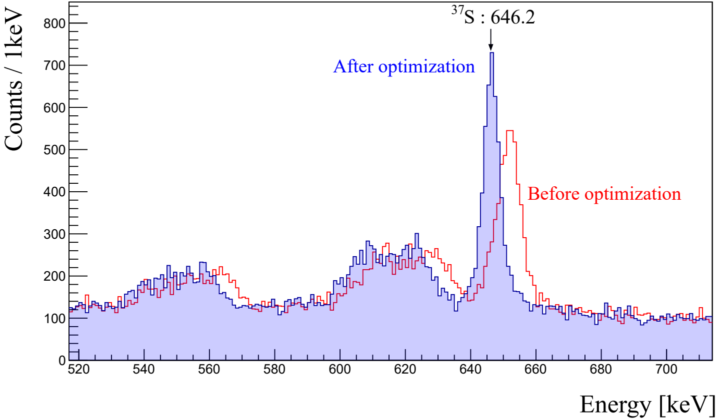
1. After the merging with PRISMA, the Doppler correction depends on the value of the calibrated TOF. One must correct the TOF value by checking that the centroids of the γ ray peaks appear at the correct energy.
2. Other variables such as the MCP and AGATA positions and angles can affect the FWHM. $\rightarrow$ Search for the values of those parameters which minimize the FWHM.





Doppler shift correction optimization II

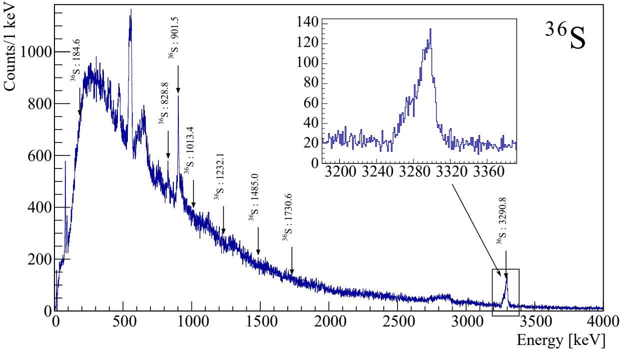
Bring the peaks to the correct energy and reduce the FWHM by optimizing the Time of Flight, AGATA position, AGATA and PRISMA angles.



Simulation

The aim is to extract the lifetime by comparing the line shapes of the peaks with a GEANT4 simulation. Start with ^{36}S as a check! We want to check whether our result is compatible with K.H. Speidel *et al.* (2008). Steps:

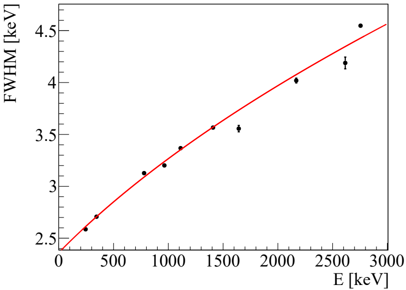
1. Optimize the simulation: reproduce the experimental conditions and resolution.
2. Determine what lifetime value reproduces better the experimental line shape.



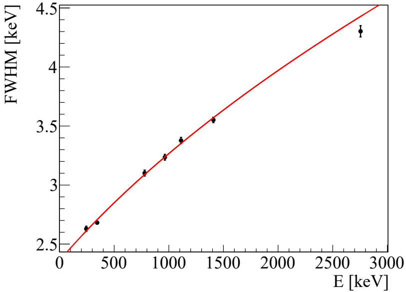
Optimization of the GEANT4 simulation I

Reproduce the experimental FWHM of the peaks as a function of the energy using the calibration source data:

$$\tilde{E}_\gamma = E_\gamma + \varepsilon(\mu, \sigma)$$



(a) Experimental data



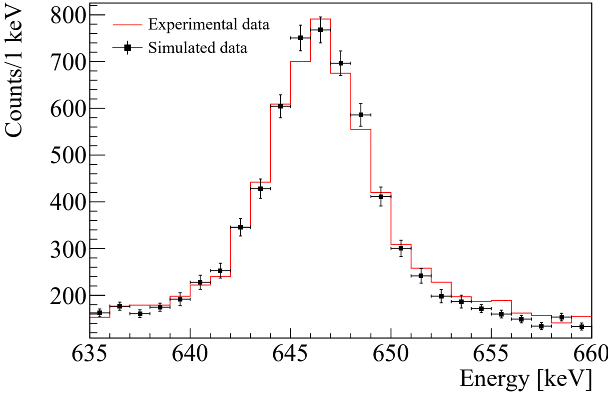
(b) Simulated data

$$FWHM = \sqrt{a + b \cdot E_\gamma}$$

Optimization of the GEANT4 simulation II

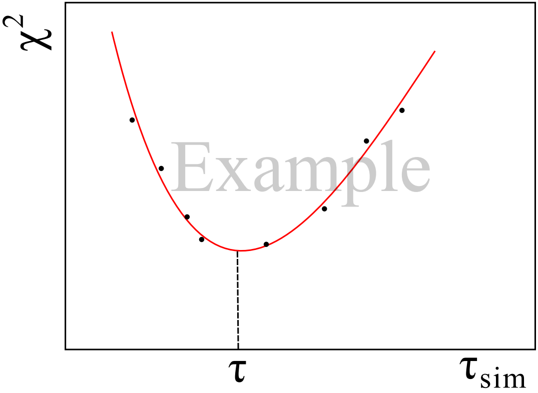
Introduce an smearing in the velocity to reproduce the FWHM of the Doppler corrected peaks:

$$\tilde{\beta} = \beta + \varepsilon(\mu, \sigma)$$

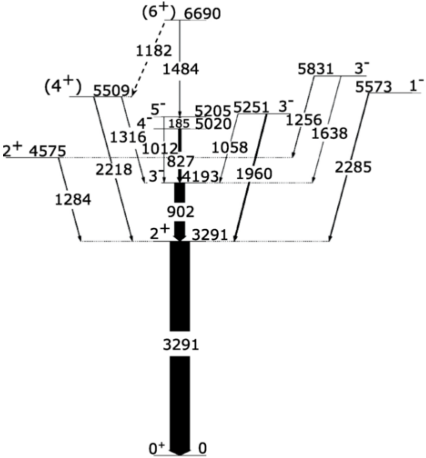


How to extract the lifetime?

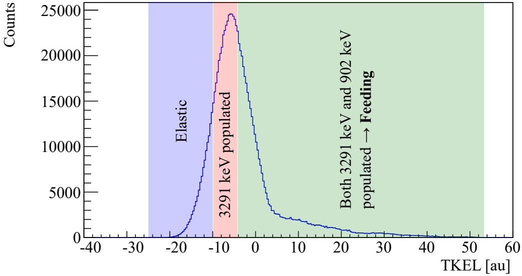
Run the simulation for a set of lifetimes and calculate the χ^2 for each lifetime value by comparing the simulation and the experimental data.

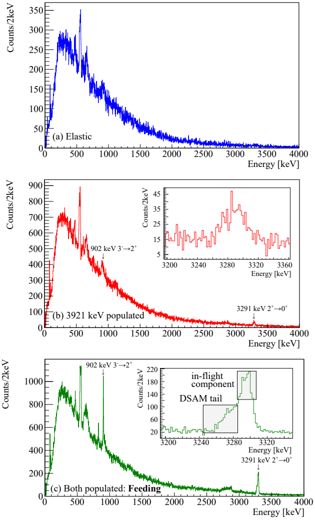


L. Grocutt et al. Phys. Rev. C 106, 024314 (2022)

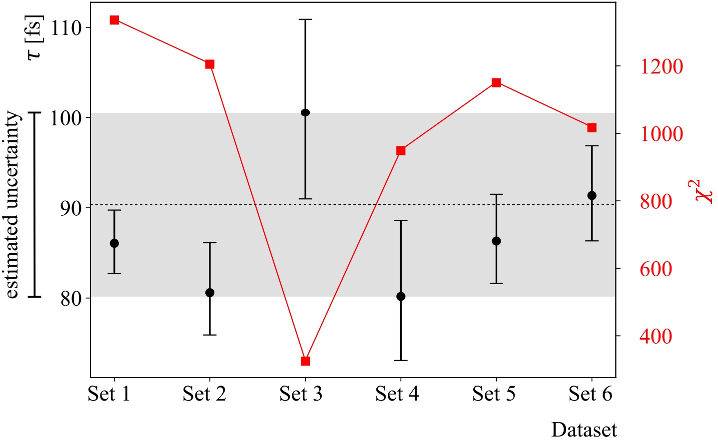


Removing the feeder: TKEL gates





Uncertainty estimation

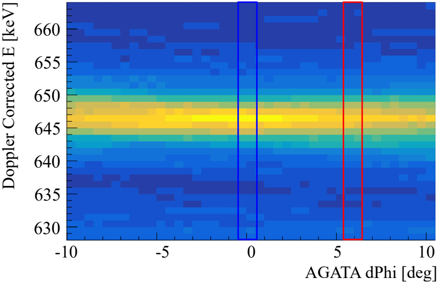


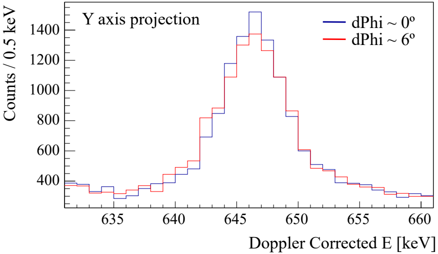
PRISMA efficiencies

Z	MCP efficiency [80%]	TOF efficiency [85%]	PPAC efficiency [90%]
S (16)	81.0267	85.3695 %	95.0936 %
P (15)	78.251	82.3986 %	93.9292 %
Si (14)	75.6866	79.361 %	88.8927 %
Al (13)	72.9378	75.7002 %	81.2404 %
Mg (12)	67.2531	69.537 %	73.642 %

AGATA: Doppler correction optimization

- After the merging with PRISMA, the Doppler correction depends on the value of the calibrated TOF of the ions. One must correct the TOF value by checking that the centroids of the γ ray peaks appear at the correct energy.
- Other variables such as the MCP and AGATA positions and angles can affect the FWHM. $\rightarrow$ Search for the values of those parameters which minimize the FWHM.





AGATA Doppler correction optimization II

Bring the peaks to the correct energy and reduce the FWHM by optimizing the Time of Flight, AGATA position, AGATA and PRISMA angles.
We used the 646 keV transition in ^{37}S as a reference for the optimization. It was chosen for its high statistics and long lifetime (