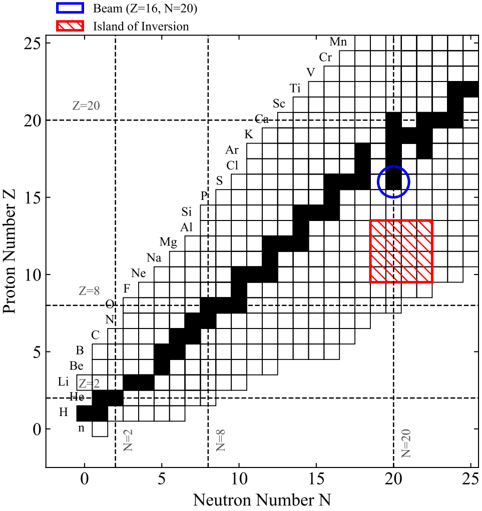
Lifetime measurements towards the N=20 island of inversion

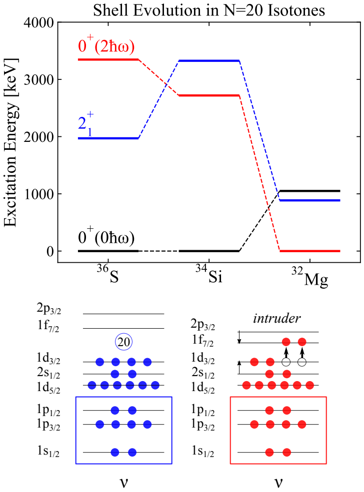
R. Nicolás del Álamo[1], I. Zanon[2], D. Brugnara[3]

on behalf of the experiment collaborators and the AGATA and PRISMA Collaborations

[1]INFN Padova and University of Padova, [2]KTH, [3]TU Darmstadt and GSI

The N=20 island of inversion





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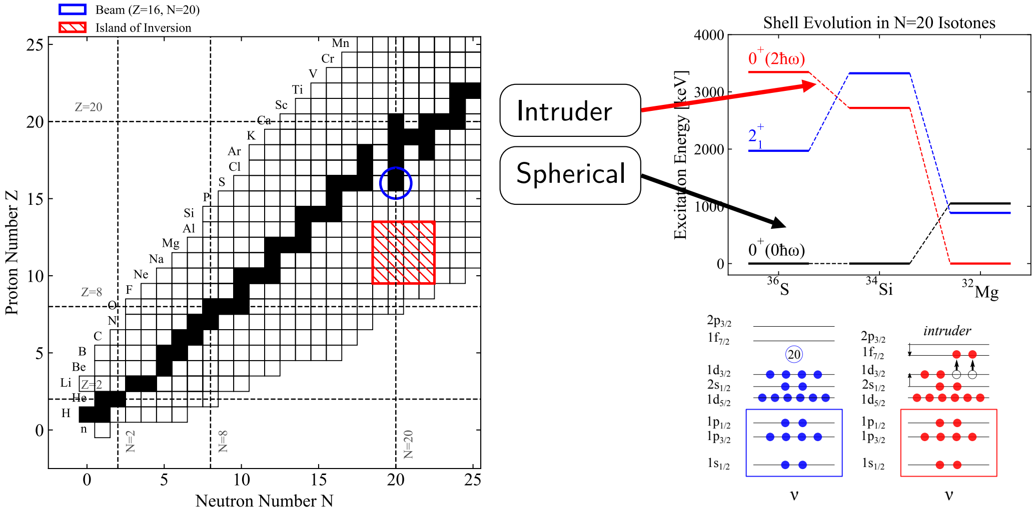

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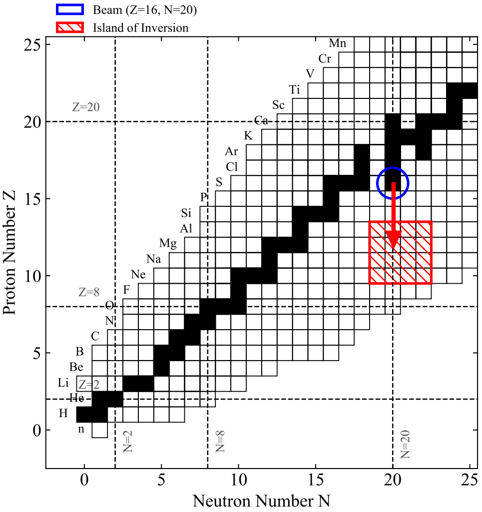

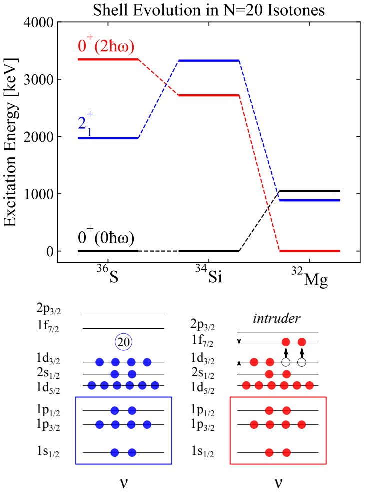

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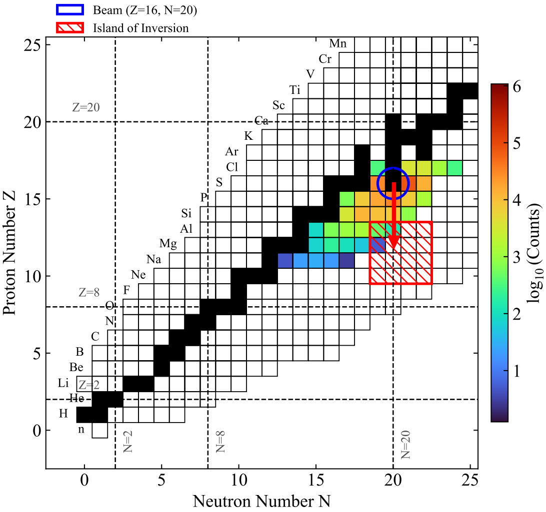

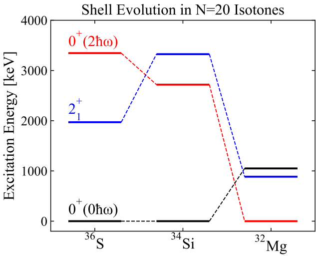

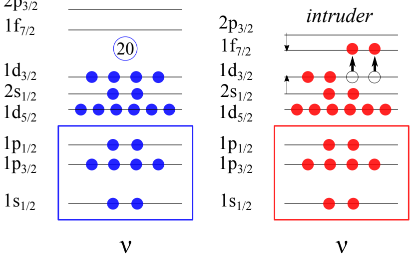

Lifetime measurements

Why do we measure lifetimes?

From Fermi's Golden rule, the electromagnetic transition probability:

$$T_{i \to f} \propto |\langle \Psi_i || \hat{O}(EL/ML) || \Psi_f \rangle|^2,$$

where $\hat{O}(EL/ML)$ is the L-order electric or magnetic operator.

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For electric transitions, the reduced transition probability

$$B(EL) = \frac{1}{2J_i+1}|\langle\Psi_i\|\hat{O}(EL/ML)\|\Psi_f\rangle|^2 \propto \frac{1}{\tau\ E_\gamma^{2L+1}}.$$

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When comparing the experimental $B(EL)$ with theoretical calculations, one can benchmark the overlap between the initial and final wavefunctions through the corresponding $\hat{O}(EL)$

Intruder band in ^{35}P

M. Salathe *et al.* PRC 102, 064317 (2020)

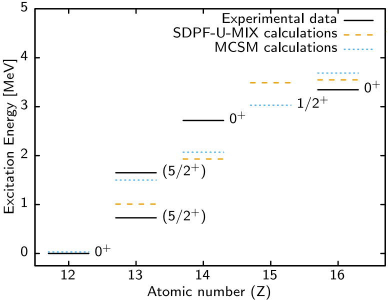
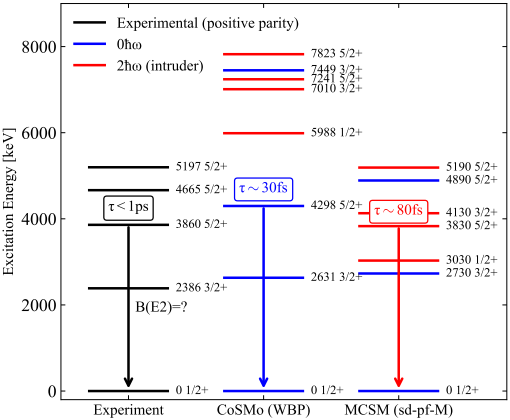


FIG. 1: Experimental (solid black lines) and calculated (dashed orange lines and dotted blue lines) 2p2h bandheads for the $N = 20$ isotones between $Z = 12$ and $Z = 16$. The orange dashed lines represent shell-model calculations performed with the SDPF-U-MIX effective interaction [4–6], while the blue dotted lines are the results of MCSM calculations [7–9]. The black solid lines represent data from Refs. [4, 10–12].

Adapted from M. Wiedeking *et al.* PRC 78, 037302 (2008), experimental lifetime limit from L. Grocutt *et al.* PRC 100, 064308 (2019)



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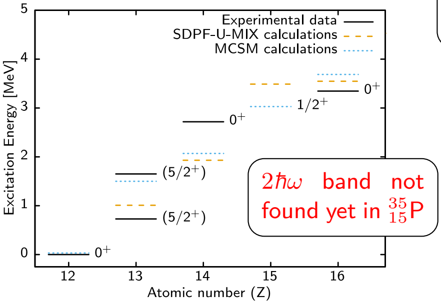

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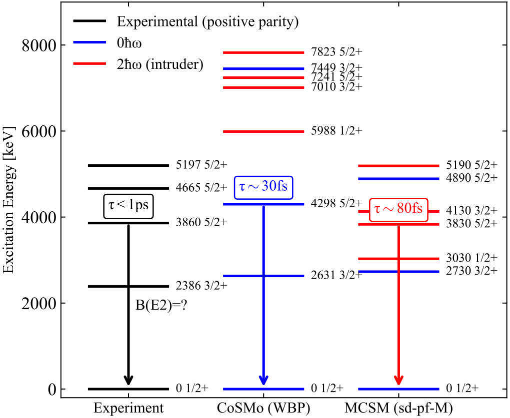
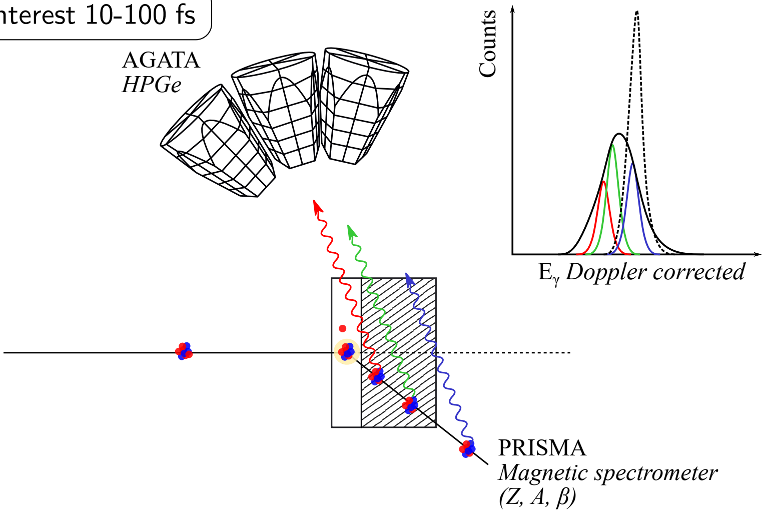


Lifetime measurements: the DSAM method

Lifetimes of interest 10-100 fs



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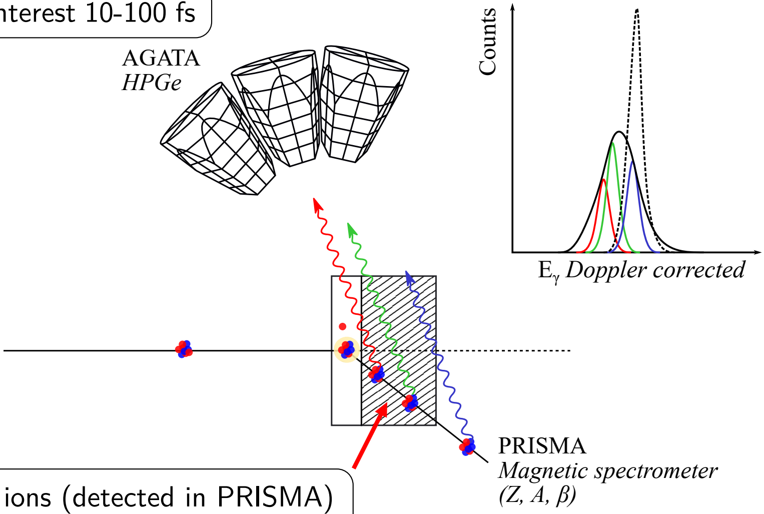
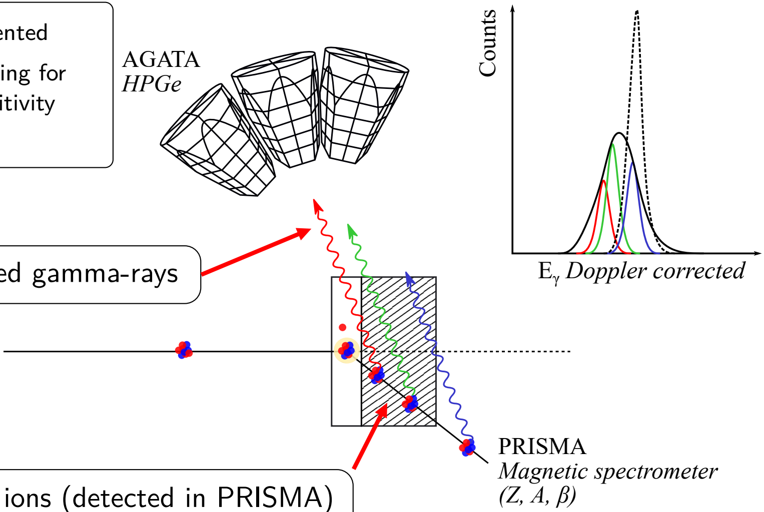


Slowed-down ions (detected in PRISMA)

Lifetime measurements: the DSAM method

- Highly segmented
- PSA & tracking for position sensitivity ($\sim$ 5mm)



Doppler-shifted gamma-rays

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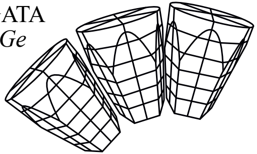
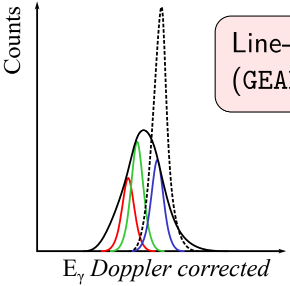
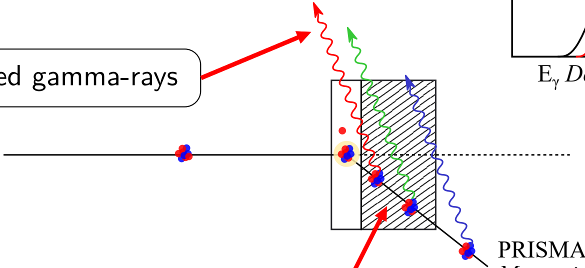
AGATA
HPGe





Line-shape analysis (`GEANT4`)

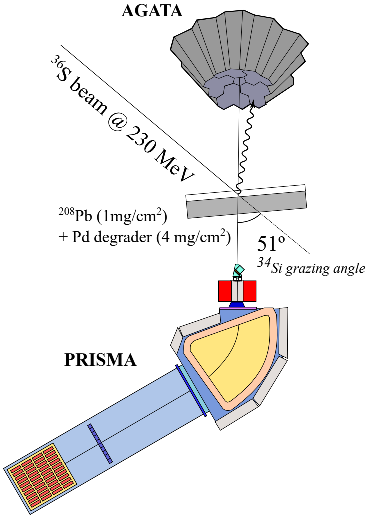
Doppler-shifted gamma-rays



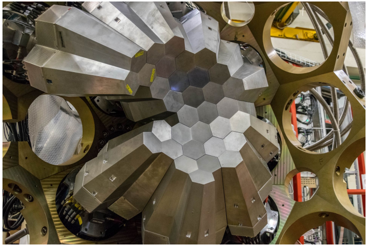
PRISMA
Magnetic spectrometer
(Z, A, β)

Slowed-down ions (detected in PRISMA)

Experimental set-up

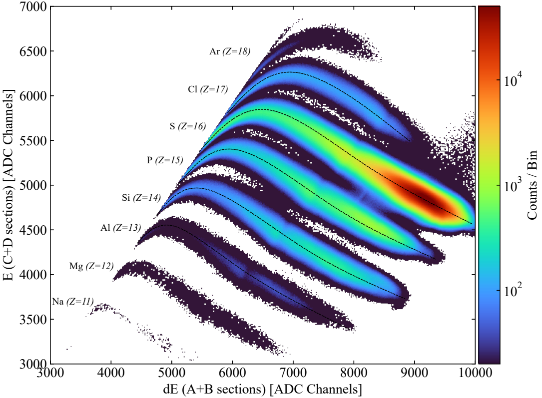


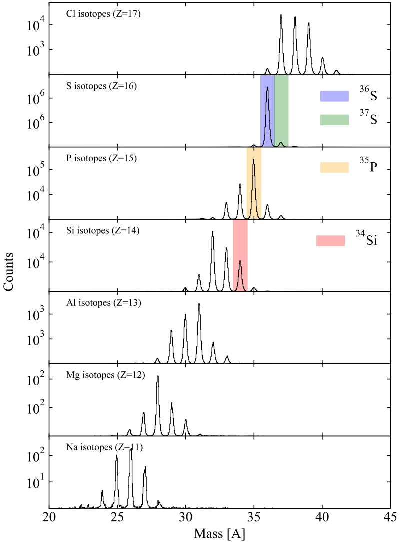
- Multi-nucleon transfer reaction, $^{208}\mathrm{Pb}(^{36}\mathrm{S}, \mathrm{X}\gamma)$ at 230 MeV.
- Target: $1\ \mathrm{mg/cm^2}\ \ ^{208}\mathrm{Pb}\ + 4\ \mathrm{mg/cm^2}\ \ \mathrm{Pd}$ (DSAM degrader)



PRISMA: Identification of the reaction channel

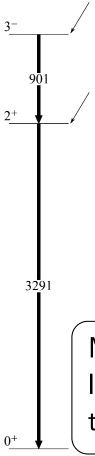
Good Z identification
$\Delta A/A \sim 1/140$ (average)





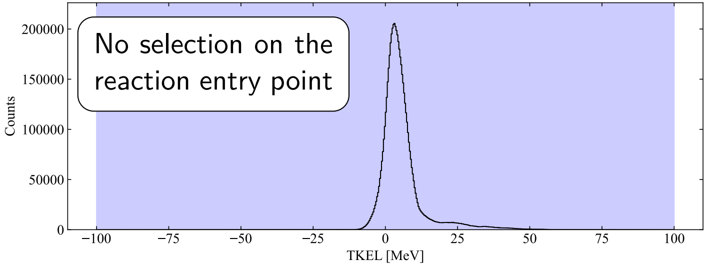
Control on the feeding (benchmark)

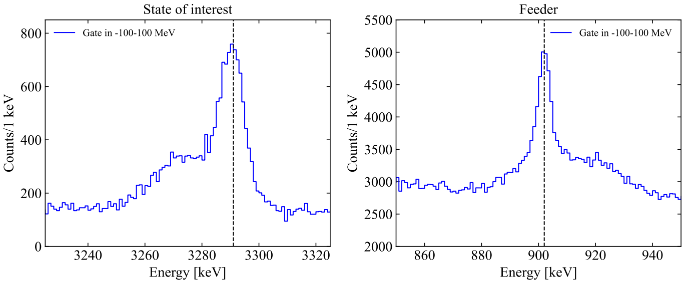
^{36}S *beam*



Measure the lifetime of the 2_1^+ state

No selection on the reaction entry point





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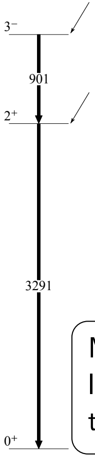
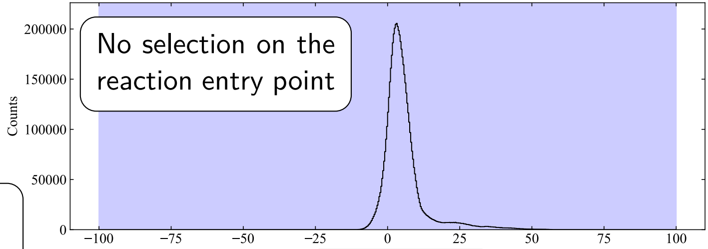
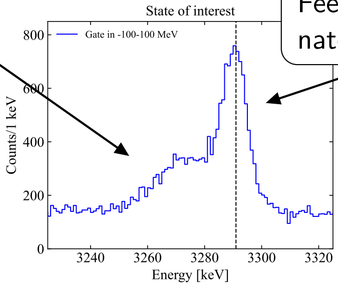


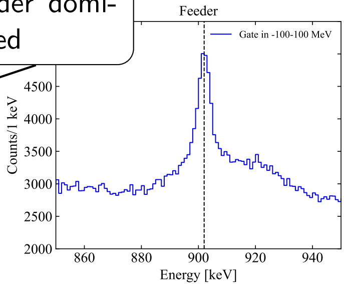


No selection on the reaction entry point

Short-lived component

Feeder dominated





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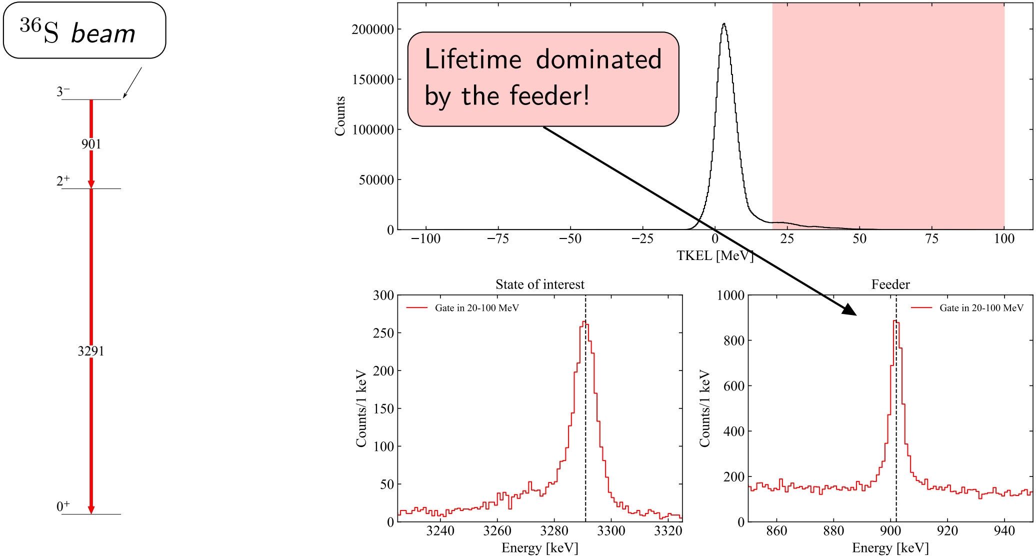

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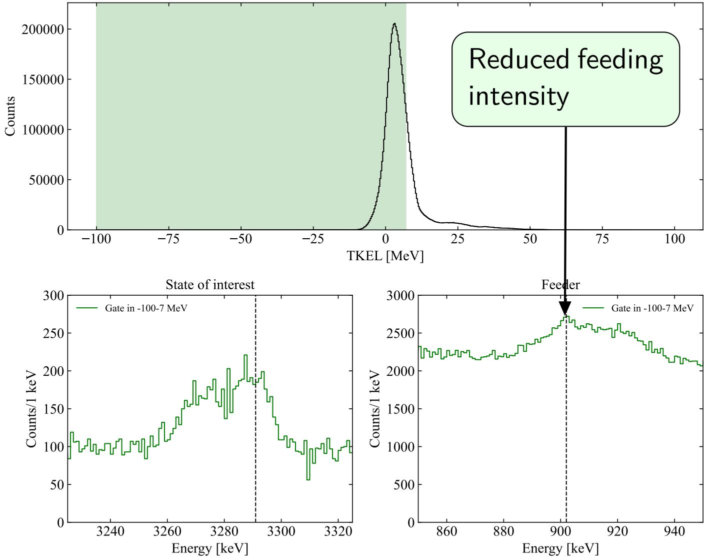

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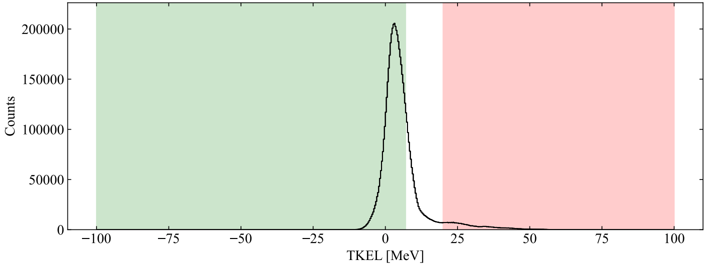
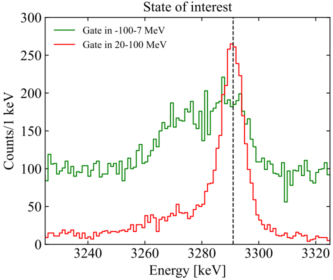
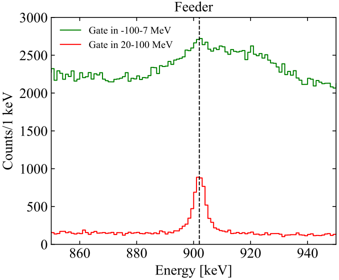
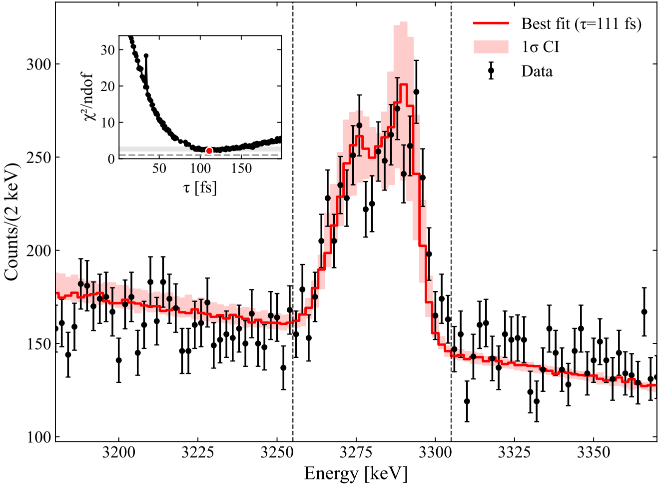


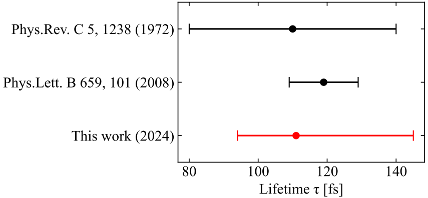




Benchmark transition: $2_1^+ \to 0_{gs}^+$ transition in ^{36}S



$$\tau = 111\,^{+34}_{-17}\ \text{fs}$$

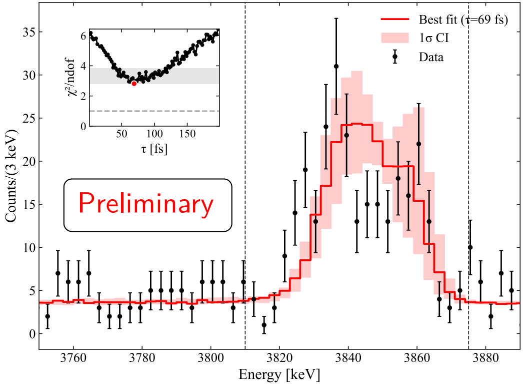


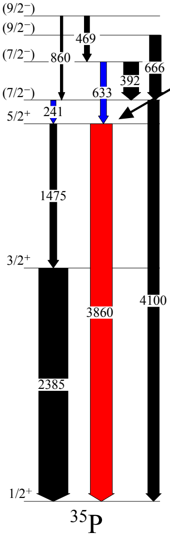
Previous measurements:
Samworth *et al.*, PRC 5, 1238 (1972).
Speidel *et al.*, PLB 659, 101 (2008).

$^{35}\mathbf{P}\ 5/2^+ \rightarrow 1/2^+_{gs}$

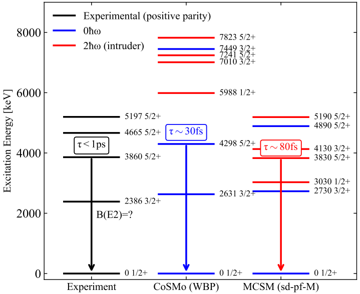
BR from L. Grocutt *et al.* PRC 100, 064308 (2019)

$$\tau = 69\,^{+50}_{-26}\ \text{fs} \Rightarrow\ B(E2) = 12^{+7}_{-5}\ \text{e}^2\text{fm}^4$$





Hard to remove the feeding with the TKEL selection



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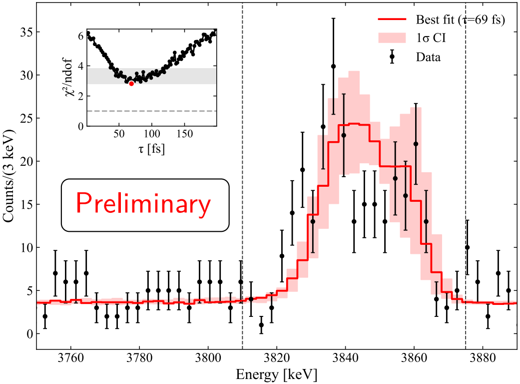
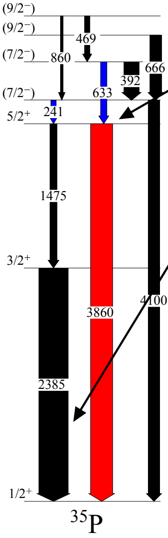
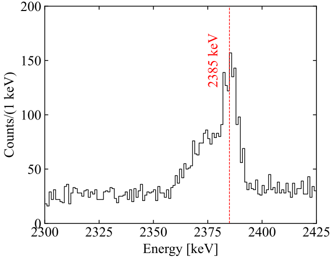




Hard to remove the feeding with the TKEL selection

DSAM tail of the $3/2^+ \rightarrow 1/2^+$ state also observed, δ unkown

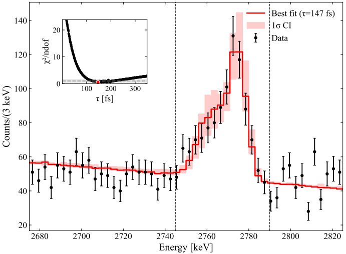


Outlook

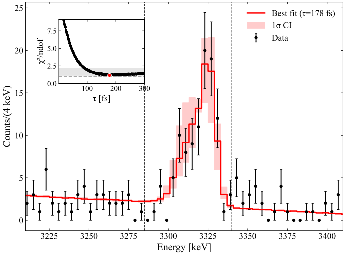
Some other lifetime studies done with AGATA in this region:

- L. Grocutt *et al.* PRC 100, 064308 (2019) $^{208}\mathrm{Pb}(^{36}\mathrm{S}, \mathrm{X}\gamma)$ (plunger)
- L. Zago, PhD thesis (2024) $^{36}\mathrm{S}(d, p)$ (plunger+DSAM)

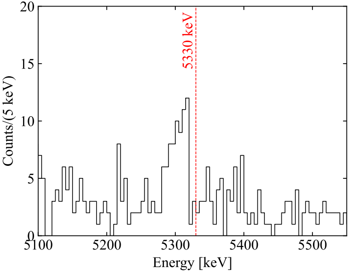
$^{37}\mathrm{S}$ $11/2^- \to 7/2^-_{gs}$ @ 2776 keV



$^{34}\mathrm{Si}$ $2^+_1 \to 0^+_{gs}$ @ 3327 keV



$^{34}\mathrm{Si}$ $2^+_3 \to 0^+_{gs}$ @ 5330 keV



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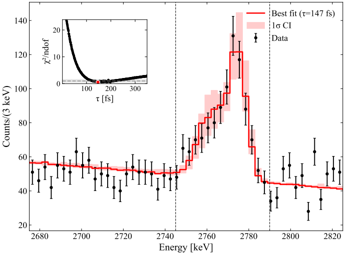

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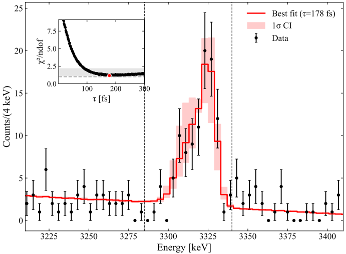

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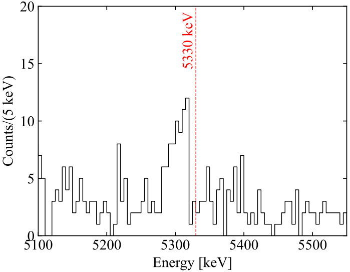

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on behalf of the experiment collaborators and the AGATA and PRISMA Collaborations

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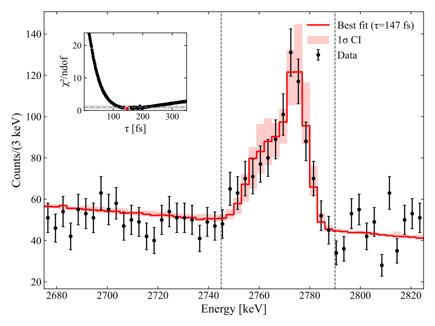
New measurements

^{37}S $11/2^- \rightarrow 7/2^-_{gs}$ @ 2775 keV

$$\tau = 147^{+104}_{-38}\ \text{fs} \Rightarrow B(E2) = 34^{+11}_{-14}\ \text{e}^2\text{fm}^4$$

SM calculations (SDPF-U) $B(E2) = 41\ \text{e}^2\text{fm}^4$

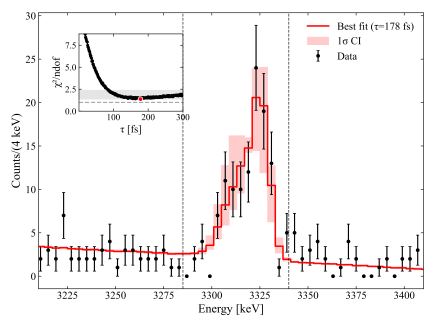
$(^{36}\text{S}\ 2^+) \otimes \nu(f_{7/2})^1$



^{34}Si $2^+_1 \rightarrow 0^+_{gs}$

$$\tau > 87\ \text{fs} \Rightarrow B(E2) < 23\ \text{e}^2\text{fm}^4$$

in agreement with R.W. Ibbotson *et al.*
Phys.Rev.Lett. 80, 2081 (1998)
$\tau = 150\,(70)$ fs (Coulex)



Lifetime measurements: the DSAM method

The lifetimes of interest are in the sub-picosecond range ($\sim$ 10-100 fs).

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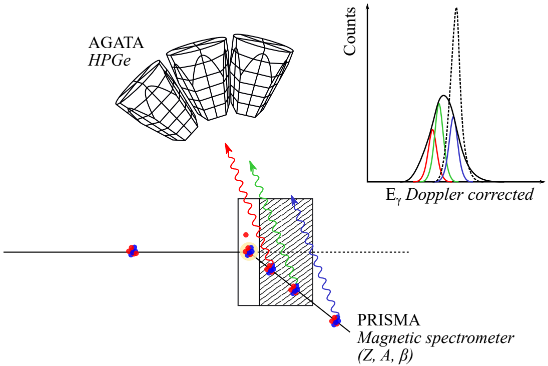

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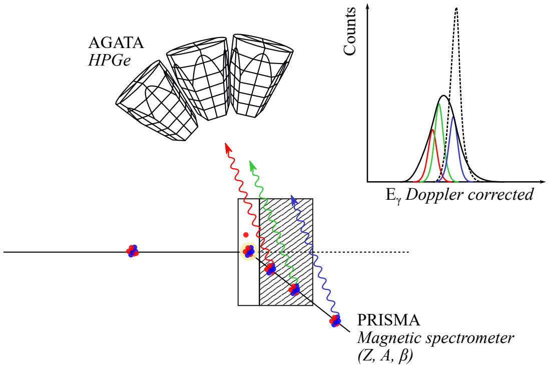

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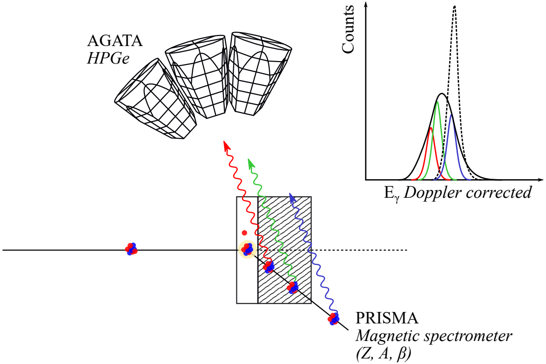
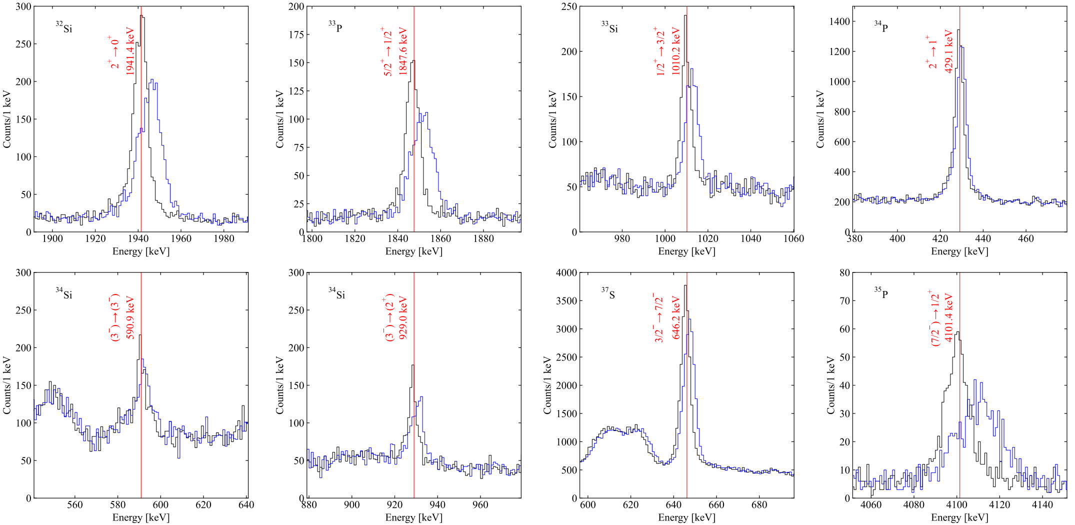
The Doppler Shift Attenuation method (DSAM) is an *indirect* method to measure the lifetimes of nuclear states decaying via γ-decay.

The lifetimes are estimated via a line-shape analysis of the peaks in the gamma-ray spectra.

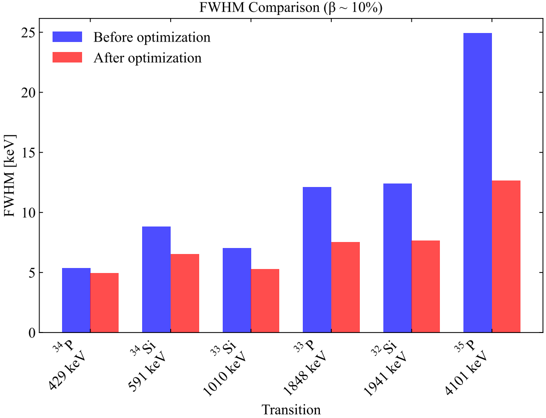


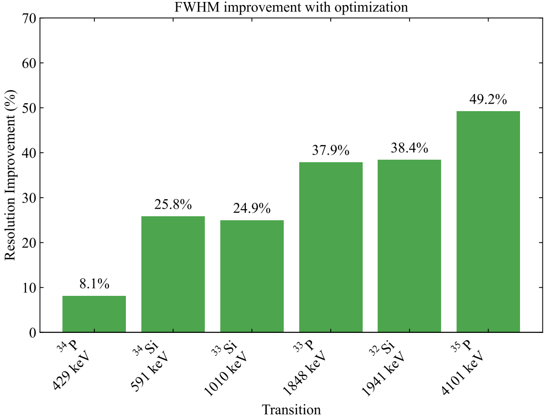
A set-up with precise Doppler correction capabilities is fundamental for this type of measurements!

AGATA: High energy calibration and DC optimization

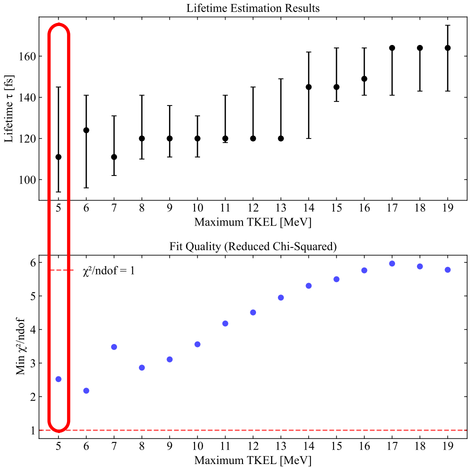


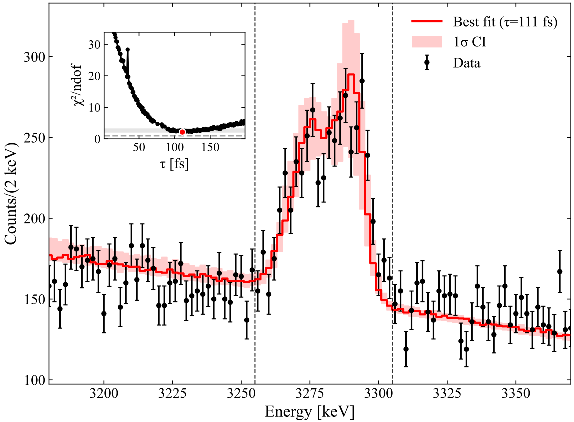
Resolution after Post-PSA and optimization of the DC





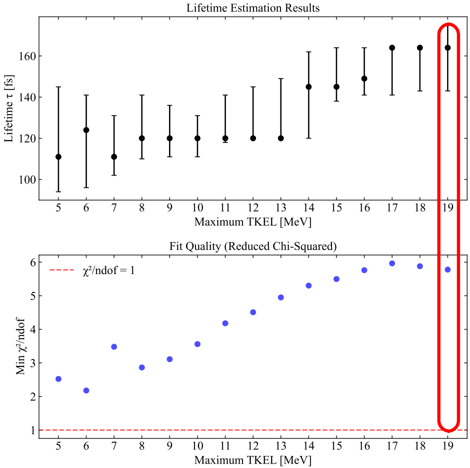
Control on the feeding (benchmark)

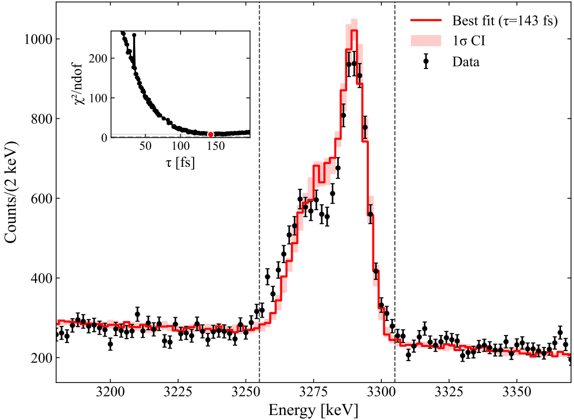




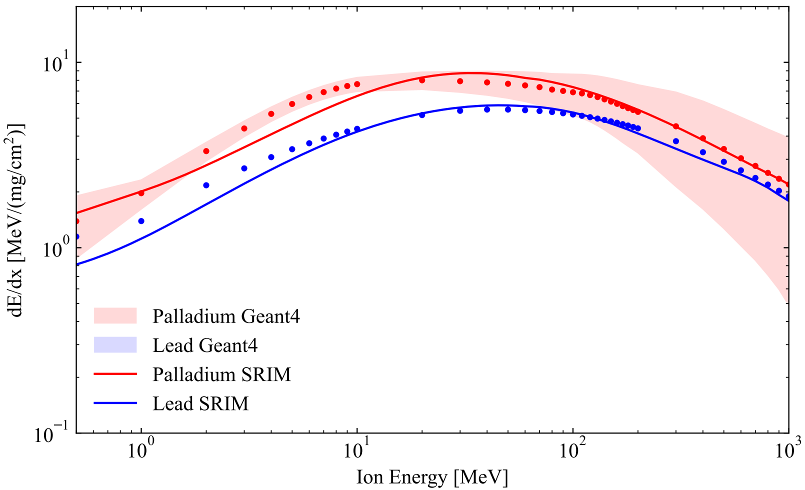
$$\tau = 111\,^{+34}_{-17}\ \mathrm{fs}$$

Control on the feeding (benchmark)



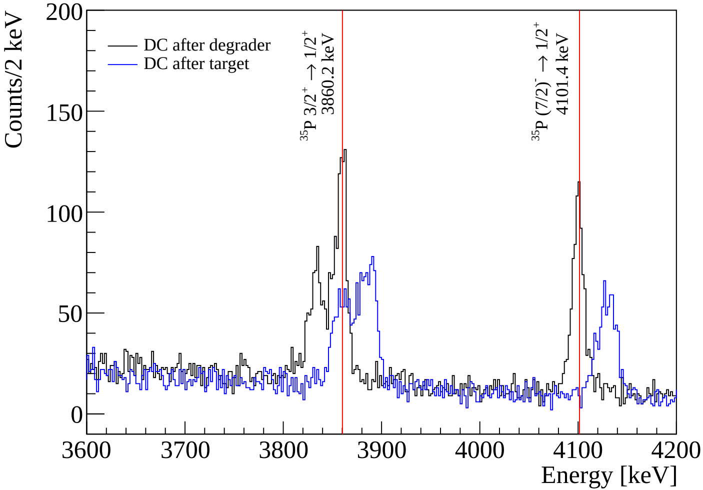


Energy loss



dE/dx [MeV/(mg/cm^2)]
10^1
10^0
10^{-1}
10^0
10^1
10^2
10^3
Ion Energy [MeV]
Palladium Geant4
Lead Geant4
Palladium SRIM
Lead SRIM

Energy loss


Counts/2 keV
Energy [keV]
DC after degrader
DC after target
^{35}P $3/2^+ \rightarrow 1/2^+$
3860.2 keV
^{35}P $(7/2)^- \rightarrow 1/2^+$
4101.4 keV
0
50
100
150
200
3600
3700
3800
3900
4000
4100
4200

Angular distributions (PRISMA)