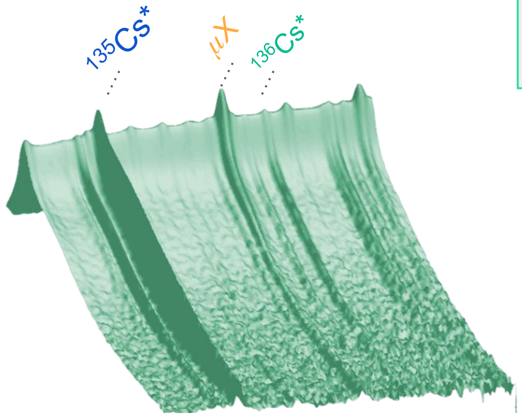
Ba-136 analysis with Midas data: peak identification, total capture and partial intensities

Slides Version 2.0
(22.05 + lessons learned and to-dos collected during the CM)



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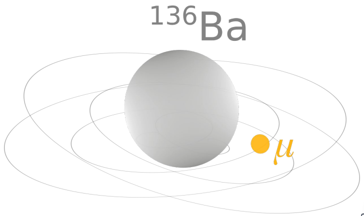


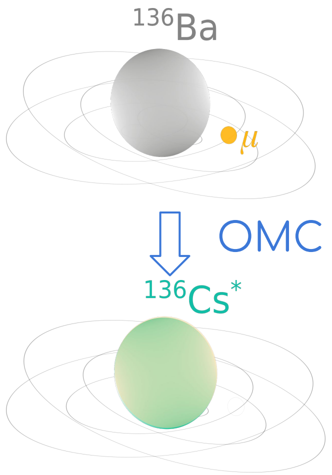
Monument

Objectives

What do we want to extract from the data?

- Total OMC rate (λ_{cap})

$$\lambda_{tot} = 1/\tau = \lambda_{cap} + H \cdot \lambda_{free}$$



Where τ is the lifetime of the muonic atom
(the X-ray down cascade is ~prompt)

+ $^{135}Cs^*$ + ...

OMC: Ordinary Muon Capture

Objectives

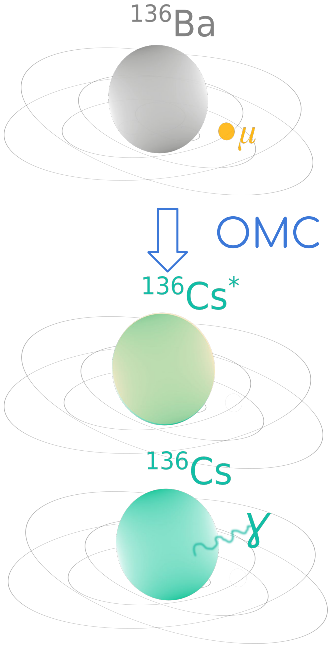
What do we want to extract from the data?

- Total OMC rate (λ_{cap})

$$\lambda_{\text{tot}} = 1/\tau = \lambda_{\text{cap}} + H \cdot \lambda_{\text{free}}$$

- Partial rate of excitations to level J (λ_j) following OMC $\lambda_j = Y_j \cdot \lambda_{\text{tot}}$

$$Y_j = \sum(I_i^\gamma)_{In} - \sum(I_i^\gamma)_{out}, \text{ where } I_i^\gamma = \frac{S_i^\gamma}{\eta_i \, \varepsilon \sum_n I(K_n)}$$



Where τ is the lifetime of the muonic atom
(the X-ray down cascade is ~prompt)

+ ^{135}Cs* + ….

OMC: Ordinary Muon Capture

Objectives

Extract intensity of γ and μX rays as well as λ_{cap}

- Total OMC rate (λ_{cap})

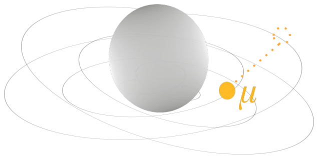
$$\lambda_{\rm tot} = 1/\tau = \boxed{\lambda_{\rm cap}} + H \cdot \lambda_{\rm free}$$

- Partial rate of excitations to level J (λ_j) following OMC

$$\lambda_j = Y_j \cdot \lambda_{\rm tot}$$

$$Y_j = \sum(I_i^\gamma)_{In} - \sum(I_i^\gamma)_{out}\text{, where } I_i^\gamma = \frac{\boxed{S_i^\gamma}}{\eta_i\ \varepsilon \boxed{\sum_n I(K_n)}}$$

^{136}Ba



Observables:

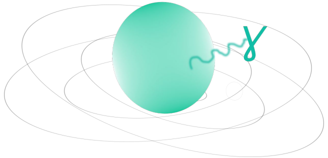
Intensity μX-rays

In: observables out: parameters extracted from data

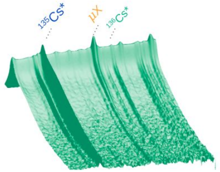
Time evolution ^{135}Cs* γs

+ ^{135}Cs* + ….

^{136}Cs



Intensity ^{136}Cs* γs



Focus here: γ-line identification, intensity (S_i, I_i) and time evolution (τ, λ_{cap})

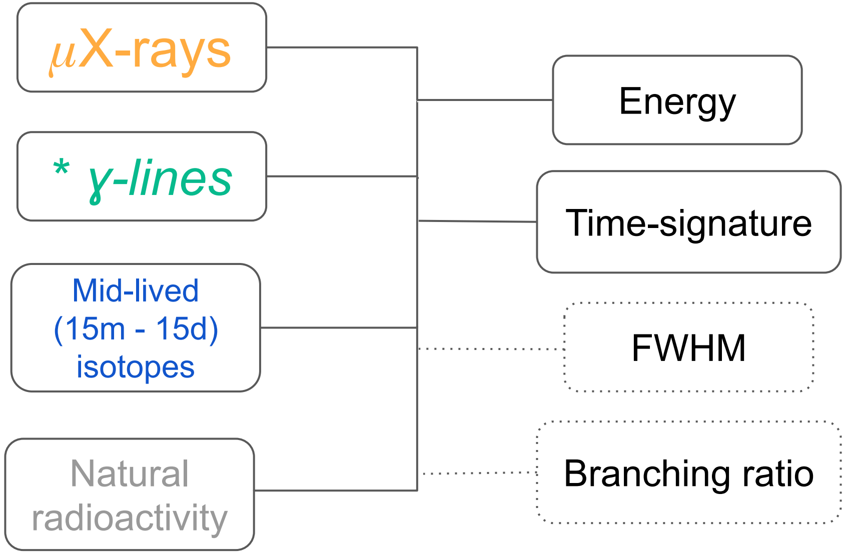
First steps: Midas Data cleaning, processing & HPGe parameters

- 1st data cleaning (removing “bad” runs)
- Midas processing into Dubna trees
- HPGe calibration
- HPGe efficiency curves

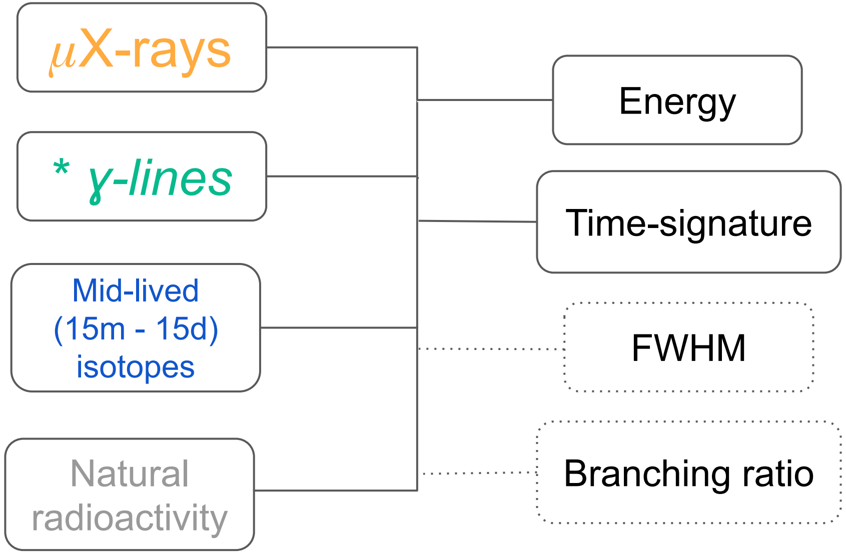
} Inputs from Daniya, Igor et al.

There is lots behind these steps, see Igor’s talk and slides in previous calls

Observables, identifiers & classifiers



Observables, identifiers & classifiers



- decay profile (τ_{fit}) , max intensity interval (Δt_{max})
- prompt, delayed, uncorrelated
- Beam on vs beam off (online / offline)

…. But to classify these spectra, we need to identify the Ɣ-lines

Ɣ-line identification

Observables, identifiers & classifiers

μX-rays

* γ-lines

Mid-lived (15m - 15d) isotopes

Natural radioactivity

Energy

Time-signature

FWHM

Branching ratio

- decay profile (τ_{fit}) , max intensity interval (Δt_{max})
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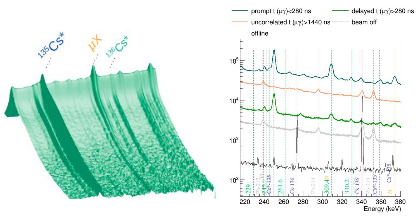
First approach:

3D-hists & overlaid spectra



…. But to classify these spectra, we need to identify the Ɣ-lines

Use preliminary parameters

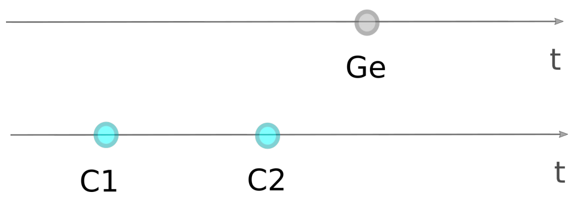
Rough estimate

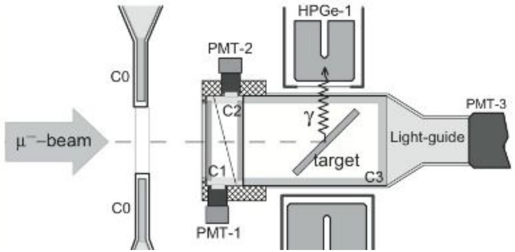
Quantify parameters

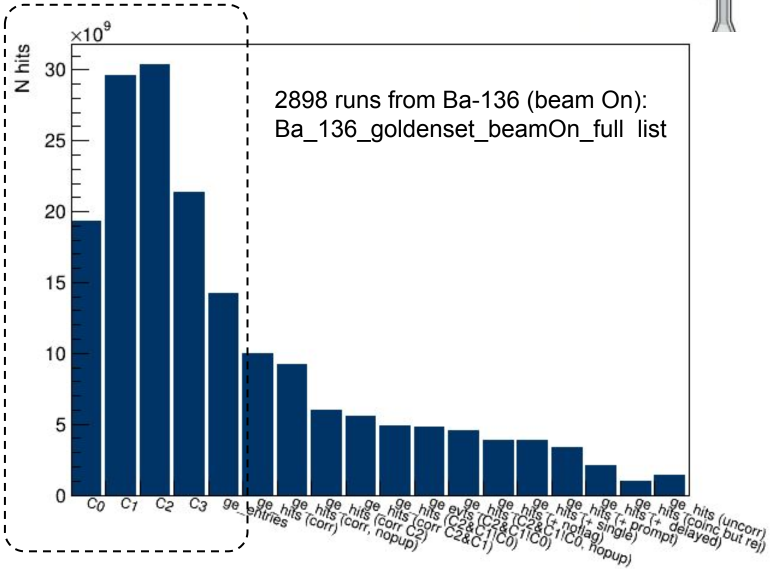
Building the spectra

Data quality cuts & preliminary classification

Events: C# hits (channel 1 to 4), Ge hits (ch 1-8, exc. ch 2 and 6)





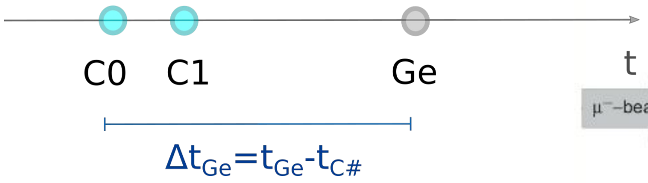


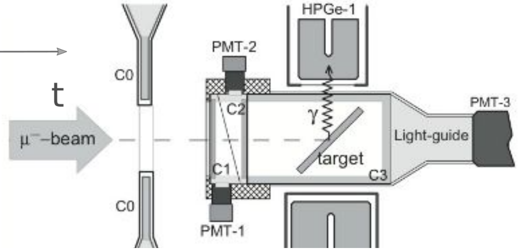
Building the spectra

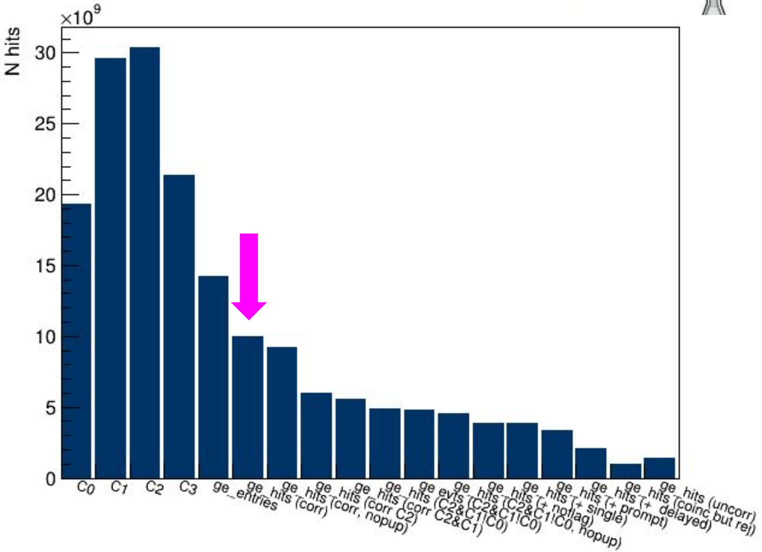
Data quality cuts & preliminary classification

Events: C# hits (channel 1 to 4), Ge hits (ch 1-8, exc. ch 2 and 6)

- **Correlated:** Ge hit* close enough to a C# hit $W = -100 < \Delta t_{Ge} < 1440$ns.







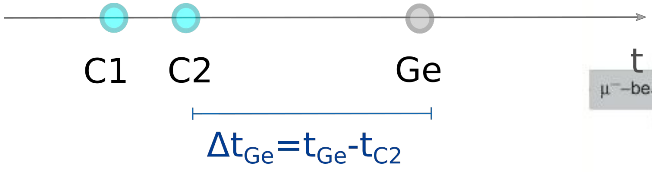
(*) Here Ge_2 and Ge_6 are excluded

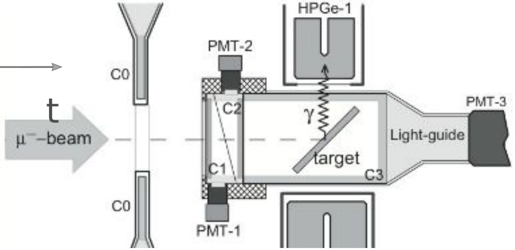
Building the spectra

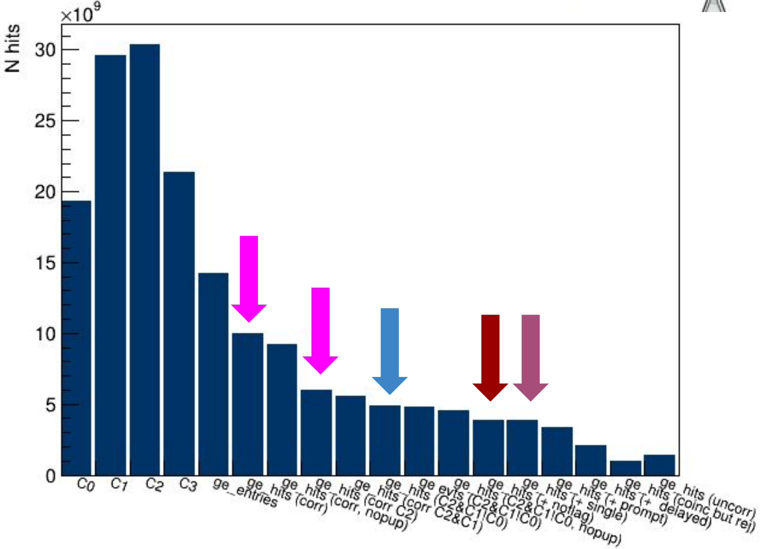
Data quality cuts & preliminary classification

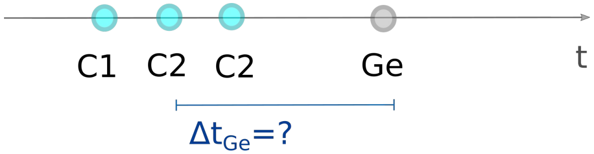
Events: C# hits (channel 1 to 4), Ge hits (ch 1-8, exc. ch 2 and 6)

- **Correlated:** Ge hit* close enough to a C# hit $W = -100 < \Delta t_{Ge} < 1440\text{ns}$.
  - **C2 Correlated:** $-100 < \Delta t_{Ge\text{-}C2} < 1400\text{ns}$ && C2==true (rejects muons corr. only to another C# hit, such as C0 or C3)
  - **Coincidence**: !C0 & C1 &C2: (!C3 not used, as it can be triggered by gammas)
  - **!Flagged:** pile up or other flags (flag 8: events with E=0)
  - **Single muons:** we need a well defined Δt_{Ge}, we thus **reject "multiple muons in W"**, such as multiple C1-C1, C2-C2, hits (ps: dt is ~ 1400ns)









Building the spectra

Data quality cuts & preliminary classification

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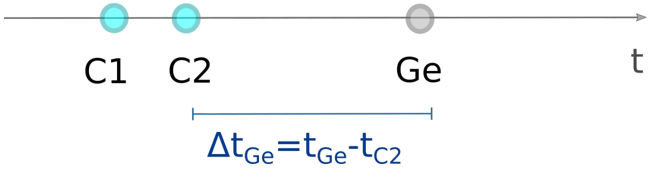
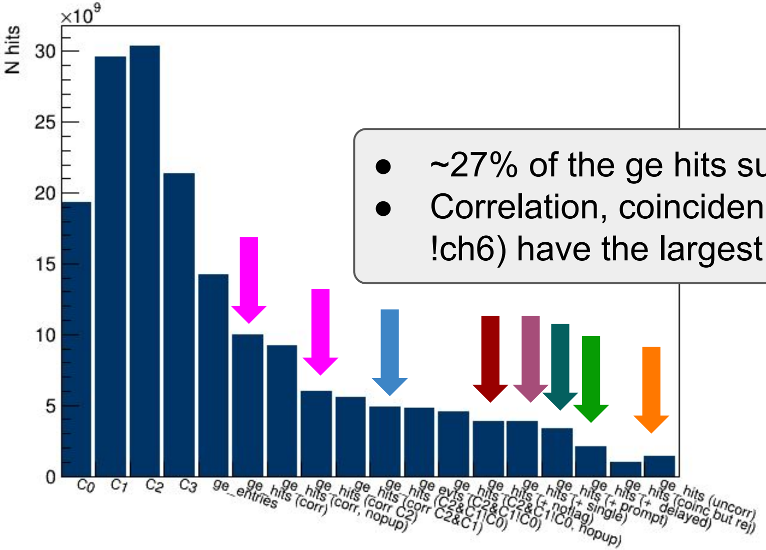
  - **Single muons:** we need a well defined Δt_{Ge}, we thus **reject "multiple muons in W"**, such as multiple C1-C1, C2-C2, hits (ps: dt is ~ 1400ns)
  - **Prompt** or **delayed**:
    $\Delta t_{Ge\text{-}C2} < 280$ ns or $280 < \Delta t_{Ge\text{-}C2} < 1440$ns
- **Uncorrelated**

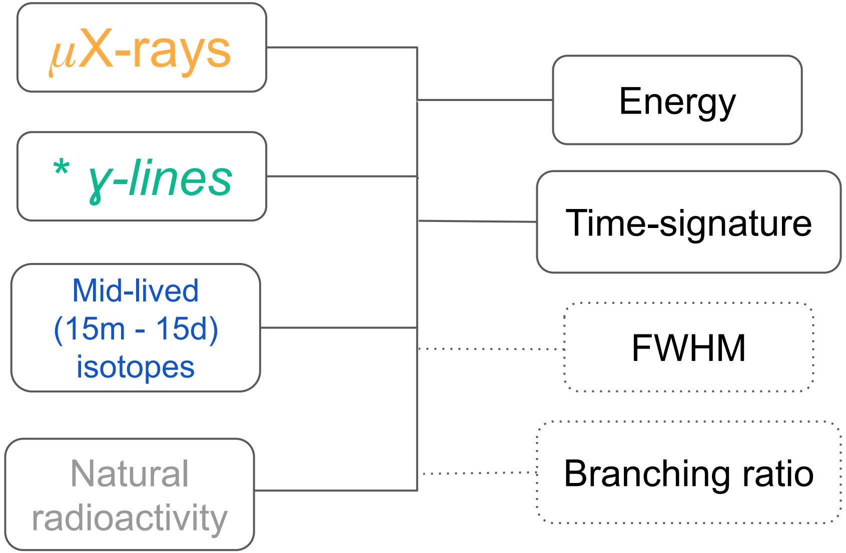
ps: Coinc but rej = coinc but flagged or multiple





- ~27% of the ge hits survive all the cuts
- Correlation, coincidence cuts, & (!ch2, !ch6) have the largest impacts.

Observables, identifiers & classifiers



Nuclear tables, uX table

Gammas from ^{136}Cs (13.16 d 3)		
Eg (keV)	Ig (%)	Decay mode
66.881 *17*	4.79 *20*	b⁻
86.36 *3*	5.18 *20*	b⁻
109.681 *7*	0.21 *3*	b⁻
153.246 *4*	5.75 *18*	b⁻
163.920 *2*	3.39 *12*	b⁻
166.576 *6*	0.37 *4*	b⁻
176.602 *4*	10.0 *4*	b⁻
187.285 *6*	0.36 *4*	b⁻

- prompt, delayed, uncorrelated
- Beam on vs beam off (online / offline)

E(level) (keV)	Jπ(level)	E(γ) (keV)	I(γ)
3520 *5*	1+		
3562.5 *7*	(13+)	635.0 *5* 1318.5 *5*	50 *25* 100 *40*
3684.0 *7*	(14+)	121.4 *5* 710.4 *3*	17 *4* 100 *30*

…. But to classify these spectra, we need to identify the Ɣ-lines

Ɣ-line identification

The isotope zoo we expect to see in the data

i) excited state:

$${}^{136}_{55}Cs^{*} \rightarrow {}^{136}_{55}Cs + \gamma$$

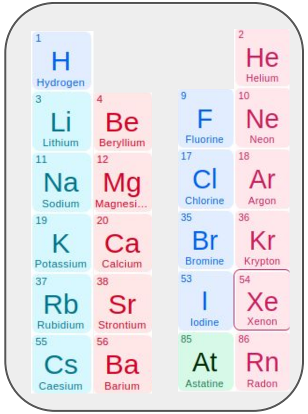
ii) n emission →

${}^{136}_{56}Ba$	*0n*	*d, τ*	*-1n*	*d, τ*	*-2n*	*d, τ*	*-3n*	*d, τ*
$-1p + 1n\,(\mu C\; or\; eC)$	${}^{136}_{55}Cs$	b^-, 13d	${}^{135(m)}_{55}Cs$	IT 53m	${}^{134(m)}_{55}Cs$	IT, 3h	${}^{133}_{55}Cs$	st
$-2p + 2n\,(\mu C\; or\; eC)$ (or p emission)	${}^{136}_{54}Xe$	st	${}^{135}_{54}Xe$ (Cs*)	IT, b^-, 15m-**9h**	${}^{134}_{54}Xe$	st or IT,~ms	${}^{133}_{54}Xe$	b^-, IT 2-5d

↑ *b^- decay*

$${}^{135}_{54}Xe \overset{b^-}{\rightarrow} {}^{135}_{55}Cs + \gamma \sim {}^{135}_{55}Cs^{*} \rightarrow {}^{135}_{55}Cs + \gamma$$

ps: half-lives and BRs are however different



Gammas emitted in b^- decay of z-1 to z isotope has the same energies of the gammas emitted in the de-excitation of the z isotope

☐ *Click on the isotopes to see their decay database*

$$\mu C\;: p + \mu \rightarrow n + \nu_\mu$$
$$eC\;: p + e \rightarrow n + \nu_e$$

d, τ: decay modes with gamma emission and half-lifes <1y.

Ɣ-line identification

The isotope zoo we expect to see in the data

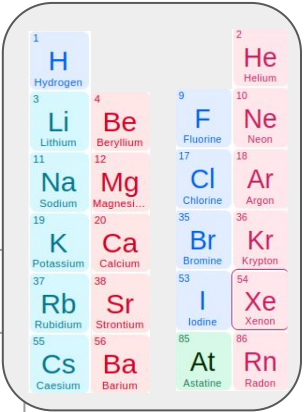
i) excited state:

$$^{136}_{55}Cs^* \rightarrow \, ^{136}_{55}Cs + \gamma$$

ii) n emission →

$^{136}_{56}Ba$	*0n*	*d, τ*	*-1n*	*d, τ*	*-2n*	*d, τ*	*-3n*	*d, τ*	*-4n*	*d, τ*
$-1p+1n\,(\mu C\, or\, eC)$	$^{136}_{55}Cs$	b^-, 13d	$^{135(m)}_{55}Cs$	IT 53m	$^{134(m)}_{55}Cs$	IT, 3h	$^{133}_{55}Cs$	st	$^{132}_{55}Cs$	
$-2p+2n\,(\mu C\, or\, eC)$ (or p emission)	$^{136}_{54}Xe$	st	$^{135}_{54}Xe$ (Cs*)	IT, b^-, 15m-**9h**	$^{134}_{54}Xe$?	st or IT,~ms	$^{133}_{54}Xe$	b^-, IT 2-5d	$^{132(m)}_{54}Xe$	IT,~ms or st
	$^{136(m)}_{53}I$	b^-, ~50s	$^{135}_{53}I$	b^-, ~7h	$^{134(m)}_{53}I$?	IT, b^-, 4-53m	$^{133(m)}_{53}I$	b^-, ~7h	$^{132(m)}_{53}I$	IT, or b^-, ~2h

α



b^- decay

ps: isotopes marked in light color don't seem to be observed in beam on/off data, isotopes marked with (?) seem to match some observed lines

Click on the isotopes to see their decay database

Also the possibility of α emission

or α-p, as it will be shown by Ng

$\mu C \; : p + \mu \rightarrow n + \nu_\mu$

d, τ: decay modes with gamma emission and half-lifes <1y.

Ɣ-line identification

The isotope zoo we expect to see in the data

The target is not 100% Ba-136:
The neutron emission rate from other isotopes in the sample can be at the level of the searched excitation, so these need to be well understood.

Ba isot	$_{enr}$Ba-136 (%)
138	**2.41**
137	**1.54**
136	95.27
135	0.74
134	0.04

$^{138}_{56}Ba \xrightarrow{+\mu} {}^{138}_{55}Cs^{*} \longrightarrow {}^{138}_{55}Cs + \gamma$ *(suppressed)*

$^{138}_{56}Ba \xrightarrow{+\mu} {}^{138}_{55}Cs^{**} \xrightarrow{-n} {}^{137}_{55}Cs^{(*)} \rightarrow {}^{137}_{55}Cs + \gamma$

$^{137}_{56}Ba \xrightarrow{+\mu} {}^{137}_{55}Cs^{*} \longrightarrow {}^{137}_{55}Cs + \gamma$ *(suppressed)*

$^{137}_{56}Ba \xrightarrow{+\mu} {}^{137}_{55}Cs^{**} \xrightarrow{-n} {}^{136}_{55}Cs^{(*)} \rightarrow {}^{136}_{55}Cs + \gamma$

ɣ from de-excitation:

- ^{138}Cs* (suppressed, compared to -n)
- ^{137}Cs* (probable after -n)
- ^{136}Cs*(probable, searched line)

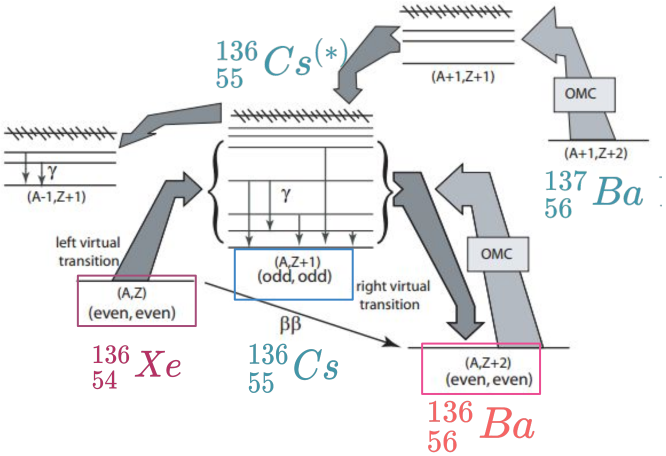
ɣ from unstable isotopes:

- ^{138}Cs (b$^-$, IT, 33m) -> Ba-138 (st) + ɣ
- ^{137}Cs (stable)
- ^{136}Cs (b$^-$, 13d) -> Ba-136 (st) + ɣ

… but the target is not 100% Ba-136:

The neutron emission rate from other isotopes in the sample can be at the level of the searched excitation, so **these need to be well understood**.

Due to the high E transfer, a concurrent process to the excitation (i) is the neutron emission (ii), which produces other daughter isotopes



Additional measurement of Ba (natural)

Ba isot	$_{enr}$Ba-136 (%)	$_{nat}$Ba (%)
138	**2.41**	72
137	**1.54**	**11**
136	95.27	8
135	0.74	6.6
134	0.04	2.4

Main ɣ-lines from OMC by Barium:

$$^{138}_{56}Ba \xrightarrow{+\mu} {}^{138}_{55}Cs^* \longrightarrow {}^{138}_{55}Cs + \gamma$$ *(suppressed)*

$$^{138}_{56}Ba \xrightarrow{+\mu} {}^{138}_{55}Cs^{**} \xrightarrow{-n} {}^{137}_{55}Cs^{(*)} \longrightarrow {}^{137}_{55}Cs + \gamma$$

$$^{137}_{56}Ba \xrightarrow{+\mu} {}^{137}_{55}Cs^* \rightarrow {}^{137}_{55}Cs + \gamma$$ *(suppressed)*

$$^{137}_{56}Ba \xrightarrow{+\mu} {}^{137}_{55}Cs^{**} \xrightarrow{-n} {}^{136}_{55}Cs^{(*)} \rightarrow {}^{136}_{55}Cs + \gamma$$

3.5%

ɣ from de-excitation:

- ^{138}Cs* : suppressed, compared to -n
- ^{137}Cs* : probable after -n, but low %
- ^{136}Cs* : probable + searched line
- ^{135}Cs*: probable

ɣ from unstable isotopes?:

- ^{138}Cs (b⁻, IT, 33m) -> Ba-138 (st) + ɣ : suppressed
- ^{137}Cs (stable) : 0
- ^{136}Cs (b⁻, 13d) -> Ba-136 (st) + ɣ : probable
- ^{135m}Cs (IT, 53m) : probable

Cross population

i) $$^{136}_{56}Ba \xrightarrow{+\mu} {}^{136}_{55}Cs^* \longrightarrow {}^{136}_{55}Cs + \gamma$$ *i) searched line, less likely than n-emission*

ii) $$^{136}_{56}Ba \xrightarrow{+\mu} {}^{136}_{55}Cs^{**} \xrightarrow{-n} {}^{135}_{55}Cs^* \longrightarrow {}^{135}_{55}Cs + \gamma$$ ***(ii) well present in the spectrum***

95.3%
(x27 larger)

$$^{135m}_{55}Cs \xrightarrow{53m} {}^{135}_{55}Cs + \gamma$$ ***well present in the spectrum***

$$^{136}_{55}Cs \xrightarrow{13d} {}^{136}_{56}Ba + \gamma$$ ***well present in the spectrum*** *(more clearly in beam off data)*

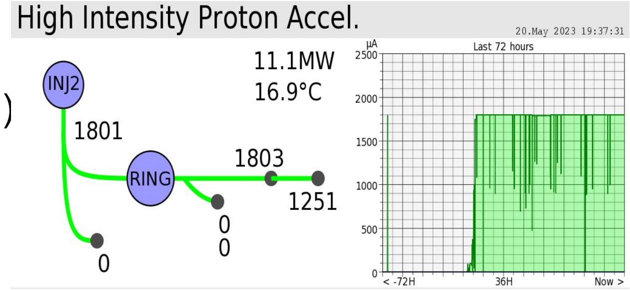
The excited state is commonly present after neutron emission, and given that *-n* is much more frequent, we get much more ɣ's from ^{135}Cs* than from ^{136}Cs*

Before we continue..

We make sure that the selected data is stable

2898 runs from Ba-136 (beam On)

Expected from a stable dataset:
Beam flux ∝ C# hits ∝ correlated Ge hits (all proportional, ∝)
uncorrelated Ge hits (constant, independent of the beam)



Data classification:
0) stable
1) unstable beam: beam current has dropped under average value

2) prompt/delayed ratio unstable
3) uncorr events unstable: larger rate of uncorr event.

From the newest Ba-136 only 8 out of the 2898 selected runs (beam on) are excluded.
See details in (Data cleaning slides)

ɣ-line identification:

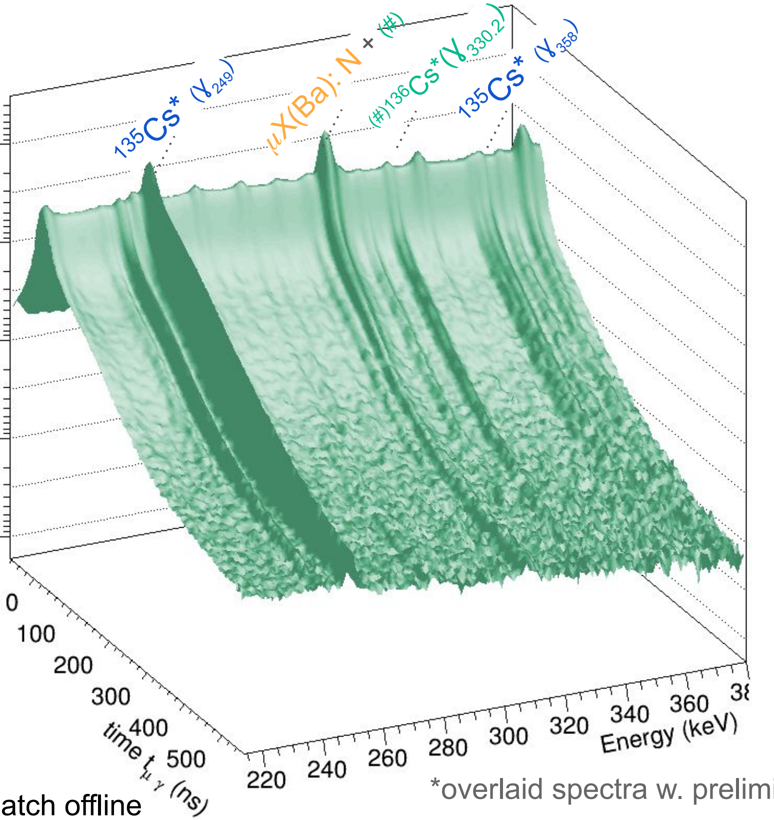
Using energy and time classifiers (prompt, delayed …)

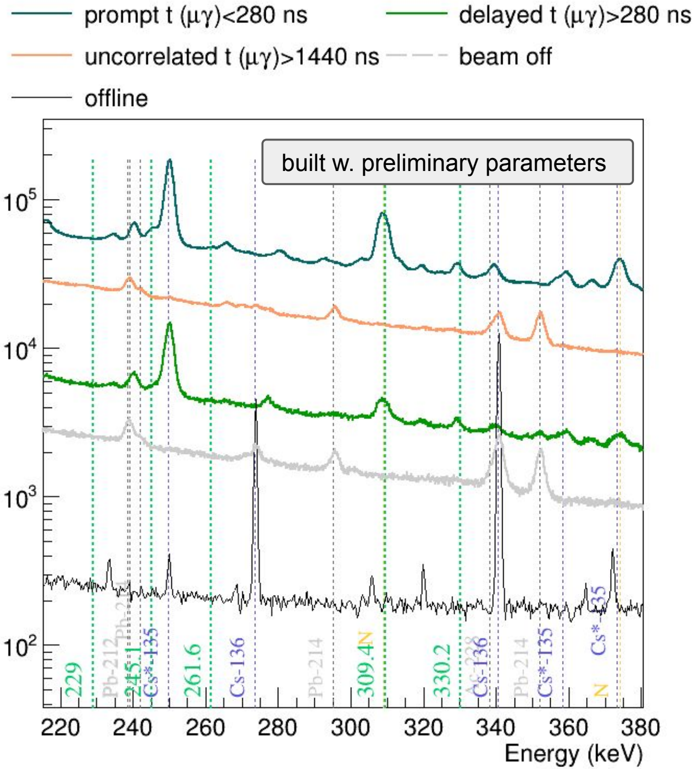
μX-rays

** γ-lines

Mid-lived (15m - 15d) isotopes

Natural radioactivity





Full list of lines here
Beam off vs offline here
All 3D plots here
Spectra recalibrated to match offline

*overlaid spectra w. preliminary parameters & qualitative time profile from 3D hist

Observables, identifiers & classifiers

μX-rays

* γ-lines

Mid-lived (15m - 15d) isotopes

Natural radioactivity

Energy

Time-signature

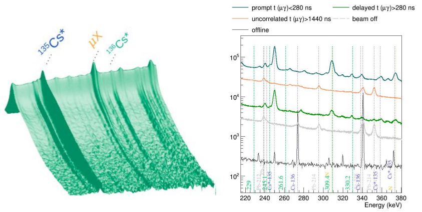
FWHM

Branching ratio

- decay profile (τ_{fit}) , max intensity interval (Δt_{max})
- prompt, delayed, uncorrelated
- Beam on vs beam off (online / offline)

First approach:

3D-hists & overlaid spectra



⇨ preliminary parameters

Observables, identifiers & classifiers

- μX-rays
- * γ-*lines*
- Mid-lived (15m - 15d) isotopes
- Natural radioactivity

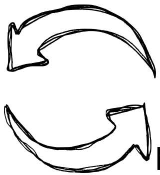
- Energy
- Time-signature
- FWHM
- Branching ratio

- decay profile (τ_{fit}) , **max intensity interval (Δt_{max})**
- prompt, delayed, uncorrelated
- Beam on vs beam off (online / offline)

we don't want to fully/perfectly fit every single ɣ-line….

The Ba γ-*lines* are specially faint, short lived & swamped in μX background.

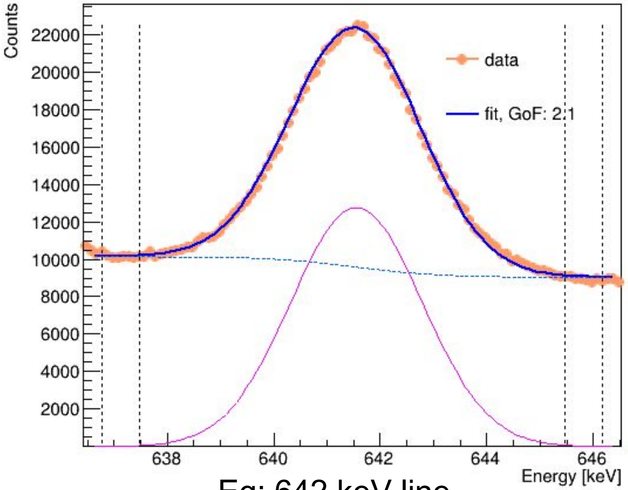
Rough estimate



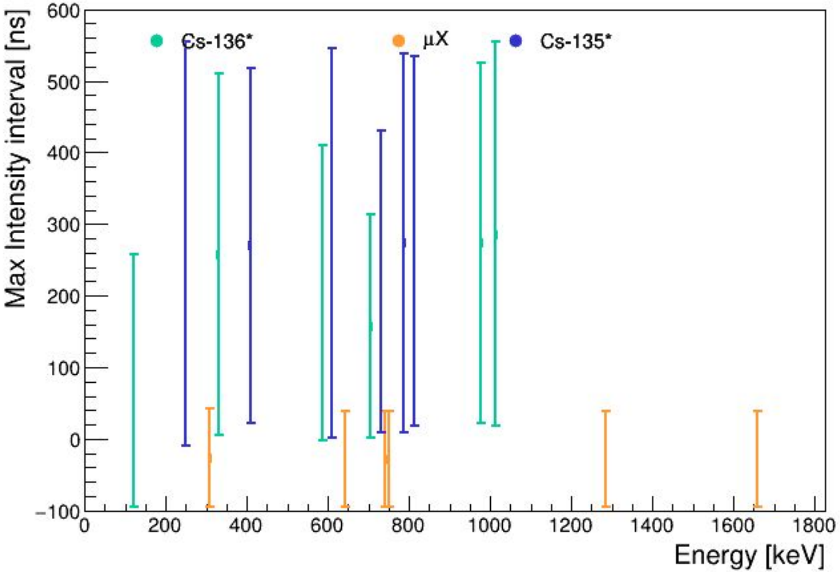
Quantify parameters

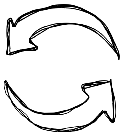
Ɣ-line identification

maximum intensity interval (Δt_{max}): point at which integrating more time-binned sections decrease the signal to noise ratio



Eg: 642 keV line





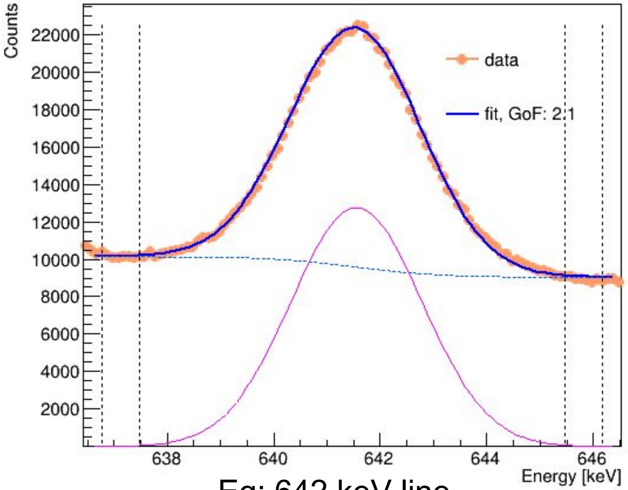
i) Signal estimated from 1-2 keV around mean, noise from sidebands.

ii) Resulting hists are fit, method is run again for signal estimation around ± 3 σ.

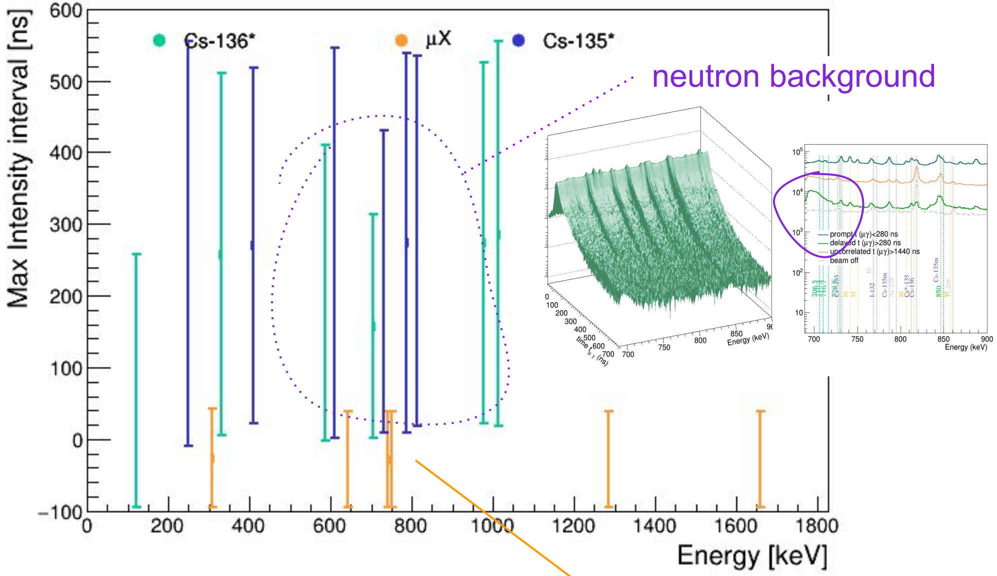
Only after optimization it is possible to fit some faint *γ*-lines*

ɣ-line identification

maximum intensity interval (Δt_{max}) as time signature / classifier



Eg: 642 keV line

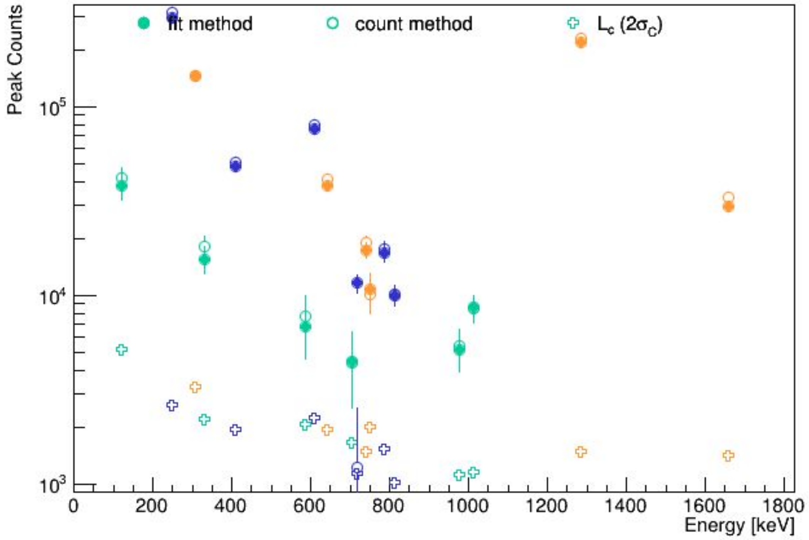


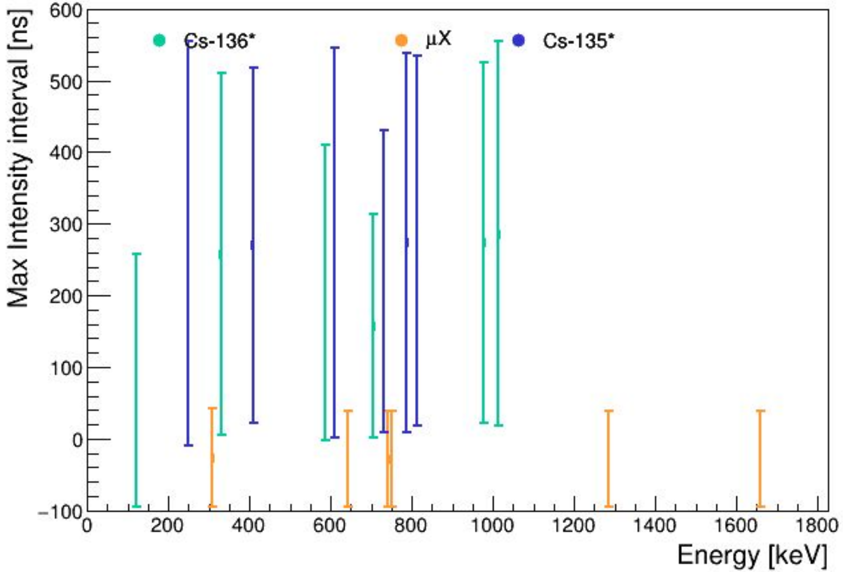
Results can be used to further confirm lines / understand the spectra, obtain time resolution and parameters for prompt / delayed / uncorrelated

3 σ_t~ ± 60 ns
→ σ_t~ ± 20 ns

Ɣ-line identification

S_i estimation within Δt_{max} : comparison for fit and count methods





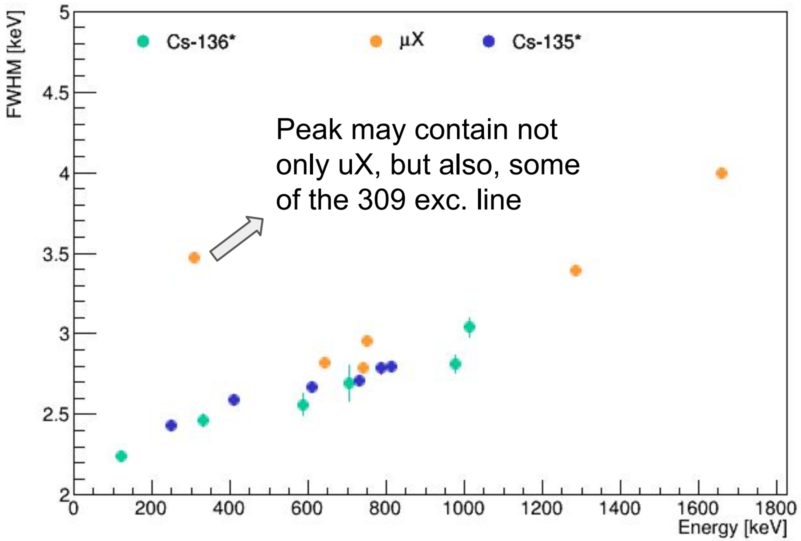
Resulting histograms are fit, peak counts (bk subtracted S_i) are calculated within Δt_{max}

Only after optimization it is possible to fit some faint *γ*-lines* and know better their E, σ_E

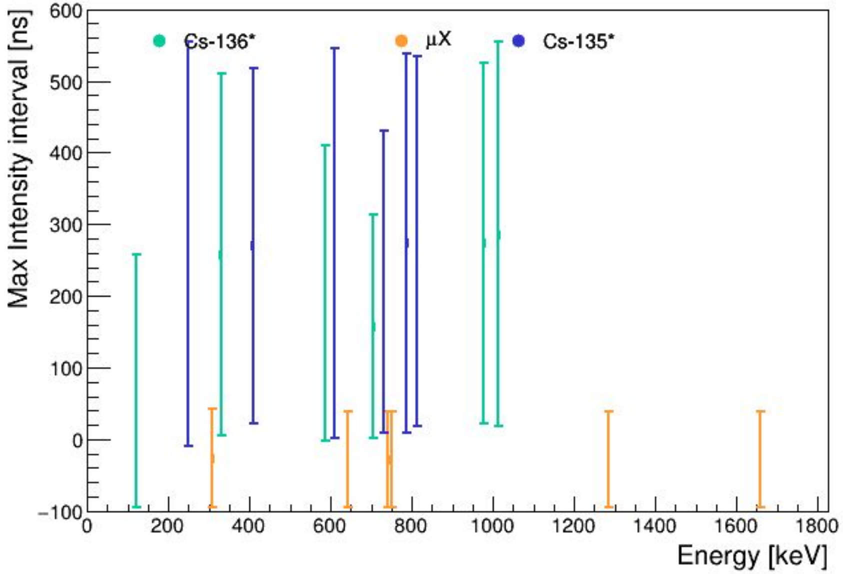
Ps: count method often yields higher values as it does not subtract the 'tails' which are counted separately in the fit method

Ɣ-line identification

FWHM as “double-line” identifier

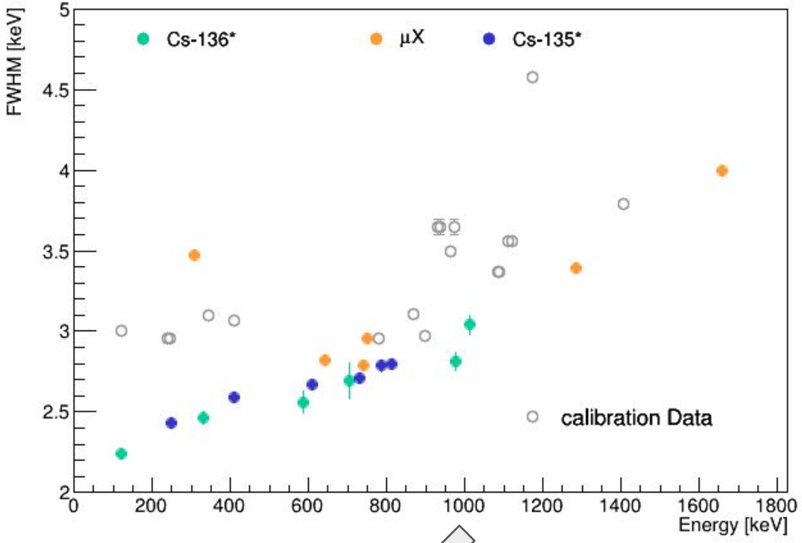


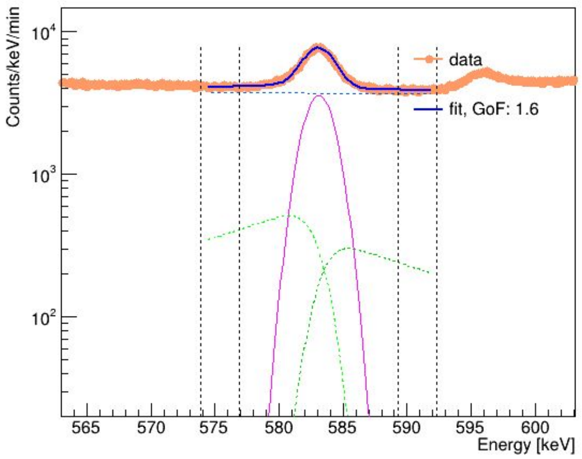
Peak may contain not only uX, but also, some of the 309 exc. line



Ɣ-line identification

FWHM as “double-line” identifier



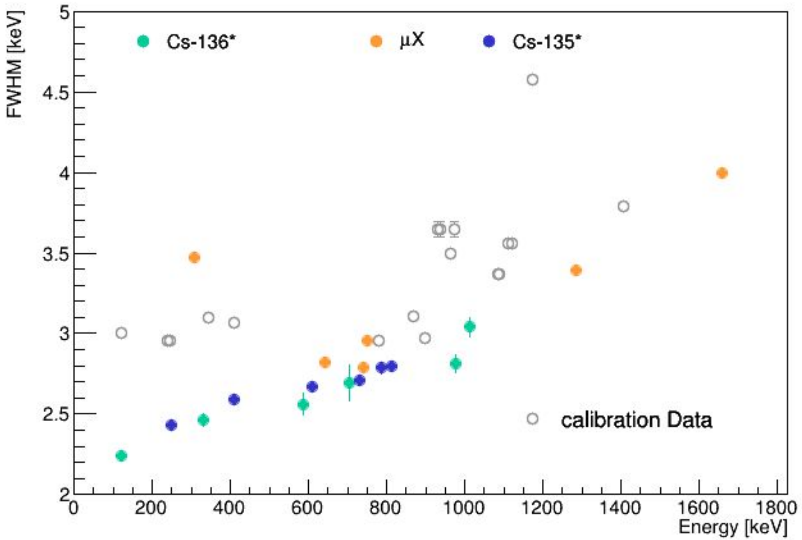


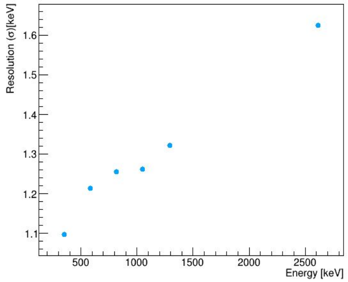
… Large side tails in ~~Midas~~ Ba-136 data

Note that calibration data does not (yet) provide a FWHM calibration curve

ɣ-line identification

FWHM as "double-line" identifier





See spectra recalibrated to match offline

Ideally, we would constrain the FWHM of the peaks using the values from the calibration

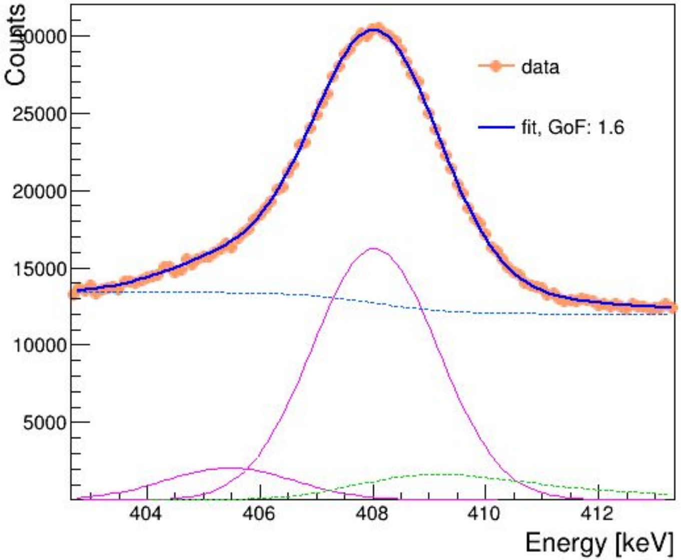
However, even if the estimation from calibrations improve, the resolution in the data might be different (peak shift)

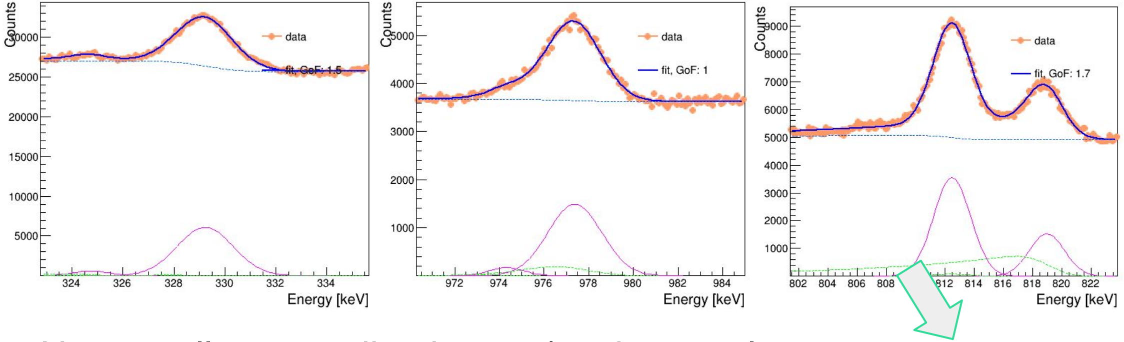
One could use the resolution from uncorrelated peaks, but there aren't many and they aren't strong

Solution: Do not constrain the resolution in the main fits but make sure they don't look to much off expectations (comparison to those from uncorrelated peaks)

ɣ-line identification

S_i estimation within Δt_{max} : extended fit around line ($E \pm 6\sigma_E$)





Now small surrounding bumps/peaks are also taken into account. Fit constraints tuned as to provide GoF ~ 1

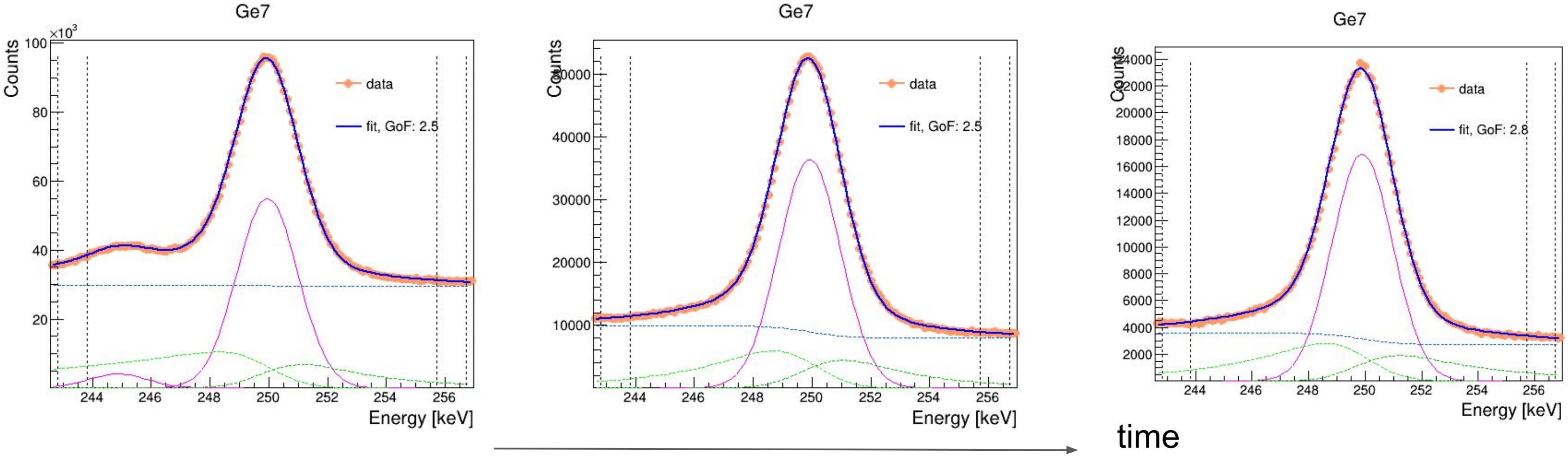
See this slide on fit parameters.

TO DO: fix tails to assume constant fraction of gaussian for a given energy window

Only after optimization it is possible to fit some faint *γ*-lines* and know better their E, σ_E

Ɣ-line identification

With optimized peak parameters, we can better fit time slices S_i

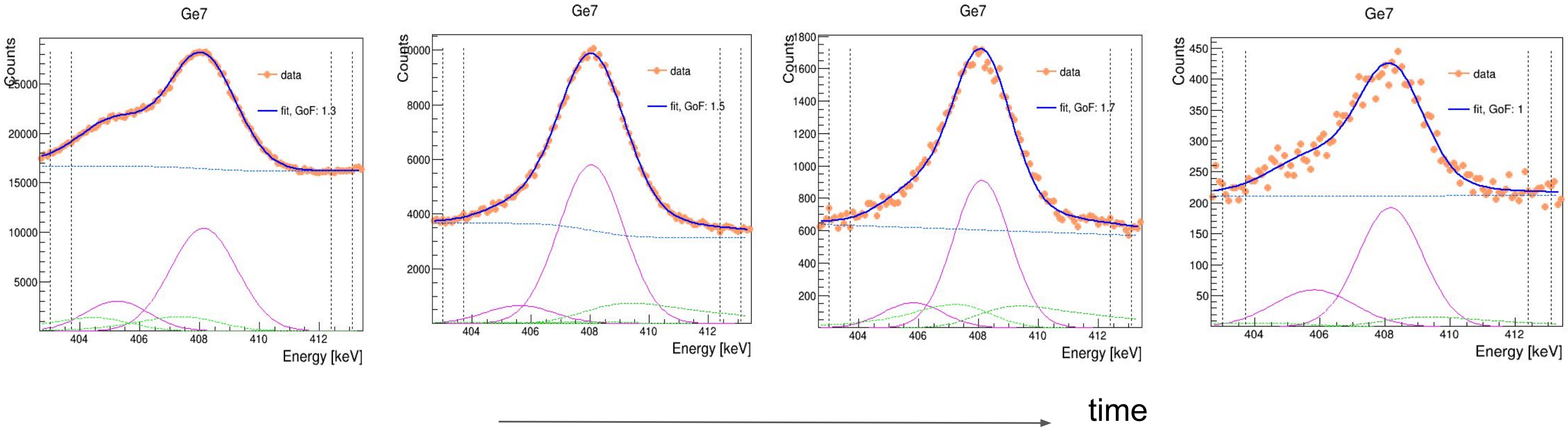


Peak positions ~ fixed. Resolutions “flexible” but not too much. Amplitude of tails and neighboring bumps unconstrained: background changes in time.

TODO: gaussian amplitudes can change in time, but fix tail fractions

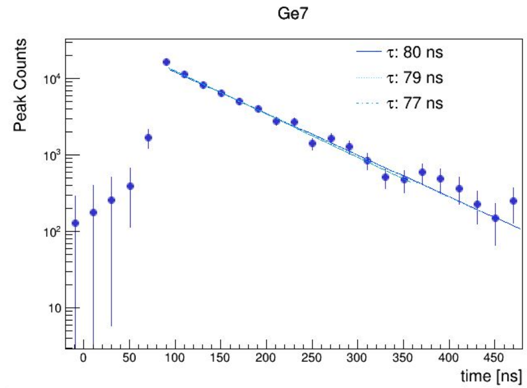
ɣ-line identification

With optimized peak parameters, we can better fit time slices S_i



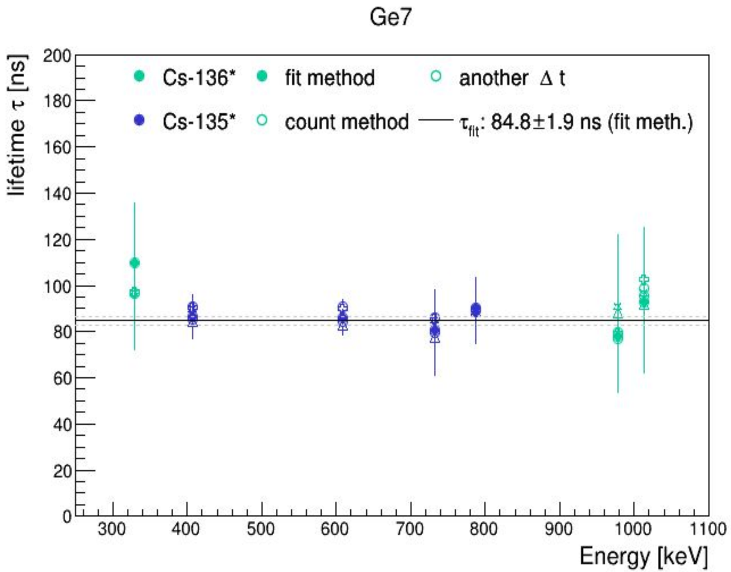
Peak positions ~ fixed. Resolutions “flexible” but not too much. Amplitude of tails and neighboring bumps unconstrained: background changes in time.

Total OMC rate: preliminary τ estimation from the de-excitation γ-lines

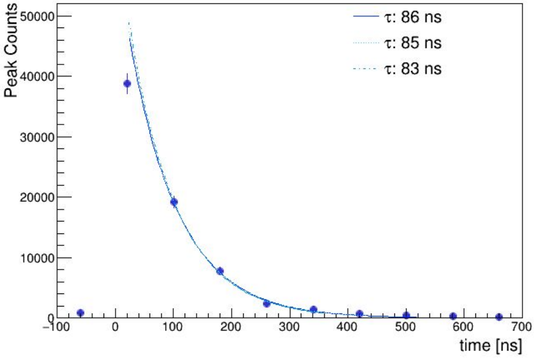


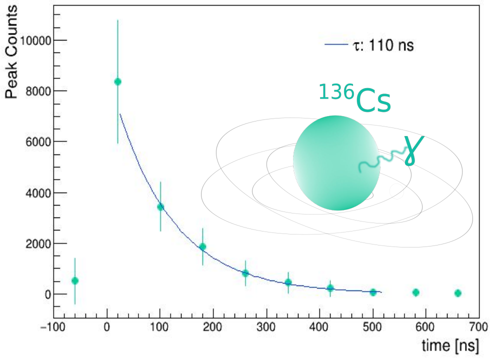
^{135}Cs* γ-lines produce the best fits as they are more intense.

The first 2 points are excluded (due to σ_t). The fit is performed for 3 different time regions and binnings

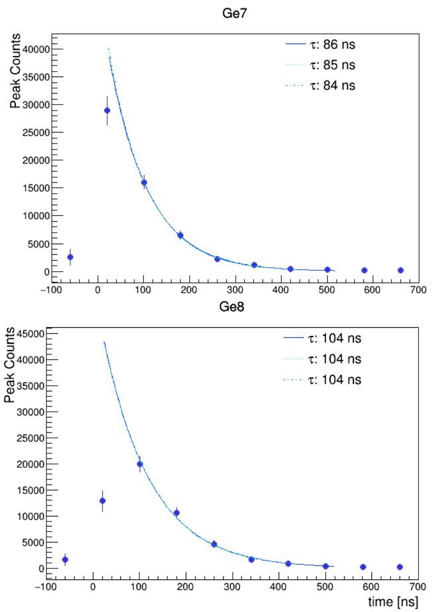


τ is the error-weighted average and calculated only for the values obtained with the fit method (although counting method produces curves with similar time decay constant). Cs-136 lines don't change much the average τ, as they have large errors.



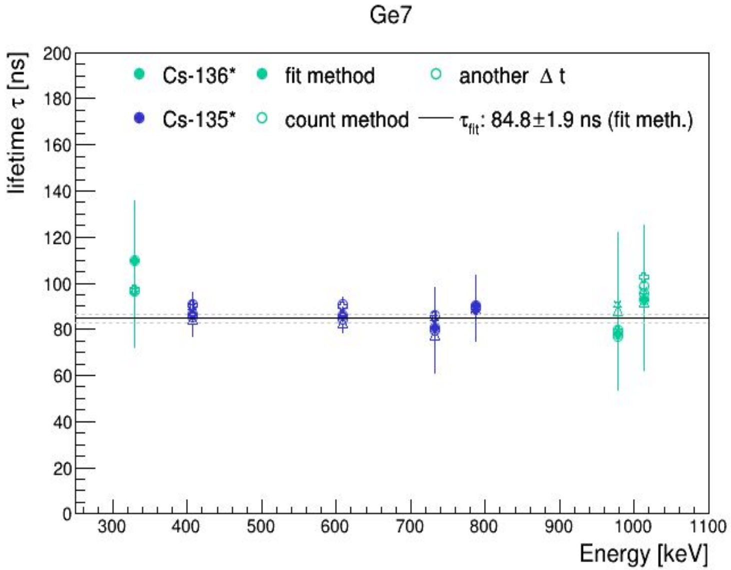


Total OMC rate: preliminary τ estimation from the de-excitation γ-lines



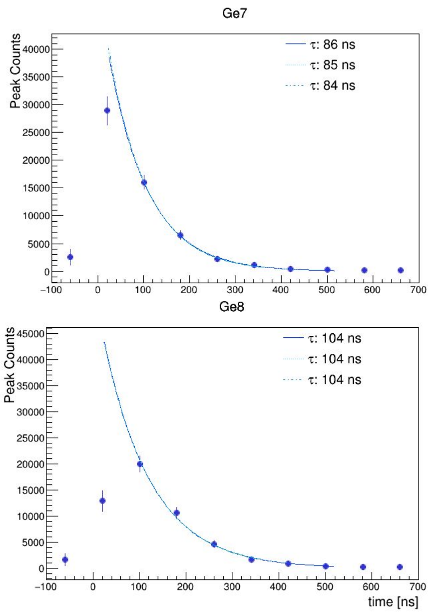
408 keV line for Ge7 and 8

Detector	τ [ns]	σ [ns]
Ge1	77.1	2.2
Ge3	84.3	1.5
Ge4	83.3	2.0
Ge5	89.8	1.7
Ge7	84.8	1.9
Ge8	92.6	1.9



Ge7 seems to be the detector with the best "time" resolution. The fits from other detectors (in yellow) did not perform as good. Other detectors still need to be checked. Fit parameters still to be tuned.

Total OMC rate: preliminary τ estimation from the de-excitation γ-lines



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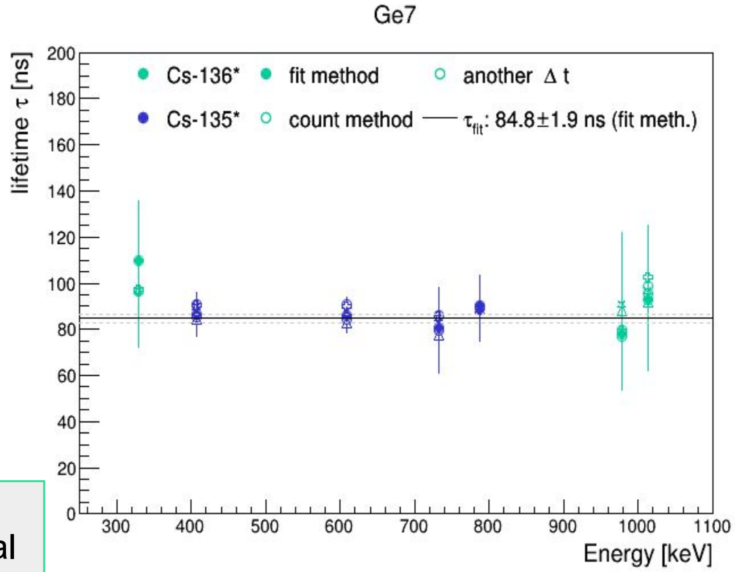
Detector	τ [ns]	σ [ns]
Ge1	77.1	2.2
Ge3	84.3	1.5
Ge4	83.3	2.0
Ge5	89.8	1.7
Ge7	84.8	1.9
Ge8	92.6	1.9

TO DO: use different "start" for each detector & energy based on max interval of neighboring muX lines. Also, include linear component in the fit, this may be important for a few lines



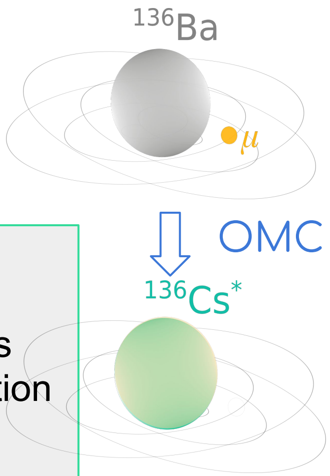
Ge7 seems to be the detector with the best "time" resolution. The fits from other detectors (in yellow) did not perform as good. Other detectors still need to be checked. Fit parameters still to be tuned.

Objectives

What do we want to extract from the data?

- Total OMC rate (λ_{cap})

$$\lambda_{\text{tot}} = 1/\tau = \lambda_{\text{cap}} + H \cdot \lambda_{\text{free}}$$



Where τ is the lifetime of the muonic atom
(the X-ray down cascade is ~prompt)

\+ ^{135}Cs* + ….

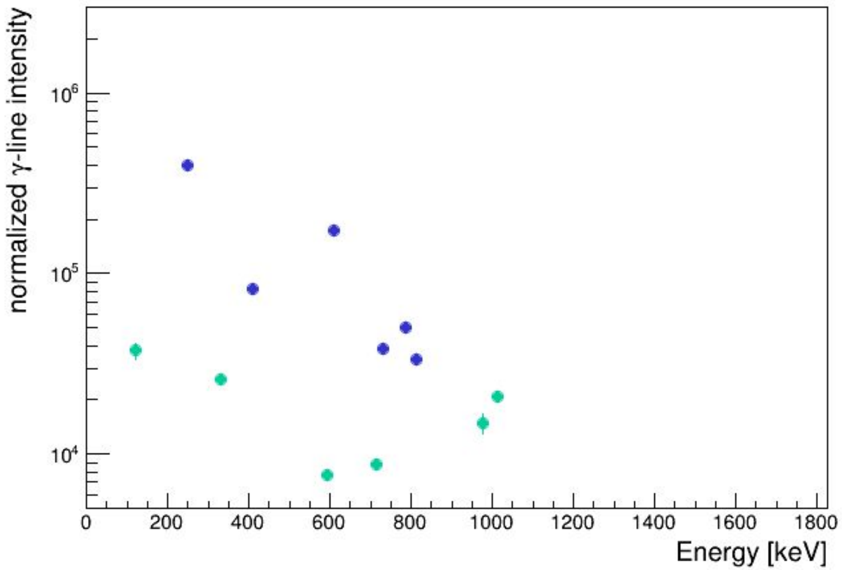
Approach: exponential + linear fit of peak counts vs time
Uncertainties:

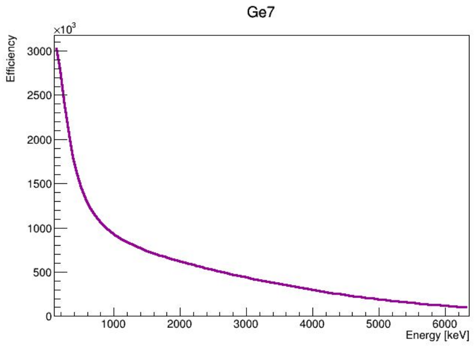
- Peak counts: constant underestimation/overestimation does not affect much the time decay. Nor does one "bad" estimation of peaks in a single time-slice. Fit and count methods yield similar values.
- Time resolution: Start the fit at later/stable time. Use muX to decide this time. Time resolution/distortion shape might be complicated to estimate

Target uncertainty: ± 2ns?

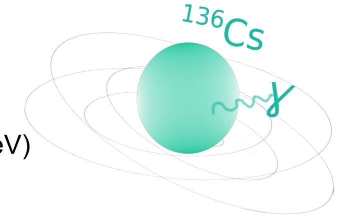
ɣ-line identification

S_i estimation within Δt_{max} & corrected for τ and efficiency





$$I_i^{\gamma} = \frac{S_i^{\gamma}}{\eta_i\, \varepsilon \sum_n I(K_n)\, \tau_{corr}}$$



E(level)(keV)	Jπ(level)	γ-Energy (keV)
3684	(14+)	*121.4*
3257.8	**(13-)**	**330.2, 1013.7**
4086.7	15-	706.5
4359.2	16-	979.1
4396.1	16-	1015.9

See level scheme

To obtain partial capture rate: estimate the intensity from the uX K-lines to obtain the partial gamma-line intensities. Extend method to other lines, estimate “feeding”.

τ correction: If we don’t integrate all the peak counts, we have to correct for that

$$\int_0^\infty e^{\left(-\frac{t}{\tau}\right)} dt = 1$$

$$\int_{t_1}^{t_2} e^{\left(-\frac{t}{\tau}\right)} dt < 1$$

Uncertainties:

- τ
- t_1: specially due to the time resolution

Ps: uncertainty on t_2 has virtually no effect

This correction may lead to systematics of ~5-15%.

Solution: apply this method and correction only for lines that have muonic or close by background. Otherwise integrate full spectra

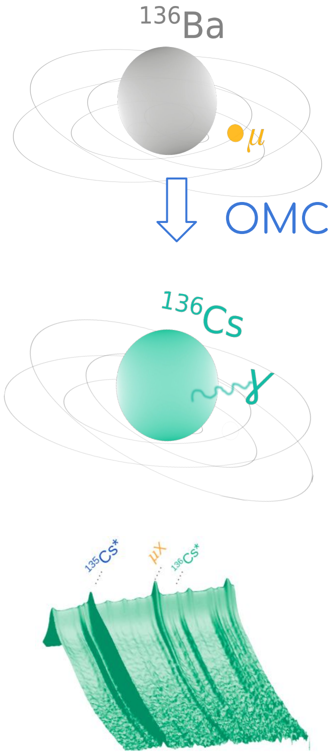
Efficiency: What are the systematic uncertainties?

- Is it necessary to estimate S_i in both peak counts and efficiency in the same way?
- What is the true error on the efficiencies?
- Maybe we should have a list of % errors for efficiency ratios? (eff(E)/sum(Eff(Klines))
- Bootstrapping to estimate errors?

$$I_i^\gamma = \frac{S_i^\gamma}{\eta_i \, \varepsilon \sum_n I(K_n) \tau_{corr}}$$

Conclusions

- Over 100 lines clearly identified in the Ba-136 spectra. Main lines are from uX, Cs$^{(*)}$-135, Cs$^{(*)}$-136
- Cs excitation lines are faint, often swamped in background and decay fast. Use of “cyclic” analysis approach to dig out signal
- Parameters for prompt / delayed have been optimized. This will be useful for further identifying fainter lines & lines mixed w. uX
- Preliminary total capture measured. Best value from Ge7 ~85 ns.
- First steps toward partial capture rates. Do we expect the high values for Jπ?
- Beam off measurements -> better go beam offline (see back up)



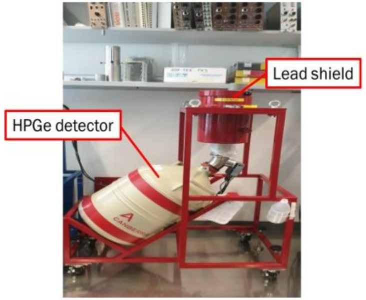
Back up slides

Comparison beam off & offline data Ba-136

Beam off / offline data Ba-136

i) Beam off: Taken during periods the beam went off or with the shutter closed (this analysis): runs 42888-42907 (with 20 runs of ~ 1h)

ii) Offline: Taken at the external HPGe detector, for ~ 7 days (Analysis by Malaysian group, see Ng slides)



Differences:

Time after irradiation (ii)>>(1), data taking time (ii)>>(1)

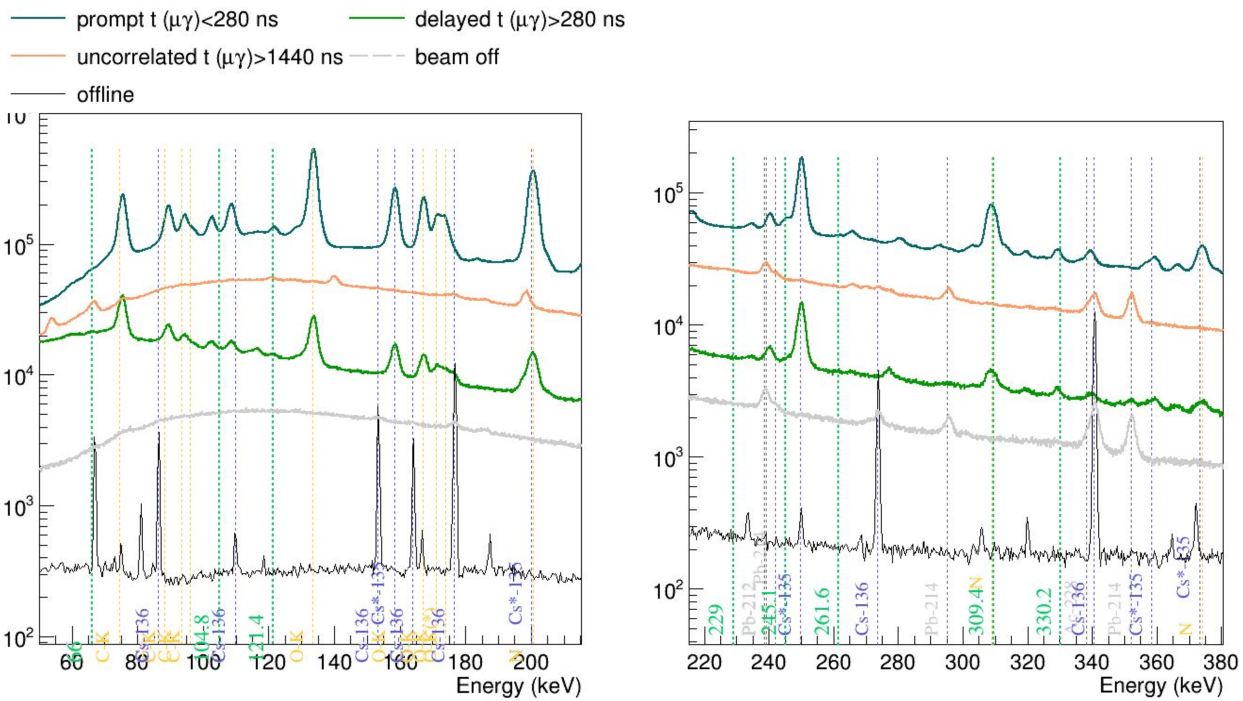
Detector geometry, efficiency, resolution, and background

Objectives of this analysis:

Can we cross-check the results of (ii) using data of (i) or can we even observe isotopes that (ii) could not?

First step: Comparison of Spectra

Which lines do we see only (or also) in beam off data?



- We see some of Cs-136, but at worse resolution(*) and SNR
- We see much more of natural background (due to geometry/efficiency)

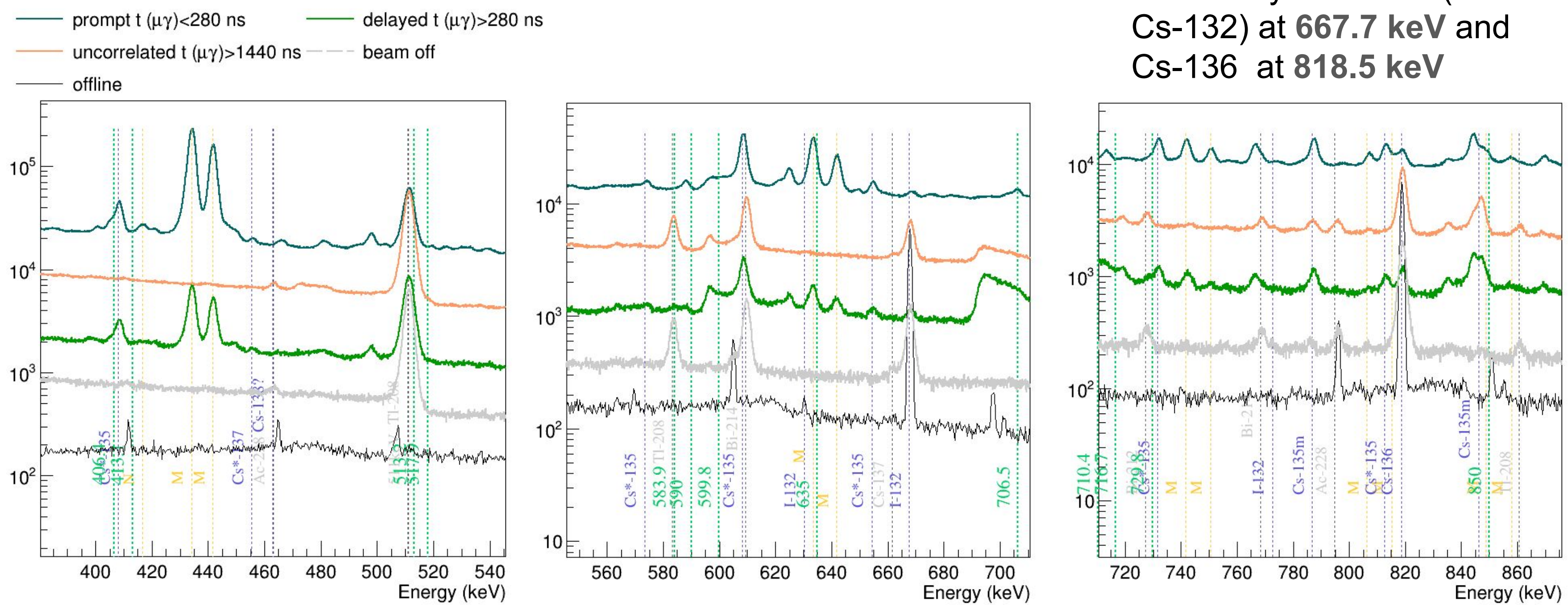
Here shown: 20h data(**) from Ge-7 (which seemed to have a good energy resolution) compared to 24h offline (from Ng)

(**)Spectra were re-calibrated

First step: Comparison of Spectra

Which lines do we see only (or also) in beam off data?

- We see some of Cs-134 at ~ 695 (but too close to Bi-214).
- We clearly see I-132 (or Cs-132) at **667.7 keV** and Cs-136 at **818.5 keV**



Most visible lines beam-off data

- **667.7 keV line:** Cs-132 (6.5 d, BR: 98%, only line). Might have some bit of I-132 (t~3h, 99%*). The latter is however not strong as its 772.6 keV line (76%) is not prominent (nor it is its quick decay).
- **818.5, 1048.073 keV lines**: Cs-136 (13d, BR: 100% & 80%). Lines are clear, but the time decay is long. (Another line with good BR is the 340.547 keV (42.2%), but it slightly overlaps with Ac-228)
- 351.93, 511, 583.19, 2614.53 keV lines: Pb-14, e^-e^+ annihilation (+some lines around it), Tl-208 lines (used as a proxy- they should be stable)
- 1293.587 keV line: Ar-41 (neutron activated atmospheric Ar-40) gas returns from the chimney (Acc. Stella)

(*) summed with the 669.8 and 671.4 keV lines w. low BR (4.6% and 3.5%)

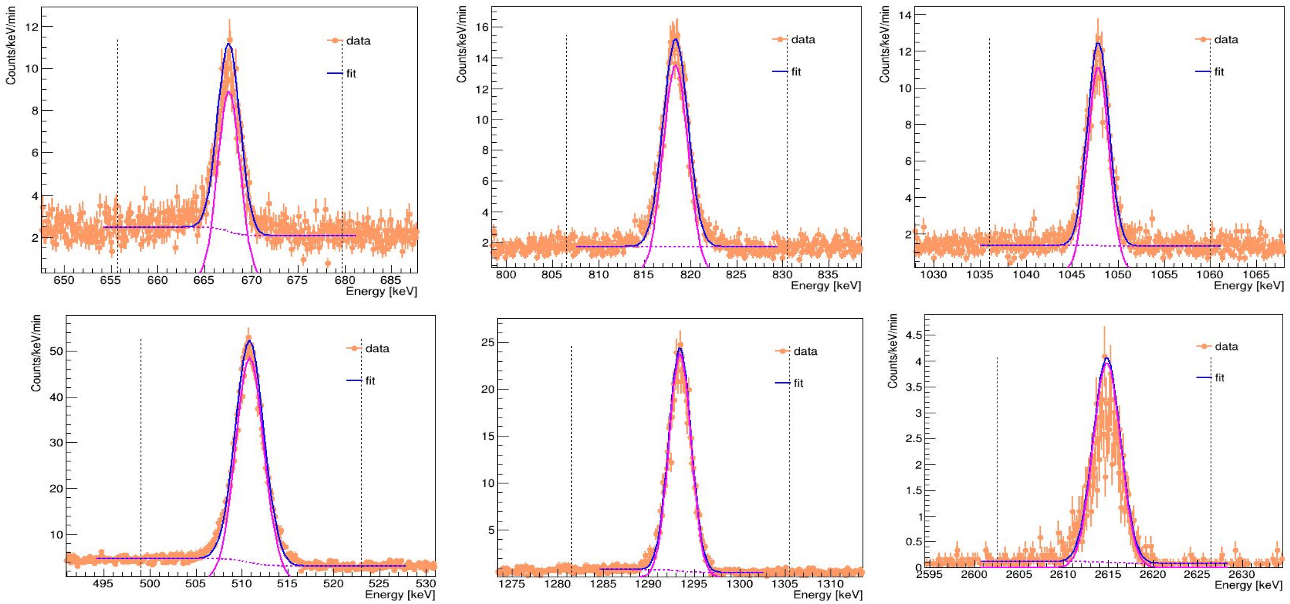
Method: first, fit the peaks observed during beam off

- To obtain good stats, 2h of data was accumulated for the each fit.
- Fit: Gaussian + step function

The data is normalized per run time.

667.7, 818.5, 1048.1 keV lines:

511, 1293.6, 2614.5 keV lines



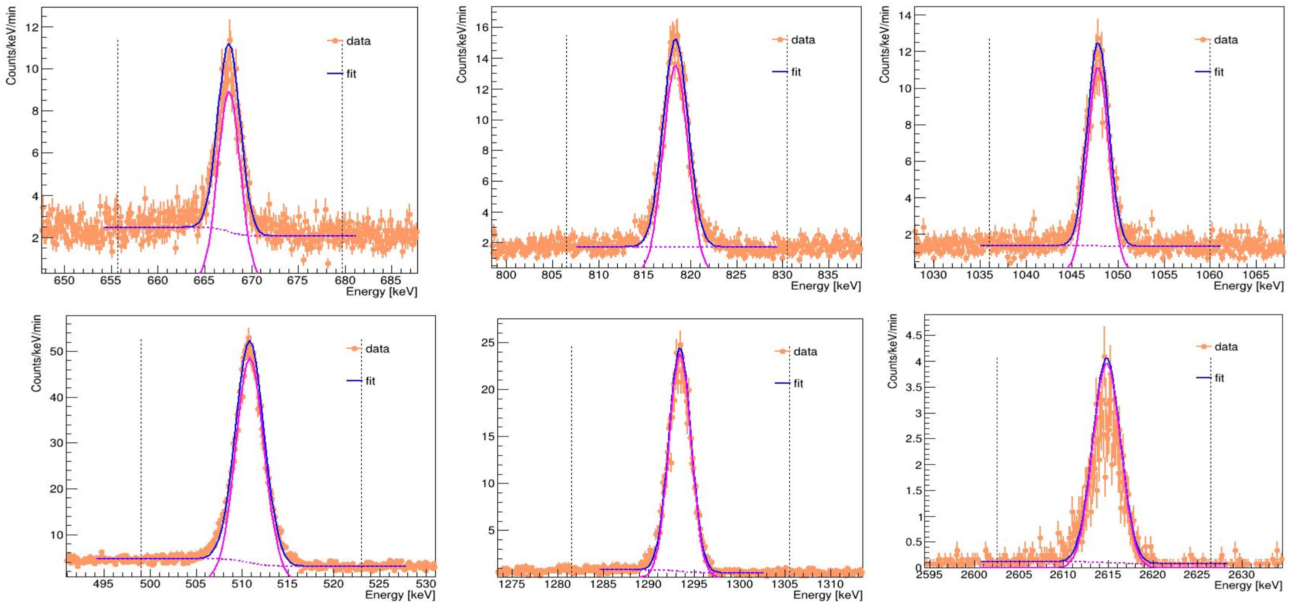
Method: first, fit the peaks observed during beam off

To count the number of events in the peak, the **area of the gaussian fit** is calculated or the events are **counted within +/- 3*σ****, then subtracted by the background estimated from the side bands

*The resolution is estimated from the fit

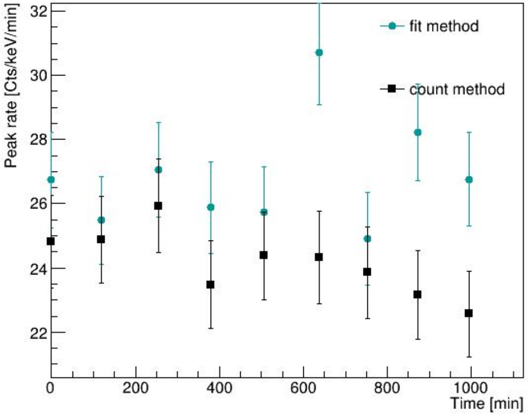
667.7, 818.5, 1048.1 keV lines:

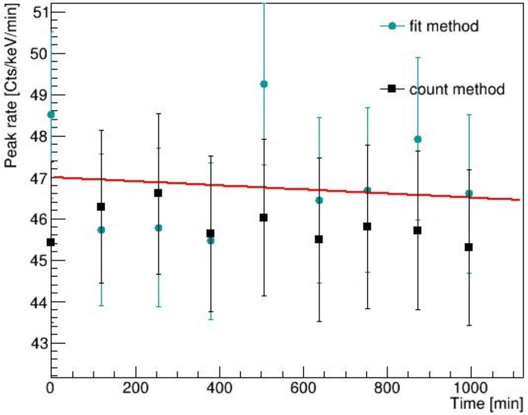
511, 1293.6, 2614.5 keV lines

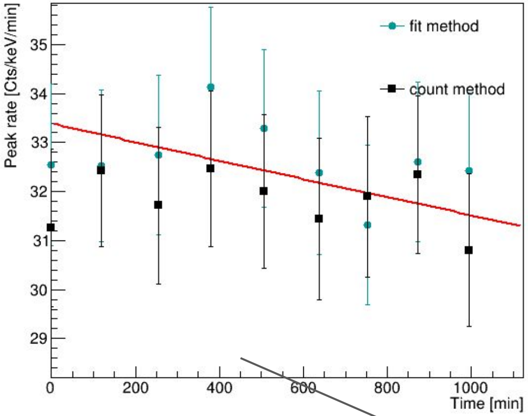


Results: Peak rate vs time. Trend is not as clear as in offline analysis

667.7 keV (Cs-132*, 6.5d) & 818.5, 1048.1 keV (Cs-136, 13d) lines:



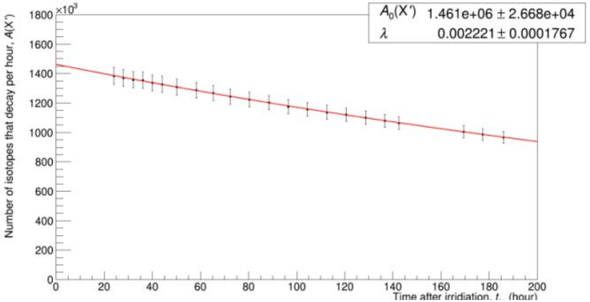




Different fit results for the same isotope

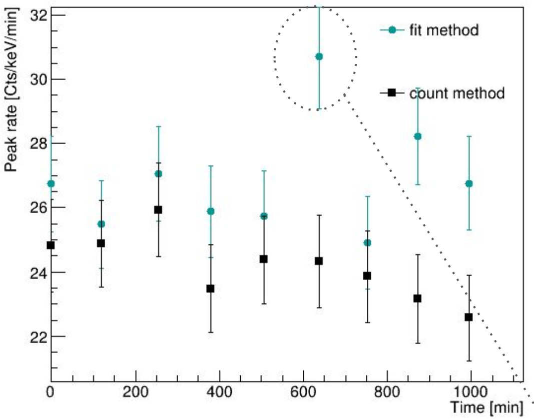
Comparison: Ng's fit Cs-136, ~200h

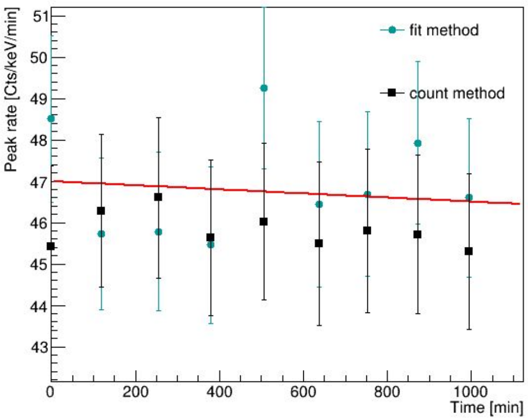
Decay curve of the peak at 340.5 keV

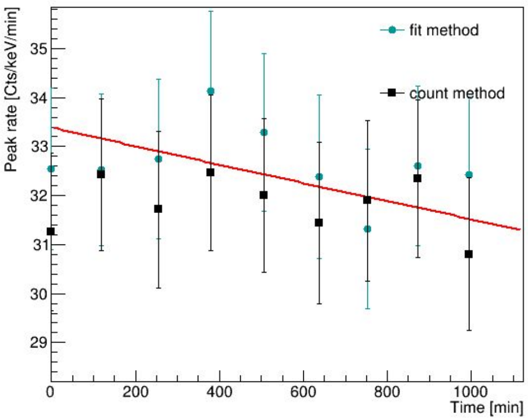


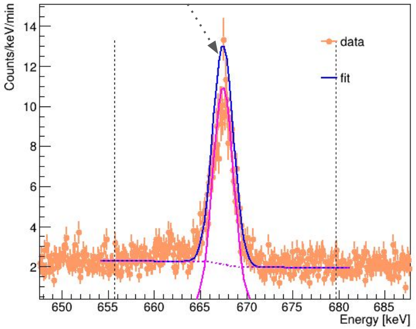
Results: Peak rate vs time.

667.7 keV (Cs-132*, 6.5d) & 818.5, 1048.1 keV (Cs-136, 13d) lines:





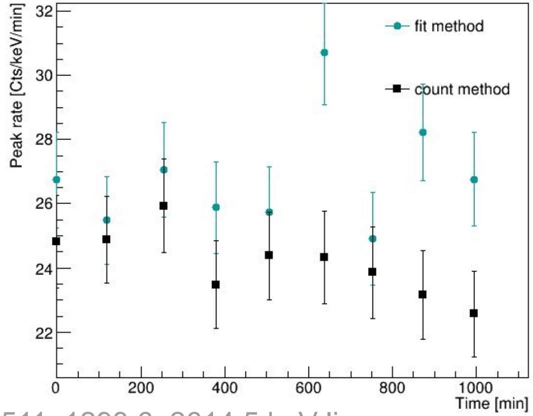


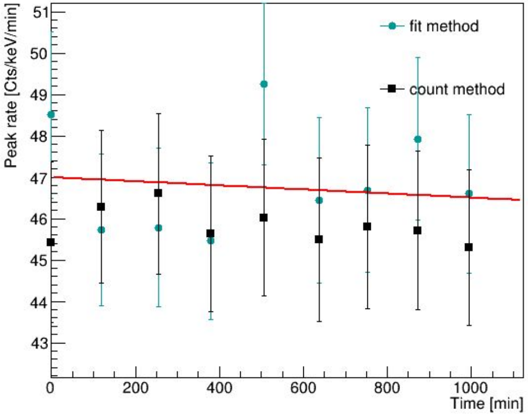


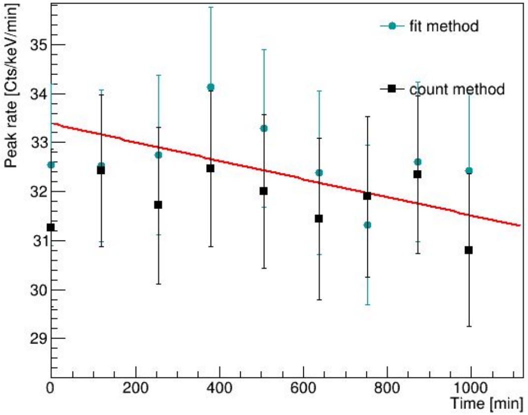
Fit method is somehow less stable than counting? Or is this some binning effect?

Results: Peak rate vs time.

667.7 keV (Cs-132*, 6.5d) & 818.5, 1048.1 keV (Cs-136, 13d) lines:

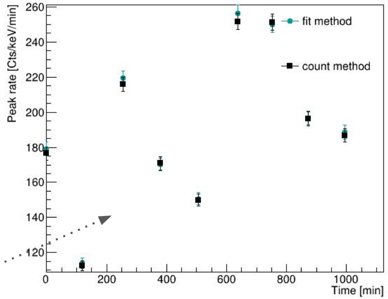


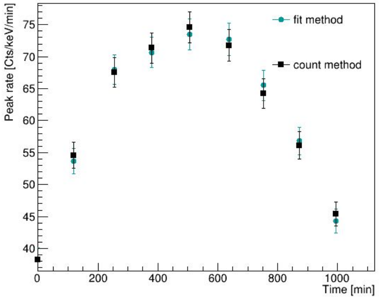


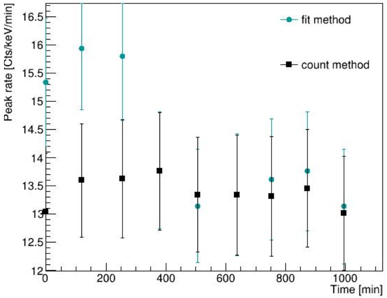


511, 1293.6, 2614.5 keV lines

Comparison: other "constant" or independent lines



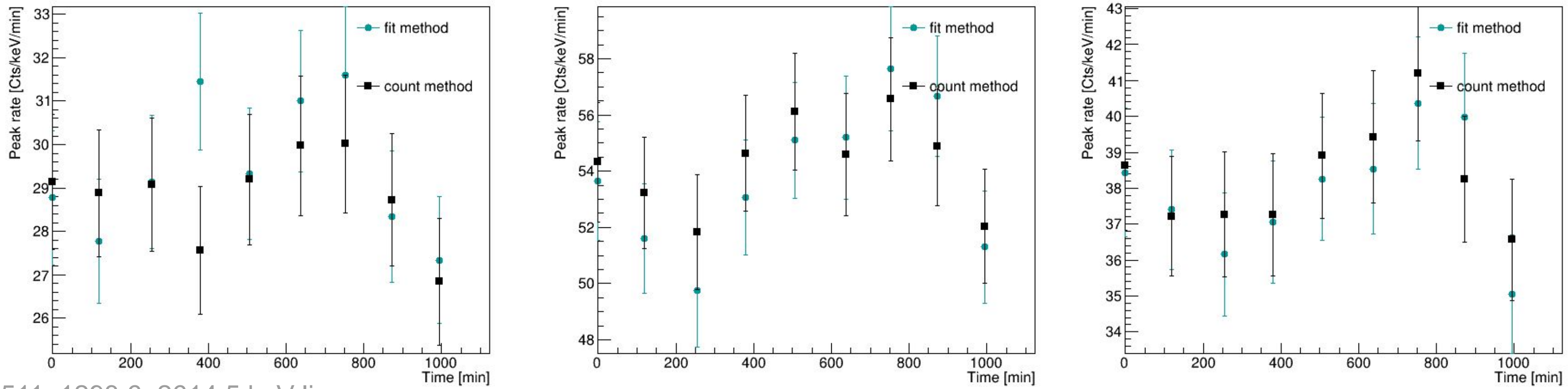




Fit method agrees well with counting for high stats

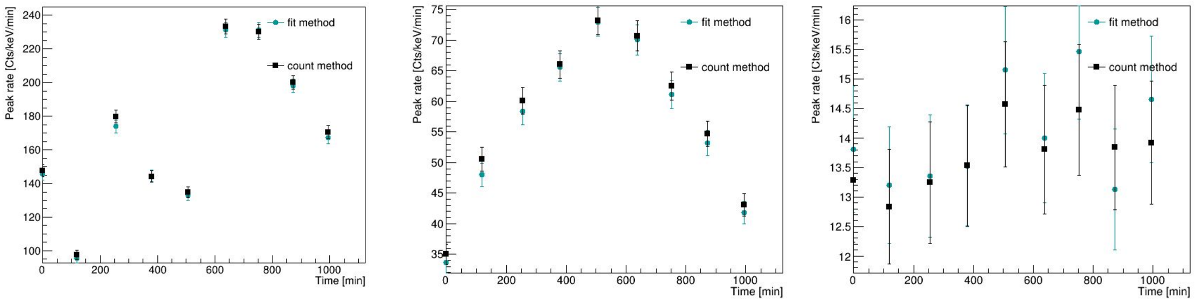
Results: Peak rate vs time. Same “trends” observed for Ge-8

667.7 keV (Cs-132*, 6.5d) & 818.5, 1048.1 keV (Cs-136, 13d) lines:

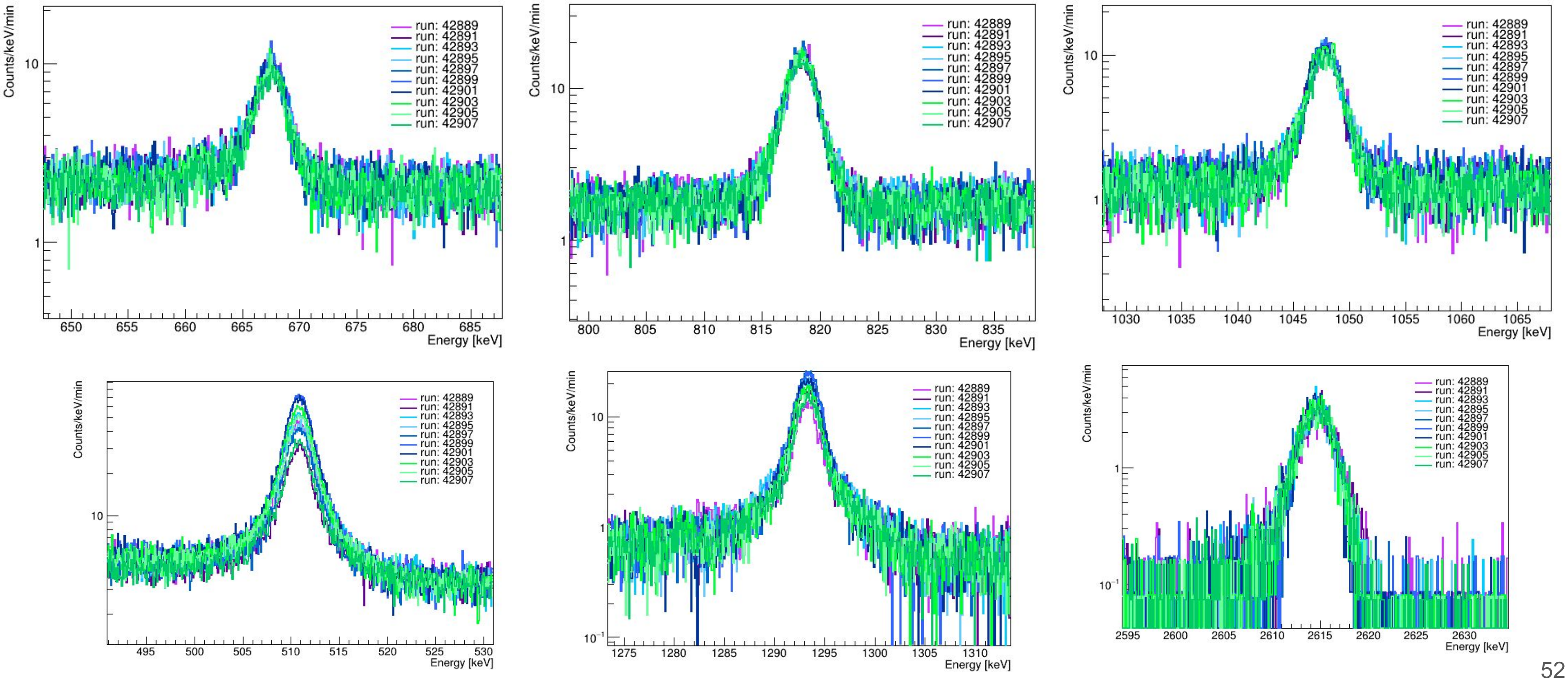


511, 1293.6, 2614.5 keV lines

Comparison:
other “constant”
or independent
lines



Another look at the data: Spectra comparison per run

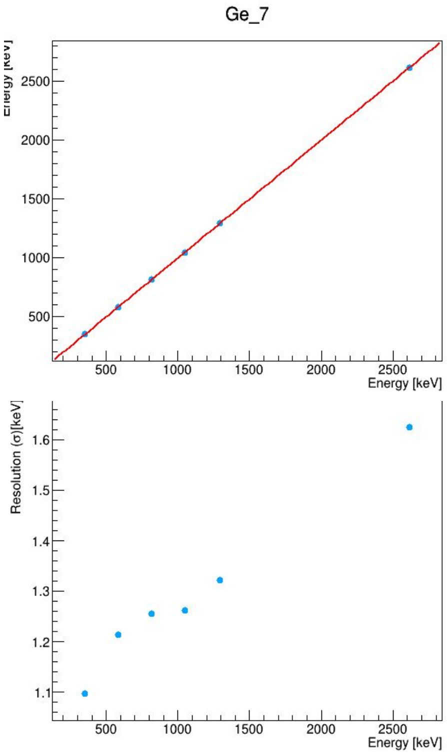


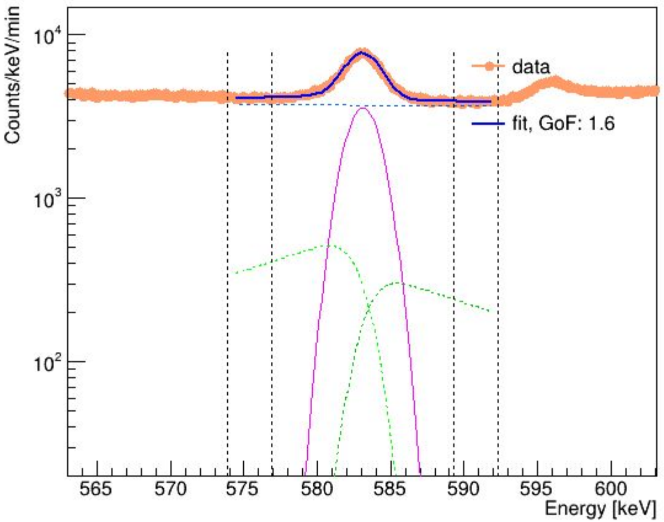
Conclusions

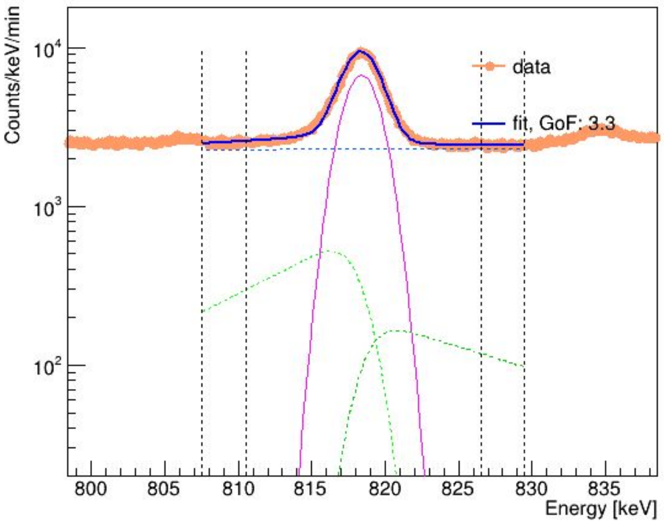
- The beam-off data is not ideal for the identification of "mid-lived" (a few days) isotopes
- The 667.7 keV line is mostly not I-132 (as it is still clear in the offline data) - however, the intensity of Cs-132 is surprisingly high (~ to Cs-136)
  - $^{136}Ba + \mu \rightarrow {}^{136}Cs \rightarrow {}^{132}Cs + 4n$ (4n emission)
  - $^{134-132}Ba + \mu \rightarrow {}^{134-132}Cs + 0\text{-}2n$ (but $0.01\% < {}^{134-132}Ba < 0.7\%$)
- Given the resolution and efficiency (geometry/SNR), also for short-lived isotopes, it would be better to measure the target on the top of a HPGe right-afterwards (the target may not be much more active than the Ar-41 line, which presents one of the highest rates in the spectrum)
  - Even if we cannot transport the target outside of the beam-hall, one can think of just placing it at the top of a HPGe
  - -> something to be studied for the next beam-time

Data “Recalibration”

To match the peaks of the offline spectra, data is slightly “recalibrated” using peaks from the uncorrelated spectra







However, only 6 lines are used and they max energy is 2.6 MeV

```
351.93, 583.19, 818.5, 1048.073,  1293.587, 2614.53
```

Fit Functions & Parameters

Peaks are fit using 4 functions

$$g(E) = \frac{n}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(E-\mu)^2}{2\sigma^2}\right],$$

$$f_{\text{lin}}(E) = a + b \cdot E,$$

$$f_{\text{step}}(E) = \frac{d}{2} \text{erfc}\left(\frac{E-\mu}{\sqrt{2}\sigma}\right),$$

$$h(E) = \frac{c}{2\beta} \exp\left(\frac{E-\mu}{\beta} + \frac{\sigma^2}{2\beta^2}\right) \text{erfc}\left(\frac{E-\mu}{\sqrt{2}\sigma} + \frac{\sigma}{\sqrt{2}\beta}\right)$$

Functions from the Gerda calib paper

- Gauss (3): A, μ, σ
- Linear (2): a, b
- Step (1): d
- Tail (2): c, β
- Right Tail (2): c_r, β_r

'Strictly' constrained
Estimated from data but less constrained
Might be estimated but is allowed to be 0

Neighboring gauss:

- Gauss (3): A_2, μ_2, σ_2
- Tail (2): c_2, β_2

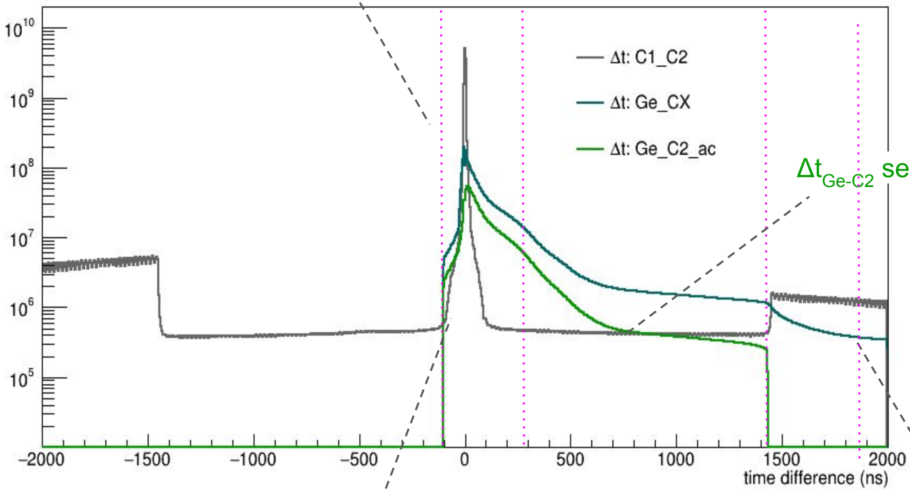
Minimum of 3 non-zero parameters. Effective minimum of 4 (Gauss + linear) and maximum of 15 parameters.

Time distributions counters and Germanium

Time spectra & preliminary time window

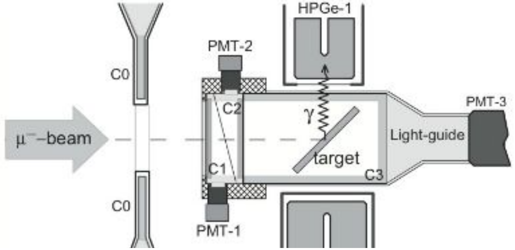
Preliminary time cuts: The objective is to optimize them, per channel!

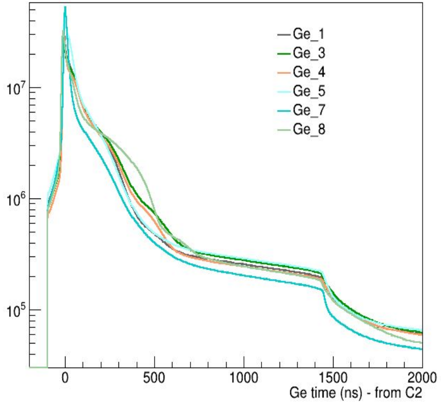
Ge_2 and Ge_6



$\Delta t_{Ge\text{-}C2}$ selected events

Tail decay: Single muon selection?





$\Delta t_{Ge}=t_{Ge}-t_{C\#}$