Normalization of the Mu2e Charged Lepton flavor Violation Experiment

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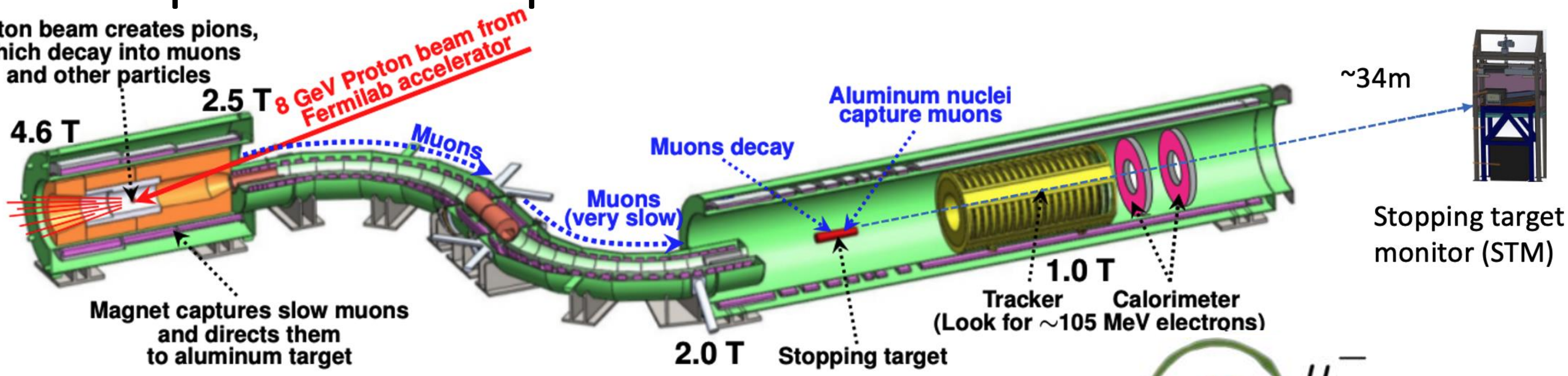
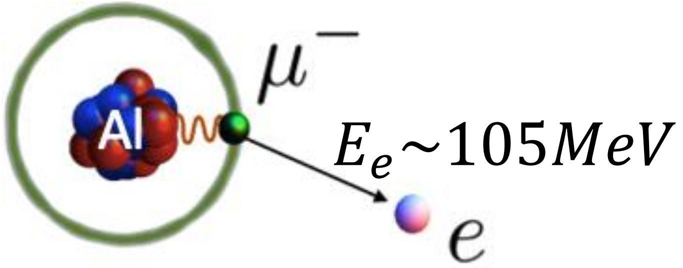
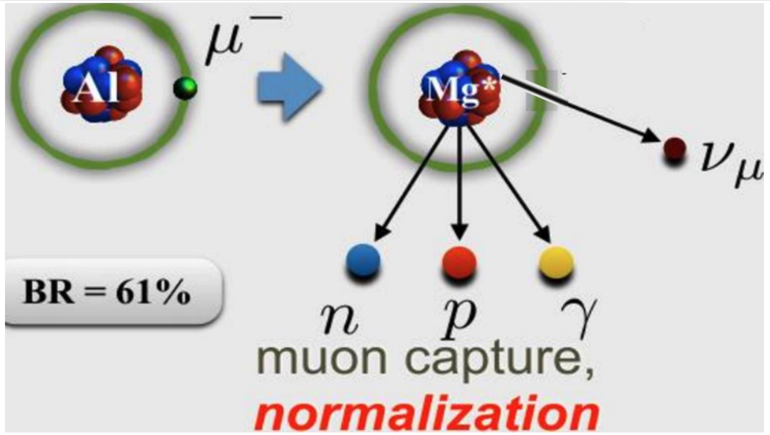
Mu2e experiment set-up





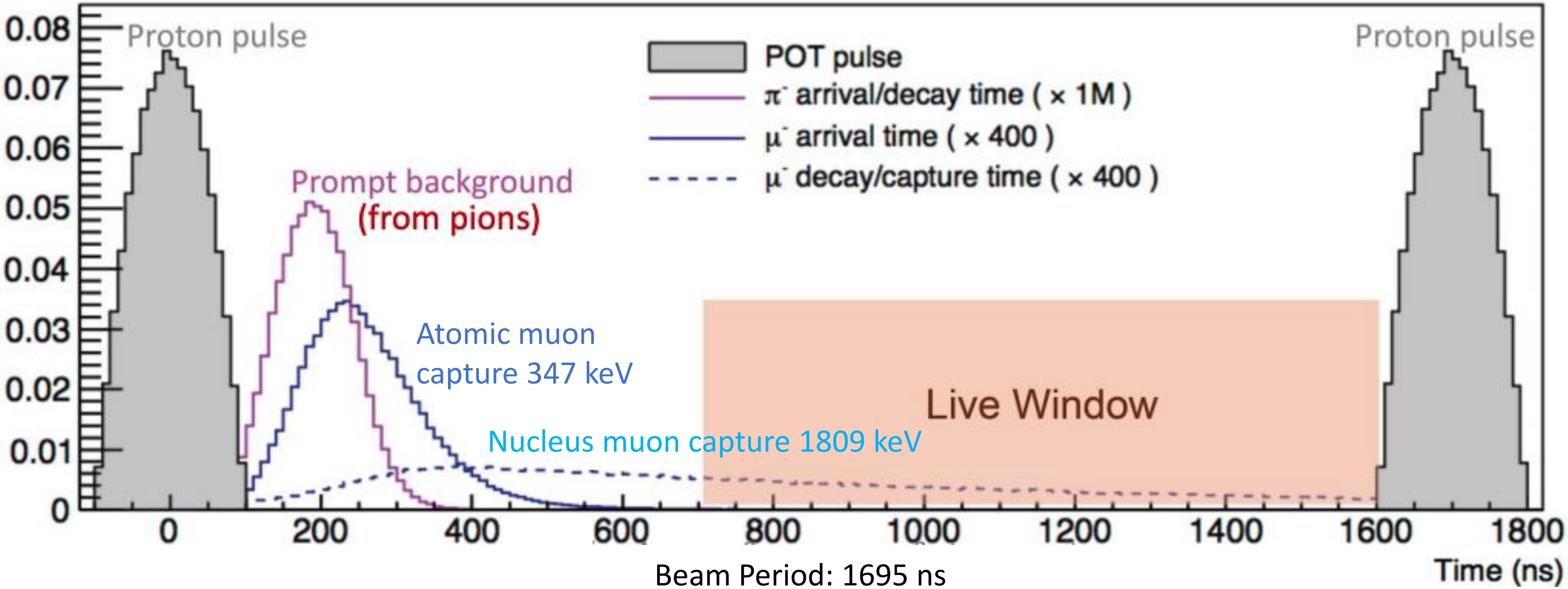
$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)} \Leftrightarrow R_{\mu e} =$$

Proportional to



Charged Lepton Flavor Violation signal measurable with single-event-sensitivity(SES) of 2.5 $\times 10^{-17}$

Mu2e Beam structure

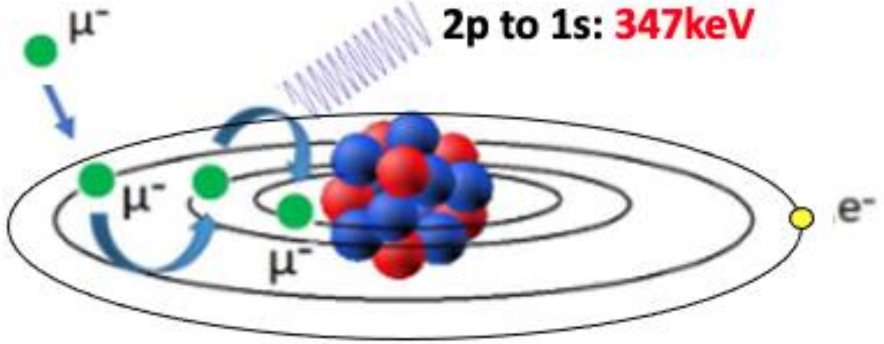


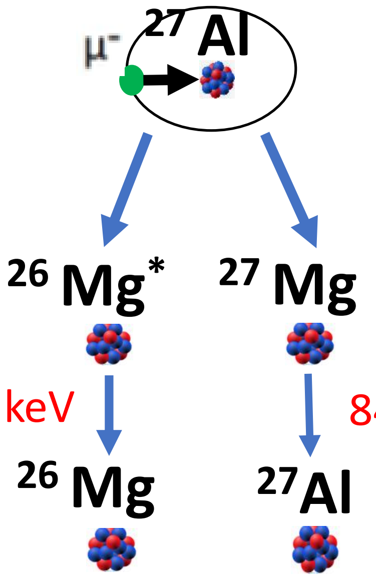
Beam Period: 1695 ns

Atomic muon capture: **347 keV line**
Nucleus muon capture: **1809keV line**
Activated daughters resulting from nuclear capture : **844 keV line** (collected during Beam-off 1 seconds)

3 important energy lines

- Prompt: 347 keV X-ray 79.8(8)% of μ captures, $\boldsymbol{\tau}$ **=10ps**
- Semi-prompt: 1.809MeV γ ray 51(5)% of μ captures, $\boldsymbol{\tau = 864ns}$
- Delayed: 844keV γ ray 9.3% of μ captures, $\boldsymbol{\tau}$ **= 13 mins**





$$\mu^- + {}^{27}_{13}Al \rightarrow \nu_\mu + {}^{26}_{12}Mg^* + n$$

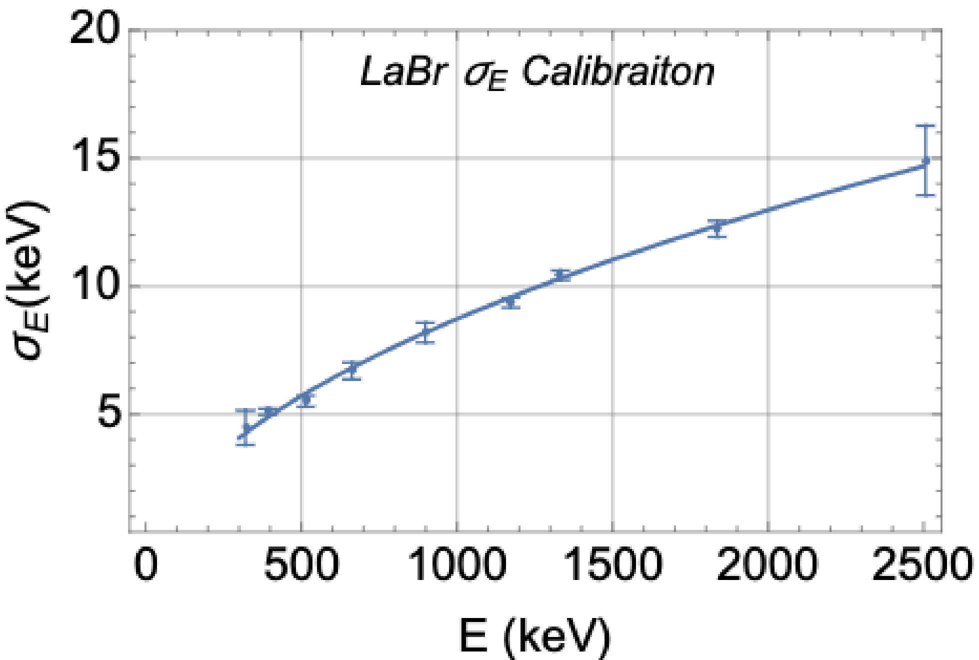
$$\hookrightarrow {}^{26}_{12}Mg + \gamma$$ 1809 keV

844 keV $${}^{27}_{12}Mg \rightarrow {}^{27}_{13}Al + e^- + \overline{\nu_e} + \gamma$$

$LaBr_3$ and HPGe

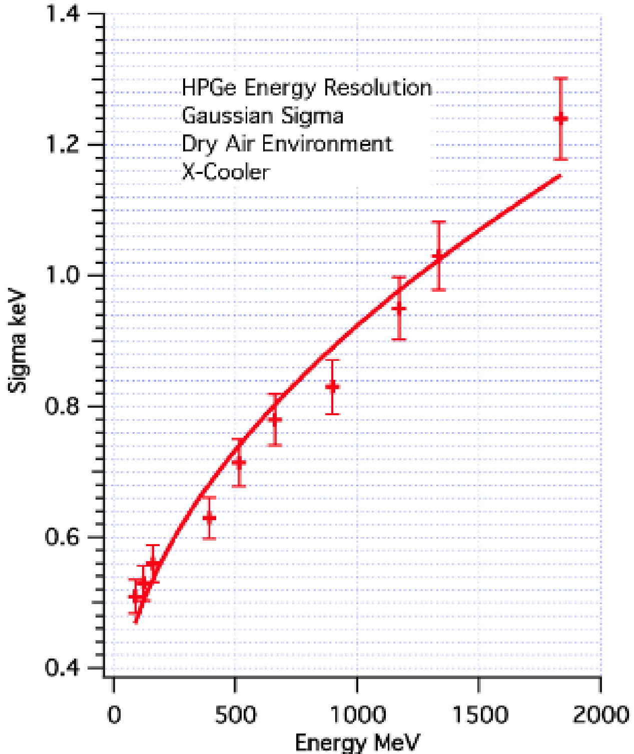
$LaBr_3$(Ce+Sr) detector:

energy resolution(@1809keV): 10 keV
rising edge ~ 5ns
decay tail ~ 26ns
pulse width 200ns
high-rate capability ~800KHz
observed average energy ~3MeV



HPGe detector:

energy resolution(@1809keV): 1 keV
rising edge ~ 400ns
decay tail ~ 60μs
limited rate capability ~73KHz
observed average energy ~5MeV



Error budgets for 1809keV from muon capture

Systematic Uncertainties		
Factors	Values	Uncertainty(%)
$P_{capture}$	0.61	0.3
Br_{1809}	0.51	5
$G_{accep}(0.5cm^2)$	3.34e-9	3
Target Path Atten	0.964	1
Absorber× Photopeak acceptance	0.218($LaBr_3$) 0.017(HPGe)	2
Total		**6.2**

Uncertainty of branching ratio of 1809

- Present : 10% [Measday et. al]
- AlCap+ Measday : 7%
- **Mu2e goal: 5% normalizing to 347keV(2p to 1s)**

- Total error budget (statistical and systematic error budget) is 10%, so 6.2% systematic error leaves 3.8% statistical error
- Lower systematic error, allows higher statistical error, which means lower integration time

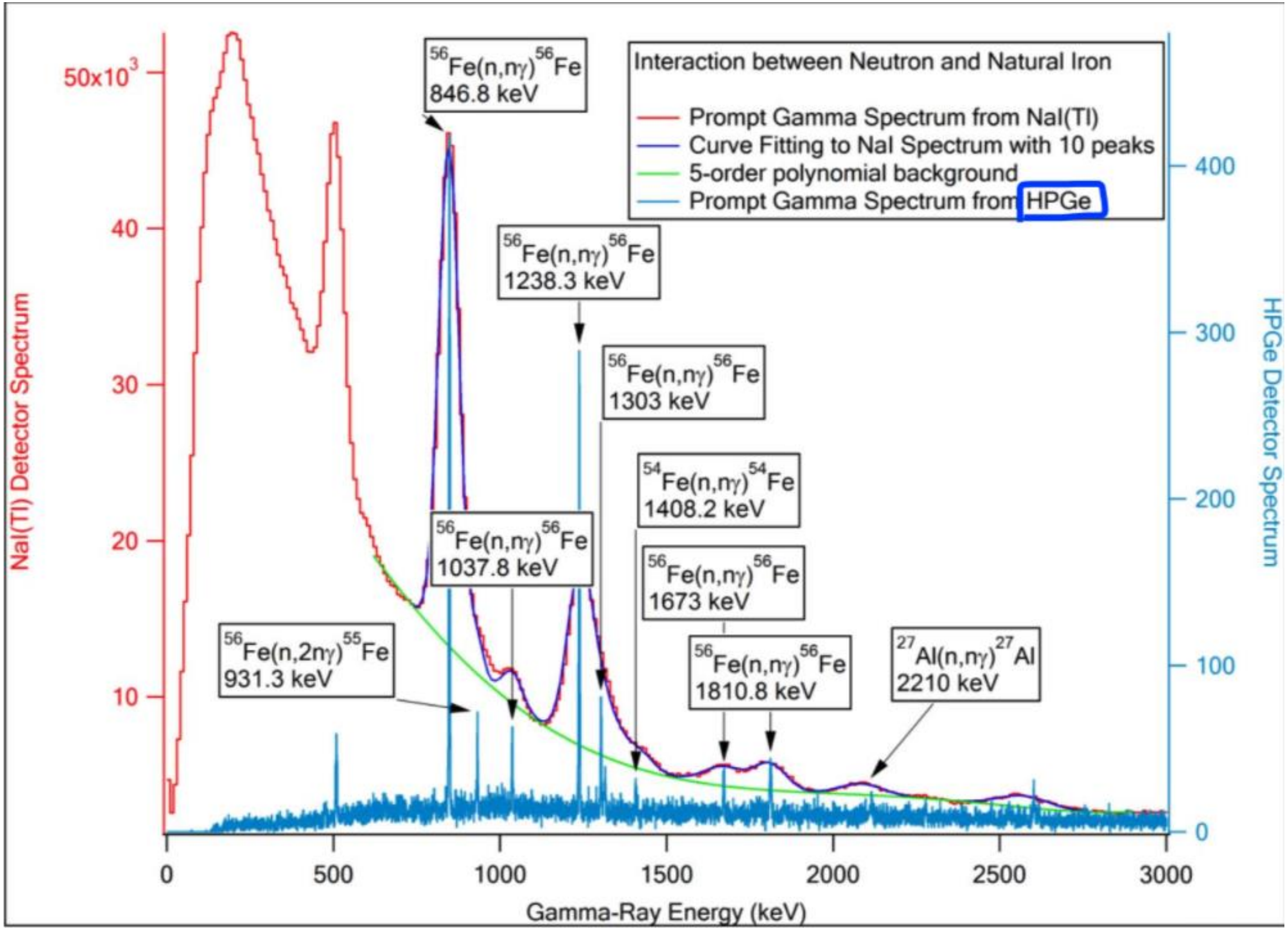
Two detectors to accurately measure the lines

- 1809 keV line is the 'Golden Channel' directly proportional to the stopped muon numbers.
- The high-rate capability $LaBr_3$ allows short integration times.
- The 347 keV and 844 keV will be used as verification lines.
- HPGe will be used to check for interfering lines in the $LaBr_3$ signals.

Three possible interfering sources:

(1) Technology independent lines. Lines directly from the source.
(2) An interference unique to the technology, for example, created by a neutron fluence.
(3) An interference created by the electronic response, for example pile up.

An example: measuring lines in NaI with help from HPGe

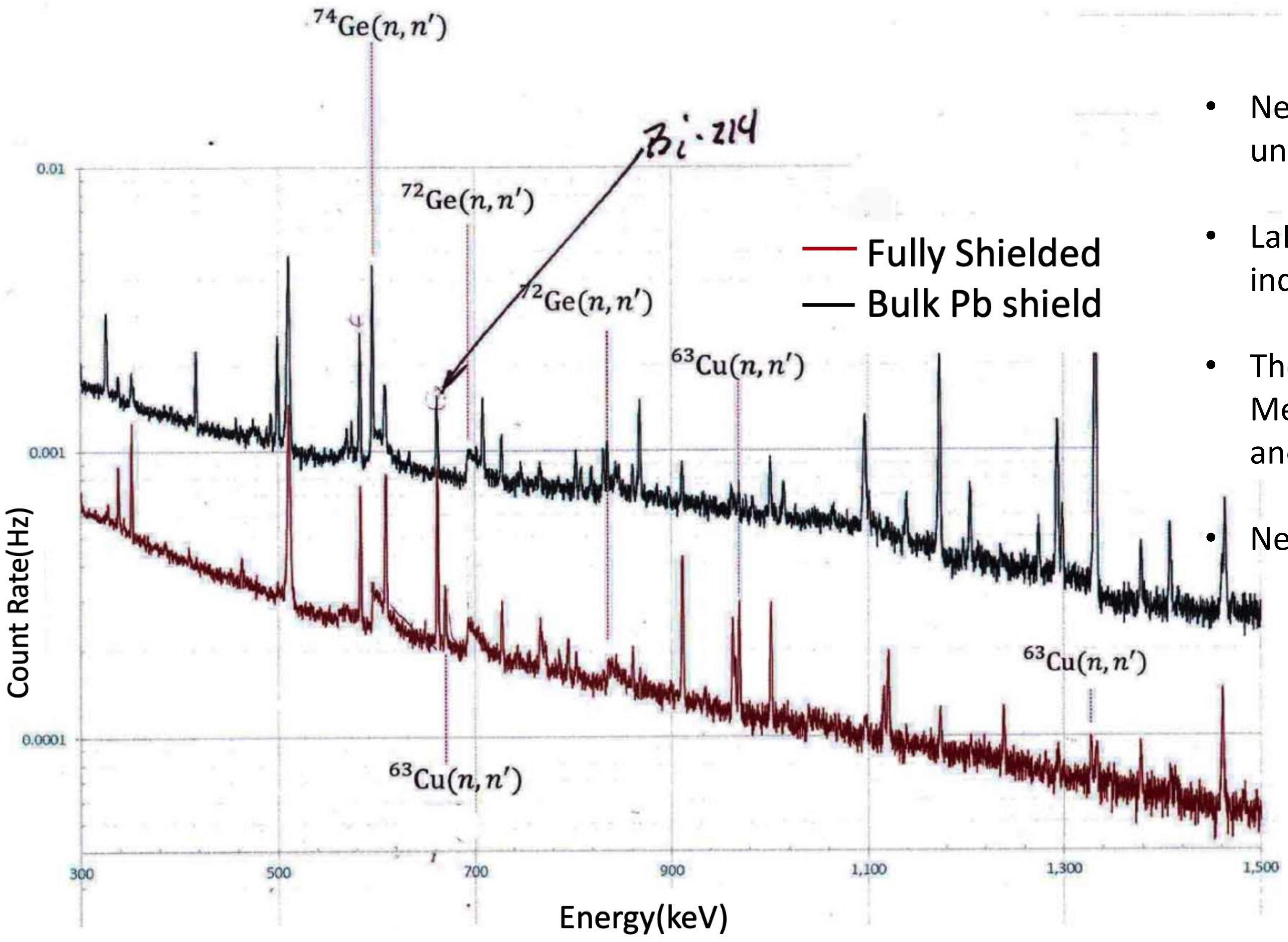


Technology independent lines

Enhanced Lanthanum Bromide
$LaBr_3$(Ce+Sr)
has energy resolution:
X 10 better than NaI
X 10 worse than HPGe

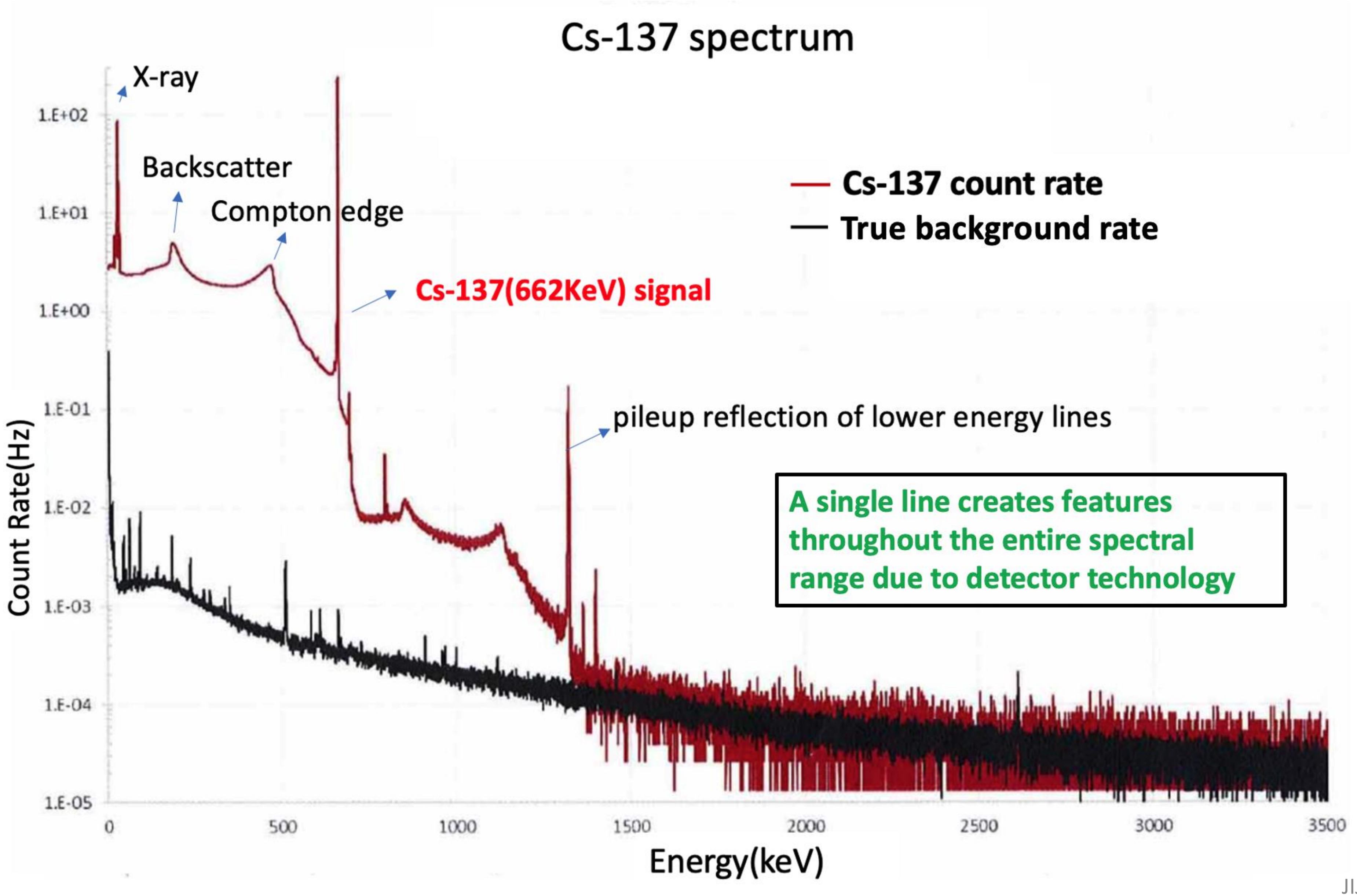
HPGe will be used to resolve interfering lines in $LaBr_3$

HPGe is exposed to a neutron fluence



- Neutron induced lines can be detector unique
- $LaBr_3$ and HPGe will have different neutron induced background
- The neutron fluence for fast neutron > ~ 1 MeV and thermal neutron can be measured and cross check between detectors
- Neutron fluence will be monitored

An example: interference created by the electronic response



Resolving interfering lines in $LaBr_3$

$$\frac{N_{347}}{N_{1809}} = \frac{N_{stopped\ muons}\ \varepsilon_{Geo}\ \varepsilon_{Detector}\ \varepsilon_{pileup} \ldots \Gamma_{347}}{N_{stopped\ muons}\ \varepsilon_{Geo}\ \varepsilon_{Detector}\ \varepsilon_{pileup} \ldots \Gamma_{1809}}$$

want to measure

Simplify as

$$\frac{N_{347}}{N_{1809}} = \frac{\phi_{347}\,\Gamma_{347}}{\phi_{1809}\Gamma_{1809}}$$

Γ_{347} is well-known and assuming HPGe measured line have no interference line

$$\Gamma_{1809}^{HPGe} = \Gamma_{347}\frac{\phi_{HPGe}^{347}}{\phi_{HPGe}^{1809}}\frac{N_{HPGe}^{1809}}{N_{HPGe}^{347}} \quad (1)$$

Make the same measurement using $LaBr_3$ to check for interfering sources δ_{energy}

$$\Gamma_{1809}^{LaBr} = \Gamma_{347}^{LaBr}\frac{\phi_{LaBr}^{347}}{\phi_{LaBr}^{1809}}\frac{N_{LaBr}^{1809}}{N_{LaBr}^{347}}(1-\ \delta_{347+1809}) \quad (2)$$

δ_{1809} is not expected

Demanding (1) and (2) be identical

$$\frac{\Gamma_{1809}^{HPGe}}{\Gamma_{347}} = \frac{\Gamma_{1809}^{LaBr}}{\Gamma_{347}^{LaBr}}(1-\ \delta_{347+1809}) \quad (3)$$

Similarly, apply to 844 keV,
Which is measured during beam-off and has low background: δ_{844} = 0 (expected)

$$\frac{\Gamma_{844}^{HPGe}}{\Gamma_{347}} = \frac{\Gamma_{844}^{LaBr}}{\Gamma_{347}^{LaBr}}(1-\ \delta_{347}) \quad (4)$$

Combine to check δ_{1809}

$$\frac{\Gamma_{844}^{HPGe}}{\Gamma_{1809}^{HPGe}} = \frac{\Gamma_{844}^{LaBr}}{\Gamma_{1809}^{LaBr}}(1-\delta_{1809})$$

Error budgets for 1809keV from muon capture

Systematic Uncertainties		
Factors	Values	Uncertainty(%)
$P_{capture}$	0.61	0.3
Br_{1809}	0.51	5
$G_{accep}(0.5cm^2)$	3.34e-9	3
Target Path Atten	0.964	1
Absorber× Photopeak acceptance	0.218($LaBr_3$) 0.017(HPGe)	2
Interference lines	negligible	negligible
Total		**6.2**

Long integration time for measuring possible interfering lines will make this systematic error negligible

- Total error budget (statistical and system error budget) is 10%, so 6.2% systematic error leaves 3.8% statistical error
- Lower systematic error, allows higher statistical error, which means lower integration time
- The relationship between statistical error $\Delta\delta$ and integration time t: $t = \Delta\delta^2$

Time to achieve 10% stopped muon number measurement

	LaBr Detector	
Line	Mag	No Mag
1809 keV	3 mins	5 mins
844 keV	10 hrs	42 hrs
347 keV (Flash)	30 mins	3 hrs
347 keV (Off Flash)	1 min	5 mins

cross-check

	HPGe Detector	
Line	Mag	No Mag
1809 keV	32 mins	54 mins
844 keV	13 hrs	40 hrs
347 keV (Flash)	30 hrs	170 hrs
347 keV (Off Flash)	1.2 hrs	5 hrs

cross-check

- 1809keV: the 'Golden Channel' is directly proportional to the stopped muon number.
- 844keV: cross-check stopped muon number;
  check for interfering lines;
- 347KeV: improve 1809 branching ratio
  cross-check stopped muon number;
  check for interfering lines;
- Using the 'Golden Channel', $LaBr_3$ can do 10% stopped muon number measurement in 5 mins integration.
- $LaBr_3$ is 10 time faster than HPGe
- HPGe is used to:
  cross check stopped muon number;
  improve the branching ratio of 1809;
  check for interfering lines for $LaBr_3$ detector

Summary

- Considered all the systematic error and statistical error, with negligible systematic error from measuring the interfering lines using HPGe and $LaBr_3$ together, the integration time of 5 mins can achieve 10% uncertainty stopped muon number measurement.

Thank you & Reference

- [1] Measday et. al., Phys. Rev. C 76, 035504 (2007)

Resolving interfering lines in LaBr3

Using HPGe measuring the fast neutron and the thermal neutron fluence: N_{fast}=$F_{fast}\ \delta$ N_{slow}=$F_{slow}\ \delta$, F is the fluence, δ is the cross section that can be checked by table

↑ solution

$$S_{Measured}=S_{True}+\delta_{\Sigma I}$$

Require both detectors. HPGe corrected at high rate for pile up line

↑ solution

Where $\delta_{\Sigma I}$ represents lines from 3 distinct possible interfering sources;

(a) An interference unique to the technology, like neutron fluence in slide 10

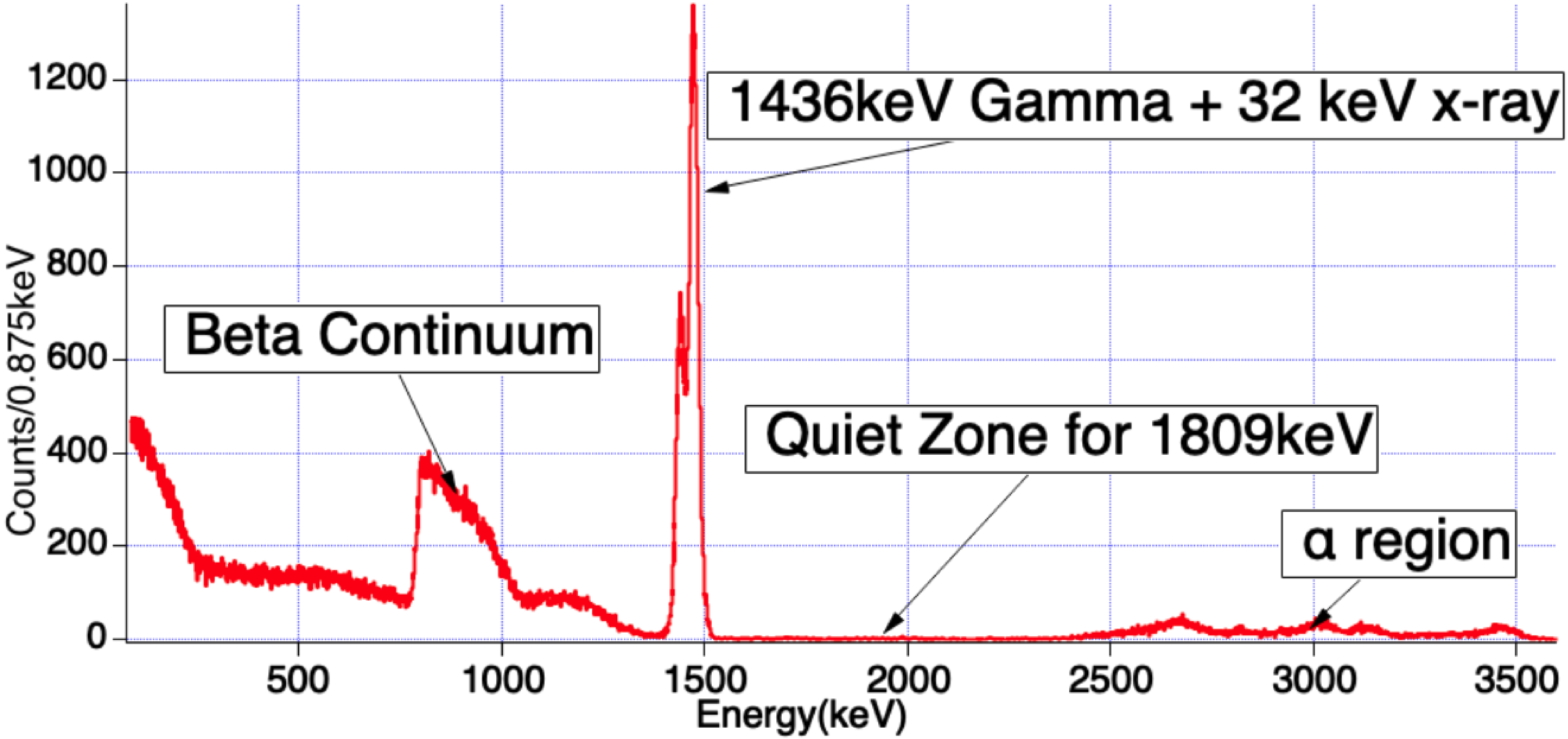
(b) An interference created by the electronic response of the technology: like source of pile up in slide 11

(c) A technology independent source which is also independent of the signal source: resolution issue in last slide

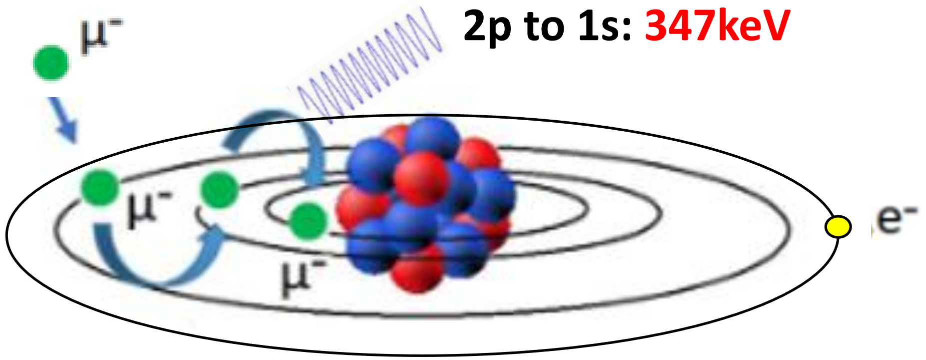
↓ solution

Require both detectors

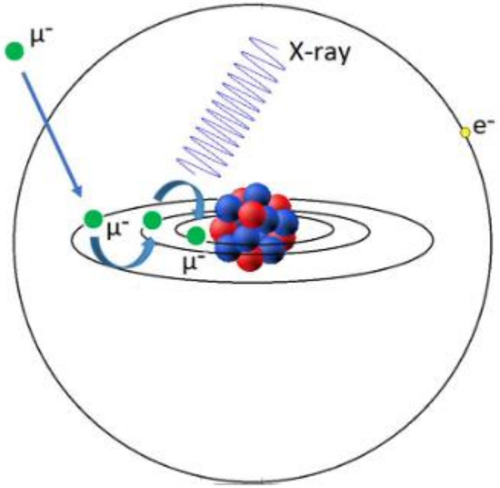
$LaBr_3$ self-background



3 important gamma rays



- Prompt: atomic capture, order 10ps
- Semi-prompt: nuclear capture, order 1 μs
- Delayed: activated daughters resulting from nuclear capture, order 10 mins



- $\mu^- + {}^{27}_{13}Al \rightarrow \mu^- + {}^{27}_{13}Al + \gamma$
- Prompt: 2p-1s, 347 keV X-ray 79.8(8)% of μ stops
- $\mu^- + {}^{27}_{13}Al \rightarrow v_\mu + {}^{26}_{12}Mg + n + \gamma$
- Semi-prompt: 1.809MeV γ ray 51(5)% of μ captures, $\tau = 864ns$
- $\mu^- + {}^{27}_{13}Al \rightarrow v_\mu + {}^{26}_{12}Mg\,, \quad {}^{26}_{12}Mg \rightarrow {}^{24}_{12}Al + {}^{1}_{1}p + 2{}^{1}_{0}n + \gamma$
- Delayed: 844keV γ ray 9.3% of μ captures, $\tau = 13$ mins