Long-lived Nuclear Gamma Rays from Ordinary Muon Capture on ^{76}Se

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25 & 26 Apr 2022

OMC4DBD collaboration meeting

Irradiation and Measurement Summary

Muon momentum: **39 MeV/c**

Irradiation time**: ~72 hours**

Time between beam stop and offline measurement: **13.5 hours**

Offline measurement time: **81.5 hours**

<u>Target information:</u>

^{76}Se, metallic

Diameter: 1.8 mm **(Different from yesterday slide)**

Thickness: 1.8 mm

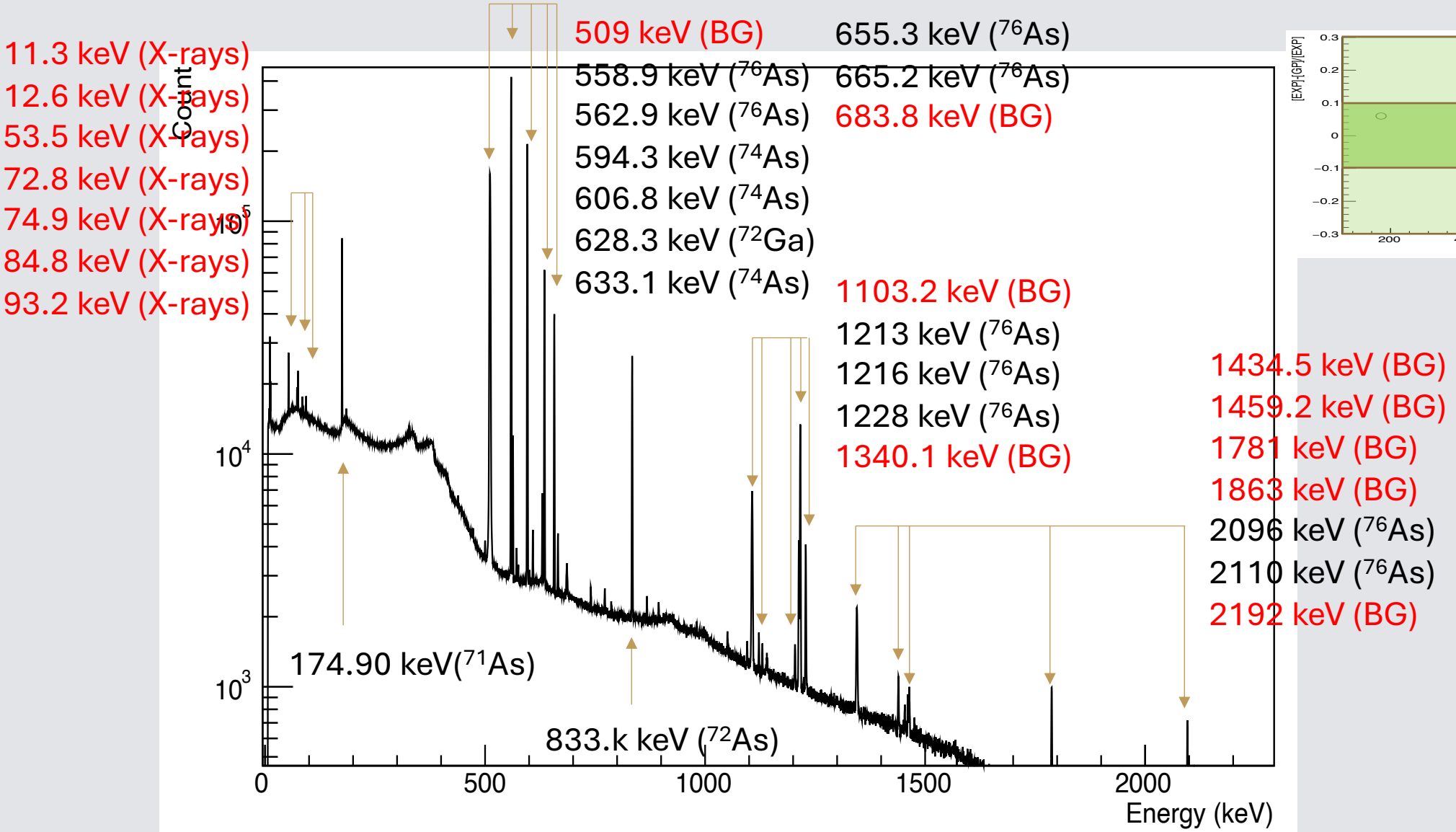
Mass: 2g

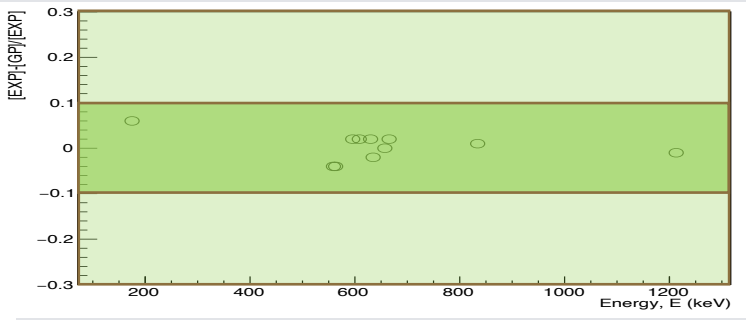
From detector information given by Daniya:

Muon intensity, N_μ = 31.6 x 10^3 μ/s

Probability of capture, η_c = 0.956

Overall Spectrum from ^{76}Se offline measurement





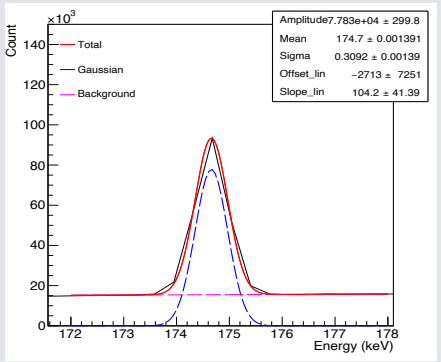
Calibration check

Step by step to obtain Br(X') and Giant Resonance Peak

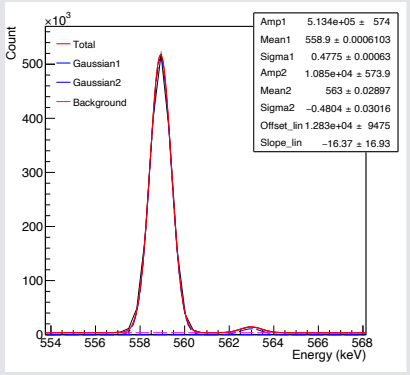
1) Peak assignment and calibration

2) Peak fitting
(Gaussian + Linear) or (2 Gaussian + Linear)

174.7 keV



558.9 keV and 563 keV



3) Yield Calculation

$Y(\gamma)$ = Amplitude x sigma x $\sqrt{2\pi}$

4) Fitting of decay curve $Y(\gamma)$ vs time

$Y(\gamma)=Y_0 \exp(-\lambda/t)$

5) Sensitivity of measurement

$$i_m(X) = a(X) \times \frac{\sqrt{Y(BG)}}{Y(\gamma)}$$

6) Number of Isotope produced during measurement

$$N(X) = \frac{Y(\gamma)}{\varepsilon(\gamma) Br(\gamma)\left[1 - exp\frac{t'}{t_m}\right]}$$

7) RI production rates

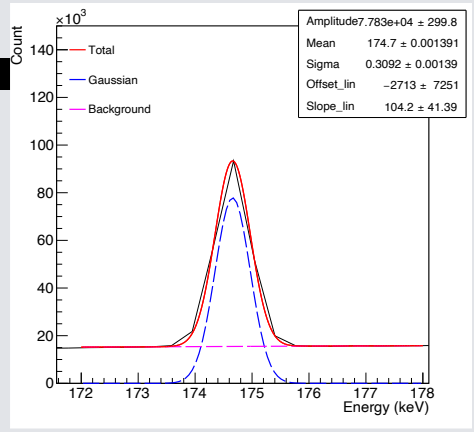
$$R(X) = \frac{N(X')}{t_m\left[1-exp\frac{t}{t_m}\right]}$$

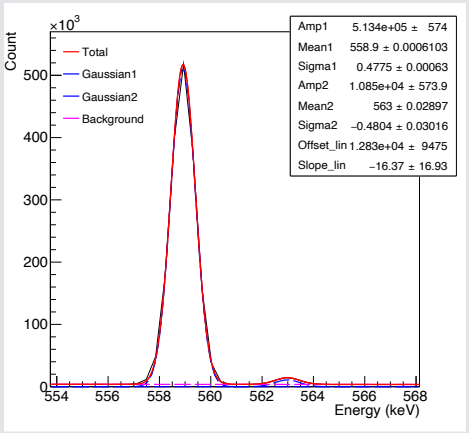
8) Branching ratio of Isotope in %

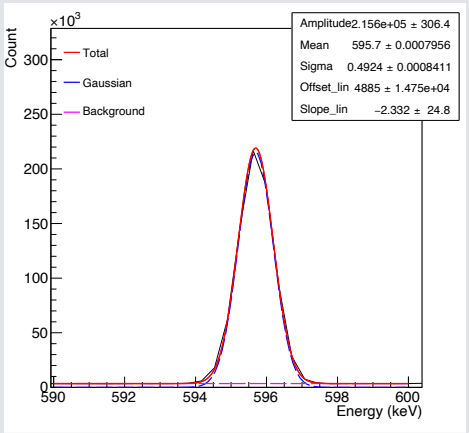
$$Br(X') = \frac{R(X')}{N_\mu \cdot \eta_s \cdot k_{xs} I(X)}$$

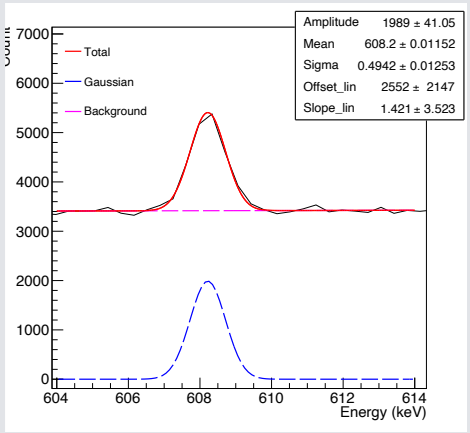
9) Compare with PNEM output to obtain its' GR distribution

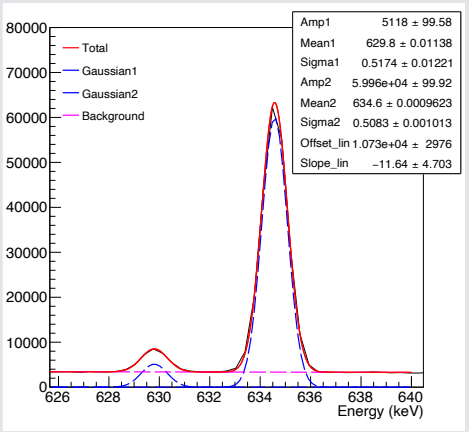
Peak fitting

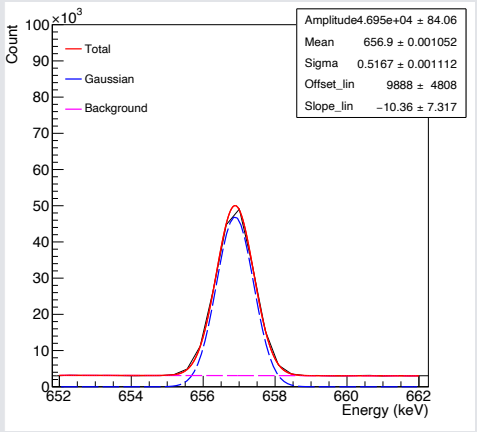


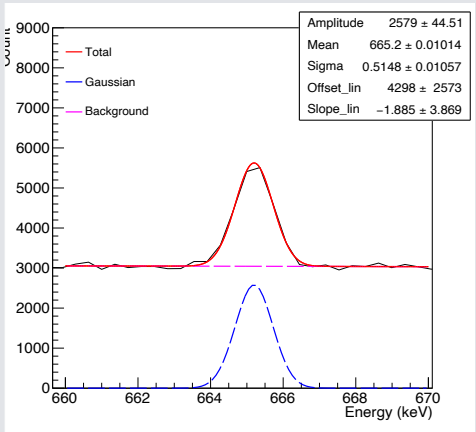


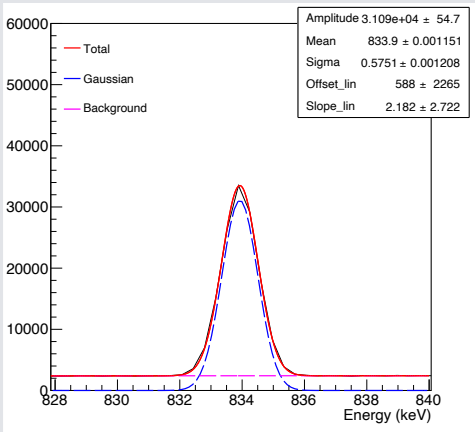


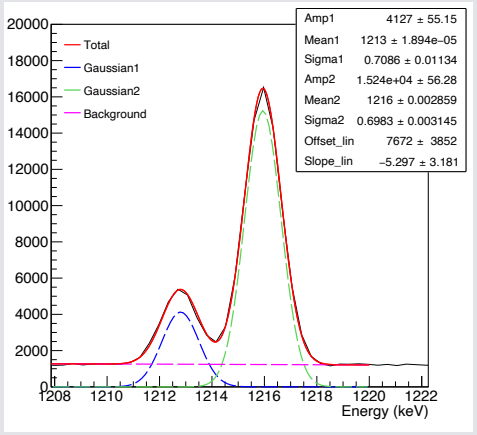


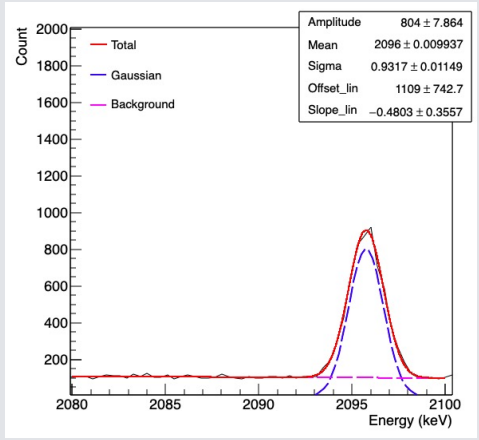


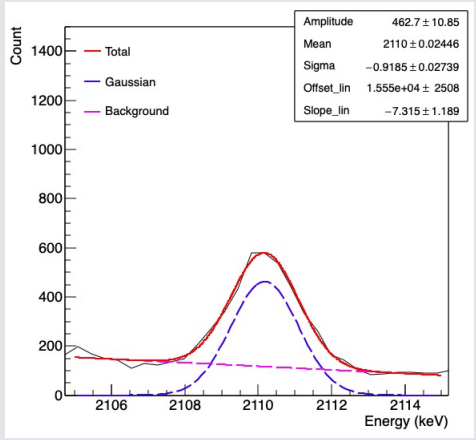




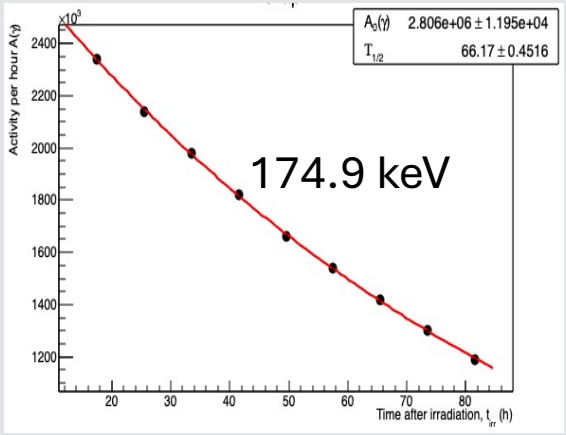


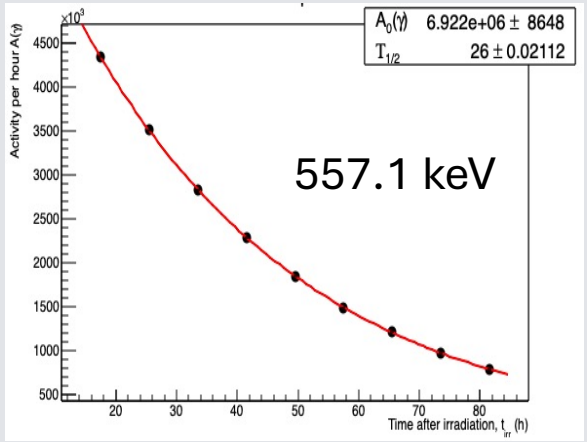


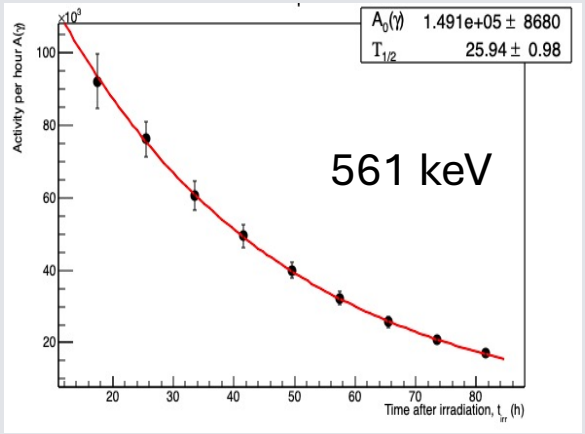


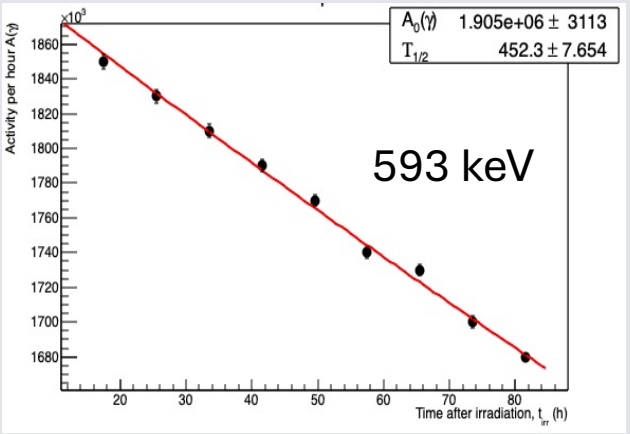


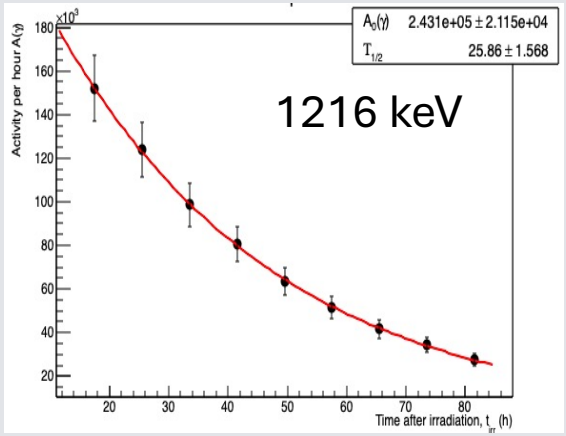
Decay Curve

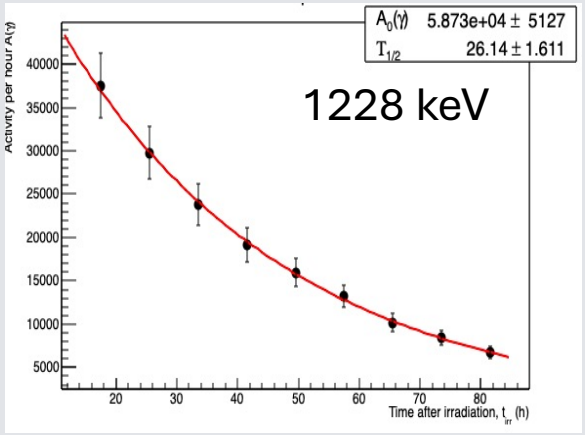

$A_0(\gamma)$ 2.806e+06 ± 1.195e+04
$T_{1/2}$ 66.17 ± 0.4516
174.9 keV
Activity per hour A(γ)
Time after irradiation, t_{irr} (h)

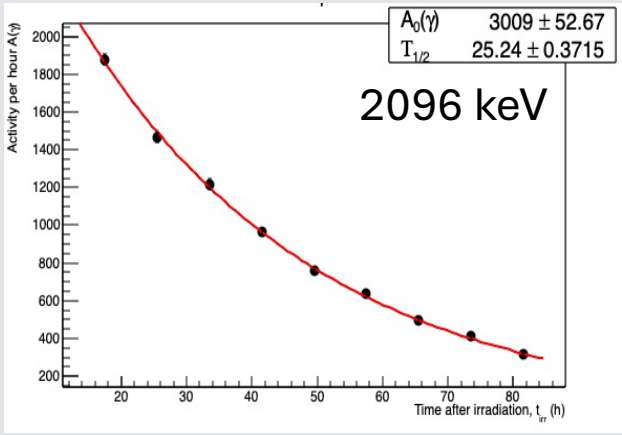

$A_0(\gamma)$ 6.922e+06 ± 8648
$T_{1/2}$ 26 ± 0.02112
557.1 keV
Activity per hour A(γ)
Time after irradiation, t_{irr} (h)

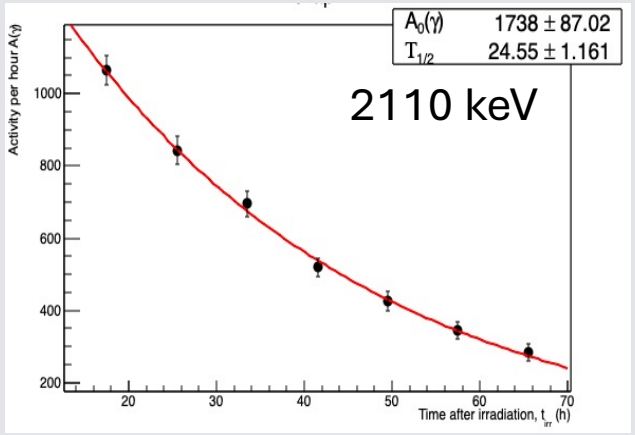

$A_0(\gamma)$ 1.491e+05 ± 8680
$T_{1/2}$ 25.94 ± 0.98
561 keV
Activity per hour A(γ)
Time after irradiation, t_{irr} (h)


$A_0(\gamma)$ 1.905e+06 ± 3113
$T_{1/2}$ 452.3 ± 7.654
593 keV
Activity per hour A(γ)
Time after irradiation, t_{irr} (h)


$A_0(\gamma)$ 2.431e+05 ± 2.115e+04
$T_{1/2}$ 25.86 ± 1.568
1216 keV
Activity per hour A(γ)
Time after irradiation, t_{irr} (h)


$A_0(\gamma)$ 5.873e+04 ± 5127
$T_{1/2}$ 26.14 ± 1.611
1228 keV
Activity per hour A(γ)
Time after irradiation, t_{irr} (h)


$A_0(\gamma)$ 3009 ± 52.67
$T_{1/2}$ 25.24 ± 0.3715
2096 keV
Activity per hour A(γ)
Time after irradiation, t_{irr} (h)

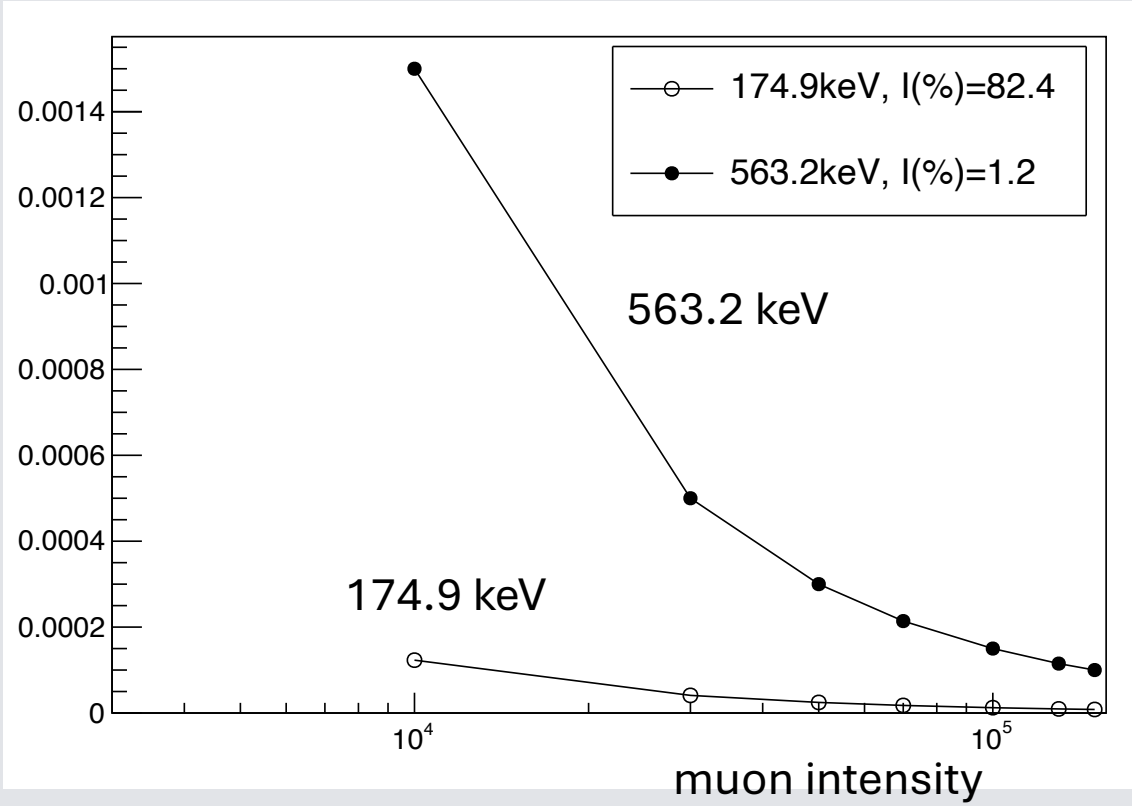

$A_0(\gamma)$ 1738 ± 87.02
$T_{1/2}$ 24.55 ± 1.161
2110 keV
Activity per hour A(γ)
Time after irradiation, t_{irr} (h)

Observed RI peaks

- All RIs coming from As isomer.
- The observed RI comes from ^{76}As, ^{74}As, ^{72}As and ^{71}As shows only RI following neutron emissions.
- Relative yield between each peaks reflects their intensity of the peak as reported in nuclear data table.

RI origin	Energy gamma (keV)	Half-life (s/m/h/d)
^{76}As	559.1 (45%), 563.0 (1.2%), 657.1 (6.2%), 665.3 (0.36%), 1212.9 (1.44%), 1216.08 (3.42%), 1228.5 (1.22%), 2096.3(0.55%), 2110.8(0.33%)	26.2 h
^{75}As	stable	
^{74}As	595.8 (59%), 608.4 (0.55%), 634.8 (15.4%)	427.2 h
^{73}As	stable	
^{72}As	629.9 (8.07%), 834.1 (81%)	26 h
^{71}As	174.9 (82.4%)	65.3 h

Measurement sensitivities



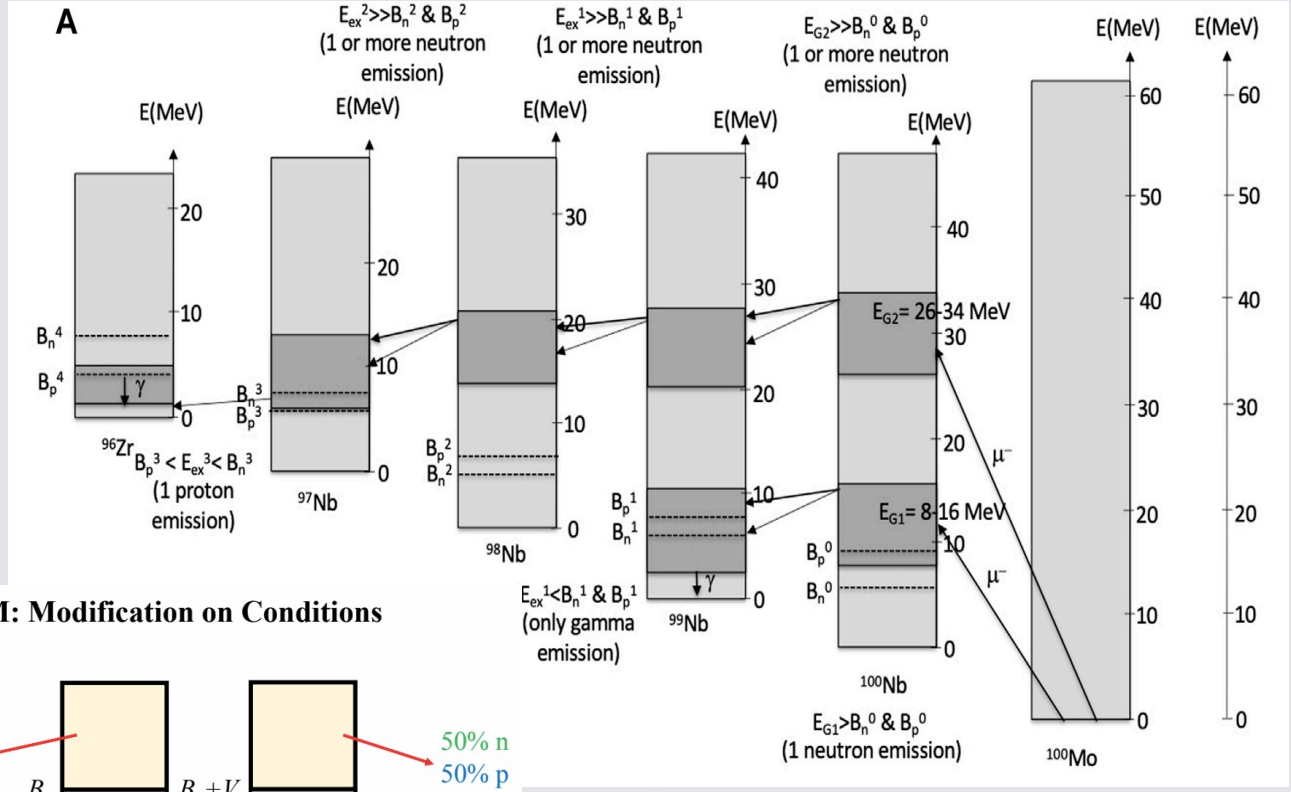
- Based on the overall observation on each gamma rays, the sensitivity vs muon intensity curve is produced.
- Comparison between low, medium and high intensity gamma peak sensitivities shows proportional decrement with higher muon intensity

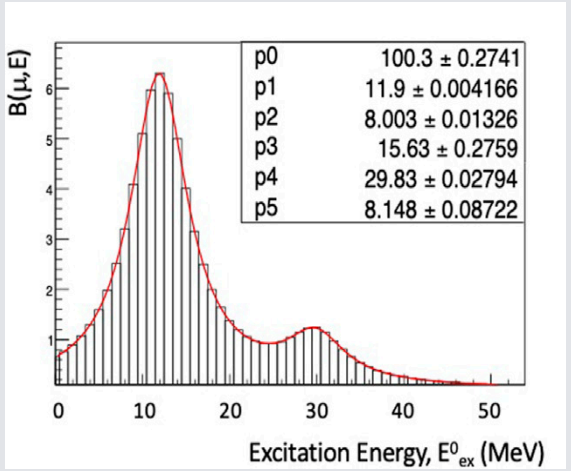
Br(X’) and R(X’) from ^{76}Se(μ,xnν) reaction

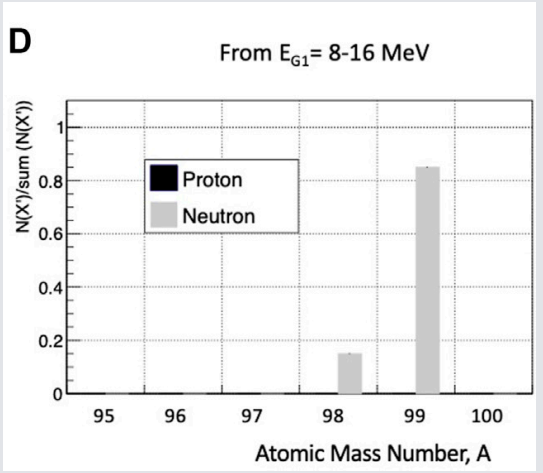
A	Br(X’) in %	err	N(X')	err	R(X')	err
71	0.00675	3.241E-03	6.20E+07	1.09E+06	1.227E+06	2.31E+04
72	0.00176	9.945E-04	3.33E+07	4.23E+06	1.113E+06	1.56E+05
73						
74	0.11809	1.824E-01	3.25E+09	7.667E+08	4.758E+07	5.389E+07
75						
76	0.47876	9.860E-01	3.37E+09	2.108E+09	1.055E+08	6.761E+07

A=76 gives the **highest** probability **~47.8%,**
follows by **A=74(11.8%),**
A=72(0.2%) and **A=71(0.7%)**

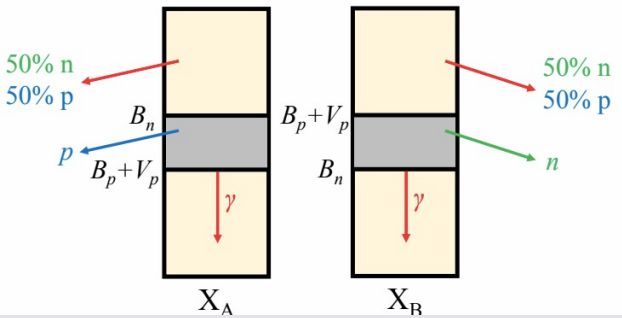
Improved proton-neutron emission model (PNEM2022)







PNEM: Modification on Conditions



Emission probability based on neutron/proton binding energy + Coulomb Barrier – Z. W. Ng PhD Thesis, 2022

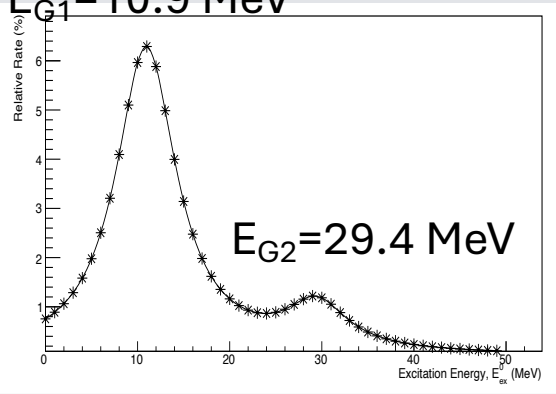
For ^{40}Ca (μ,xnν) :

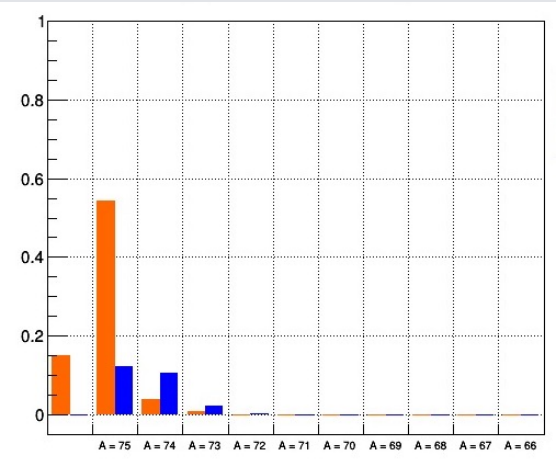
Reaction	Experiment	Coulomb + 50% prob.	Coulomb only	Without Coulomb
(μ⁻, ν)	27	**24.4**	24.4	**22.3**
(μ⁻, νn)	43	**46.8**	**61.6**	56.8
(μ⁻, ν2n)	3	**2.4**	**9.9**	7.6
(μ⁻, ν3n)	0	**0.08**	**0.7**	0.5
(μ⁻, ν4n)	-	0	0	0
(μ⁻, νp)	10	**12.6**	**0**	2.1
(μ⁻, νpn)	11	**11.0**	**2.5**	7.4
(μ⁻, νp2n)	3	2.6	**0.8**	**3.1**
(μ⁻, νp3n)	-	0.08	0.04	0.2

Muon capture Strength, B(μ)

Trial using B(μ) distribution by PNEM to produce experimental data.

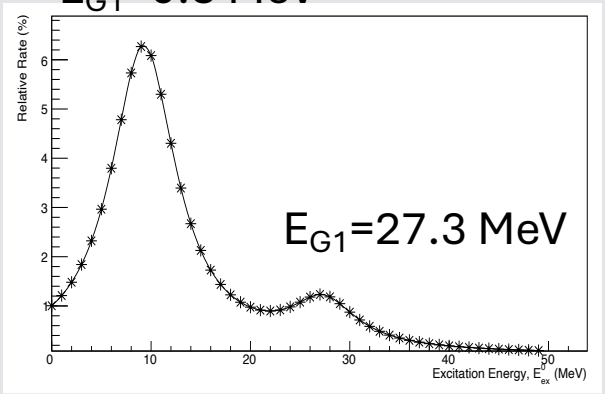
E_{G1}=10.9 MeV

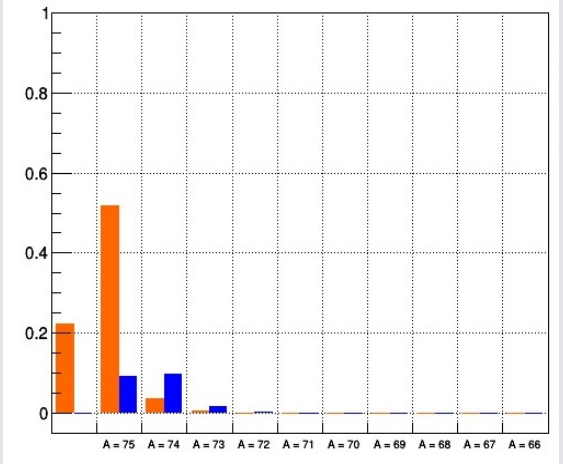




Case 1

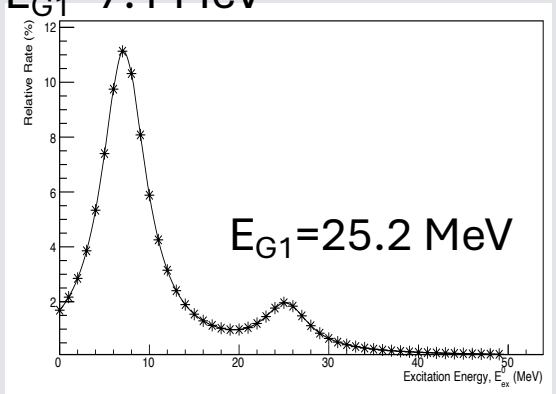
E_{G1}=9.3 MeV

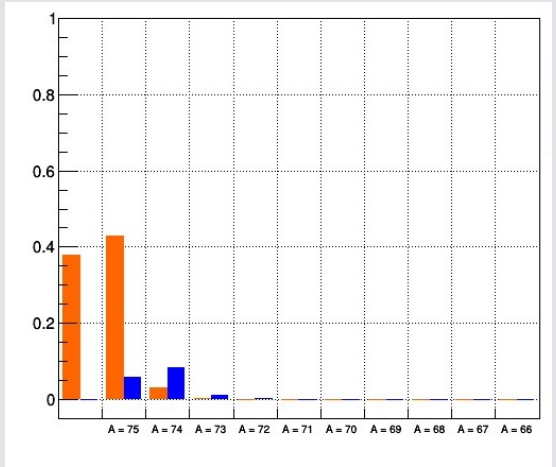




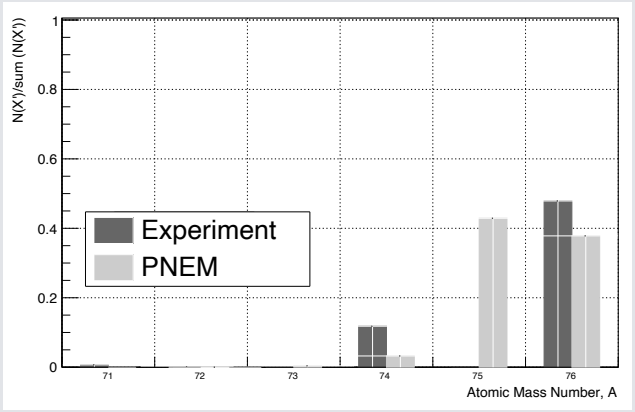
Case 2

E_{G1}=7.1 MeV





Case 3



using case 3, comparison with the Br(X') from experimental data give χ^2~1.2 the smallest compare to other assumed case.

Conclusion

- 29 gamma peaks have been observed following muon capture on ^{76}Se reaction.
  - Most of the come from As isomer associated with neutron emission.
  - Their half-life is between 24 hours to 500 hours.
- Measurement sensitivities shows that 0.6 ppm for peak at 174.9 keV.
  - sensitivities of measurement using enriched isotope could improved by highly intense muon beam.
- Branching ratio, Br(X') for the RI produced following the reaction shows 0 n channel to be the highest probability.
- Using the improved PNEM simulation, giant resonance peak is located at E_{G1}= 7.14 MeV and E_{G2} = 25.2 MeV