Lifetime measurements of low-lying octupole states in ^{224}Ra

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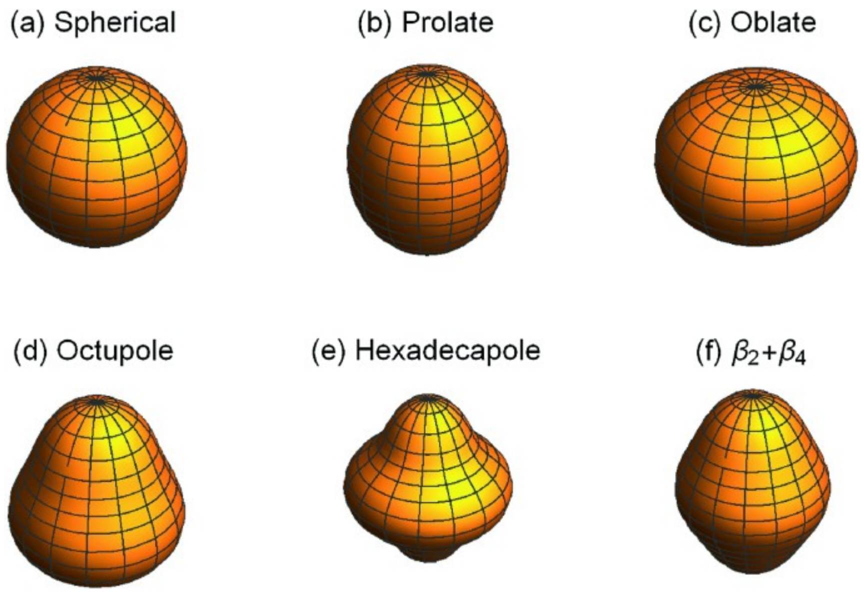
GRIFFIN

Motivation

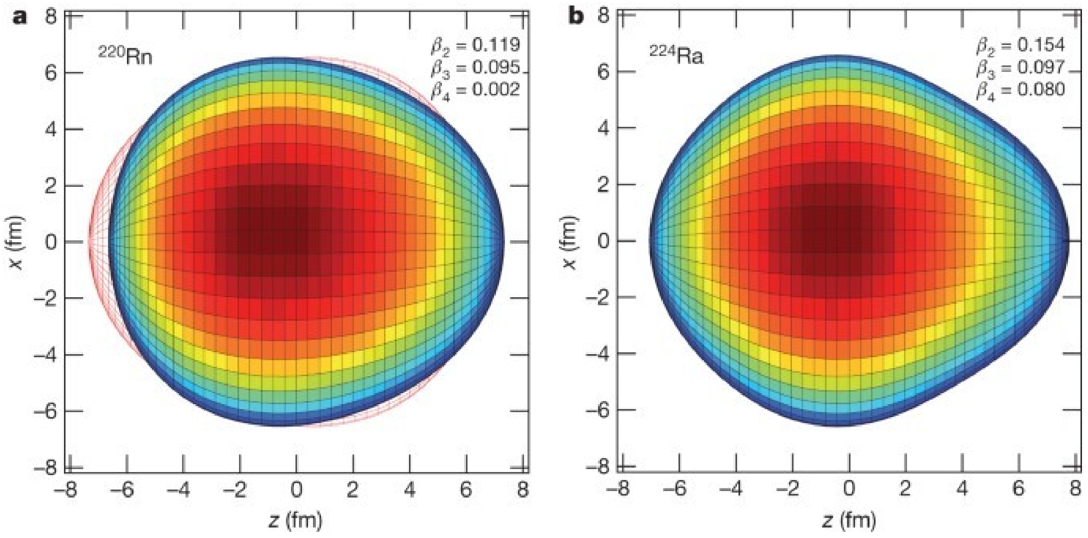
- Nuclei far away from closed shells tend to be deformed.
- Some of these nuclei become reflection asymmetric (pear shaped).
- These octupole deformed nuclei have displacement of their centres of mass and charge.

$$R(\theta, \phi) = c(\alpha_{\lambda\mu}) R_0 \left[1 + \sum_{\lambda=0}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda\mu} Y_{\lambda\mu}(\theta, \phi) \right]$$



Motivation

- Low-lying 1^- and 3^- states are clear signatures of enhanced octupole correlations.
- Enhanced E1 transitions can be a good indication of reflection asymmetry.
- Can also arise from octupole vibrational states.



L. P. Gaffney et al. Nature, 497(7448):199-204, 2013.

Motivation

- Large intrinsic electric dipole moments are observed in octupole regions of the nuclear chart.

$$D_0 = e\frac{NZ}{A}\left[\langle z_{p.c.m}\rangle - \langle z_{n.c.m}\rangle\right] \qquad D_0 = (\pm)D_0^{macro} + (\pm)D_0^{shell}$$

- Schiff's theorem tells us that for a point like nucleus, with a permanent EDM, the dipole moment is shifted to the atomic electrons and they will rearrange themselves to give a zero atomic EDM.

- Treating the nucleus as the finite object it is gives rise to the Schiff moment and an overall EDM.

$$S \approx 1.0 \times 10^{-4} \frac{I}{I+1} \beta_2 (\beta_3)^2 Z A^{2/3} \frac{[\mathrm{keV}]}{E_- - E_+} e\,\eta\,[\mathrm{fm}^3]$$

Motivation

- ^{224}Ra has a very small intrinsic electric dipole moment due to the cancellation of the macroscopic and microscopic components.

- The odd mass nuclei around ^{224}Ra are good candidates for a large Nuclear Schiff Moment.

- B(E1, $1^- \rightarrow 0^+$) values are key predictions for DFTs.

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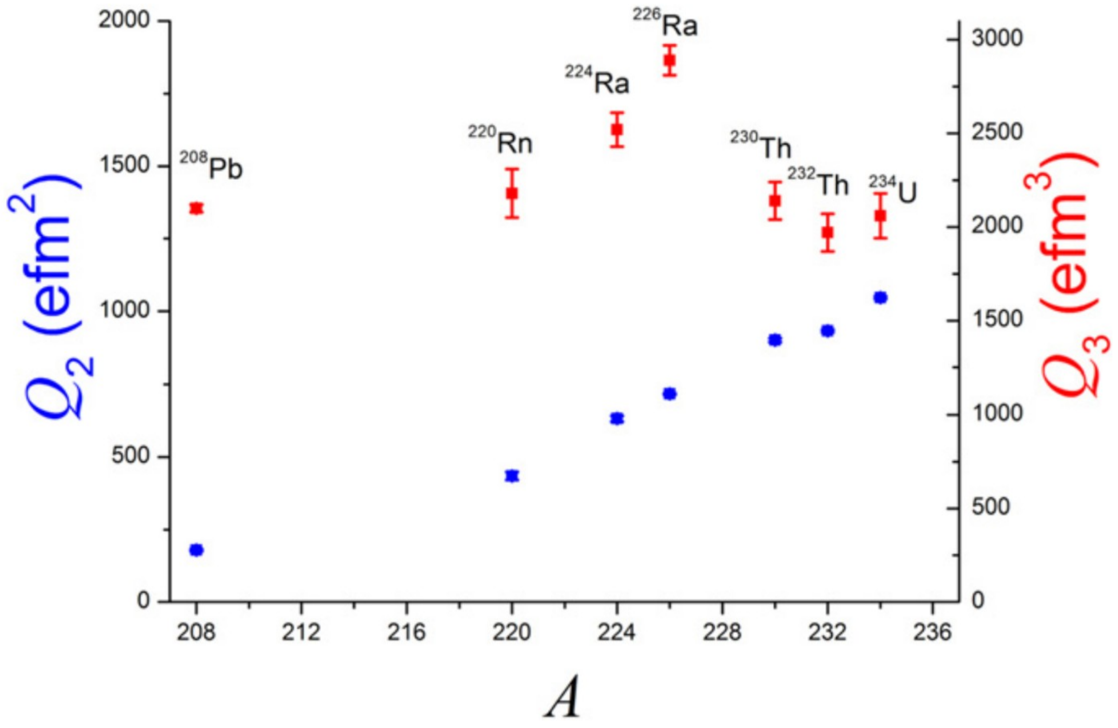

P.A. Butler 2016 J. Phys. G: Nucl. Part. Phys. 43 073002.

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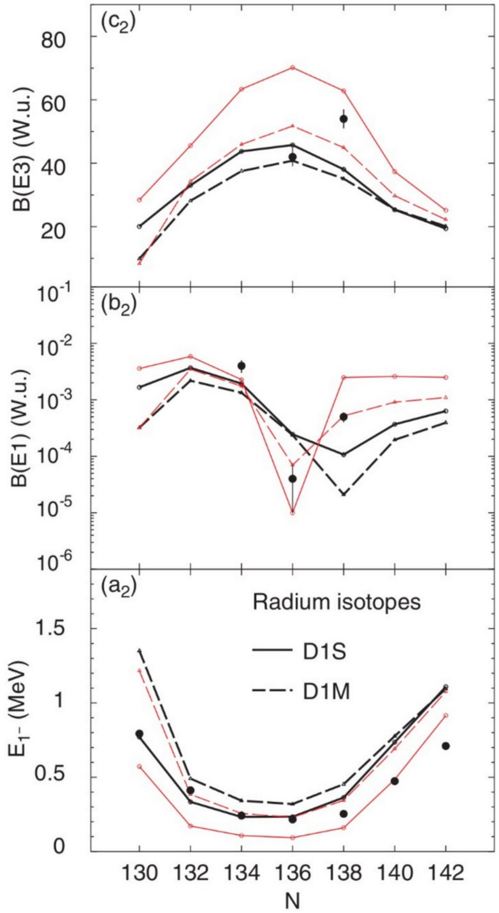


Bullet points = experimental results

Full black lines = Gogny D1S

Dotted black lines = Gogny D1M

Red lines = Generator Coordinate Method (GCM)

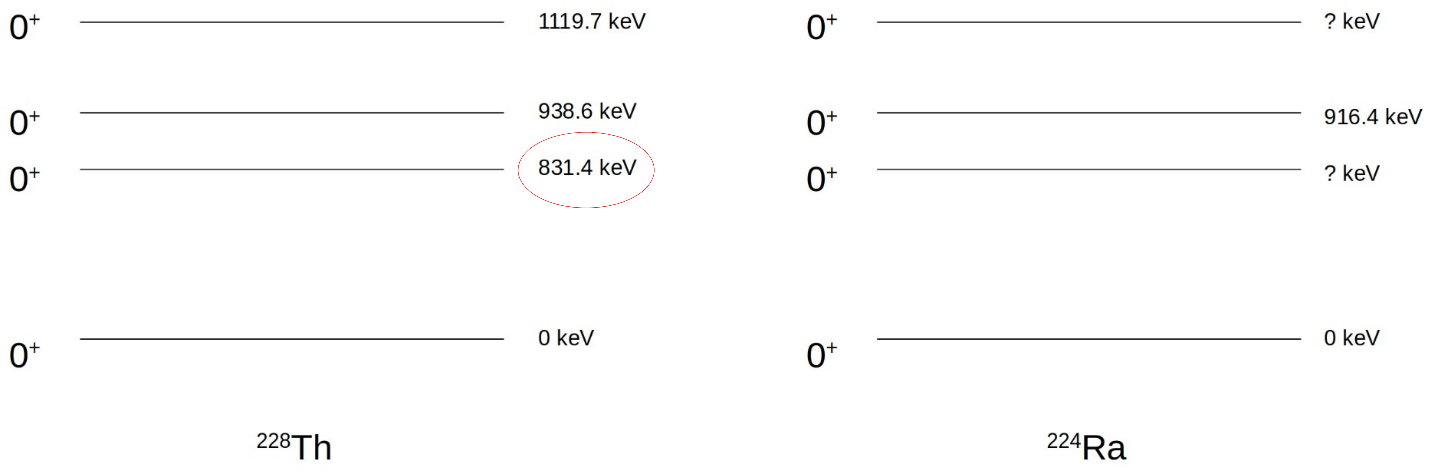
L. M. Robledo 2013 Physical Review C 88, 051302(R)

Motivation

- Electric Monopole (E0) transitions are only observed in atomic nuclei.
- There appears to be missing states in ^{224}Ra, when compared to ^{228}Th.
- This could be the two-octupole phonon band head, measurement of the lifetime will help determine this.

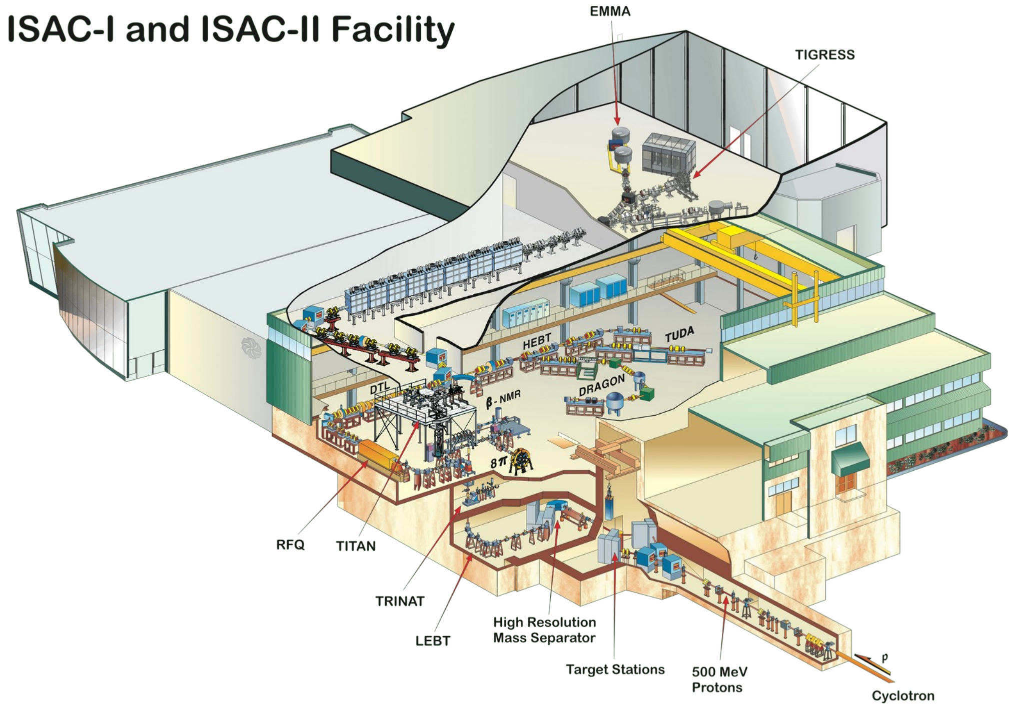
$$\rho(E0) = \frac{< f|M(E0)|i >}{eR^2}$$

$$B(E0) = \rho^2(E0)e^2R^4$$



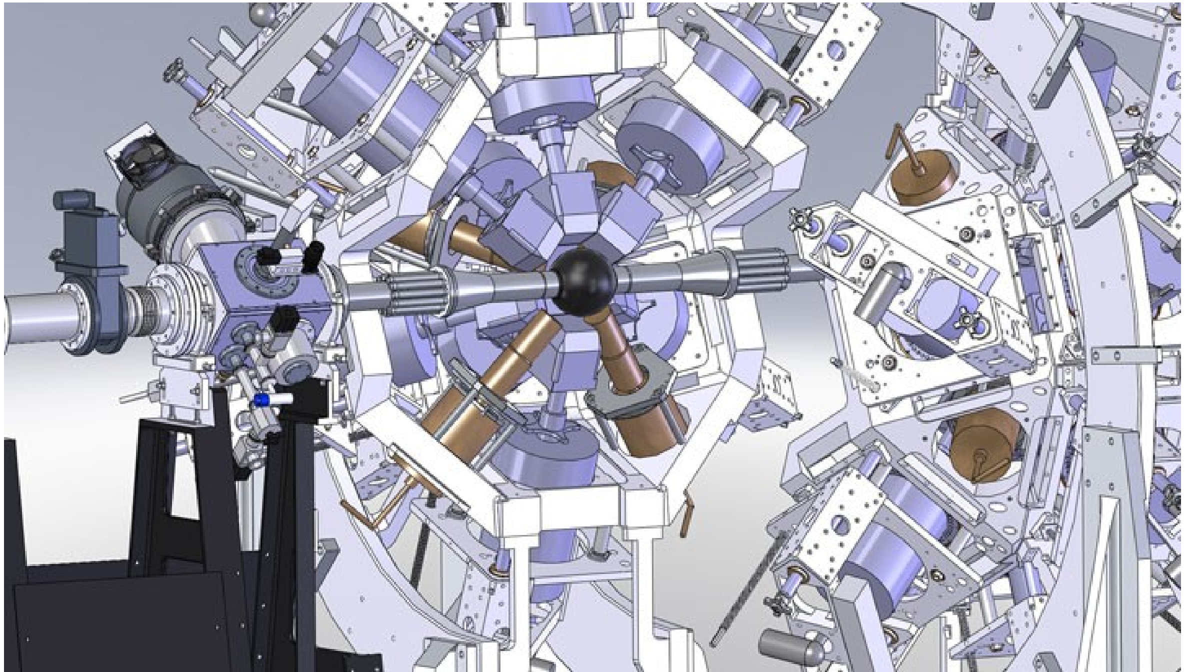
Experimental Details

- Proton beam on UC_x target to make ^{224}Fr ions.
- ^{224}Ra populated from beta decay of ^{224}Fr and then implanted into Moving Tape Collector.

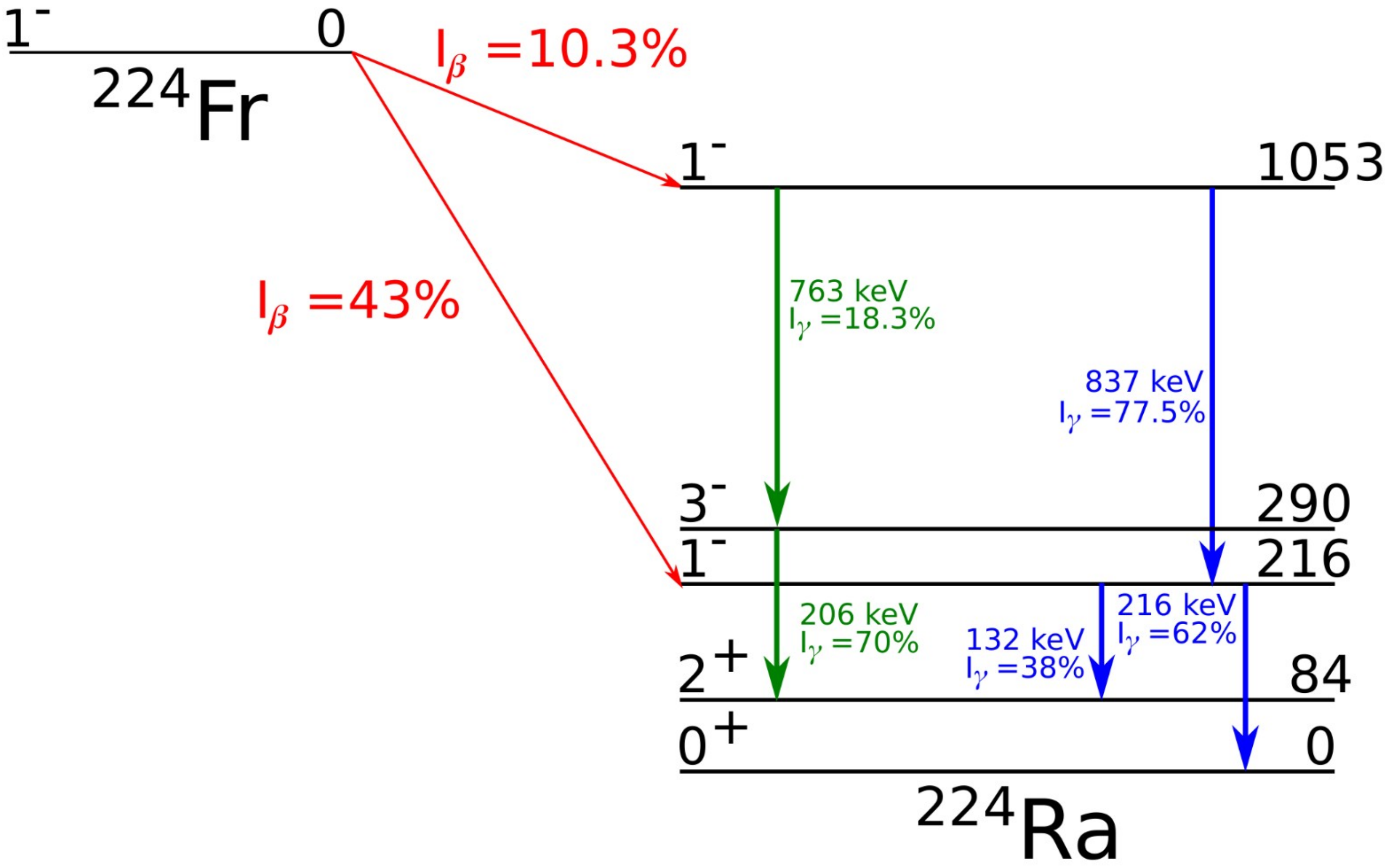


Experimental Details

- GRIFFIN (15 HPGe Clover Detectors) (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei).
- 8 $LaBr_3$(Ce).
- PACES (Si(Li)) (Pentagonal Array for Conversion Electron Spectroscopy).



Experimental Details



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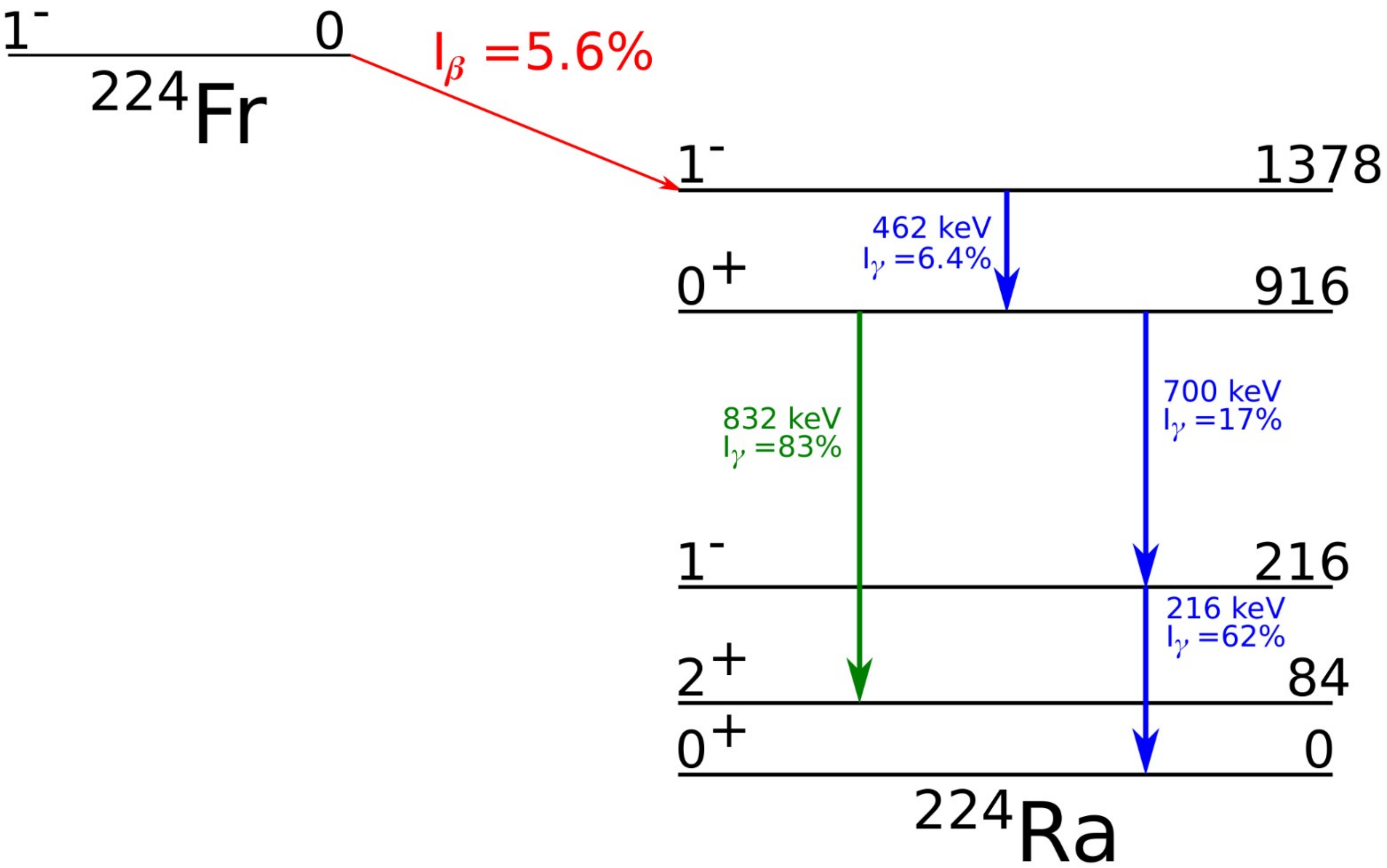
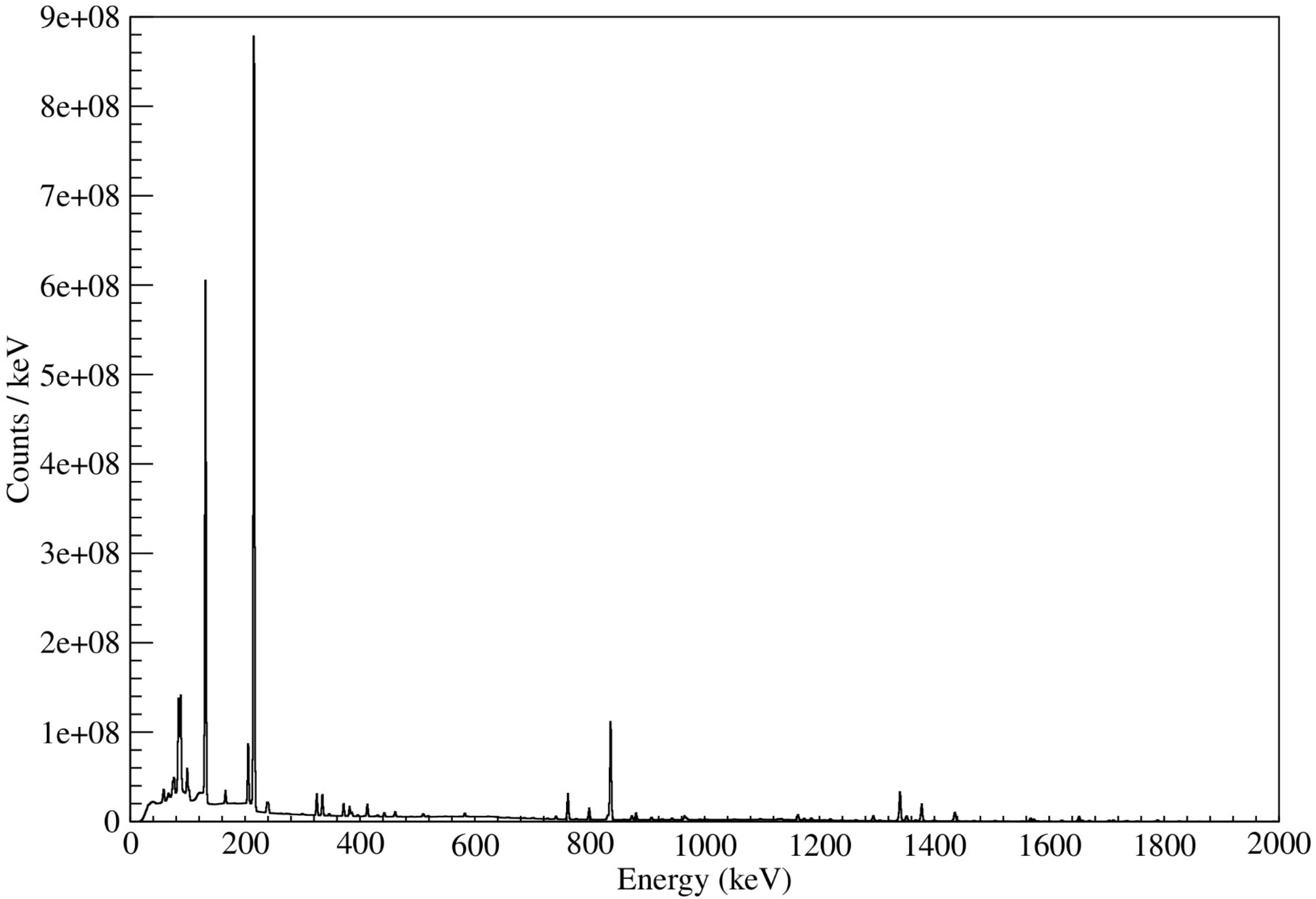
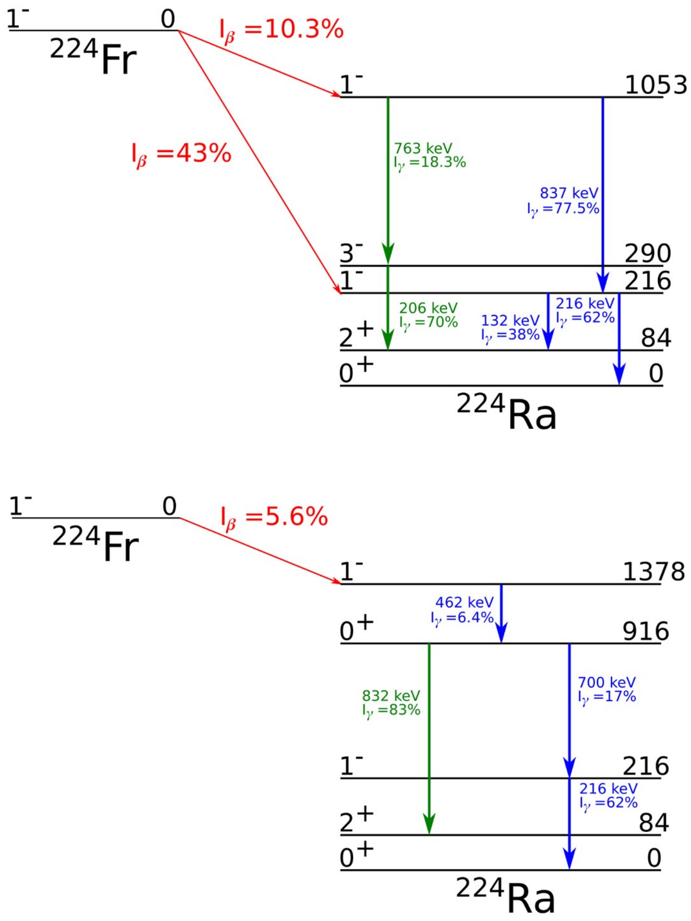
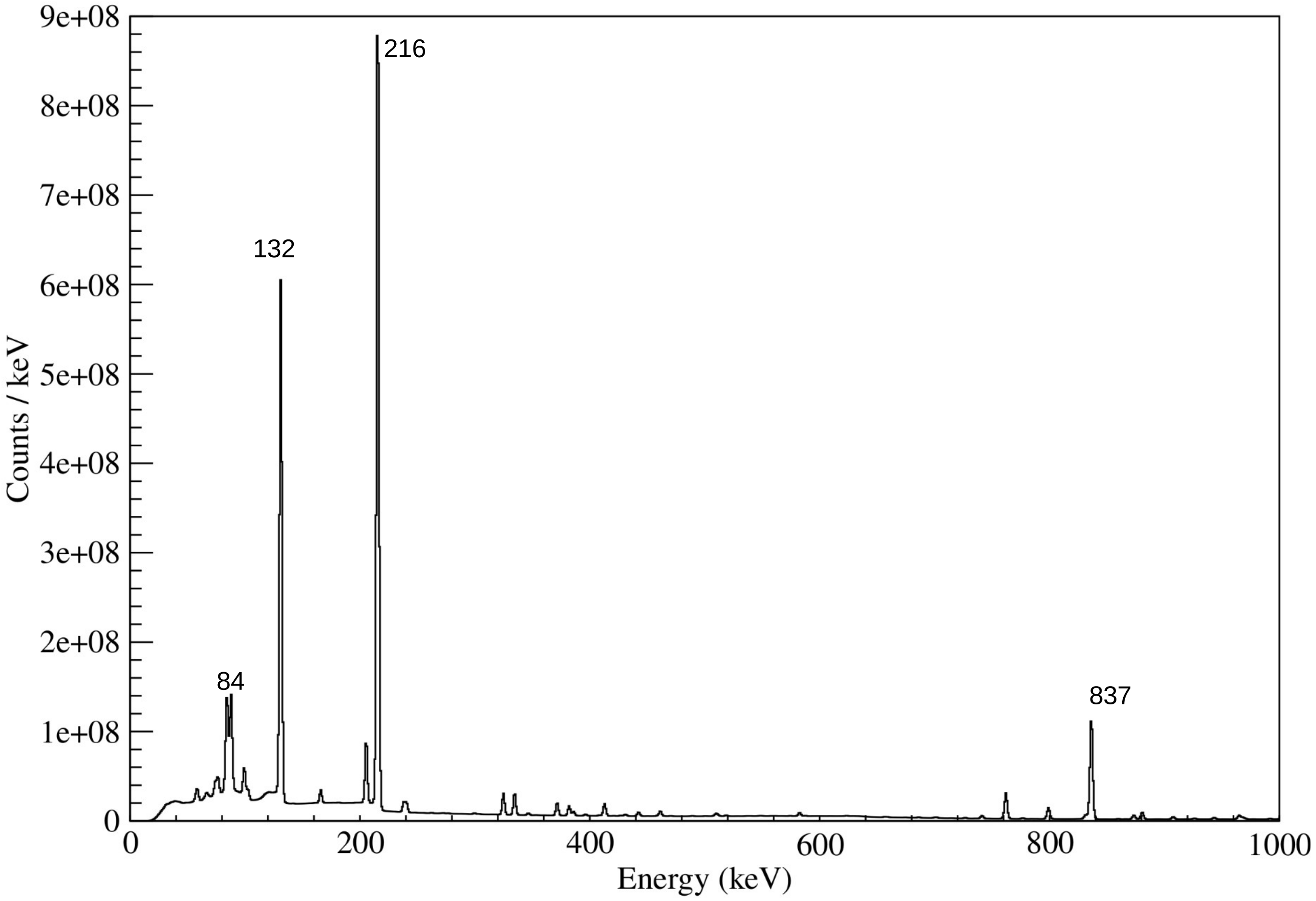


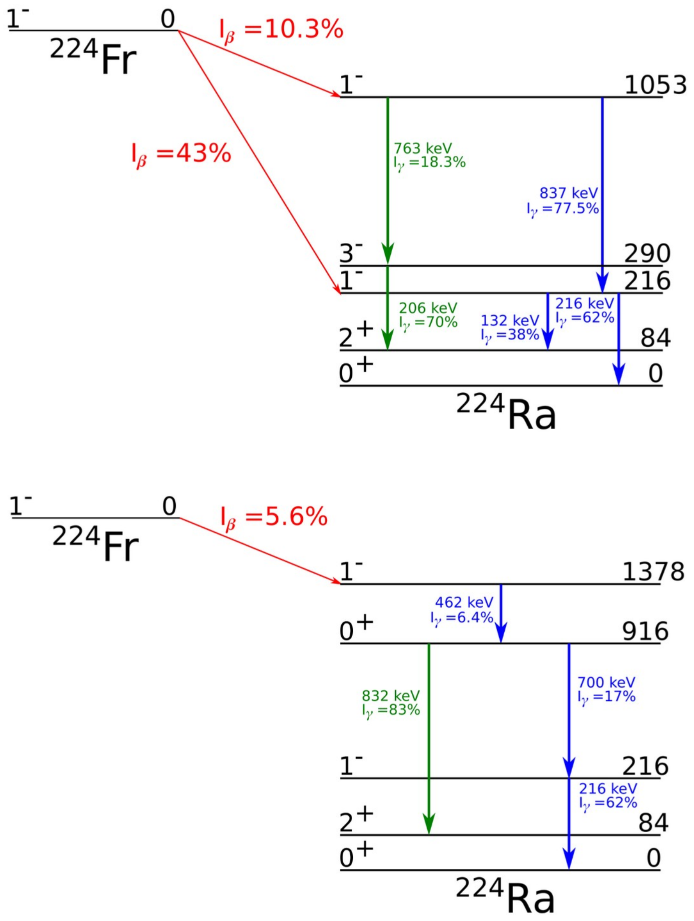
GRIFFIN Spectra



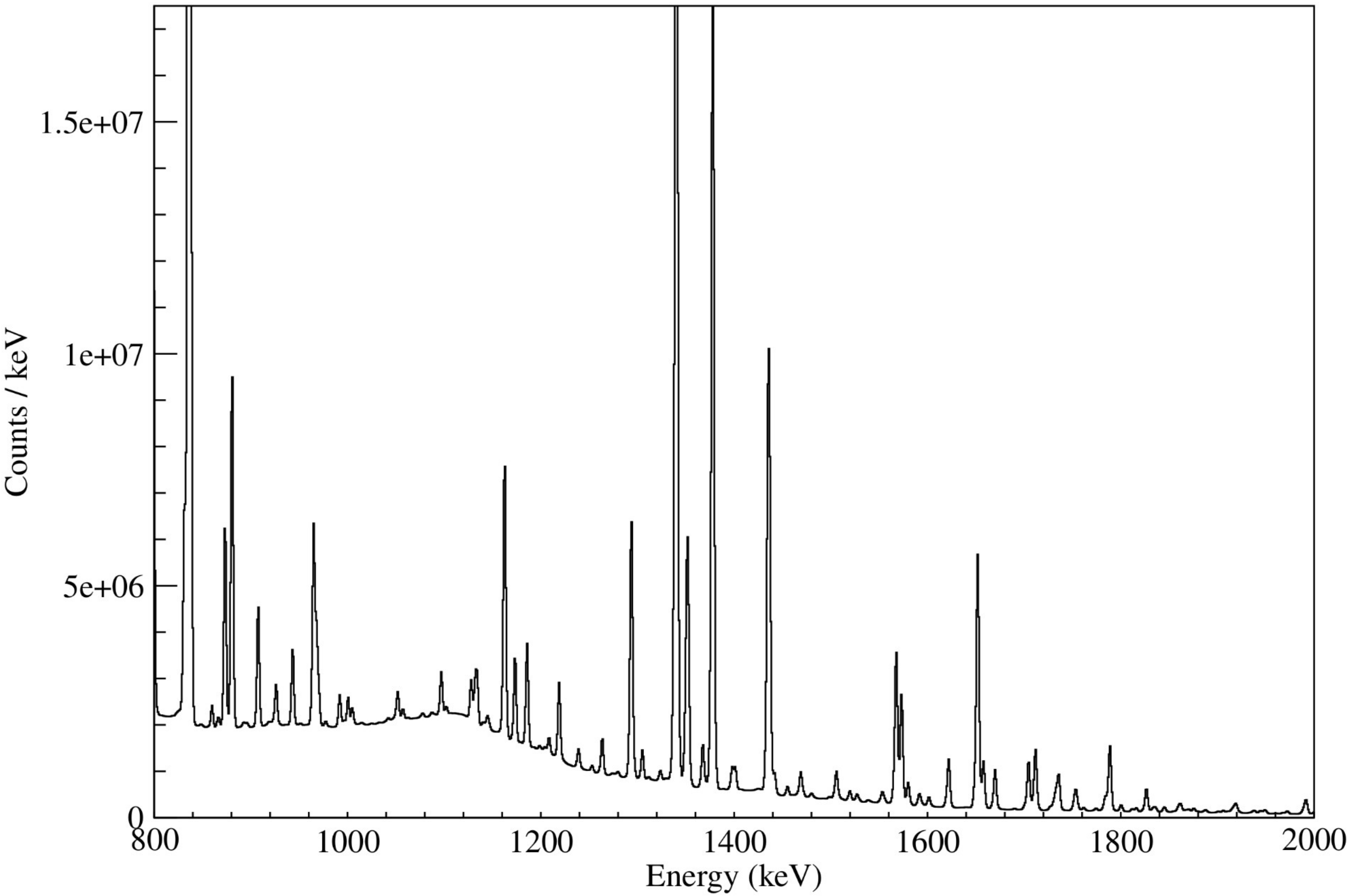


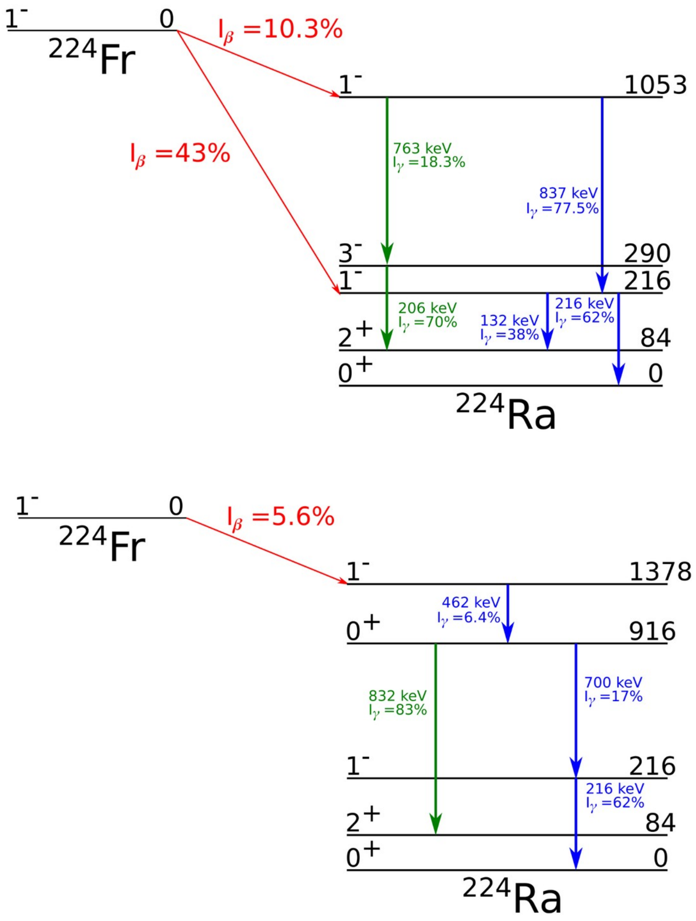
GRIFFIN Spectra



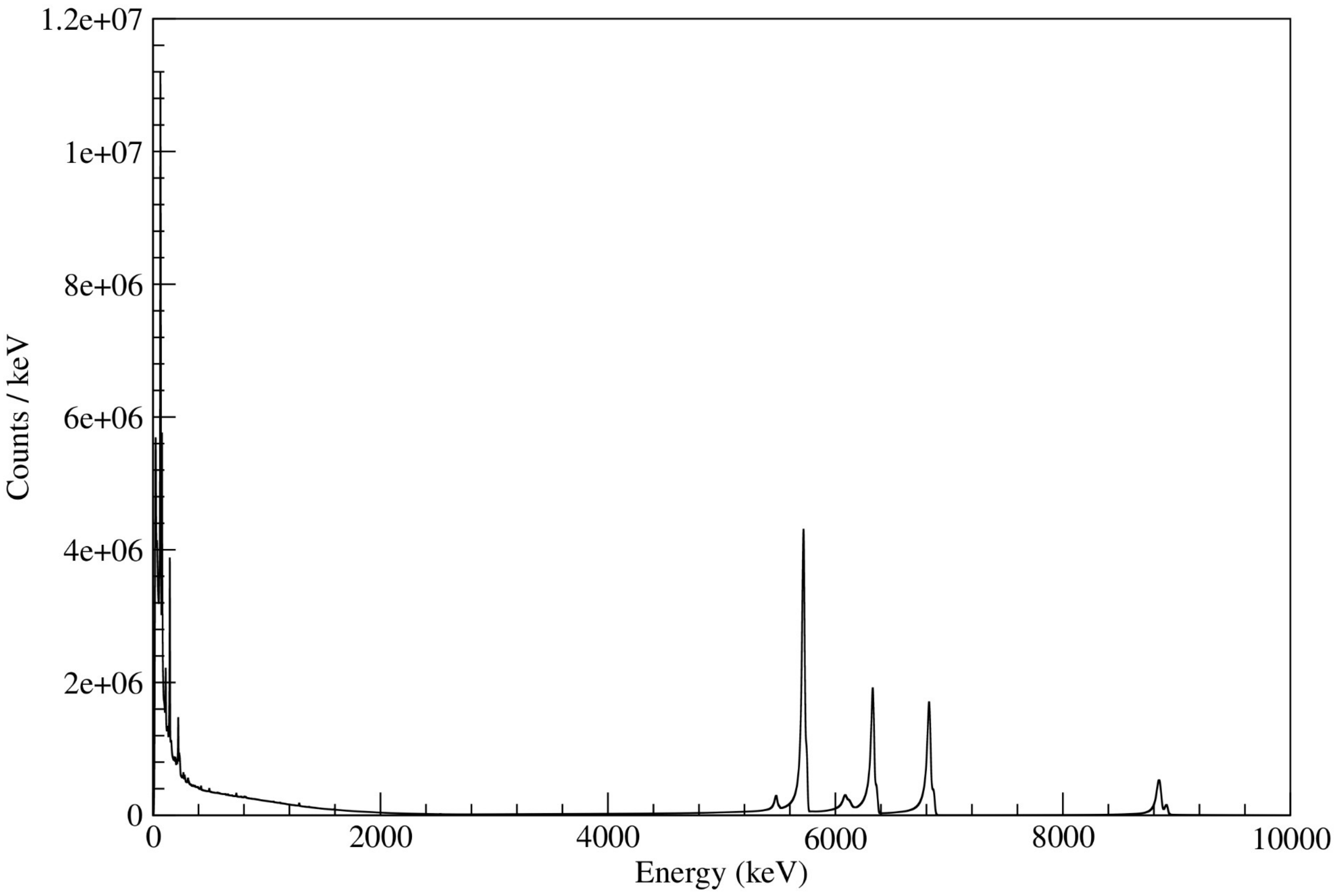


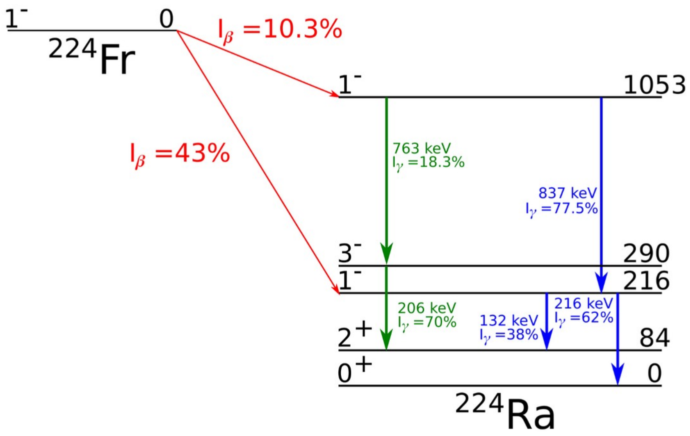
GRIFFIN Spectra

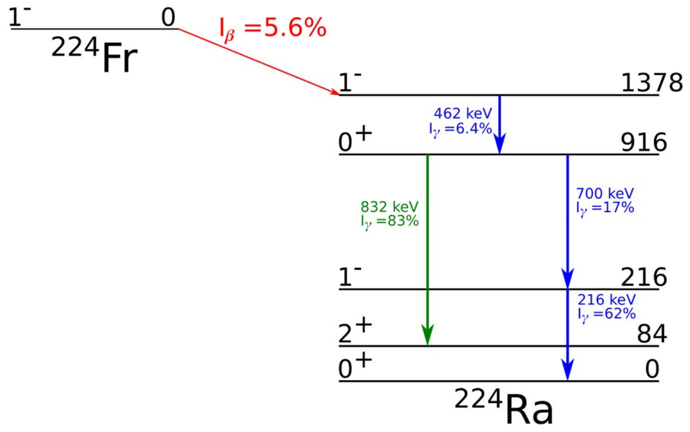




PACES Spectra







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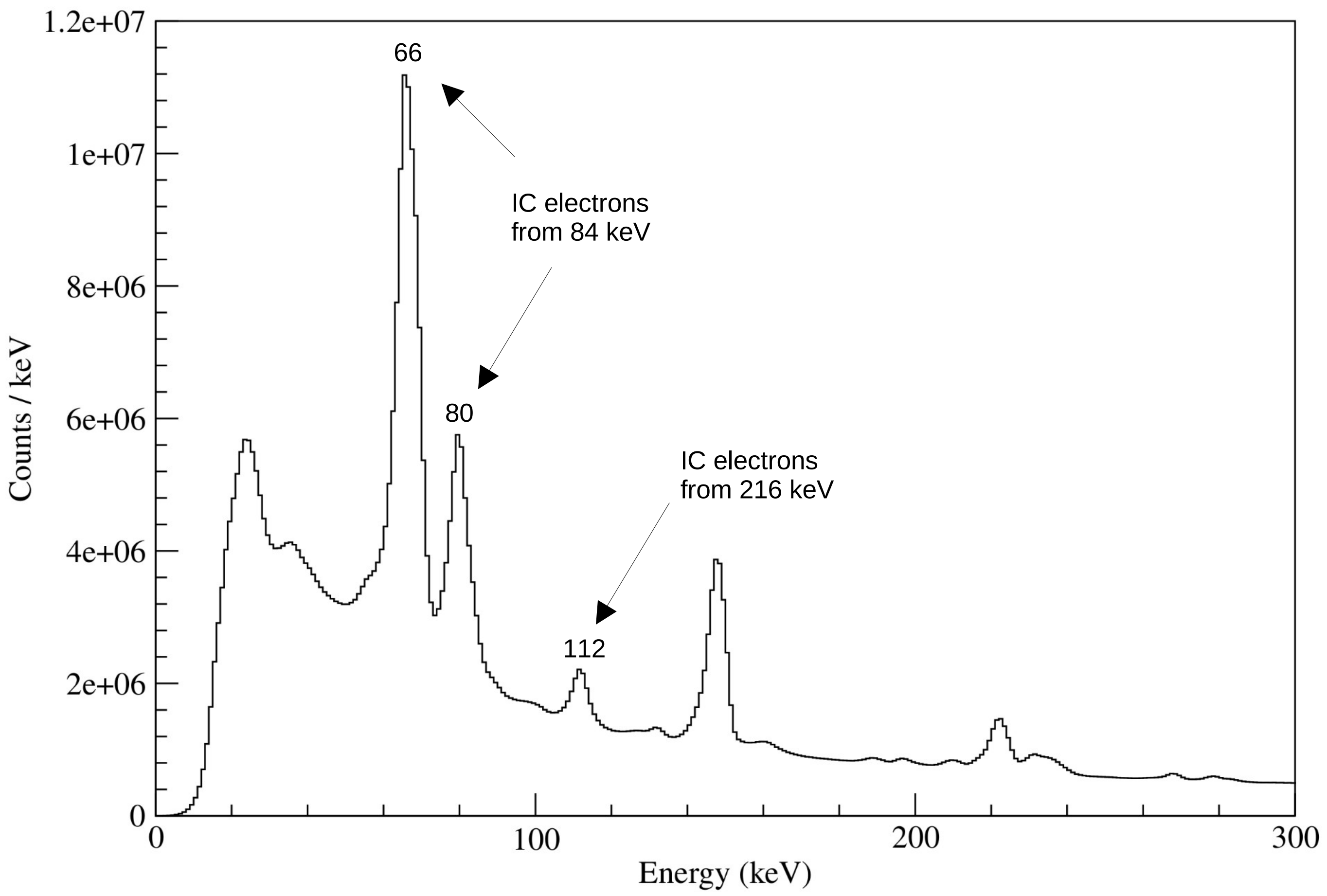

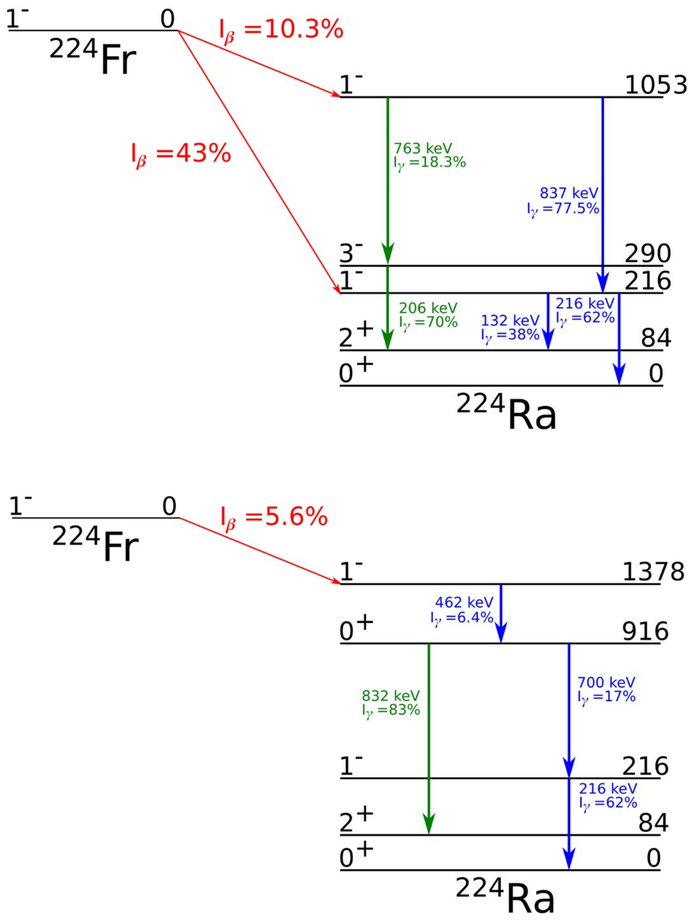

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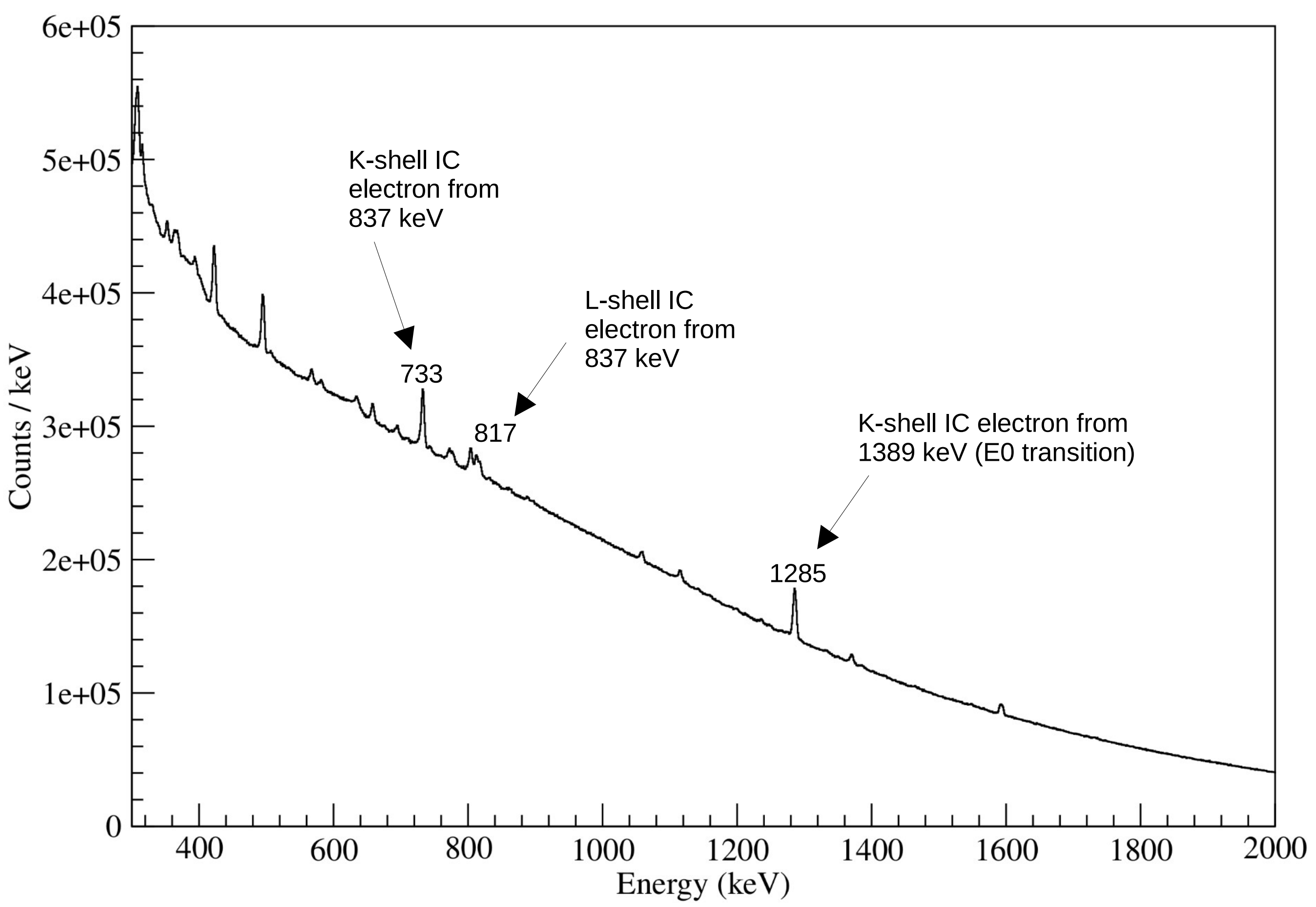

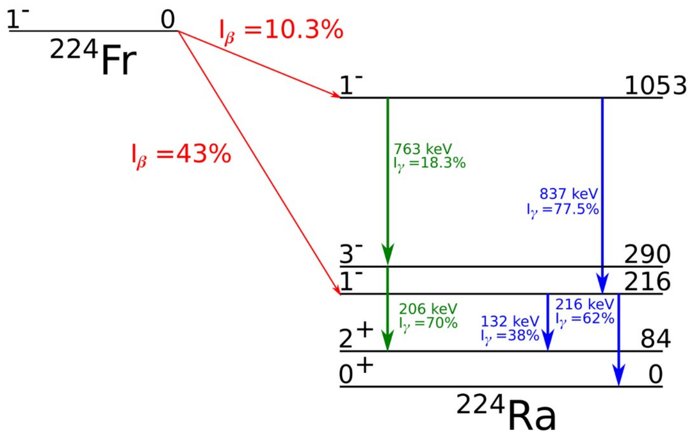

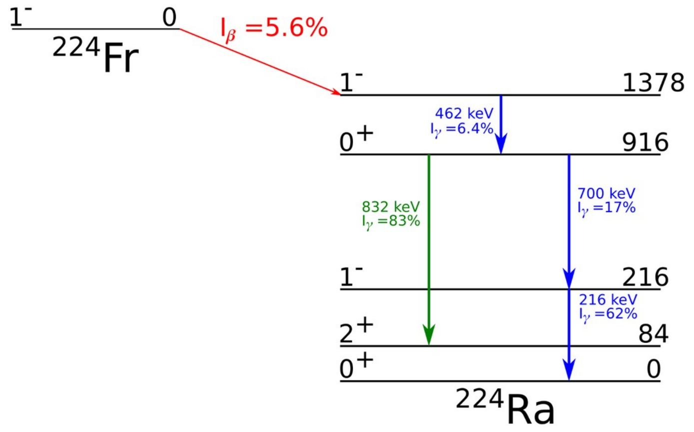

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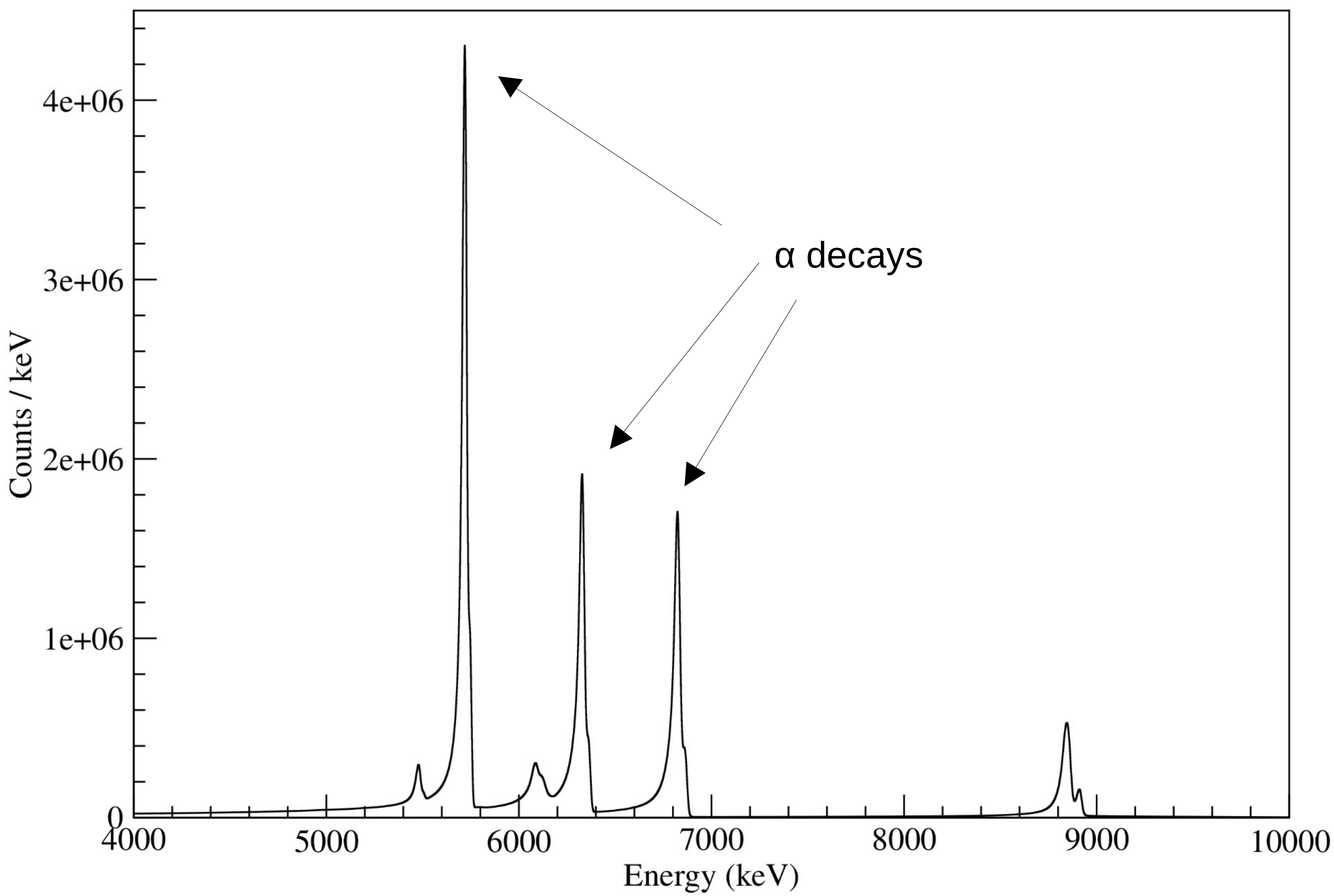
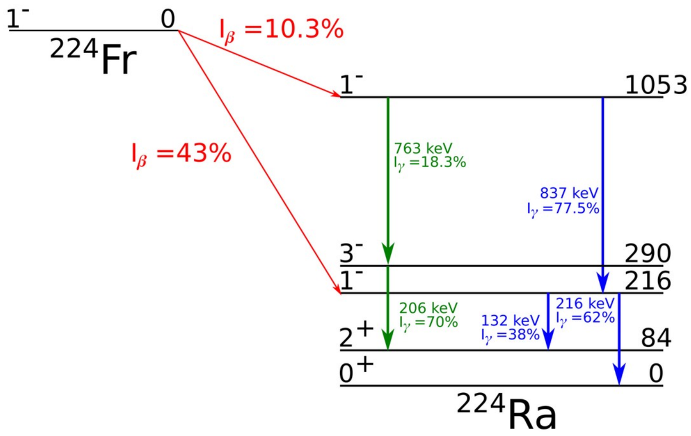
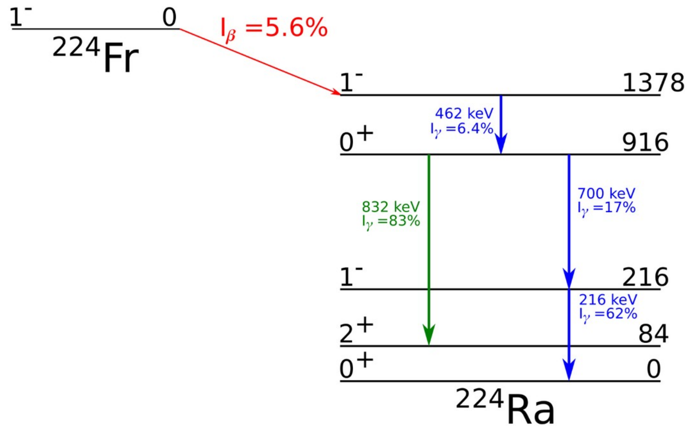
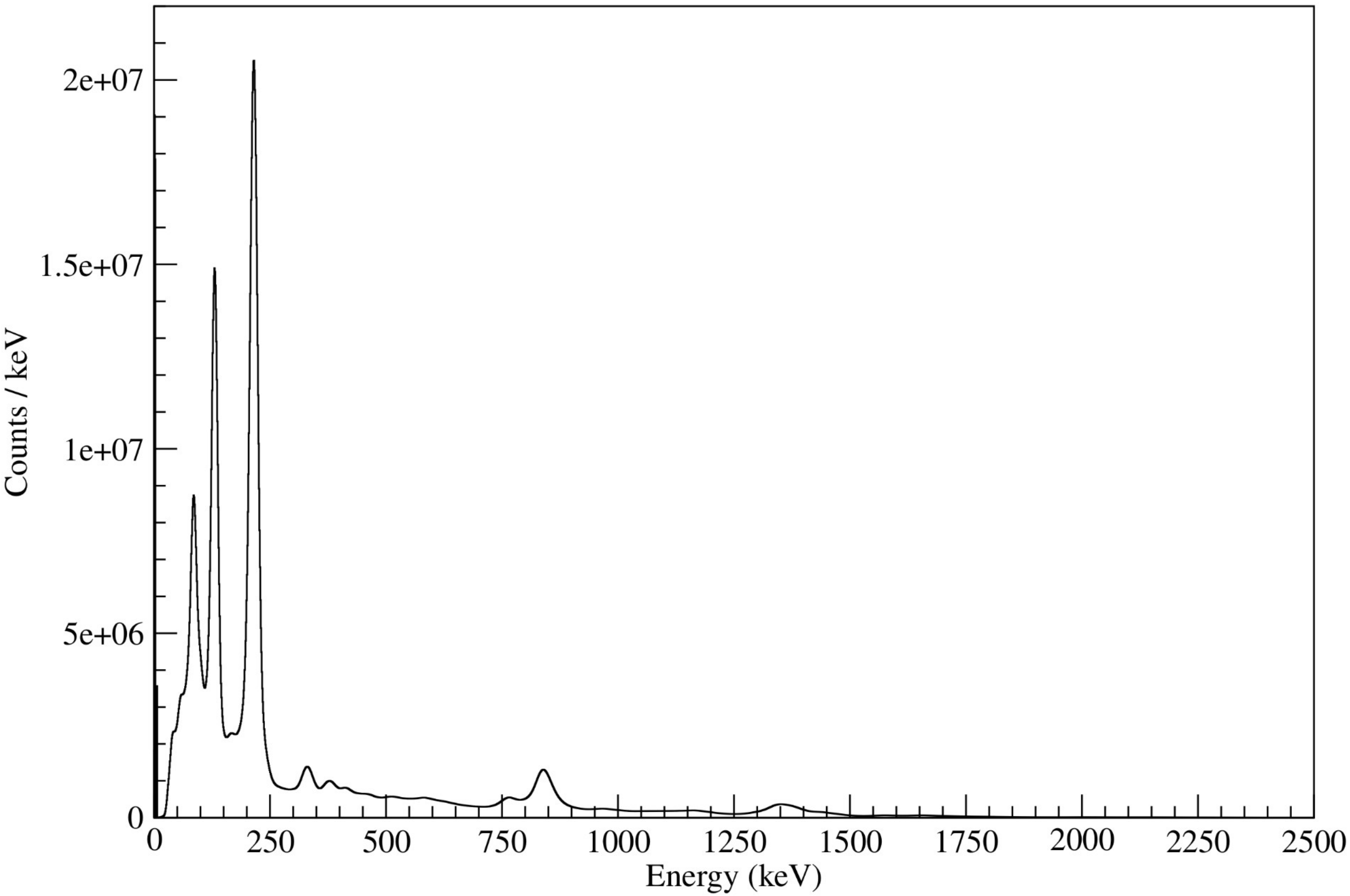
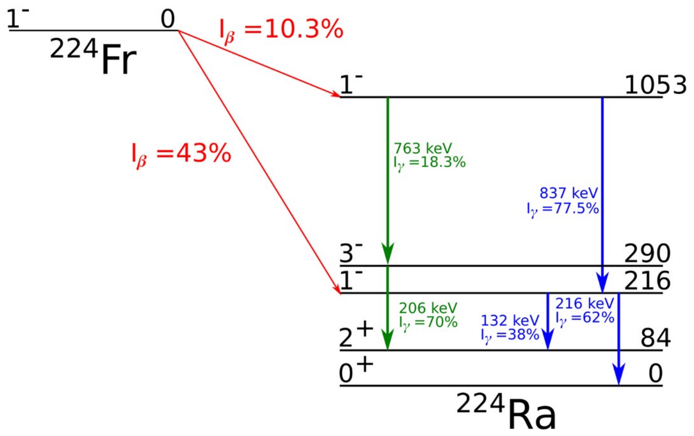


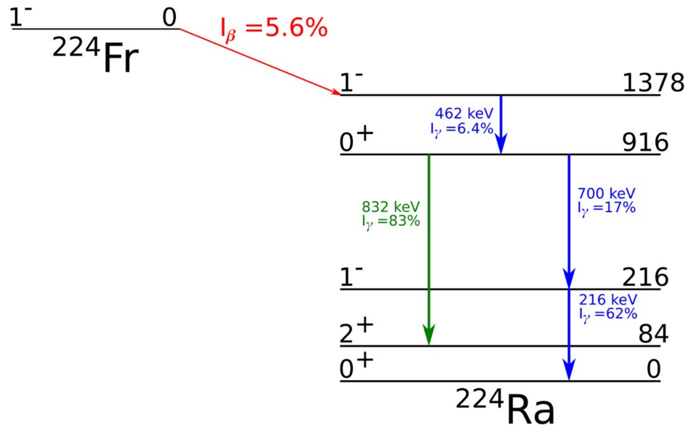




$LaBr_3$ Spectra







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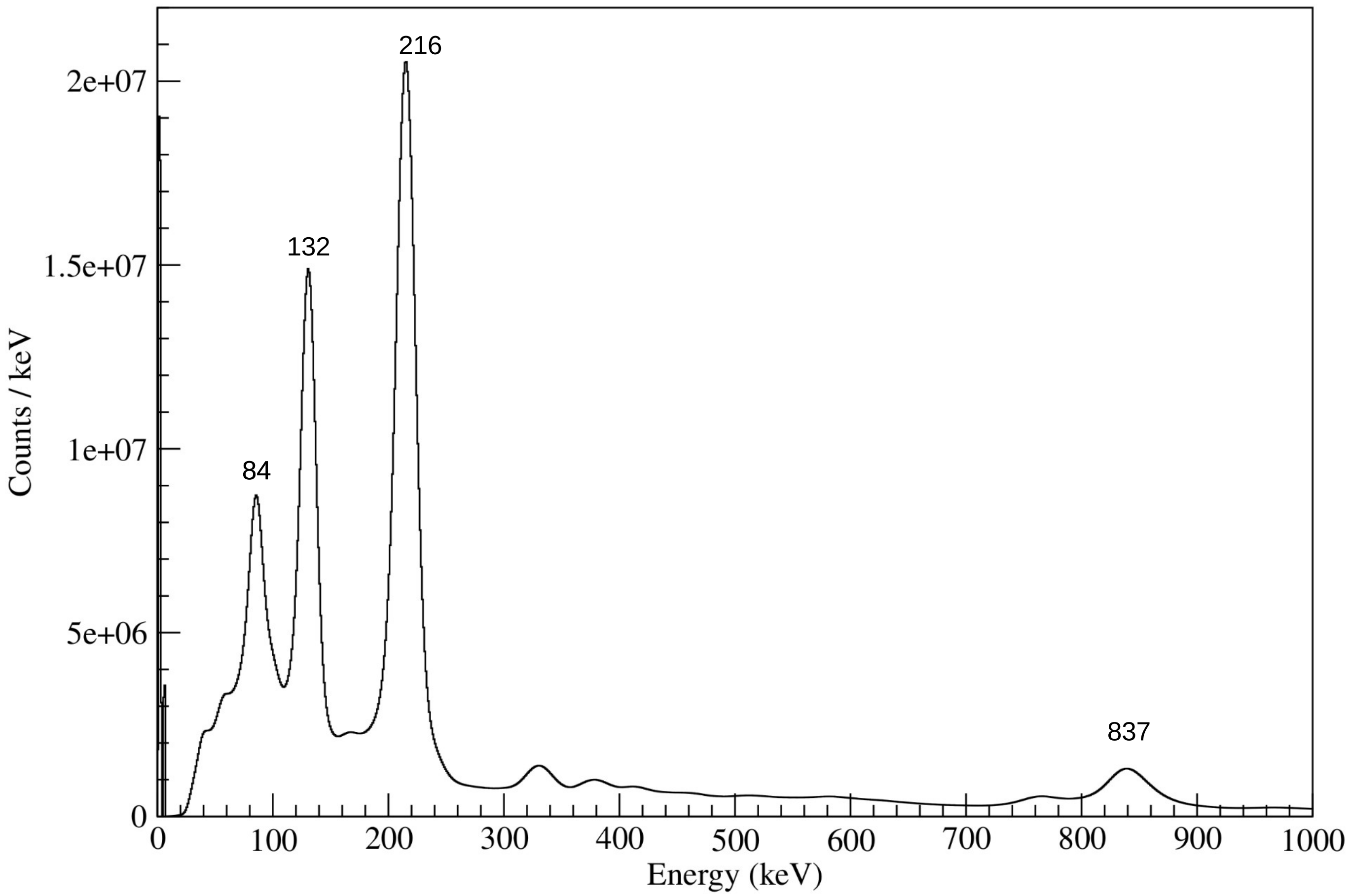
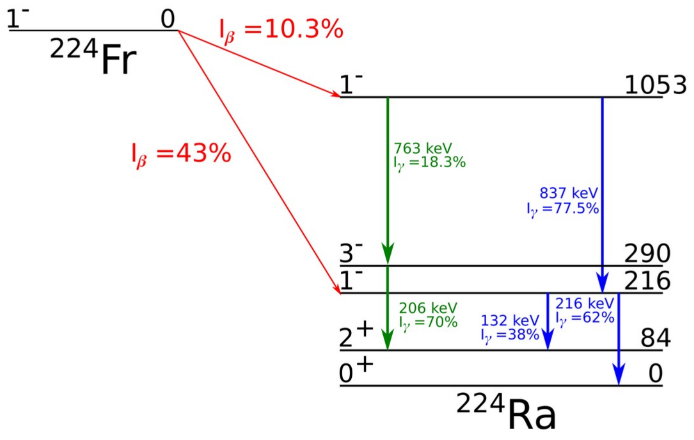
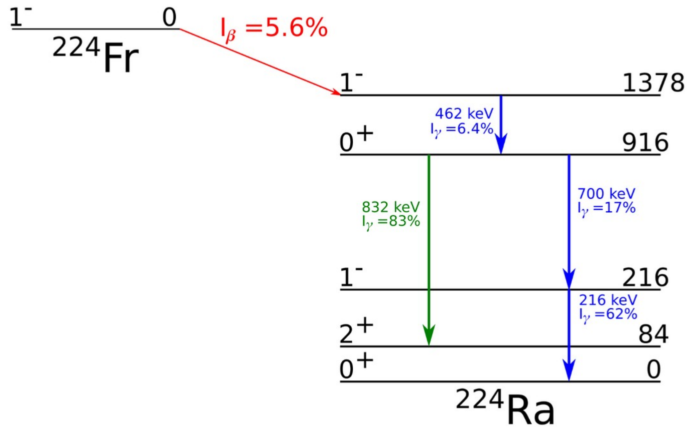






Convolution Method

- Fitting the product of a Gaussian and exponential function to a TAC curve makes it possible to determine the lifetime of the corresponding state.

$$f(x;\mu,\sigma,\lambda) = \frac{\lambda}{2}\exp\left(\frac{\lambda}{2}(2\mu + \lambda\sigma^2 - 2x)\right)\operatorname{erfc}\left(\frac{\mu + \lambda\sigma^2 - x}{\sqrt{2}\sigma}\right)$$

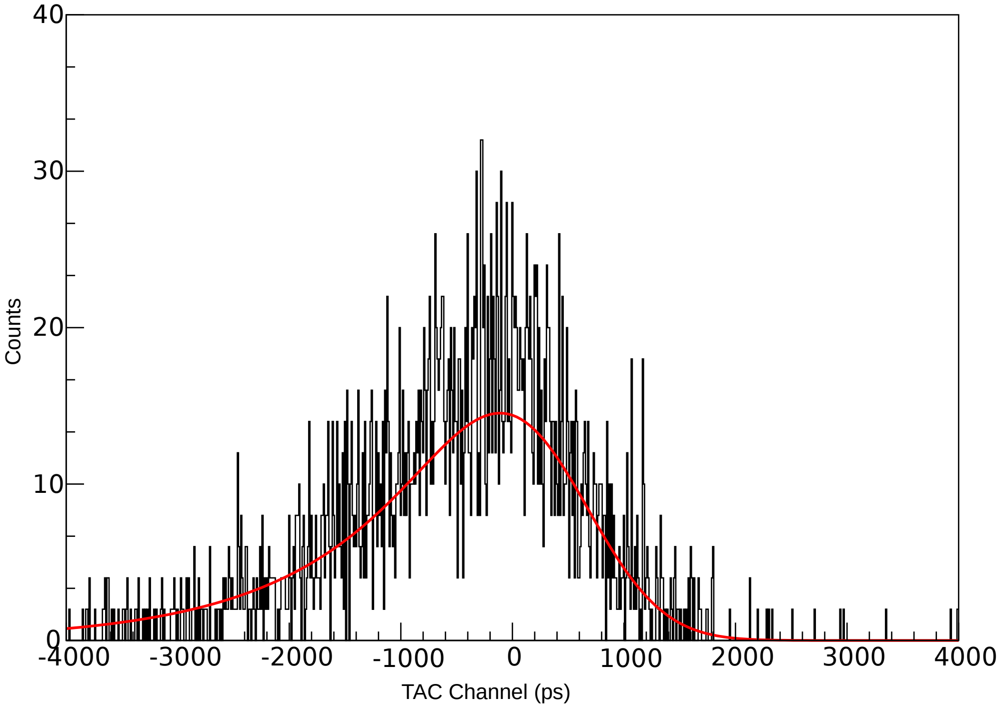
λ = Rate of decay of the exponential.

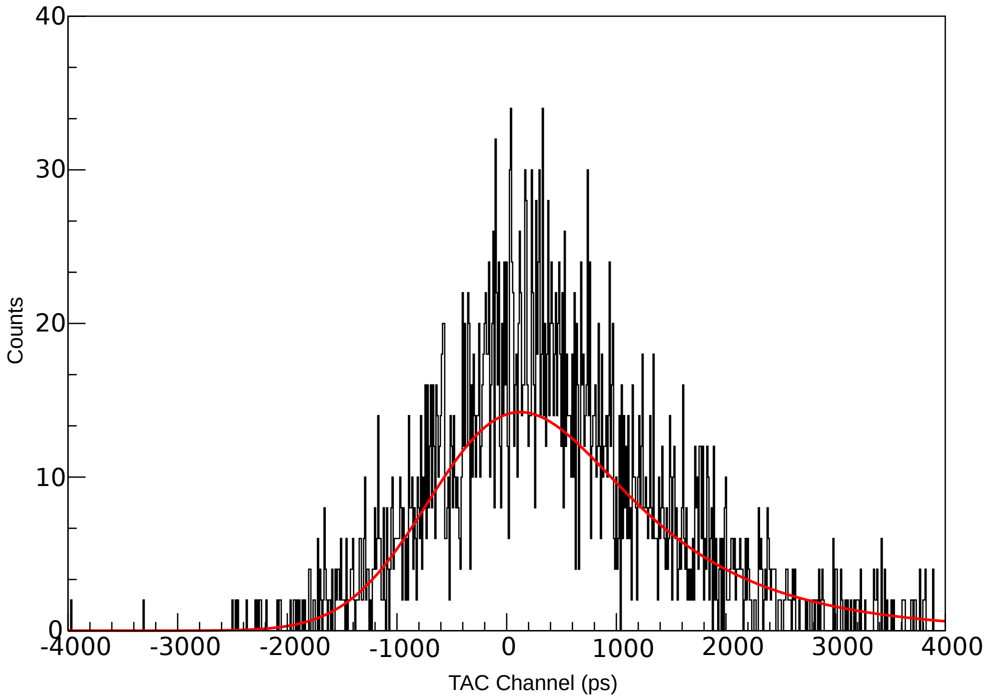
μ = Centroid of the Gaussian

σ^2 = Variance of the Gaussian

$$\begin{aligned}\operatorname{erfc}(x) &= 1 - \operatorname{erf}(x) \\ &= \frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-t^2}\, dt\end{aligned}$$

Preliminary Results: 2^+ State





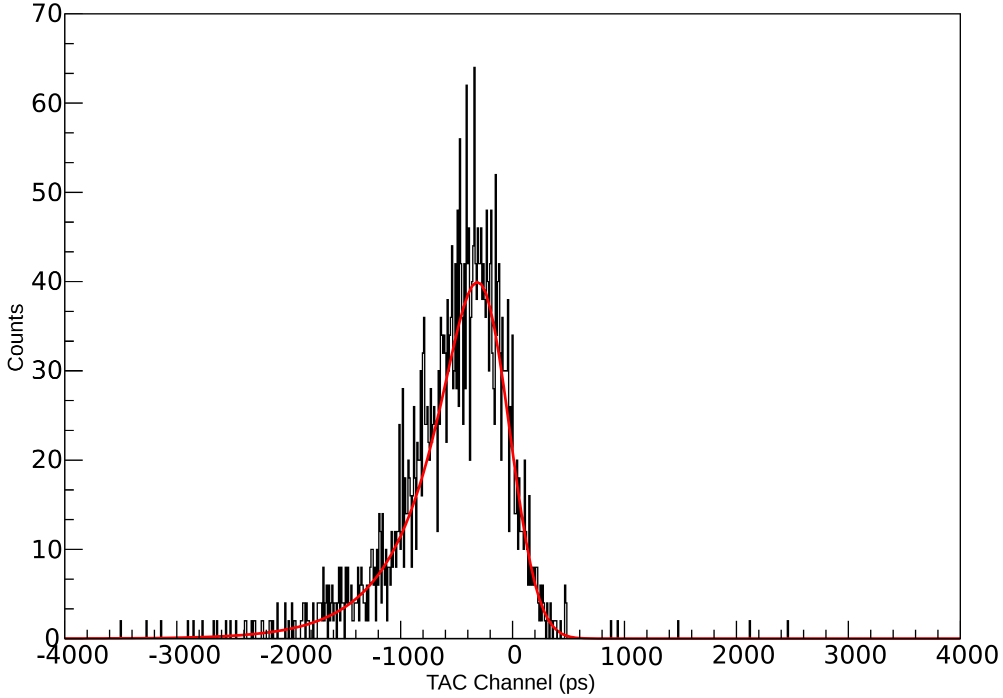
Anti-delayed Lifetime = 1172(65)ps

Delayed Lifetime = 1067(67)ps

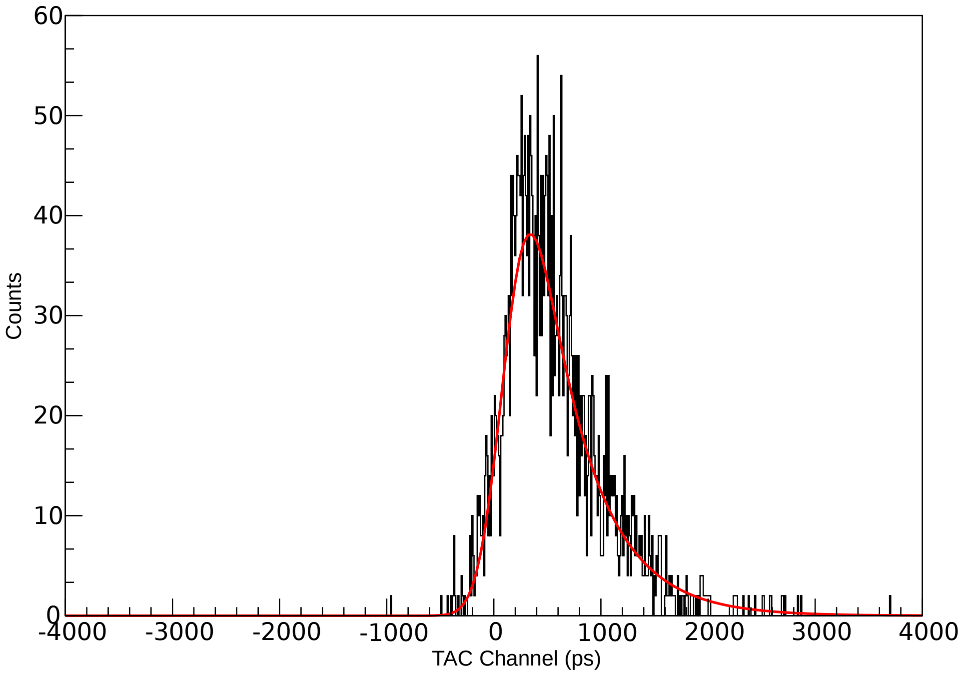
Average Lifetime = 1122(46)ps

NNDC Lifetime = 1079(27)ps

Preliminary Results: 1⁻ State



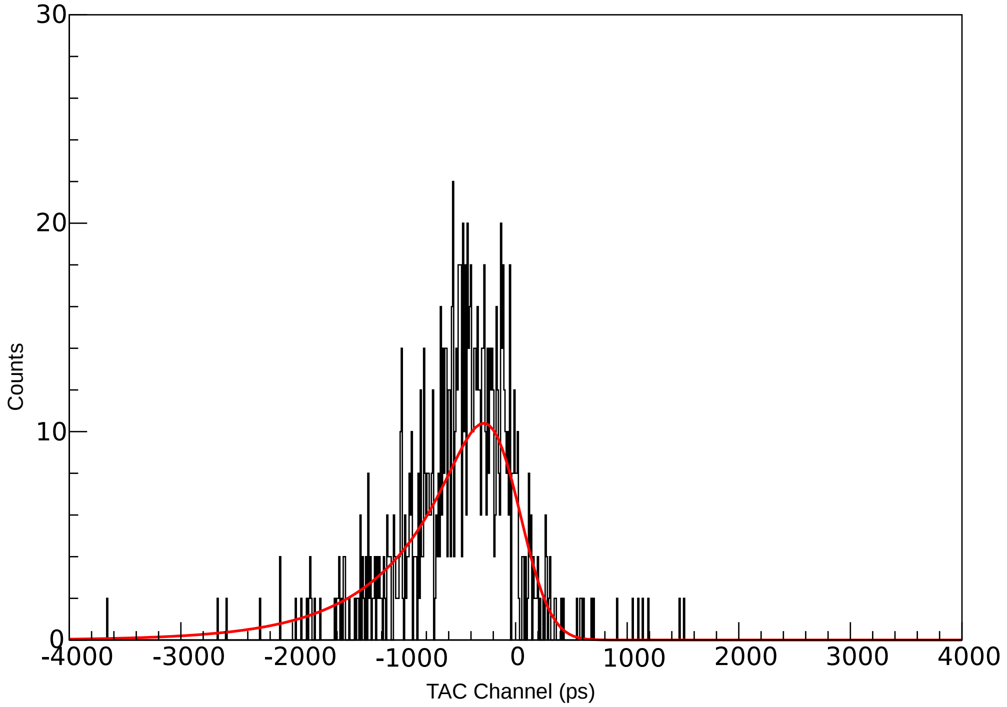
Anti-delayed Lifetime = 472(17)ps



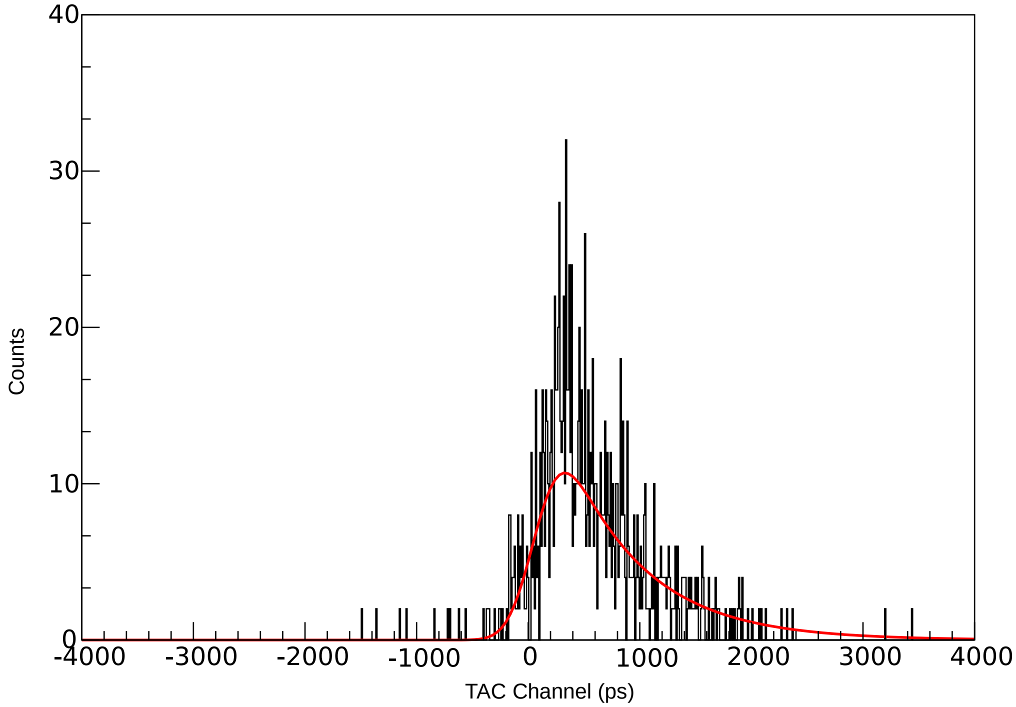
Delayed Lifetime = 421(18)ps

Average Lifetime = 447(12)ps

Preliminary Results: 3^- State



Anti-delayed Lifetime = 649(69)ps



Delayed Lifetime = 699(61)ps

Average Lifetime = 677(46)ps

Preliminary Results

J^{π}	Average Lifetime (ps)	Lifetime Values from literature (ps)
2^+	1122(46)	1079(27) (NNDC)
1^-	447(12)	> 325 (Gaffney et al)
3^-	677(46)	718(313) (Gaffney et al)

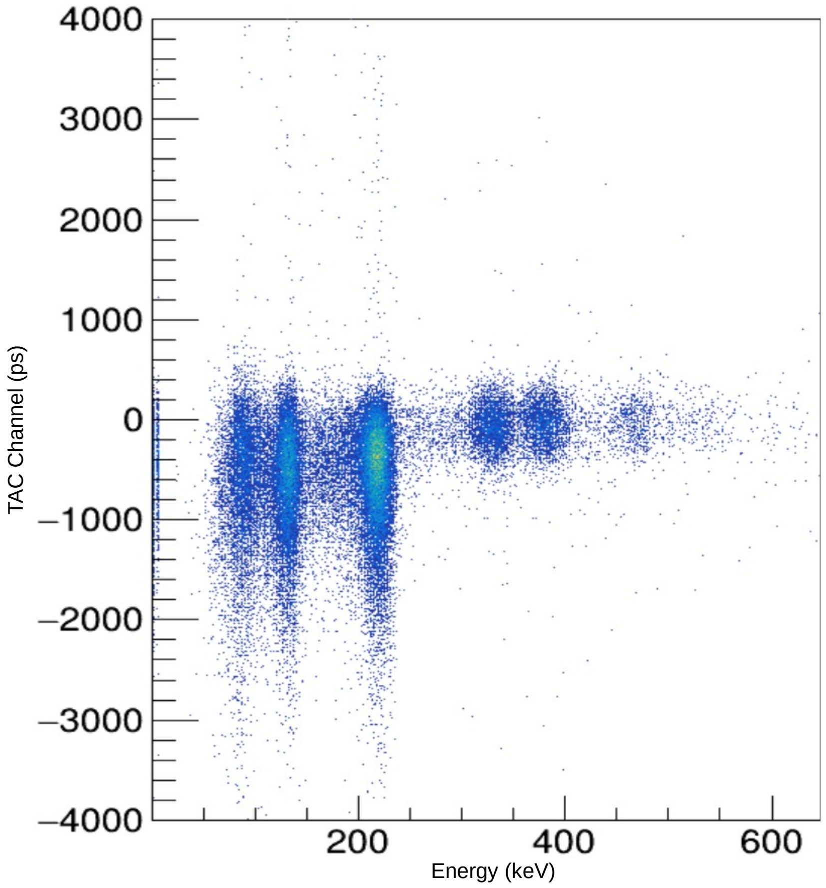
GCD Method

- Used for shorter lived states that have TAC distributions too prompt for the convolution method.

- Fitting the delayed and anti-delayed TAC spectra and then calculating the difference between their centroids allows for calculation of the lifetime.

$$\Delta C(E_1, E_2) = C_D - C_A = PRD(E_1, E_2) + 2\tau$$

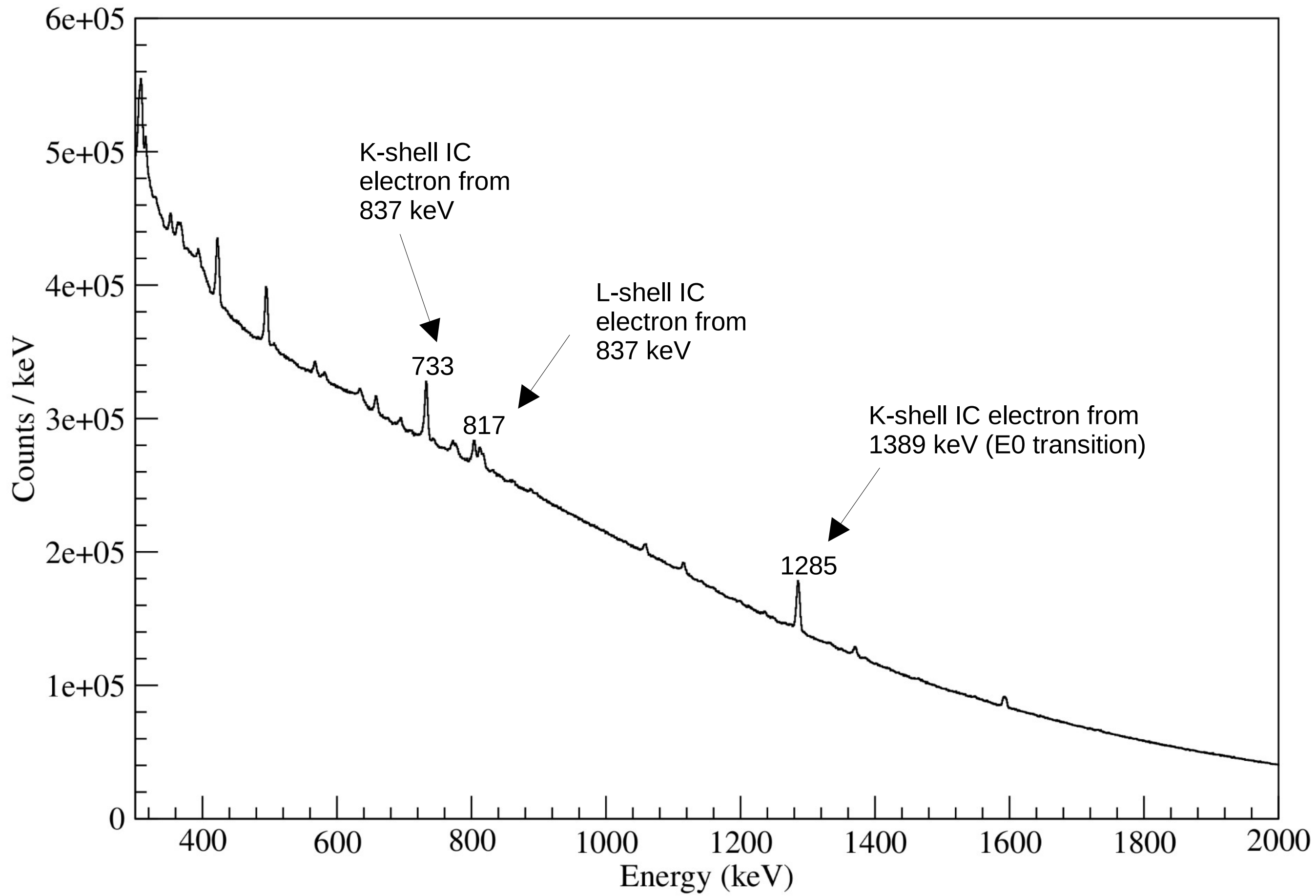
- The prompt response difference allows us to correct for time walk.



Conclusions and Future Work

- Lifetime measurement of the 2^+ state agrees with the accepted value from the NNDC.
- Lifetime measurements of the 1^- and 3^- states agree with Gaffney et al.
- Measure the lifetime of the 0^+ state.
- Use the GCD method to compare results and measure shorter lived states.
- Look for E0 transitions in the PACES spectra.
- Identify unknown transitions from GRIFFIN spectra.

PACES Spectra



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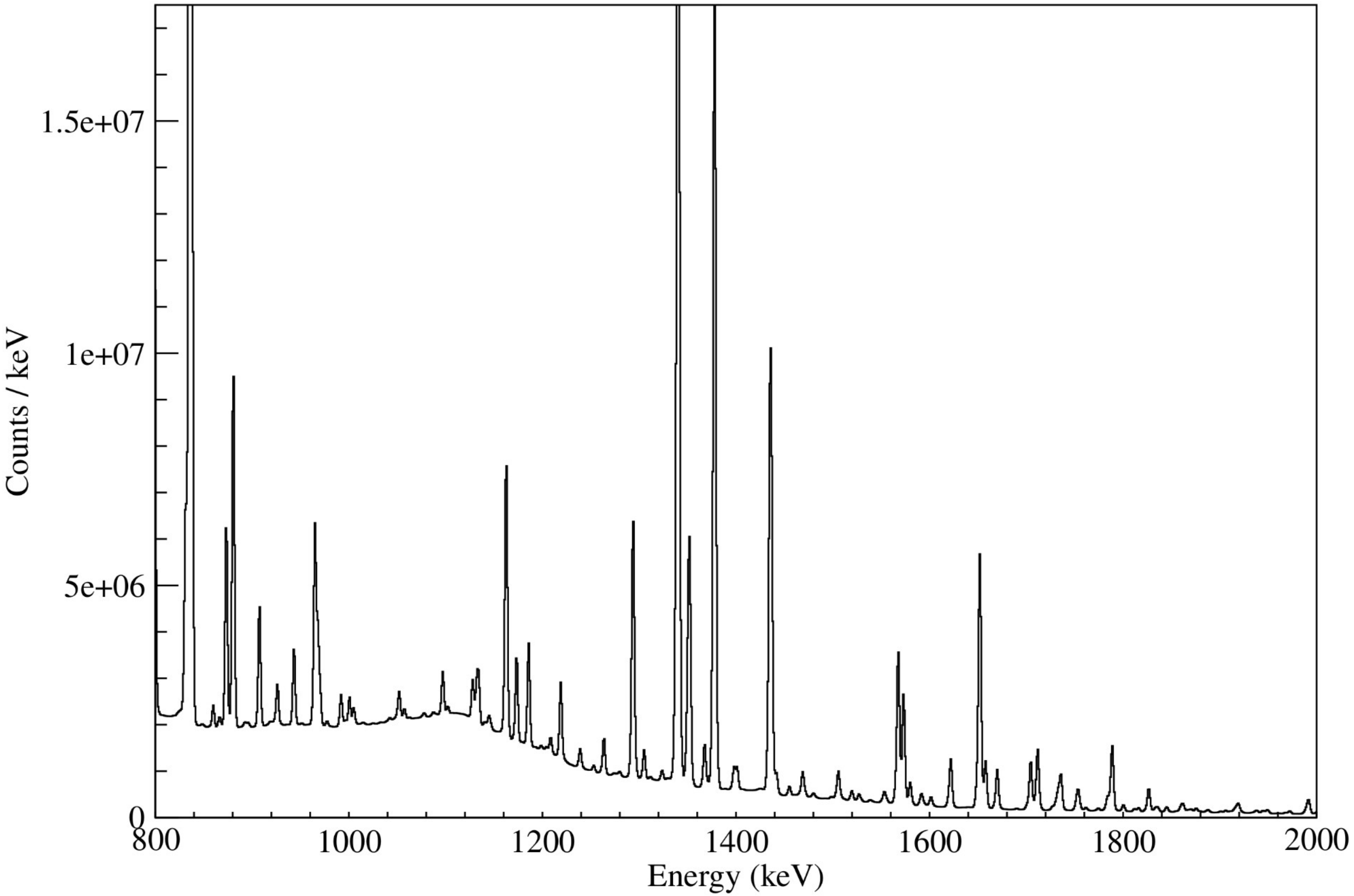
GRIFFIN Spectra



Acknowledgements

- D. O'Donnell[1], A.A. Avaa[2], G. Ball[3], M. Bowry[1], P.A. Butler[3], A. Garnsworthy[2], S. Georges[2], L.P. Gaffney[3], P. Jones[4], F. Liu[3], S.M. Morales[5], J.R. Murias[2], B. Olaizola[6], F. Rowntree[3], P. Spagnoletti[3], C. Svensson[2].

1. University of the West of Scotland, United Kingdom
2. TRIUMF
3. University of Liverpool, United Kingdom
4. iThemba Labs, Johannesburg, South Africa
5. Universidad Complutense, Madrid, Spain
6. CSIC

Thanks for listening

Preliminary Results

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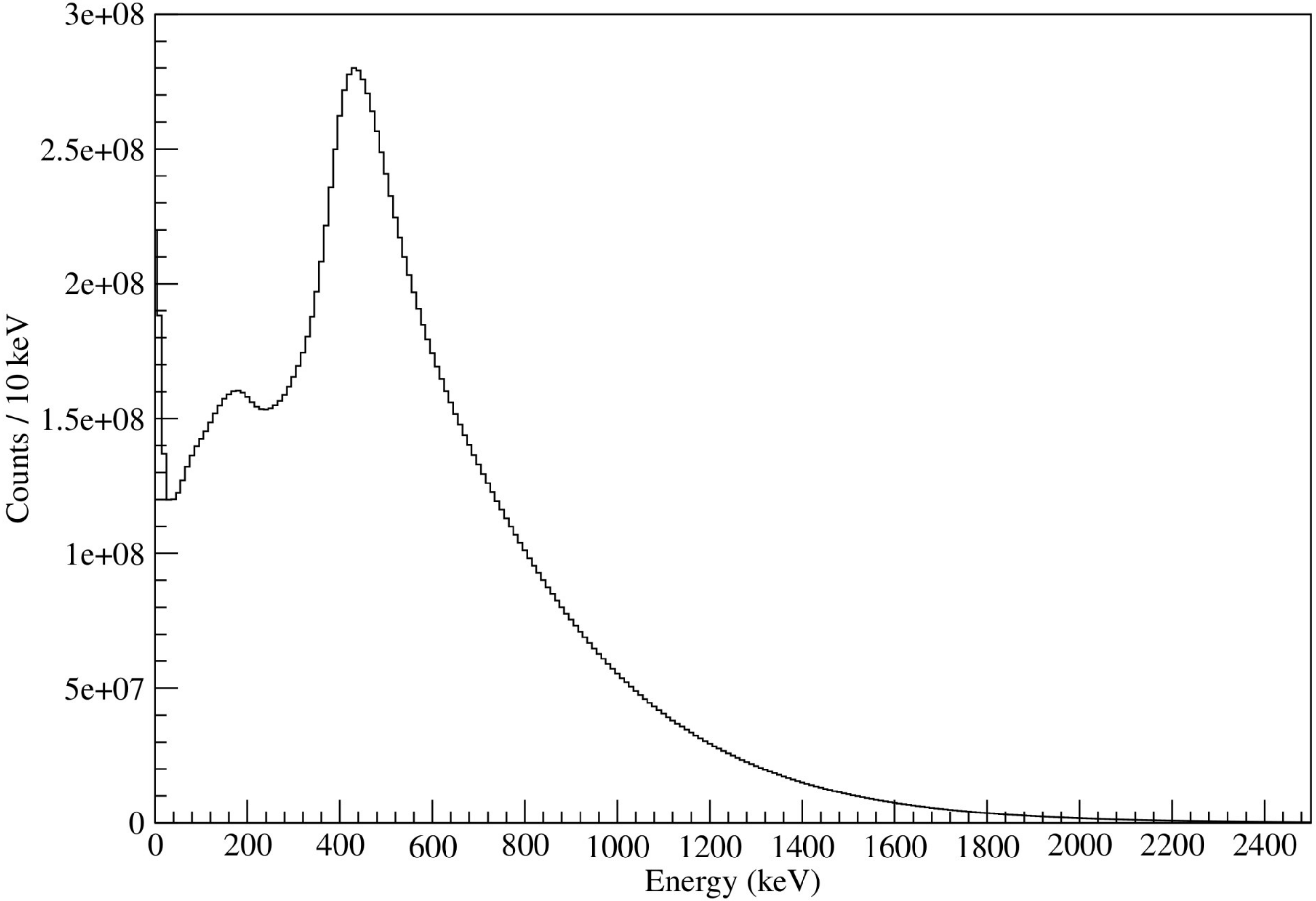
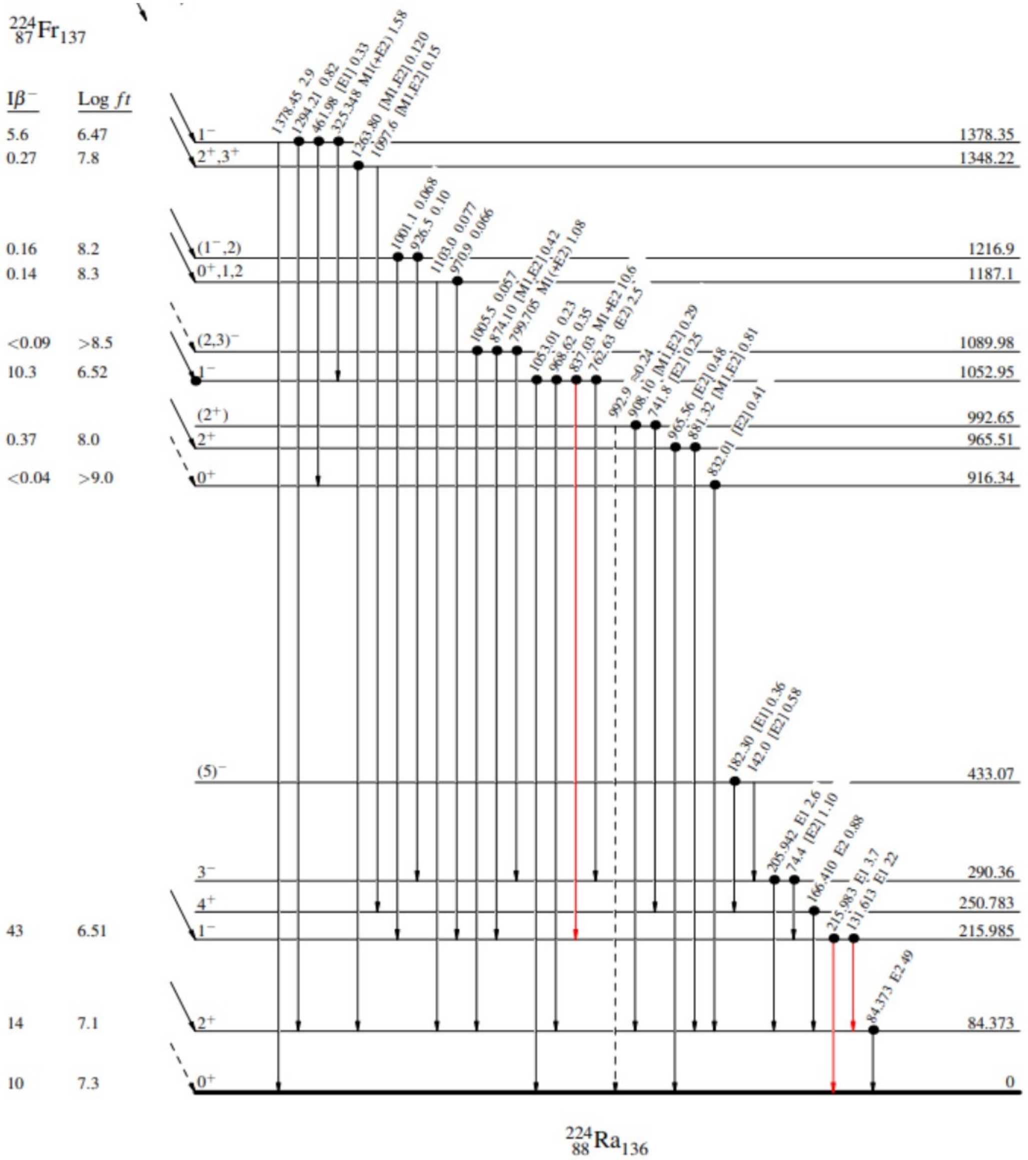
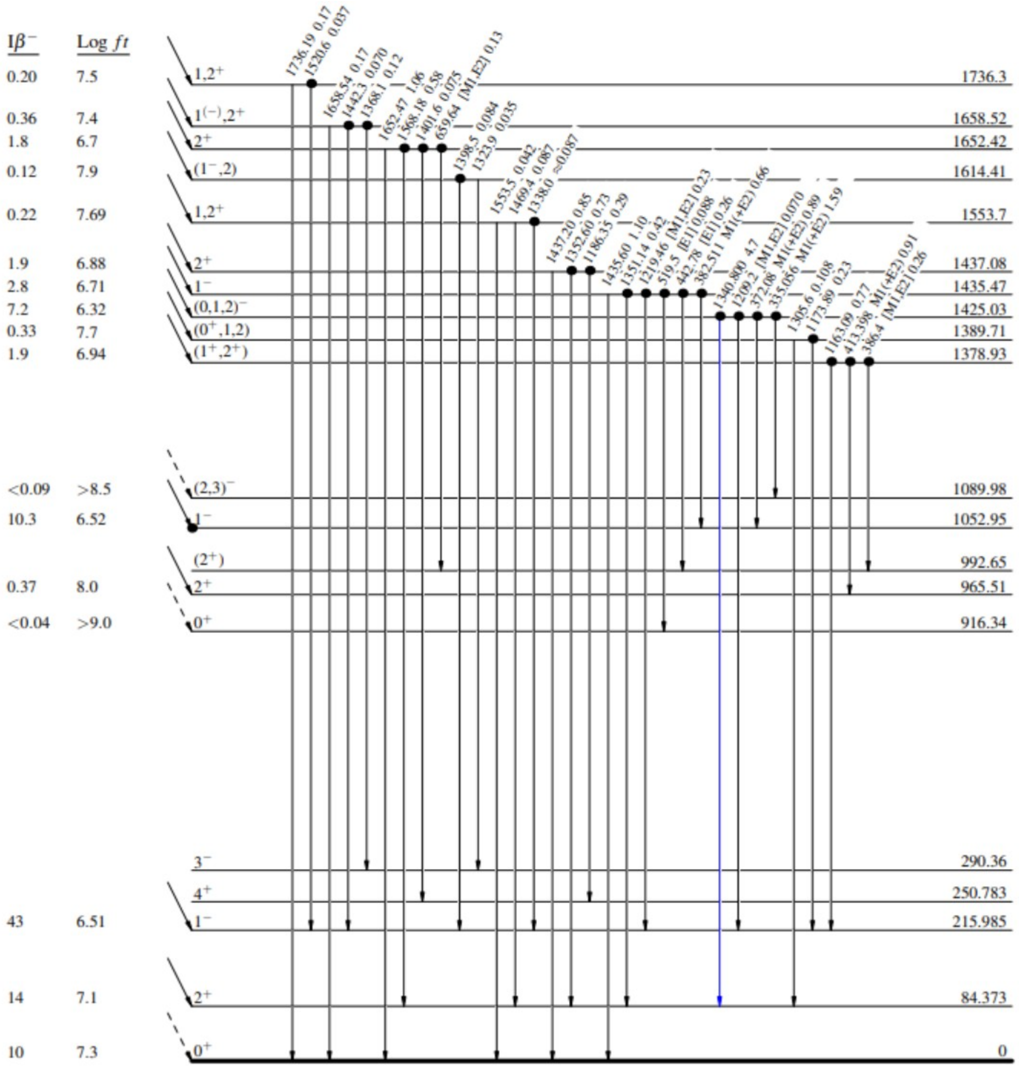
ZDS Spectra



3e+08
2.5e+08
2e+08
1.5e+08
1e+08
5e+07
0
Counts / 10 keV
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Energy (keV)



$^{224}_{87}Fr_{137}$
Iβ⁻
Log ft
1⁻ 1378.35
2⁺,3⁺ 1348.22
(1⁻,2) 1216.9
0⁺,1,2 1187.1
(2,3)⁻ 1089.98
1⁻ 1052.95
(2⁺) 992.65
2⁺ 965.51
0⁺ 916.34
(5)⁻ 433.07
3⁻ 290.36
4⁺ 250.783
1⁻ 215.985
2⁺ 84.373
0⁺ 0
$^{224}_{88}Ra_{136}$


Iβ⁻
Log ft
0.20 7.5 1,2+ 1736.3
0.36 7.4 1(−),2+ 1658.52
1.8 6.7 2+ 1652.42
0.12 7.9 (1−,2) 1614.41
0.22 7.69 1,2+ 1553.7
1.9 6.88 2+ 1437.08
2.8 6.71 1− 1435.47
7.2 6.32 (0,1,2)− 1425.03
0.33 7.7 (0+,1,2) 1389.71
1.9 6.94 (1+,2+) 1378.93
<0.09 >8.5 (2,3)− 1089.98
10.3 6.52 1− 1052.95
(2+) 992.65
0.37 8.0 2+ 965.51
<0.04 >9.0 0+ 916.34
3− 290.36
4+ 250.783
43 6.51 1− 215.985
14 7.1 2+ 84.373
10 7.3 0+ 0
1736.19 0.17
1520.6 0.037
1658.54 0.17
1442.3 0.070
1368.1 0.12
1652.47 1.06
1568.18 0.58
1401.6 0.075
659.64 [M1,E2] 0.13
1398.5 0.084
1323.9 0.035
1553.5 0.042
1469.4 0.087
1338.0 ≈0.087
1437.20 0.85
1352.60 0.73
1186.35 0.29
1435.60 1.10
1351.14 0.42
1219.46 [M1,E2] 0.23
519.5 [E1] 0.088
442.78 [E1] 0.26
382.511 M1(+E2) 0.66
1340.800 4.7
1209.2 [M1,E2] 0.070
372.08 M1(+E2) 0.89
335.056 M1(+E2) 1.59
1305.6 0.108
1173.89 0.23
1163.09 0.77
413.398 M1(+E2) 0.91
386.4 [M1,E2] 0.26

$^{224}_{88}Ra_{136}$