The Experimental Study of Shape Coexistence in ^{114}Sn via GRIFFIN

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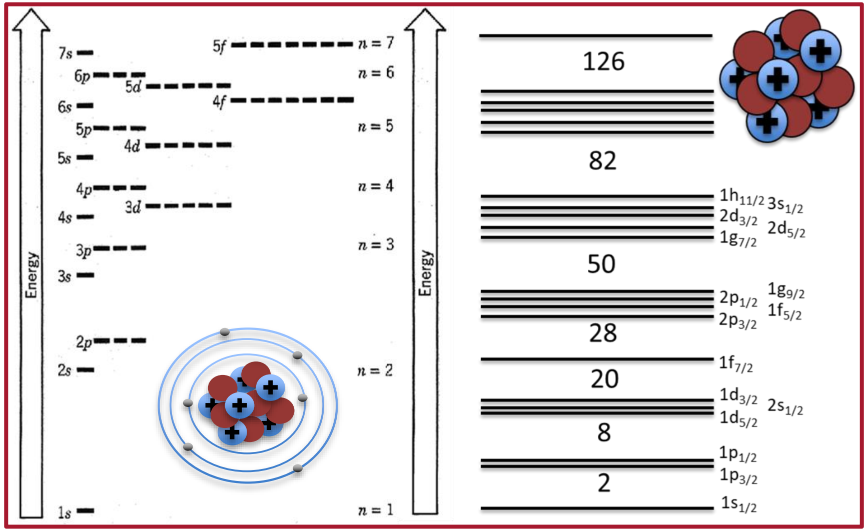
Shell Model and "Magic" Nuclei

- Nucleons arranged in respective *shells*
- Filled valence shells are associated with increased stability
  - "**Doubly- / Singly-Magic**"
- "**Magic**" nuclei characteristically spherical in ground state

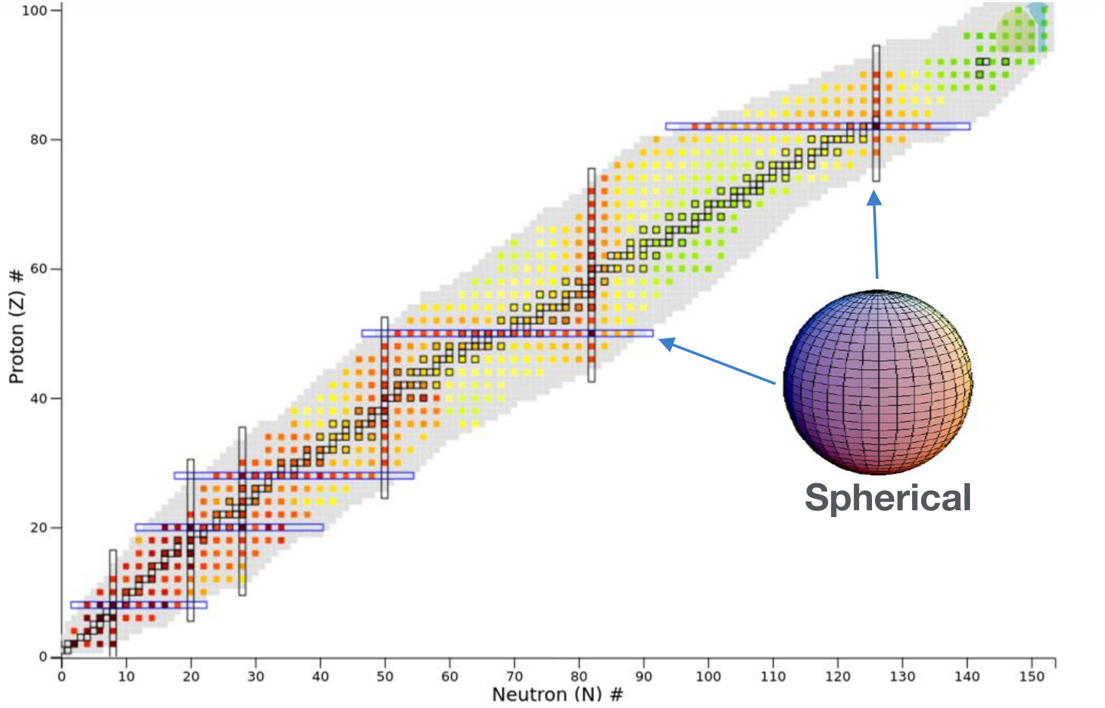
ELECTRONS NUCLEONS



Atomic properties attributed to valence **electrons**

Nuclear properties attributed to interactions between valence **nucleons**

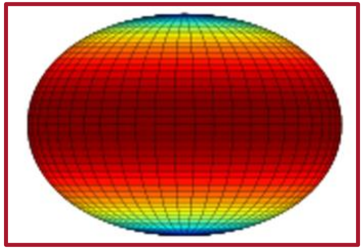
Quadrupole Deformation



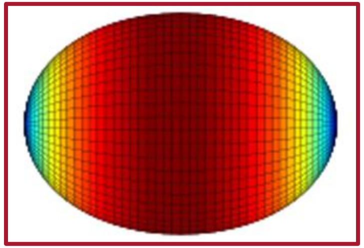
Excitation energy of the 2_1^+ state in even-even nuclei from NNDC NuDat

Spherical

Oblate (earth)



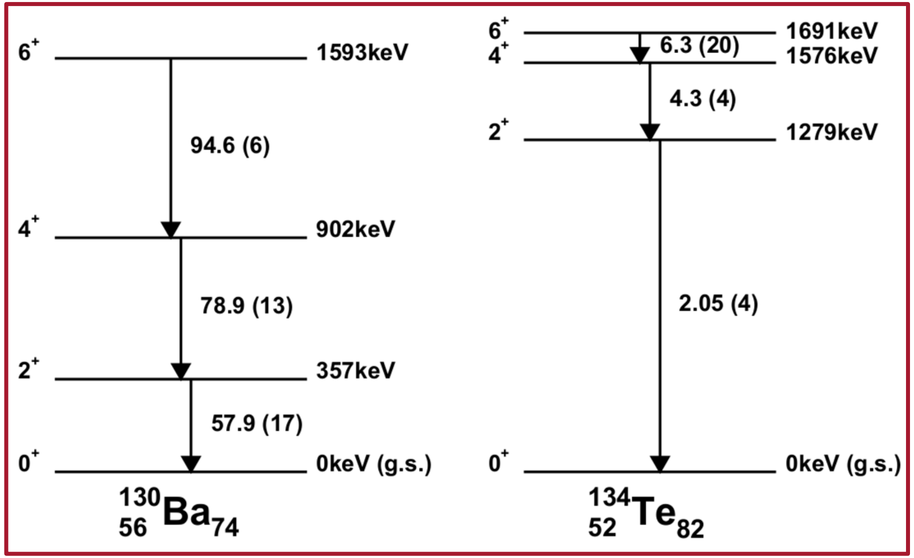
Prolate (rugby ball)



Signatures of Nuclear Shape: B(E2)

- Non-magic ^{130}Ba shows highly collective excitations
  - **High B(E2)** values
  - Indicative of the **rotational band** and deformed nuclear shape

- Singly-magic ^{134}Te shows non-collective excitations
  - Low B(E2) values
  - Seniority scheme implies sphericity

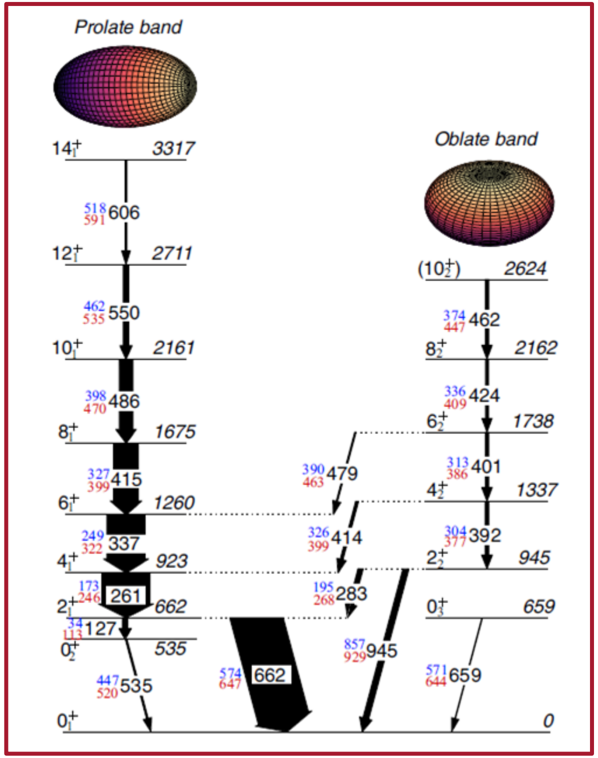


Rotational Band

Seniority Scheme

^{186}Pb and Shape Coexistence

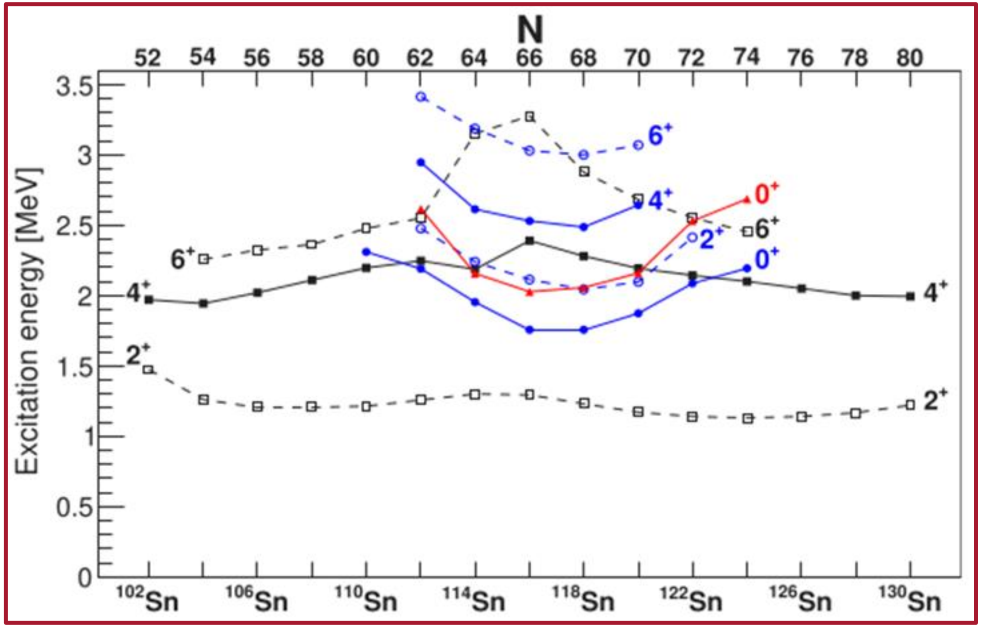
- Z=82 closed proton shell implying spherical shape in g.s.
- **Shape coexistence** is Two or more states having distinct properties and different intrinsic shapes within a narrow energy range
  - Characterized by **rotational bands** of excited states allowed by deformed shapes (prolate & oblate, etc.)



Ojala, J. *et al.* Reassigning the shapes of the 0+ states in the ^{186}Pb nucleus. *Commun Phys* 5, 213 (2022)

Shape Coexistence in Sn Isotopes

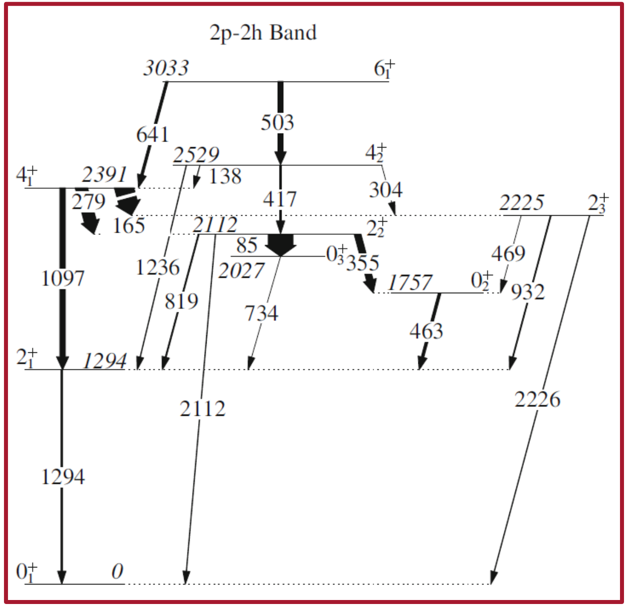
- Closed proton shell @ Z=50
- Near spherical g.s.
- First excited 2^+ corresponds to a non-collective breaking of neutron-pair
  - Excitation E ≈ 1.3 MeV
  - Low $B(E2;2_1^+\rightarrow 0_1^+)$
- Mid-shell rotational band built upon 2p-2h configuration
  - Hypothesised to be built upon 0_2^+ state (blue)



Garrett P. E. *et al.* An experimental view on shape coexistence in nuclei. *Progress in Particle and Nuclear Physics* 124, (2022), 103931

^{116}Sn Shape Coexistence

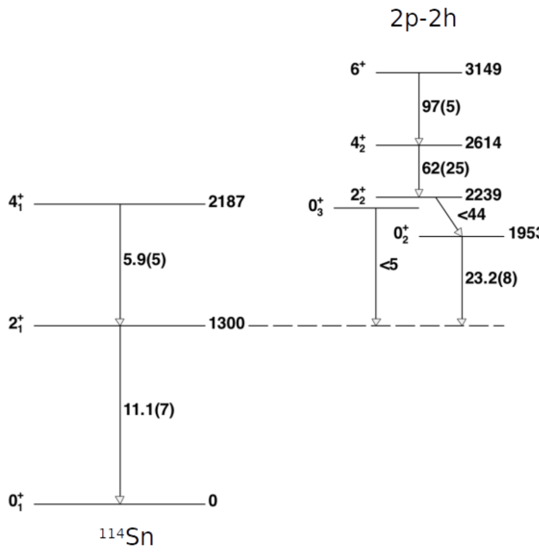
- Findings from Pore et. al (2016) regarding ^{116}Sn suggest a reevaluation of the head of the 2p-2h band within this nucleus
  - $B(E2;2^+_2\rightarrow0^+_3) / B(E2;2^+_2\rightarrow0^+_2) \approx 2.2$
  - Based upon intensity measurement of very weak 85-keV transition



E_{level} (keV)	$T_{1/2}$ ref. [5]	$J^\pi_i \rightarrow J^\pi_f$	E_γ (keV)	I_γ	BR_γ	$B(E2)$ (W.u.)
2112.19(14)	1.89(10) ps	$2^+_2 \rightarrow 0^+_3$	85.294(88)	0.00166(10)	0.0091(6)	99.7(84)
		$2^+_2 \rightarrow 0^+_2$	355.432(18)	0.939(23)	5.16(14)	44.4(28)

A Case for ^{114}Sn Inquiry

- ^{114}Sn level scheme is highly similar to that of ^{116}Sn and other mid-shell Tin isotopes
  - Missing observation of key $2_2^+ \rightarrow 0_3^+$ transition
- No established lifetime or branching ratios from 2_2^+ state of interest
  - Existing lifetime lower limit of $\tau > 2.1$ ps
- Most recent β-decay study of ^{114}Sb→^{114}Sn was M. E. J. Wigmans et. Al, Phys. Rev. C **14**, 229 (1976)

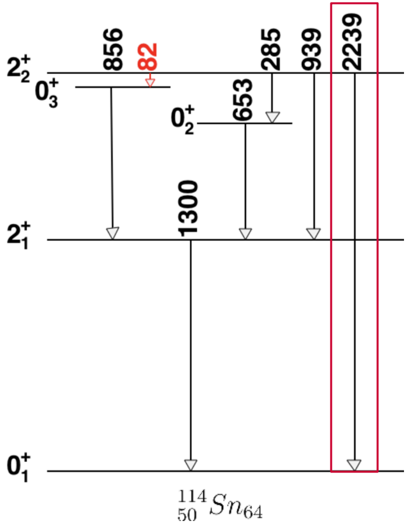


Challenge of the 82-keV Transition

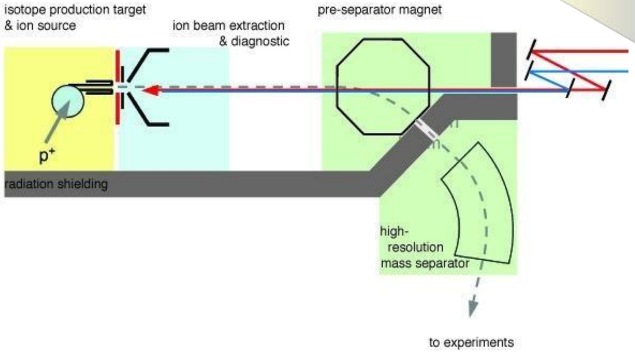
$$\frac{\lambda(2_2^+ \rightarrow 0_3^+)}{\lambda(2_2^+ \rightarrow 0_1^+)} = \left[\frac{E_\gamma(2_2^+ \rightarrow 0_3^+)}{E_\gamma 2_2^+ \rightarrow 0_1^+)}\right]^5 = \left[\frac{82keV}{2239keV}\right]^5 = 6.6 \times 10^{-8}$$

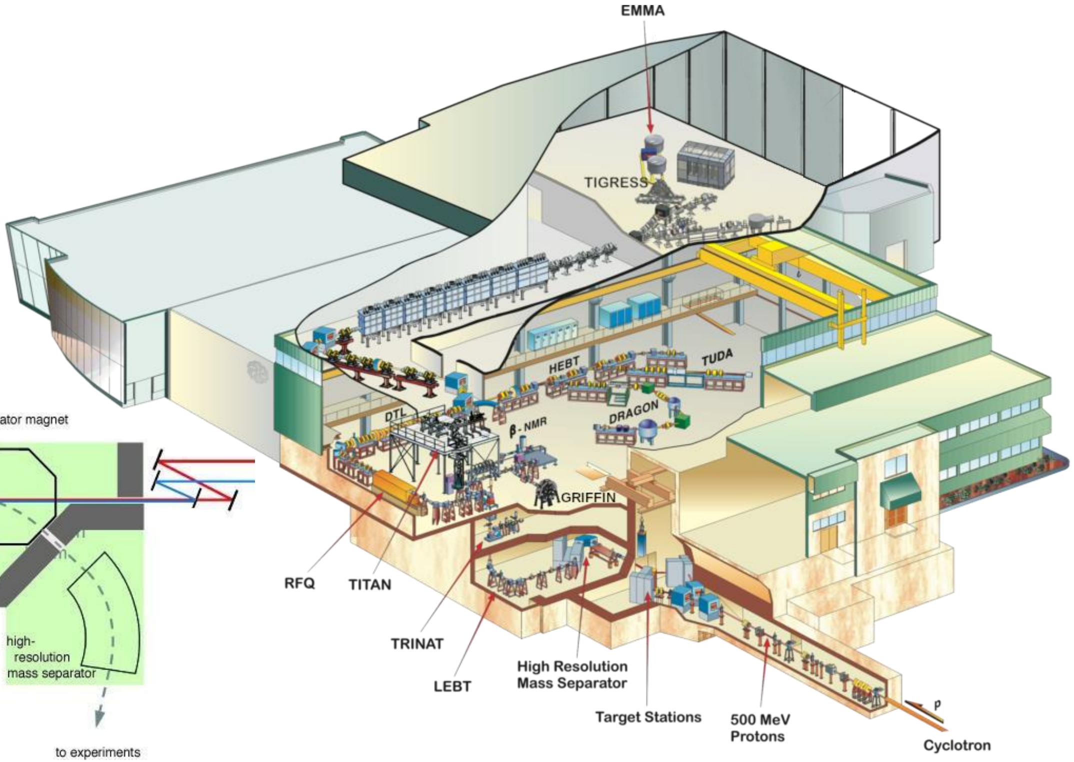
Eqn. 1 – Decay rate ratio of competing $2_2^+ \rightarrow 0_3^+$(82keV) to $2_2^+ \rightarrow 0_1^+$(2239keV) transitions via single particle estimate

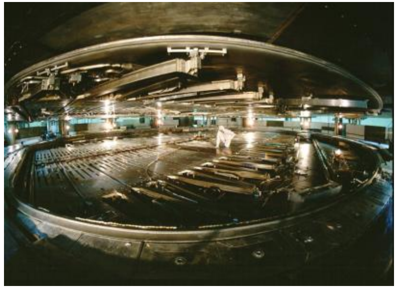
- For E2 transitions, transition rate is proportional to E_γ^5
- Energetic favourability of 2239-keV transition depopulating the 2_2^+ state is predicted to occur 1.52 x10^7 times for each 82-keV transition
- If consistent with Pore et. al's measurements the relative intensity of the 82-keV transition is predicted to be increased by a factor of 10^3



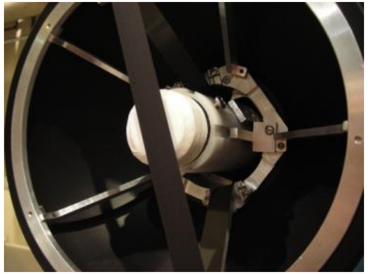
ISAC @ TRIUMF

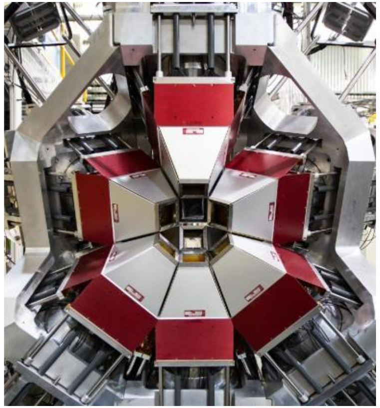

isotope production target
& ion source
ion beam extraction
& diagnostic
pre-separator magnet
p+
radiation shielding
high-
resolution
mass separator
to experiments


EMMA
TIGRESS
HEBT
TUDA
DTL
β - NMR
DRAGON
GRIFFIN
RFQ
TITAN
TRINAT
LEBT
High Resolution
Mass Separator
Target Stations
500 MeV
Protons
p
Cyclotron



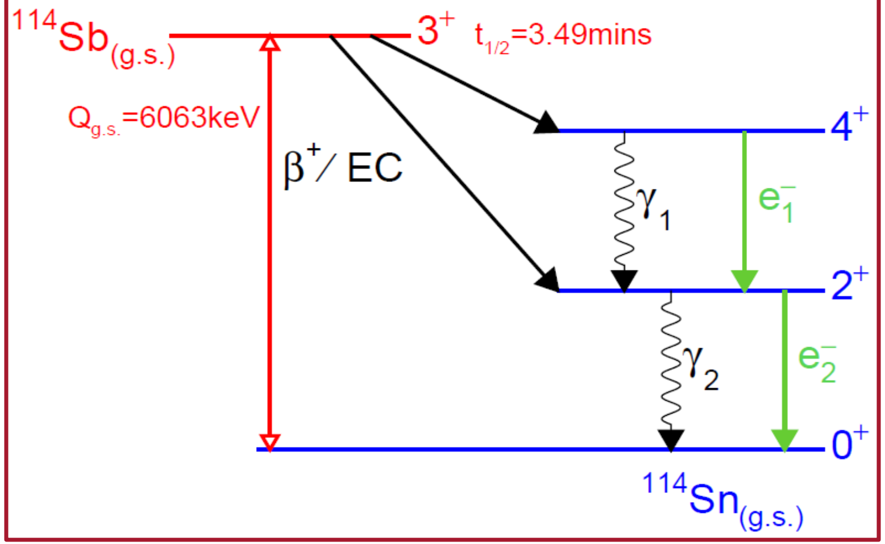
GRIFFIN Spectrometer

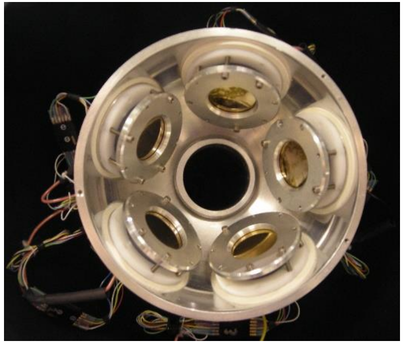




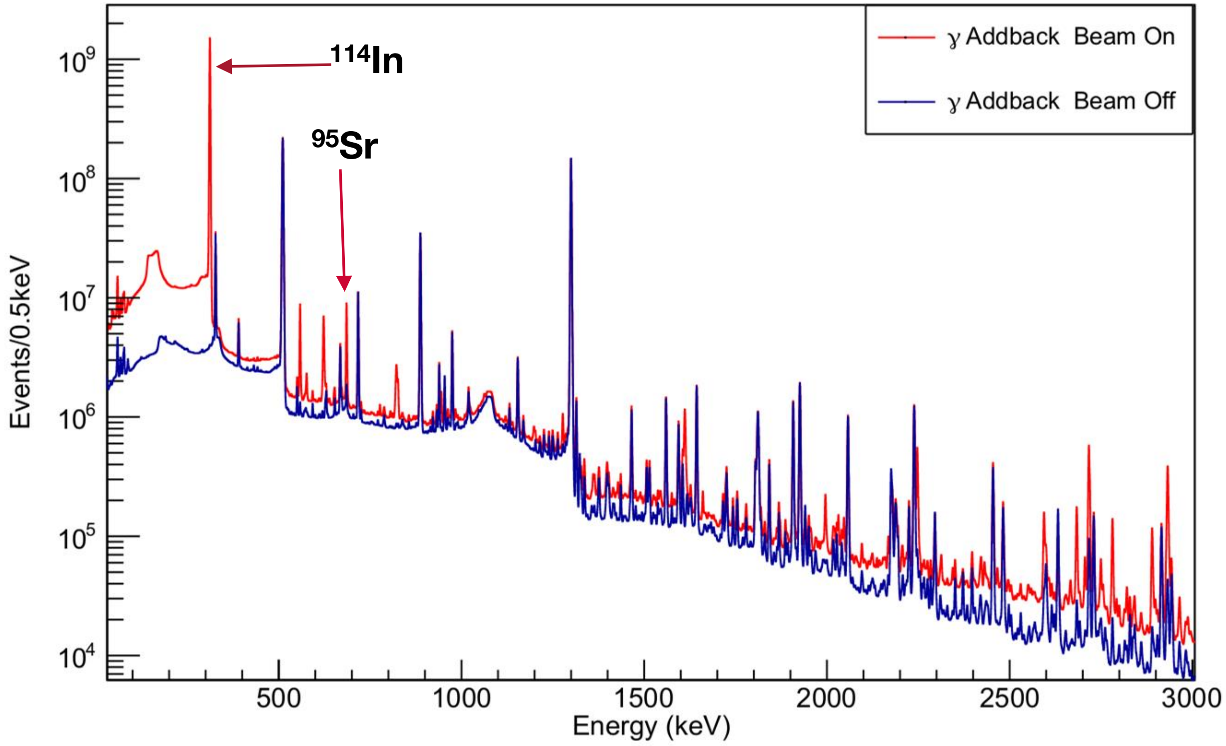
$$\beta^+ : \; {}^{114}_{51}\mathrm{Sb}_{63} \rightarrow {}^{114}_{50}\mathrm{Sn}^*_{64} + \beta^+ + \nu_e$$

$$\mathrm{EC} : \; {}^{114}_{51}\mathrm{Sb}_{63} + e^- \rightarrow {}^{114}_{50}\mathrm{Sn}^*_{64} + \nu_e$$





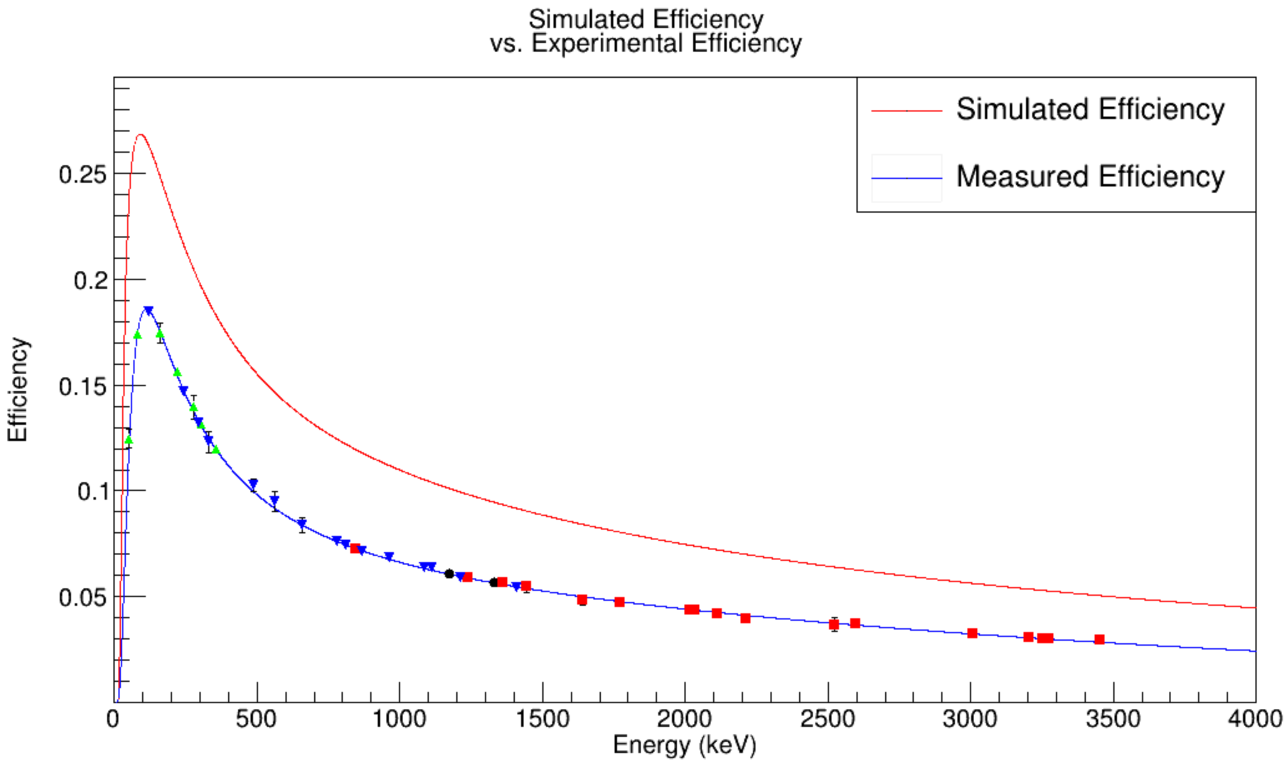
γ-Events



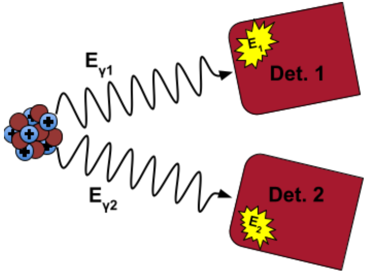
- High intensity of ^{114}In imposed significant limitations on DAQ

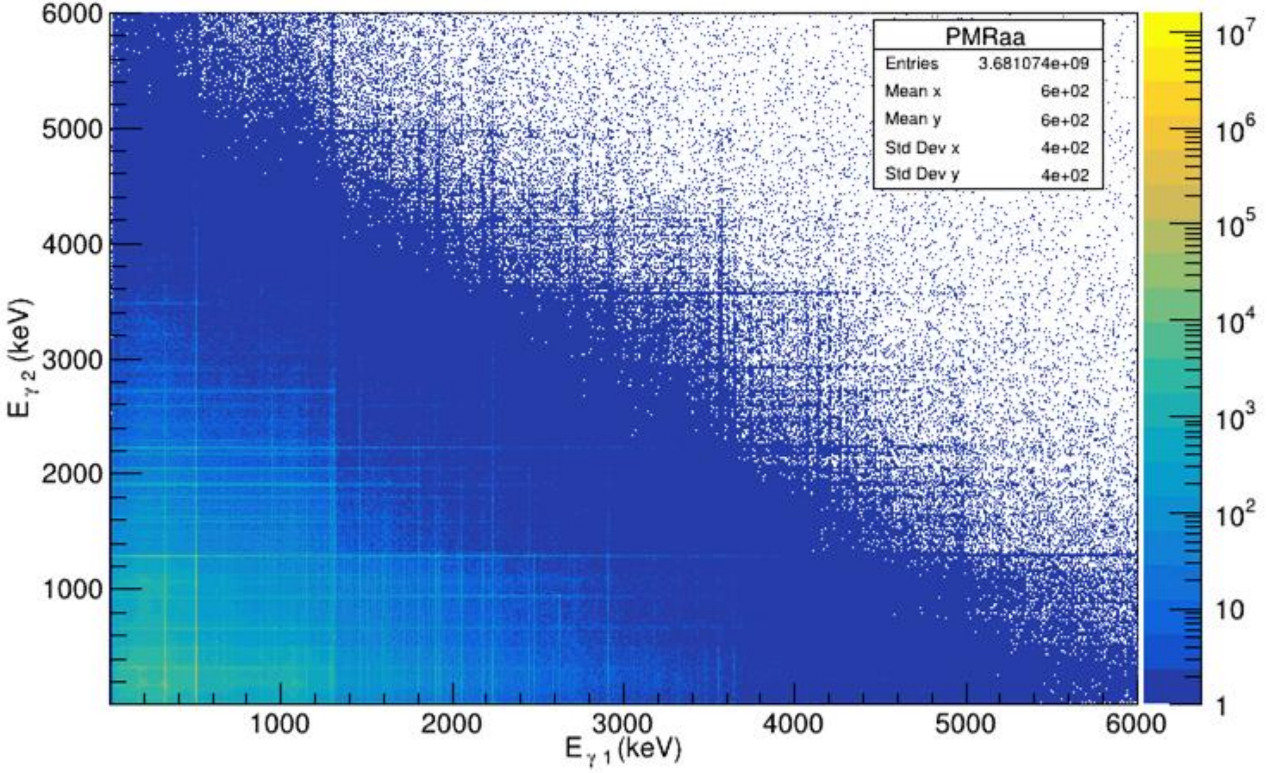
	Proposal	Experiment
Beam Intensity	1.0E6 pps	5.0E5 pps
$\mathbf{t_{implantation}}$	2100 s	390 s
$\mathbf{t_{decay}}$	210 s	390 s

γ-Efficiency

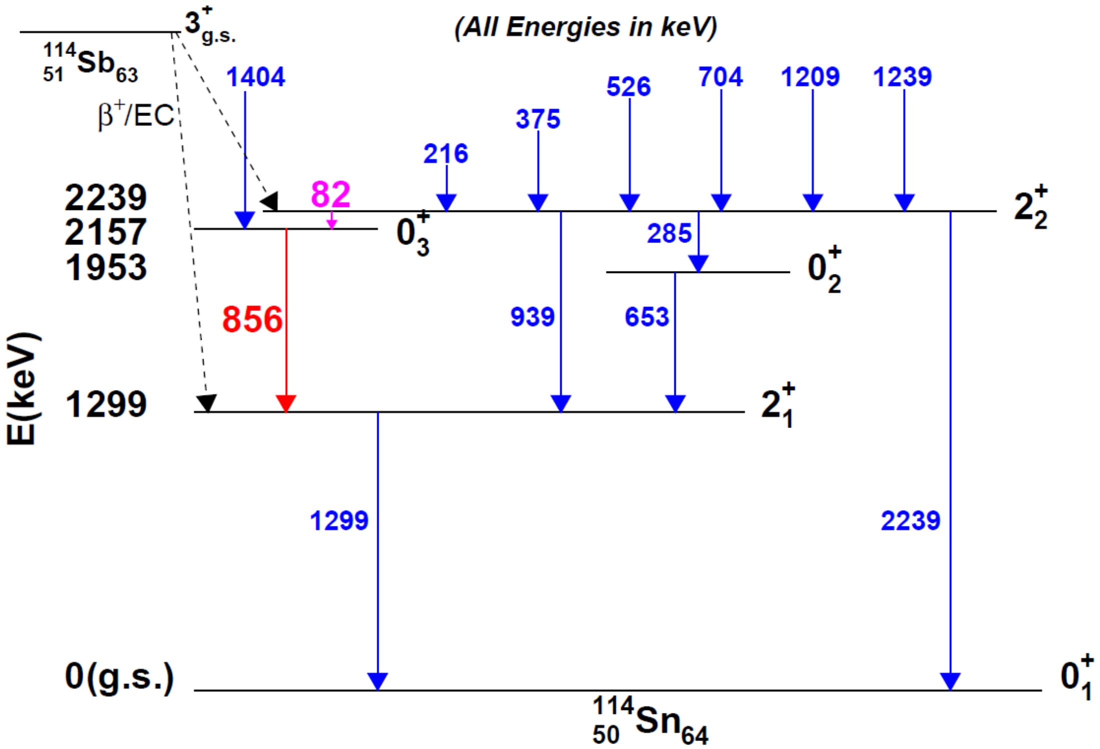


γ-γ Coincidence

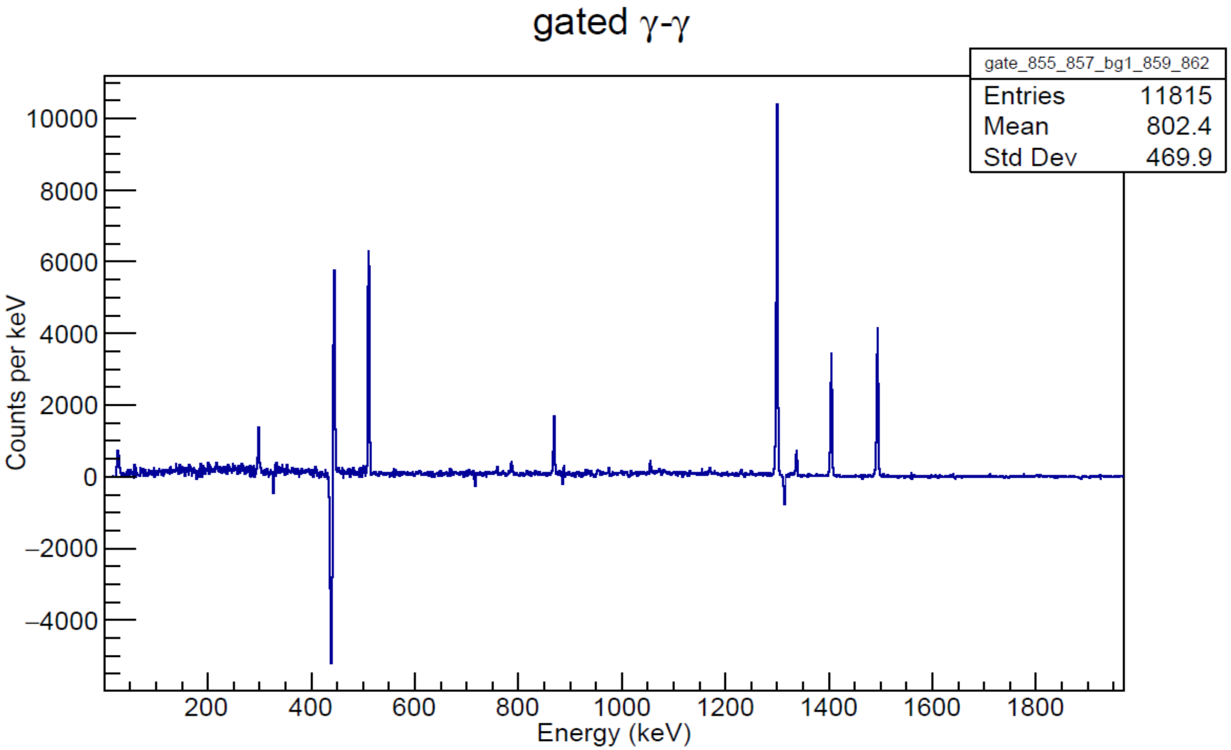




Partial Level Scheme of ^{114}Sn

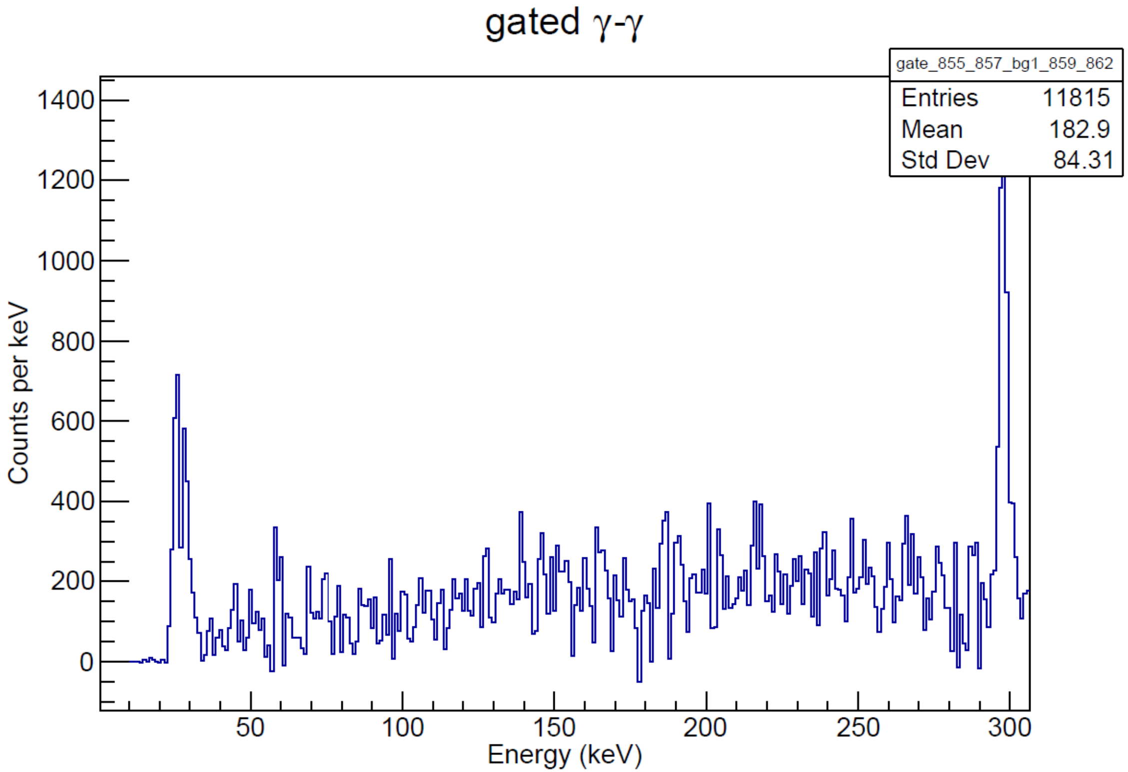


856-keV Gate



gated γ-γ
gate_855_857_bg1_859_862
Entries 11815
Mean 802.4
Std Dev 469.9
Counts per keV
10000
8000
6000
4000
2000
0
−2000
−4000
200
400
600
800
1000
1200
1400
1600
1800
Energy (keV)

856-keV Gate (zoom)



Conclusions and Outlook

- $^{114}Sn^{*}$ populated via ^{114}Sb decay to GRIFFIN w/ intensity of 5E5 pps over ~48 hour experiment
- 5.7 TB of data collected over ~48 hours of beam-time
- Preliminary analysis of γ-γ coincidences did not observe the weak $2^+_2 \rightarrow 0^+_3$ transition
  - Established the **upper limit $B(E2;2^+_2 \rightarrow 0^+_3) / B(E2;2^+_2 \rightarrow 0^+_2) \leq 10$**
  - Established **upper limit on Branching ratio $(2^+_2 \rightarrow 0^+_3) / (2^+_2 \rightarrow 0^+_2) \leq 0.0207$**
  - E0 transitions, γ-γ-γ coincidences, and feeding ratios still to be investigated
- A large number of γ-γ coincidences have been collected
  - Extend level scheme of ^{114}Sn
  - γ-γ angular correlation measurements
  - Fast-timing measurements with $LaBr_3$ (Ce) detectors
- Significant amount of analysis ahead

Acknowledgements

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Madison Daignault (SFU Dept. of Chemistry)

Isaiah Djianto (SFU Dept. of Chemistry)

Matthew Martin (SFU Dept. of Physics)

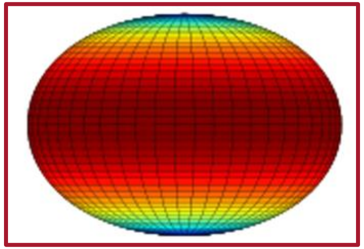
Dr. Krzysztof Starosta (SFU Dept. of Chemistry)

Elliot Wadge (SFU Dept. of Physics)

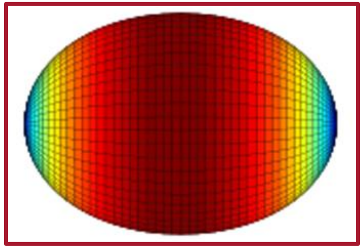
Nuclear Shapes*

- Described by a multipole expansion in λ:
  - $$R(\theta,\phi) = c(\alpha)R_0\left[1+\sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda}\alpha_{\lambda\mu}Y_{\lambda\mu}(\theta,\phi)\right]$$
- Multipole order: 2^λ
  - 2^0 = monopole - breathing mode
  - 2^1 = dipole - center of mass shift
  - 2^2 = quadrupole - reflection symmetric deformation
- Deformed nuclear shape arises from long-range multipole-multipole interactions between protons and neutrons in the nuclear valence space

Oblate (earth)



Prolate (rugby ball)



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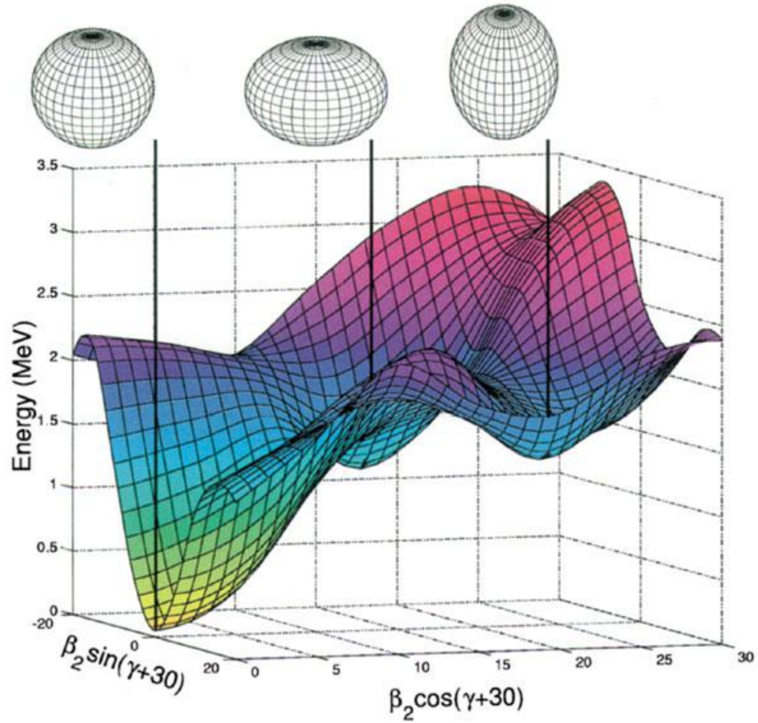


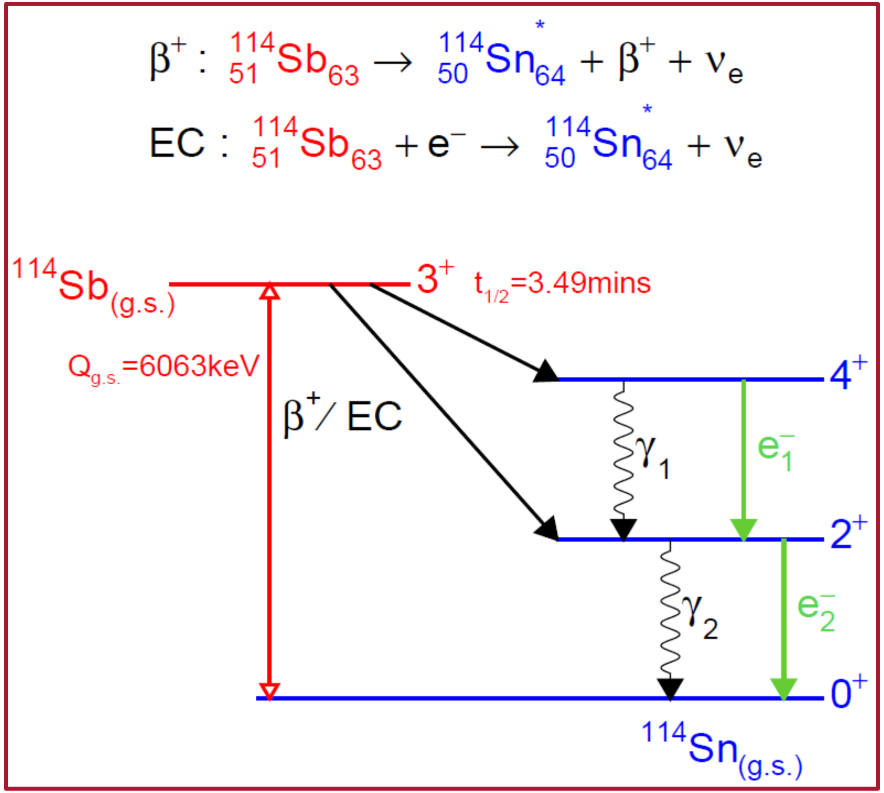
Decay of ^{114}Sb to ^{114}Sn**

β⁺-decay

- Protons are spontaneously converted to neutrons, releasing a positron and an electron neutrino

Electron Capture (EC)

- Proton spontaneously captures an atomic electron, converting it to a neutron and neutrino



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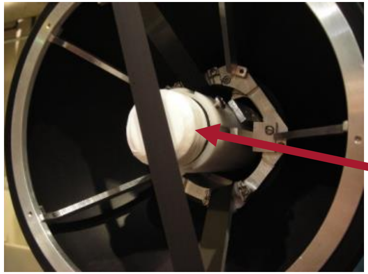

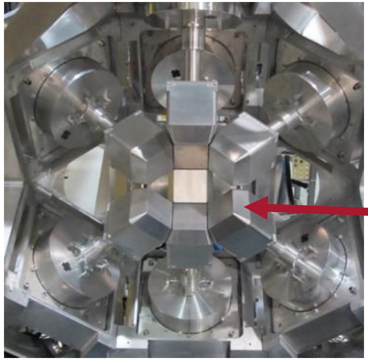

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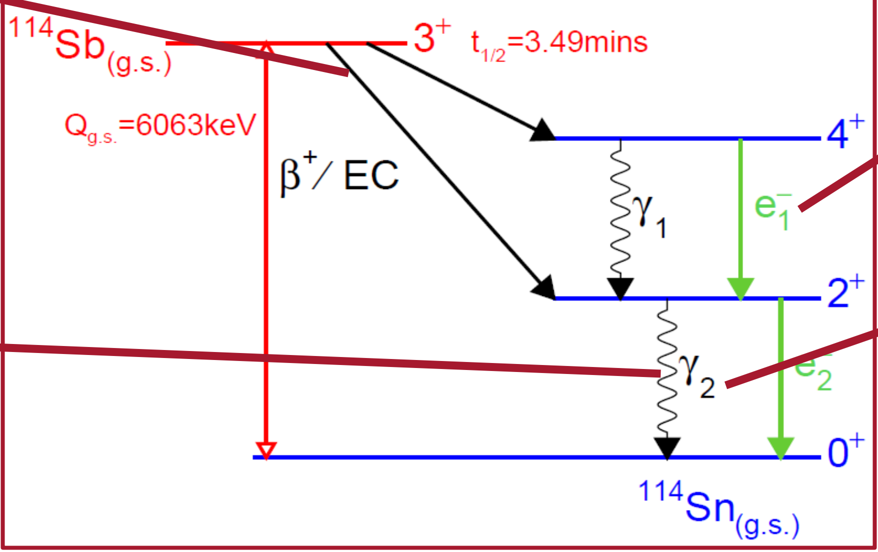

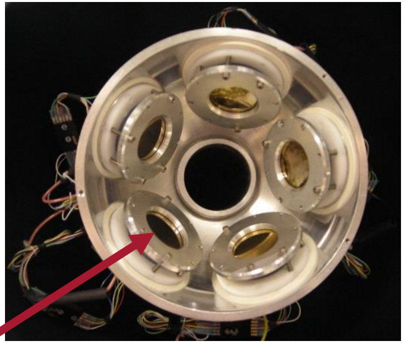

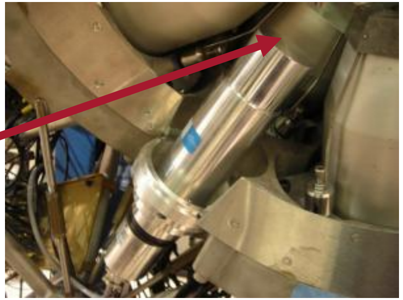

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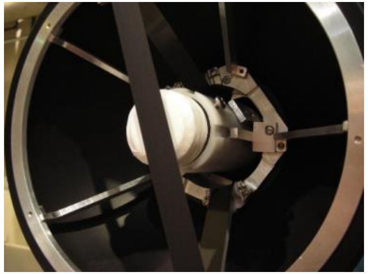

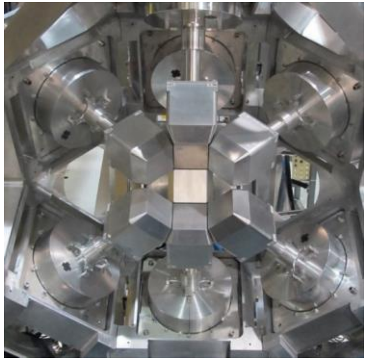

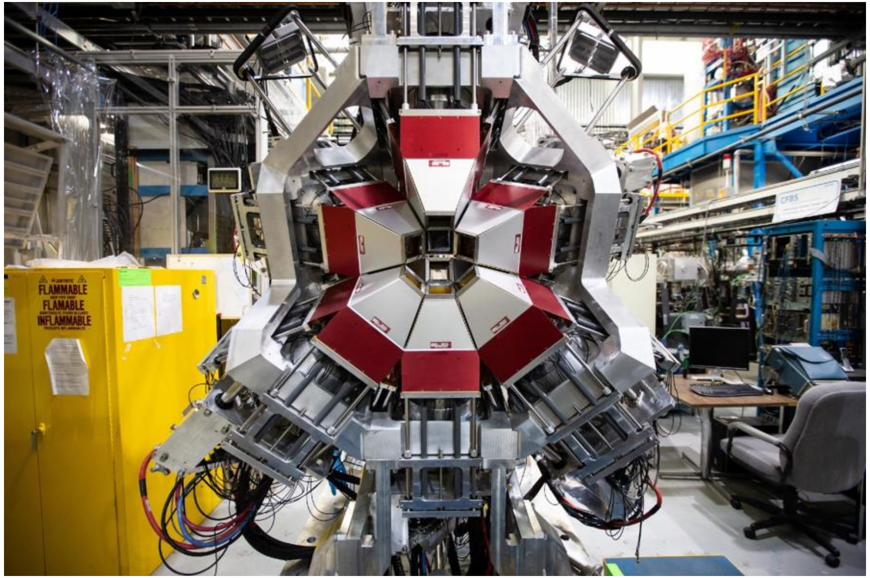

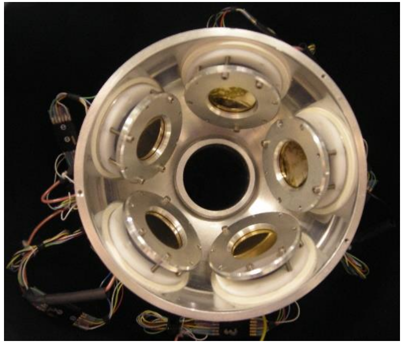

γ-Events*