Lawrence Livermore National Laboratory

Experiments on the elusive ^{229}Th meta-stable

Sept. 25, 2012

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

LLNL-PRES-584333

Outline of talk

- Motivation
- Our energy experiment
  - Prior and planned
- Summary

Interest in ^{229}Th meta-stable

- Parameters for ^{229}Th meta-stable
  - Half-life ~hours?
  - Difference between meta-stable and ground states
    - Spins differ by *h-bar* - laser excitation?
    - Prior studies assume energies differ by 3.5 eV, we get 7.6 eV; however, ^{229m}Th is still the lowest nuclear level
  - Ability to manipulate a nuclear level with optical systems (e.g., lasers)
- Precision clock
  - Narrow line width via long half-life
  - Less sensitive to external E and B
  - E. Peik and Chr. Tamm, *Euro. Phys. Lett.* **61** (2003)
- Effects of chemical environment on nuclear decay
  - Atomic/Nuclear bridge
  - E. Tkalya, *et al.*, *Phys. Rev.* **C 61**, 064308 (2000)
- Qubit for quantum computing

Gateway for controlling nuclear transitions for applied and fundamental research

History of the ^{229m}Th energy level studies

- L.A. Kroger and C.W. Reich, *Nucl. Phys.* **A 259**, 29 (1976)
  - 0.1 keV from ground state
- D.G. Burke, *et al.*, *Phys. Rev.* **C 42**, R499 (1990). Infer: ^{230}Th(d,t)^{229}Th
- C.W. Reich and R.G. Helmer, *Phys. Rev. Lett*. **64**, 271 (1990).
  - 1 ± 4 eV
- R.G. Helmer and C.W. Reich, *Phys. Rev.* **C 49**, 1845 (1994).
  - 3.5 ± 1.0 eV (A valiant effort)
- G.M. Irwin and K.H. Kim, *Phys. Rev. Lett*. **79**, 990 (1997).
  - Claim direct measurement
- S.B. Utter, *et al.*, *Phys. Rev. Lett*. **82**, 505 (1999).
  - Refutes Irwin and Kim
- Z.O. Guimarães-Filho, and O. Helene, *Phys. Rev.* **C 71,** 044303 (2005).
  - 5.5 ± 1.0 eV
- B.R. Beck, *et al.*, *Phys. Rev. Lett.* **98**, 142501 (2007)
  - 7.6 ± 0.5 eV

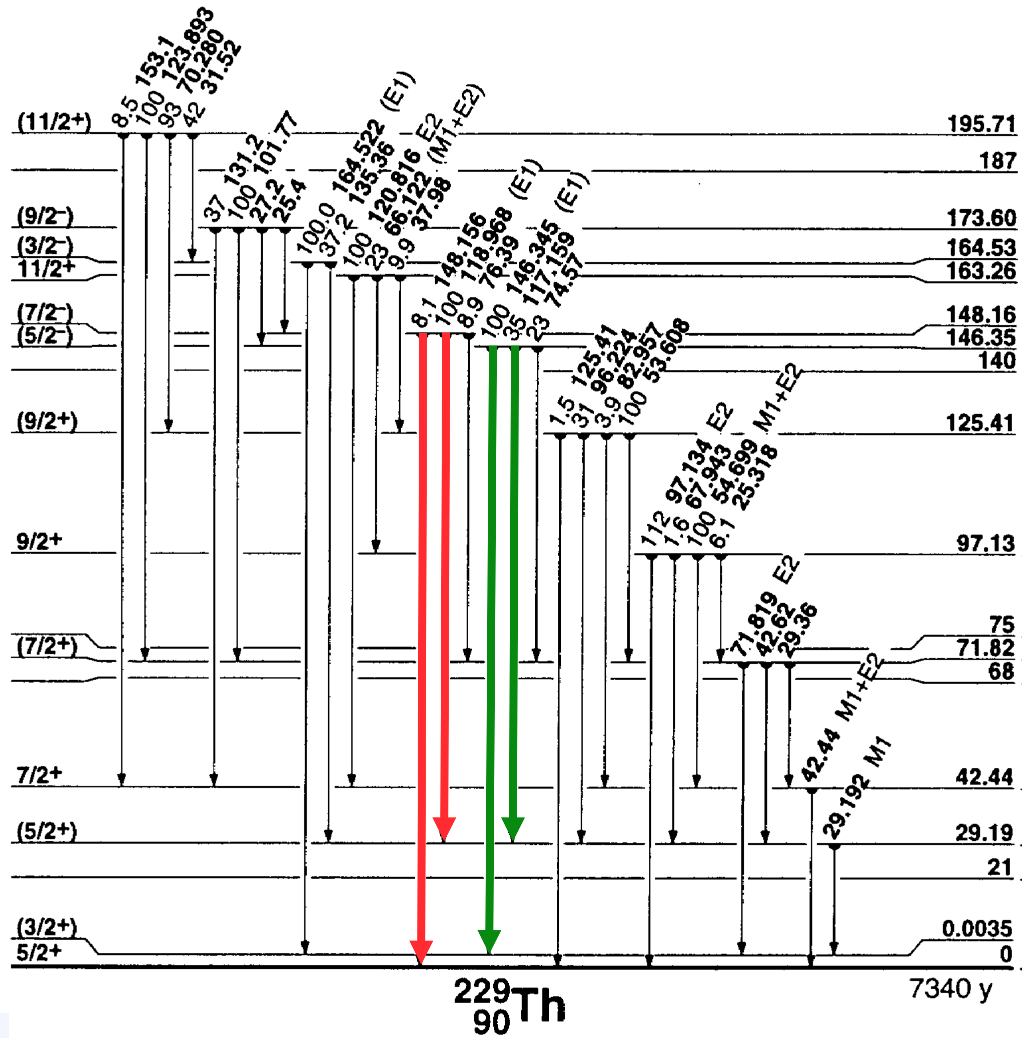
History of the ^{229m}Th half-life studies

- The ^{229m}Th half-life calculations are unreliable, ranging from 10 μs to 1000 hours.
- E. Browne, *et al*., *Phys. Rev.* **C 64**, 014311 (2001).
  - 6 hr < $\tau_{1/2}$ or $\tau_{1/2}$ > 20 d
- T. Mitsugashira, *et al*., J. Radioanal. Nucl. Chem. **255**, 63 (2003)
  - $\tau_{1/2}$ = 13.9 ± 3 hr.
- E. Ruchowska, *et al*., *Phys. Rev.* **C 73**, 044326 (2006).
  - Gamma decay calculation: 11 hr for 3.5 eV and 2.2 hr for 5.5 eV.
- T.T. Inamura and H. Haba, Phys. Rev. C 79, 034313 (2009)
  - 1 min. < $\tau_{1/2}$ < 3 min.

A better determination of the energy and a reliable half-life measurement are needed before other experiments can be performed.

Measuring the ^{229m}Th energy level

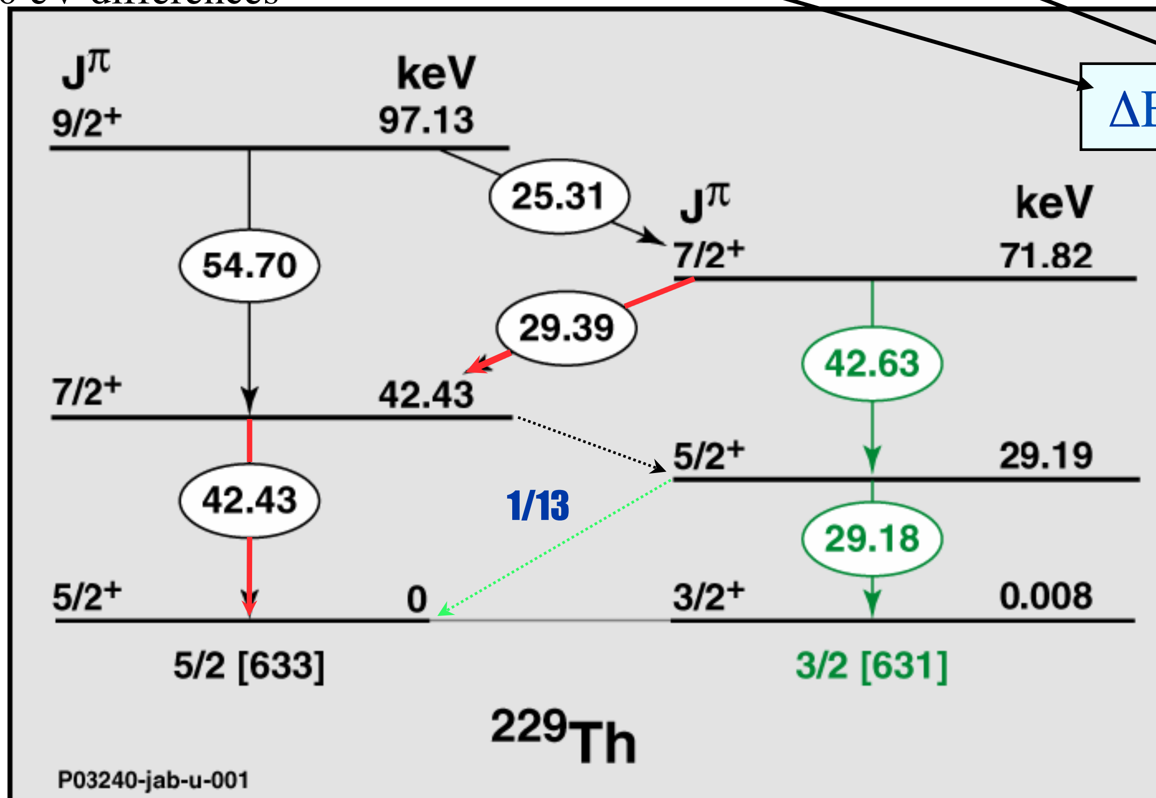
- Directly
  - Measure the eV-ish gamma from the decay of the metastable state to the ground state
  - Not currently seen?
- Difference
  - Prior measurements
    - e.g. Helmer and Reich Inferior scheme
      (148.1 - 118.9) - (146.1 - 117.1)
      (148.1 - 146.1) - (118.9 - 117.1)
      Note 2000 eV differences
  - Our measurement
    - Superior scheme
- Infer
  - Prior measurements
  - Collision data: ^{230}Th(d,t)^{229}Th
  - Lifetime measurement



Second best better than third best

- Second best differencing scheme
  - (42.43 + 29.39) - (42.63 + 29.19) = (29.39 - 29.19) - (42.63 - 42.43)
  - ~ 200 eV differences

ΔE_{29} - ΔE_{42}



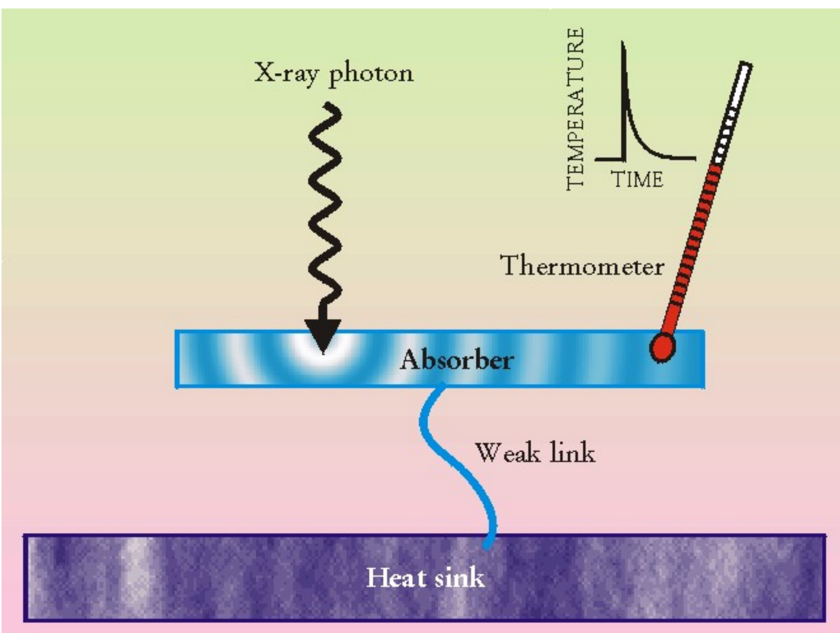
Best differencing scheme is to measure the 29.18 keV gammas. Requires a detector with ~12 eV FWHM.

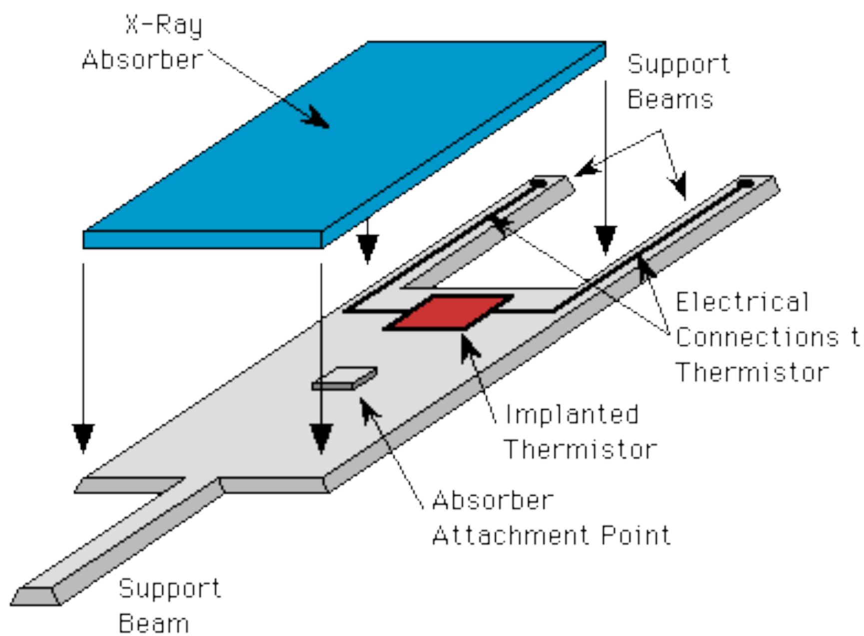
NASA's XRS detector

- A high-resolution micro-calorimeter
  - 6 eV FWHM at 6 keV and 60 mK
  - We ran it at ~90 mK and got 26 eV FWHM up to 60 keV
  - XRS as 32 pixels of which 28 are the hi-res. HgTe absorbers
  - 25 of the 28 pixels were clean (i.e., low electronic noise)
  - 11 good days of data
- To increase count rate, we had NASA insert the ^{233}U source into the inner shield of the XRS (self-shielding a problem). The ^{241}Am was outside and moveable.
  - For crystal spectrometer, the source/detector distance is a show stopper (Our distance ~centimeter, for crystal spec. it would be ~meter).
- NASA claims 9 eV FWHM at 29 keV maximum energy

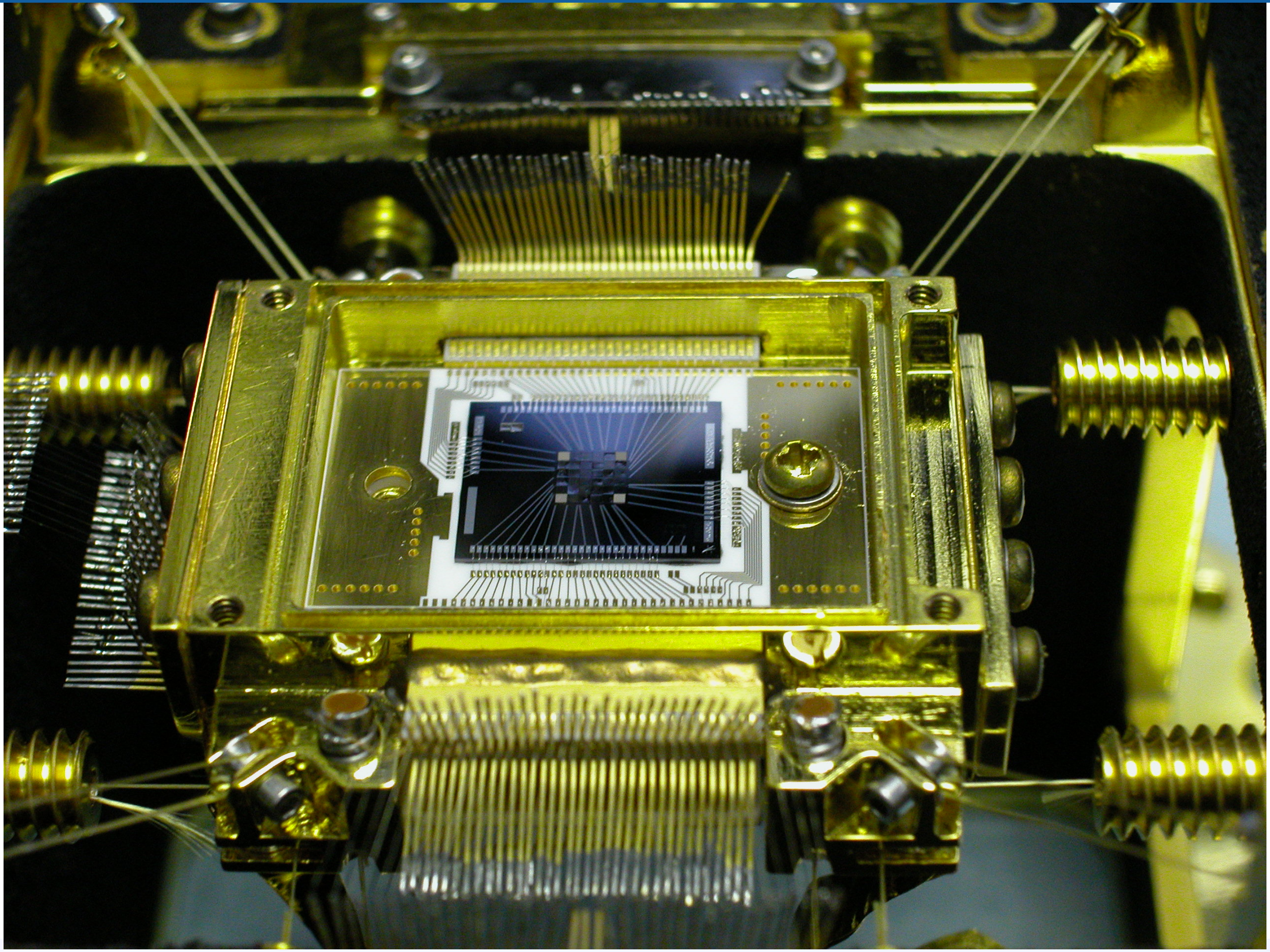
NASA's XRS absorber

- ***Works by:*** high sensitivity thermistor, low heat capacity materials, and operating at very low temperatures (~50 mK).
- ***Limited by:*** thermodynamic noise, thermometer sensitivity, choice of materials.

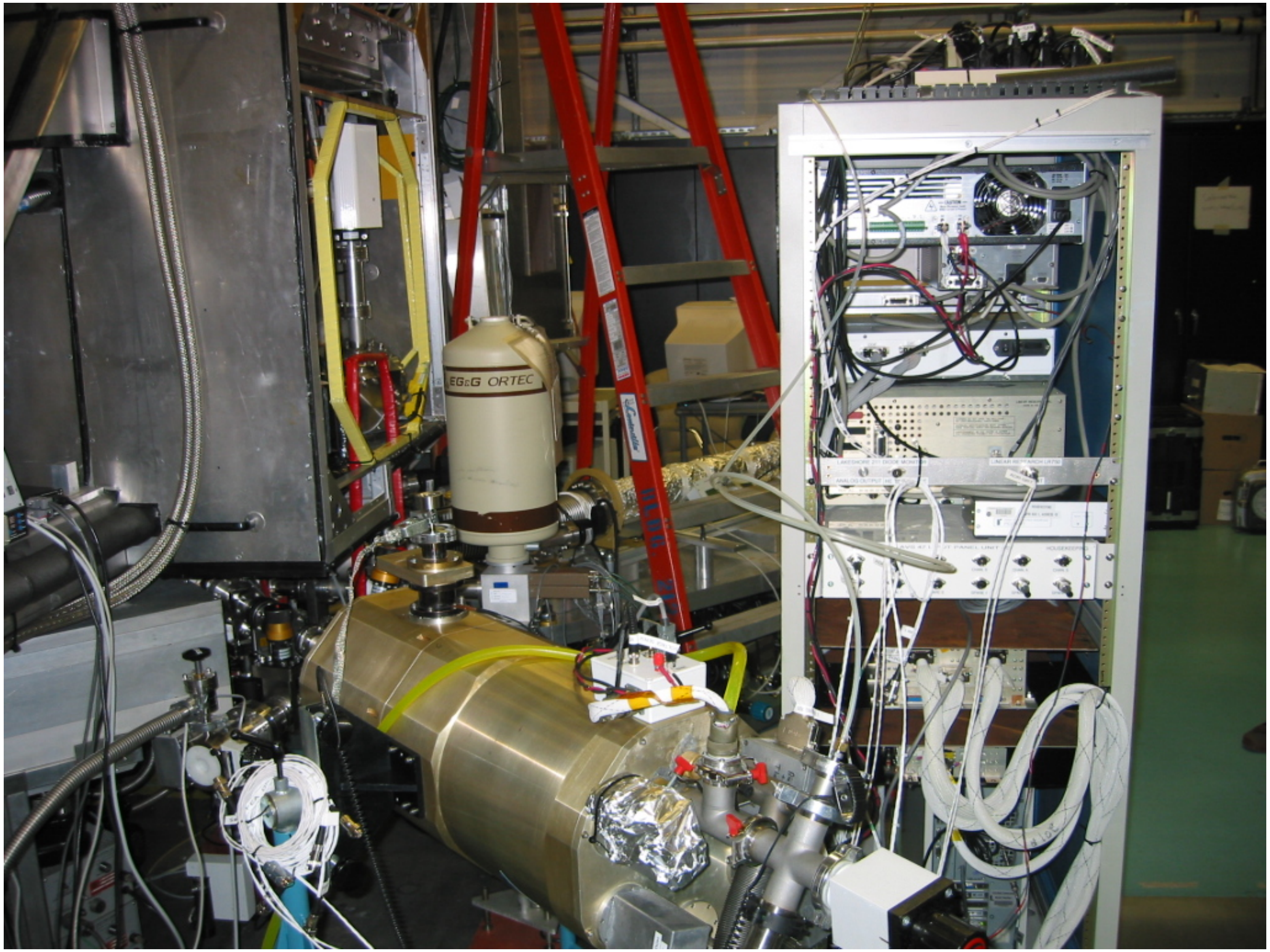




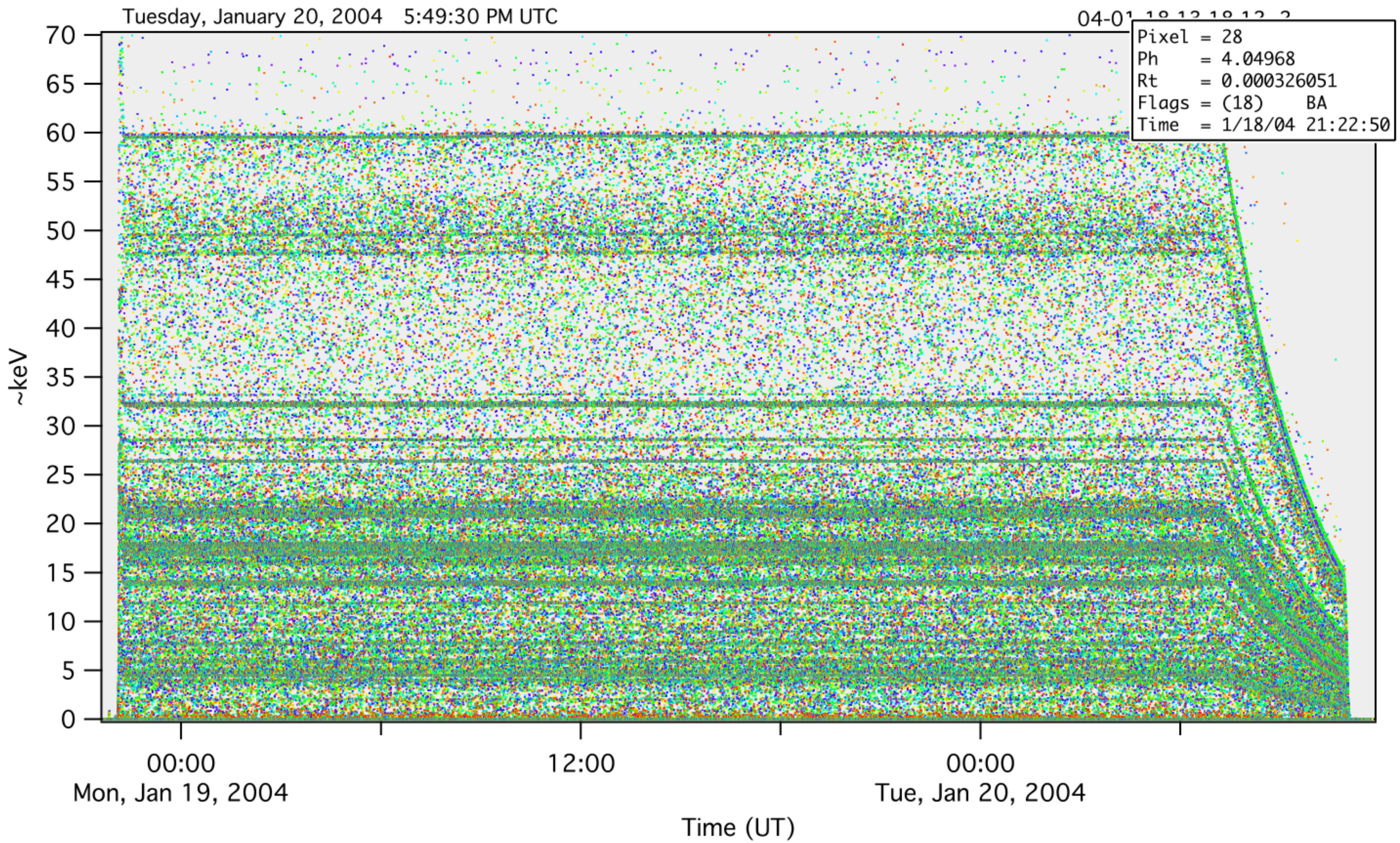
The XRS/EBIT absorbers, all 36 of them



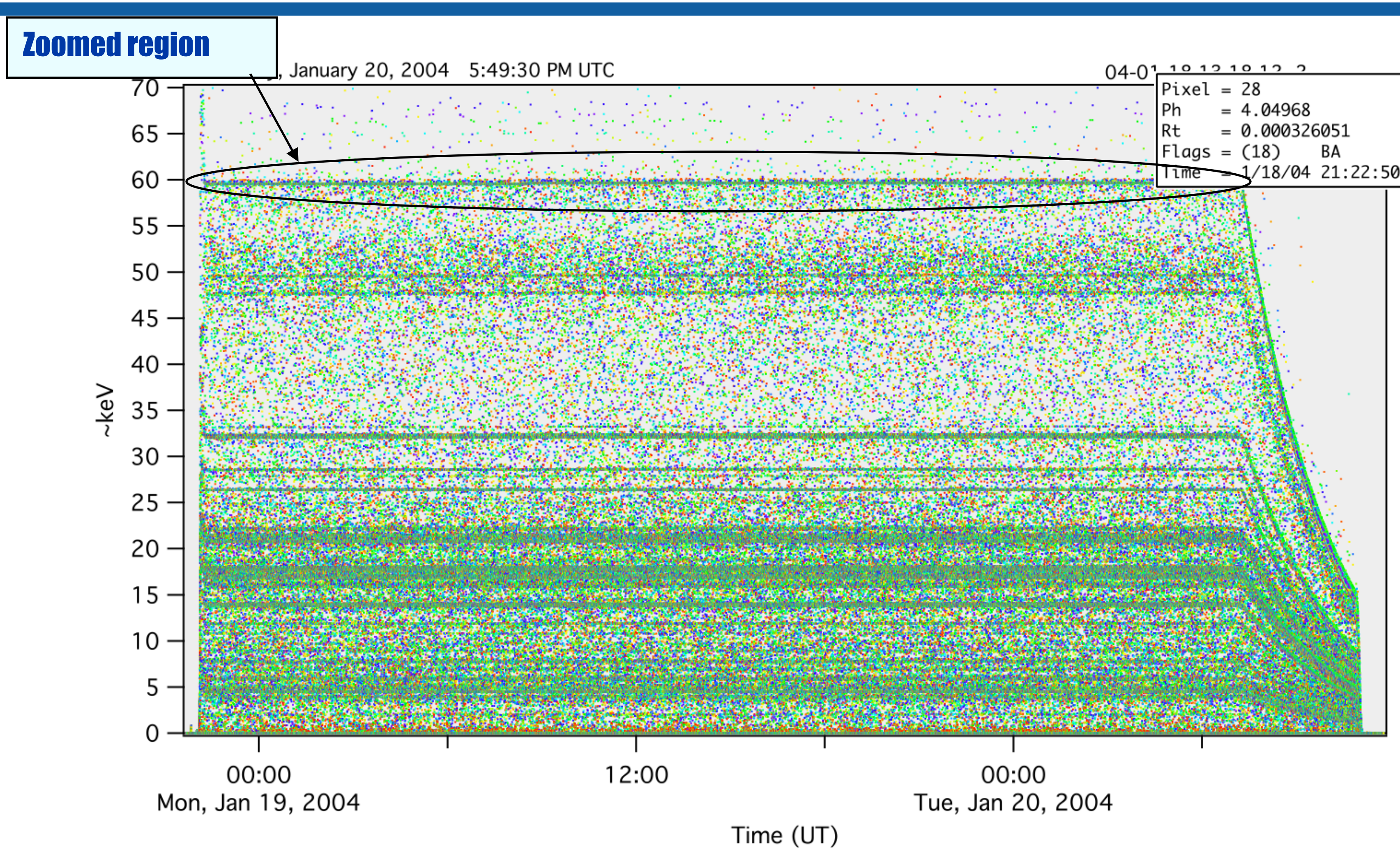
EBIT/XRS



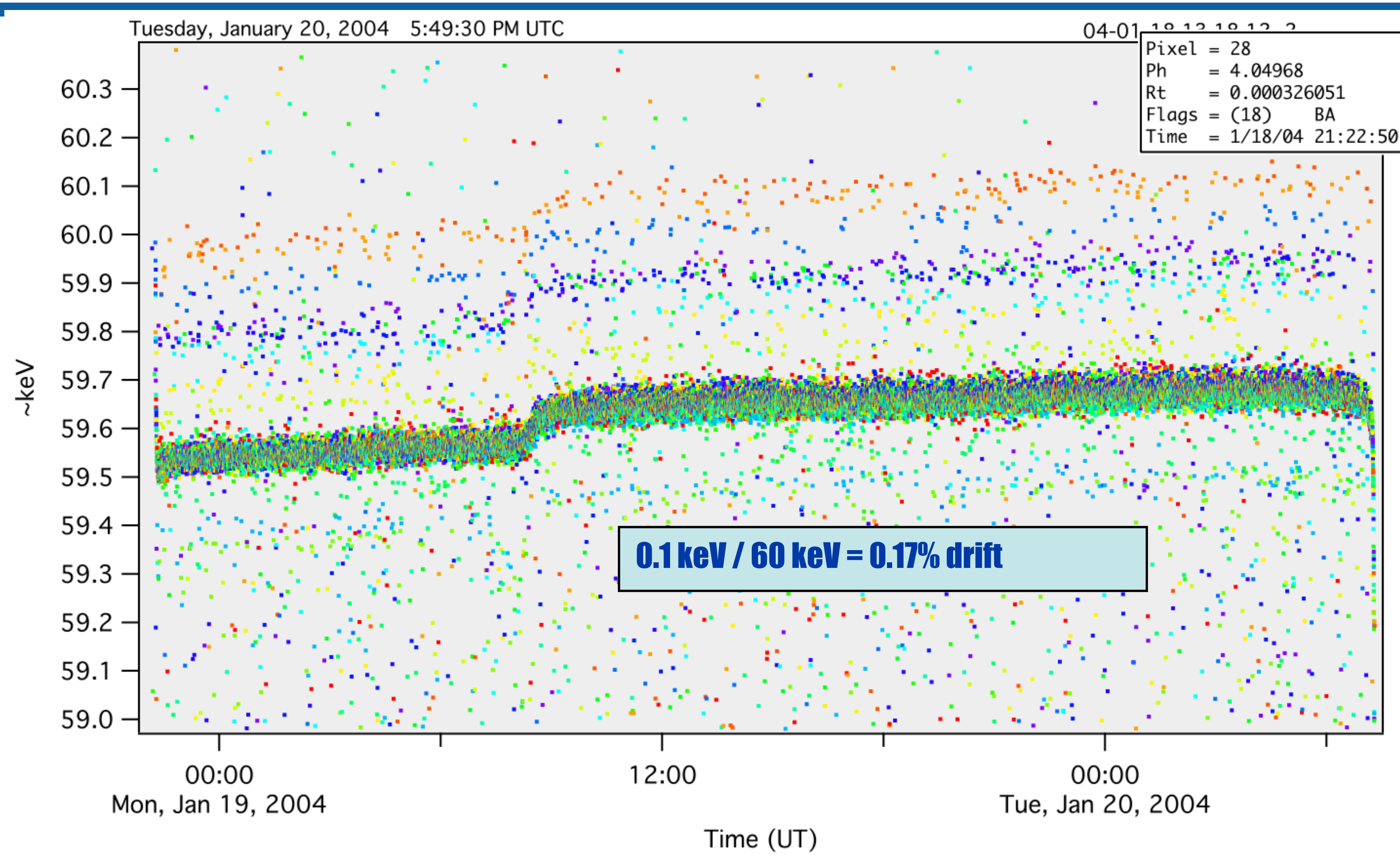
Roughly calibrated event sequence



Roughly calibrated event sequence



Roughly calibrated event sequence zoomed

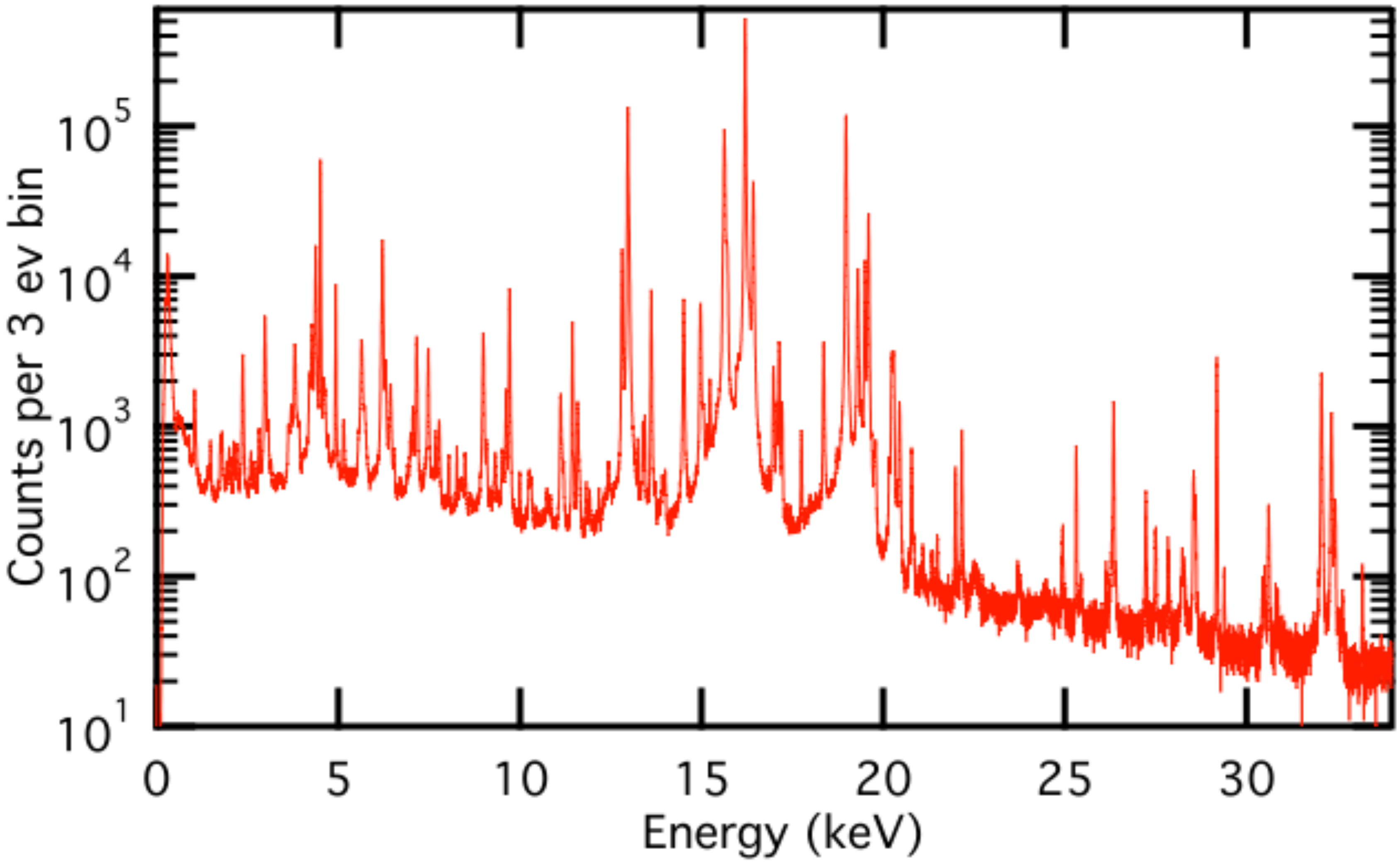


Each dot is a single event. Each pixel has a different color.

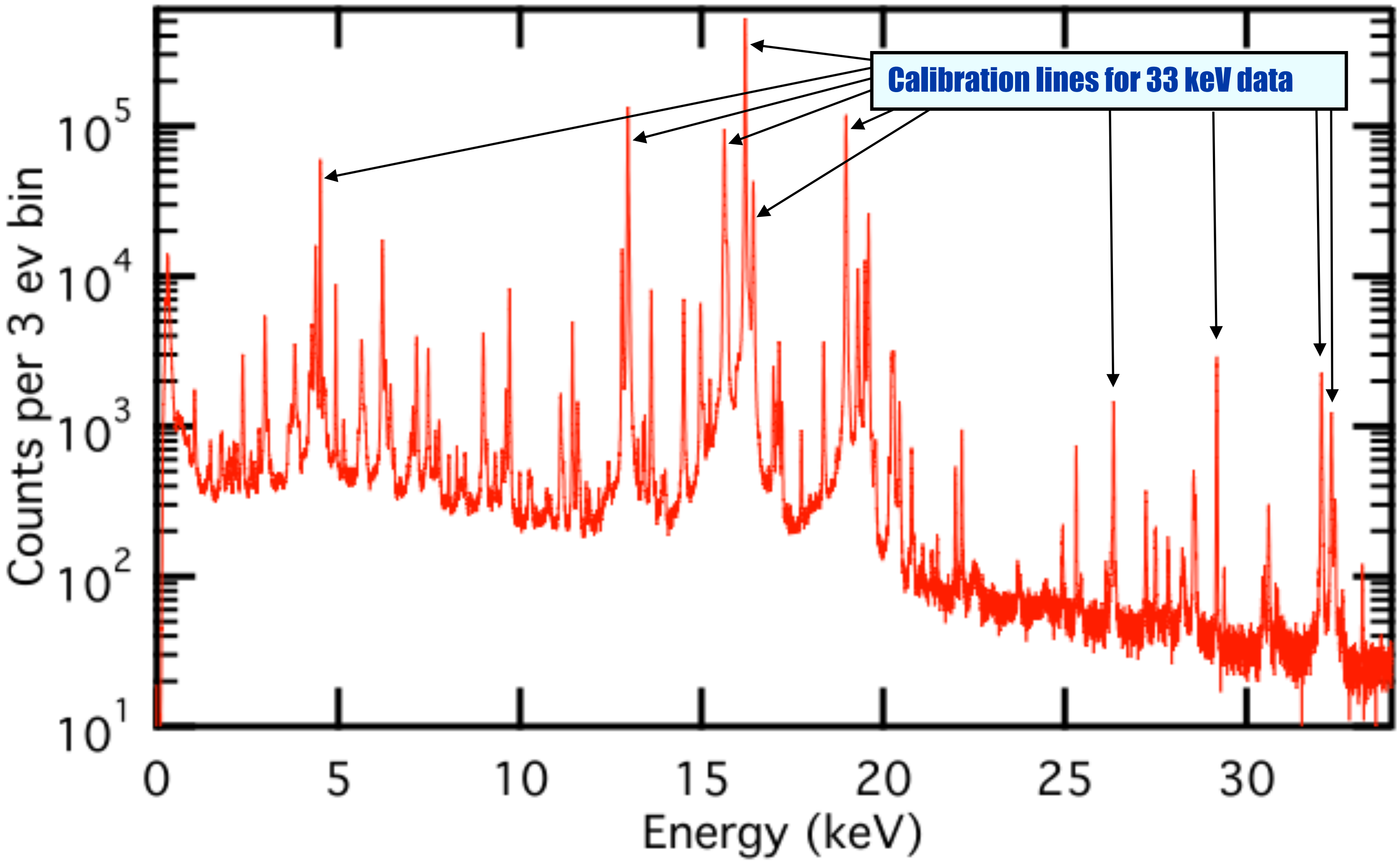
Processing the data

- 25 "good" pixels x 11 datasets
- Each dataset drift corrected using strongest line: intra-dataset drift removed
- Across dataset drift corrected using strongest line : inter-dataset drift removed
- Each pixel summed across datasets, producing 25 spectra
  - Determination of ΔE_{29}
    - 10 "standard" lines used to calibrate each of the 25 spectrum to 33 keV in energy
    - All 25 calibrated spectra summed (next slide)
  - Determination of ΔE_{42}
    - 10 lines + 3 more used to calibrate each of the 20 spectrum to 60 keV
      - 5 pixels ignored because they did not have ^{241}Am 59.5 keV line
    - Calibration used on all pixels for each dataset to obtain 20 x 11 spectra, from which average and standard deviation were obtained

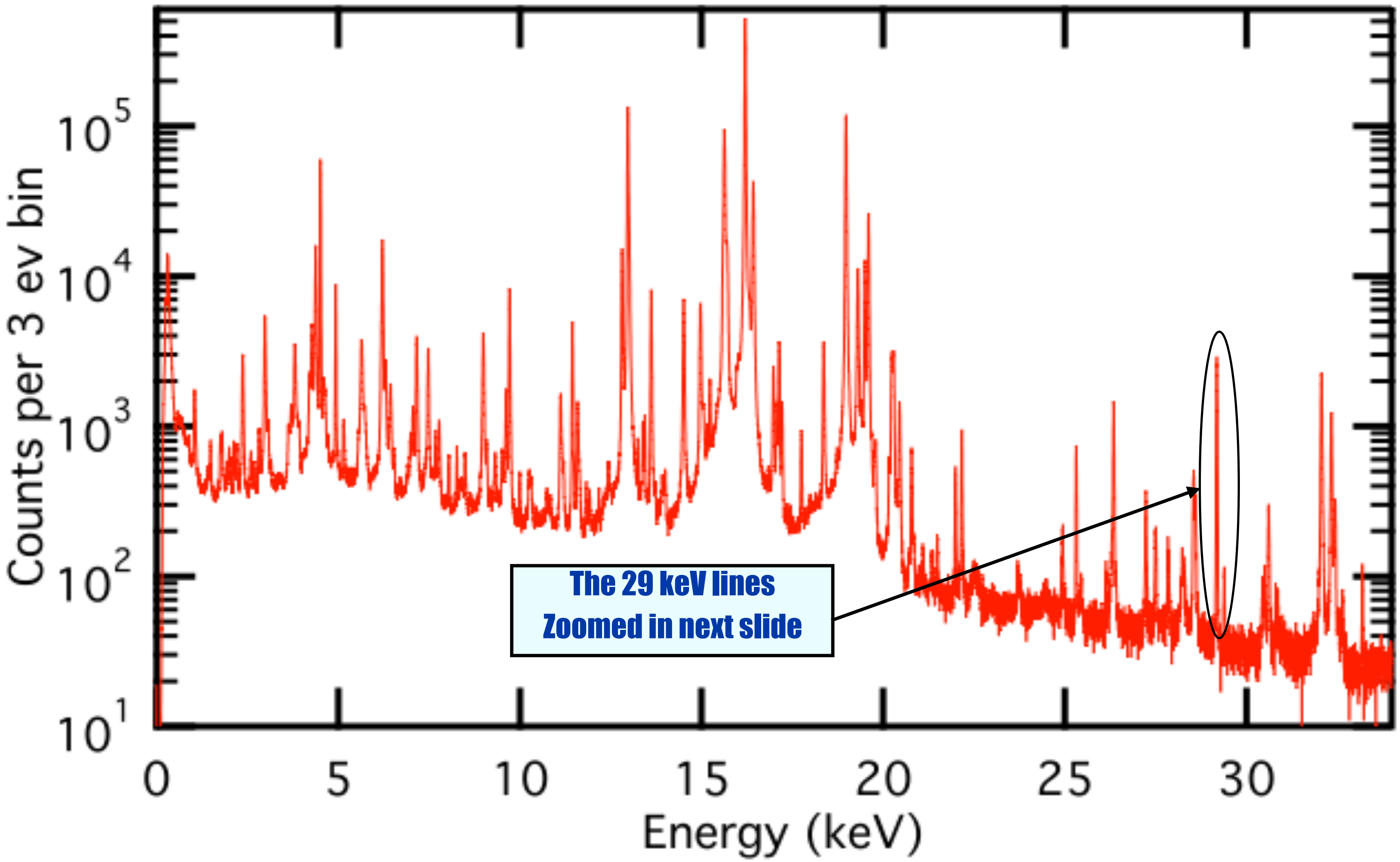
XRS summed spectrum to 33 keV; 25 pixels x 11 datasets



XRS summed spectrum to 33 keV; 25 pixels x 11 datasets

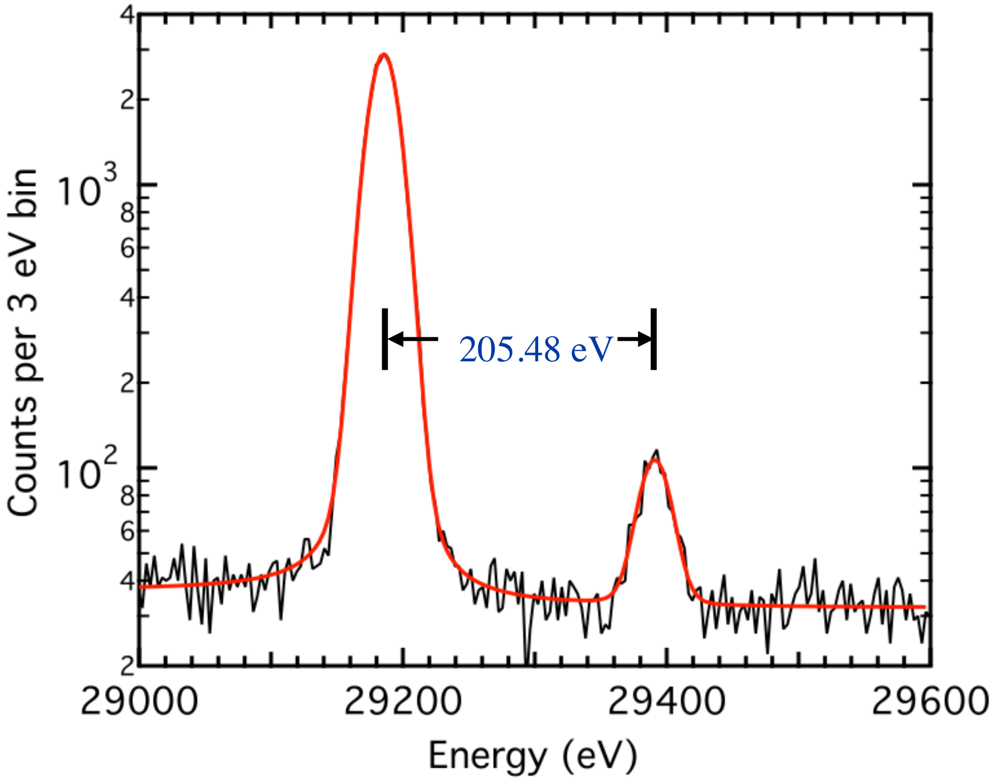


XRS summed spectrum to 33 keV; 25 pixels x 11 datasets



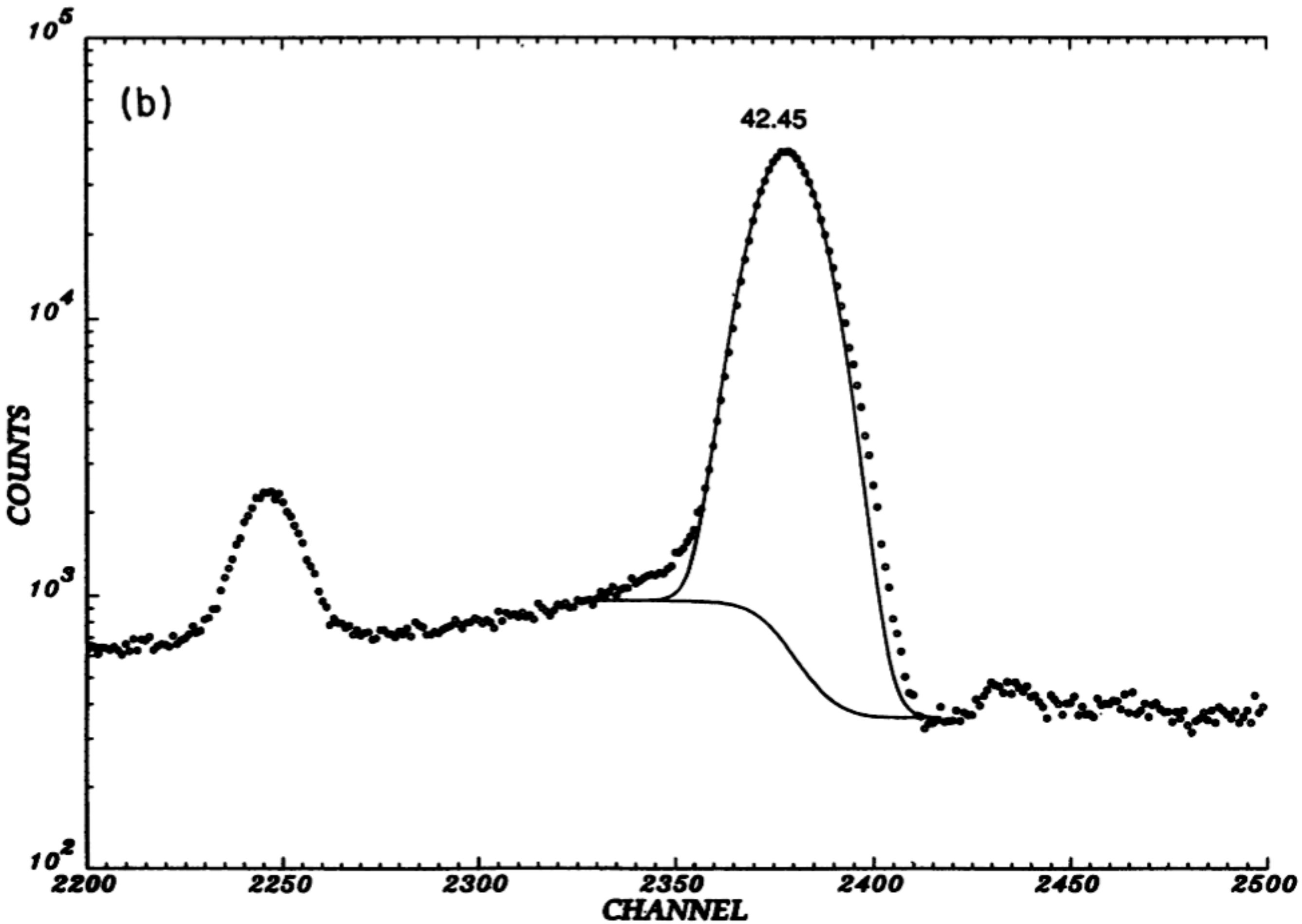
The 29 keV lines

- Spectrum is a sum of all pixels and all datasets
    - Line width increased ~10% from un-summed data
- The 29184.6 eV line is a doublet, corrected later
- The 29390 eV line is the weakest, ~700 counts total, ~2 count/day/pixel
- 205.48 ± 0.50 eV. Uncertainty due to statistics in 29390 eV line

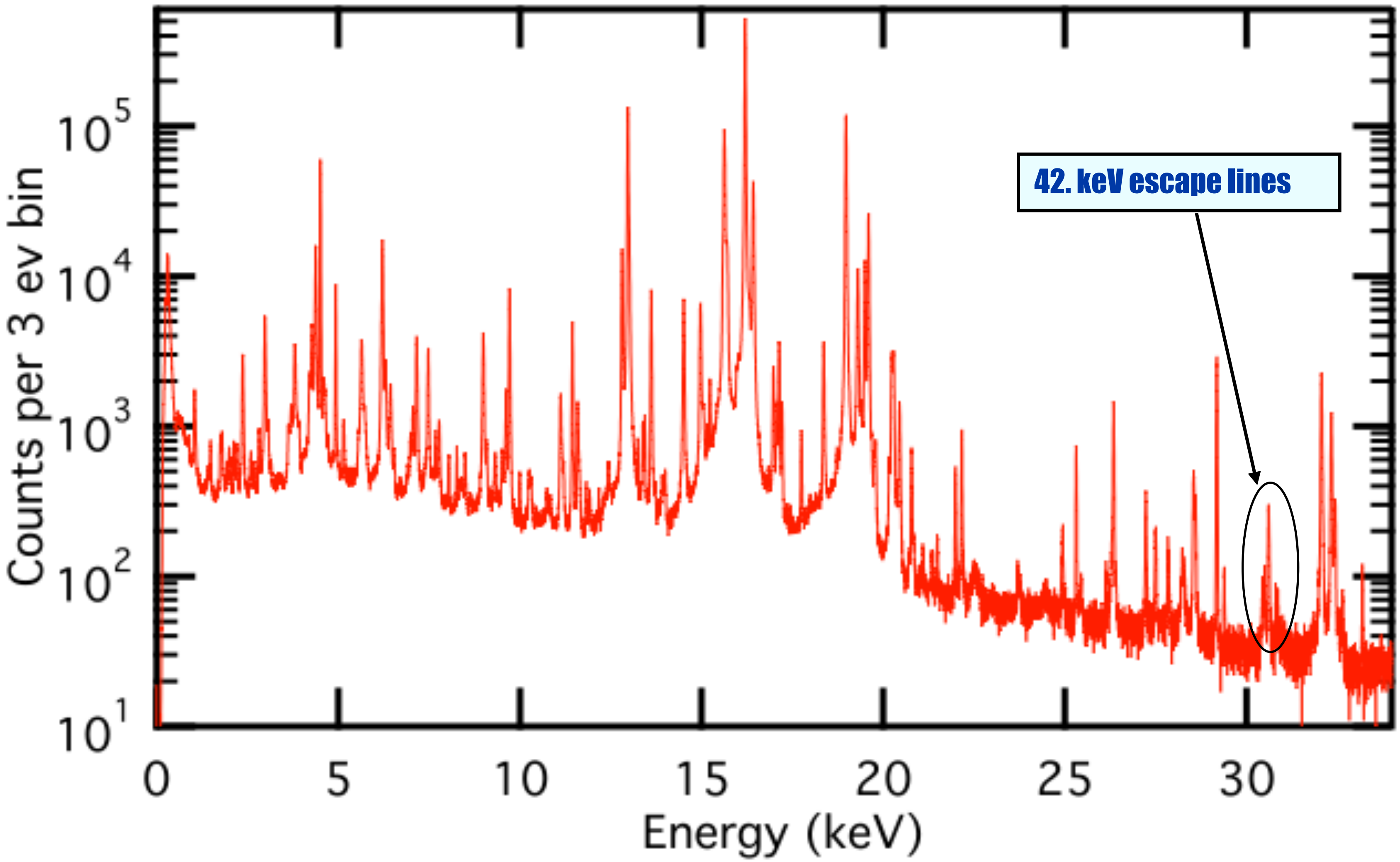


Helmer & Reich unresolved 42. keV lines

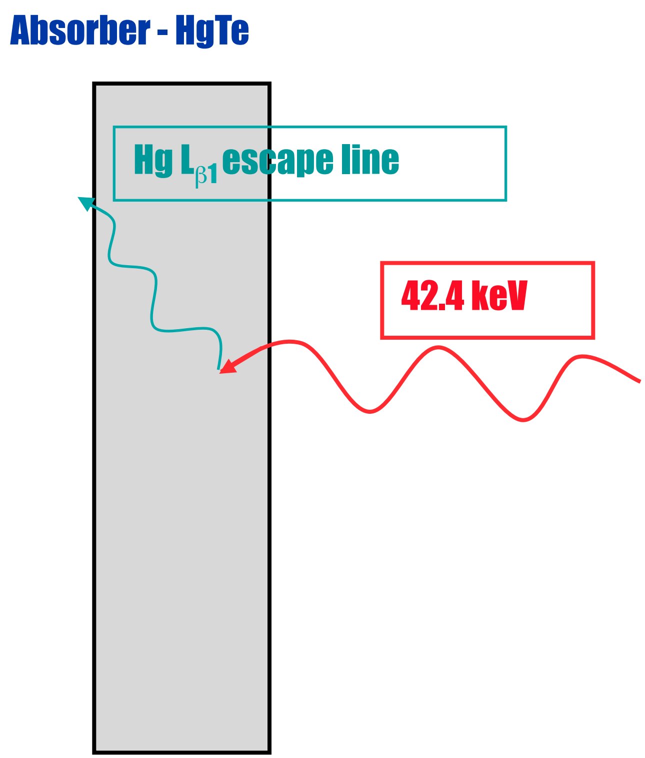
- We need to calibrate the 42.4 keV line
- In references 42.4 keV line has large (~20 eV) uncertainty due to 42.6 keV line



XRS summed spectrum to 33 keV; 25 pixels x 11 datasets



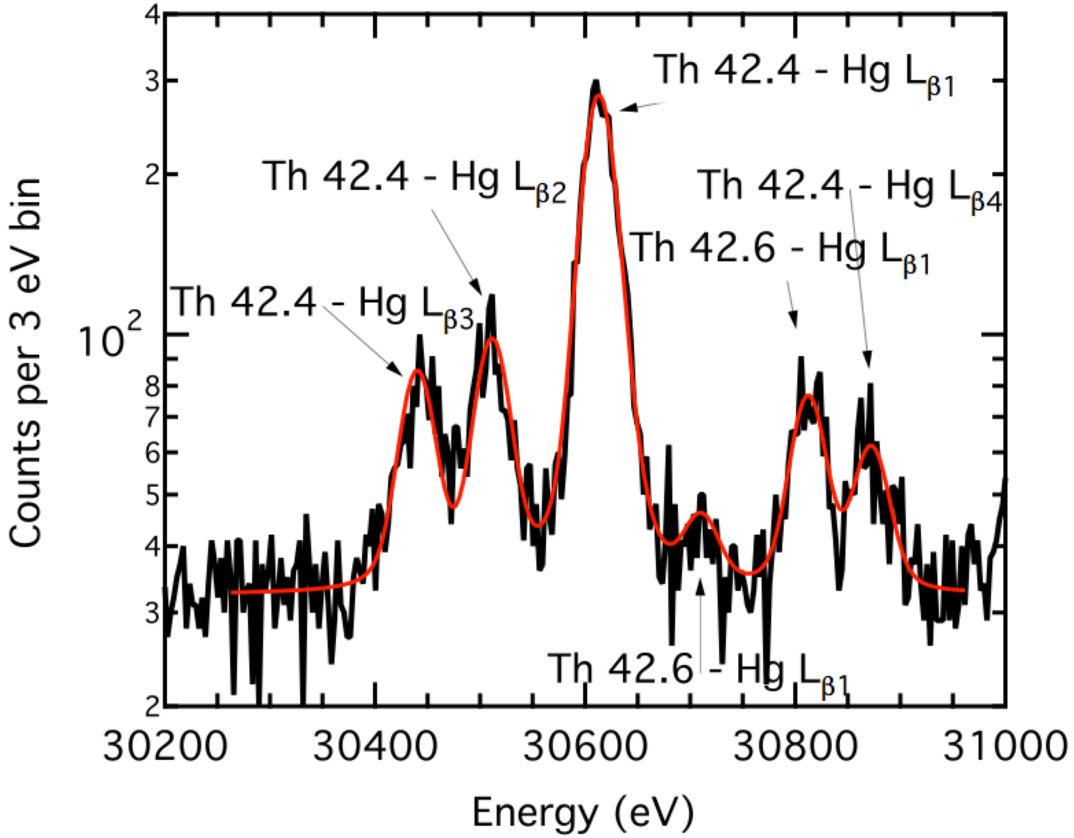
What is an escape line?



Measured energy is 42.4 keV minus the escape line's energy

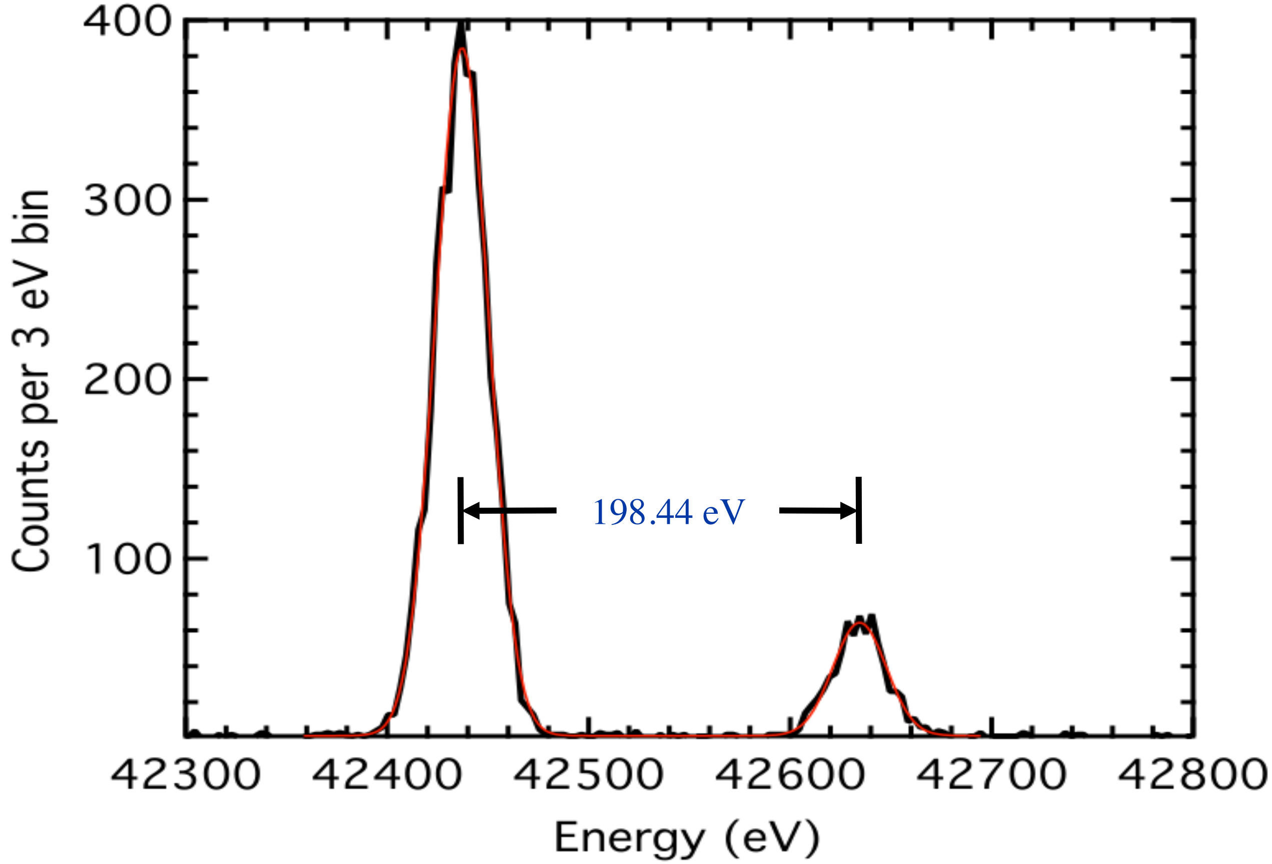
42 keV Hg escape lines

- We get 42434.9 ± 2.4 eV
- Barci, *et al*. get 42434.4 ± 1.1 eV
- Statistics not good enough to measure 42.6 - 42.4 keV splitting

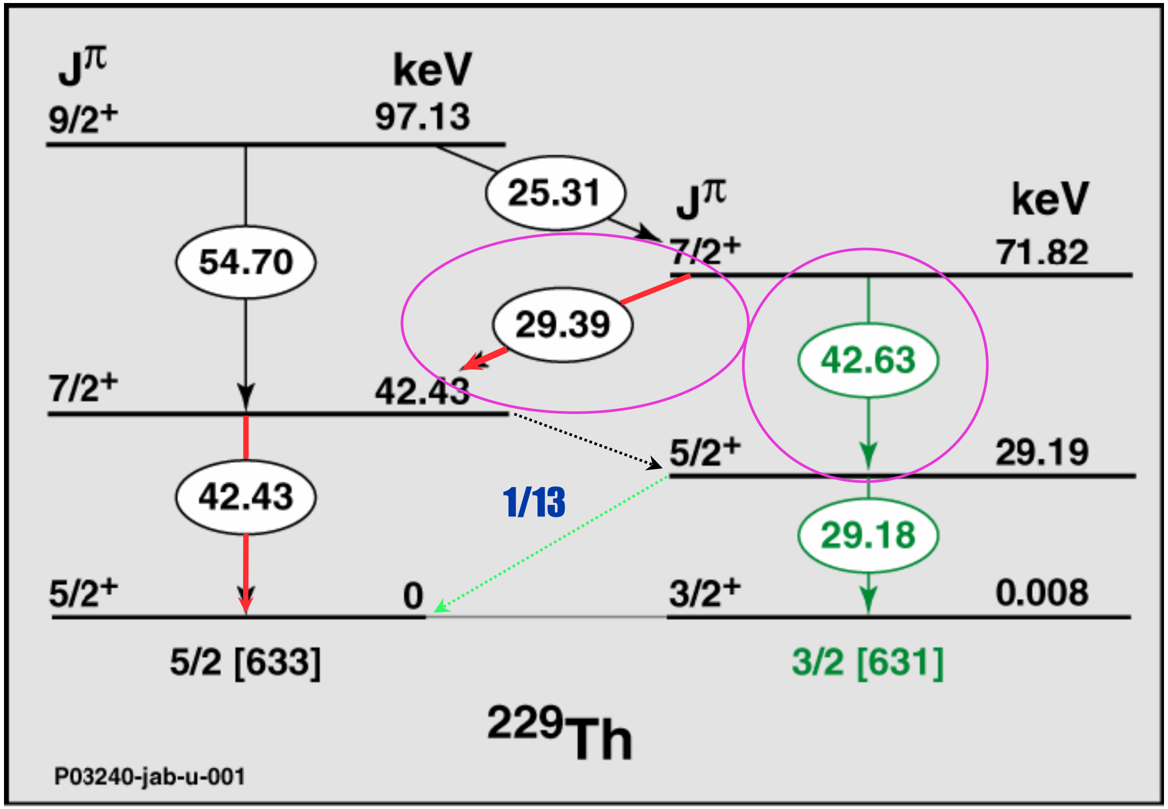


The 42 keV lines

- The 42 keV lines for pixel 0 summed over all datasets
- 198.44 eV is average of the 220 spectra and 0.22 eV is its uncertainty
- 0.22 eV mainly due to counting statistics in the 42.6 keV line



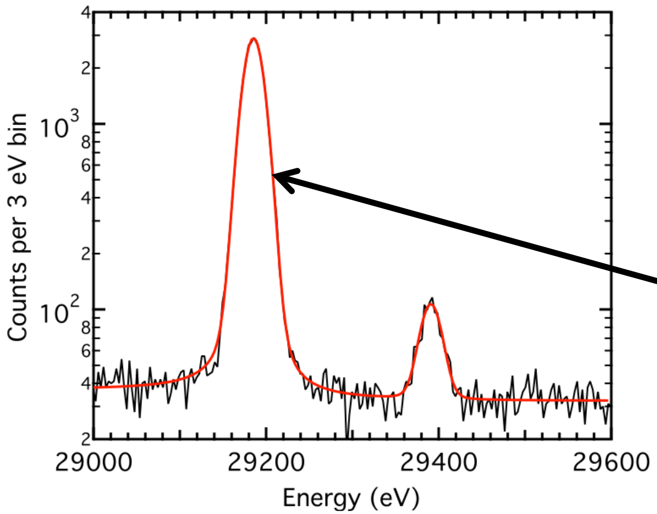
Calibrating 29.19 keV' s branching ratio



We measure b * 29.19 keV + (1 - b) * 29.18 keV and not 29.18 keV

where b is the branching ratio of the 29.19 keV to ground

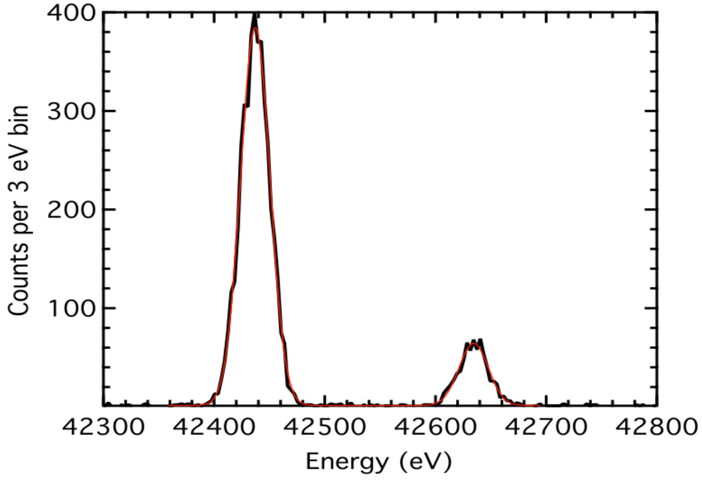
Our prior energy measurement using XRS

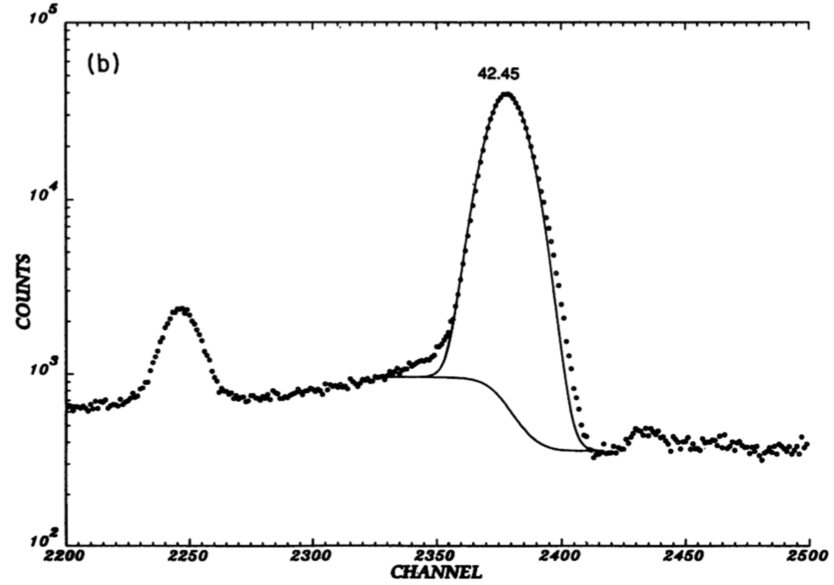


(29.39 + 42.43) keV – (42.63 + 29.18) keV

Result: 7.6 eV ± 0.5 eV

This line is a doublet made up of gammas from 29.18 keV decay to ground (~8%) and the meta-stable (~92%) states.





The answer

- What we are after: ΔE_{29} - ΔE_{42}
- $\Delta E_{29} = 205.48 \pm 0.50$ eV
  - Main uncertainty from weak 29390 eV line
  - The 29194.6 eV line is a doublet, decays to the metastable and to the ground state
  - We measure branching ratio $b = 1/13$ from another intra/inter-band decay
    - Consistent with line width ($b < 0.1$) and
    - Helmer and Reich calculation of 1/14
- $\Delta E_{42} = 198.44 \pm 0.22$ eV
- $\Delta E_{29} - \Delta E_{42} = 7.0 \pm 0.5$ eV
- $E(^{229m}Th) = (\Delta E_{29} - \Delta E_{42}) / (1 - b) = 7.6 \pm 0.5$ eV

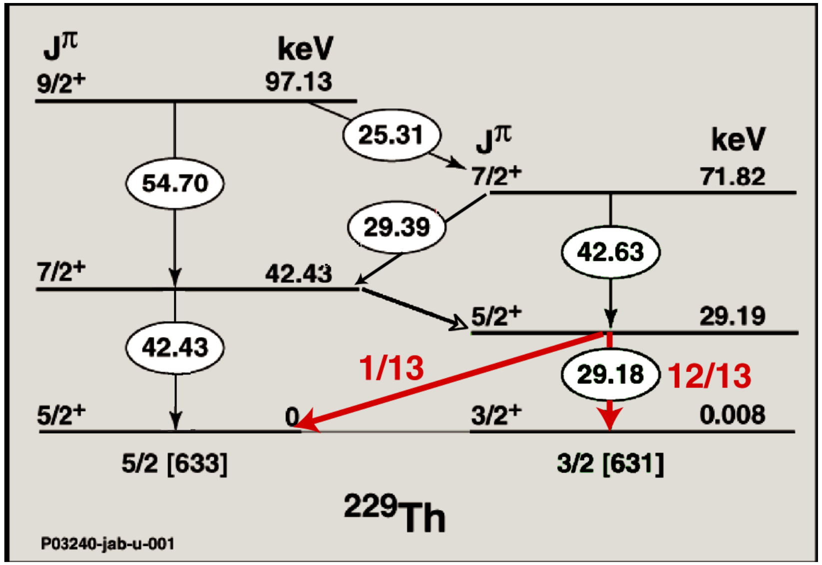
Summary

- ^{229}Th meta-stable to ground state transition looks promising for future precision clock, qubit and/or nuclear/atomic interaction experiments.

- Better determination of energy is needed and half-life needs to be measured before further experiment are feasible.

Proposed improved energy measurement

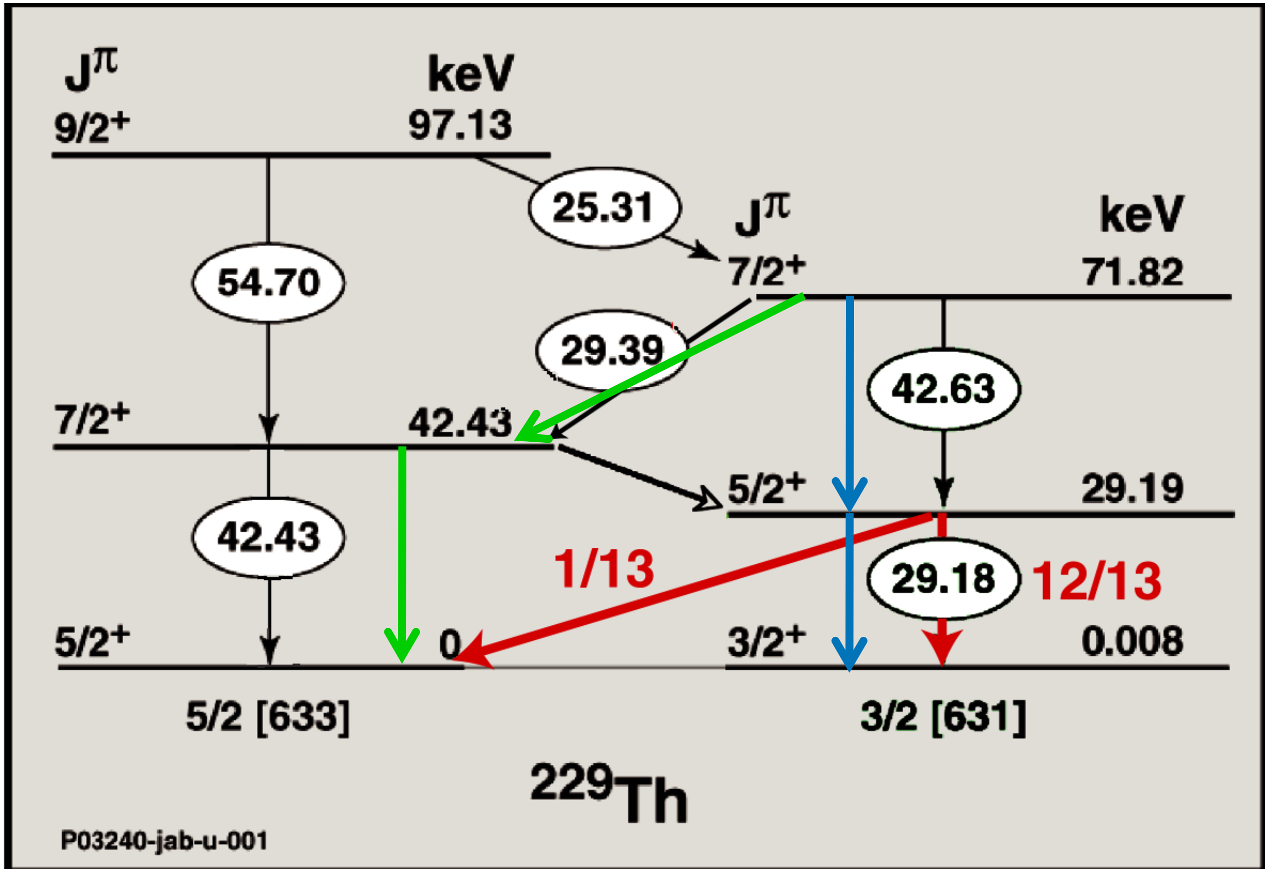
- Measure the energy from the difference of the two gammas that decay from the 29.19 keV level
- Redeploy NASA/EBIT XRS calorimeter with 9 eV FWHM at 29 keV. This yields a statistically limited 0.2 eV uncertainty in 40 days
- XRS currently achieves 4 eV FWHM at 6 keV
- We would have a dedicated XRS and could run for a year - uncertainty < 0.1 eV



Proposed energy experiment using XRS detector

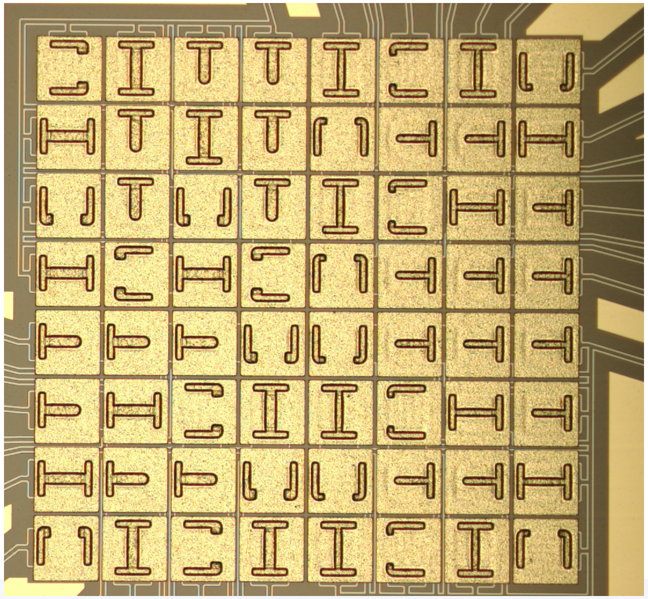
Prior measurement: (29.39 + 42.43) keV – (42.63 + 29.18) keV

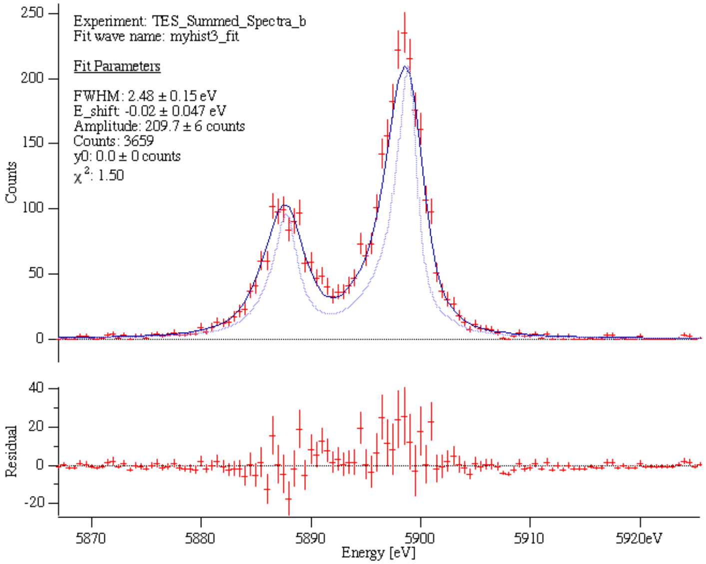
Proposed: Resolve 29.19 keV doublet



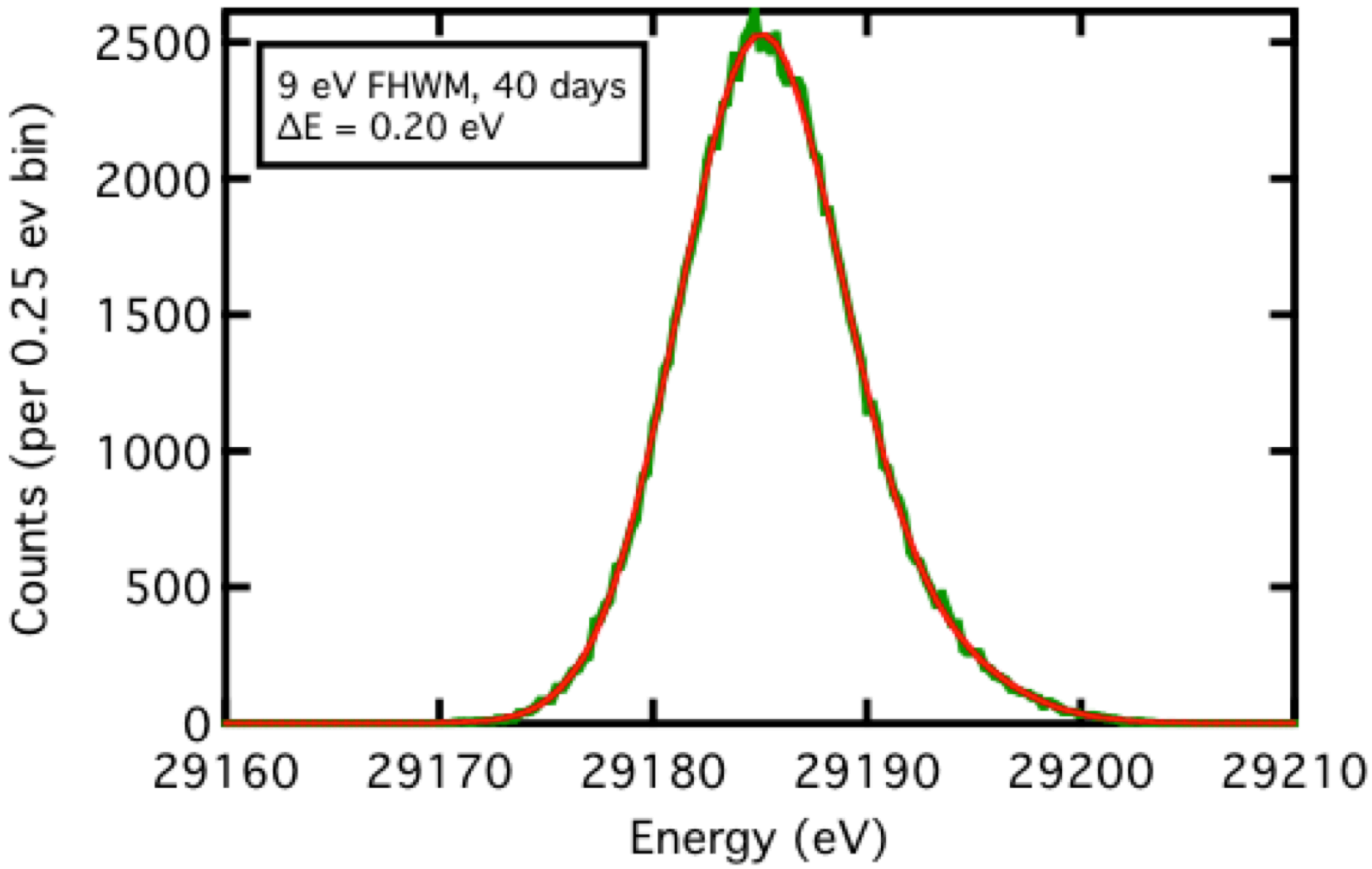
4th Generation? Constellation-X detectors

- Higher resolution:
  - 2eV at 6 keV with a 0.01-10 keV bandpass
  - ~0.5 eV with a 0.01-1.0 keV bandpass
  - 10 eV with a 0.1-100 keV bandpass
- Much higher throughput: ~100-1000 cps/per pixel
- Much higher pixel count through multiplexing, 100s-1000s pixels





Simulation of energy determination with higher resolution



Simulation of energy determination with even higher resolution