Precise Mass Measurements of Astrophysical Interest made with the Canadian Penning Trap Mass Spectrometer

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Radioactive Nuclear Beams 6

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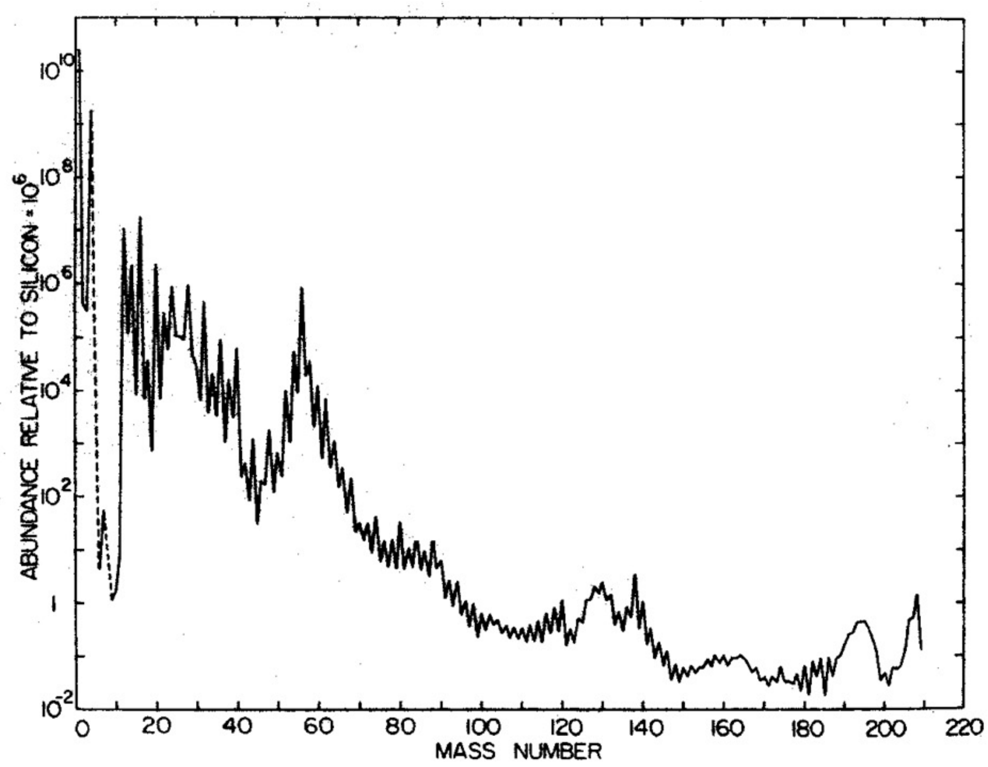
Outline

- Introduction
  - How the elements in the universe were created
    - rp-process
    - r-process
- Overview of the CPT apparatus at ANL
  - the method behind our madness
- Results
  - Waiting-point nuclide ^{68}Se
  - Preliminary result for ^{64}Ge
  - Measurements along the r-process
- Summary

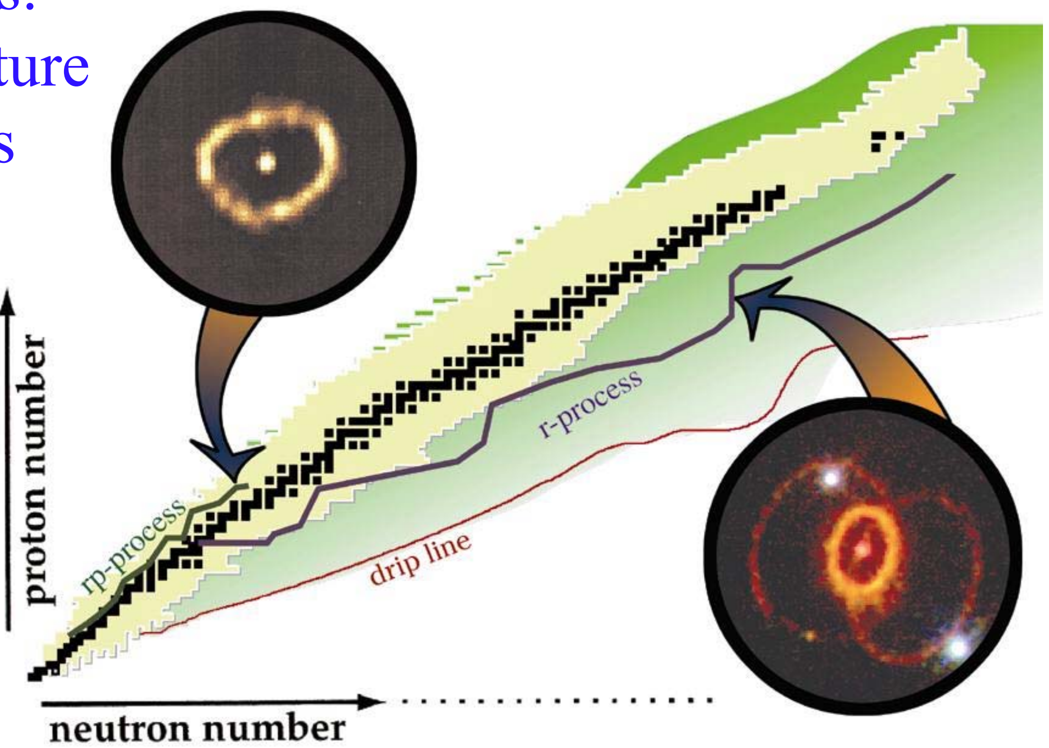
The Objective …

To explain this:



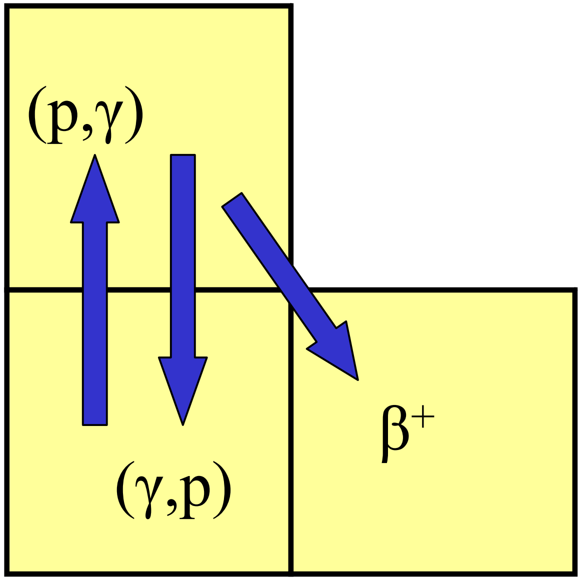
Creation of the elements

rp-process:
rapid capture
of protons



r-process:
rapid capture
of neutrons

Mass-dependent signatures



$$\text{time} - \text{scale} \propto \frac{e^{-\frac{Q}{kT}}}{A(Q)}$$

$$\text{isotope production} \propto A(Q) \cdot e^{\frac{Q}{kT}}$$

$$\text{energy production} \propto A(Q) \cdot Q \cdot e^{\frac{Q}{kT}}$$

Common parameter: Q (mass difference)

In equilibrium: (p,γ) ↔ (γ,p)

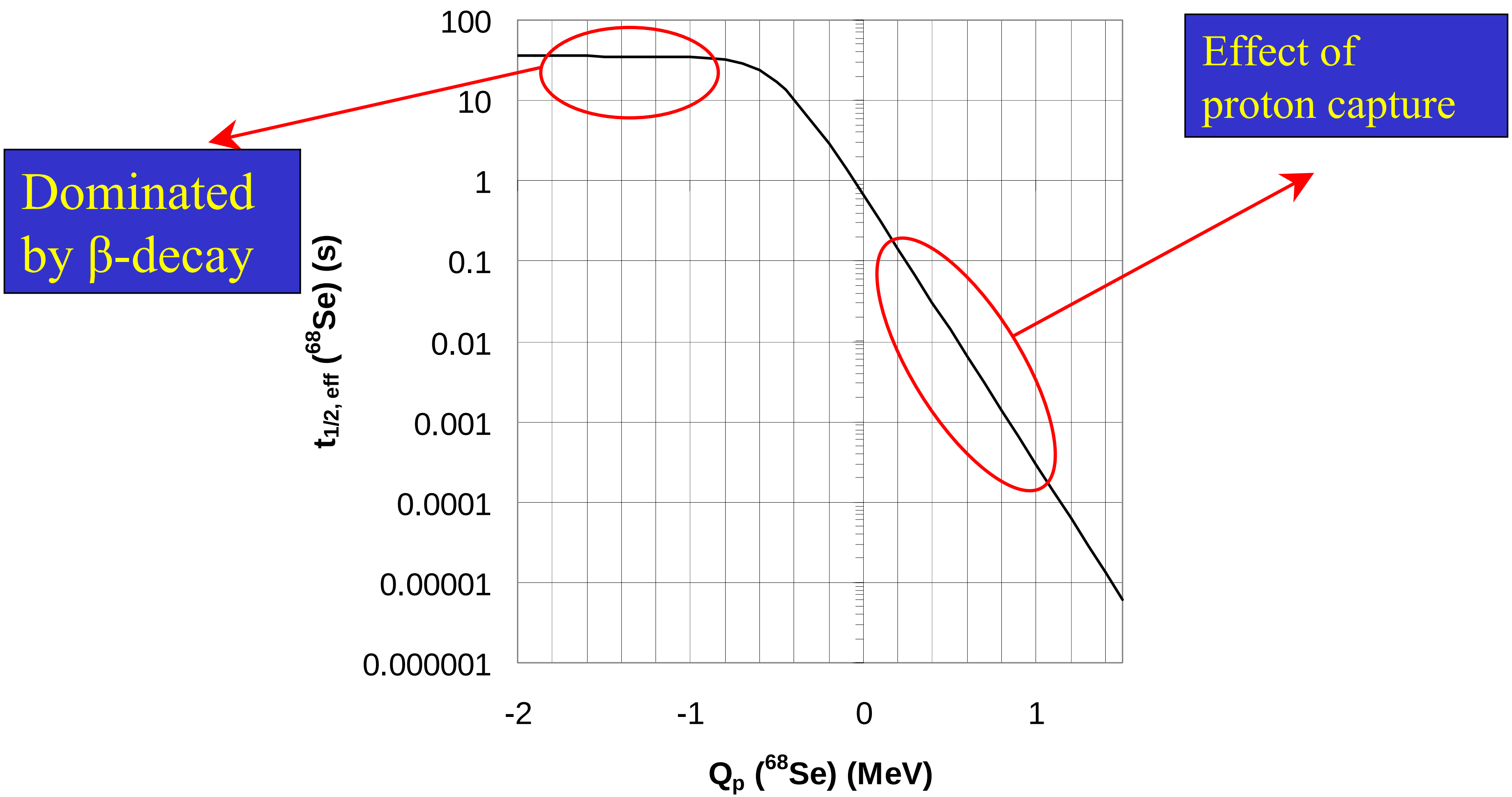
Process stalls until β-decay -- waiting-point nuclide

To determine equilibrium, need Q_p

Precision required ~ kT ~ 100 keV (~ $1.5/10^6$)

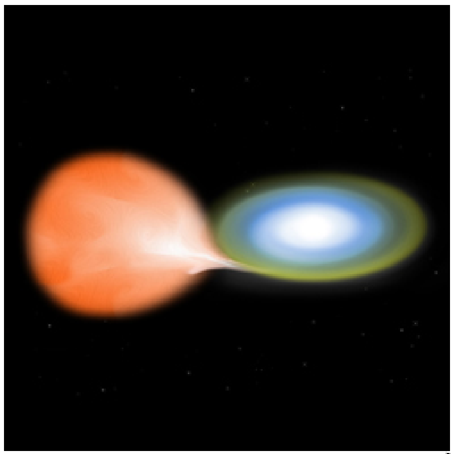
Effective lifetime of waiting-point nuclides

$$\lambda_{effective} = \lambda_\beta + \lambda_p \qquad \lambda_p \propto \exp\{Q_p/kT\}$$



Astrophysical rp-process

From: www.nscl.msu.edu/research/ria/whitepaper.pdf



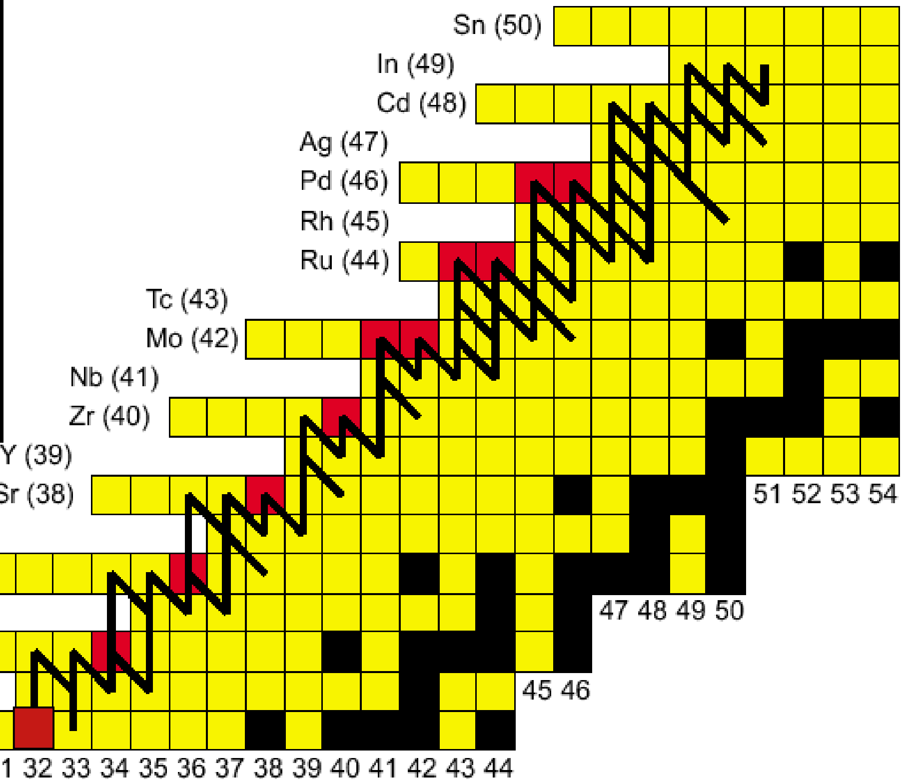
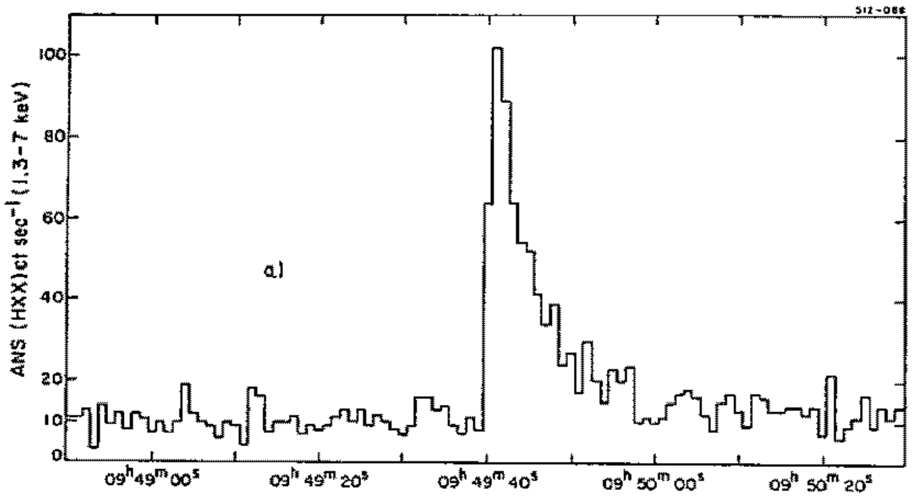


Figure 7: rp-process path predicted by network calculations. The waiting points are indicated in red, other proton-bound nuclei in yellow. Adapted from [sch98a].

Timescale

X-ray burst



Timescale of X-ray burst:

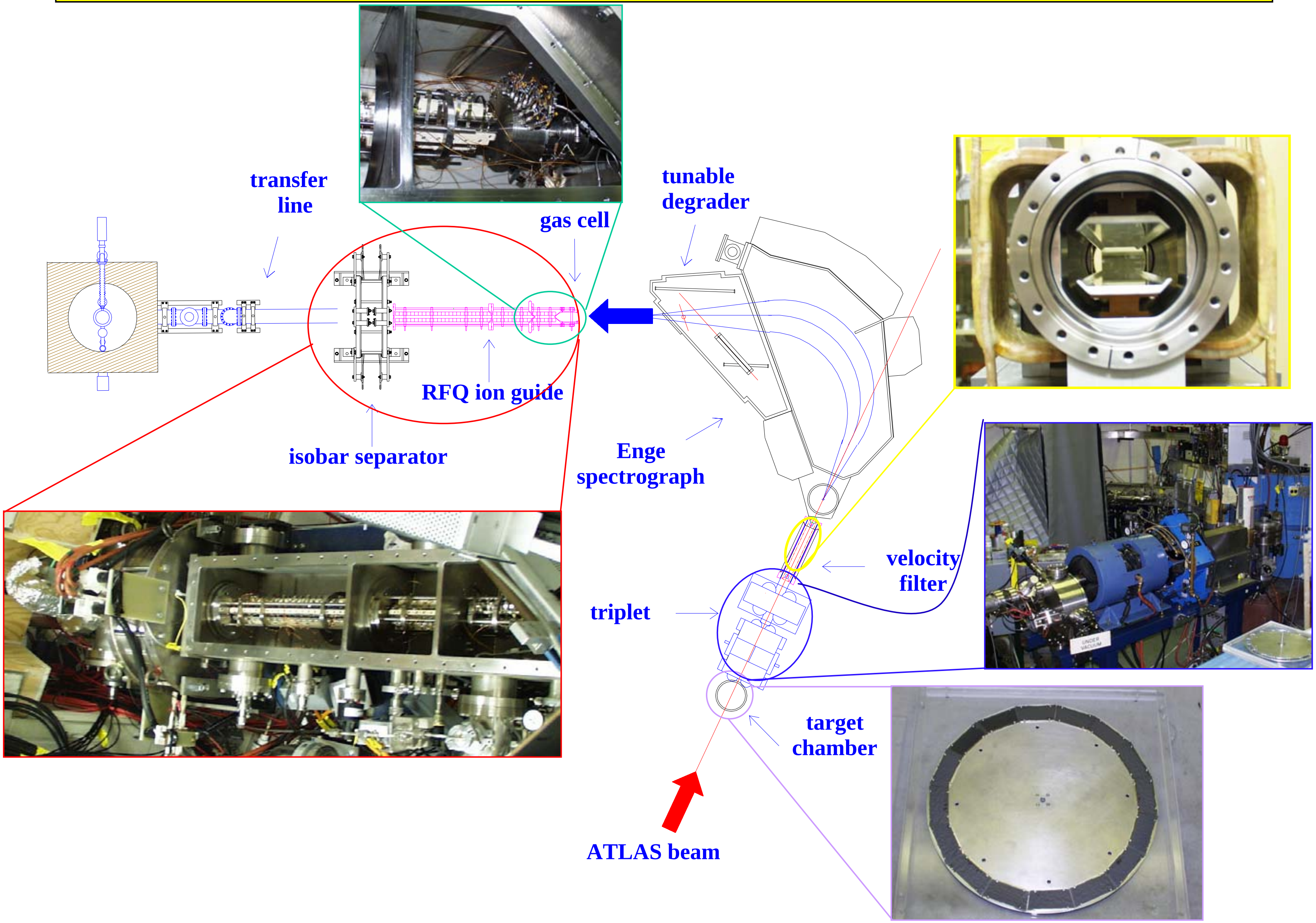
10-100 seconds

Waiting-point nuclide	β-decay half-life
^{64}Ge	63.7 s
^{68}Se	35.5 s
^{72}Kr	17.2 s
^{76}Sr	8.9 s
^{80}Zr	4.6 s

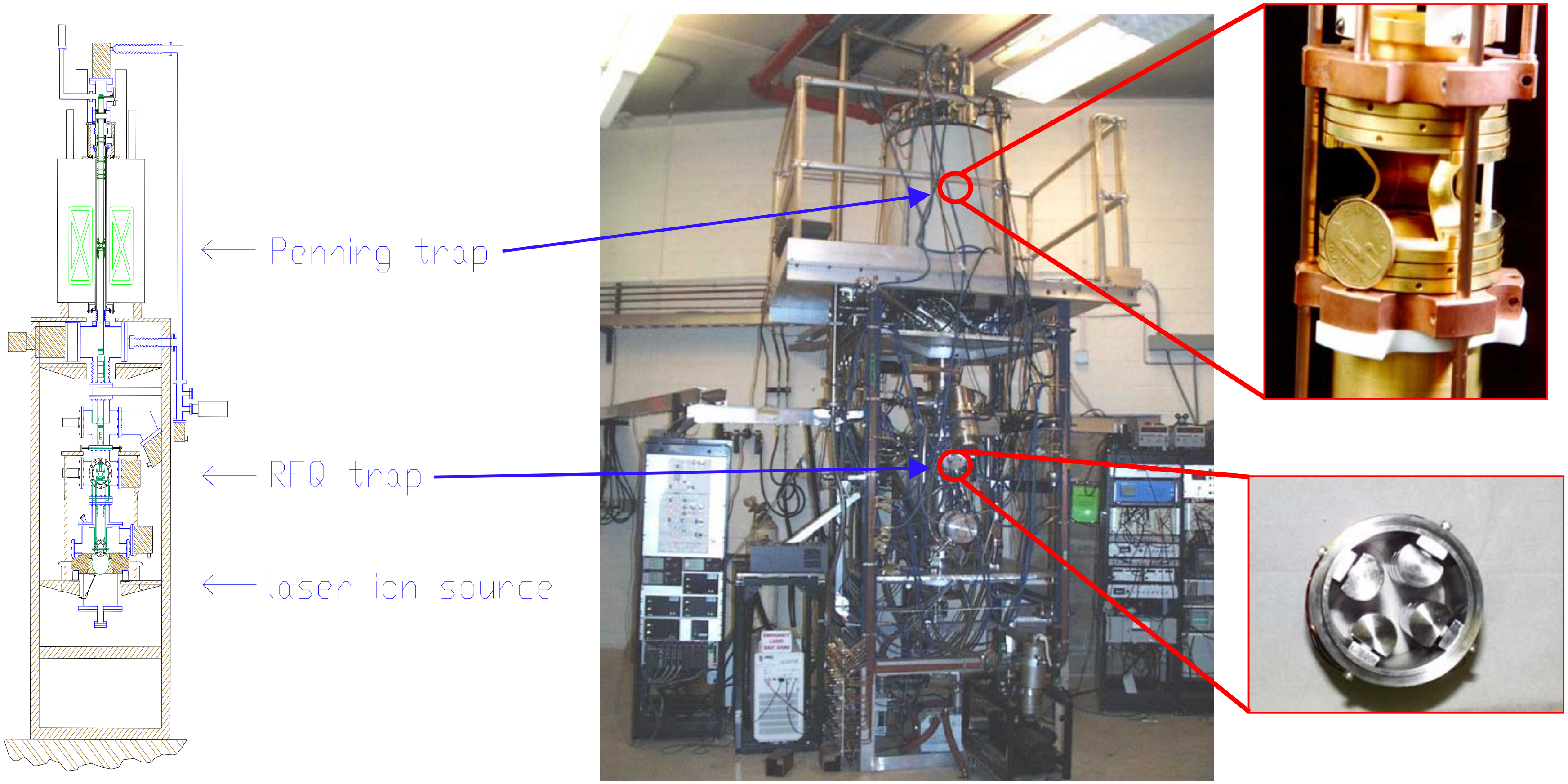
The most important waiting-point nuclides to investigate:

^{64}Ge and ^{68}Se

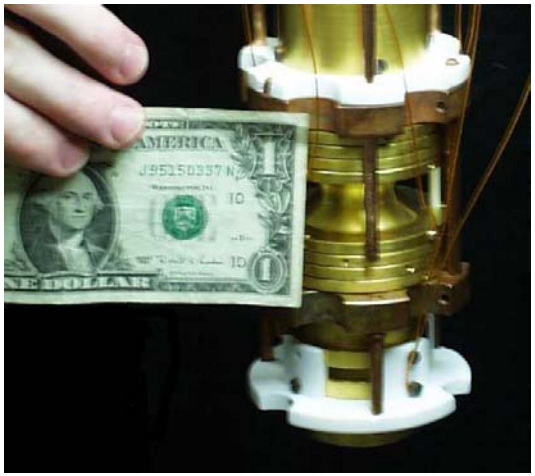
Overview of the CPT apparatus at ANL



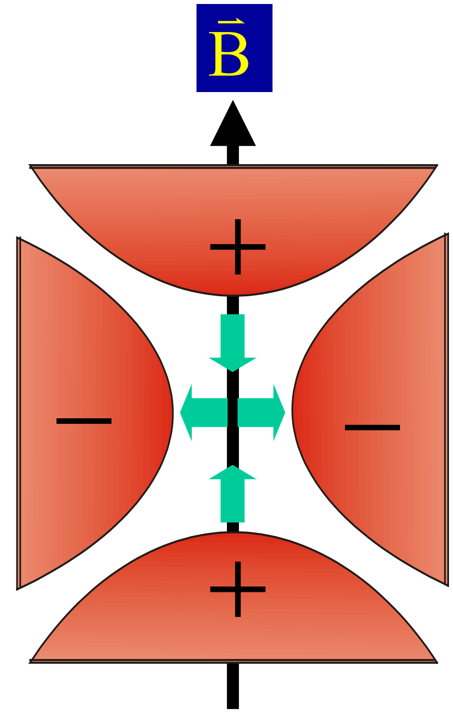
The CPT at ANL



Penning trap mass spectrometry



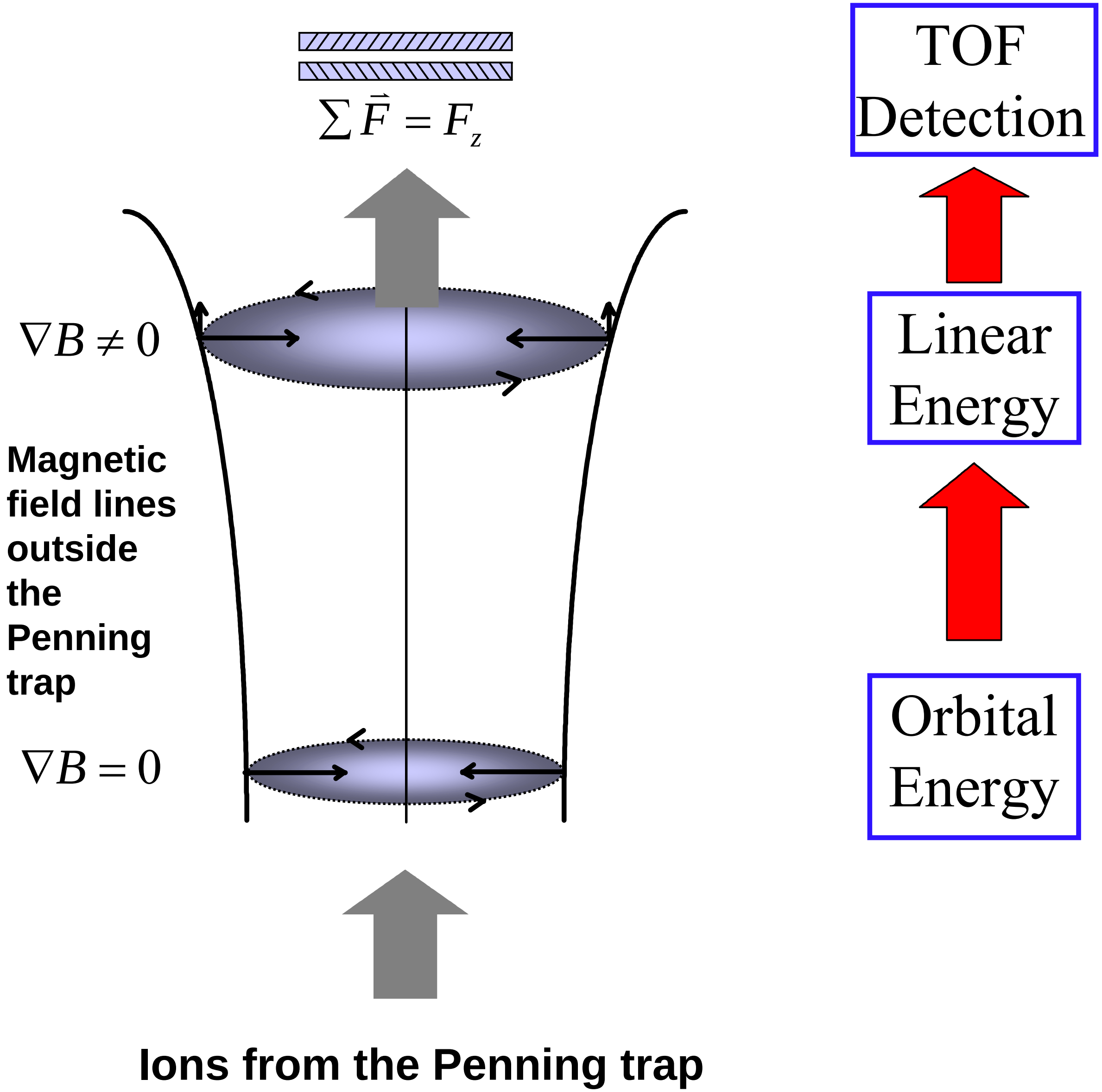
$$\omega_c = \frac{qB}{m}$$



A homogeneous magnetic field provides radial confinement and an axially harmonic electric potential provides axial confinement.

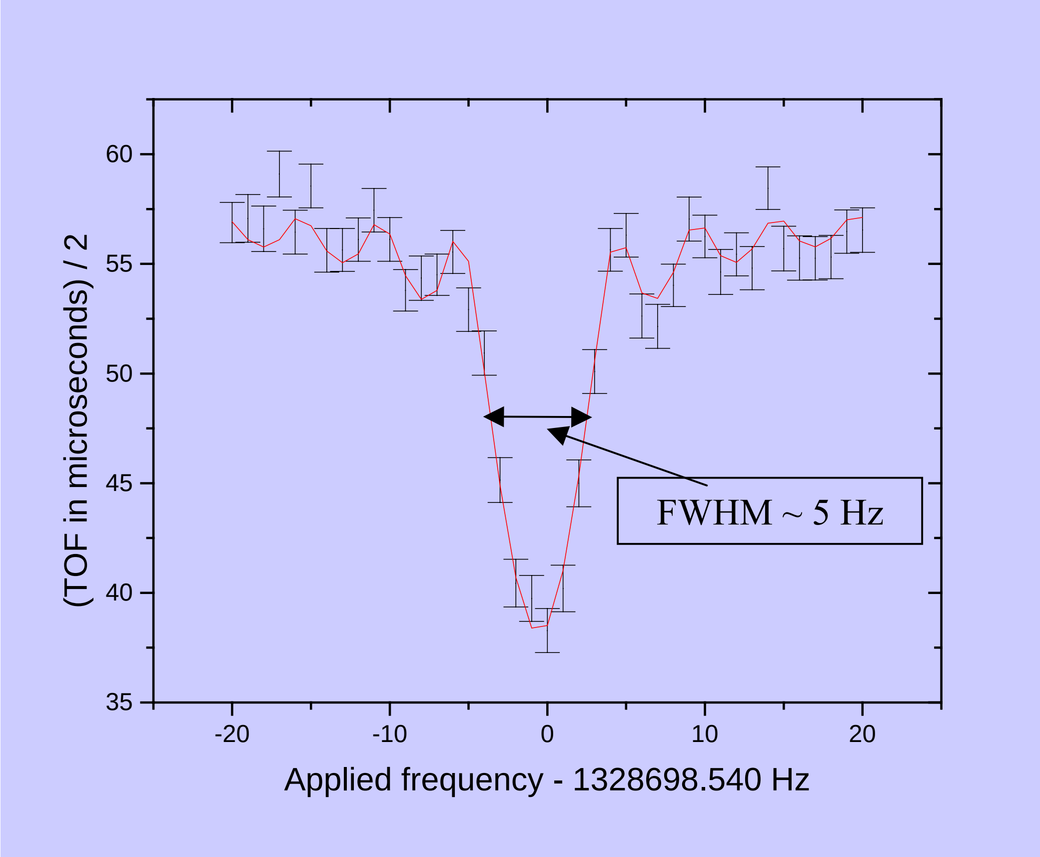
Since ω_c depends upon the magnetic field strength and the mass of the ion, and not on the electric fields, accurate and precise mass measurements can be made.

Conversion of radial energy to axial energy



Sample TOF spectra

Calibration: $C_5 H_8$



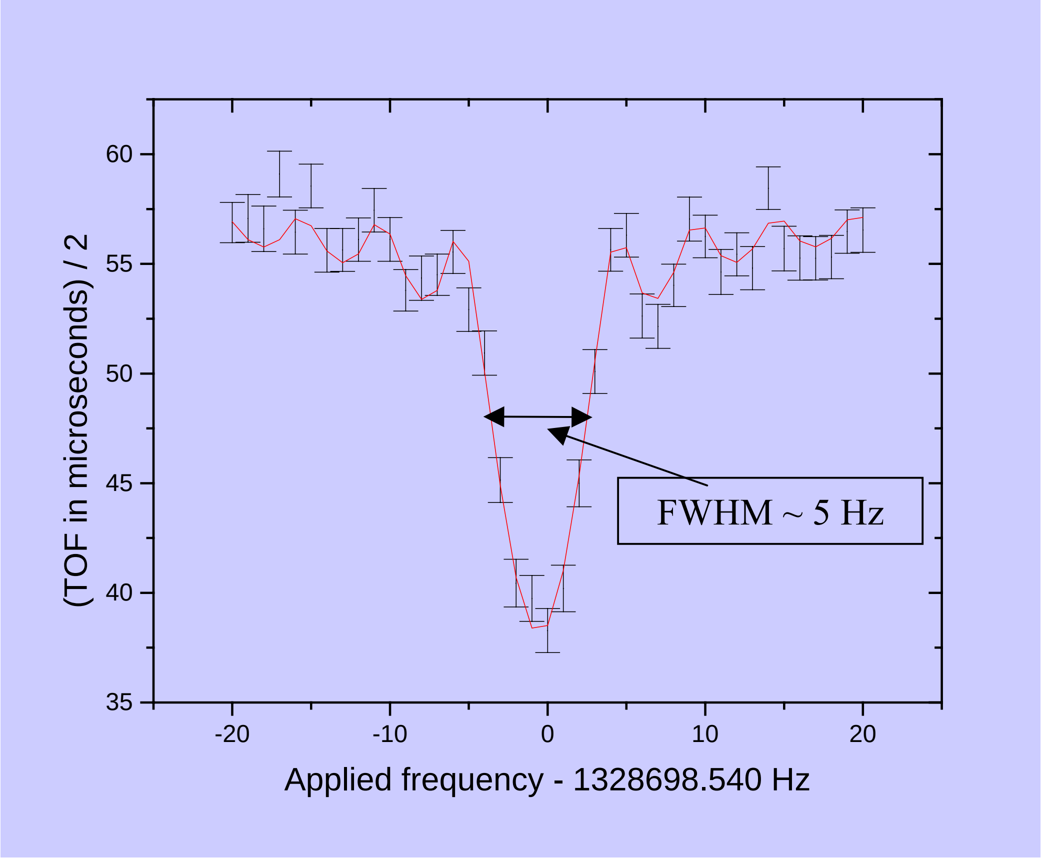
$$\omega_c = \frac{qB_c}{m_c}$$

Unknown: $\omega_? = \frac{qB_?}{m_?}$

$$\frac{Unknown}{Calibration} \Rightarrow m_? = \frac{m_c \omega_c}{\omega_?}$$

Sample TOF spectra

Calibration: $C_5 H_8$

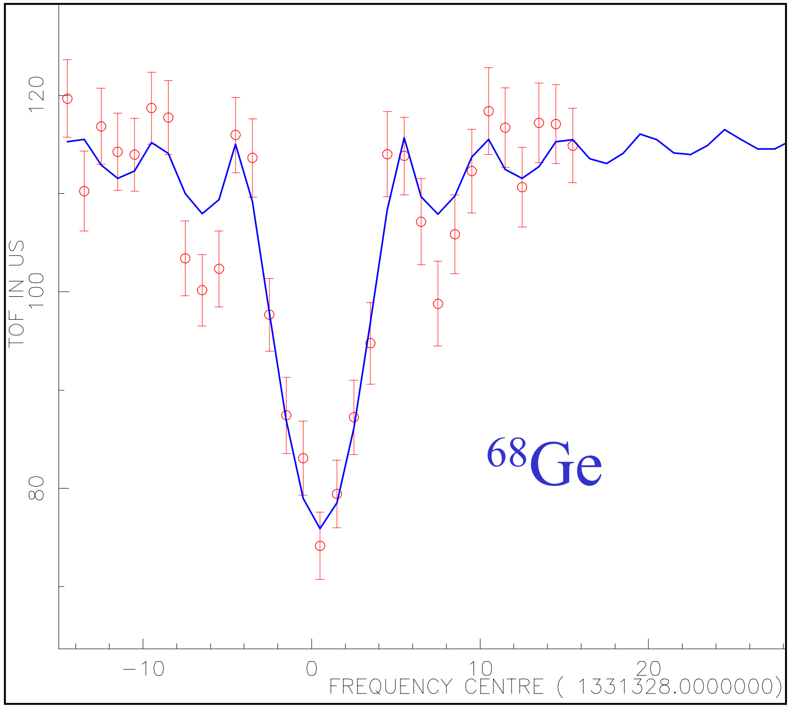


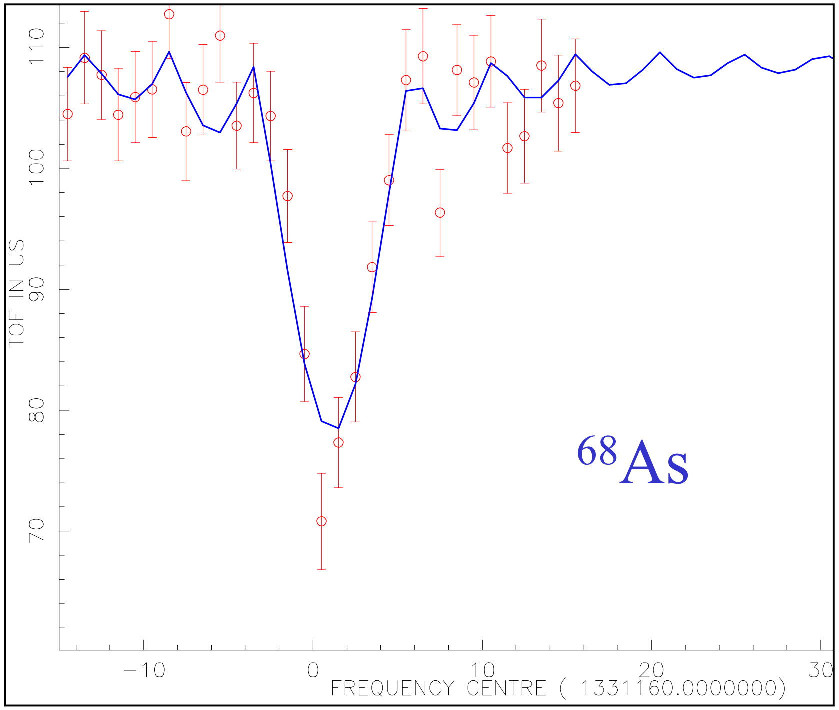
$$\text{Resolution} = \frac{\Delta\omega_{FWHM}}{\omega}$$

$$\Delta\omega_{FWHM} \sim \frac{0.9}{T_{RF}}$$

$$\text{Precision, } \frac{\text{m}}{\Delta \text{m}} \propto \frac{T_{RF}\, qB\sqrt{N}}{m}$$

Measurements along the rp-process





6400 ions

15 minutes

7 ions/second

6250 ions

15 minutes

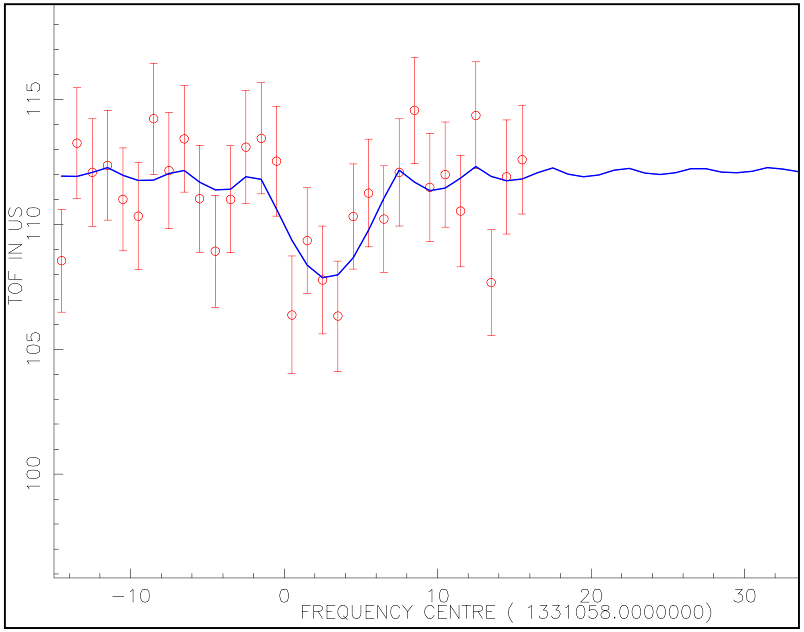
7 ions/second

Resonance obtained of ^{68}Se

200 ms excitation

FWHM ~ 5 Hz

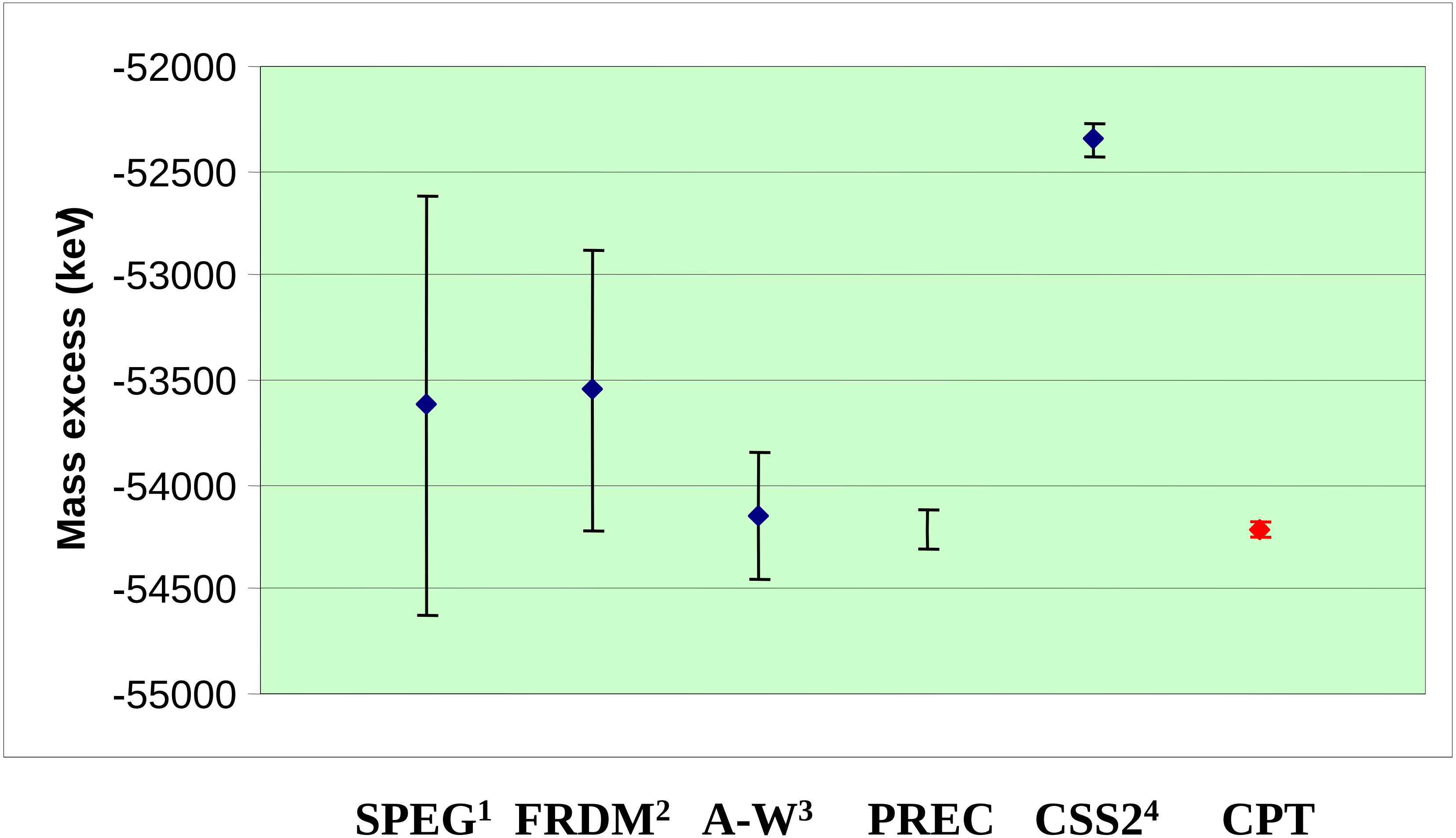
~ 250 keV



With all data collected, m = 67 941 779 (20) μu

(a precision of ~ $3/10^7$)

How does this measure up?



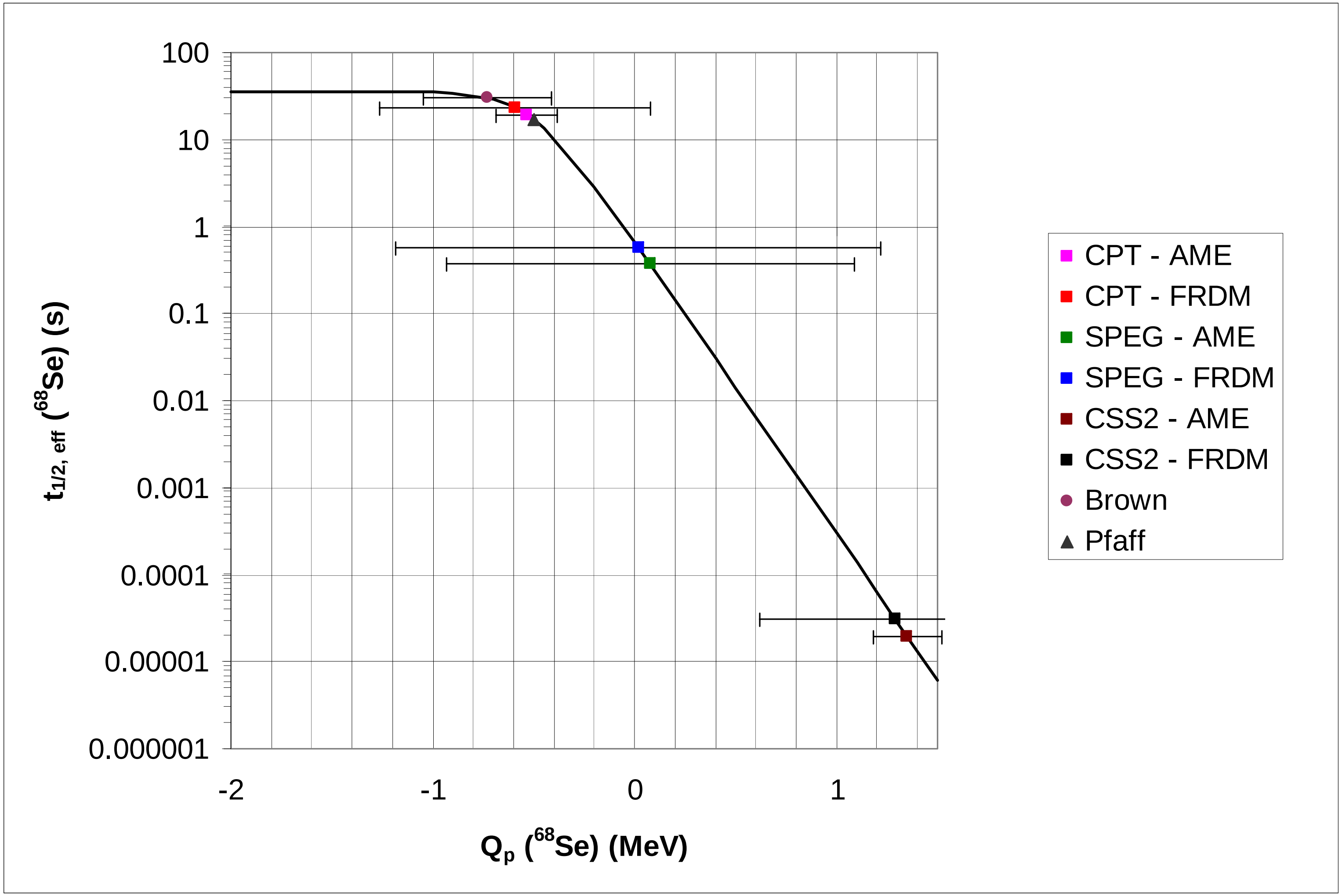
[1]G.F. Lima et al., Phys. Rev. C **65,** 044618 (2002).

[2]P. Möller et al., At. Data Nucl. Data Tables **59,** 185 (1995).

[3]G. Audi and A.H. Wapstra, Nucl. Phys. **A595,** 409 (1995).

[4]A.S. Lalleman et al., Hyperfine Interact. **132**, 315 (2001).

Effective lifetime of the waiting-point nuclide ^{68}Se



Mass measurements along the rp-process

From: www.nscl.msu.edu/research/ria/whitepaper.pdf

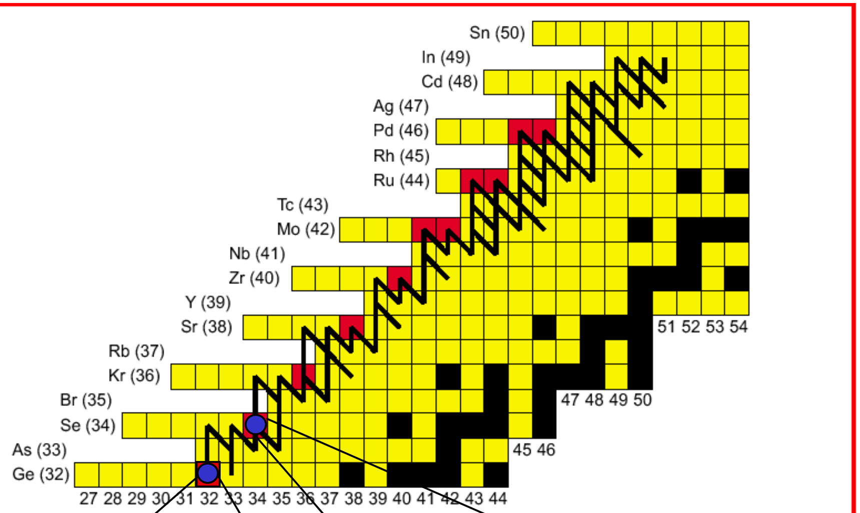
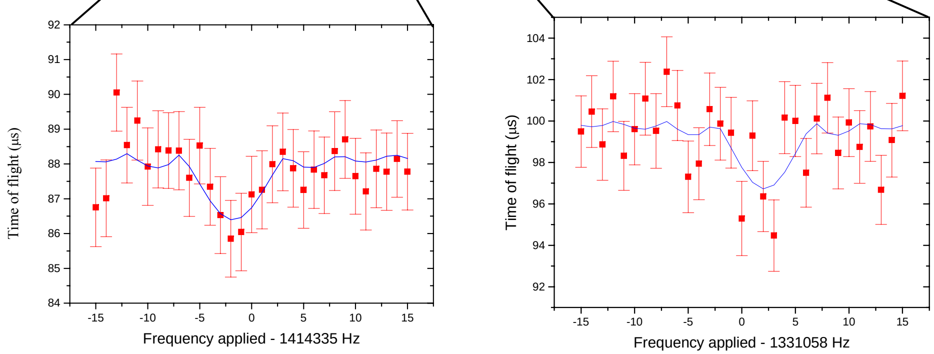
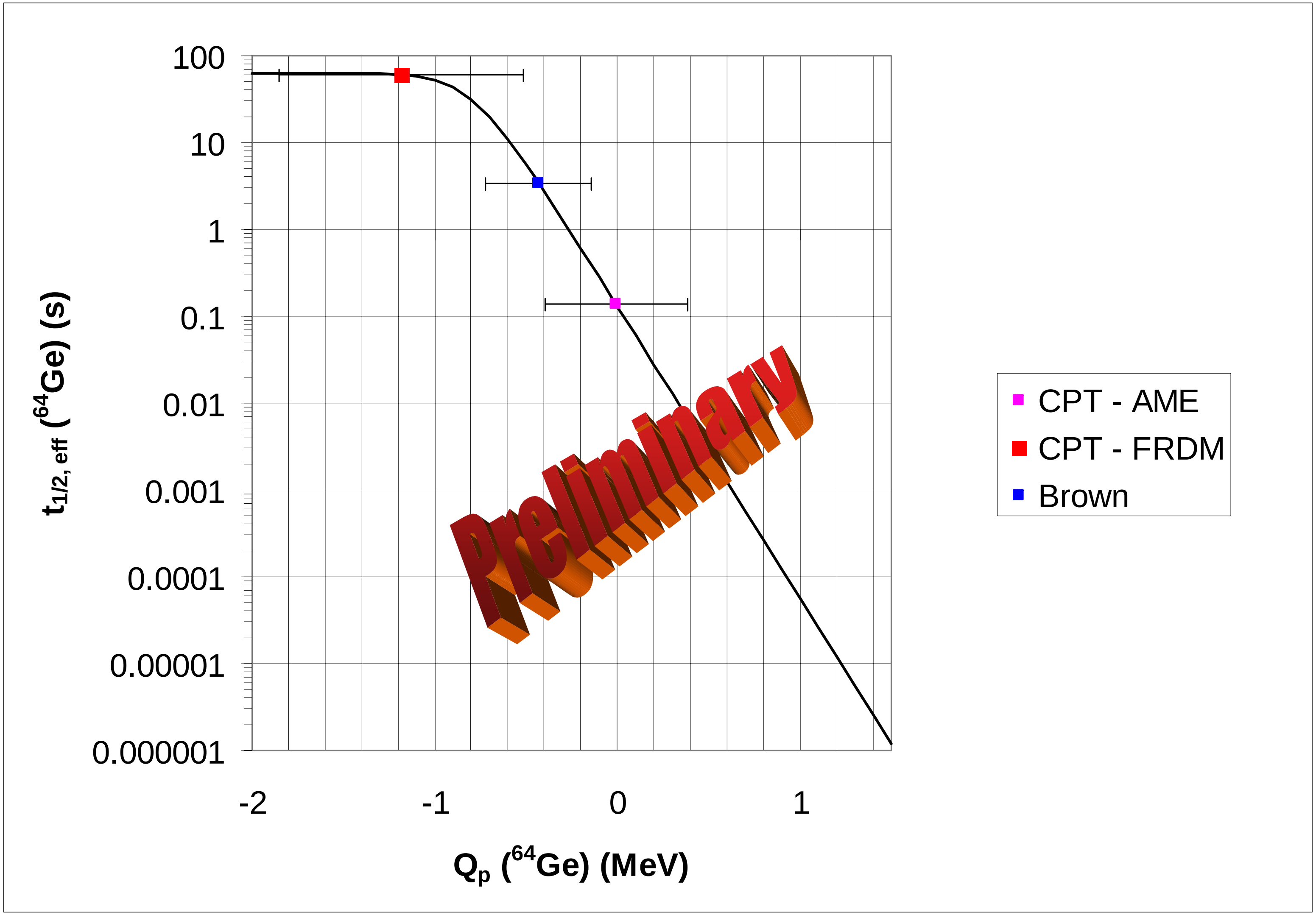


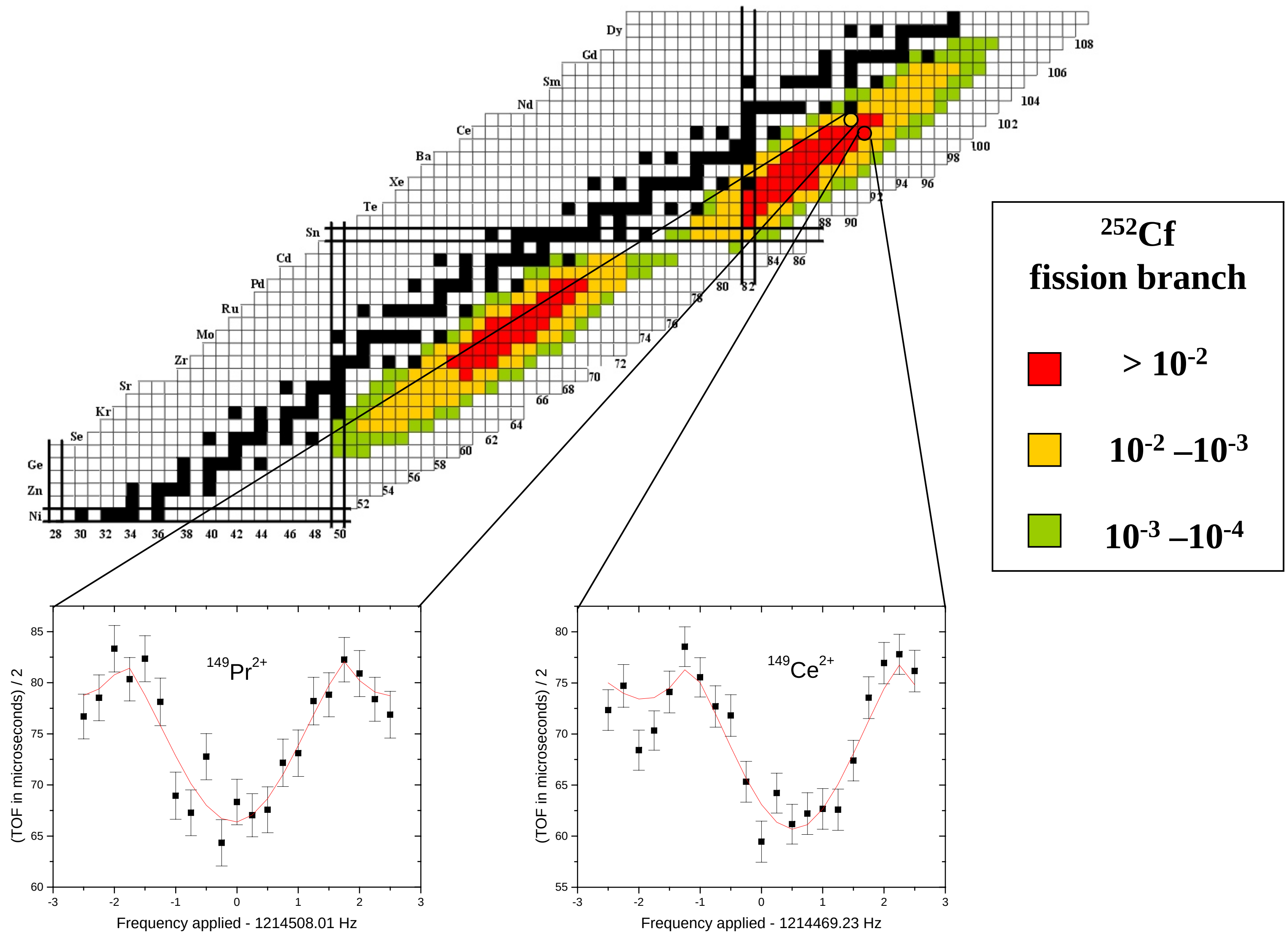
Figure 7: rp-process path predicted by network calculations. The waiting points are indicated in red, other proton-bound nuclei in yellow. Adapted from [sch98a].



Effective lifetime of the waiting-point nuclide ^{64}Ge

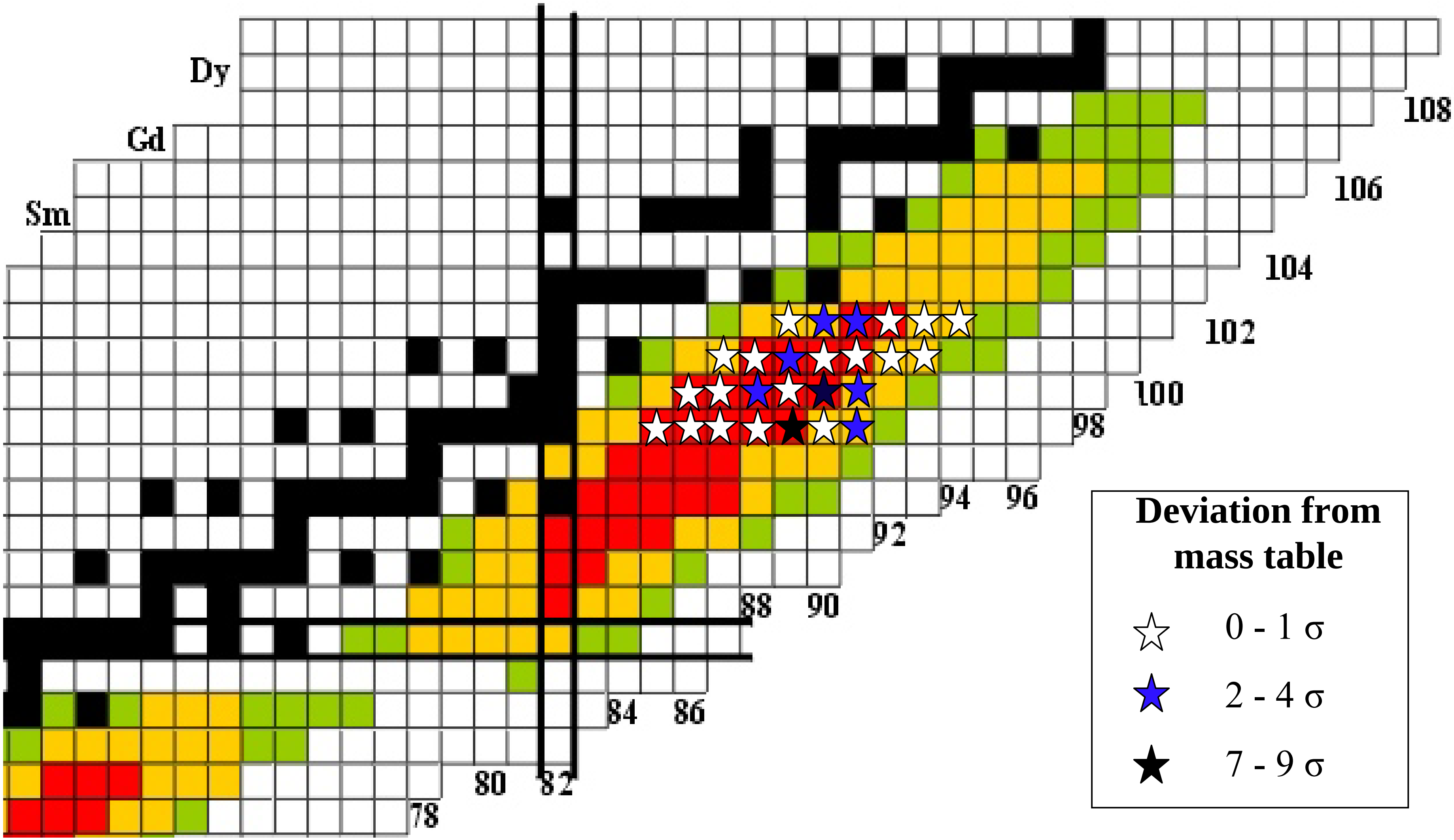


Measurement of neutron-rich nuclides

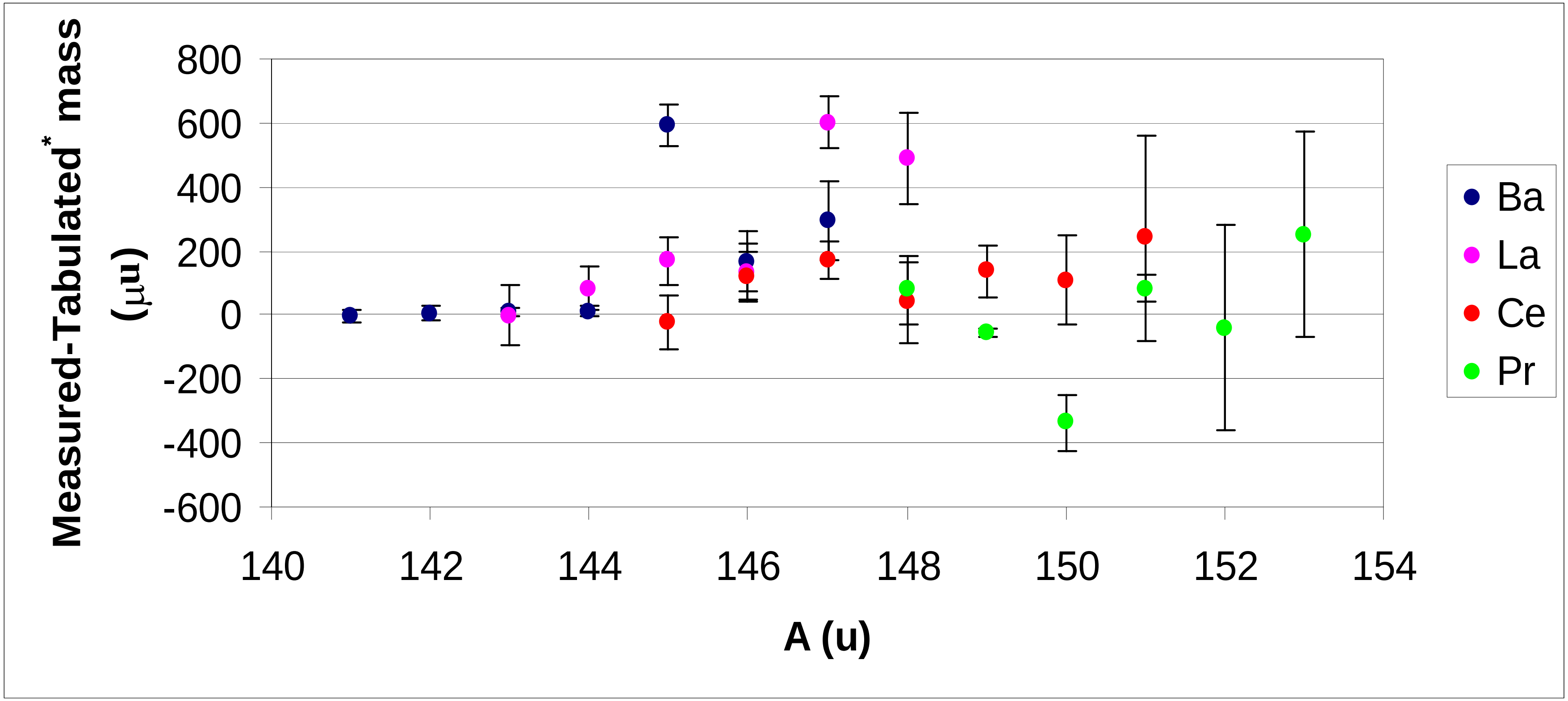


Data obtained

26 neutron-rich isotopes measured

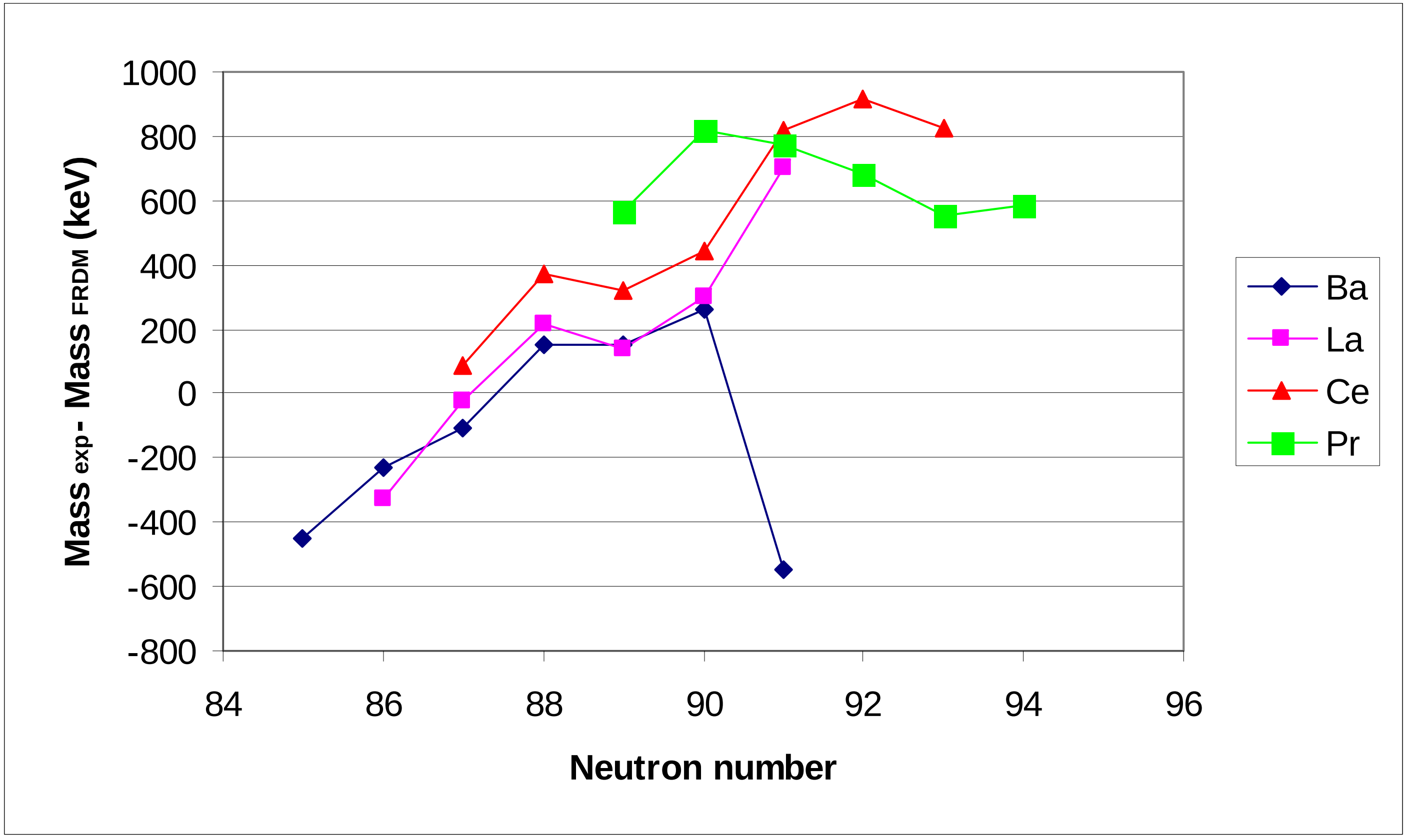


Fission fragment results

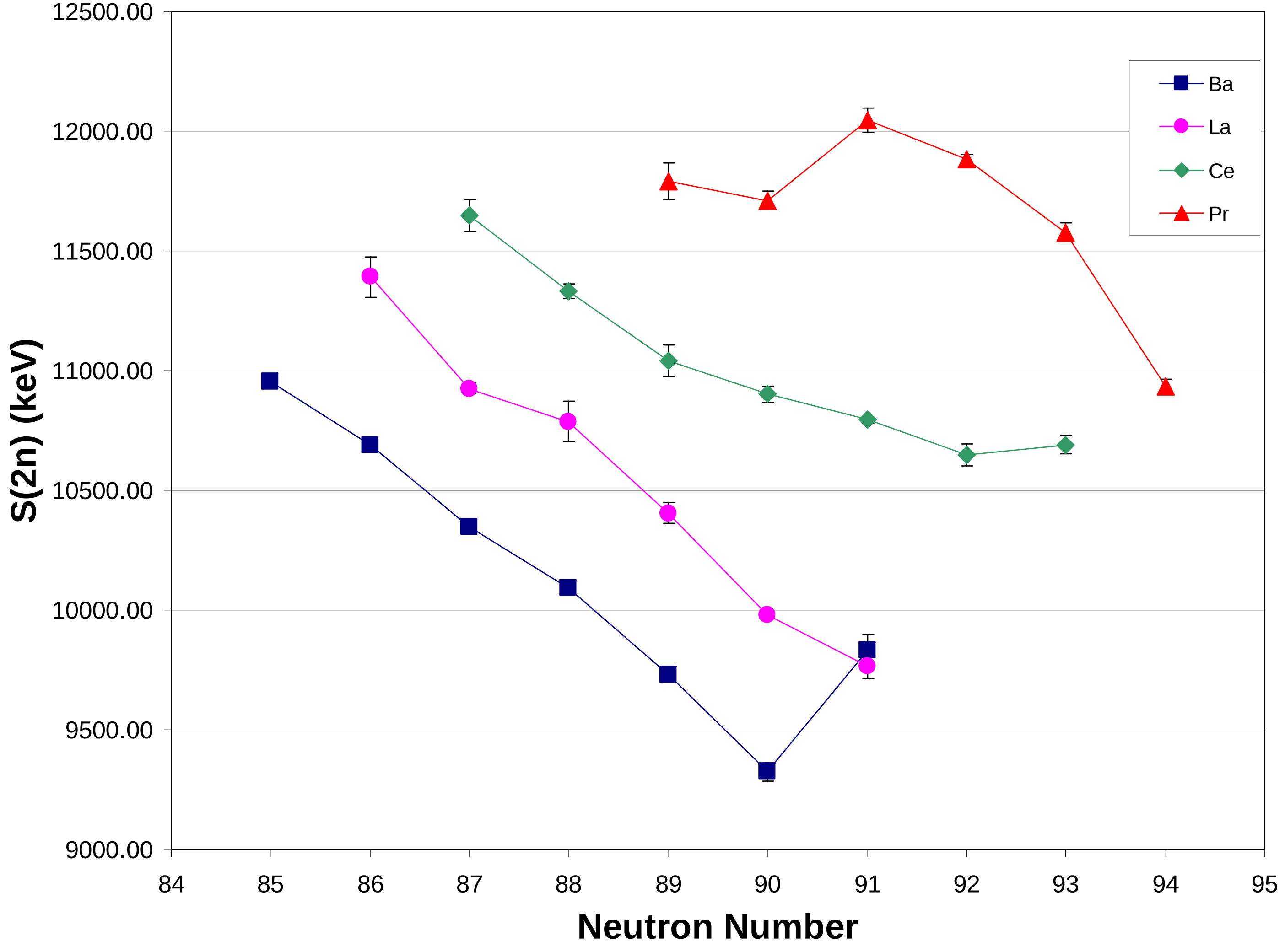


*G. Audi and A.H. Wapstra, Nucl. Phys. **A595,** 409 (1995)

Comparison with the FRDM



S(2n) plot


12500.00
12000.00
11500.00
11000.00
10500.00
10000.00
9500.00
9000.00
S(2n) (keV)
84
85
86
87
88
89
90
91
92
93
94
95
Neutron Number
Ba
La
Ce
Pr

Summary

- Elements heavier than iron are created from explosive astrophysical events (rp-process and r-process)
- Timescale of rp-process is dominated by the waiting-point nuclides
    - Effective lifetime depends on Q_p (ie: mass)
- Nuclides of interest are created and transferred to the Penning trap with a novel injection system for weakly-produced, short-lived isotopes
- Measurements made of ^{68}Se, ^{64}Ge, ^{107}Sn, ^{108}Sb, ^{145}Ba, ^{150}Pr …
    - Effect from ^{64}Ge uncertain, but ^{68}Se causes a significant delay
    - Measured masses of neutron-rich isotopes are less bound than predicted
        - where's the neutron drip-line???
        - where does the r-process path occur???

CPT Collaboration

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