Precise mass measurements of nuclides approaching the r-process

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• Introduction
  – How the elements in the universe were created
    – r-process
    – Why mass measurements are required

• How mass measurements are made with the CPT

• Results
  – Mass measurements approaching the r-process
  – Comparisons with mass models

• Summary
The Objective ...

To explain this:
Creation of the elements

rp-process: rapid capture of protons

Masses of nuclides along the paths are needed to determine the exact path the processes take.

r-process: rapid capture of neutrons
Possible sources of the r-process

r-process environment:  \[ T \sim 1-2 \text{ GK} \]
\[ n_n \sim 10^{24} / \text{cm}^3 \]

Supernovae???

Merging neutron stars???
In equilibrium: \((n,\gamma) \leftrightarrow (\gamma,n)\)

Process stalls until \(\beta\)-decay -- waiting-point nuclide

To determine equilibrium, need \(S_n\)
Abundances:

\[ \frac{Y(Z, A+1)}{Y(Z, A)} = n_n \frac{G(Z, A+1)}{2G(Z, A)} \left[ \frac{A+1}{A} \frac{2\pi\hbar^2}{m_u kT} \right]^{3/2} \exp \left( \frac{S_n}{kT} \right) \]

- \( Y(Z, A) \equiv \) abundance of nuclide (Z, A)
- \( n_n \equiv \) neutron number density
- \( m_u \equiv \) mass of 1 u
- \( G(Z, A) \equiv \) nuclear partition function
- \( S_n \equiv \) neutron separation energy

**Abundance maxima:**

\[ \frac{dY}{dA} = 0 \]

\[ S_n = kT \ln \left[ \frac{2}{n_n} \left( \frac{m_u kT}{2\pi\hbar^2} \right)^{3/2} \right] \]

*Independent of neutron capture cross-section!!!
Mass-dependence

\[ S_n = kT \ln \left( \frac{2}{n_n} \left( \frac{m_u kT}{2\pi \hbar^2} \right)^{3/2} \right) \]

For \( T=1.5 \text{ GK}, \ n_n=10^{24} / \text{cm}^3, \ S_n \sim 3 \text{ MeV} \)

Due to pairing effects, can look at \( S_{2n} \) instead with:

\[ S_{2n} = 2S_n \]
So why not use mass models???
Validity of waiting-point approximation

Overview of the CPT apparatus at ANL
The CPT at ANL

Penning trap

RFQ trap

laser ion source
How a Penning trap works

- constant axial magnetic field
- particle orbits in horizontal plane
- \( \omega_c = \frac{qB}{m} \)
- free to escape axially
How a Penning trap works

- Add an axial harmonic electric field to confine particles
- Axial oscillations:
  \[ \omega_z = \sqrt{\frac{eV}{md^2}} \]
How a Penning trap works

Radial motion is split into two components by the electric field:

\[ \omega_{\pm} = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}} \]
How a Penning trap works

However: \( \omega_c = \omega_+ + \omega_- \)

Recall: \( \omega_c = \frac{qB}{m} \)

\( \omega_c \) depends only on:

- the mass
- the magnetic field
- not on the electric fields

Can use \( \omega_c \) to make accurate and precise mass measurements
How a Penning trap works

Dipole excitation:

Resonances at: $\omega_+$ and $\omega_-$

Quadrupole excitation:

Resonances at: $2\omega_+$, $2\omega_-$,

$\omega_+ + \omega_- = \omega_c$
Penning trap mass spectrometry

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

Since $\omega_c$ 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

\[ \sum \vec{F} = F_z \]

Magnetic field lines outside the Penning trap

\[ \nabla B \neq 0 \]

\[ \nabla B = 0 \]

Ions from the Penning trap

TOF Detection

Linear Energy

Orbital Energy
Sample TOF spectra

Calibration: $C_5H_8$

Applied frequency = 1328698.540 Hz

FWHM ~ 5 Hz

Unknown:

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

Unknown:

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

$$\frac{\text{Unknown}}{\text{Calibration}} \Rightarrow m_? = \frac{m_c \omega_c}{\omega_?}$$
Sample TOF spectra

Calibration: \( \text{C}_5 \text{H}_8 \)

Resolution \( = \frac{\Delta \omega_{\text{FWHM}}}{\omega_c} \)

\( \Delta \omega_{\text{FWHM}} \sim \frac{0.9}{T_{RF}} \)

Precision \( \propto \frac{T_{RF} q B \sqrt{N}}{m_c} \)
Measurement of neutron-rich nuclides

- Frequency applied - 1214508.01 Hz

- Frequency applied - 1214469.23 Hz

- \( ^{252}\text{Cf} \) fission branch:
  - \( > 10^{-2} \)
  - \( 10^{-2} - 10^{-3} \)
  - \( 10^{-3} - 10^{-4} \)
Data obtained

Deviation from mass table

🌟 0 - 1 σ
🌟🌟 2 - 4 σ
🌟🌟🌟 7 - 9 σ
Fission fragment results

![Graph showing fission fragment results]

Fission fragment results

Comparison with the FRDM

The graph compares the experimental mass (Mass $^{\text{exp}}$) with the mass predicted by the FRDM model (Mass $^{\text{FRDM}}$) in keV, as a function of the neutron number. The data points for Ba, La, Ce, and Pr are shown, indicating the deviation between the two models.
$S_{2n}$ for Ba isotopes

![Graph showing $S_{2n}$ for different isotopes of Barium. The graph includes data points for AME 2003, FRDM, CPT, and HFBCS-1.]
$S_{2n}$ for La isotopes
$S_{2n}$ for Ce isotopes

![Graph showing $S_{2n}$ for Ce isotopes](image)
$S_{2n}$ for Pr isotopes

![Graph showing $S_{2n}$ for Pr isotopes with varying $N$ values and different models indicated by different markers: AME 2003, FRDM, CPT, and HFBCS-1.](image-url)
Summary

• More than half of the elemental abundances with $A>70$ were created in the r-process
  • Mass measurements are required to determine the r-process path (via $S_{2n}$)
• Fission fragments from $^{252}$Cf were collected and transferred to the Penning trap with a novel injection system for weakly-produced, short-lived isotopes
• Measurements of Ba, La, Ce, and Pr isotopes have been made and are in good agreement with trends from FRDM or HFBCS-1 models
• More mass measurements are needed to further test mass model predictions approaching the neutron-drip line
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