Ion traps, atomic masses and astrophysics

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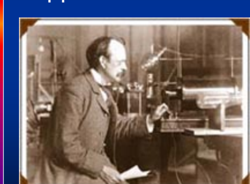
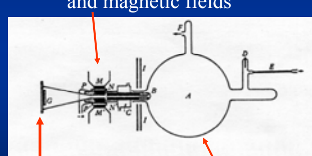
Outline

- Some history
- Atomic masses
- Ion traps
- rp-process nucleosysnthesis

British beginnings…

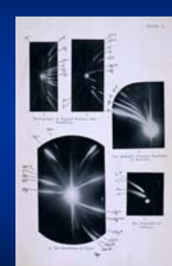
- J.J. Thomson (1913)
- Positive ray parabola apparatus





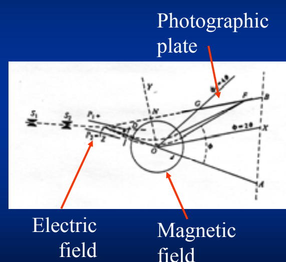
Positive ray parabolas


ISOTOPES



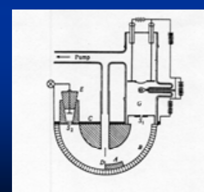
The 1st mass spectrometer

- F.W. Aston (1919)



Meanwhile back in Chicago…

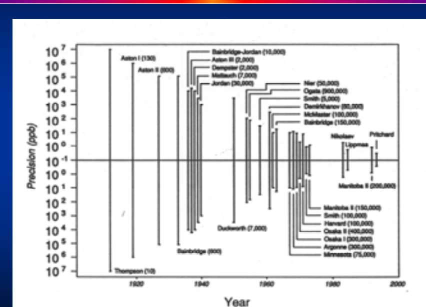
- A.J. Dempster (1918)
- Monoenergetic ion source
- Direction focusing; no energy focusing



Canadian Family Tree

- Atomic mass determinations group at the University of Manitoba

Evolution of precision

- 

Information from atomic masses

- Binding energies of nucleons

$$(B.E.)_{nuclear} = Z \cdot (M_p + M_e) + N \cdot M_n - M(Z,N) - (B.E.)_{elect}$$

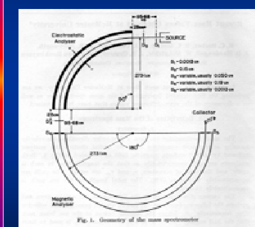
- Energy released in nuclear reactions and decays

$$Q = (M_T + M_B) - (M_P + M_E)$$

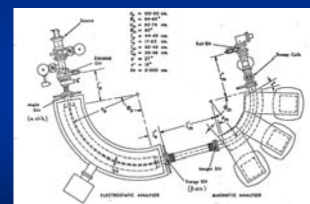
- $(B.E.)_{nuclear}$ ~ 10 MeV/nucleon
  - Differences in B.E. ~ 1MeV
  - Need to know this to 0.1- 1% (1 - 10 keV) or better in some cases.
  - Need a precision of 10 ppb or better

At the Univ. of Manitoba

- Two mass spectrometers were built:

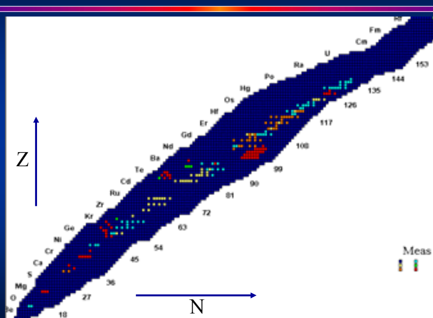


Manitoba I: "Big Ed"

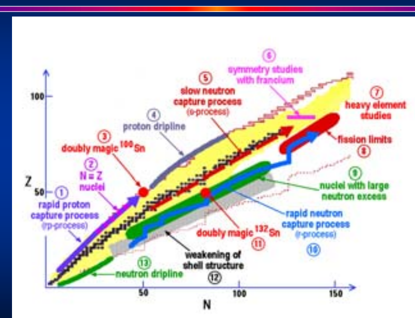


Manitoba II: "Betsy"

Measurements made



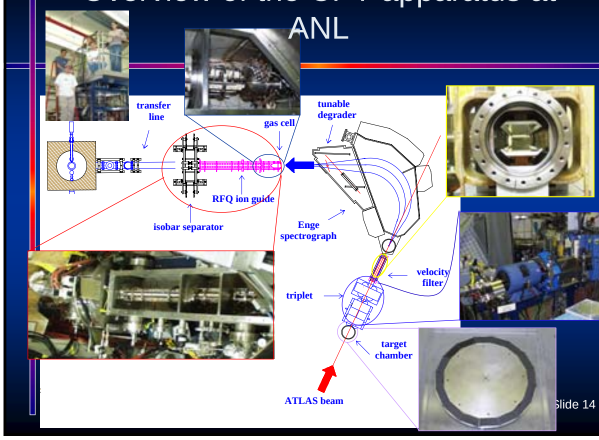
The lure of unstable nuclides



Penning Traps

- To study unstable nuclides we need:
  - Precision
  - Accuracy
  - Sensitivity
- Ion traps can provide all of these.

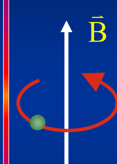
Overview of the CPT apparatus at ANL



The anatomy of a Penning trap

- Shapes of the electrodes
- Correction electrodes
- Carefully chosen materials

How a Penning Trap works-1

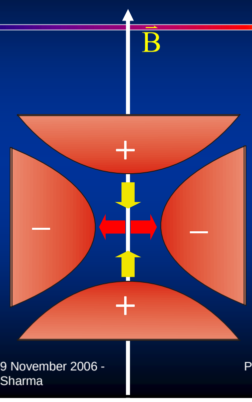


- Constant axial magnetic field
- particle orbits in horizontal plane

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

- free to escape axially

How a Penning Trap works-2



- Add an axial harmonic electric field to confine particles
- axial oscillations:

$$\omega_z = \sqrt{\frac{eV}{md^2}}$$

- Radial motion split into two components by electric field:

→ω_+ : reduced cyclotron freq.

→ω_-: magnetron frequency

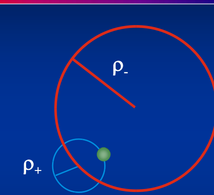
How a Penning Trap works-3

Where:

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

and

$$\omega_c = \omega_+ + \omega_-$$



Ion motion in the radial plane:

$$v_x = -\rho_+\omega_+ \sin(\omega_+ t) - \rho_-\omega_- \sin(\omega_- t)$$

$$v_y = \rho_+\omega_+ \cos(\omega_+ t) + \rho_-\omega_- \cos(\omega_- t)$$

ower absorbed by ion in electric field: $P = q\vec{v}\cdot\vec{E}$

How a Penning Trap works-4

For a dipole field:

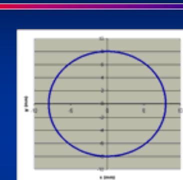
Resonances at $\omega_D = \omega_+$ and ω_-

For a quadrupole field:

Resonances at $\omega_Q = \omega_+ + \omega_- = \omega_c$

How a Penning Trap works-7

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



ω_c depends only on:

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

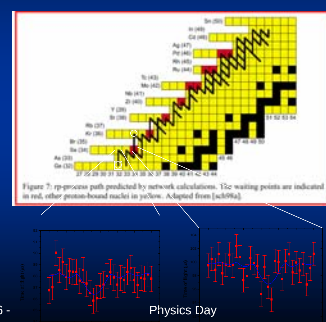
Can use ω_c to make accurate and precise mass measurements

rp-process measurements

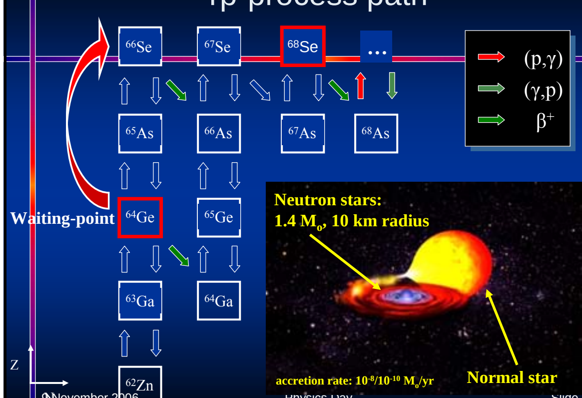
- Observed elemental abundances cannot be reproduced by only considering nuclear reactions in quiescent stars.
- Need to consider some explosive processes as well:
  - X-ray bursts – rp-process (involves proton rich nuclides)
  - Supernovae – r-process (involves neutron rich nuclides)

Mass measurements along the rp-process

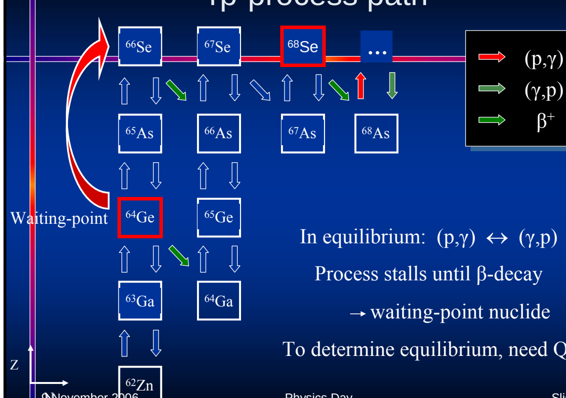
From: www.nscl.msu.edu/research/ria/whitepaper.pdf



rp-process path



rp-process path

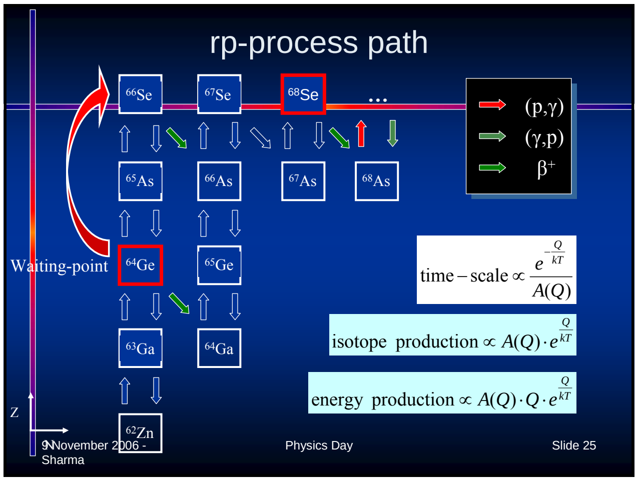


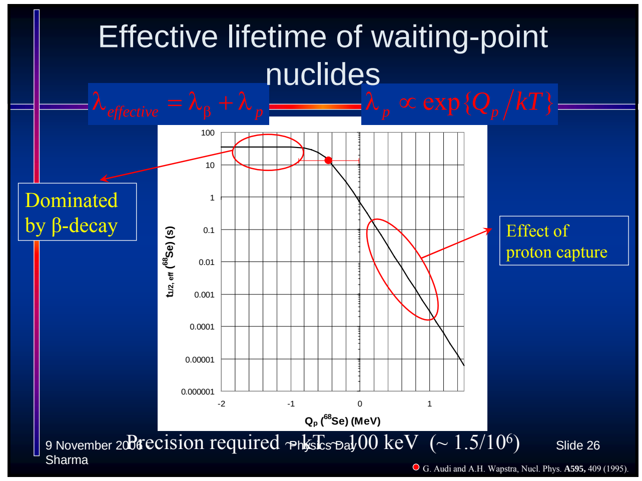
In equilibrium: (p,γ) ↔ (γ,p)

Process stalls until β-decay

→ waiting-point nuclide

To determine equilibrium, need Q_p


rp-process path
66Se
67Se
68Se
...
65As
66As
67As
68As
64Ge
65Ge
63Ga
64Ga
62Zn
Waiting-point
(p,γ)
(γ,p)
β+
time – scale ∝ e^(−Q/kT) / A(Q)
isotope production ∝ A(Q)·e^(Q/kT)
energy production ∝ A(Q)·Q·e^(Q/kT)
Z
N
9 November 2006 - Sharma
Physics Day
Slide 25


Effective lifetime of waiting-point nuclides
λ_effective = λ_β + λ_p
λ_p ∝ exp{Q_p/kT}
Dominated by β-decay
Effect of proton capture
t1/2, eff (68Se) (s)
Qp (68Se) (MeV)
Precision required ~kT ~ 100 keV (~ 1.5/10^6)
G. Audi and A.H. Wapstra, Nucl. Phys. A595, 409 (1995).
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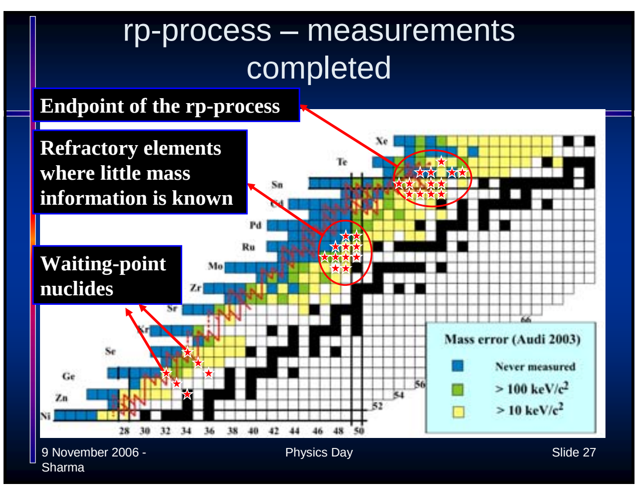
Slide 26


rp-process – measurements completed
Endpoint of the rp-process
Refractory elements where little mass information is known
Waiting-point nuclides
Mass error (Audi 2003)
Never measured
> 100 keV/c2
> 10 keV/c2
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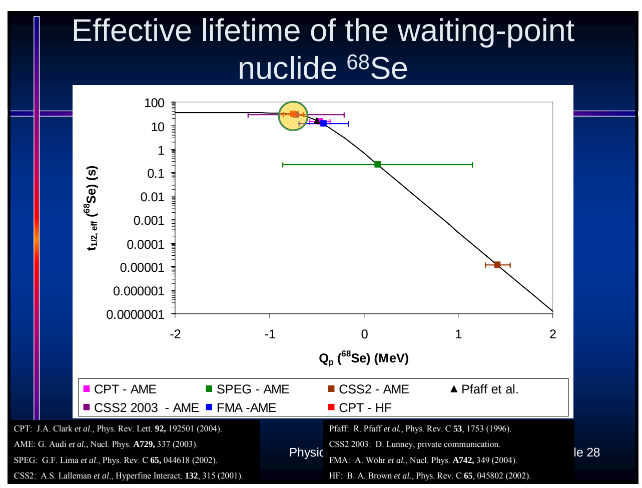
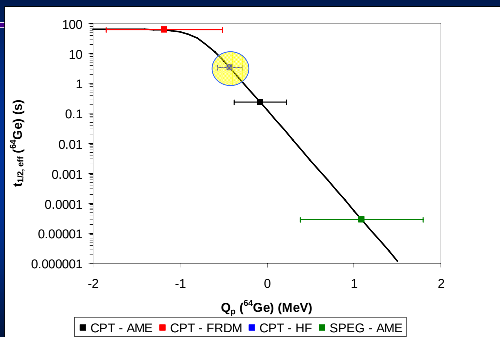

Effective lifetime of the waiting-point nuclide 68Se
t1/2, eff (68Se) (s)
Qp (68Se) (MeV)
CPT - AME
SPEG - AME
CSS2 - AME
Pfaff et al.
CSS2 2003 - AME
FMA -AME
CPT - HF
CPT: J.A. Clark et al., Phys. Rev. Lett. 92, 192501 (2004).
AME: G. Audi et al., Nucl. Phys. A729, 337 (2003).
SPEG: G.F. Lima et al., Phys. Rev. C 65, 044618 (2002).
CSS2: A.S. Lalleman et al., Hyperfine Interact. 132, 315 (2001).
Pfaff: R. Pfaff et al., Phys. Rev. C 53, 1753 (1996).
CSS2 2003: D. Lunney, private communication.
FMA: A. Wöhr et al., Nucl. Phys. A742, 349 (2004).
HF: B. A. Brown et al., Phys. Rev. C 65, 045802 (2002).

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



AME: G. Audi *et al.*, Nucl. Phys. **A729,** 337 (2003).
FRDM: P. Möller *et al.*, At. Data Nucl. Data Tables **59**, 185 (1995).
HF: B. A. Brown *et al.*, Phys. Rev. C **65**, 045802 (2002).
SPEG: G.F. Lima *et al.*, Phys. Rev. C **65,** 044618 (2002).

Conclusions

- A Penning trap mass spectrometer is a powerful tool for the study of exotic nuclei.
- Can make measurements that shed light on:
- Astrophysics
- Tests of fundamental symmetries
- Nuclear structure
- Others

CPT Collaboration

University of Manitoba

R.C. Barber, J.A. Clark, J. Fallis, H. Sharma, K.S. Sharma, Y. Wang

Argonne National Laboratory

B. Blank, J.P. Greene, J. Guest, A.A. Hecht, A.F. Levand, B. Lundgren, G. Savard, N. Scielzo, D. Seweryniak, I. Tanihata, W. Trimble, A.C. Villari, B.J. Zabransky

McGill

F. Buchinger, J.E. Crawford, S. Gulick, J.K.P. Lee, G. Li

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