Lawrence Livermore National Laboratory

Trapping and Fundamental Symmetries

August 1+2, 2013

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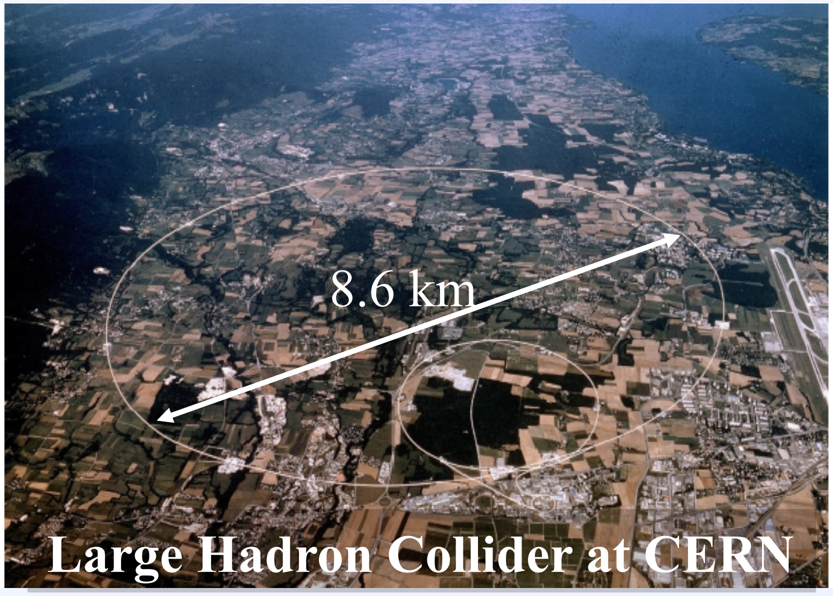
Today many nuclear science experiments use traps…

- Traps provide access to nuclear recoil following β decay
  - β-decay angular correlation measurements
  - β-delayed neutron emission
- Traps allow precision mass measurements
  - $0^+ \rightarrow 0^+$ Fermi decay
  - Neutrinoless ββ decay
  - Nuclear structure, astrophysics studies
- Traps provide other opportunities for precision atomic spectroscopy
  - Electric dipole moment searches
  - Parity violation in high-Z atoms
- Others…

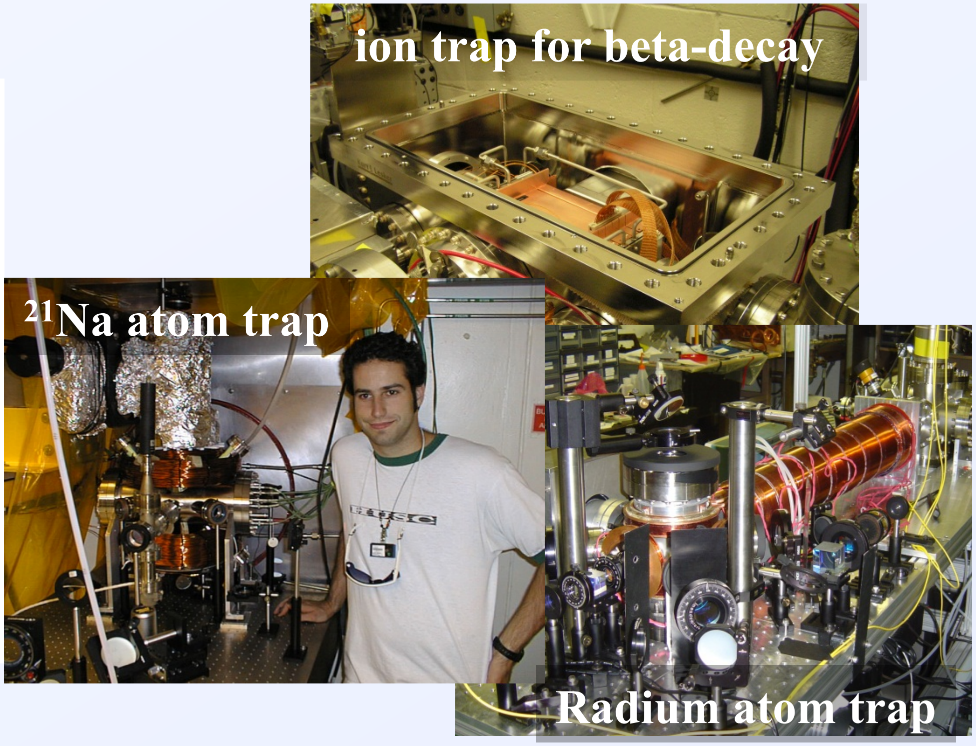
Beyond the Standard Model

High energy ··········→ *Low energy*

nuclear and atomic physics



Large Hadron Collider at CERN



ion trap for beta-decay

^{21}Na atom trap

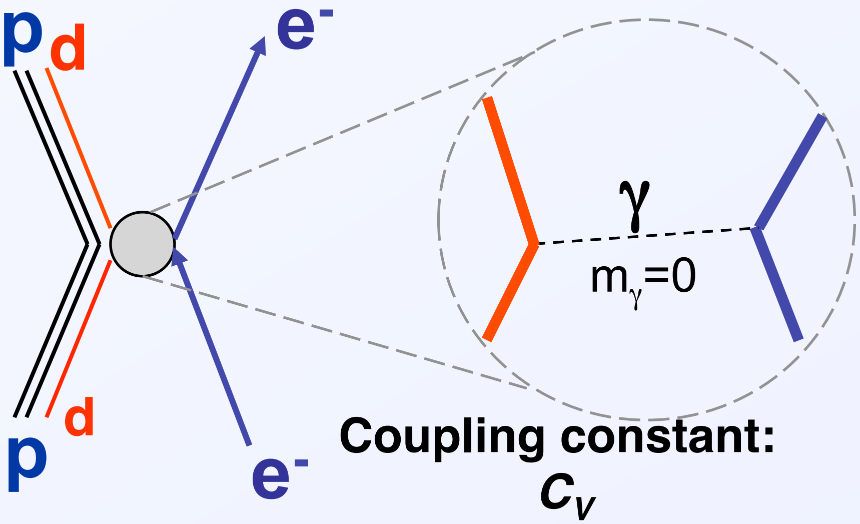
Radium atom trap

Direct searches for new phenomena and particles at colliders

Indirect searches with high precision for subtle deviations from SM predictions

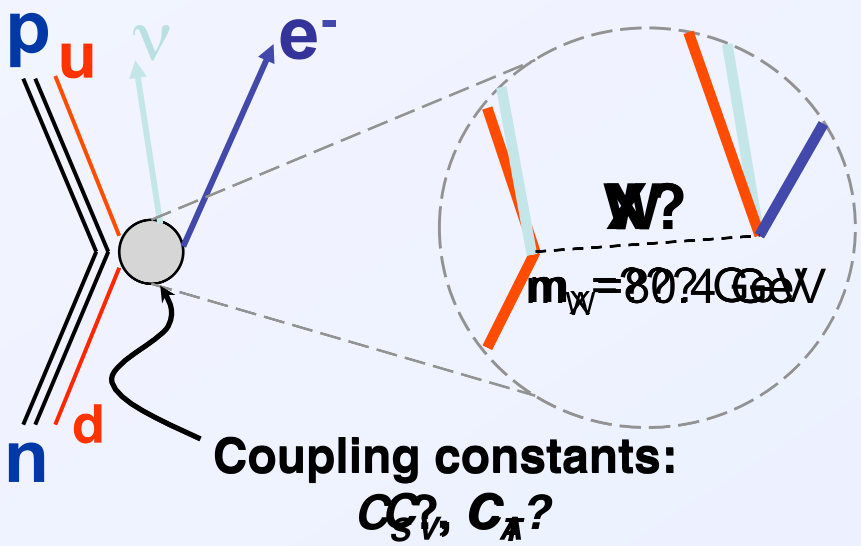
Electroweak theory predicts a symmetry between EM and weak interaction

Electromagnetism



Coupling constant:
C_V

Weak Interaction



Coupling constants:
$C_S?$, $C_T?$
C_V, C_A

1979 Nobel Prize in Physics for electroweak theory

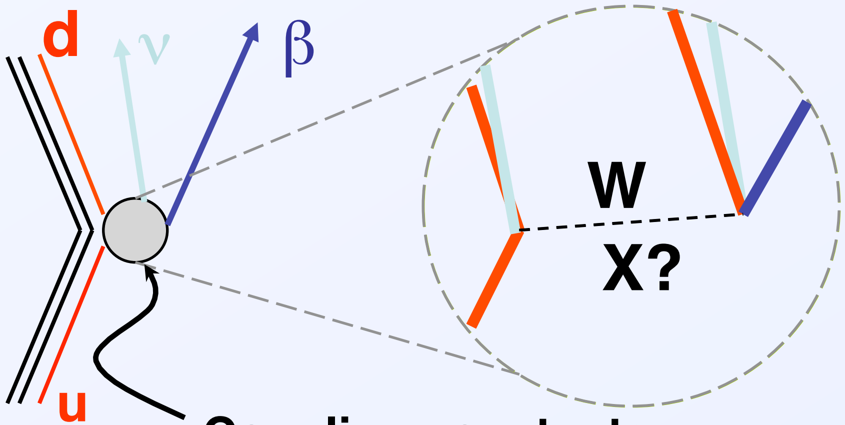
1984 Nobel Prize in Physics for discovery of the weak bosons

The bosons are verified by experiment…

…but precision can be improved
(it may not be the whole story)

Nuclear β decay correlations

The form of the interaction results in certain correlations between the emitted β and ν and the spins…



Coupling constants:
C_S?, C_V, C_A, C_T?

$$\boxed{dW = dW_o\varepsilon\left[1+\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu}a+\frac{\Gamma m_e}{E_e}b\right]}+\vec{J}\cdot\left(\frac{\vec{p}_e}{E_e}A+\frac{\vec{p}_\nu}{E_\nu}B+\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}D\right)+\ldots\Big]$$

If <J>=0

$$dW_0 = F(Z,E_e)p_eE_e(E_0-E_e)^2\,dE_e\,d\Omega_e\,d\Omega_\nu$$

🟦 Compare experimental values to SM predictions

🟧 Put limits on terms “forbidden” by SM

Intuitive Picture: Superallowed $0^+ \rightarrow 0^+$ Fermi Decay

Angular correlations between momentum and spin vectors of the emitted particles in beta-decay yield information about the properties of the exchanged boson.

$$\boxed{dW = dW_o \varepsilon \left[1 + \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} a + \frac{\Gamma m_e}{E_e} b \right]}$$

Superallowed Fermi decay:

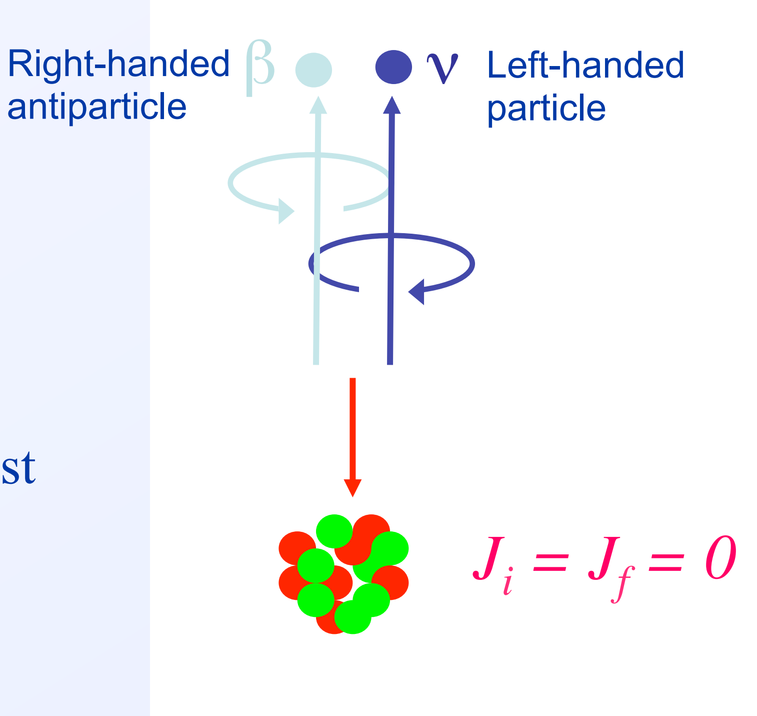
$$J_i = 0 \rightarrow J_f = 0$$

Leptons carry off no net angular momentum

Left-handed character of W boson:

the spins of the (opposite helicity) leptons must anti-align… → beta and neutrino emitted preferentially in the same direction

$$\boxed{a = 1}$$



Boson Mass Range That Can Be Probed

If you observe a nuclear β decay,
even in a table-top experiment,
you are already at 80.4 GeV/c^2.

How high can you go?

Coupling $\sim (M^2 - q^2)^{-1} \longrightarrow M^{-2}$ (as $q \to 0$)

Observable $\sim (\text{Coupling})^2 \longrightarrow M^{-4}$ (as $q \to 0$)

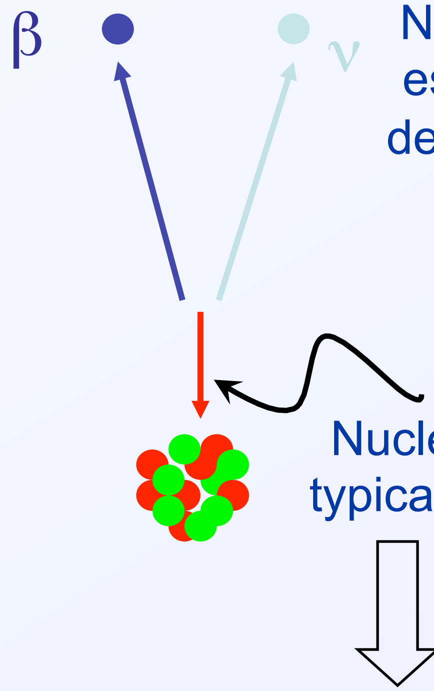
$\delta a/a = 1\ \% \longrightarrow (0.5*0.01)^{-4} M_W \sim 300$ GeV/c^2

$\delta a/a = 0.1\% \longrightarrow (0.5*0.001)^{-4} M_W \sim 550$ GeV/c^2

Sensitivity also depends on the system studied (β, μ, collider, etc.)…

The Beta-Neutrino Angular Correlation

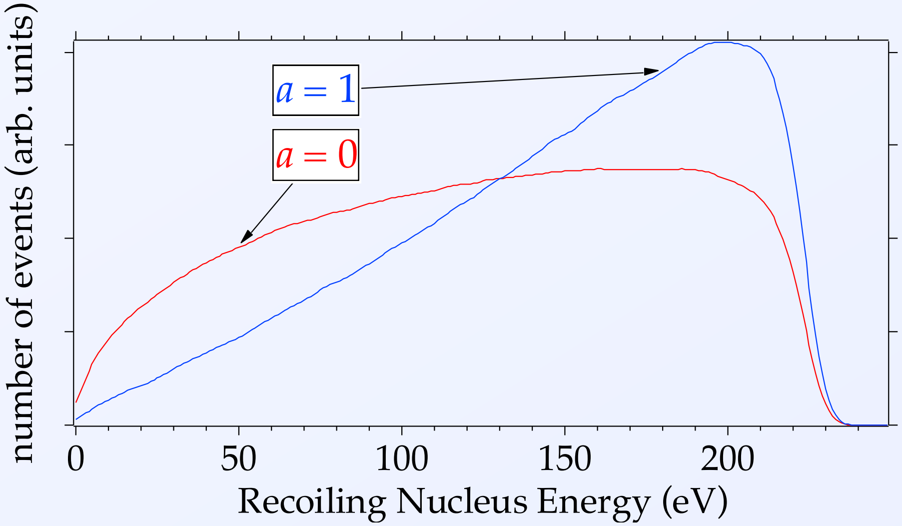
Neutrino too difficult to detect – correlation must be inferred from nuclear recoil



Neutrino escapes detection!

Nuclear recoil typically <1 keV

Example Recoil Energy Spectrum (^{21}Na)



$a > 0$ leads to larger average recoil energy

Direct detection -- acceleration of daughters

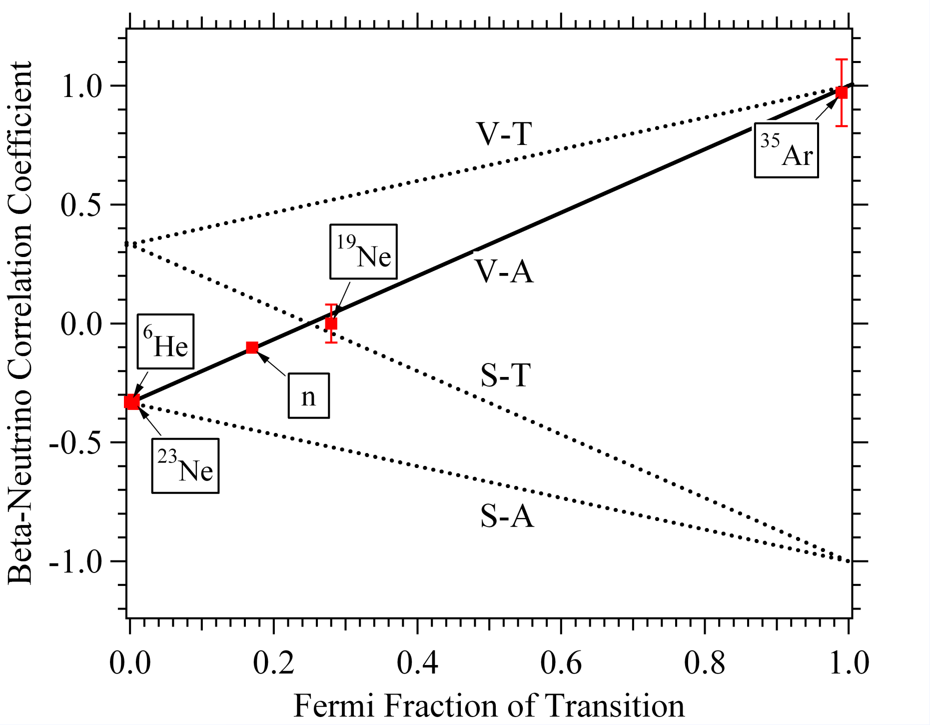
Energy shift in subsequent particle emission

Sensitive to detector thresholds and resolution

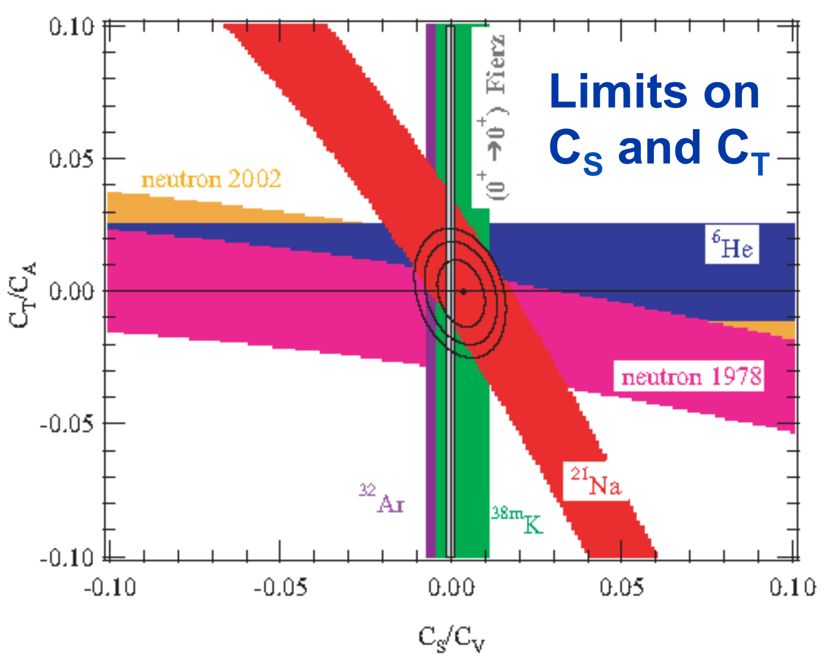
Correlation easily perturbed by scattering

Weak Interactions in Nuclei

Historically the V-A structure of the weak interaction was determined by measurements of the beta-neutrino correlation in noble gas nuclei in the 1960’s



Today, precise measurements of the beta-neutrino correlation are conducted to search for scalar or tensor contributions from exotic weak bosons



P.A. Vetter *et al.*, PRC 77, 035502 (2008)

Traps provide access to nuclear recoil

Traps provide a “massless” sample of radioactive nuclei suspended in vacuum

- Negligible scattering in source volume → nuclear recoil available for study
- Collect sample in ~1-mm^3 volume → excellent geometry for radiation detection
- Make efficient use of rare nuclei → high statistics needed for precision measurements

$\beta-\nu$ correlation measurements using nuclei

Parent	*Technique*	*Group, Lab*	*Results & Status*
^{35}Ar	Penning trap	Leuven+/ISOLDE	on going
^{35}Ar	Paul trap	LPC+/GANIL	on going
^{38m}K	Laser trap	SFU+/TRIUMF	Gorelov *et al.* PRL 94 (2005) 142501; Upgrade in progress
^{21}Na	Laser trap	Berkeley	Scielzo *et al.* PRL 93 (2004) 102501 ; Vetter *et al.* PRC 77 (2008) 035502
^{6}He	Paul trap	LPC+/GANIL	Flechard *et al.* JPG 38 (2011) 055101; Upgrade in progress
^{8}Li	Paul trap	ANL+/ Northwestern/LLNL	Li et al. PRL 110 (2013) 092502; Upgrade in progress
^{6}He	Laser trap	ANL+/CENPA	on going
^{6}He	Electrostatic trap	WIS (SOREQ)	in preparation
^{32}Ar	Penning trap	Texas A&M	In preparation

Fermi (*) **(*) pure or dominant**

Mixed

Gamow-Teller (*)

Best limits on Fermi, Mixed, and Gamow-Teller transitions are:

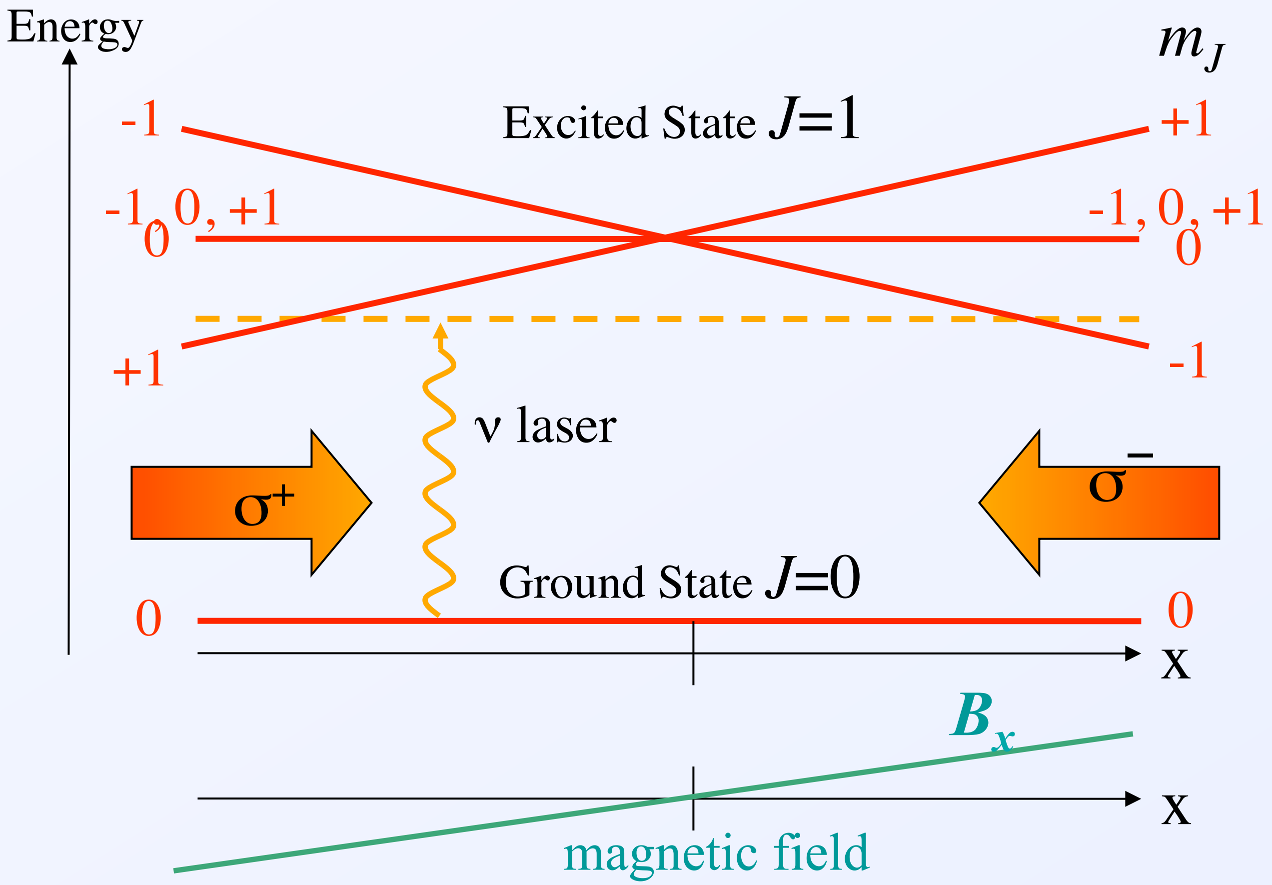
$$\delta a/a = 0.005\text{-}0.01$$

$$(M\sim 300\text{-}360 \text{ GeV})$$

A Simplified Magneto-Optical Trap

In one dimension with atomic transition J=0→J=1

Create damped harmonic oscillator: $F = -k\cdot v+\mu B_x m_J$



Velocity-dependent force: Doppler shift alters laser frequency seen by atoms

$$\Delta\nu = -k\cdot v$$

Position-dependent force: Zeeman shifts from magnetic field

$$\Delta\nu = \mu B_x m_J$$

1997 Nobel Prize in Physics for laser cooling and trapping of atoms

Ion confinement using electric fields

To confine in 1D, need a restoring force:

$$F_z = -k_z(z - z_o)$$

and the potential required is:

$$V = \frac{k_z}{2q}(z - z_o)^2$$

or in a simpler form:

$$V = \lambda_Z z^2$$

Taking the general form of 1D confinement and extending it to 2D:

$$V = \lambda_x x^2 + \lambda_y y^2$$

In a source free region:

$$\nabla^2 V = 0$$

Result is that:

$$\lambda_x + \lambda_y = 0 \qquad \therefore \lambda_x = -\lambda_y \equiv \lambda$$

$$\Rightarrow V = \lambda(x^2 - y^2)$$

(Trivial solution of $\lambda_x = \lambda_y = 0$ does not provide a restoring force)

Two main types of ion traps

$$V = \lambda(x^2 - y^2) \longrightarrow V = \lambda(x^2 + y^2 - 2z^2)$$

Provides restoring force in one dimension but not the other

Same problem in 3D…

This is solved two ways…

1989 Nobel Prize in Physics for development of ion-trap techniques

Penning trap

Confine ions by adding a static magnetic field

→ Mass measurements

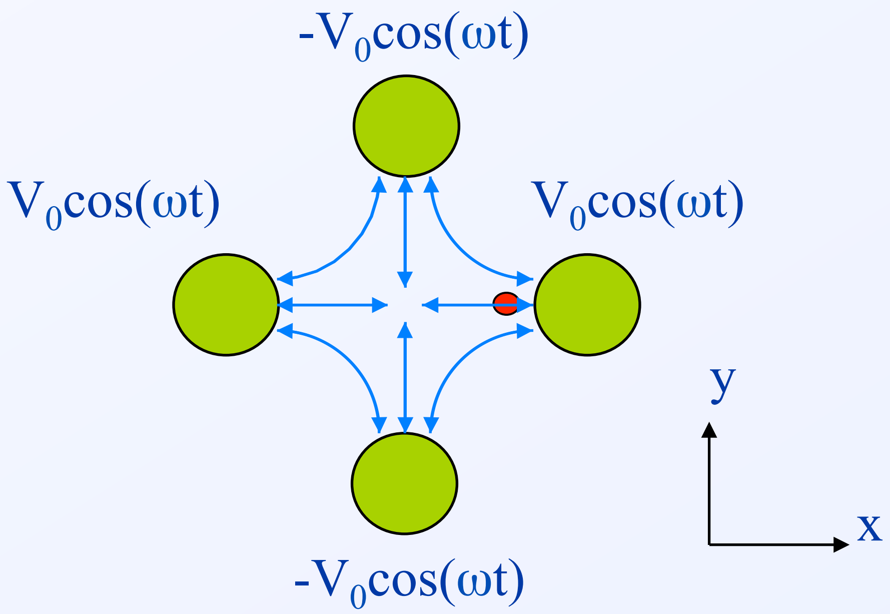
Paul trap

Confine ions using time-varying (and static) electric fields

→ Decay spectroscopy

How Ions are Trapped in a Paul (RFQ) Trap

Radial confinement: inhomogeneous RF electric field



ions attracted to RF-field minimum (at center) if stability requirements are satisfied

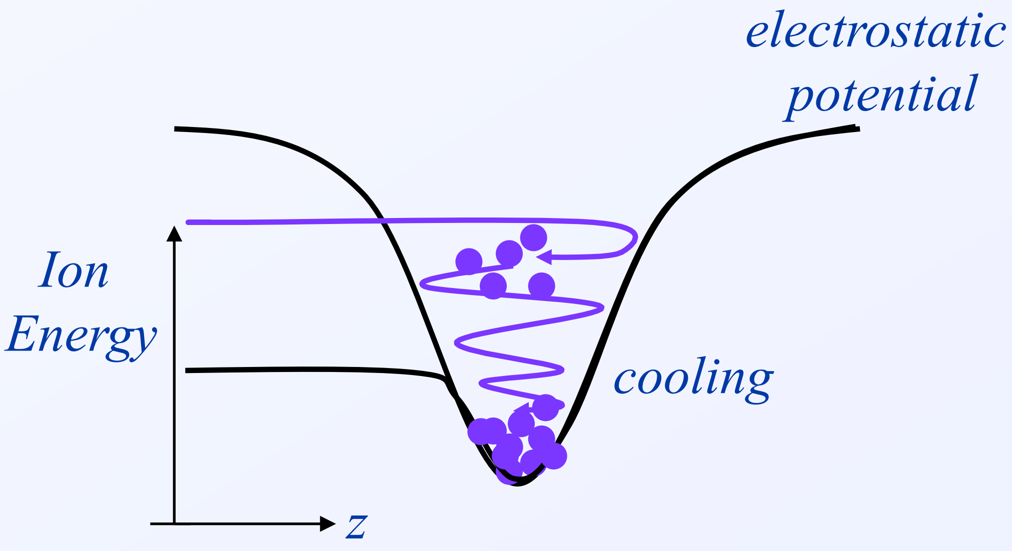
Stability depends on a combination of ion properties (*m*, *e)* and trap properties (*V_0*, ω, *r_0*)

$$q = \frac{2eV_0}{m r_0^{\,2} \omega^2} \qquad 0 < q < 0.9$$

Potential increases quadratically away from center → force is largest near electrodes and zero at center

How Ions are Trapped in a Paul (RFQ) Trap

Axial confinement: DC electric field



Bunched beam enters trap region

Trap closes

Ions cooled in 10-1000 ms to <1 eV using helium buffer gas

Hold cold ions for measurement

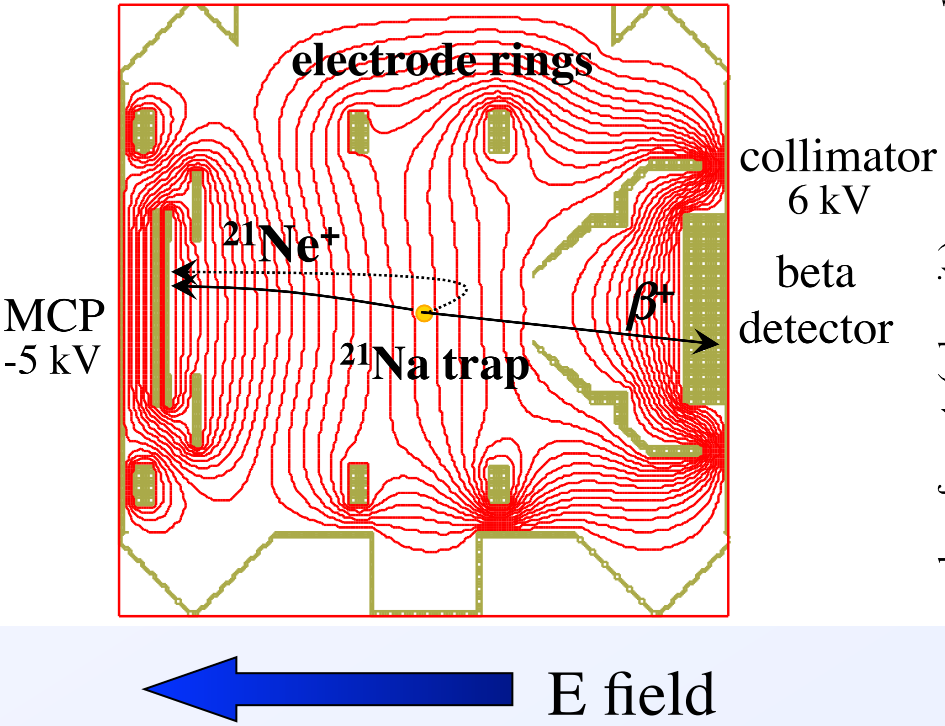
Trap opens for next bunch while retaining trapped ions

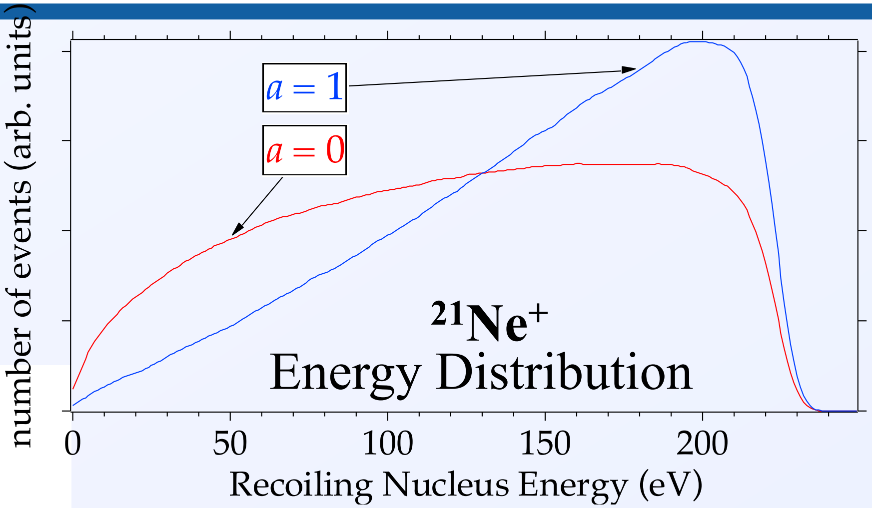
Repeat to accumulate ions

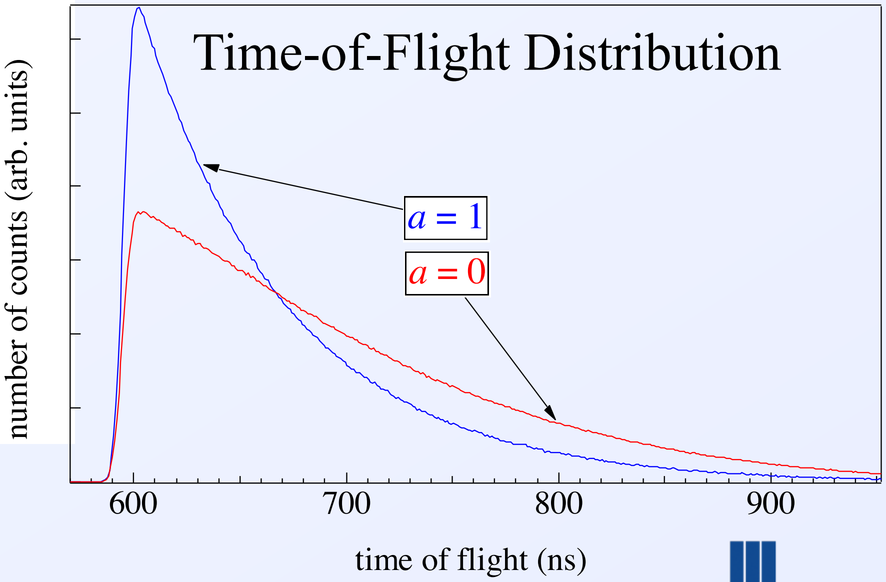
Measure a from Recoil Ion Time-of-Flight

Transform recoil ion energy distribution into a time-of-flight distribution using a static electric field

LBNL atom trap







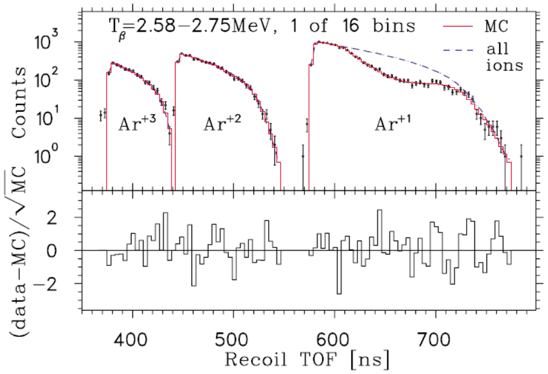
Sampling of time-of-flight results

TRINAT @ TRIUMF

A. Gorelov *et al.*, PRL **94**, 142501 (2005)

Laser trap

$^{38m}K^0 \rightarrow {}^{38}Ar^{1+} + \beta^+ + \nu$



Pure Fermi

a_{SM} = 1

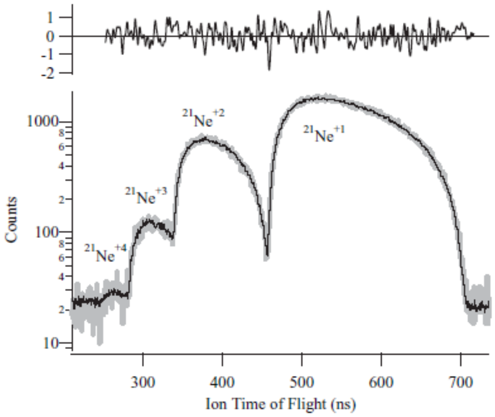
a = 0.9981±0.0048

NSD @ LBNL

P.A. Vetter *et al.*, PRC **77**, 035502 (2008)

Laser trap

$^{21}Na^0 \rightarrow {}^{21}Ne^{1+} + \beta^+ + \nu$



Fermi/Gamow-Teller Mirror

a_{SM} = 0.553±0.002

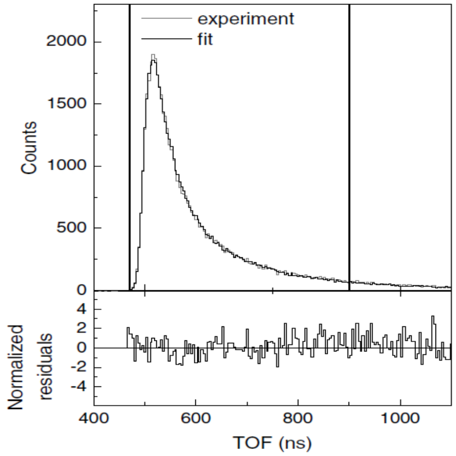
a = 0.5502±0.0060

LPCTrap @ GANIL

X. Flechard *et al.*, J. Phys G **38**, 055101 (2011)

RFQ ion trap

$^6He^{1+} \rightarrow {}^6Li^{2+} + \beta^- + \nu$



Pure Gamow-Teller

a_{SM} = -1/3

a = -0.3335±0.0105

Why is ^{8}Li a promising candidate for improvement?

^{8}Li decay has many advantages:

$$^8\mathrm{Li} \rightarrow {}^8\mathrm{Be}^* + \beta^- + \nu$$
$$\hookrightarrow \alpha + \alpha$$

Q ≈ 13 MeV (broad ^{8}Be* state at 3 MeV)

$t_{1/2}$ = 0.808 sec

- ➢ Large Q value and small nuclear mass → 12-keV nuclear recoils and large shifts in a break up
  - energy difference ±400 keV
  - angle deviation from 180^0 by up to 7^0

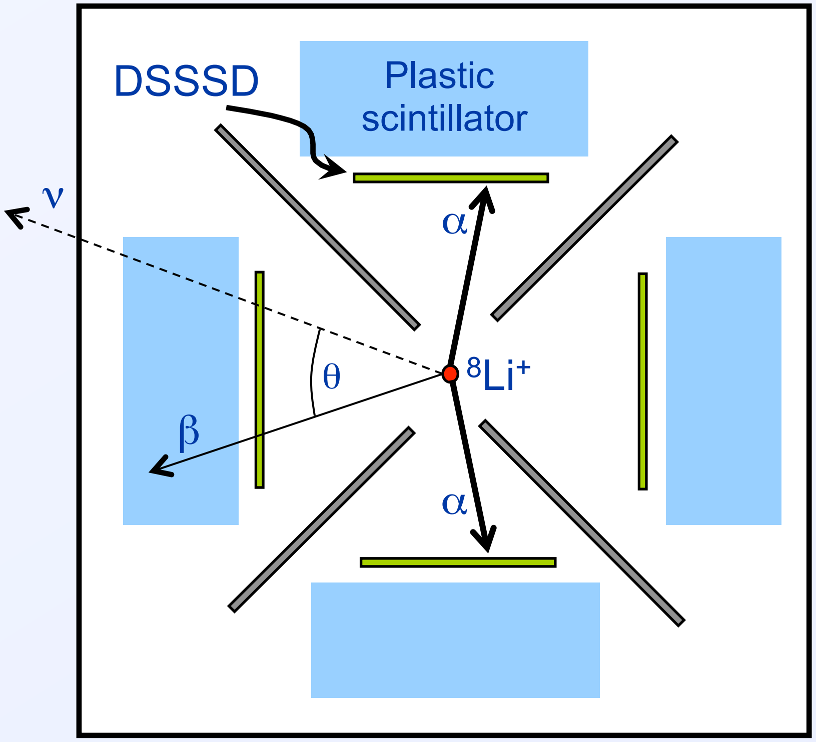
- ➢ Additional correlation between α and leptons enhances A/T difference

  $\beta-\nu$: ±1/3

  $\beta-\nu-\alpha$: ±1

- ➢ Symmetry of decay and detector array provides reduction of systematic effects

Surround trapped ions with DSSDs and plastic scintillators



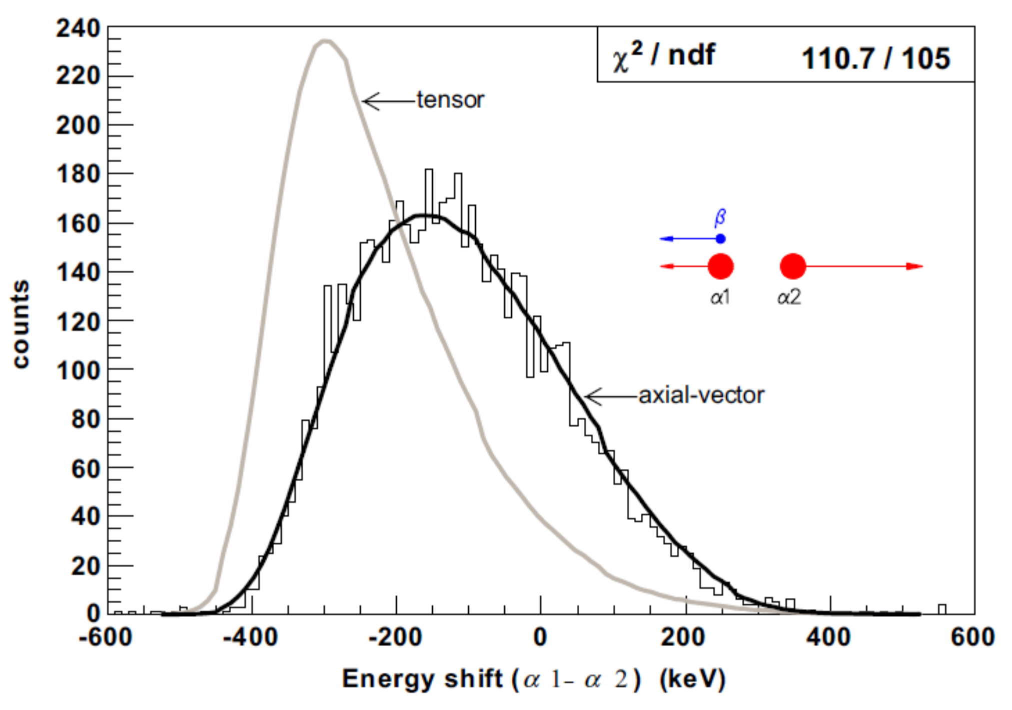
1st results: $\beta-\alpha-\alpha$ coincidences from ^{8}Li held in an RFQ ion trap

G. Li *et al.*, PRL **110**, 092502 (2013)
N.D. Scielzo *et al.*, NIM A **681**, 94 (2012)

Axial vector vs. tensor difference enhanced by $\beta-\nu-\alpha$ correlation

Symmetry of apparatus and of decay suppresses systematic effects

<1% statistical and systematic uncertainties in test of Standard Model



“Pure” Gamow-Teller decay

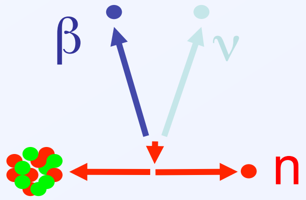
a_{SM} = -1/3

a = -0.3307±0.0090 → data for further reduction by ×3 under analysis

Other experiments: Neutron spectroscopy through conservation of momentum

Surround trapped radioactive ions with β and recoil-ion detectors to reconstruct decay kinematics to determine energy/momenta of:

Neutrons in β-delayed neutron emission



Neutron emission

Astrophysics: nucleosynthesis of elements heavier than Fe

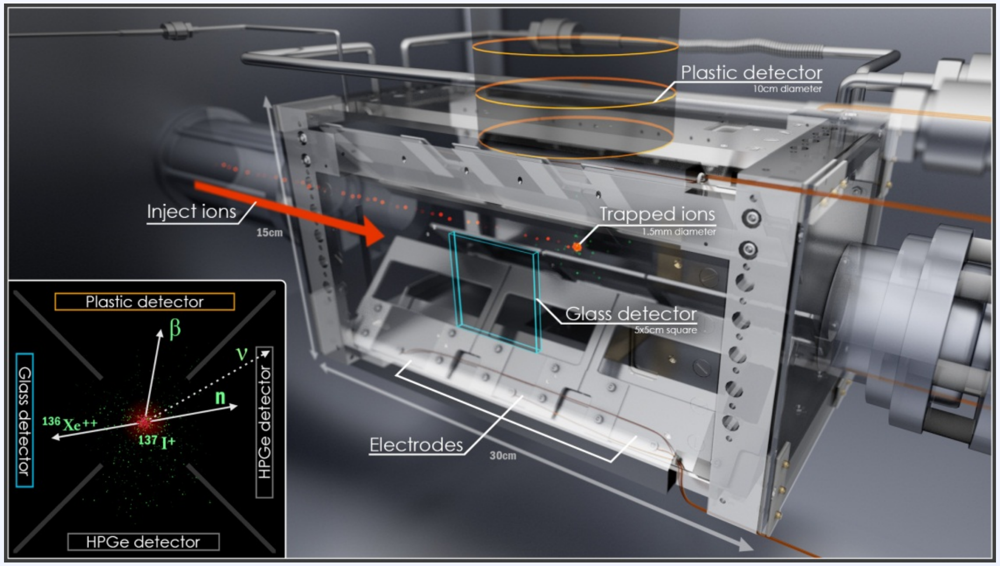
Nuclear Structure: predicting properties of neutron-rich nuclei

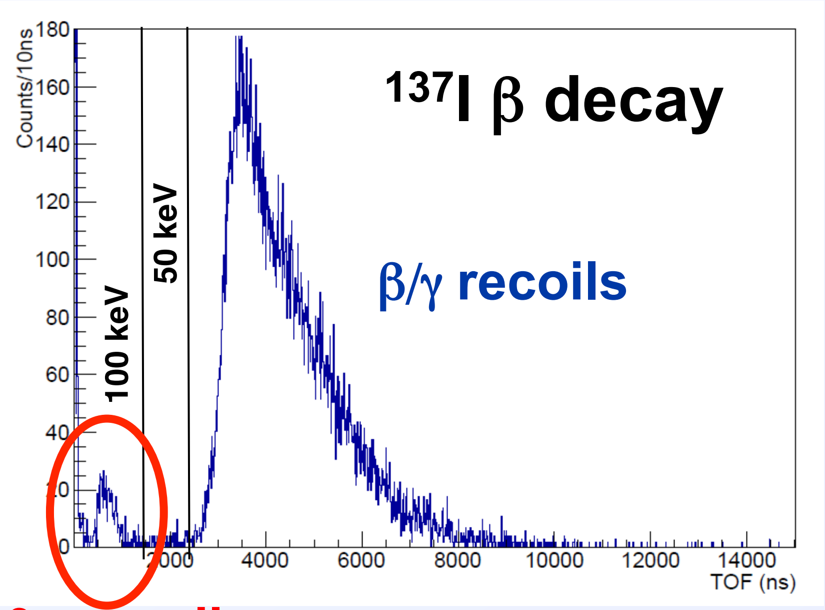
Nuclear Energy: reactor design, performance, and safety studies

Stockpile Stewardship: interpreting results involving production of fission fragments

Recoil ion momentum reveals neutron emission

Outfit ion trap from ^{8}Li experiment with plastic scintillator and MCP detectors…





βn recoils

Determine branching ratio and E_n spectrum from nuclear recoil…

No neutron detection needed!

Concept demonstrated: R.M. Yee *et al.*, PRL **110**, 092501 (2013)

Lots of interesting measurements we can make with access to the nuclear recoil…

Very likely there are others that we have yet to come up with…

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LLNL-PRES-408002

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- Traps allow precision mass measurements
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  - Nuclear structure, astrophysics studies
- Traps provide other opportunities for precision atomic spectroscopy
  - Electric dipole moment searches
  - Parity violation in high-Z atoms
- Others…

Penning Trap Mass Spectrometry

Motivations for making mass measurements

Physics & Chemistry

basic information required

$\delta m/m \approx 1\cdot10^{-6}$

General Physics

fundam. constants
test of CPT

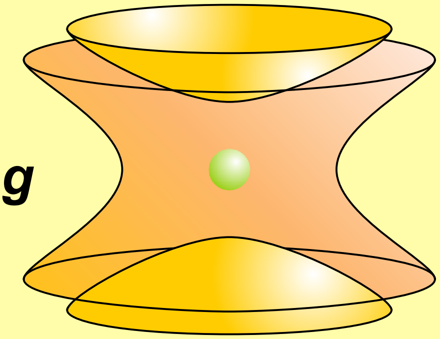
$\delta m/m \leq 1\cdot10^{-10}$

Atomic Physics

binding energy

$\delta m/m \leq 1\cdot10^{-9}$

Weighing



atomic masses

Nuclear Physics

mass formula,
models, halo

$\delta m/m \approx 1\cdot10^{-7}$

Astro-physics

nuclear synthesis,
r-, rp-process

$\delta m/m < 1\cdot10^{-7}$

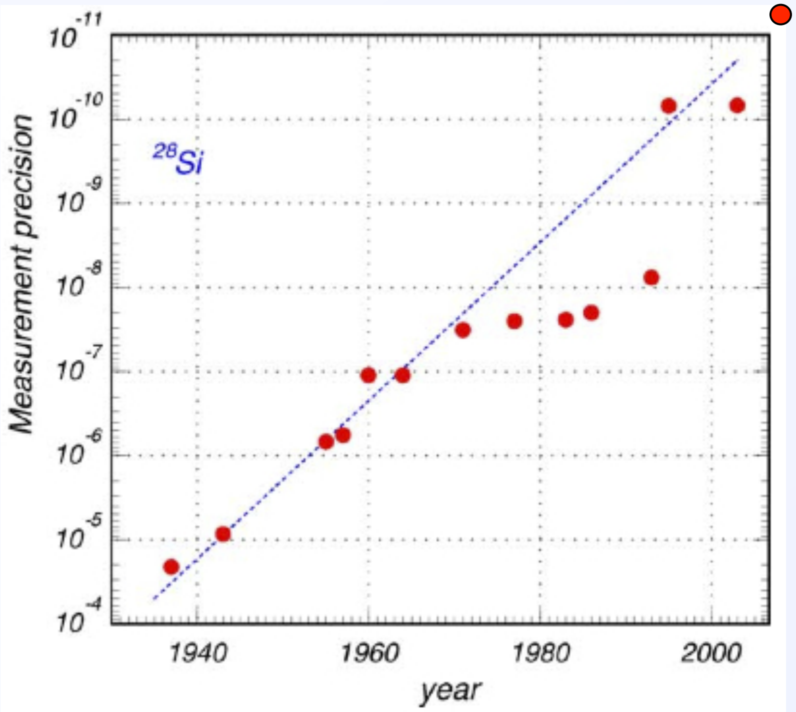
Weak Interactions

symmetry tests,
CVC hypothesis

$\delta m/m < 3\cdot10^{-8}$

K. Blaum

Mass spectrometry on exotic nuclei



Mass accuracy has improved an order of magnitude per decade for the past 100 years!

10^{-11} → eV precision on mass-100 nucleus!

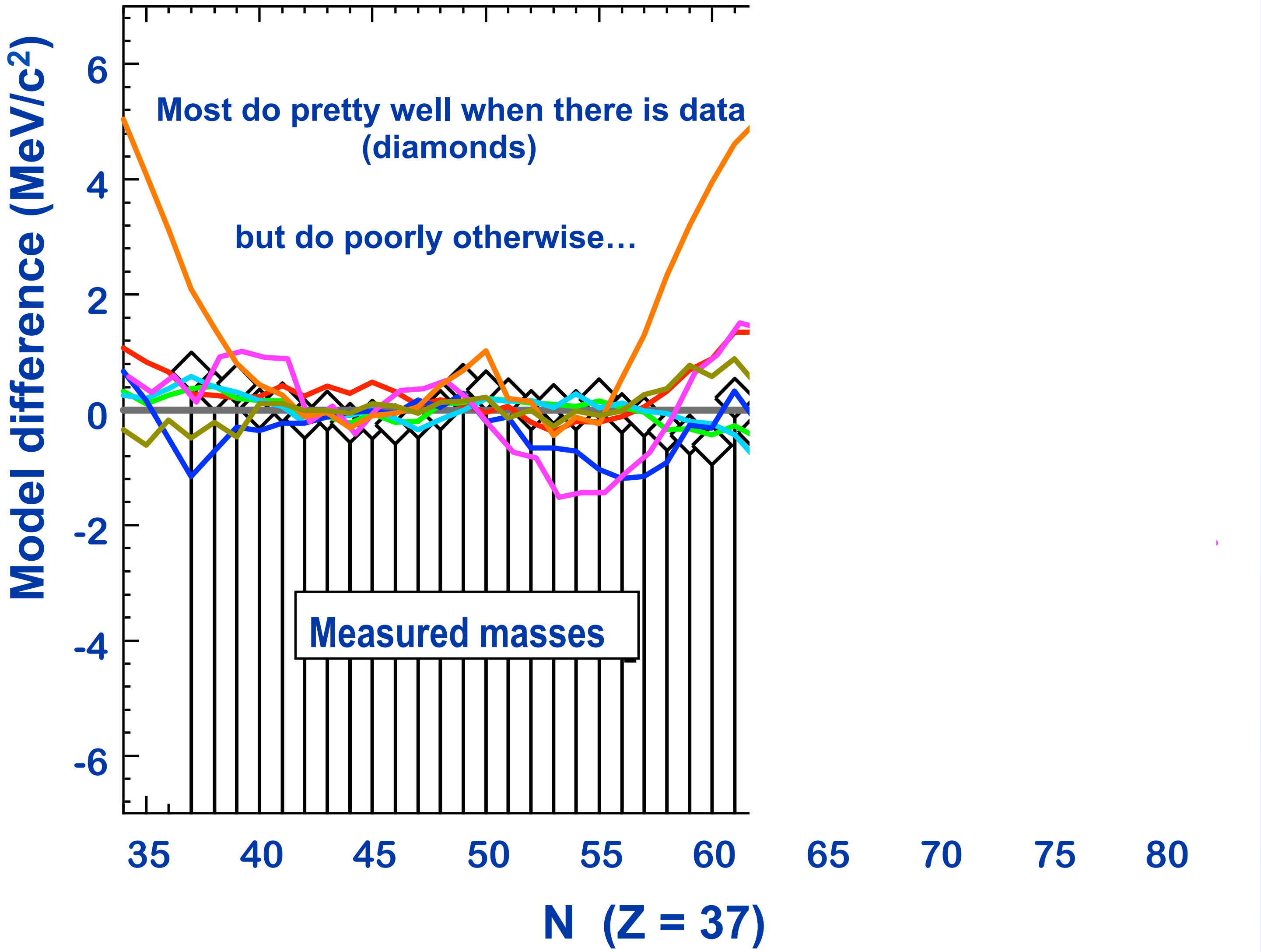
Provides the first window to the nucleus: it is the sum of the constituent particles and the forces that bind them

Decay Q values determined from mass differences

$$m(Z,N) = Zm_p + Nm_n - B/c^2$$

Z:	number of protons
m_p:	mass of proton
N:	number of neutrons
m_n:	mass of neutron
B:	binding energy

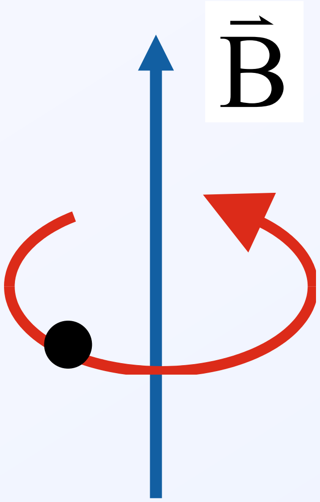
How well do mass models do?



Most do pretty well when there is data (diamonds)

but do poorly otherwise…

Ions within a magnetic field



- constant axial magnetic field
- particle orbits in horizontal plane with cyclotron frequency:

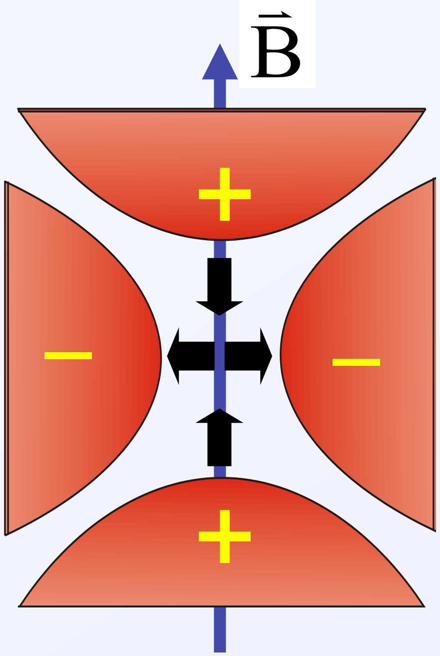
$$\omega_c = \frac{qB}{m}$$

- free to escape axially

Superconducting magnet produces a stable, uniform B field

Confine ions by adding an electric field

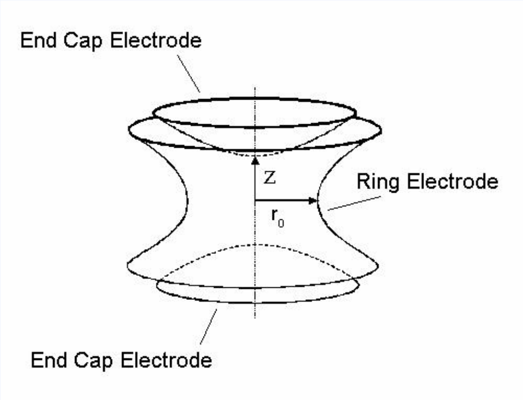
Add a harmonic potential (along magnetic field axis) to confine particles.

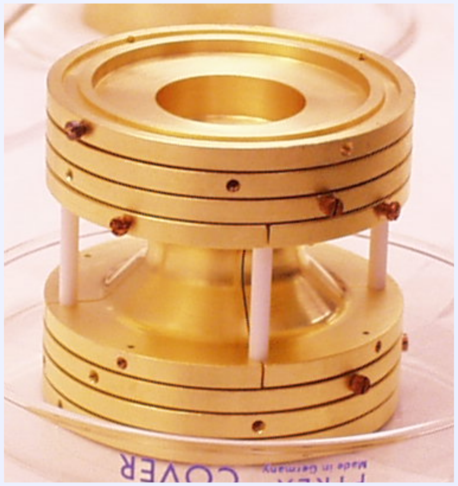


Confining potential:

$$V = \frac{V_o}{2d^2}(z^2 - \frac{r^2}{2})$$

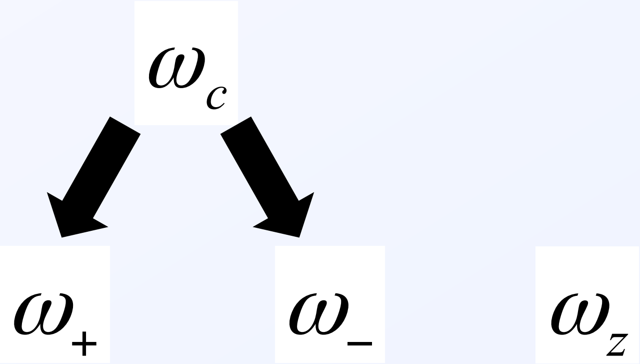
Electrode structure:





Ideal Penning trap: Motion

Effect of the electric field is to split the radial motion into two components:



ω_c

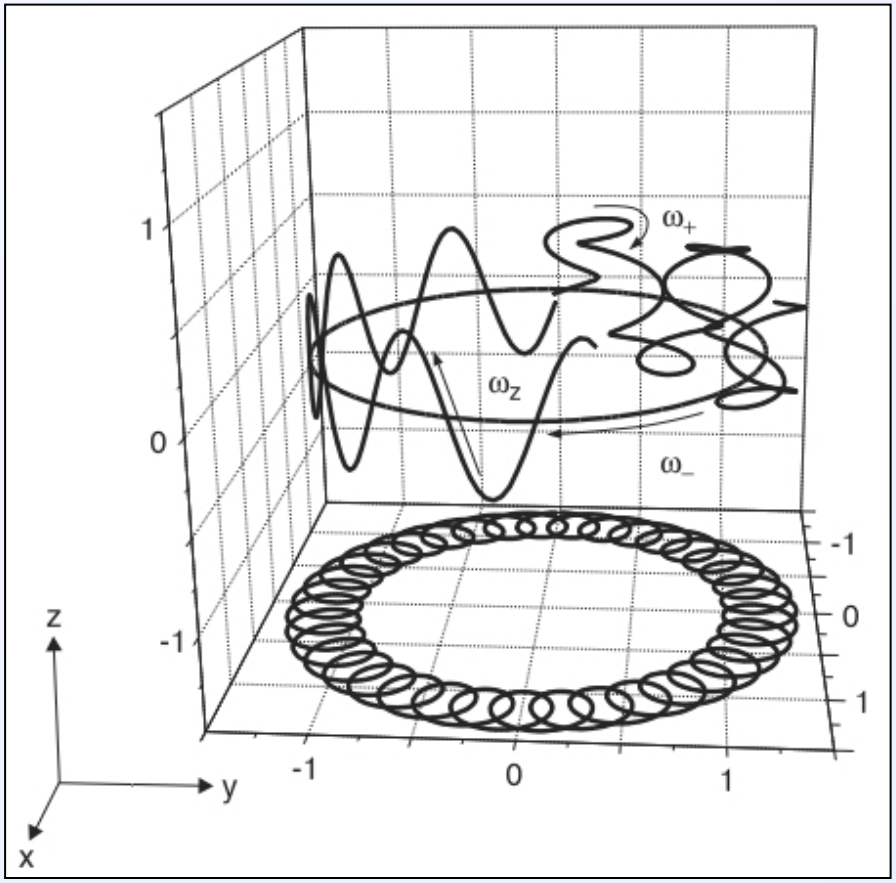
ω_+ ω_- ω_z

ω_+: reduced cyclotron motion (*B*)

ω_-: magnetron motion (*E*×*B*)

ω_z: simple harmonic oscillation (*E*)

$$\omega_\pm = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$



Frequency hierarchy:

$$\omega_- << \omega_z << \omega_+ \sim \omega_c$$

Determining mass of ions in a Penning trap

Masses determined by coupling ω_+ and ω_- motion at ω_c frequency

$$\omega_c = \omega_+ + \omega_- = \frac{qB}{m}$$

ω_c depends on:

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

Mass can also be determined by measuring 3 frequencies…

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2 = \left(\frac{qB}{m}\right)^2$$

Measurement cycle

Ions are loaded into Penning trap

Excite ions using dipole ω_- field

RF quadrupole electric field (to couple ω_+ and ω_- motions) at frequency ω_0 is applied

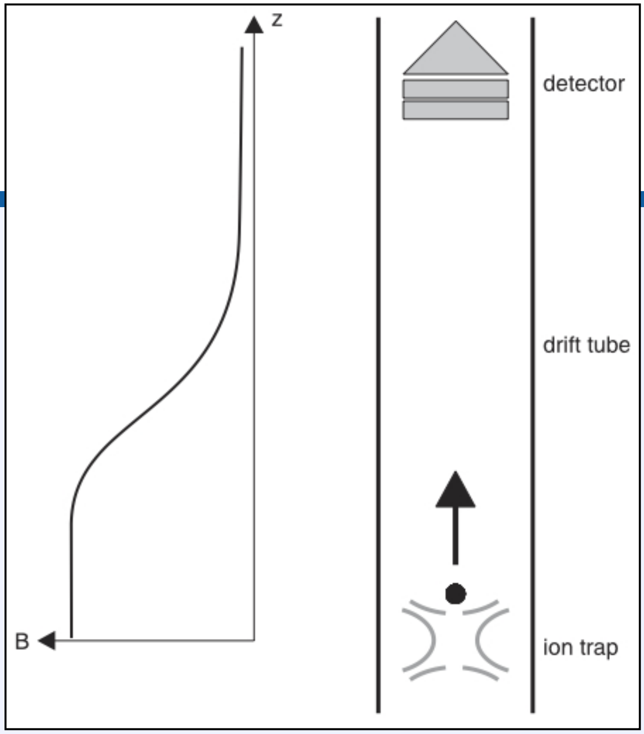
The ion motion is excited – particularly if ω_0 in near ω_c

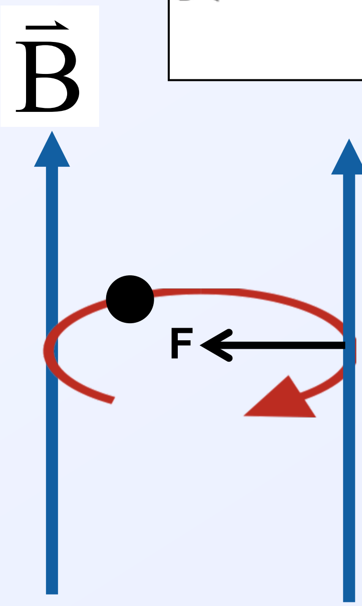
Ion is ejected from the trap and guided toward a microchannel plate ion detector

The decreasing trap *B* field converts any ω_c radial energy into axial energy

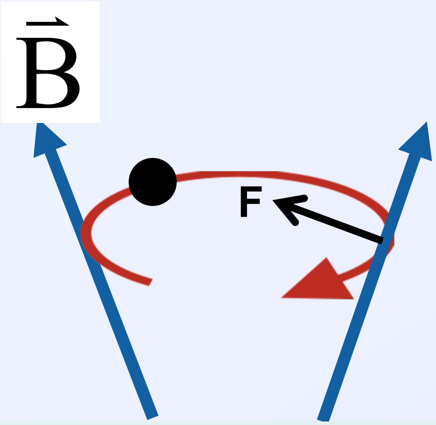
Higher energy ions arrive with shorter time-of-flight

This cycle is repeated at different values of ω_0 over and over





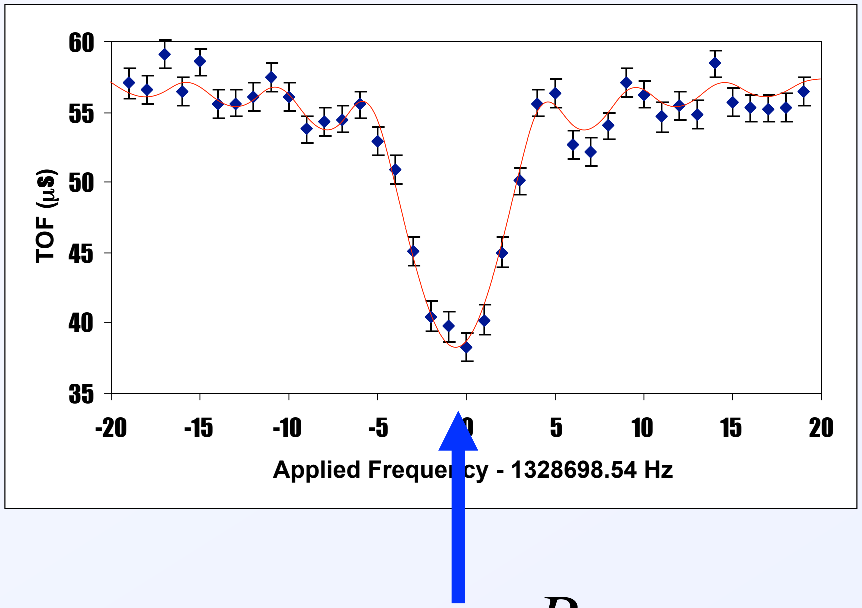
in the trap



As the ion leaves the trap the field gets weaker…

Determining the cyclotron frequency

Sample TOF spectrum



$$\omega_c = \frac{q_c B}{m_c}$$

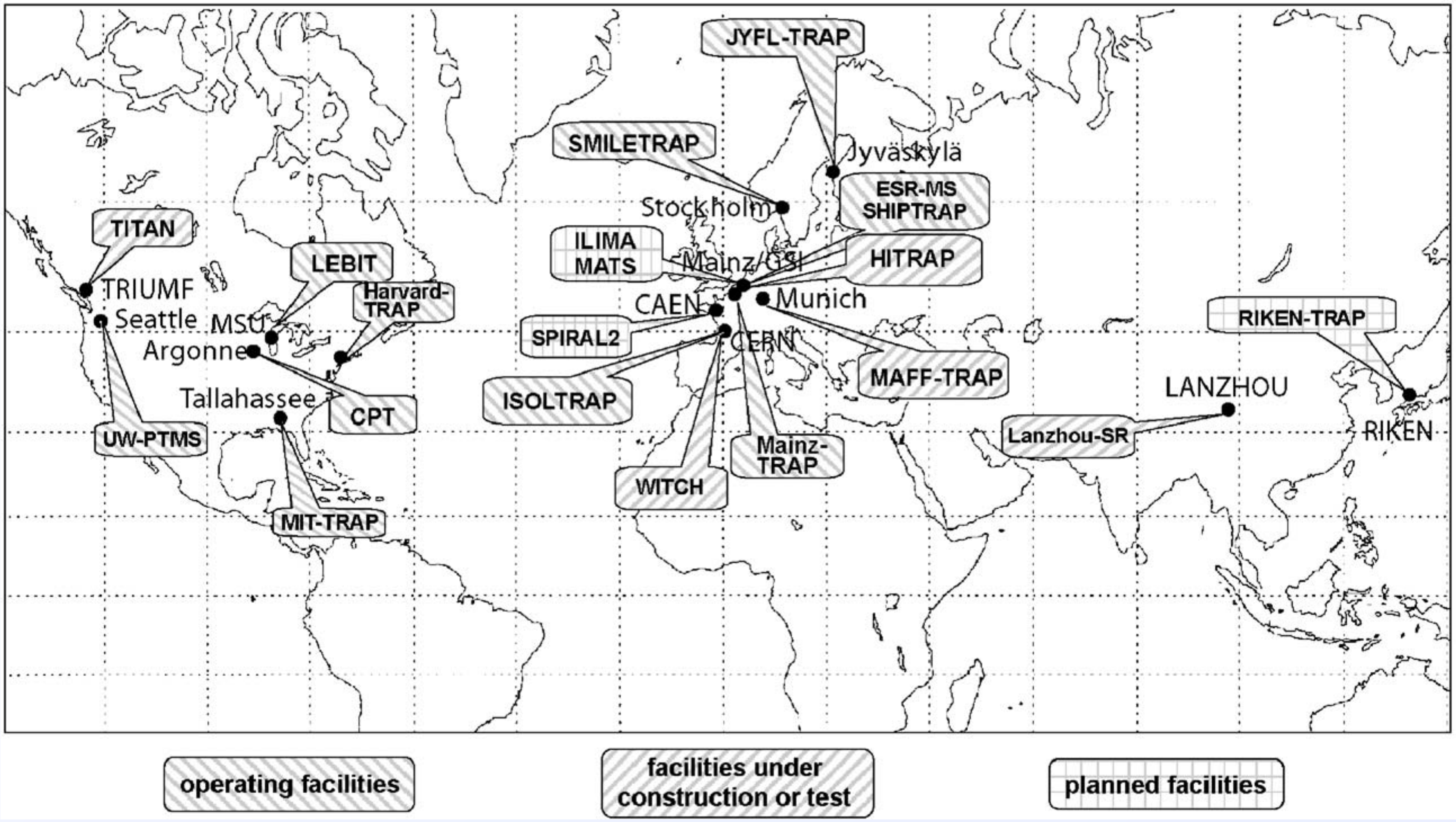
Well-known mass is needed to determine *B*

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

Typical calibrants are composed of:

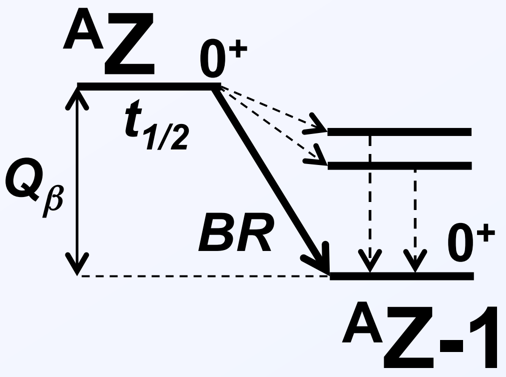
^{12}C:	Δm = 0
^{1}H:	Δm = 0.09 eV
^{16}O:	Δm = 0.15 eV

Worldwide effort for high precision mass measurements



K. Blaum, Phys. Rep. **425,** 1 (2006)

Superallowed $0^+ \rightarrow 0^+$ Fermi β decay



Relationship between partial halflife, matrix element, and phase space:

$$\frac{t_{1/2}}{BR} = \frac{K}{G_V^2 \cdot \left|M_F\right|^2 \cdot f\left(Z, Q_\beta\right)}$$

Rearranging gives “ft value”:

$$ft = \frac{K}{2G_V^2}$$

$$\left|M_F\right|^2 = 2$$

For $0^+ \rightarrow 0^+$ decays

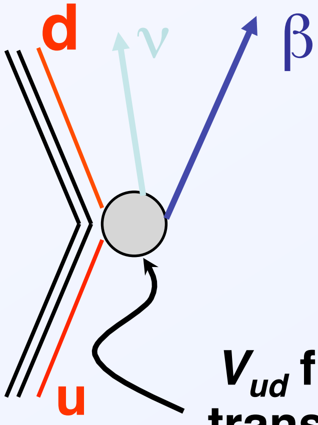
And including a bunch of small-ish corrections:

$$Ft \equiv f\left(1+\underbrace{\delta_R'}_{\sim1.5\%}\right)\left(1+\underbrace{\delta_{NS}-\delta_C}_{0.3\text{-}1.5\%}\right) = \frac{K}{2G_V^2\left(1+\underbrace{\Delta_R^V}_{2.4\%}\right)}$$

Many things we can investigate after studying several different nuclei

Ft **constant for $0^+ \rightarrow 0^+$ decays?**

Conserved vector current in weak interaction



symmetry between EM and weak interaction → conservation of vector part of weak interaction (like conservation of charge)

V_{ud} from u→d transformation

Presence of scalar interactions

$$dW = dW_0\left[1 + \frac{\Gamma m_e}{E_e} b\right]$$

$$\left[\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} a\right]$$

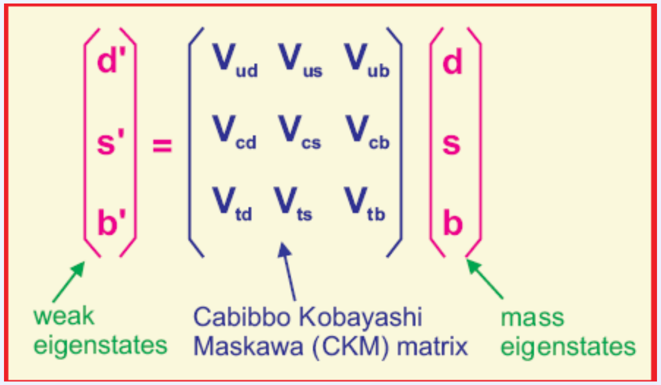
integrates to 0

Value of *Ft*?

Test unitarity of CKM matrix

Determine G_V^2 and compare to purely leptonic μ decay (G_μ^2) to extract V_{ud} matrix element

$$V_{ud}^2 = \frac{G_V^2}{G_\mu^2}$$



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1?$$

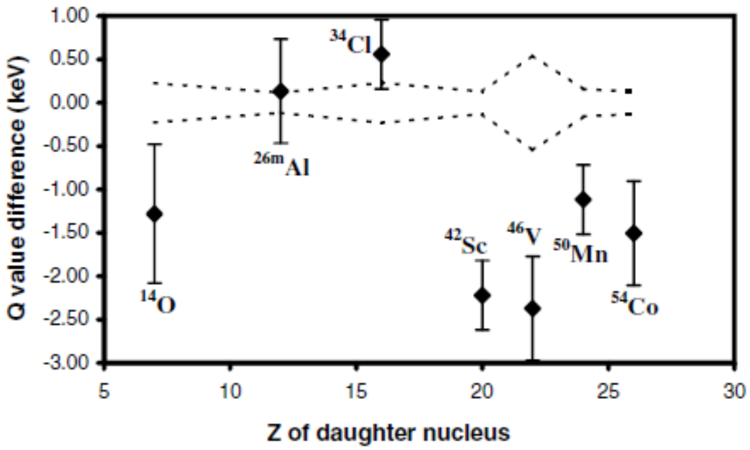
Penning traps improve precision of previously-studied isotopes and provide access to new ones

***Ft* value depends strongly on Q_β**

$$f(Z, Q_\beta) \sim Q_\beta^5$$

Penning trap measurement of ^{46}V uncovered systematic shift in previous data from (^{3}He,t) measurements

Difference between earlier (^{3}He,t) measurements of Q value and modern data



G. Savard *et al.*, PRL **95**, 102501 (2005)

Penning traps allow measurement of isotopes where both parent and daughter are radioactive

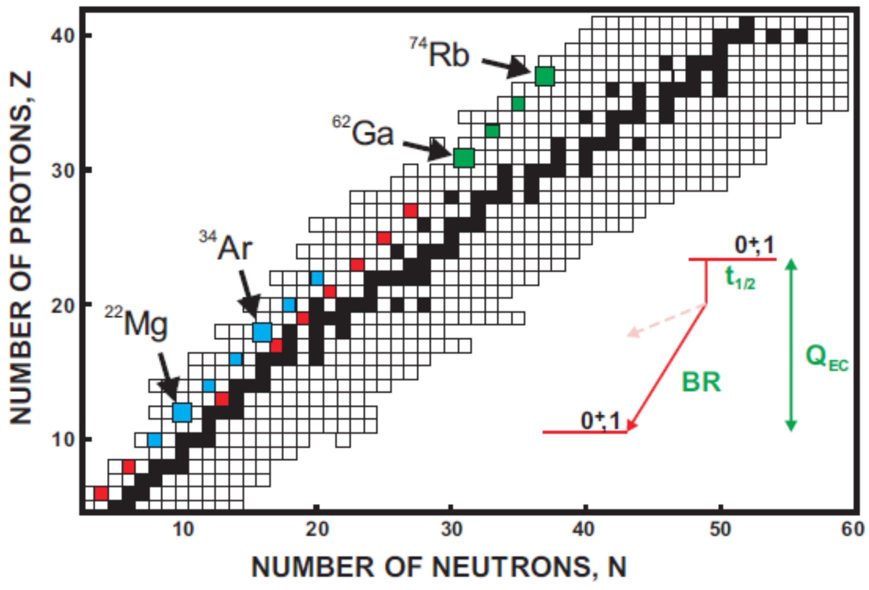
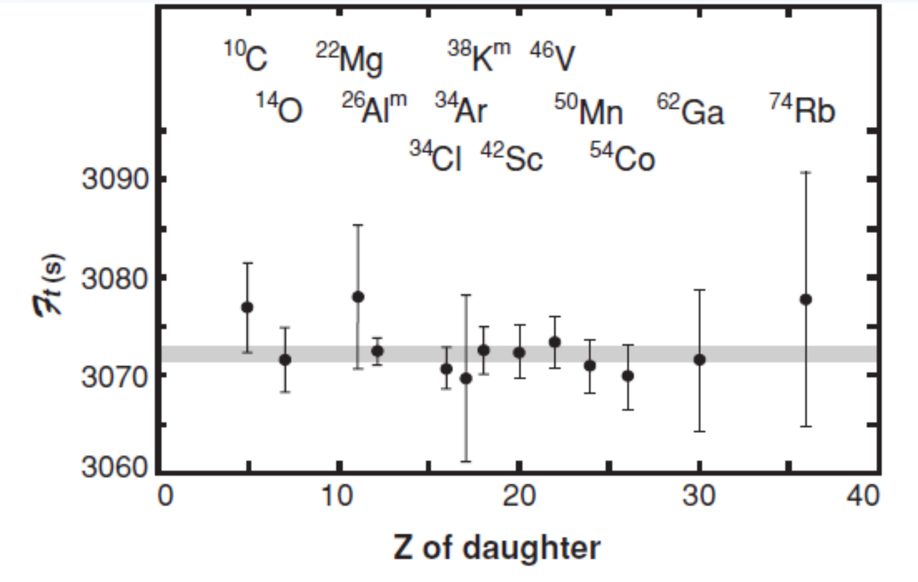
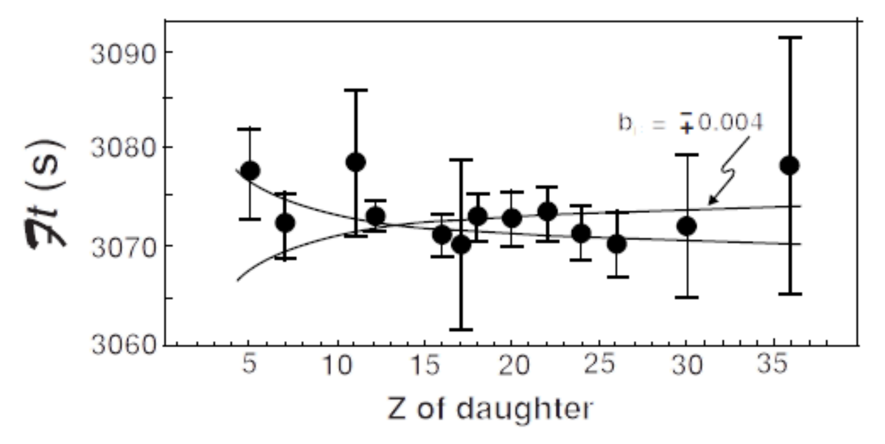


Figure from J.C. Hardy

Results and impact on weak interaction physics





<u>Constancy of *ft* values:</u>

Values constant to ±0.4% for all nuclei → conservation of the weak C_V current (like EM current)

<u>Determine V_{ud} matrix element:</u>

$|V_{ud}|^2 = 0.94916 \pm 0.00044$

And when combined with $|V_{us}|^2+|V_{ub}|^2$, gives the unitarity test:

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 0.99995 \pm 0.00061$

<u>Search for scalar interaction via *b*:</u>

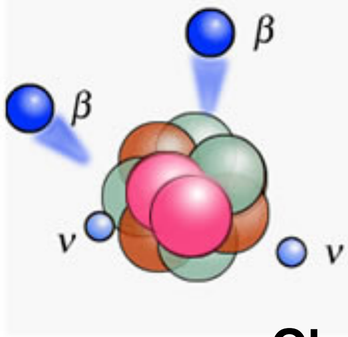
$b = -0.0022 \pm 0.0026$

J.C. Hardy and I.S. Towner, PRC 79, 055502 (2009)

Are neutrinos their own antiparticle? What is the neutrino mass scale and hierarchy?

Only known way to determine this is neutrinoless double beta decay ($0\nu\beta\beta$ decay). In principle, this is a clear signature… but extremely sensitive techniques are required

“ordinary”
$2\nu\beta\beta$ decay

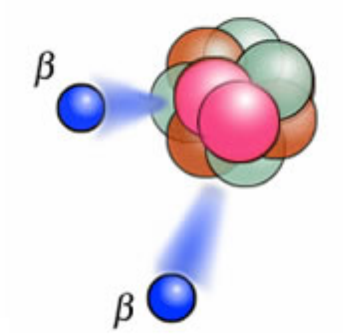


Equal numbers of matter (β^-) and antimatter ($\bar{\nu}$) emitted

Broad β energy spectrum (neutrinos escape detection)

Observed:
$T_{1/2}$~10^{21} years

$0\nu\beta\beta$ decay



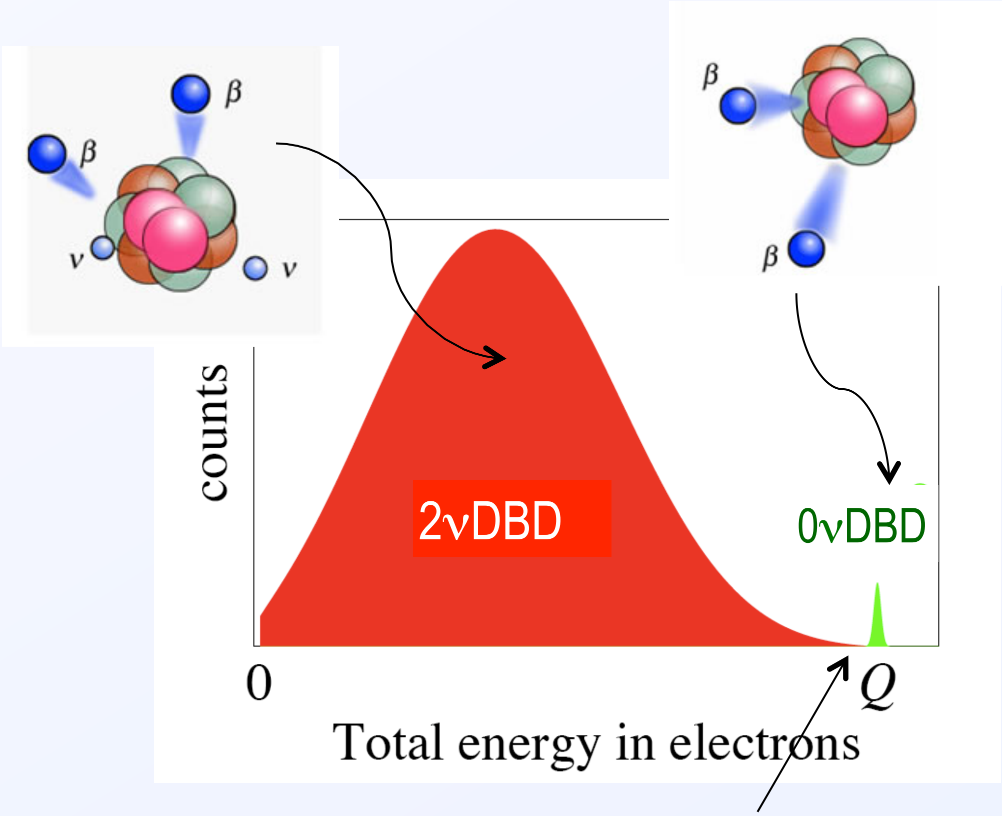
Only matter (β^-) emitted

Signal at total decay energy (all energy detected)

Recognized in 1930s…
but never been observed:
$T_{1/2}$>10^{25} years

A mechanism for matter/antimatter asymmetry

Penning traps precisely determine where to search for very tiny signal



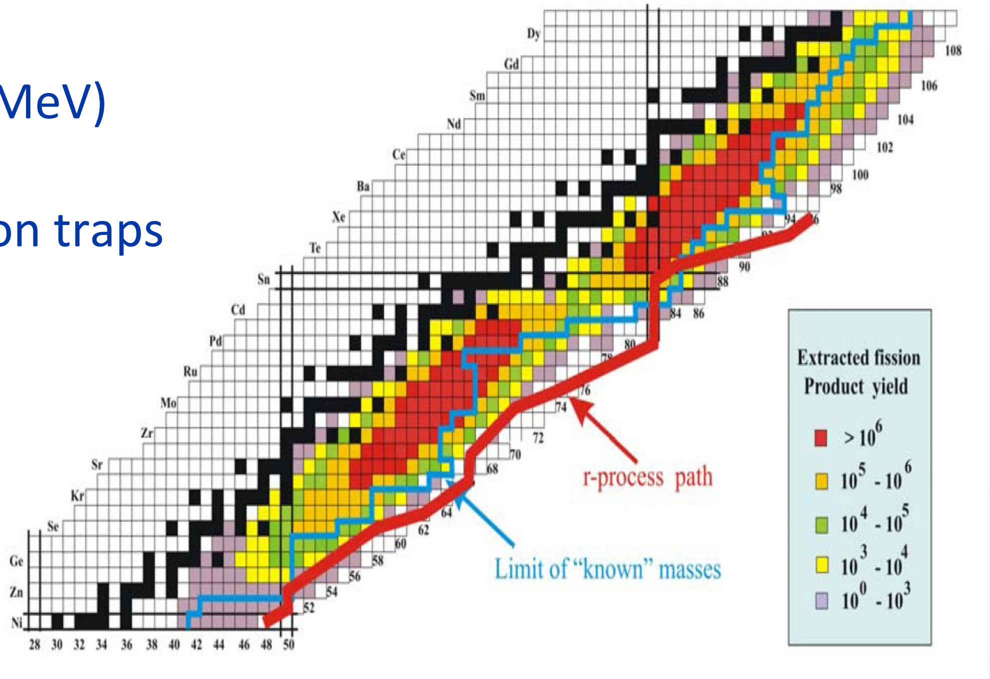
electrons carry away all the decay energy

Penning traps have pinned down Q values for the isotopes to <1 keV

^{76}Ge
B.J. Mount *et al*., PRC **81**, 032501 (2010)
S. Rahaman *et al*., PLB **662**, 111 (2008)
G. Douysset *et al*., PRL **86**, 4259 (2001)
^{130}Te
S. Rahaman *et al*., PLB **703**, 412 (2011)
N.D. Scielzo *et al*., PRC **80**, 025501 (2009)
M. Redshaw *et al*., PRL **102**, 212502 (2009)
D.A. Nesterenko *et al*., PRC **86**, 044313 (2012)
^{82}Se
D.L. Lincoln *et al*., PRL **110**, 012501 (2013)
^{150}Nd
V.S. Kolhinen *et al*., PRC **82**, 022501 (2010)
^{48}Ca
M. Redshaw *et al*., PRC **86**, 041306 (2012)
+ others

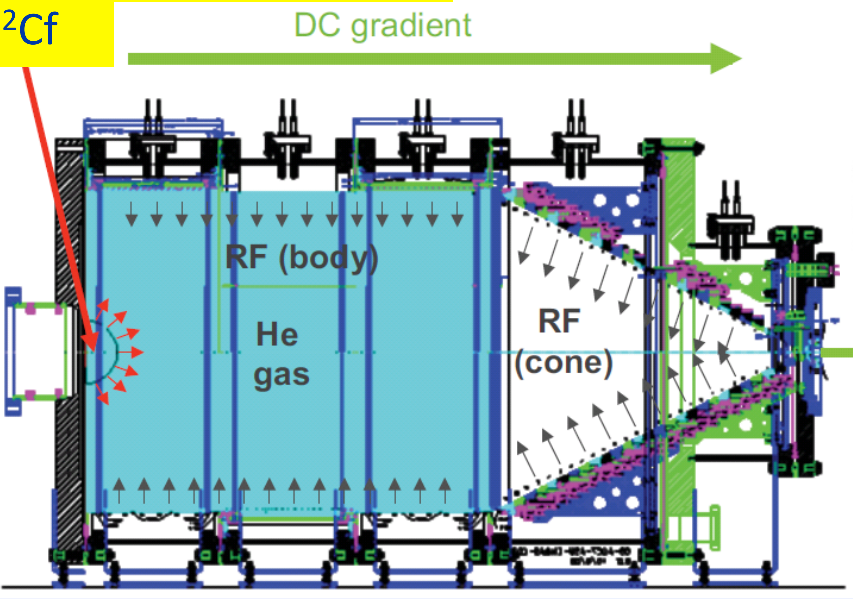
CARIBU at ANL → producing intense low-energy beams of fission products

Device transforms fission recoils (~100 MeV) into an ion beam with good ion-optics properties that couples naturally with ion traps



1 Ci of ^{252}Cf

(10^9 fissions/sec)

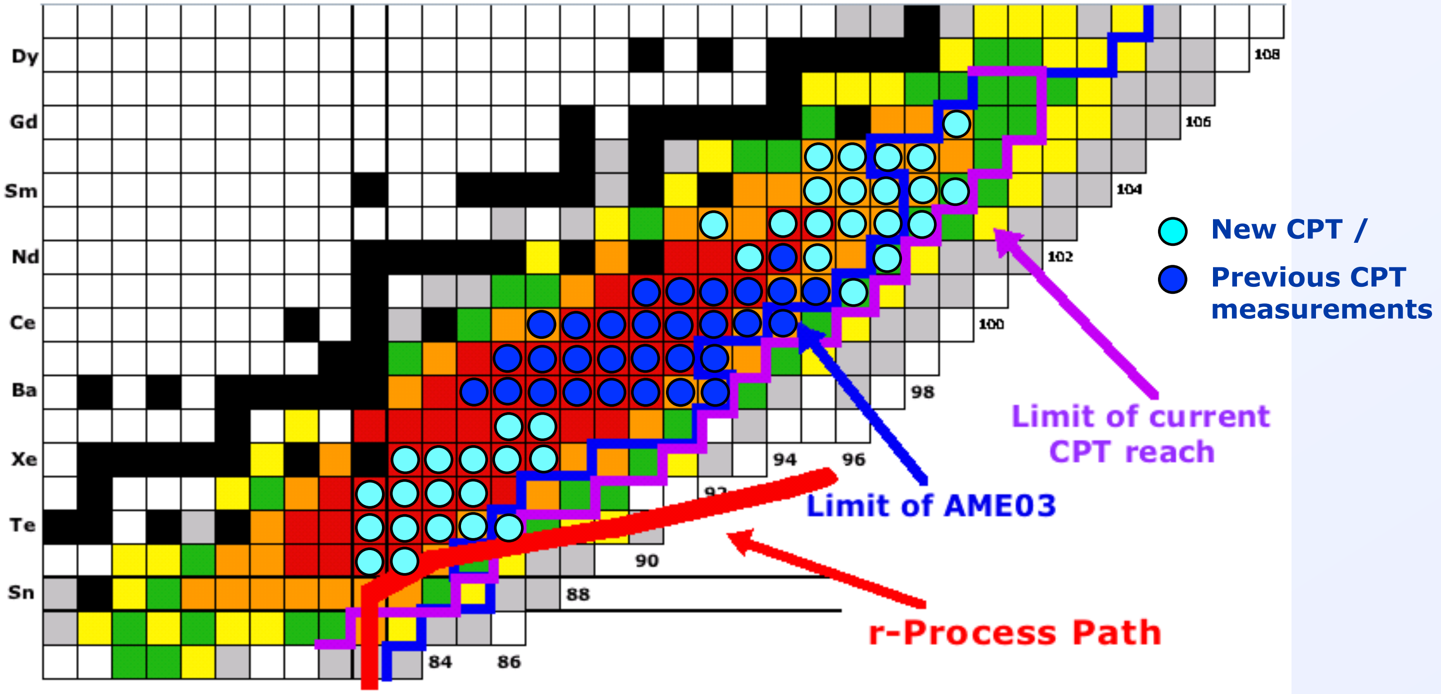


To RFQ cooler

To isobar separator, buncher, and then to experiments

Fission Fragment Measurements using the Canadian Penning Trap at ANL

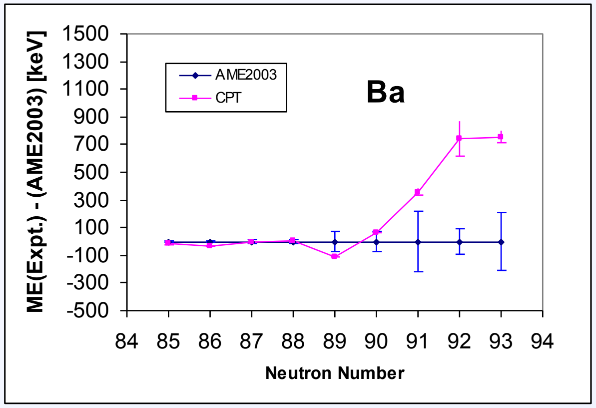
^{252}Cf Heavy Fission Peak

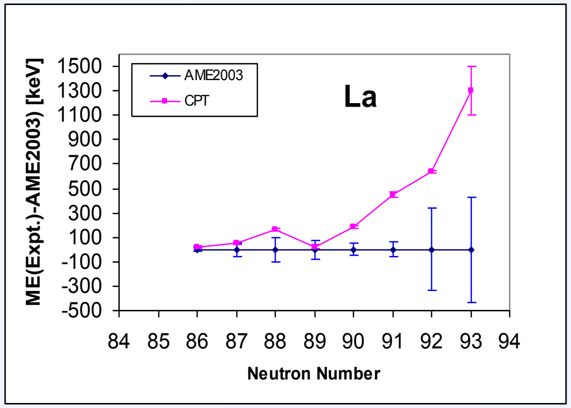


- Ongoing program of measurements since March 2008, target 15 keV uncertainty
- 40 species, 5 have never been previously measured by any means, most others improved by a typical factor of 5
- Adds to 30 measurements taken at CPT in past years with small gas catcher

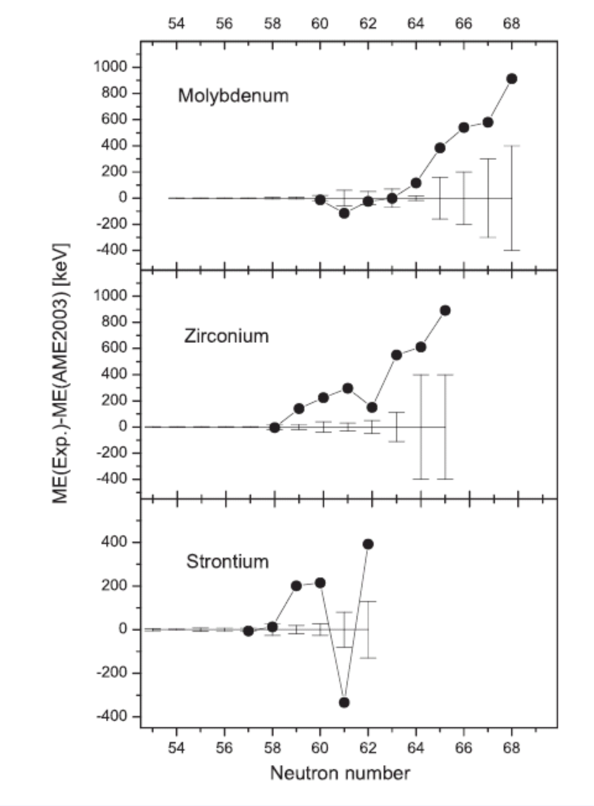
New measurements compared to the AME03

Canadian Penning Trap





JYFLTRAP



U. Hager *et al.*, Phys. Rev. Lett. **96**, 042504 (2006).

- Nuclei are more massive (or less bound) than models predict
- Deviations from 2003 atomic mass evaluation increase with neutron number

Trends suggest astrophysical r-process path is closer to stability!

The take-away message…

Trap technology has a big impact on the way nuclear data is collected…

Penning traps → used worldwide for precision mass measurements by measuring cyclotron motion in a strong, uniform *B* field

Laser traps and Paul traps → access to nuclear recoil is exploited for precision beta-decay studies

Traps allow many other fundamental symmetries tests (electric dipole moments, parity violation, etc.)

Likely to be other applications for these technologies we haven't yet come up with…