Neutrino-Mass Oriented Spectrometry at ISOLTRAP

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December 9th 2010

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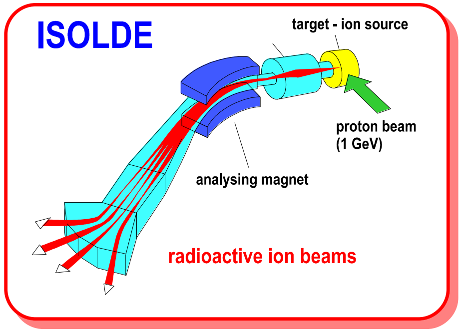

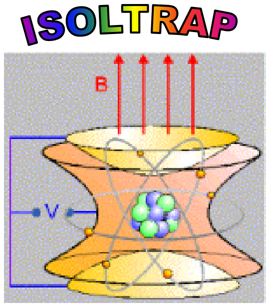

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Neutrino Mass Determination

- Neutrino-oscillation experiments are not able to measure neutrino rest mass

- Absolute neutrino mass is accessible through electron capture (EC) involving the monochromatic neutrino
  - ✓ combine Q-value measurement with electron binding energies from cryogenic micro-calorimeters
  - ✓ yield total neutrino energy and neutrino rest mass

- Neutrinoless double beta decay is also suitable to probe absolute neutrino mass
  - ✓ higher order process: *Z* is changed by 2 units, *A*=const., lepton number violating, forbidden in Standard Model

$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

0νββ–decay

Majorana neutrino

  - ✓ Experimental signature: two electrons in final state, whose energies add up to the Q-value of the nuclear transition

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Q-Value Measurements

- The Q-value is defined as the difference in energy of the reactants and products of a nuclear reaction

- In both cases it reduces to the difference in mass of the two nuclei

$$Q = m_m - m_d = \left(\frac{\nu_c^d}{\nu_c^m} - 1 \right) (m_d - m_e)$$

- Measuring the free cyclotron frequency of the ions of interest in a Penning trap and determining the frequency ratio yields the Q-value while using one ion's mass as reference

- Candidates for EC process or double beta decay have been proposed and partly measured

H.-J. Kluge and Y. N. Novikov, Nucl. Phys. News **17**, 48 (2007)
K. Zuber, Cont. Phys. **45**, 491 (2004)
S. Rahaman et *al.*, PLB 662, 111 (2008)
M. P. Bradley et *al.*, PRL 83, 4510 (1999)

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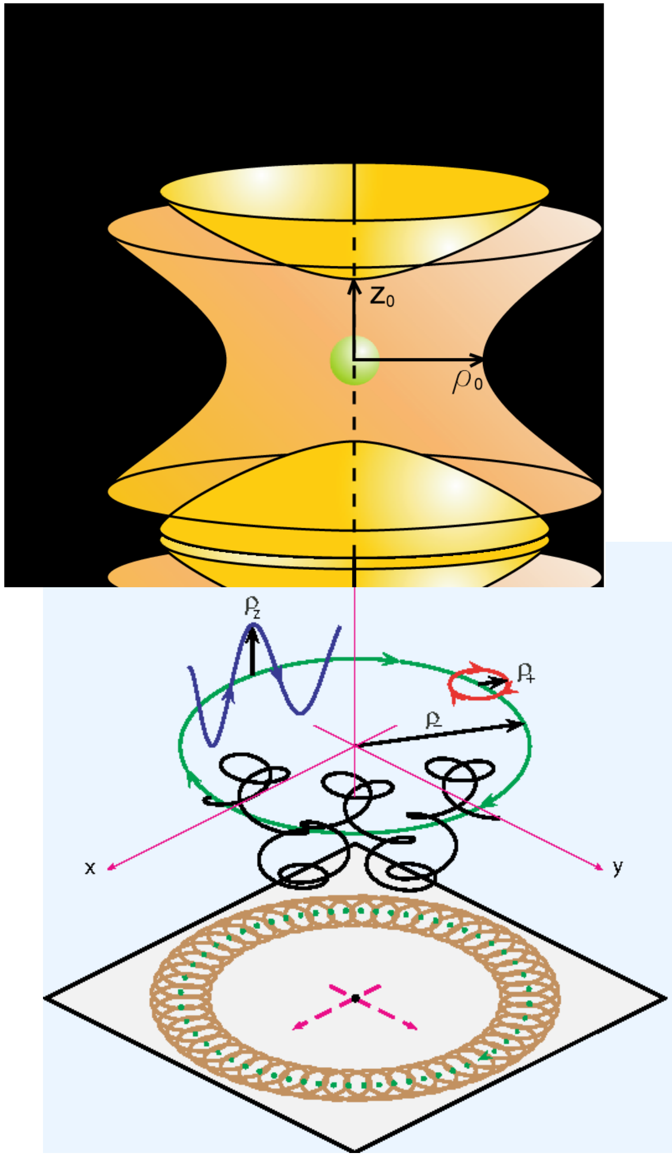
Charged Particle in a Penning Trap



magnetic field: confinement in radial direction

electric field: confinement in axial direction

⇨ three uncoupled eigenmotions

cyclotron motion $$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

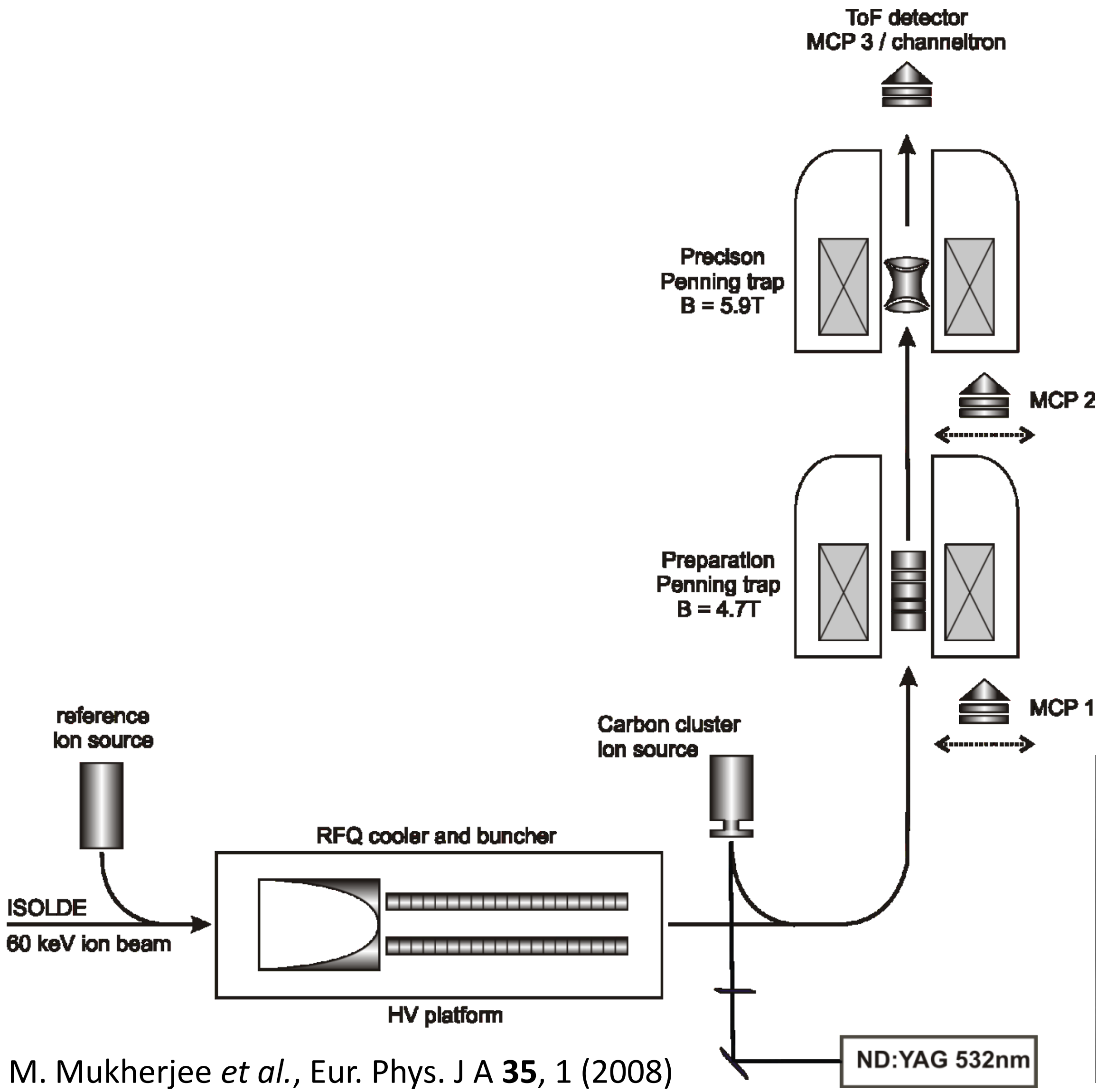
magnetron motion $$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

axial motion $$\omega_z = \sqrt{\frac{q}{m}\frac{U_0}{d^2}c_2}$$

$$\omega_c = \omega_+ + \omega_- \quad \Rightarrow \quad \omega_c = \frac{q}{m}B$$

L. S. Brown et al., Rev. Mod. Phys. **56**, 233 (1986)

Experimental Setup



M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)

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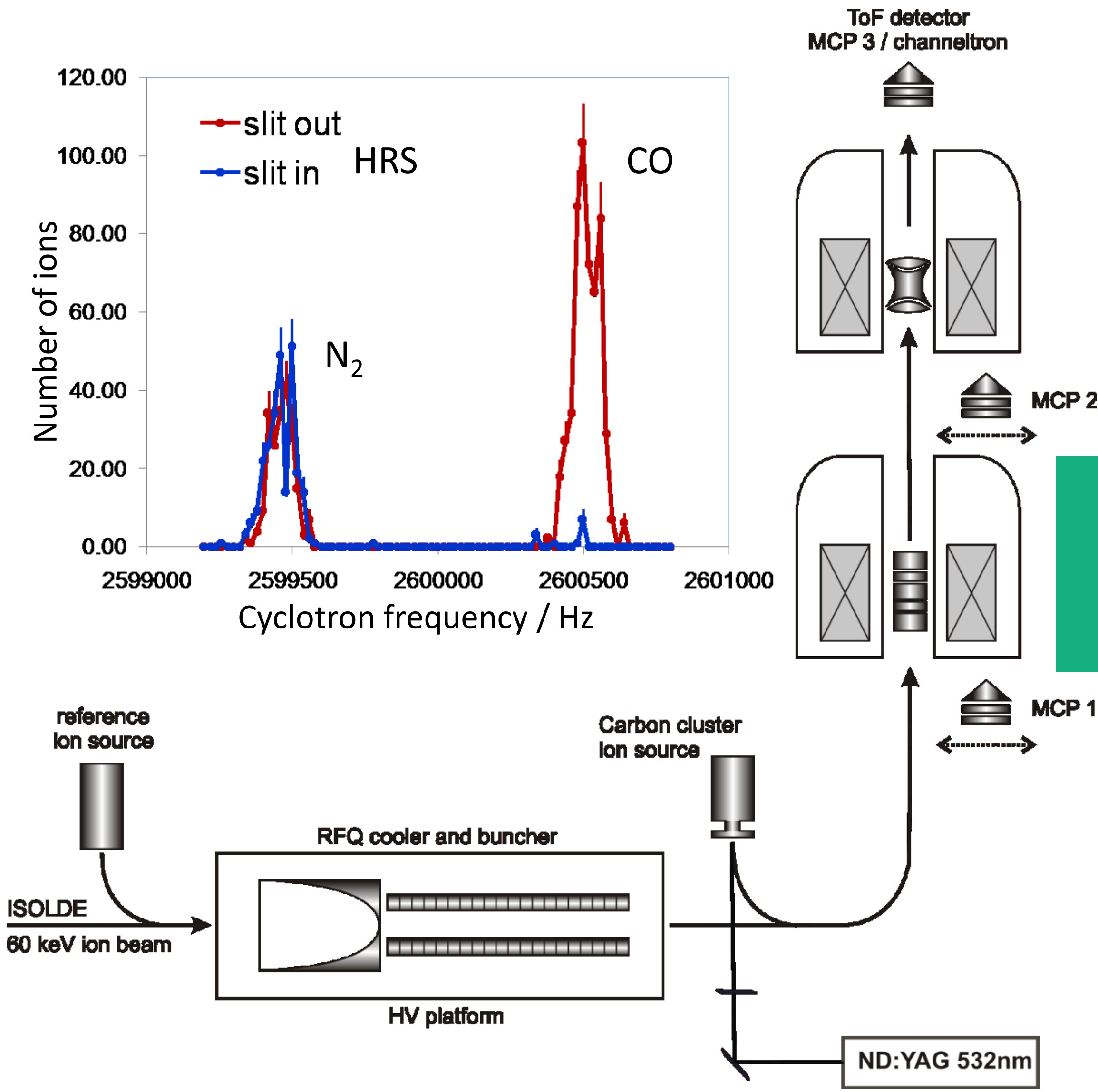
Experimental Setup



Elimination of undesired contaminations (isobaric cleaning) and preparation for injection into second trap

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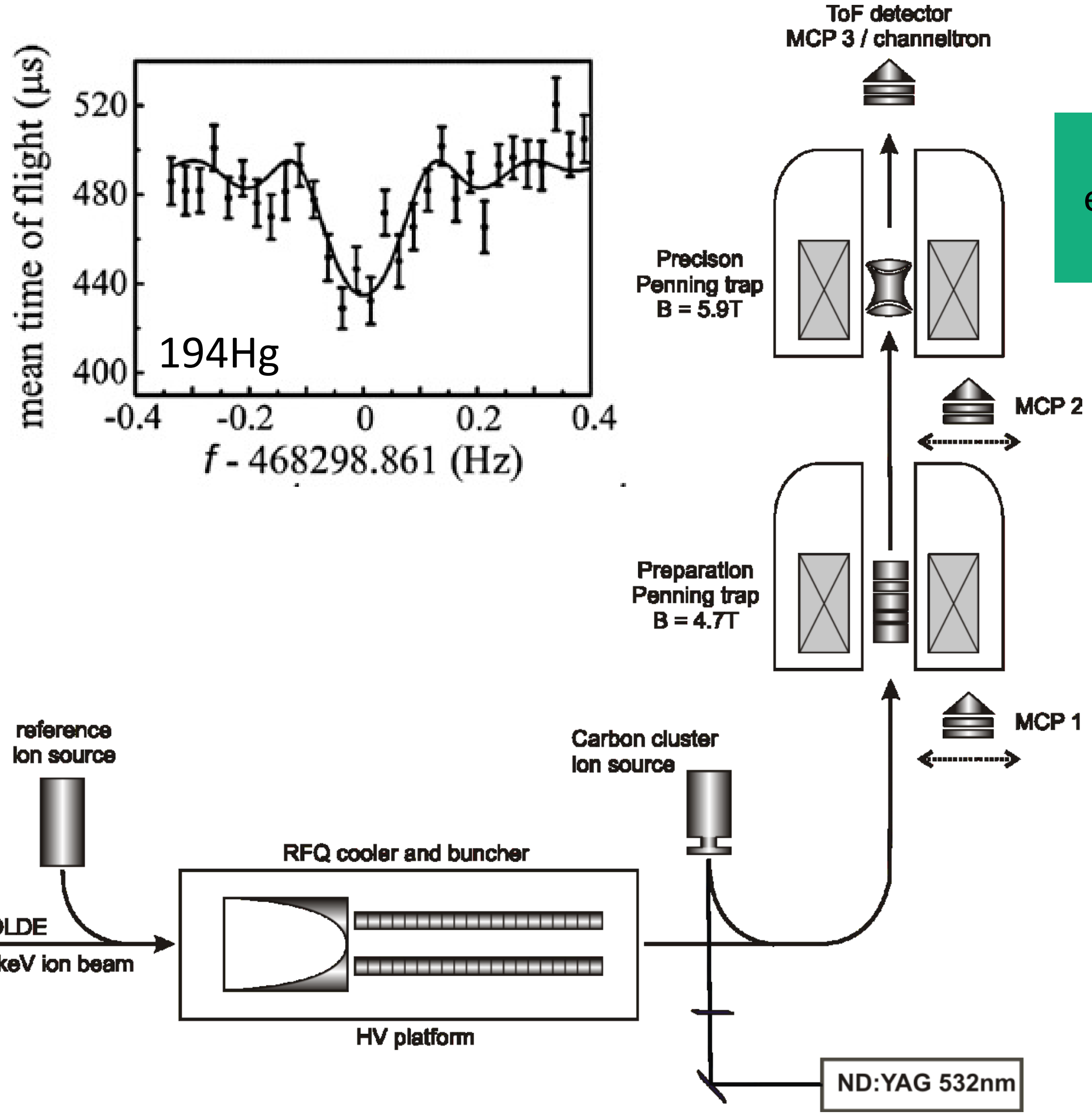
Experimental Setup

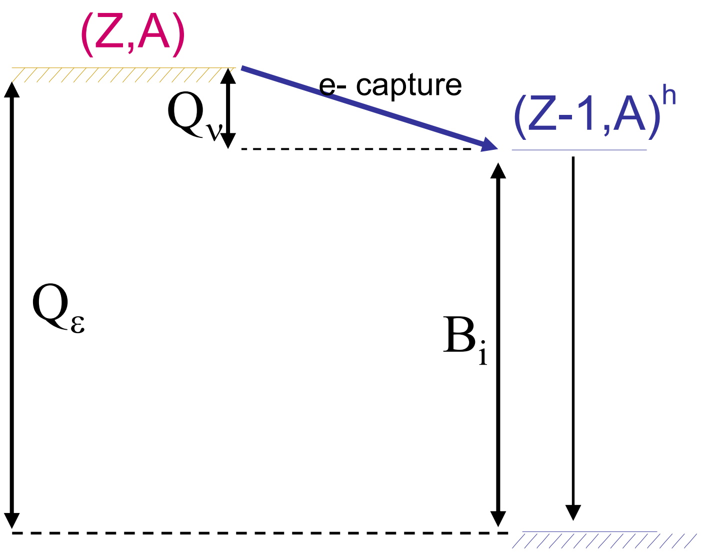


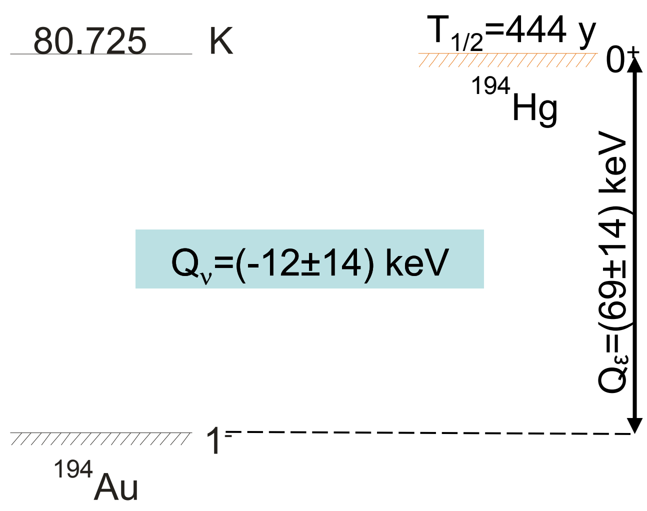
Mass determination by excitation at free cyclotron frequency

S. Eliseev et *al.*, PLB **693**, 426 (2010)

Electron Capture in ^{194}Hg

- ISOLTRAP can decide whether pair considered is suitable for micro-calorimeter measurements





$$Q_\nu = E_\nu + m_\nu = Q_\varepsilon - B_i$$

⇒*candidate* for neutrino-mass determination $Q_\varepsilon - B_i$ <1 keV

^{194}Hg because $\tau_{1/2}$ = 440(80) yr, production yield at ISOLDE sufficient

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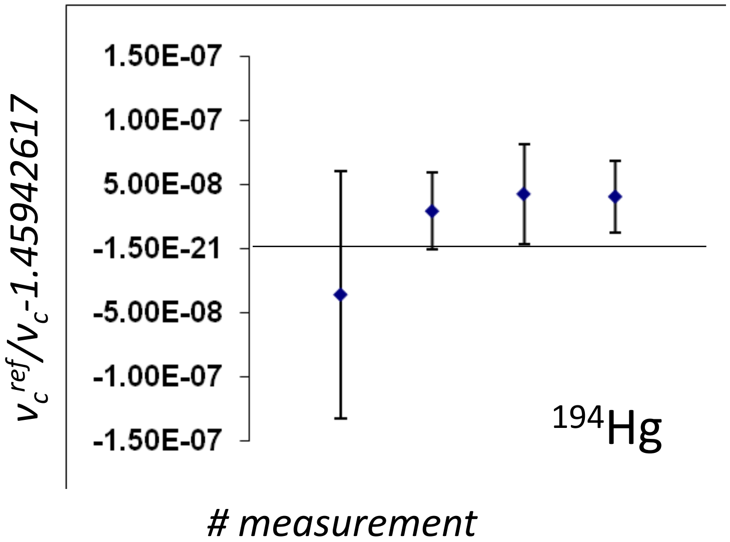
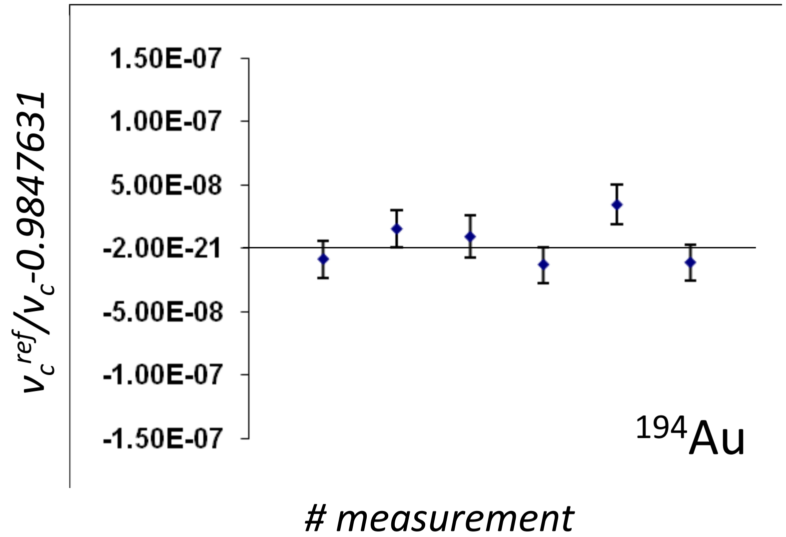
Results of ^{194}Hg-^{194}Au





^{194}Hg-^{194}Au:
ME(^{194}Hg) = -32184(3) keV
ME(^{194}Au) = -32213(2) keV

$Q_\varepsilon = (29 \pm 4)$ keV

$^{194}Hg^{78+}$ is stable against EC in K orbit

Suggest determination of neutrino mass of the de-excitation spectrum from L-capture

Reduction of upper limit of neutrino mass to 20eV

S. Eliseev et *al.*, PLB **693**, 426 (2010)

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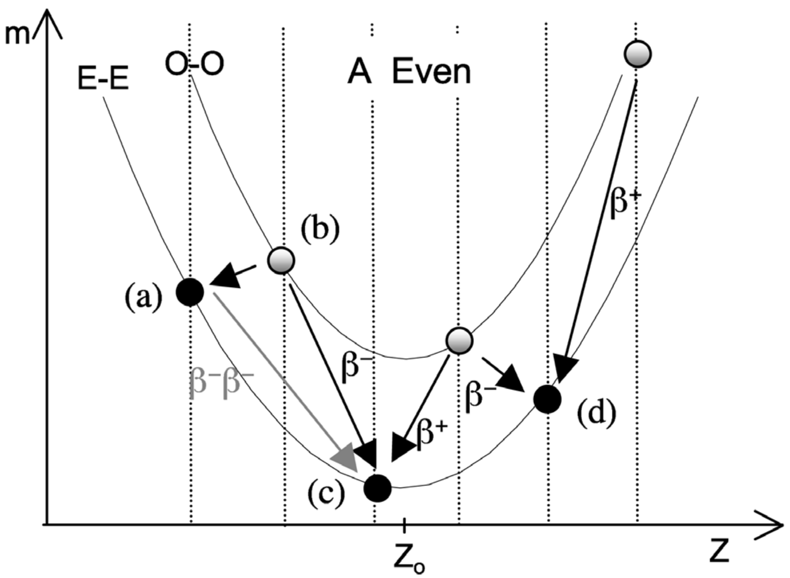
Neutrinoless Double Beta Decay

Consider 0+ → 0+ transitions for even-even nuclei with

m(Z,A) > m(Z+2,A)

and β-decay has to be forbidden or strongly surpressed

m(Z,A) < m(Z+1,A)



Measure half-life of nuclear decay but $\tau_{1/2} \approx 10^{20}$yr

Measure *Q*-value because

$\tau_{1/2} \sim Q^5$

Consider *Q* > 2MeV

$$\left(\tau^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left(\frac{\langle m_{\nu e}\rangle}{m_e}\right)^2$$

Phase-space integral

Nuclear matrix element of transition

Is ^{110}Pd a good candidate to conduct an experiment?

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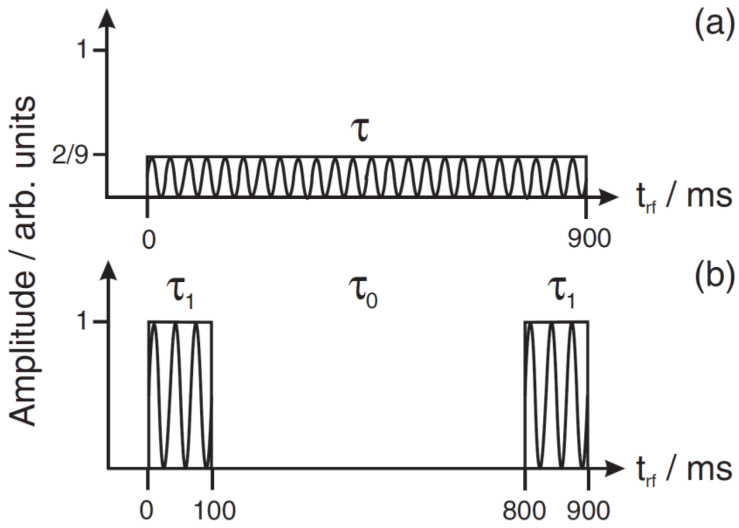
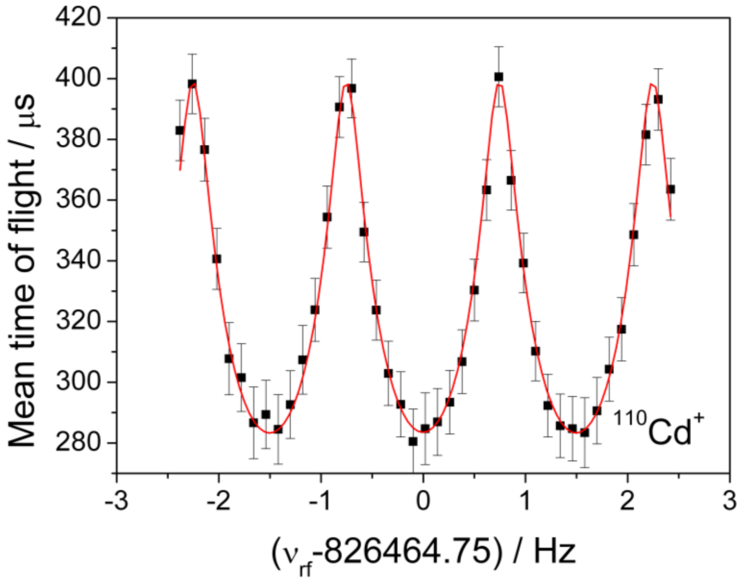
Excitation of Cyclotron Frequency





- Ramsey method of time-separated oscillatory fields used to excite the trapped ions of interest in the Penning trap
- used for a gain in precision or time.

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

S. George *et al.*, PRL **98**, 162501 (2007)

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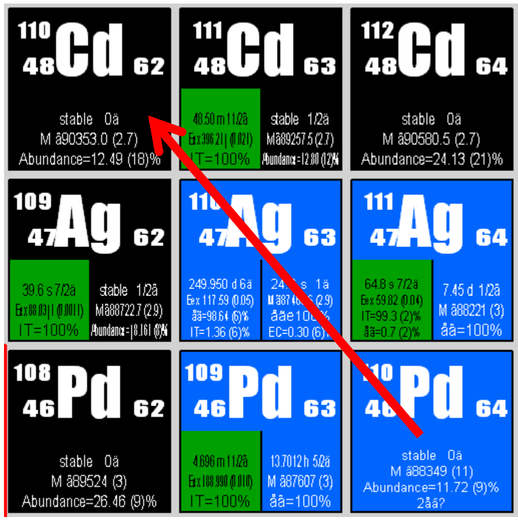
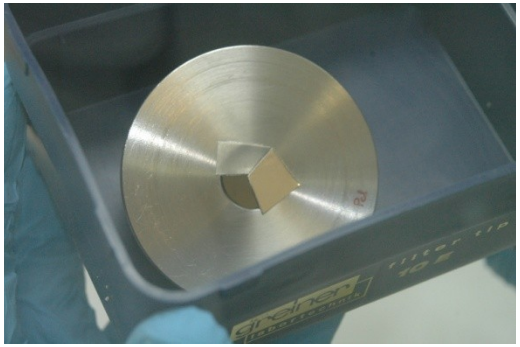
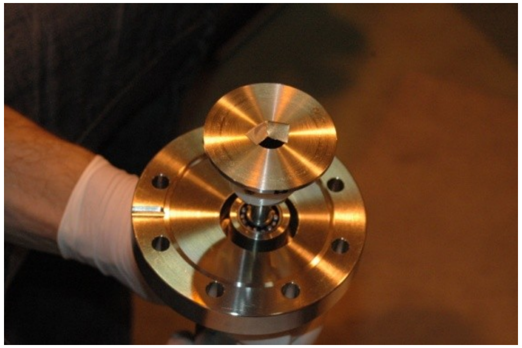
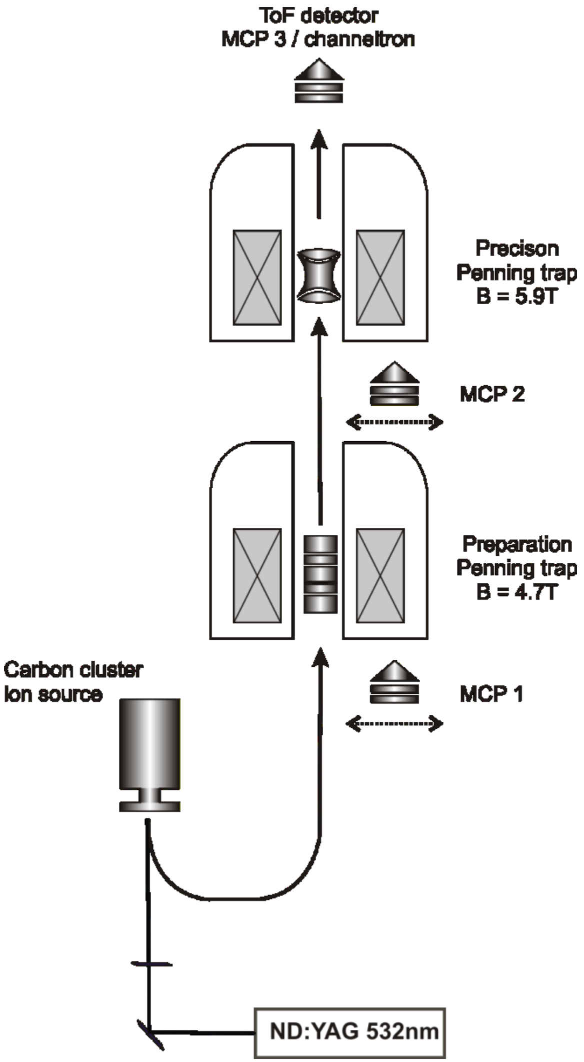
Laser Ablation Source for ^{110}Pd

$$^{110}Pd \rightarrow {}^{110}Cd + 2e^-$$









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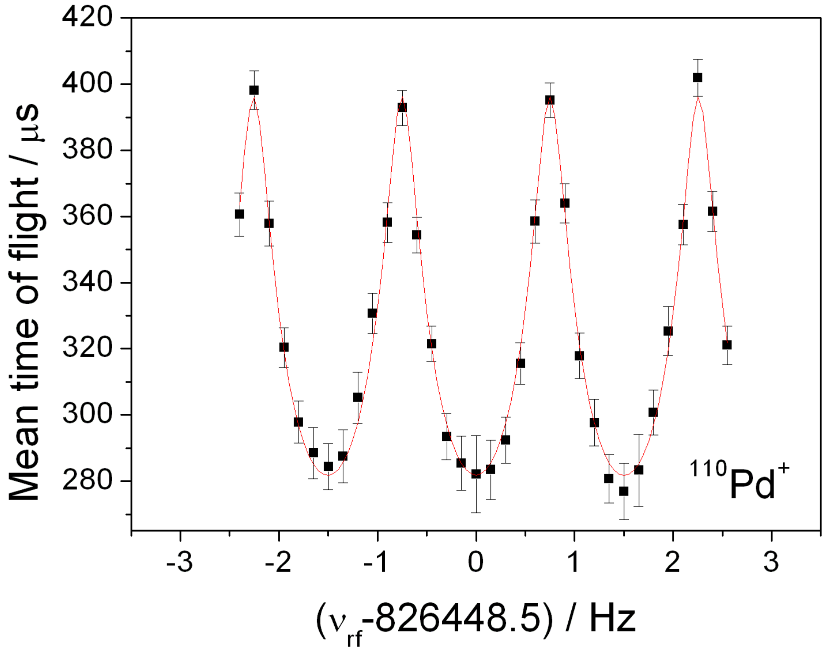
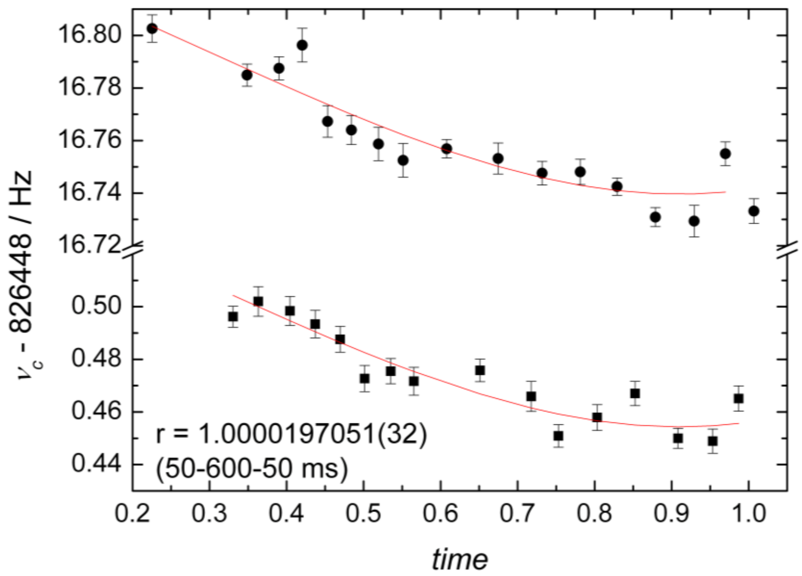
Results for ^{110}Pd





Q_{AME} = 2004 (11.33) keV
Q = 2017.78 (32) keV

Larger phase-space values with new matrix element calculations lead to reduced half-life of $\tau_{1/2} = 1.2 \bullet 10^{20}$yr

Very promising candidate also because of high natural abundance

D. Fink, diploma thesis (2010)
F. Iachello priv. comm.

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Summary and Outlook

- Neutrino-mass oriented EC and 0νββ decay processes have been studied
- Measurements were performed with online beam from ISOLDE as well as offline beam from laser ion source
- Other candidates for EC

  ^{202}Tl-Pb (accepted proposal by INTC)
- Other candidates for Double Beta Decay

  ^{48}Ca-^{48}Ti

  ^{96}Zr-^{96}Mo

  ^{124}Sn-^{124}Te

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