Measurements of low-energy beta-decay processes using Penning traps

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MPIK

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Outline

- Low-energy β-decay processes for the absolute neutrino mass determination
- Penning-trap mass spectrometry for the β-decay energy measurements
- Status of PENTATRAP
- Conclusion

Neutrino mass determination

Three main approaches to determine the absolute neutrino mass:

1) Cosmology $\Sigma m_i \equiv \sum_{i=1}^{3} m_i$

$\Sigma m_i < 0.12$ eV [Delabrouille *et al*. JCAP 2015 (2015) 011]

2) Neutrinoless Double β-decay $m_{\beta\beta} \equiv \sum_{i=1}^{3} U_{ei}^2 m_i$

$m_{\beta\beta} < 0.24$ eV [Barabash, arXiv:1702.06340, 2017]

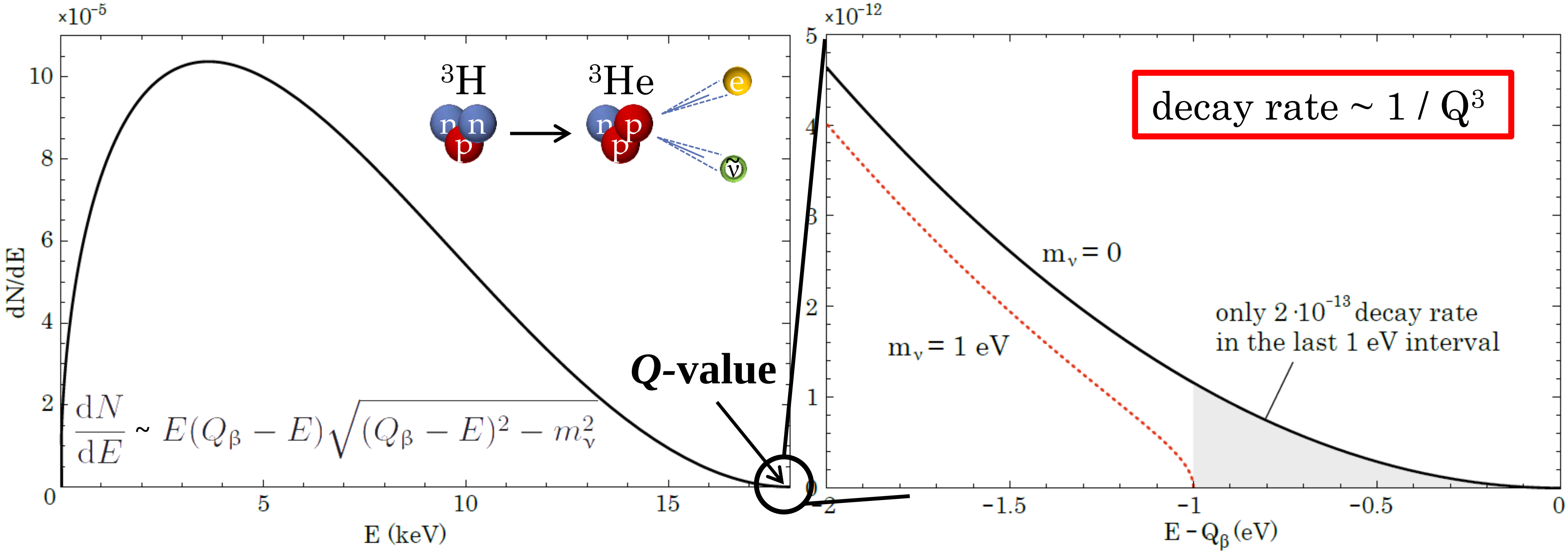
3) Kinematic Determination $m_{\nu_e} \equiv \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$

from supernova explosion $m_{\nu_e} < 5.8$ eV [Pagliaroli *et al*. Astroparticle Physics 33 (2010) 287]

from β-decay $m_{\nu_e} < 2$ eV [Otten and Weinheimer Rep. Prog. Phys. 71 (2008) 086201]

the least model dependent approach

Neutrino mass in β⁻-decay

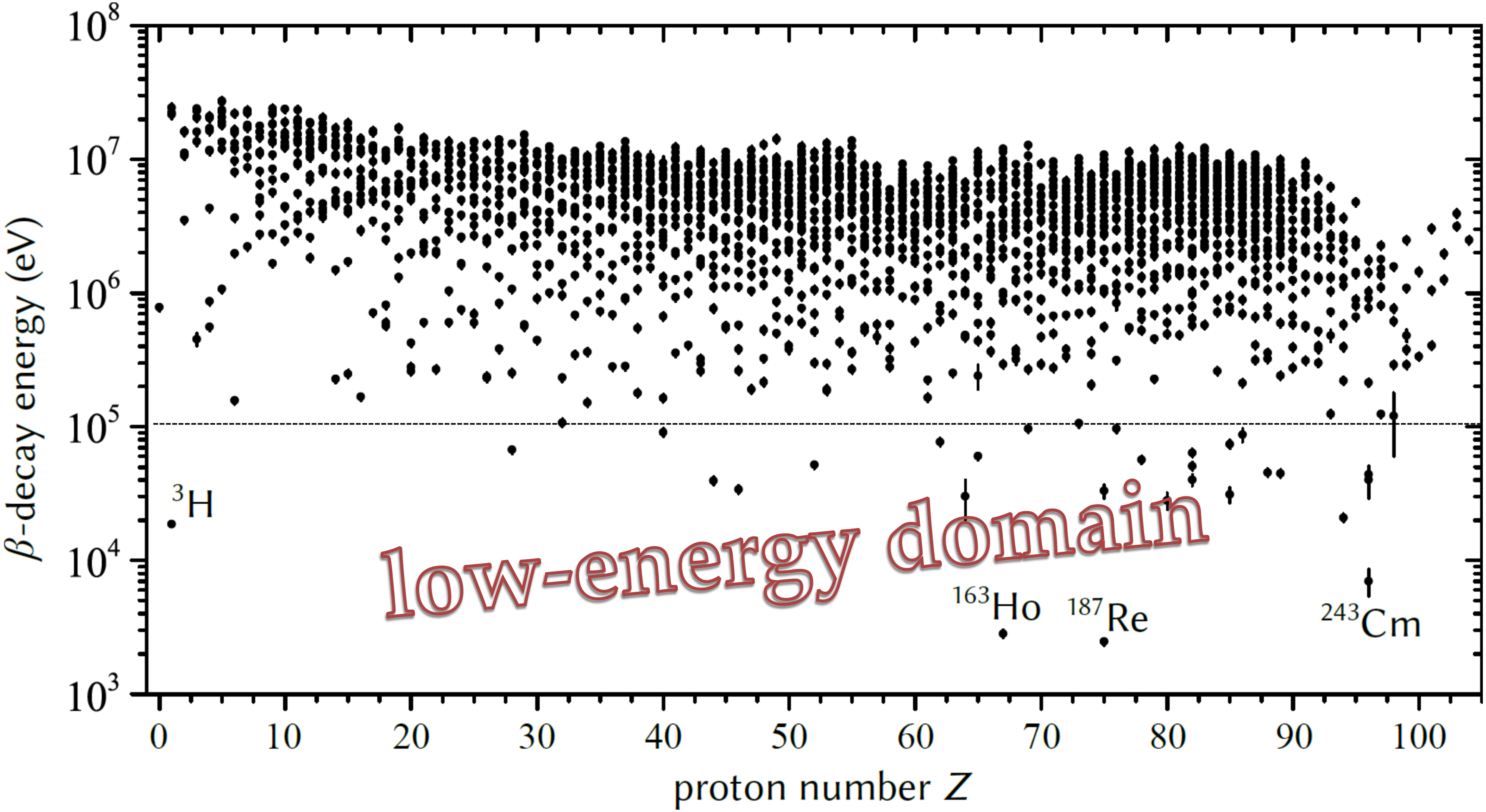


Necessary ingredients:

1. Spectrum with high statistics
2. Good theoretical description of the spectrum

→ Q-value is the most important fit parameter

β-decay energies



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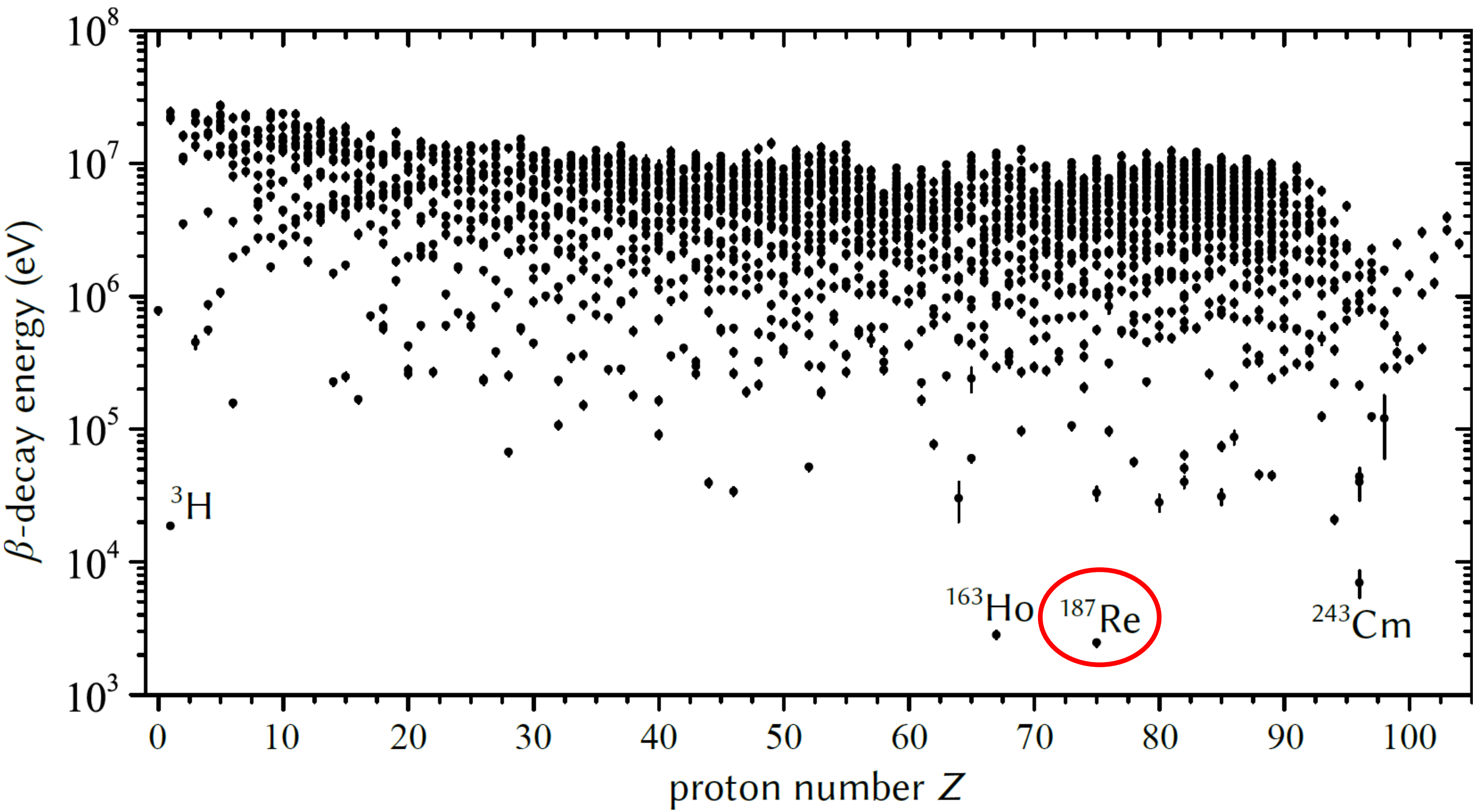
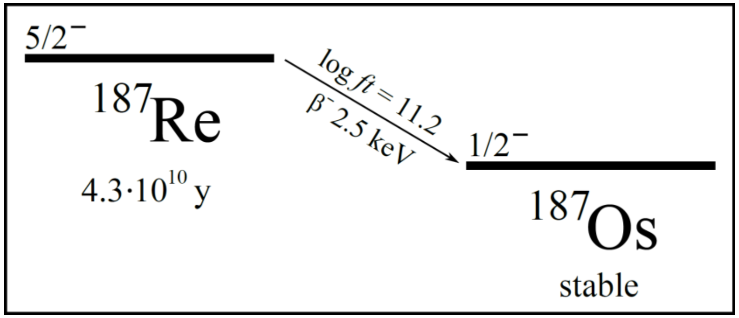
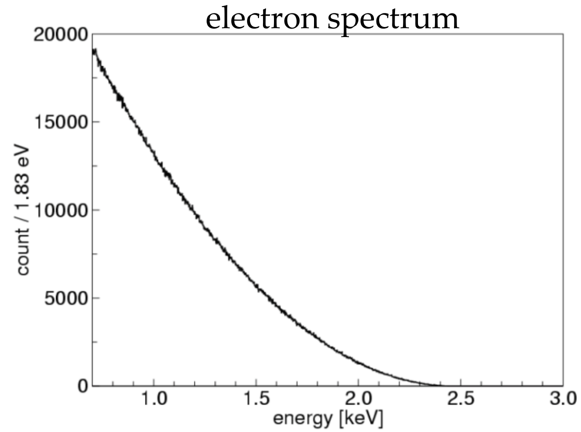
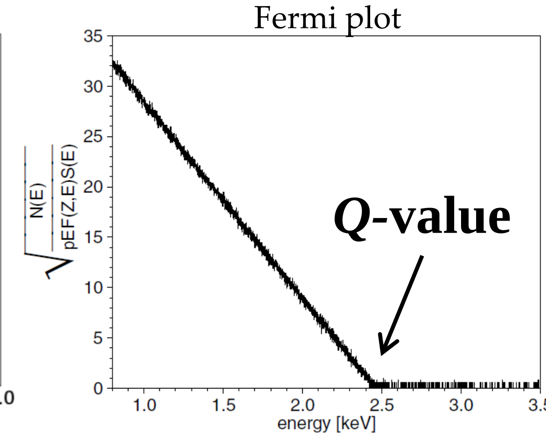


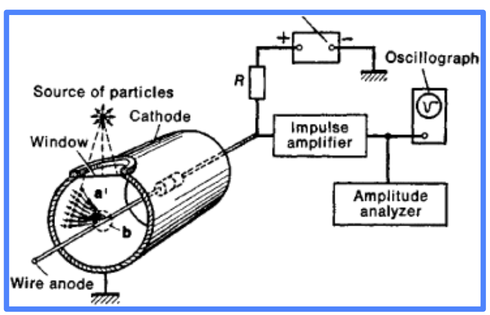
β-decay energy of ^{187}Re

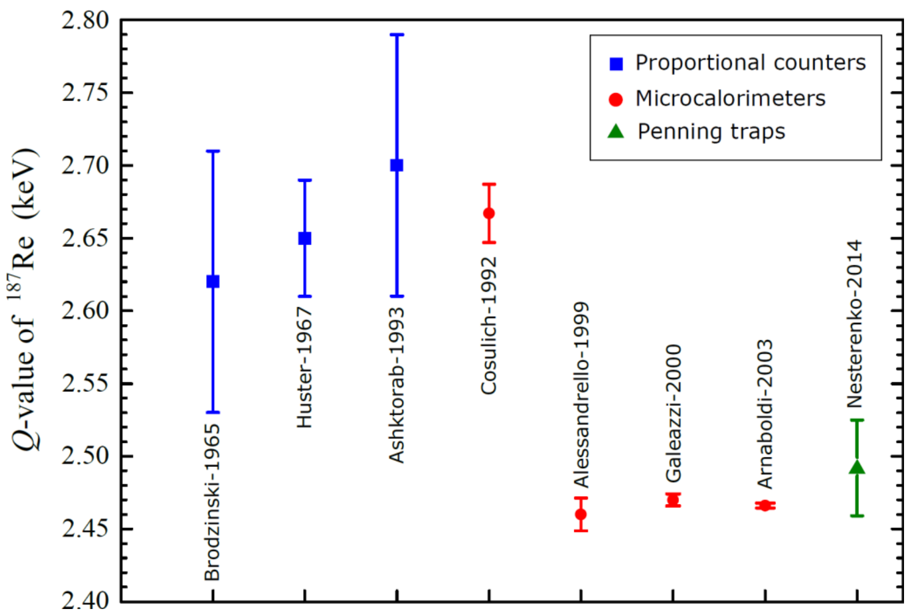


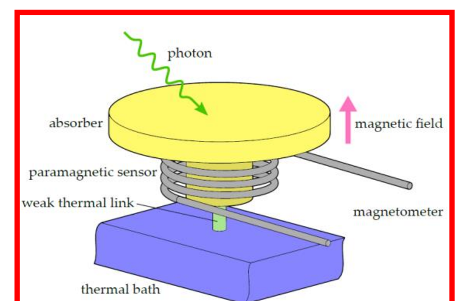




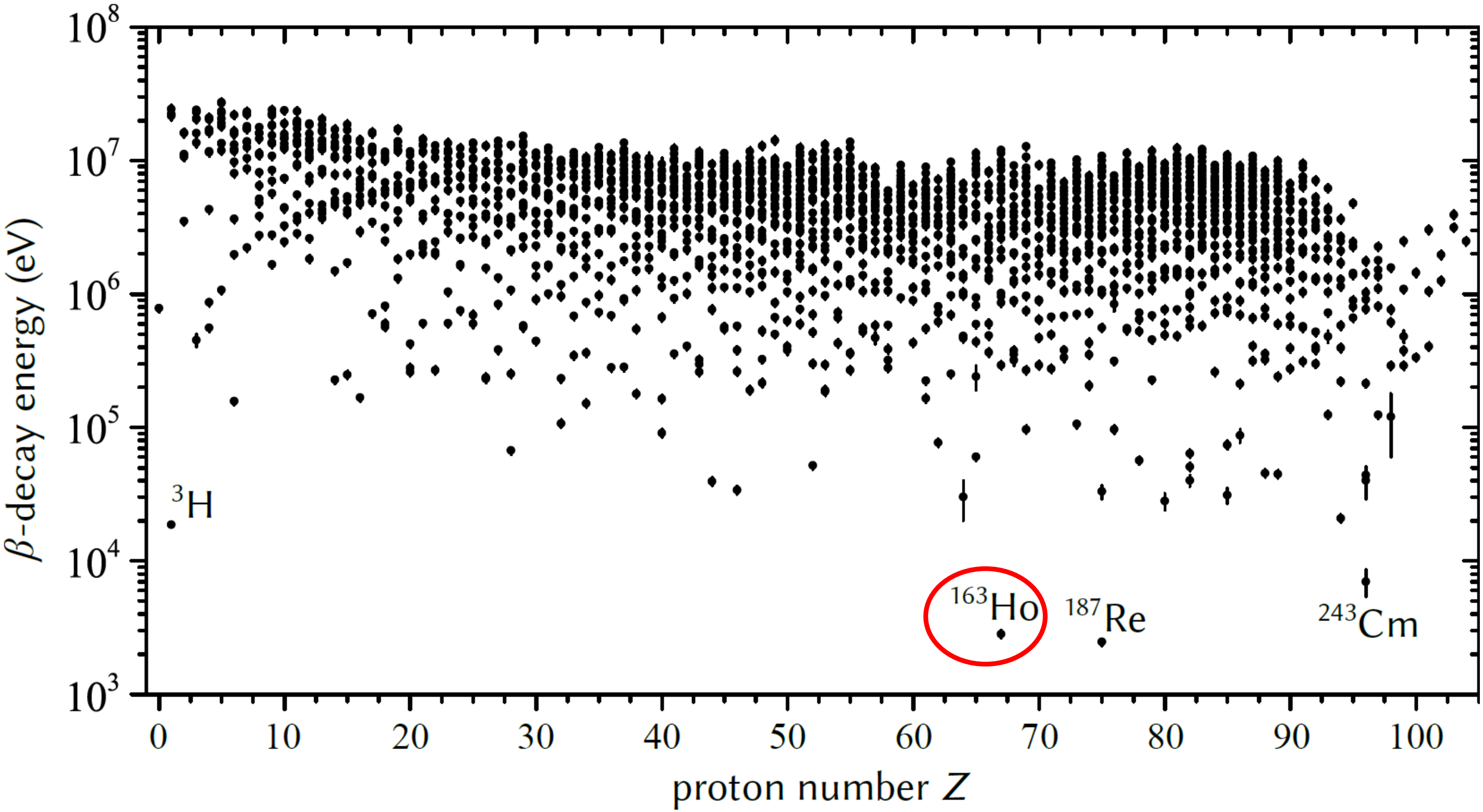
Q-value is the endpoint energy of the β-spectrum
or is the mass difference between parent and daughter atoms







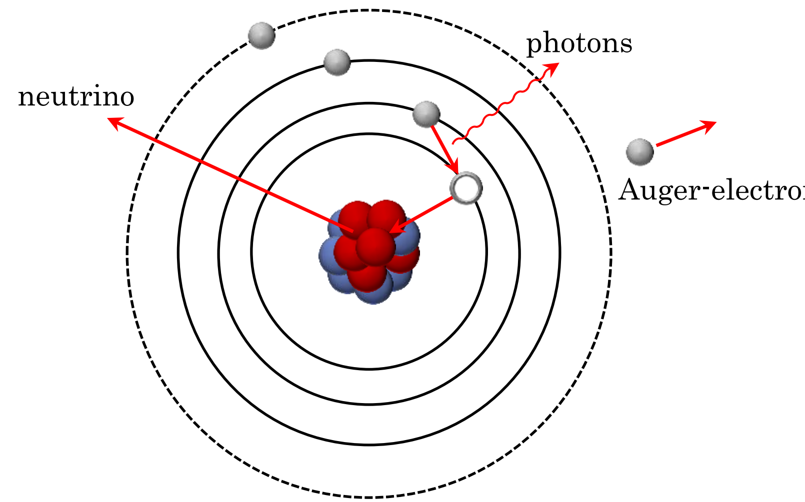
β-decay energies



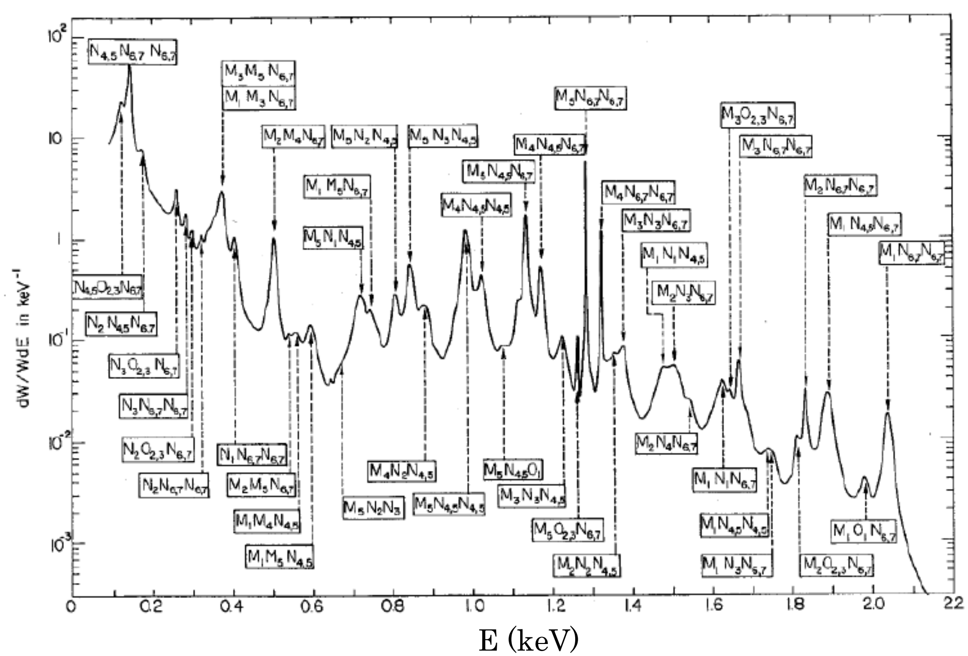
Neutrino mass in electron capture

$$^{163}_{67}\mathrm{Ho} \xrightarrow{\mathrm{EC}} {}^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

$$\hookrightarrow {}^{163}_{66}\mathrm{Dy} + E_c$$



Auger-electrons spectrum of ^{163}Ho



A.DeRjula, M.Lusignoli.
Nuclear Physics B219 (1983) 277

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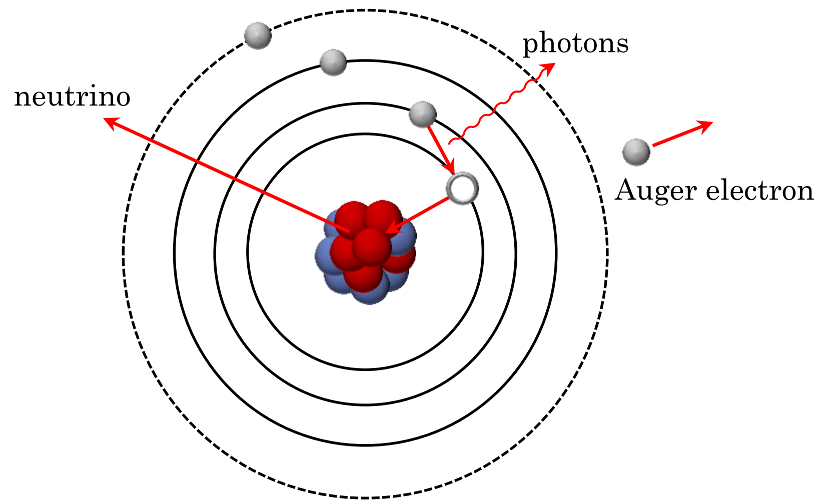
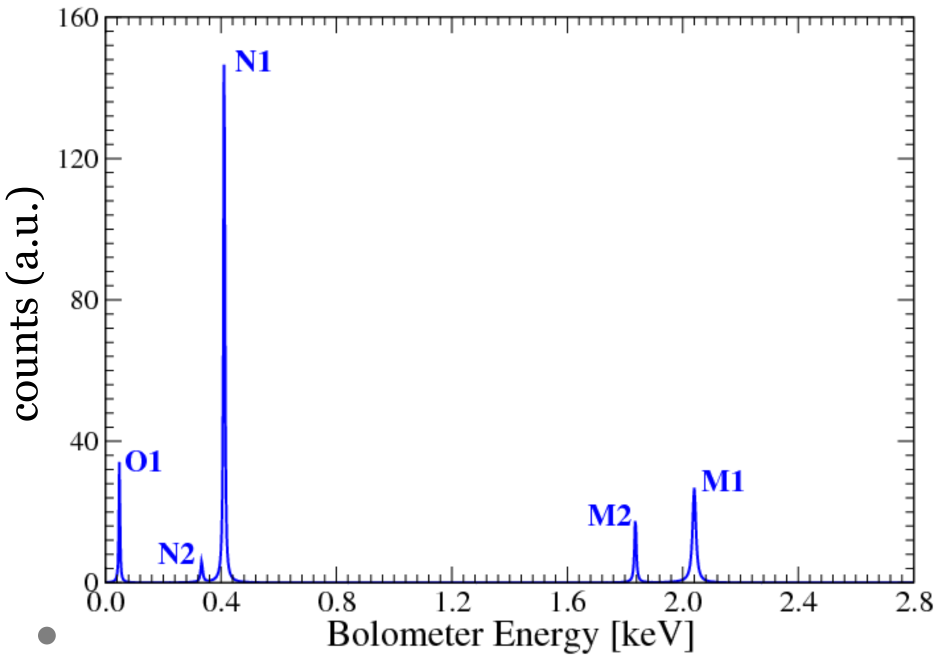


Calorimetric spectrum of ^{163}Ho



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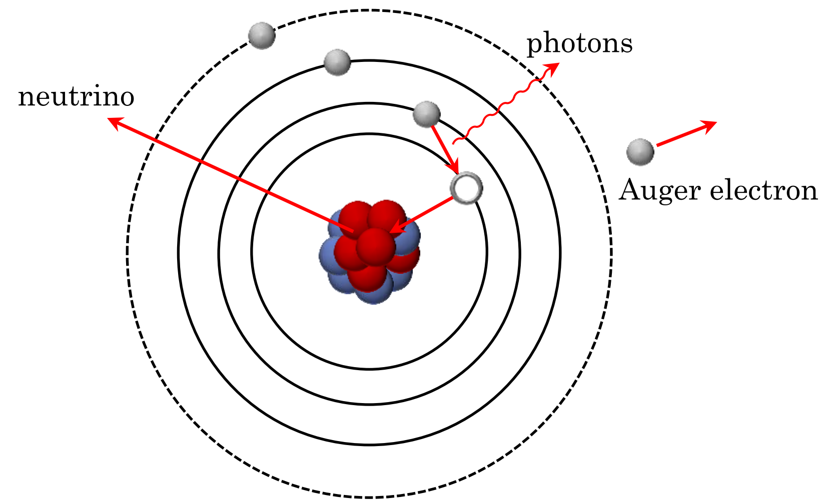

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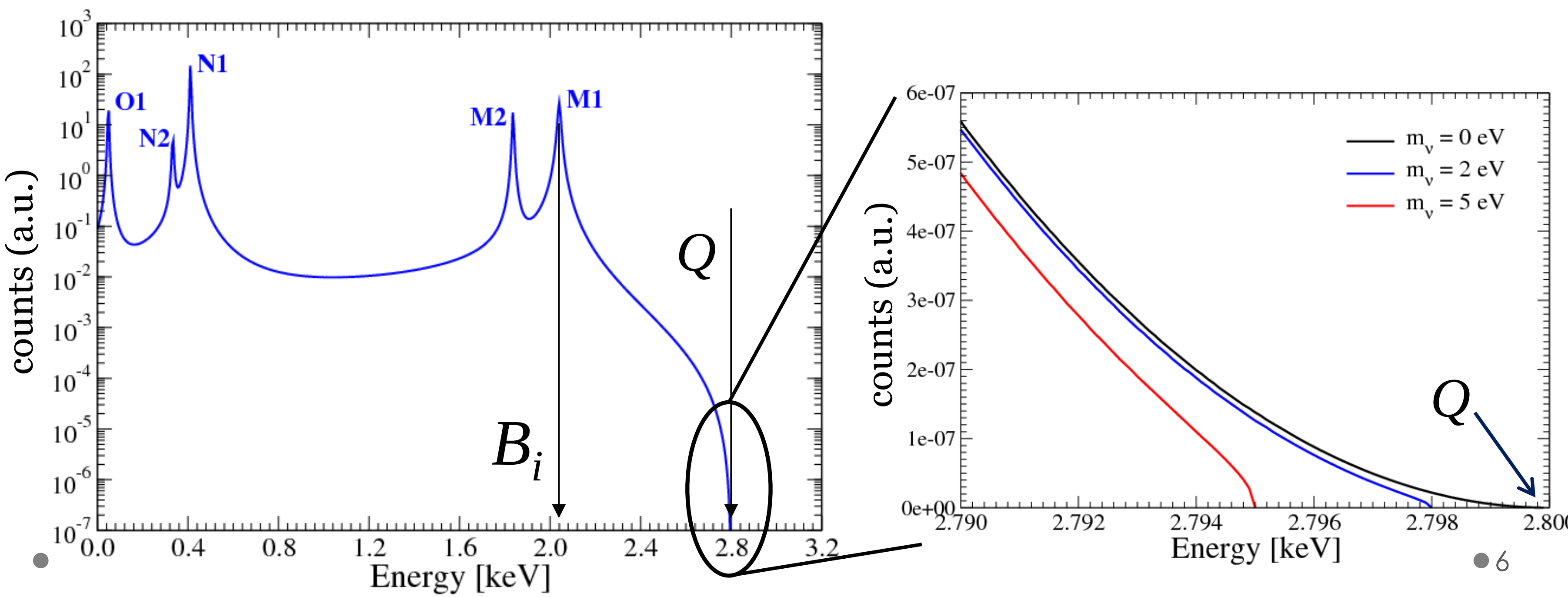

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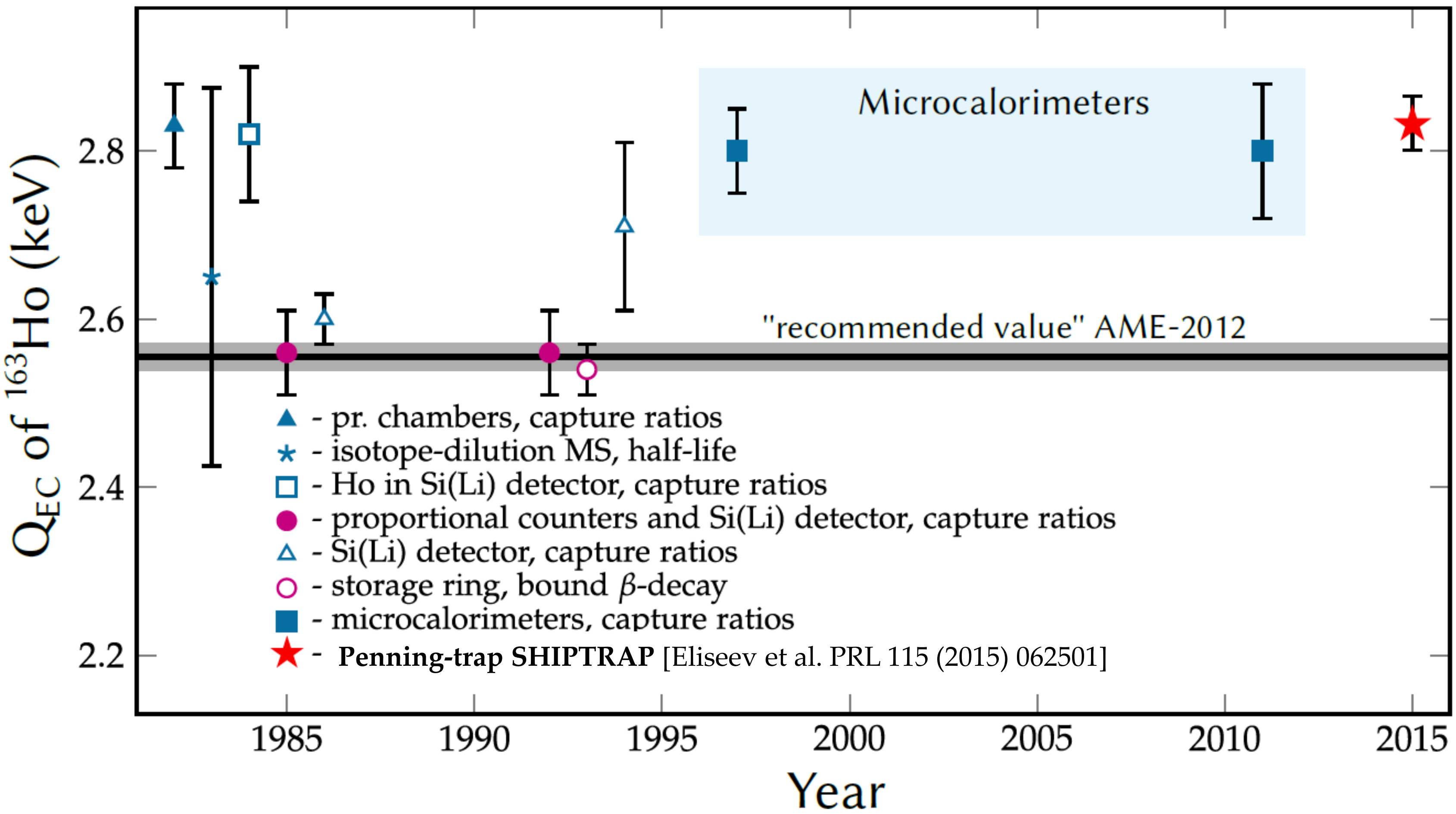
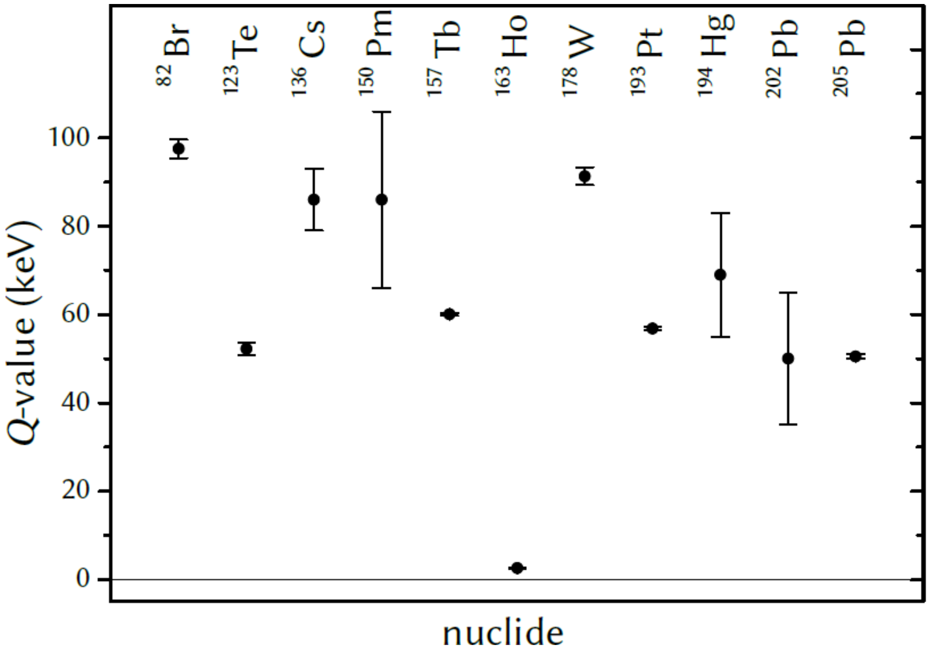
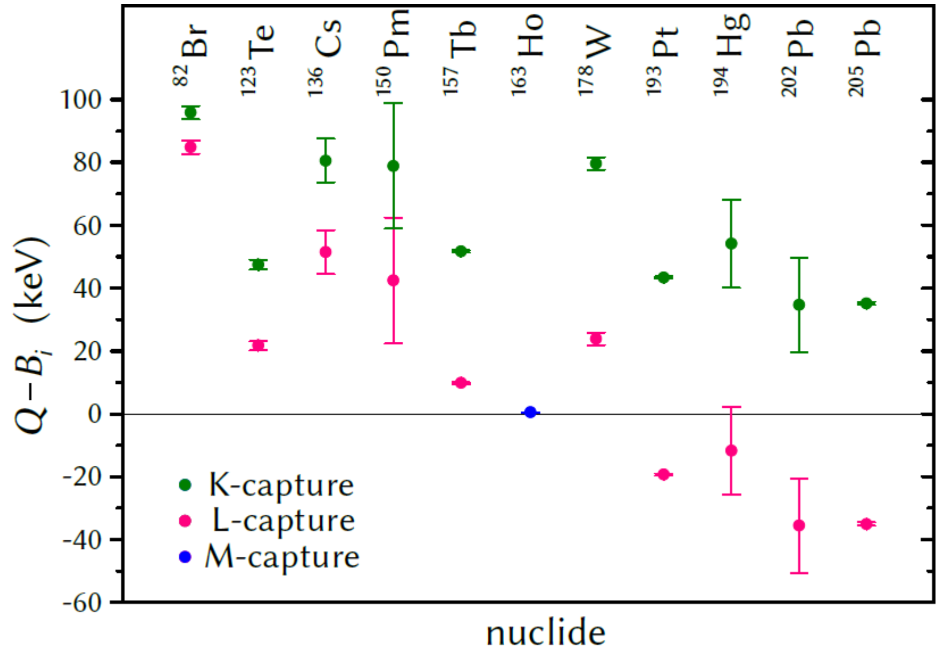


Search for new candidates

Main criteria: $Q - B_i \rightarrow 0$





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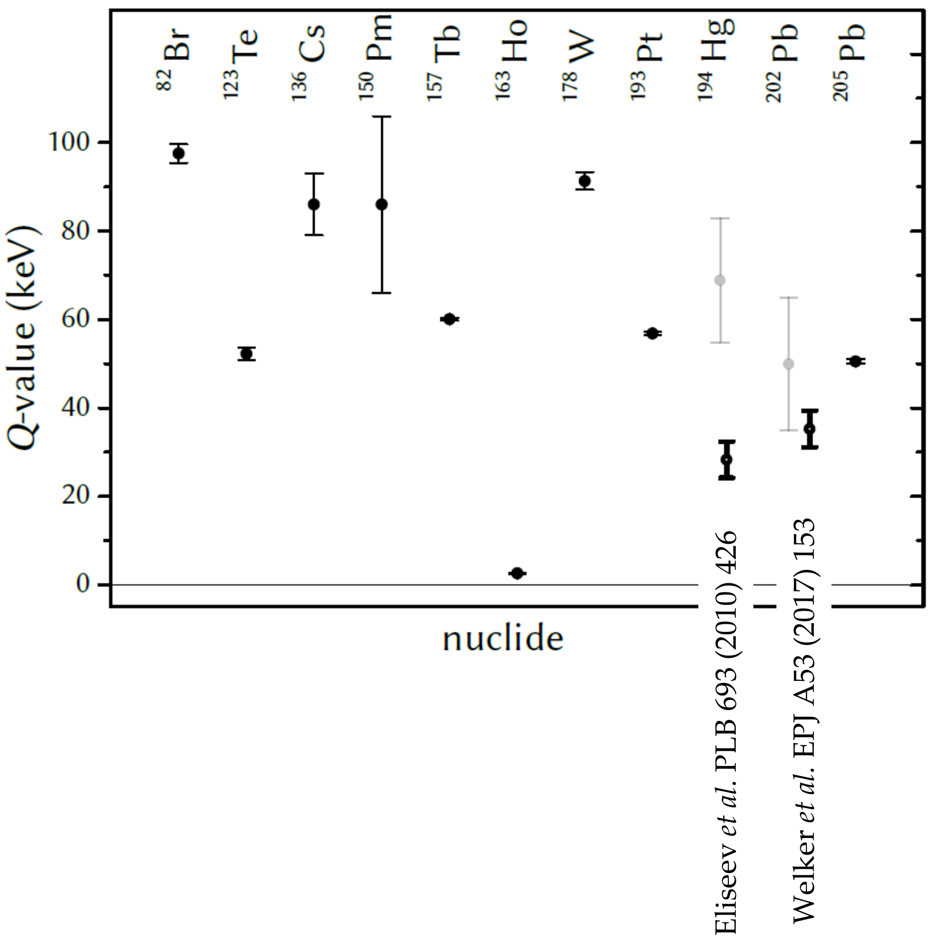

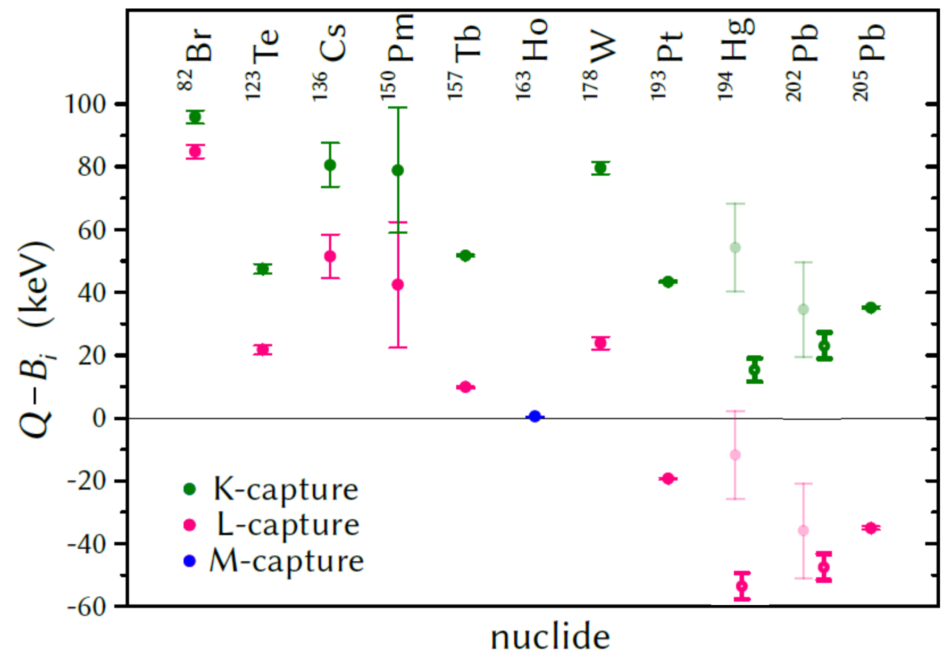

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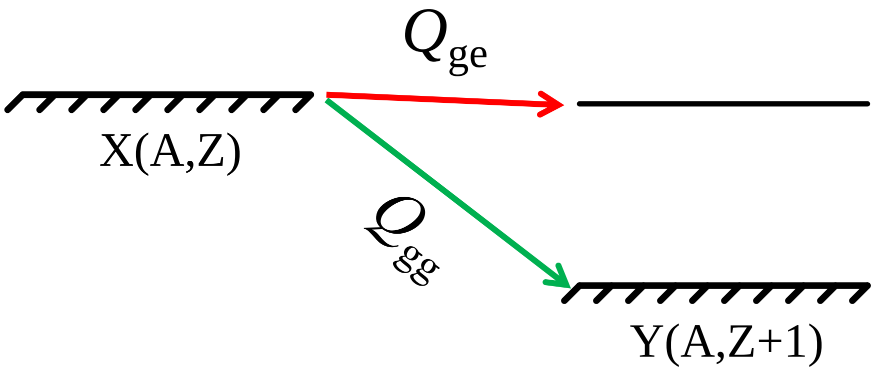

criteria for β±-decay: $Q_{ge} \to 0$

criteria for EC: $Q_{ge} - B_i \to 0$

β-transition	ΔJ^P	$T_{1/2}^{gg}$	$Q_{gg} \pm \Delta Q_{gg}$ (keV)	$E^* \pm \Delta E^*$ (keV)	$Q^{\nu}_{ge} \pm \Delta Q^{\nu}_{ge}$ (keV)	transition type
^{130}Cs → ^{130}Ba*	1^+	29 min	362 ± 9	357.38 ± 0.08	4.6 ± 9	β^-
^{131}Cs → ^{131}Xe*	0^+	9.7 d	355 ± 5	364.490 ± 0.004	-15 ± 5	L
					-11 ± 5	M
^{134}Ce → ^{134}La*	1^+	3.2 d	386 ± 29	355.479 ± 0.012	-8 ± 29	K
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^{140}Nd → ^{140}Pr*	(2,3)	3.4 d	429 ± 7	419.9 ± 0.3	2 ± 7	L
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^{146}Pm → ^{146}Nd*	1^-	5.6 y	1472 ± 4	1470.6 ± 0.1	1.4 ± 4	β^+
^{149}Gd → ^{149}Eu*	1^-	9.3 d	1314 ± 4	1312 ± 4	2 ± 6	β^+
^{155}Eu → ^{155}Gd*	2^-	4.7 y	251.8 ± 0.9	251.706 ± 0.001	0.4 ± 0.9	β^-
^{159}Dy → ^{159}Tb*	1^+	144 d	365.2 ± 1.2	363.545 ± 0.002	-0.3 ± 1.2	M
^{161}Ho → ^{161}Dy*	1^+	2.5 h	858.5 ± 2.2	804.388 ± 0.003	0.3 ± 2.2	K
				858.792 ± 0.002	-2.3 ± 2.2	M
^{171}Tm → ^{171}Yb*	2^+	1.2 y	96.5 ± 1.0	95.282 ± 0.002	1.3 ± 1	β^-
^{175}Hf → ^{175}Lu*	2^-	70 d	683.9 ± 2.0	626.53 ± 0.15	-6 ± 2	K
	1^+			672.83 ± 0.15	0 ± 2	L
^{201}Tl → ^{201}Hg*	(2)	72.9 h	482 ± 14	384.602 ± 0.018	14 ± 14	K
				464.41 ± 0.03	3 ± 14	L

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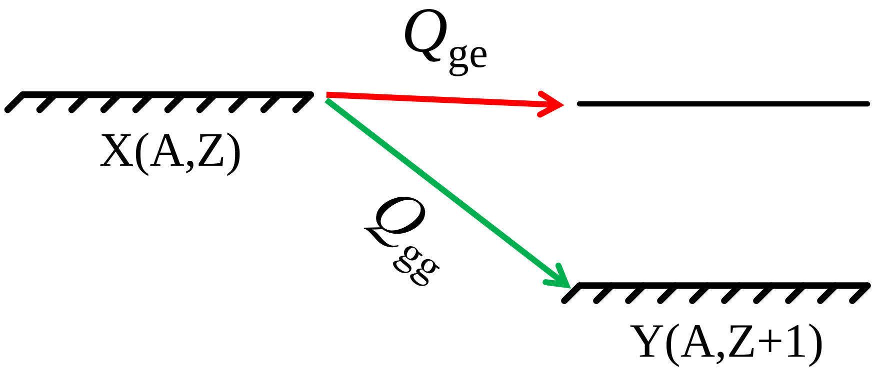

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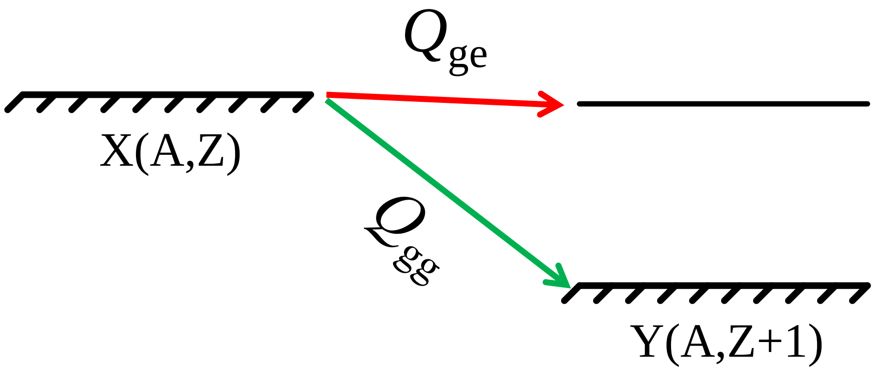

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preliminary

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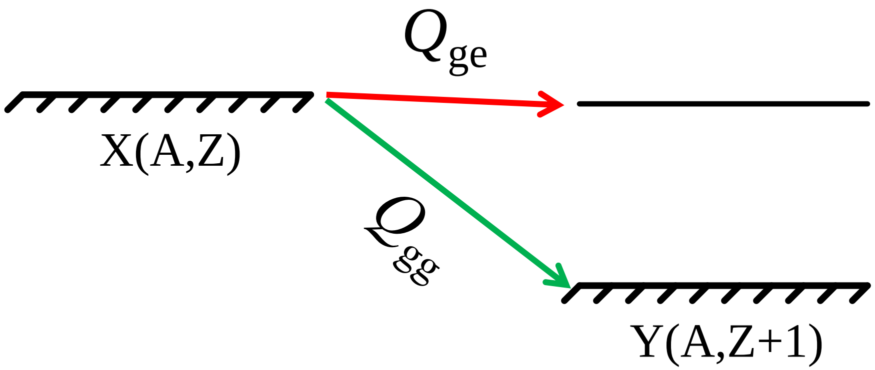

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EC is energetically forbidden

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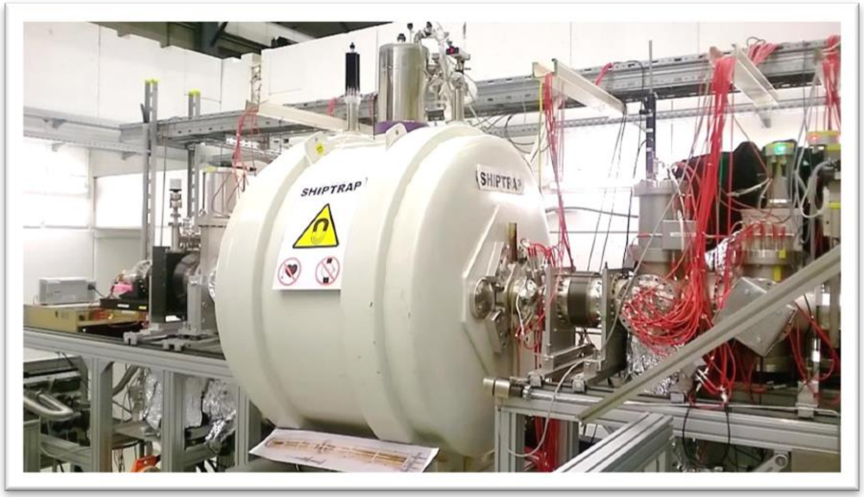
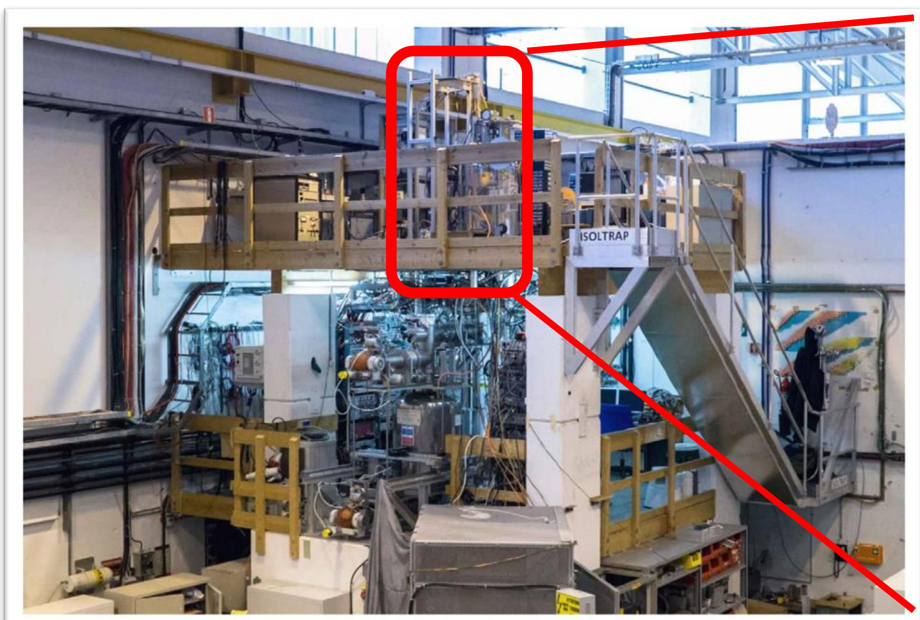
preliminary

Penning-trap Mass Spectrometry

SHIPTRAP
GSI
Darmstadt

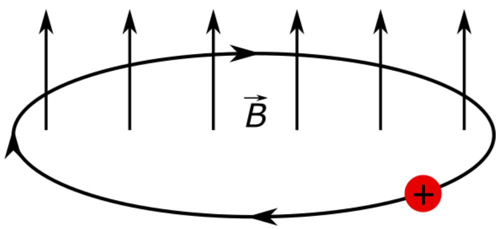


ISOLTRAP
CERN



Penning trap

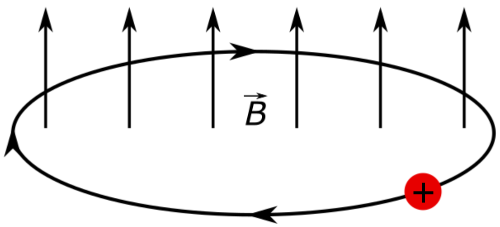
homogeneous B-field



$$\omega_c = \frac{q}{m} B$$

Penning trap

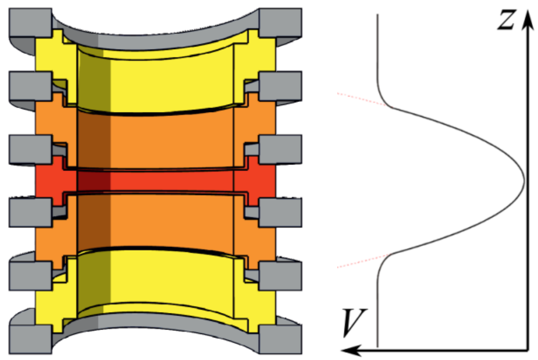
homogeneous B-field



$$\omega_c = \frac{q}{m} B$$

+

quadrupole E-field



Penning trap

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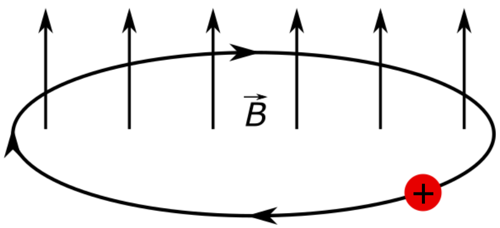

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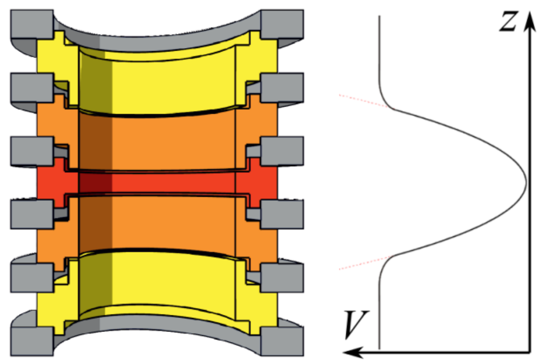

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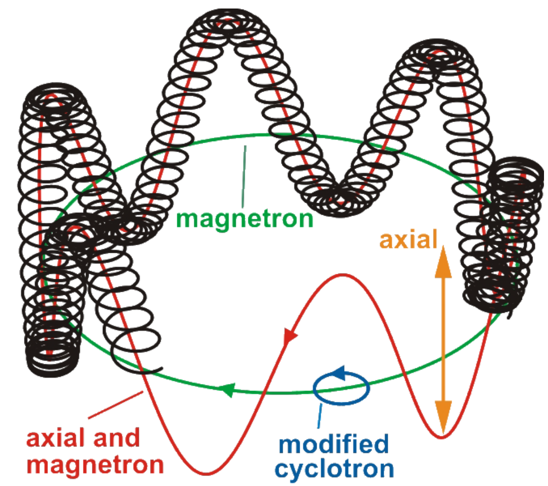

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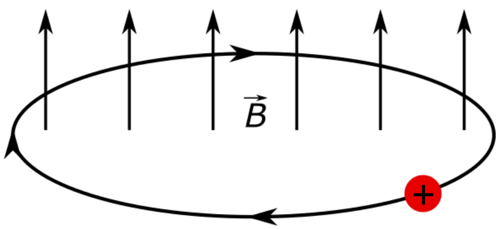
homogeneous B-field



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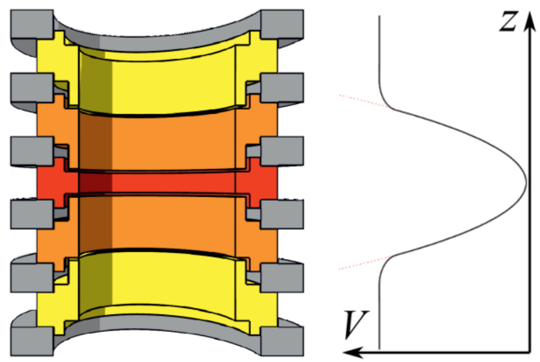

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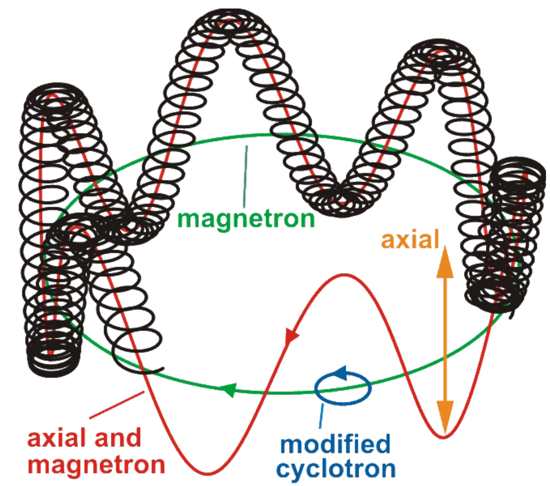
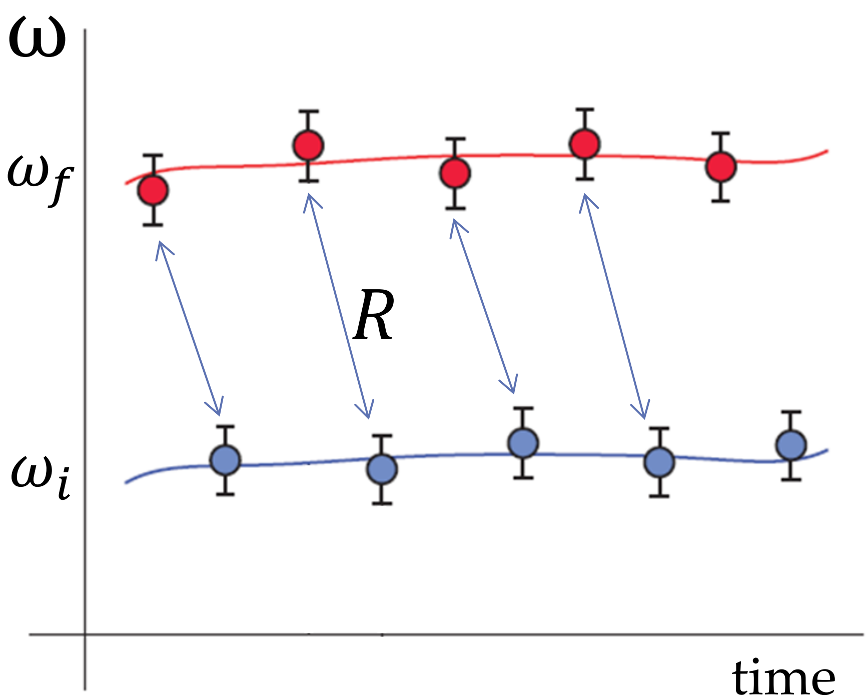


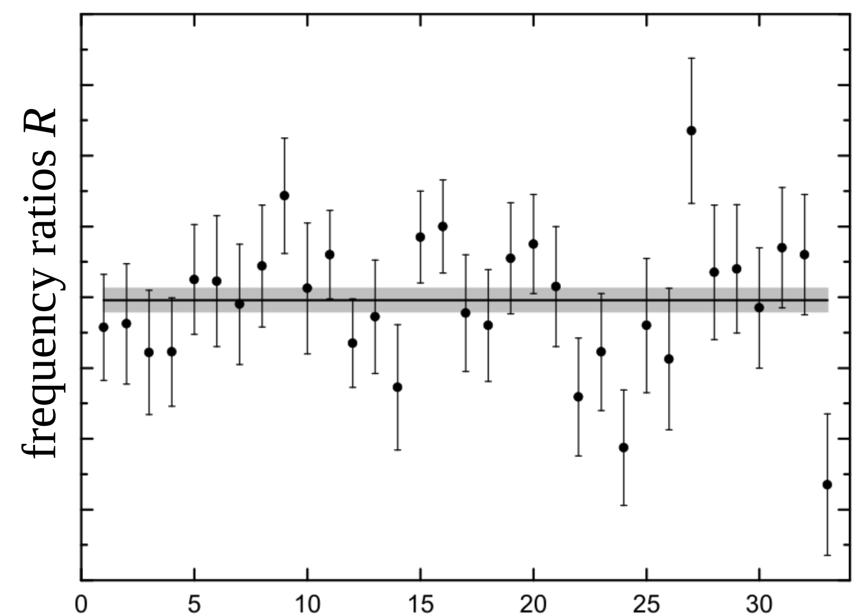
$$\omega_c^2 = \omega_+^2 + \omega_z^2 + \omega_-^2$$

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

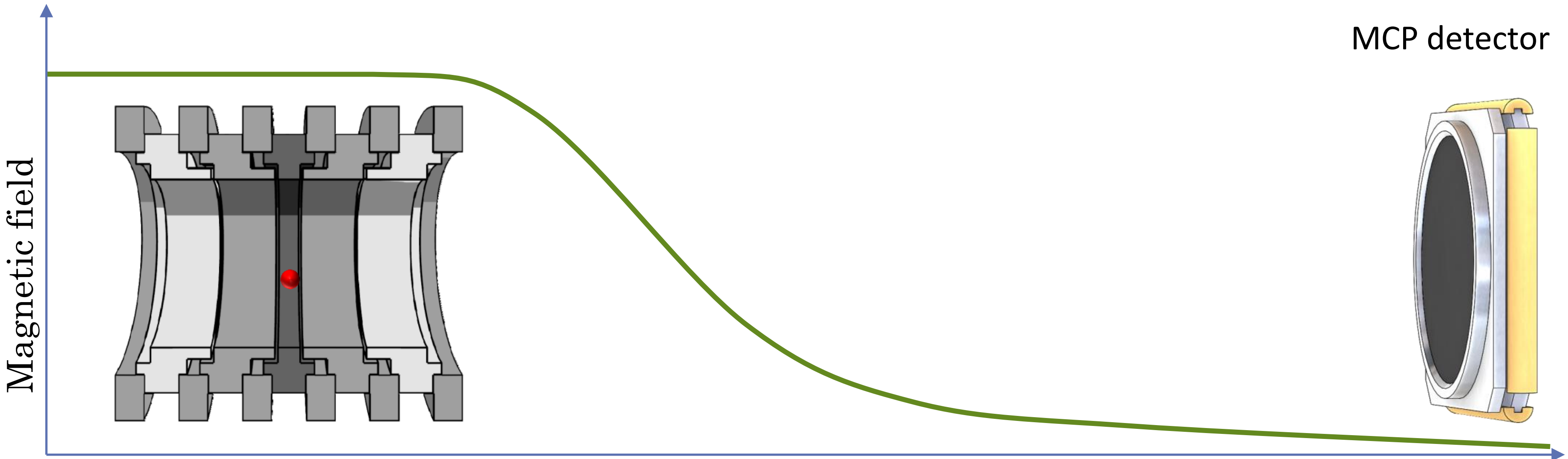
Q-value determination

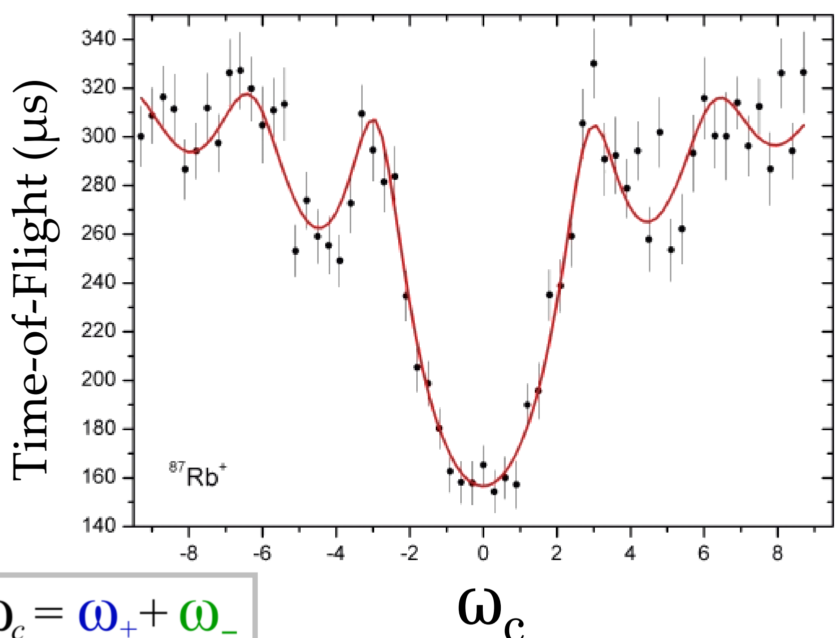
$$Q \equiv M_i - M_f = M_f\left(\frac{M_i}{M_f} - 1\right) = M_f\left(\frac{\omega_f}{\omega_i} - 1\right) = M_f(R-1)$$





ToF-ICR (Time-of-Flight Ion Cyclotron Resonance)





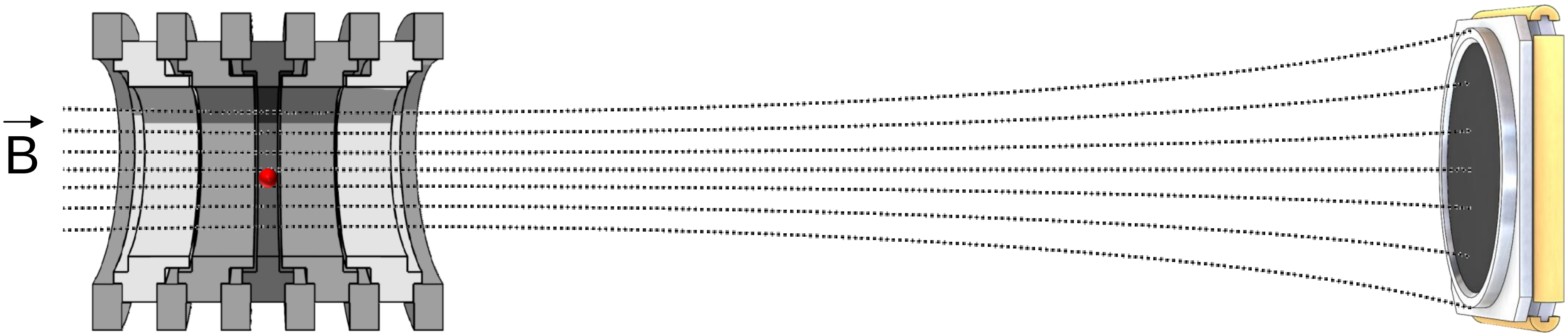
on-line measurement at ISOLTRAP (CERN)
for the Q-values determination of
^{194}**Hg** and ^{202}**Pb**

$\delta M/M \sim \mathbf{10^{-8}}$

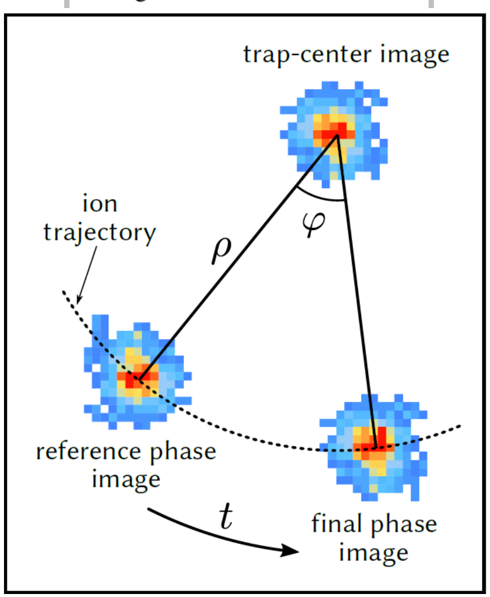
$$\boxed{\omega_c = \omega_+ + \omega_-}$$

PI-ICR (Phase-Imaging Ion Cyclotron Resonance)

Position sensitive
MCP detector



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



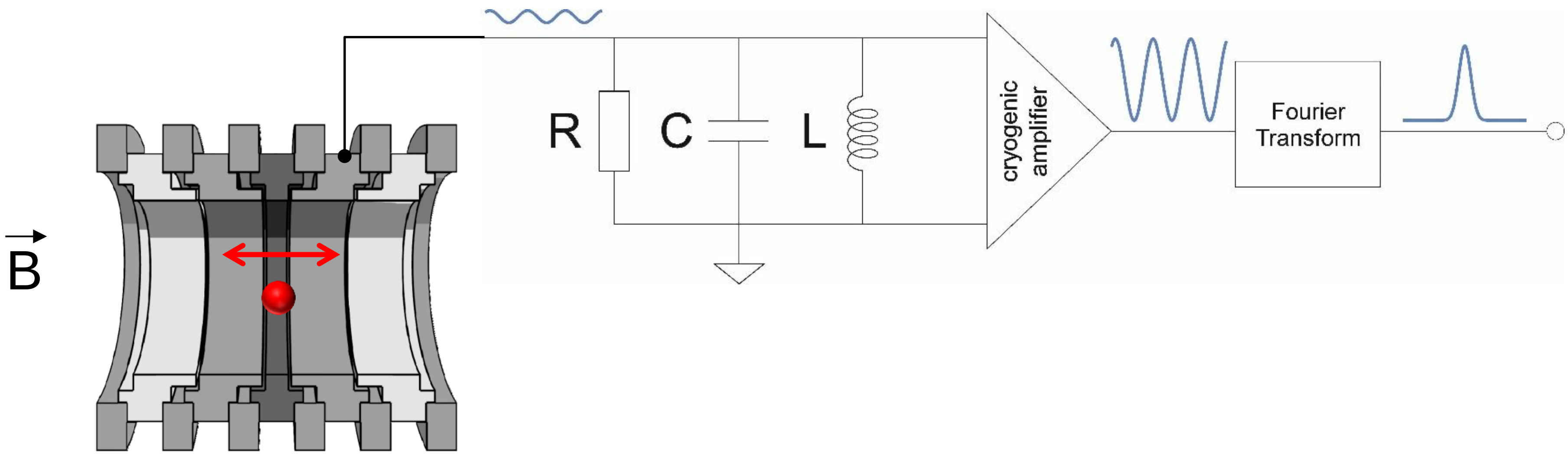
on-line measurement at ISOLTRAP (CERN)
for the Q-value determination of ^{131}**Cs**

$$\delta M/M \sim 10^{-9}$$

off-line measurement at SHIPTRAP (GSI)
for Q-values determination of ^{163}**Ho** and ^{187}**Re**

$$\delta M/M \sim 2 \cdot 10^{-10}$$

FT-ICR (Fourier Transform Ion Cyclotron Resonance)

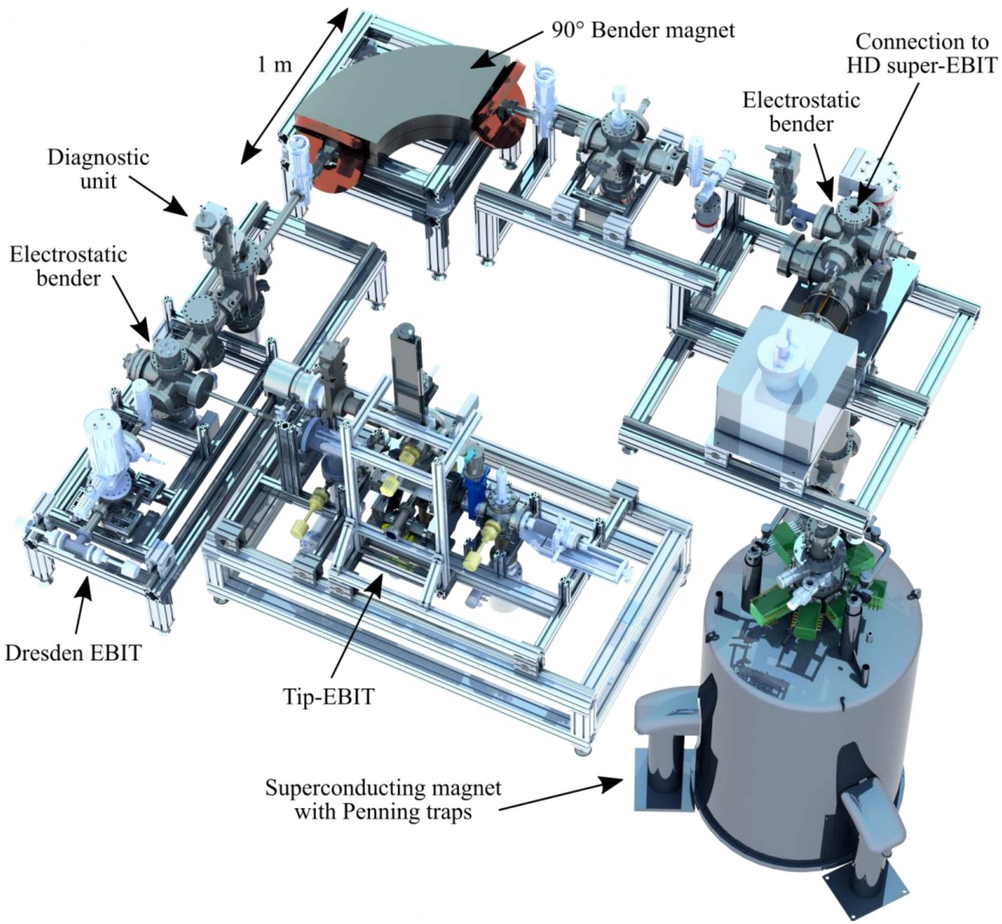


$$\omega_c^2 = \omega_+^2 + \omega_z^2 + \omega_-^2$$

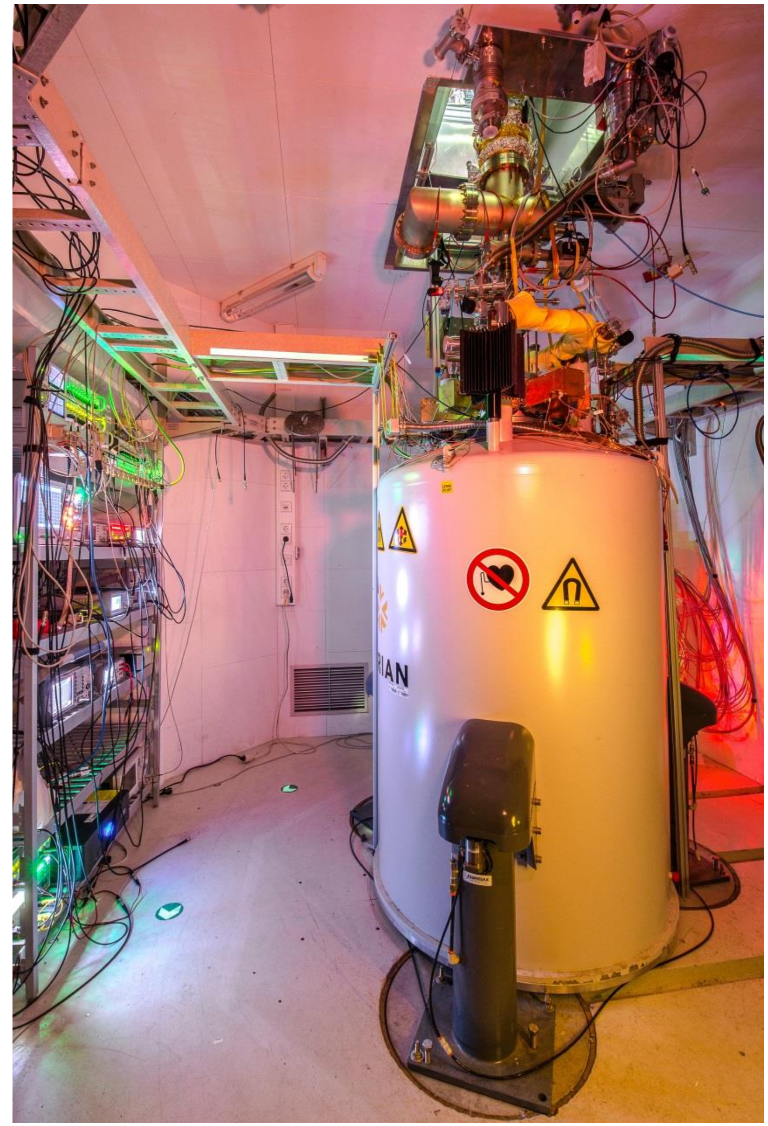
PENTATRAP (MPIK)

$\delta M/M < 10^{-11}$

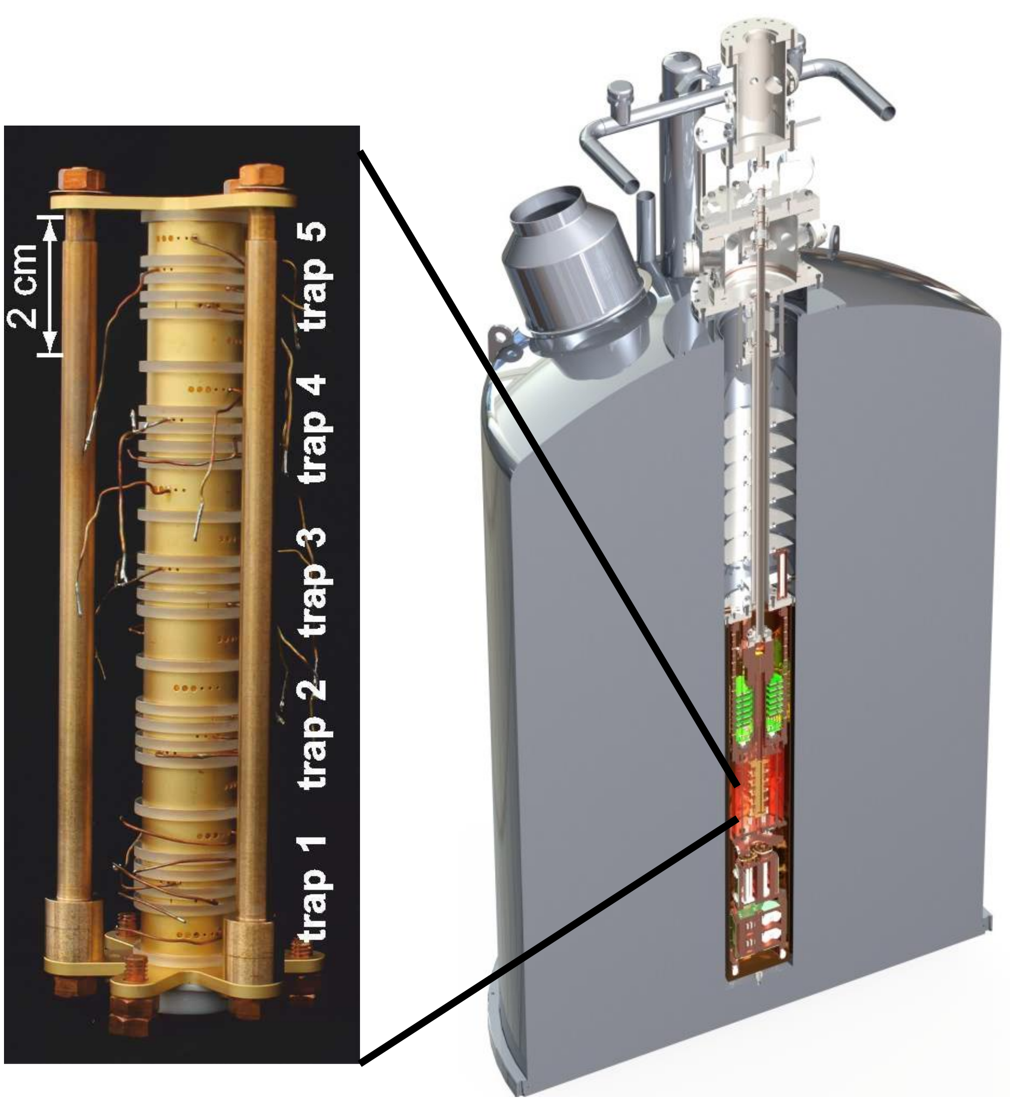
PENTATRAP

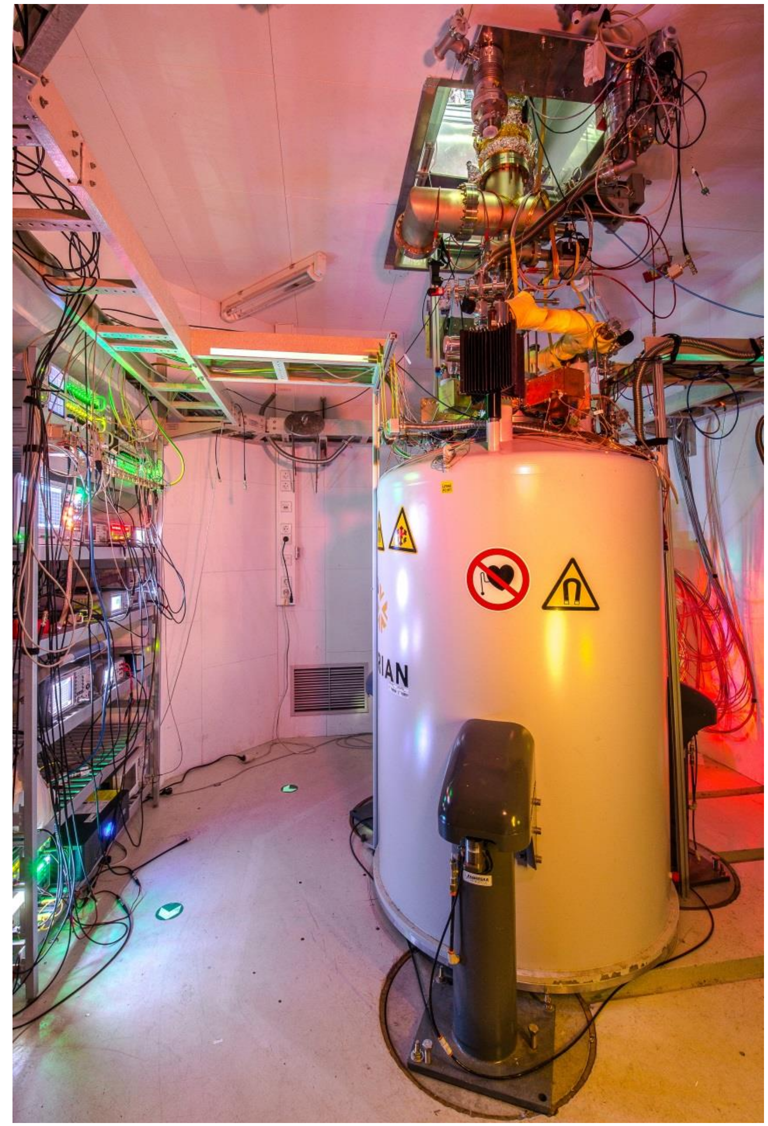


90° Bender magnet
1 m
Connection to
HD super-EBIT
Electrostatic
bender
Diagnostic
unit
Electrostatic
bender
Dresden EBIT
Tip-EBIT
Superconducting magnet
with Penning traps

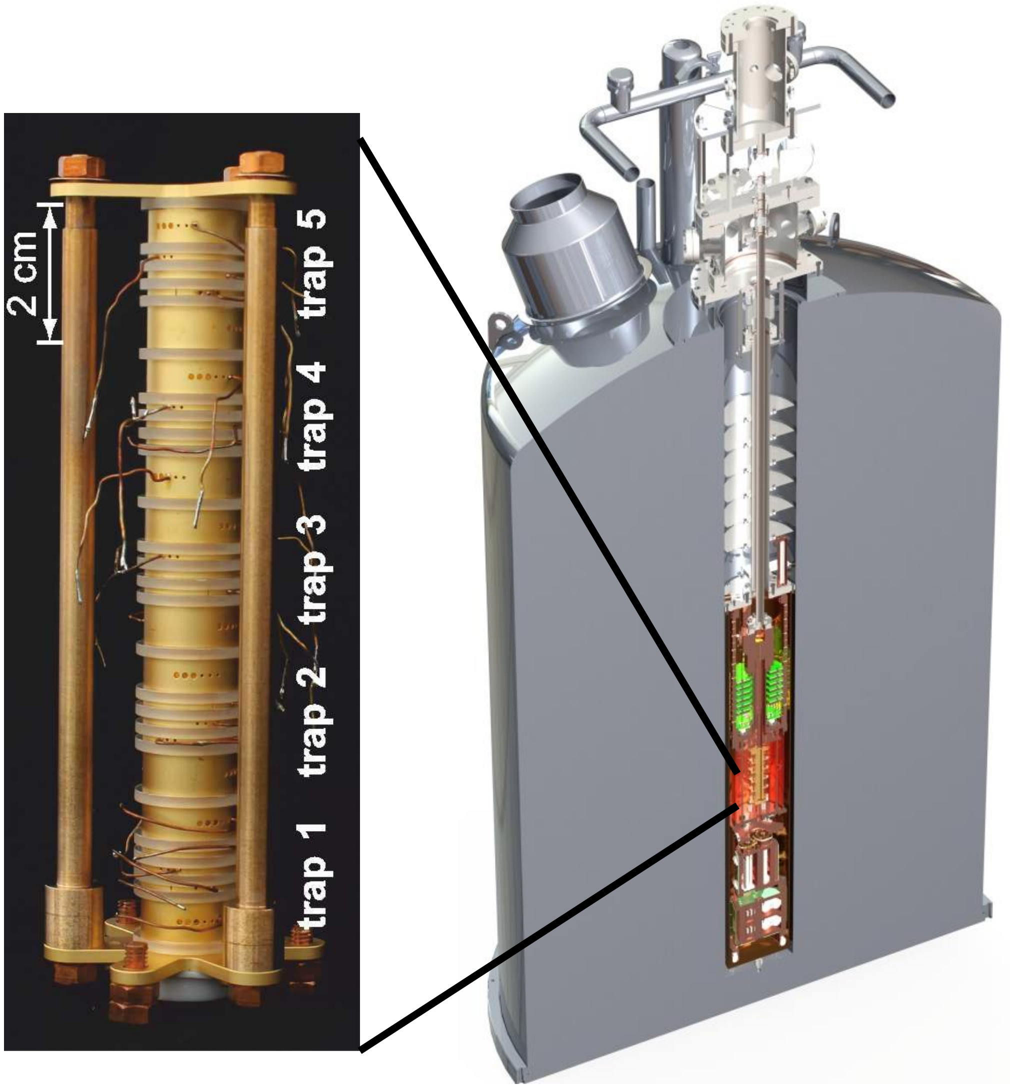


PENTATRAP





PENTATRAP



Features:

1) highly-charged ions
2) single ion sensitivity
3) simultaneous measurements in two adjacent traps

Test measurements:

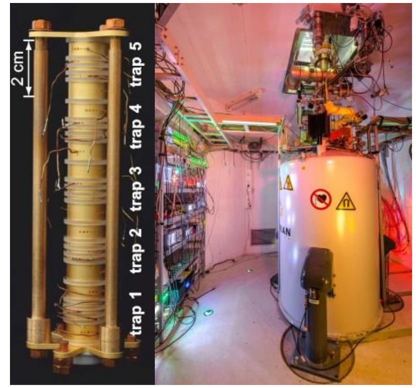
^{129}Xe / ^{131}Xe
^{131}Xe / ^{132}Xe
^{132}Xe / ^{134}Xe
PENTATRAP ($\delta M/M \sim 1 \cdot 10^{-11}$) in agreement with FSU-trap ($\delta M/M \sim 5 \cdot 10^{-11}$)

Future upgrades:

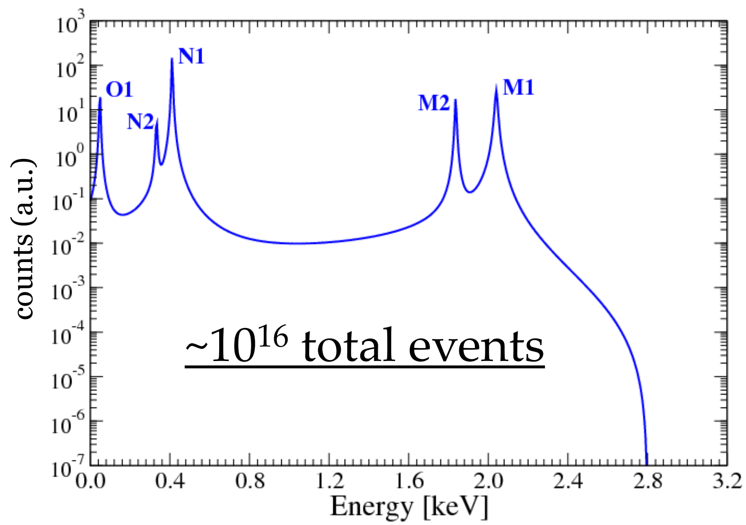
1) Cryogenic valve
2) Magnetic field stabilization by compensating coils
3) 10^{14} atoms in a sample for the ion production

Neutrino mass in EC of ^{163}Ho

PENTATRAP



Calorimetric spectrum of ^{163}Ho



+ Q-value of ^{163}Ho with $\delta Q < 1$ eV (as the main spectrum fit parameter) = sub-eV sensitivity to m_{ν_e}

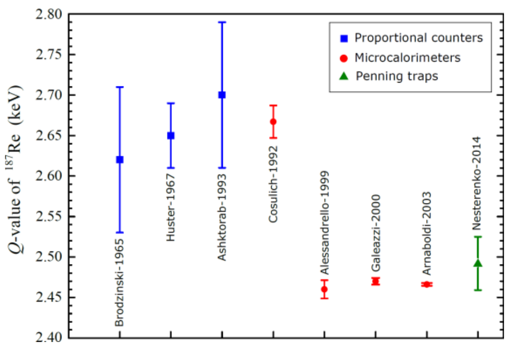
[Gastaldo *et al*. Eur. Phys. J. Special Topics 226 (2017) 1623]

Summary

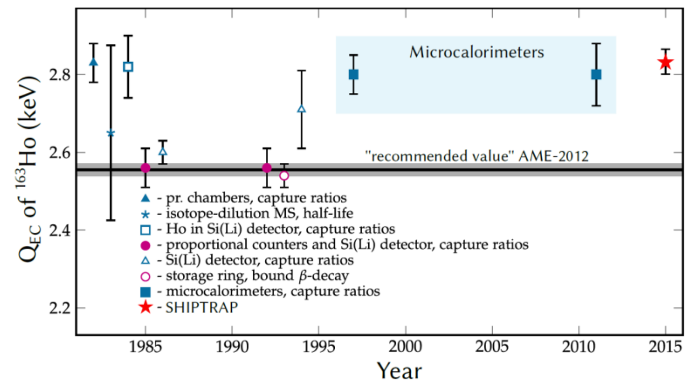
- Low-energy beta decaying nuclides
can be utilized for the absolute neutrino mass determination

- Penning-trap mass spectrometry
is the precise and accurate tool for the β-decay energy determination

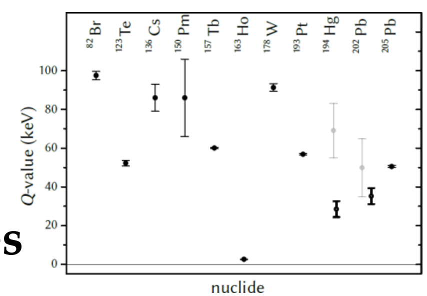
1) ^{187}Re

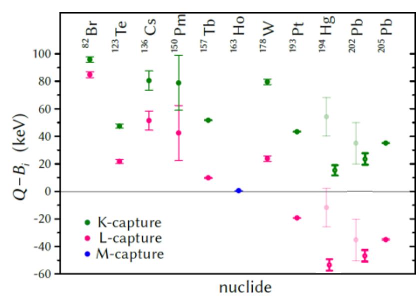


2) ^{163}Ho



3) ^{194}Hg
^{202}Pb
bad candidates





4) ^{131}Cs – not a candidate

5) PENTATRAP → Q-value of ^{163}Ho with $\delta Q < 1$ eV +
ECHo → spectrum of ^{163}Ho with total statistics ~10^{16} = sub-eV sensitivity to m_{ν_e}

Thanks for your attention!