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Search for low Q value beta decays for neutrino mass determination

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Determination of neutrino mass from single $\beta^{\pm}$/EC decay

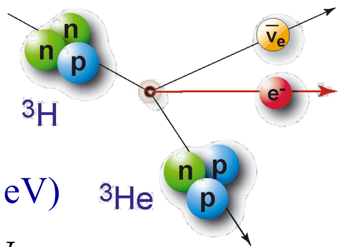
Current direct neutrino mass probes: Ground-state to ground-state (gs-to-gs) decays (β^-: Tritium, ^{187}Re; EC: ^{163}Ho)

- Lower Q-value, higher sensitivity to neutrino mass
- Model independent method

Our Purpose: Search for low Q-value decays

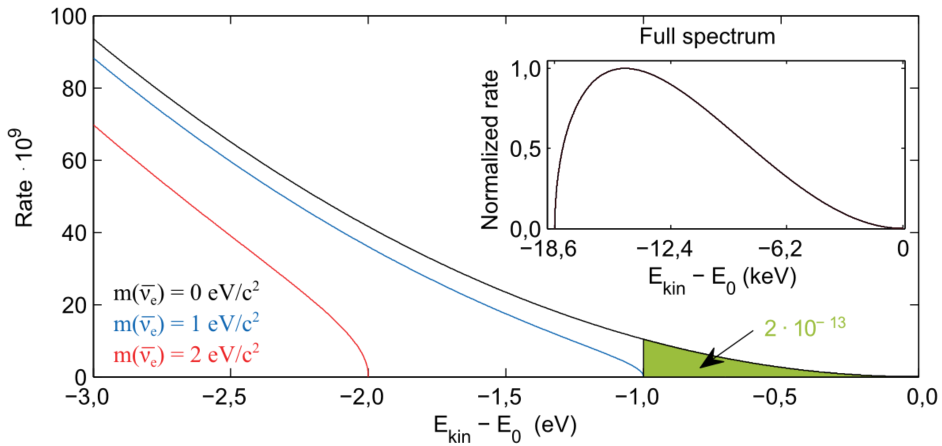
Q → 0, and Q < 1 keV (ultra-low)

Tritium (β^- decay)



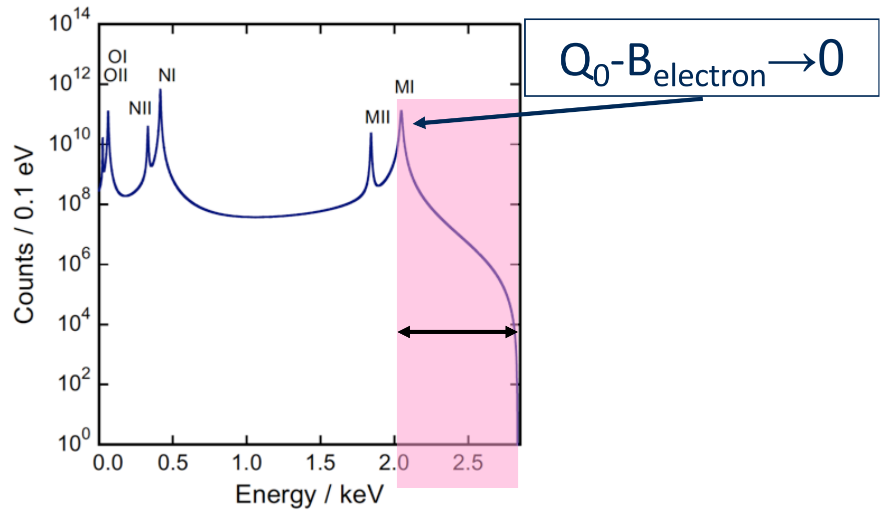
$E_0 = Q_0 - E_{rec}$ (recoil corrections: 1.72 eV)

Endpoint energy E_0 ~18.57 keV



^{163}Ho (Electron Capture)

Q_0 ~2.83 keV

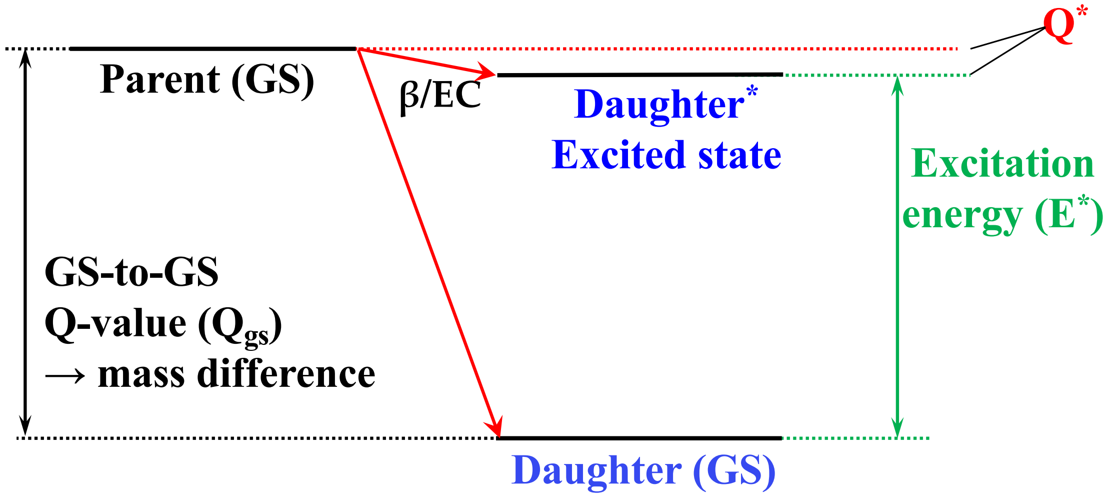


Low Q-value decays for neutrino mass determination

We search for low Q-value ground state to nuclear excited state decays.

- **Low Q-value (Q^*): < 1 keV**

J. Suhonen, Phys. Scr. 89, 054032 (2014)
*N. D. Gamage et al., Hyp. Int. **240**, 43 (2019)*



$$\boxed{Q^* = Q_{gs} - E^*}$$

E^* From gamma spectroscopy

- **Typical uncertainty ~100 eV**
- **Potentially ~10 eV**

Our work: Q_{gs} measurements

- Penning trap mass spectrometry (JYFLTRAP)
- Q_{gs} through $E = mc^2$

Nuclear theory:

- Partial half-life based on Q^*

1. β-decay of ^{115}In($9/2^+$)→^{115}Sn*($9/2^+$): Q*-value = 0.147(10) keV
E^* improvement: *V. A. Zheltonozhsky et al. 2018 EPL 121 12001*

2. β-decay of ^{135}Cs($7/2^-$)→^{135}Ba*($11/2^+$): Q*-value = 0.44(31) keV
Q_{gs} improvement: *A. De Roubin, J. Kostensalo, T. Eronen et al., Phys. Rev. Lett., 124 (22), 222503.*

Summary of measured Q-values of potential candidates

- List of measured promising low Q-value decay candidates for neutrino mass determination

Parent	T1/2	Daughter	E* (keV)	decay type	Q* (keV)	Decay	Q_0 (keV)	dQ_0 (keV)
146Pm(3−)	5.53(5) y	146Nd(2+)	1470.63(6)	1st FNU	1.3(4.2)	EC	1472.000	4.000
149Gd(7/2−)	9.28(10) dy	149Eu(5/2+)	1312(4)	1st FNU	2(6.4)	EC	1314.100	4.000
155Tb(3/2+)	5.32(6) dy	155Gd{3/2+}	815.731(3)	Allowed{?}	4.2(10.1)	EC	820.000	10.000
159Dy(3/2−)	144.4(2) dy	159Tb(5/2−)	363.5449(14)	Allowed	1.7(1.2)	EC	365.200	1.200
		159Tb(11/2+)	362.050(40)	3rd FU	3.2(1.2)	EC	365.200	1.200
161Ho(5/2−)	18.479(4) hr	161Dy{7/2+}	858.502(7)	1st FNU	1.0(2.2)	EC	858.500	2.200
		161Dy{3/2-}	858.7919(18)	Allowed	−0.3(2.2)	EC	858.500	2.200
72As(2−)	26.0(1)h	72Ge{1}	4358.7(3)	Allowed{?}	−2.8(4.0)	EC	4356.000	4.000
		72Ge(3−)	3325.01(3)	Allowed	8.9(4.0)	β+	4356.000	4.000
		72Ge(2+)	3327(3)	1st FNU	6.9(5.0)	β+	4356.000	4.000
		72Ge{1+}	3338.0(3)	1st FNU{?}	−4.1(4.0)	β+	4356.000	4.000
		72Ge{2−}	3341.76(4)	Allowed{?}	−7.9(4.0)	β+	4356.000	4.000
159Gd(3/2−)	26.24(9) h	159Tb{1/2+}	971	1st FNU{?}	0.0(1.8)	β-	970.900	0.800
77As(3/2−)	38.79(5) h	77Se(5/2+)	680.1035(17)	1st FNU	3.1(1.7)	β-	683.200	1.700
76As(2−)	26.24(9) h	76Se{2−}	2968.4(7)	Allowed{?}	−7.8(1.1)	β-	2960.600	0.900
153Tb(5/2+)	2.34(1)dy	153Gd(5/2−)	548.7645(18)	1st FNU	−1.2(4.0)	β+	1569.000	4.000
		153Gd{5/2}	551.092(19)	Allowed{?}	−3.5(4.0)	β+	1569.000	4.000
111In(9/2+)	3dy	111Cd(3/2+)	864.8(3)	2nd FU	−6.6(3.0)	EC	860.2	3.4
		111Cd(3/2+)	864.8(3)	2nd FU	−4.6(3.0)	EC	860.2	3.4
		111Cd(3/2+)	855.6(1.0)	2nd FU	4.6(3.2)	EC	860.2	3.4
		111Cd(7/2+)	853.94(7)	Allowed	6.3(3.0)	EC	860.2	3.4
131I(7/2+)	8dy	131Xe{9/2+}	971.22(13)	Allowed{?}	−0.42(0.61)	β-	970.80	0.60
		131Xe(7/2+)	973.11(14)	Allowed	−2.31(0.62)	β-	970.80	0.60
155Eu(5/2+)	5yr	155Gd(9/2−)	251.7056(10)	1st FU	0.1(1.8)	β-	252.00	2.40

Z. Ge, T. Eronen et al., Phys. Rev. Lett. 127, 272301

Z. Ge, T. Eronen et al., PHYSICAL REVIEW C 103, 065502 (2021)

Submitted

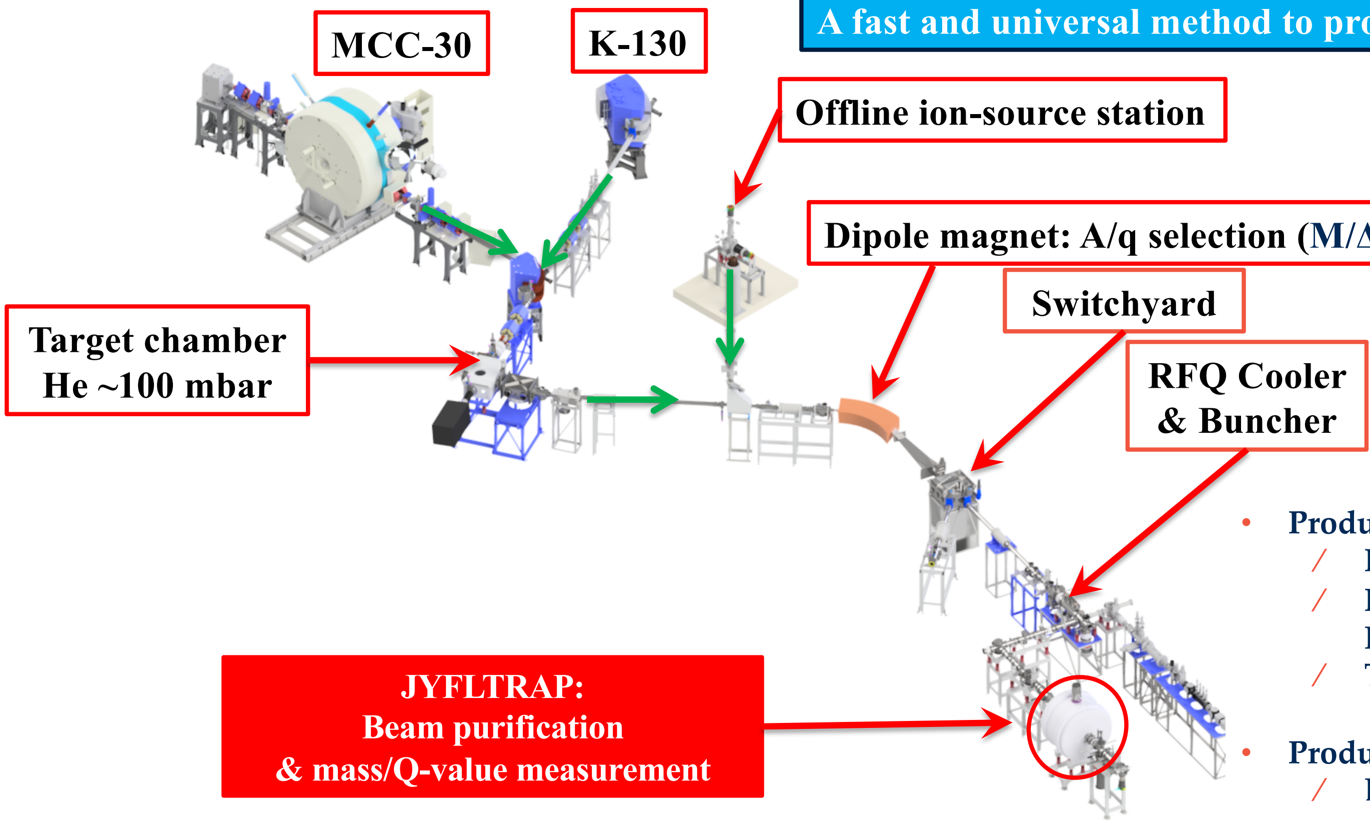
Q_0 from: *M. Wang et al. , Chinese Physics C 45, 030003 (2021)*

E* from: *National nuclear data center, Available at https://www.nndc.bnl.gov*

The Ion Guide Isotope Separator On-Line facility (IGISOL)

J. Ärje, J. Äystö et al., PRL 54 (1985) 99

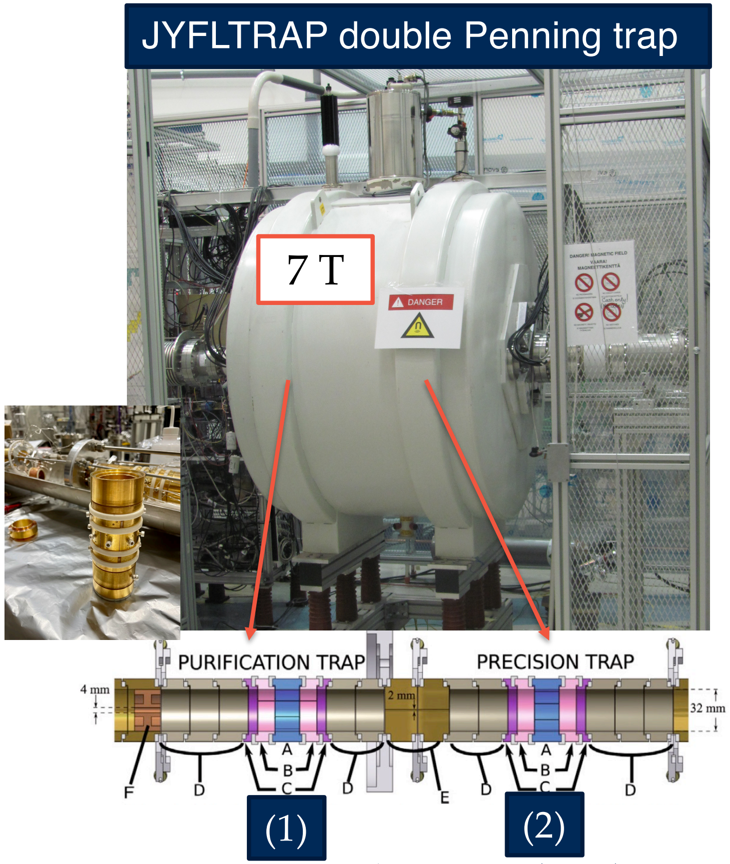
A fast and universal method to produce radioactive beams



T. Eronen et al., Eur. Phys. J. A 48 (2012) 46

- Production of ions of interest:
  - Proton beam of 5-65 MeV
  - Proton-induced fission
    Proton-induced fusion-evaporation
  - Target of ^{nat}U: 15mg/cm^2
    natural-abundance target ~2mg/cm^2
- Production of reference nucleus:
  - Electrode of reference material installed in the spark source

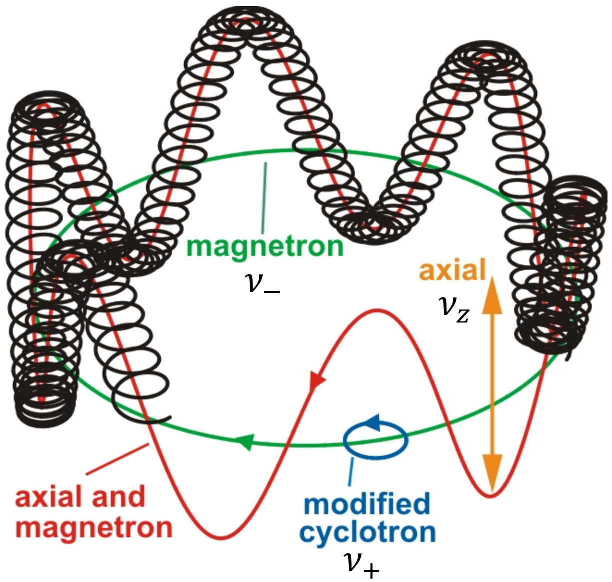
JYFLTRAP double Penning trap



Eronen et al., EPJA 48 (2012) 46

Cyclotron frequency

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



Penning trap eigenfrequencies:

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{U_0}{d^2}\frac{q}{m}}$$

$$\nu_\pm = \frac{1}{2}\left(\nu_c \pm \sqrt{\nu_c^2 - 2\nu_z^2}\right)$$

Invariance theorem

$$\nu_c^2 = \nu_-^2 + \nu_+^2 + \nu_z^2$$

Q-value and mass measurements

- **Cyclotron frequency:**

$$\nu_c = \nu_+ + \nu_- = \frac{qB}{2\pi m}$$

- **Frequency ratio *r*:**

$$r = \frac{\nu_1}{\nu_2}$$

Determine

- ***Q*-value:**

$$Q = M_2 - M_1 = (r-1)(M_1 - m_e) + m_e$$

- **Mass:**

$$M_2 = r(M_1 - m_e) + m_e$$

Eronen et al., EPJA 48 (2012) 46

methods

1. TOF-ICR

Time-of-Flight Ion-Cyclotron-Resonance (TOF-ICR) technique

G. Gräfft et al.,, Zeitschrift für Physik A: Atoms and Nuclei 297, 35 (1980).

a. Normal TOF-ICR
b. Ramsey TOF-ICR

2. PI-ICR

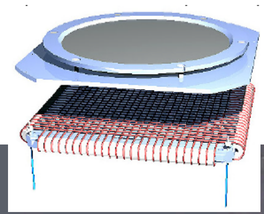
Phase-imaging Ion-Cyclotron-Resonance (PI-ICR) technique

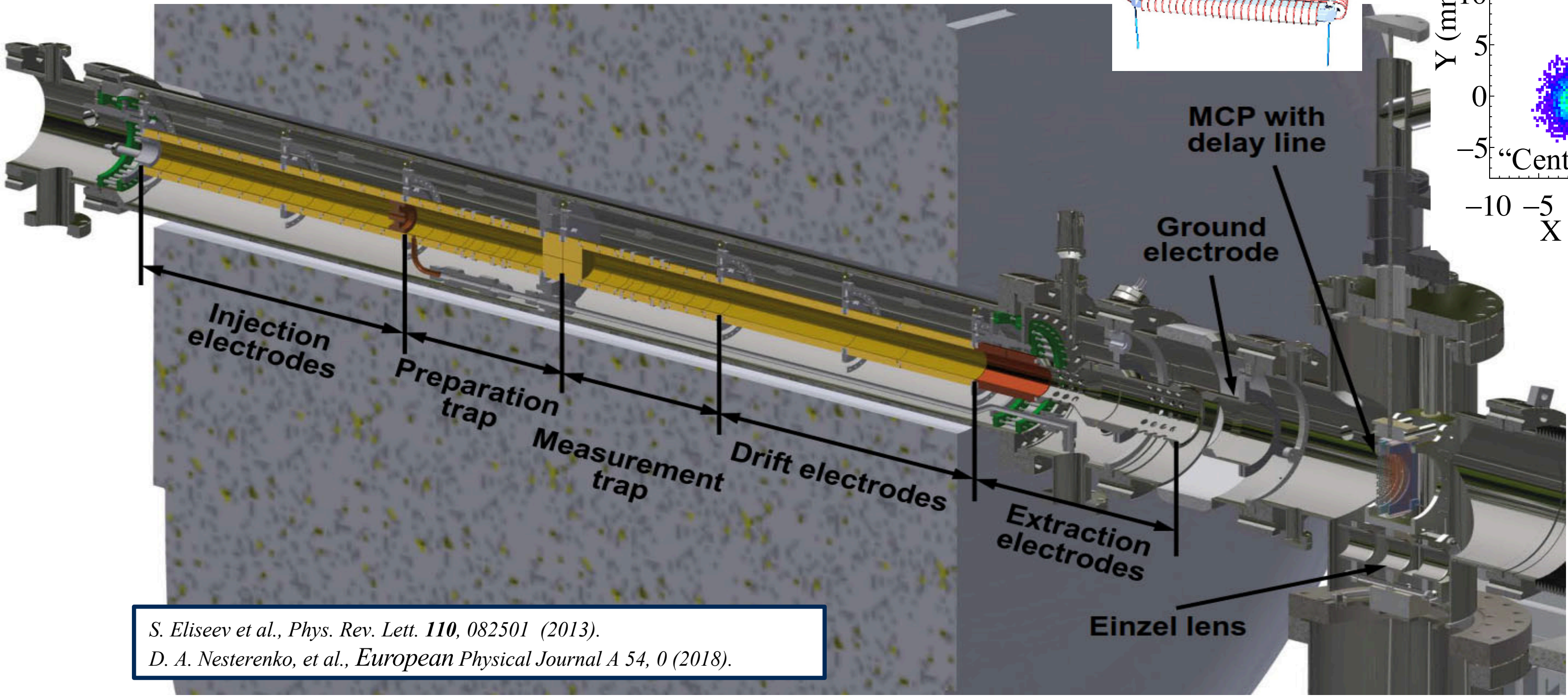
S. Eliseev et al., Phys. Rev. Lett. 110, 082501 (2013).

Phase-imaging Ion-Cyclotron-Resonance (PI-ICR)

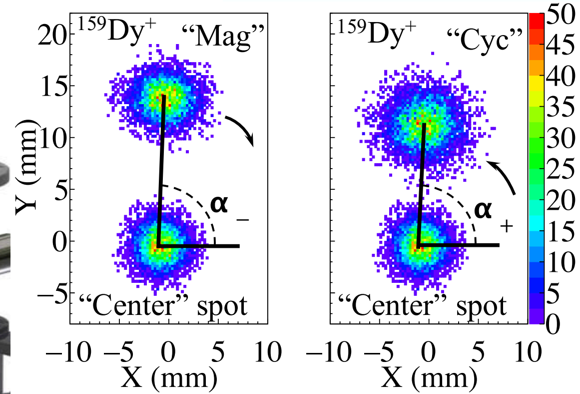
Delay-Line Microchanel Channel Plate (MCP) Detector from Roentdek GmbH

Position sensitive detector





S. Eliseev et al., Phys. Rev. Lett. **110**, 082501 (2013).
D. A. Nesterenko, et al., European Physical Journal A 54, 0 (2018).



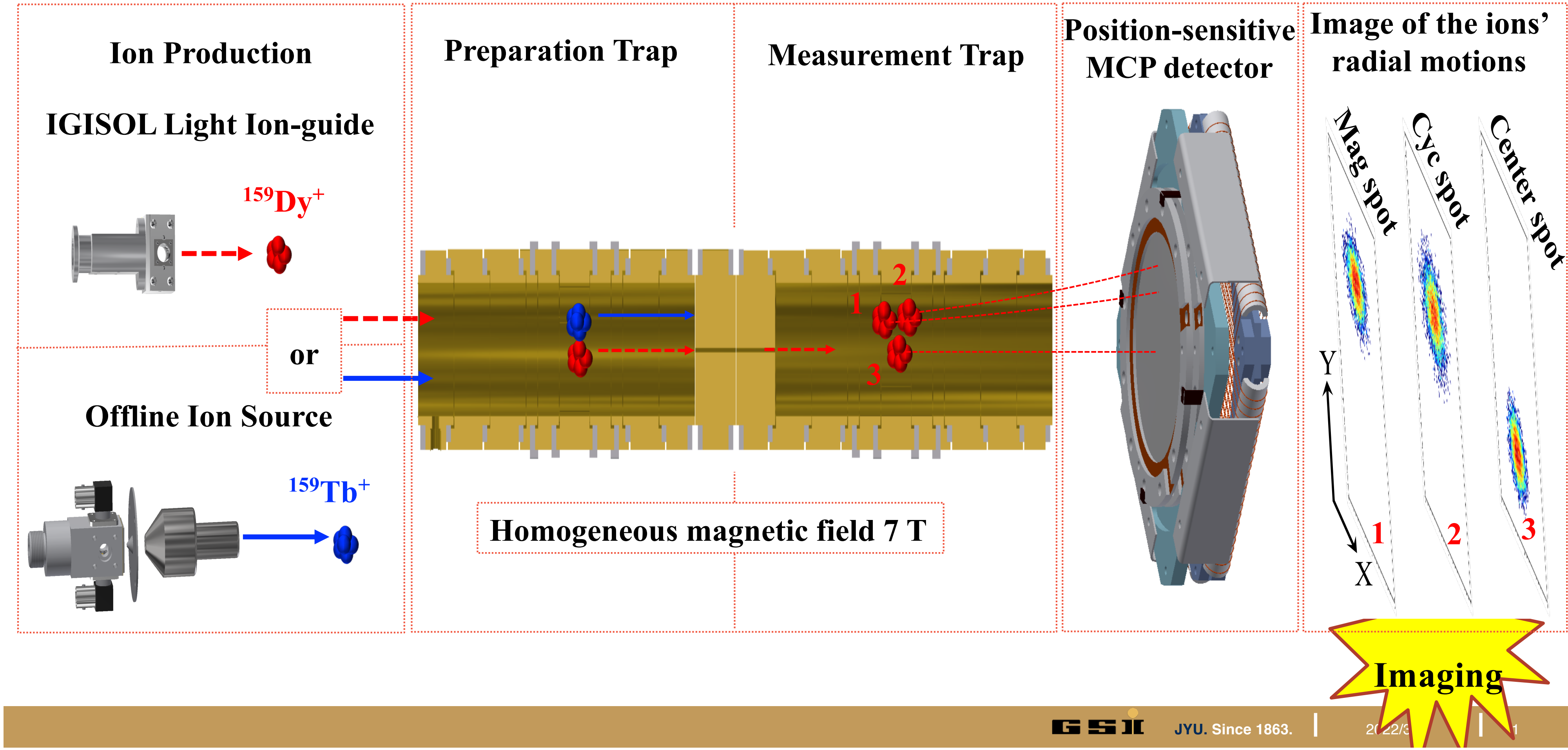
Angle between cyclotron and magnetron motion phases with respect to the center spot:

$$\alpha_c = \alpha_- + \alpha_+$$

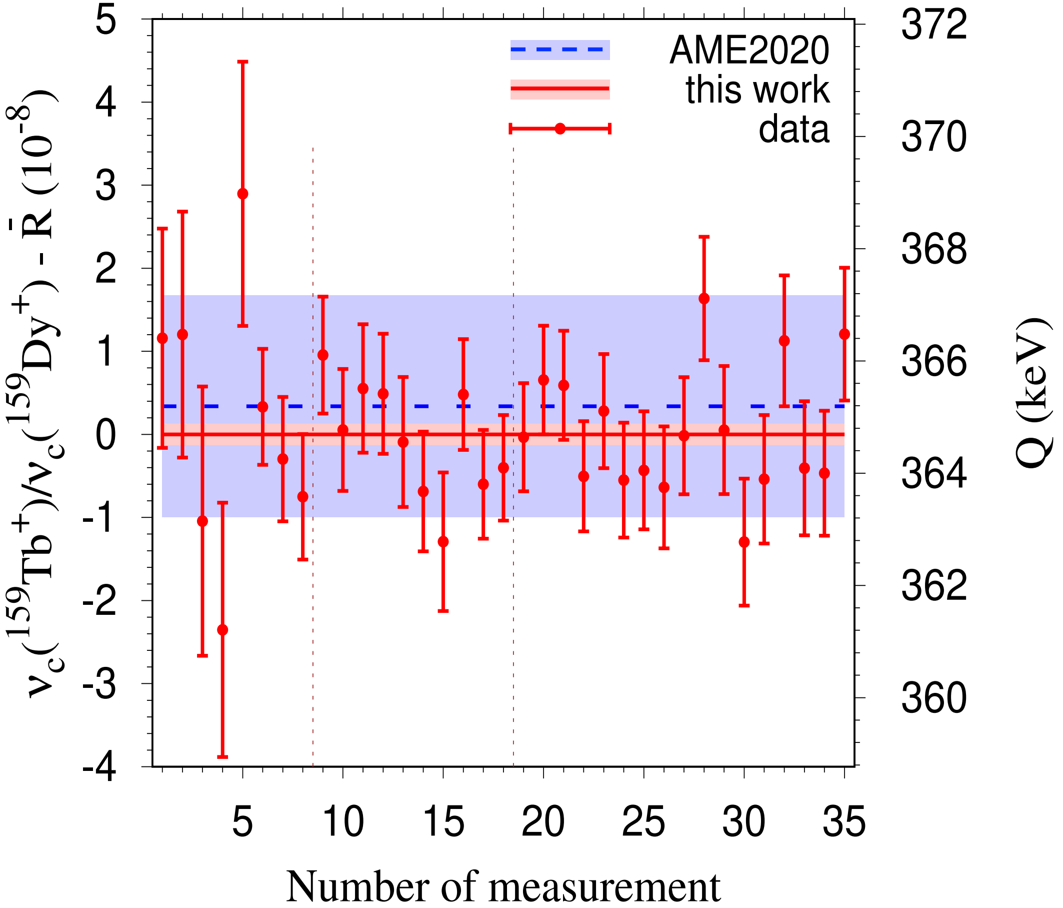
cyclotron frequency:

$$\nu_c = \nu_+ + \nu_- = \frac{\alpha_c + 2\pi n}{2\pi t}$$

Schematic of PI-ICR for 159Dy-159Tb Q-value measurement



Q-value measurement of ^{159}Dy



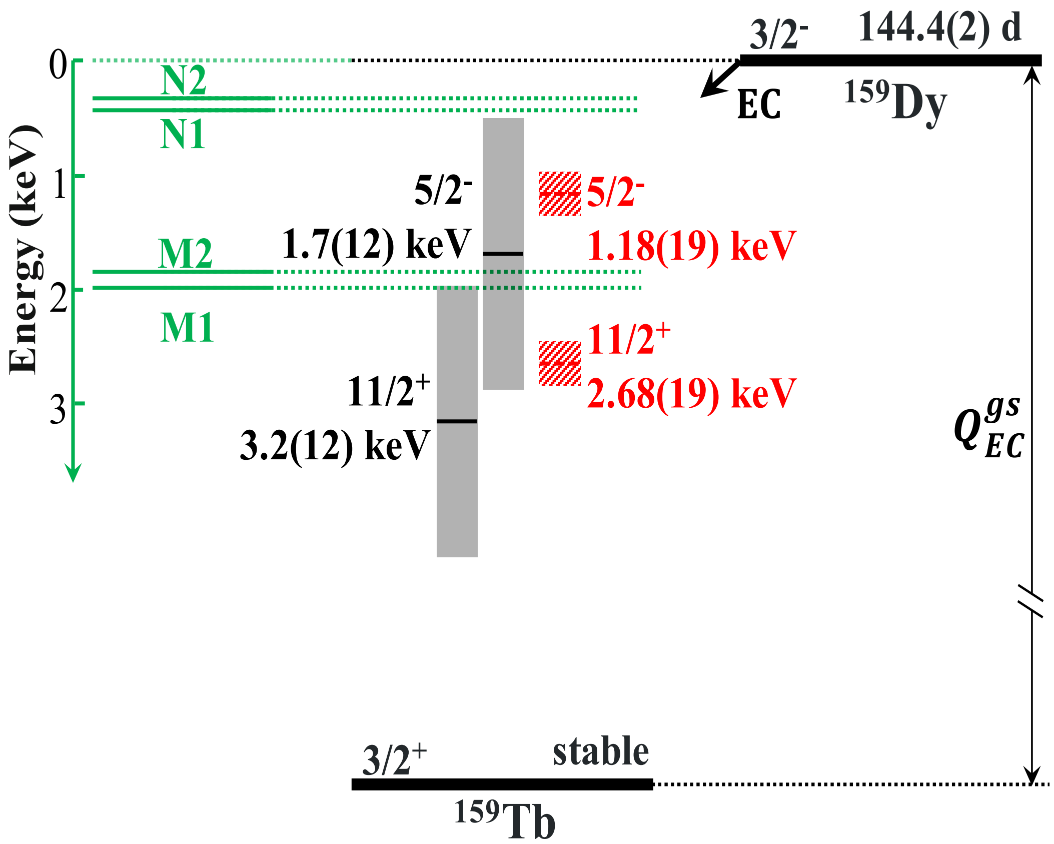
Gs-to-GS Q value (Q_{EC}^{gs})

Obtained frequency ratio r with a precision of **1.3×10^{-9}**

$\longrightarrow$

Q-value precision: **190 eV**
now **6.3 times** more precise and 0.47 keV smaller than liturature value

Level scheme of ^{159}Dy with refined Q-value



Gs-to-GS Q value (Q_{EC}^{gs})

E_i^*	+	Binding energy e_x (allowed atomic shell x of the EC)
$5/2^-$ 363.5449(14) $11/2^+$ 362.050(40)		

With the refined Q_{EC}^{gs}:

- **Captures to 5/2-**
  - only from N1 or higher orbitals
  - M2 and M1 captures forbidden at > 4σ level
- **captures to 11/2+**
  - from M1 and higher orbitals

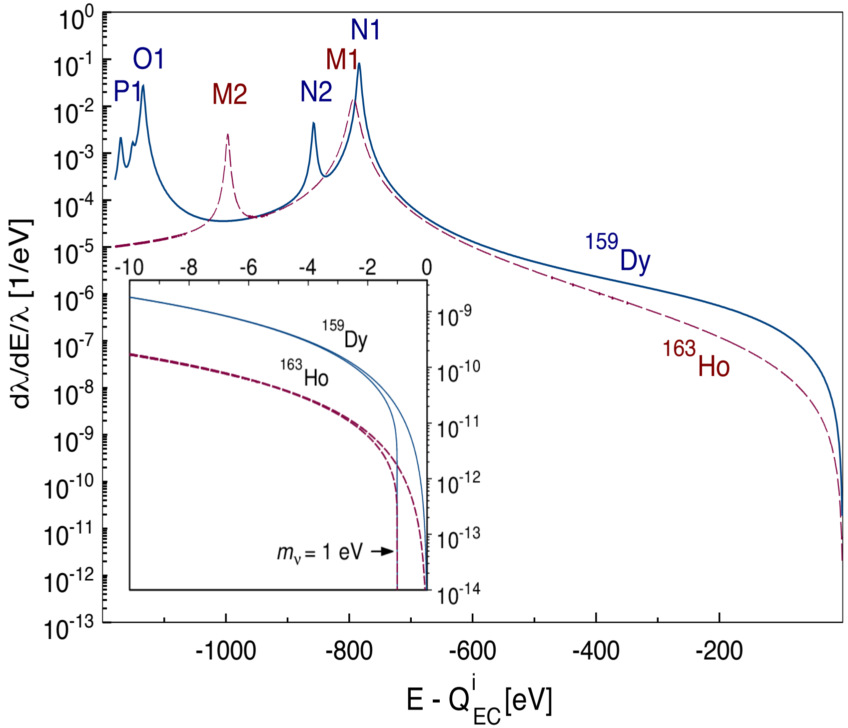
Z. Ge, T. Eronen, K. S. Tyrin et al., Phys. Rev. Lett. 127, 272301(2021)

M. Wang et al. , Chinese Physics C 45, 030003 (2021) -> AME2020
National nuclear data center, Available at https://www.nndc.bnl.gov

Results and conclusion of ^{159}Dy

EC spectrum of ^{159}Dy ($3/2^- \rightarrow 5/2^-$) compared to ^{163}Ho
(Dirac-Hartree-Fock atomic many-body calculations)

Z. Ge, T. Eronen, K. S. Tyrin et al., Phys. Rev. Lett. 127, 272301(2021)



Q_{EC}^{*} = 1.18(19) keV ⇨ the lowest EC Q value for the transition: ^{159}Dy($3/2^-$)→^{159}Tb* ($5/2^-$), lower than the GS-to-GS Q_{EC} of ^{163}Ho, utilized in presently running or planned direct neutrino mass experiments

- **allowed transition**
- **known branching ratio 1.9(5) × 10^{-6}**
- **Smallest EC Q value**

⇨ the most promising gs-to-excited state transition for future calorimetric experiment

More cases have been measured and in analysis/preparation

Collaboration list

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Theory
experiment

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