JYVÄSKYLÄN YLIOPISTO

High precision decay energy measurements of low Q-value beta decays with JYFLTRAP

Zhuang Ge

University of Jyväskylä

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

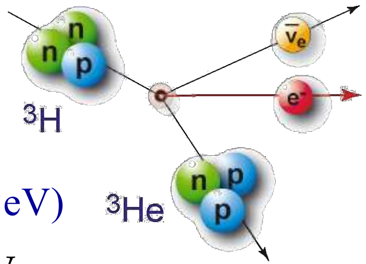
Current direct neutrino mass probes: Ground-state to ground-state (gs-to-gs) decays (β^- :Tritium, ^{187}Re; EC: ^{163}Ho)

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

Our Purpose: Search for low Q-value decays

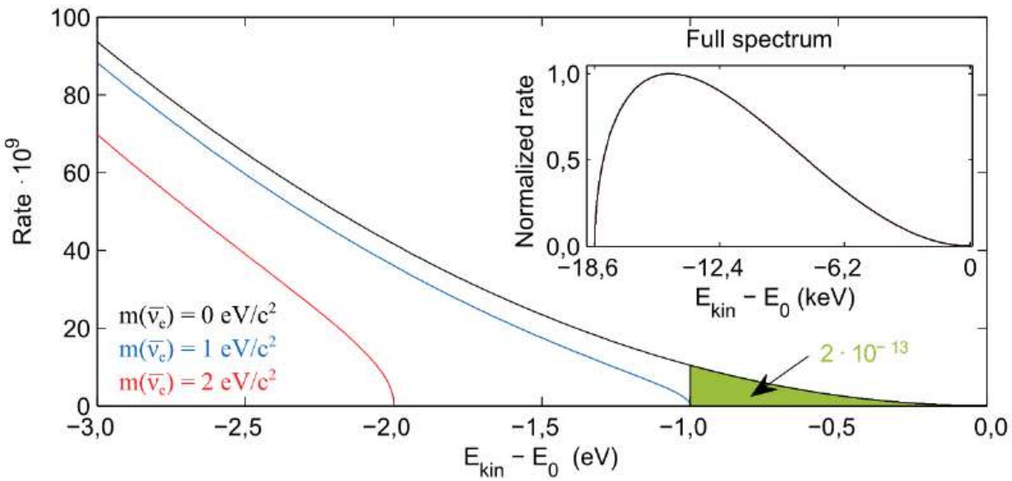
Q → 0, and Q < 1 keV (ultra-low)

Tritium (β^-decay)



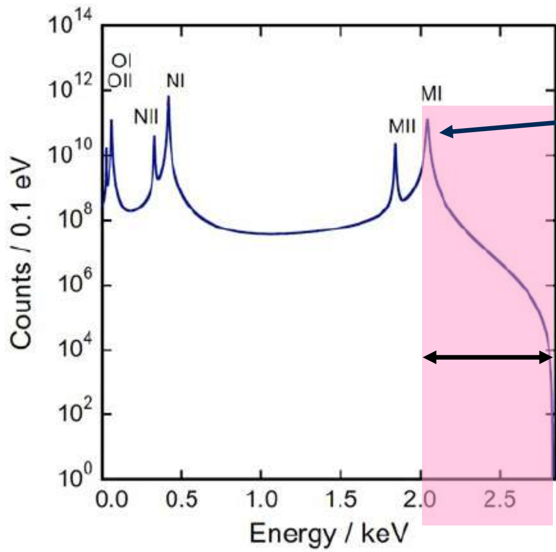
$E_0 = Q_0 - E_{rec}$ (recoil corrections: 1.72 eV)

Endpoint energy E_0 ~18.57 keV



^{163}Ho (Electron Capture)

Q_0 ~2.83 keV



$Q_0 - B_{electron} \rightarrow 0$

Situation with gs-to-gs Q-value precision

Ground-to-ground state decays

- **Measured with high precision already**
- **Beta/EC spectrum endpoint meausrements already ongoing**

gs-to-gs decay Project:

1. β-decay of ^{3}H: Q-value = 18.59201(7) keV
E. G. Myers et al , Phys. Rev. Lett. 114 (2015)

KATRIN, Project8

recent upper limit of antineutrino mass: 0.8 eV (90% C. L.) from β-decay

2. β-decay of ^{187}Re: Q-value = 2.4709(13) **keV**
P. Filianin et al., Phys. Rev. Lett. 127, 072502 (2021)

MARE stopped

3. EC in ^{163}Ho: Q-value = 2.8632(6) keV
Schweiger C., Braß M., Debierre V. et al. Nat. Phys.(2024)

ECHo, HOLMES

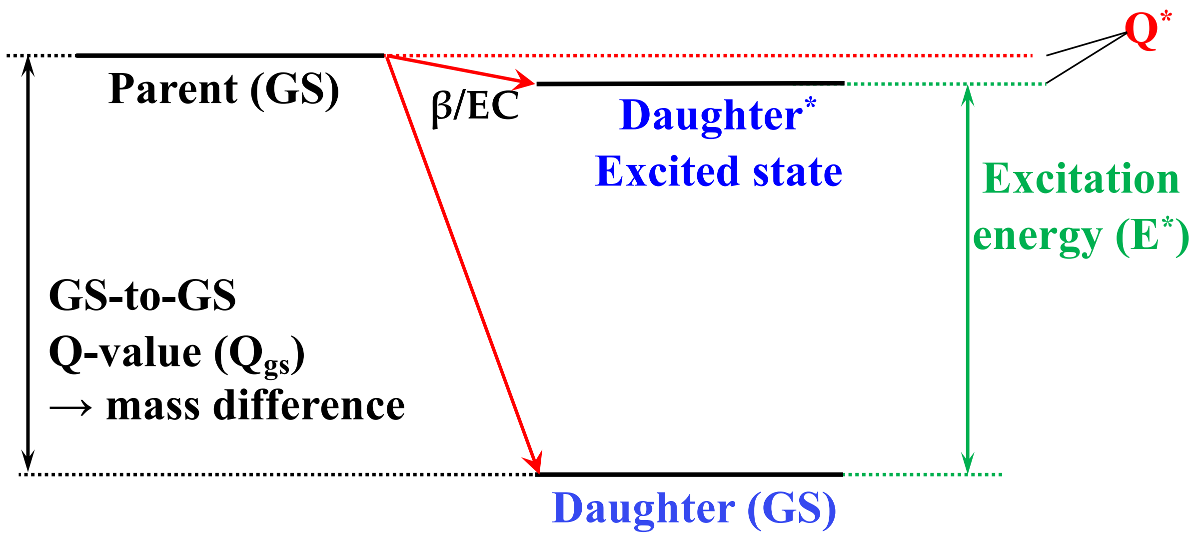
recent upper limit of neutrino mass: 150 eV (95% C. L.) from EC

Low Q-value decays for neutrino mass determination

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

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

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



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

E^* From gamma spectroscopy

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

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.***

2. EC of ^{75}Se (5/2+) →^{75}As*({3/2−, 5/2−}) : Q*-value = 0.64(51) keV
   Q_{gs} improvement: M. Ramalho, Z.Ge, T. Eronen et al., Phys. Rev. C 106, 015501 (2022)

Our work: Q_{gs} measurements

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

Nuclear theory:

- Partial half-life based on Q^*

Summary of measured Q-values of potential candidates at JYFLTRAP

- 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. C 00, 005500 (2022)

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

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

Z. Ge T. Eronen, et al., EPJA (2024)

Z. Ge, T. Eronen, et al., Physics Letters B 832 (2022) 137226

T. Eronen, Z. Ge et al., Physics Letters B 830 (2022) 137135

Z. Ge T. Eronen, et al., Phys. Rev. C 108, 045502 (2023)

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

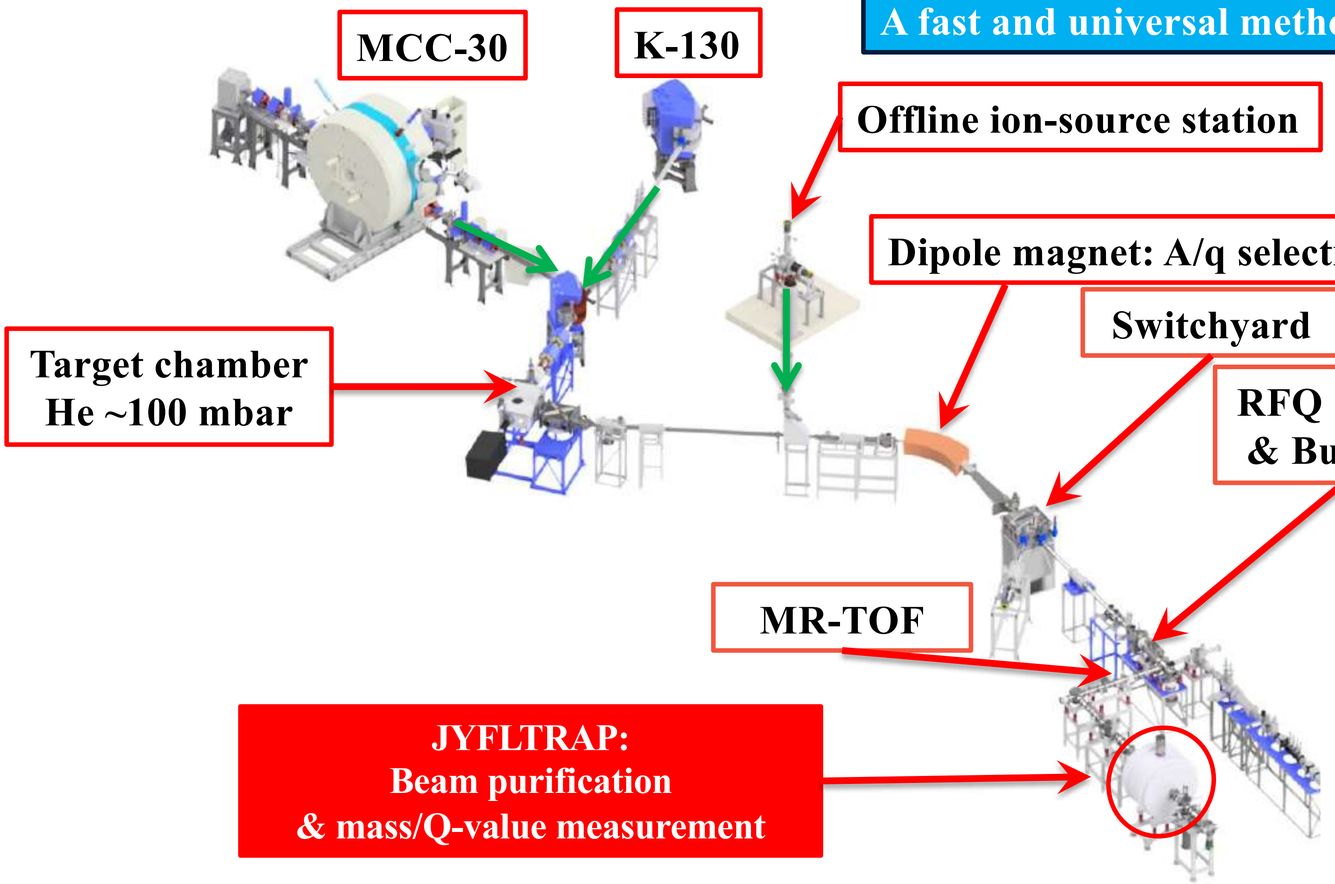
E^* from: *National nuclear data center, Available at https://www.nndc.bnl.gov*

One more long table list will not be shown in this talk

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

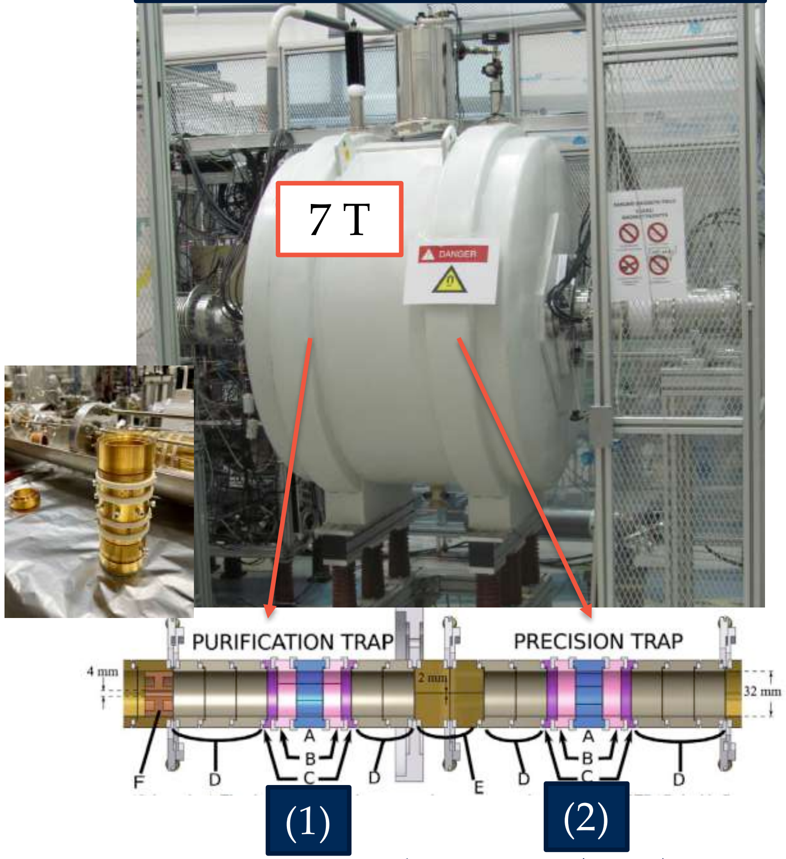


T. Eronen et al., Eur. Phys. J. A 48 (2012) 46

- 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

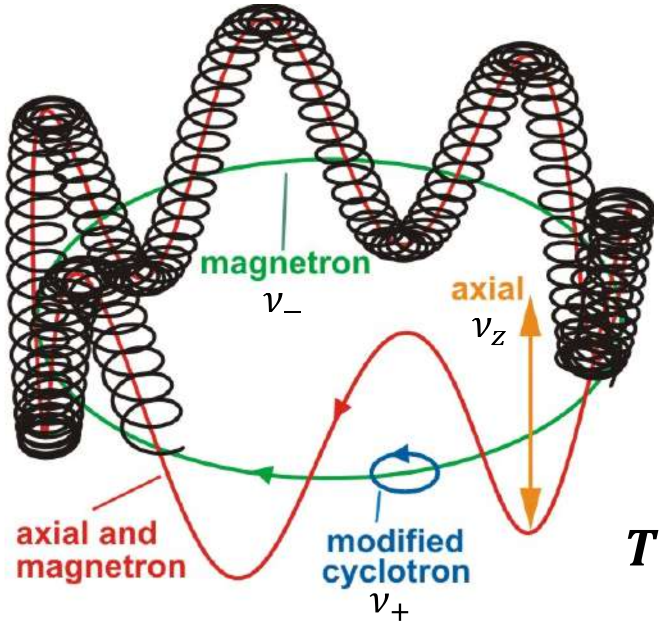
JYFLTRAP double Penning trap



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

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

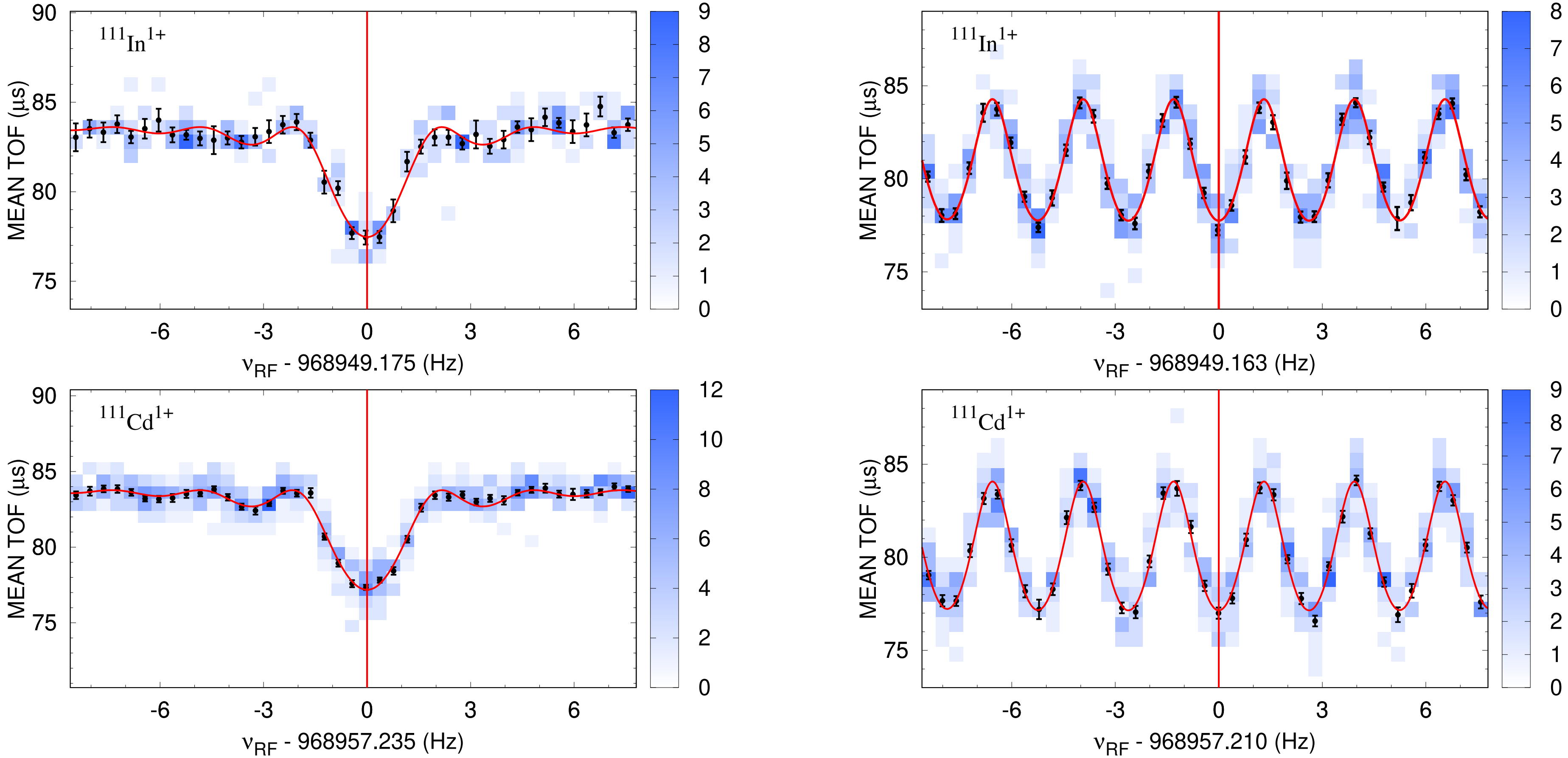
$\boldsymbol{TOF-ICR\ and\ PI-ICR}$:

$$\boldsymbol{\nu_c = \nu_+ + \nu_-}$$

TOF-ICR method

one-pulse radio-frequency (rf) field (400 ms)

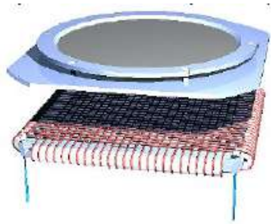
two-pulse rf field (25-350-25 ms)



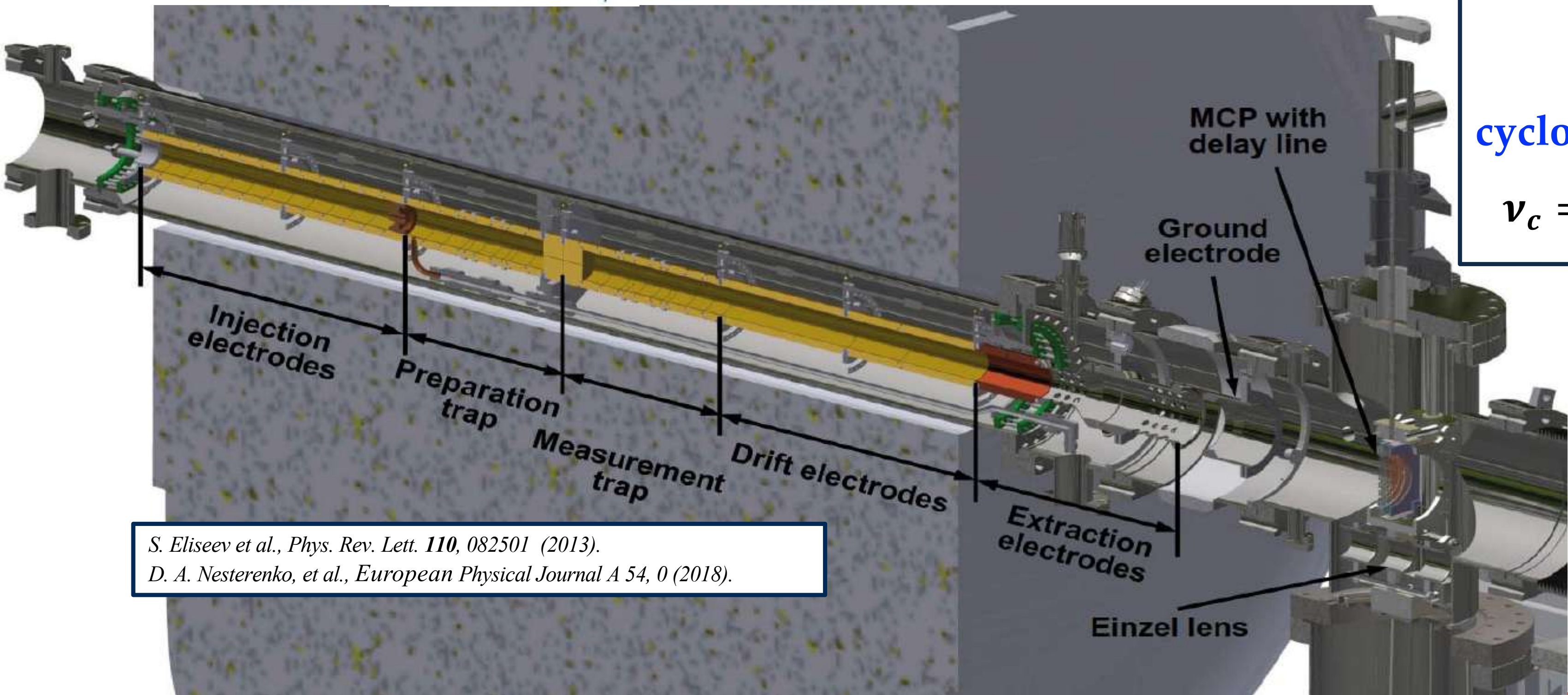
Interleaved measurements of Ion-of-interest and reference (^{111}In and ^{111}Cd)

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).

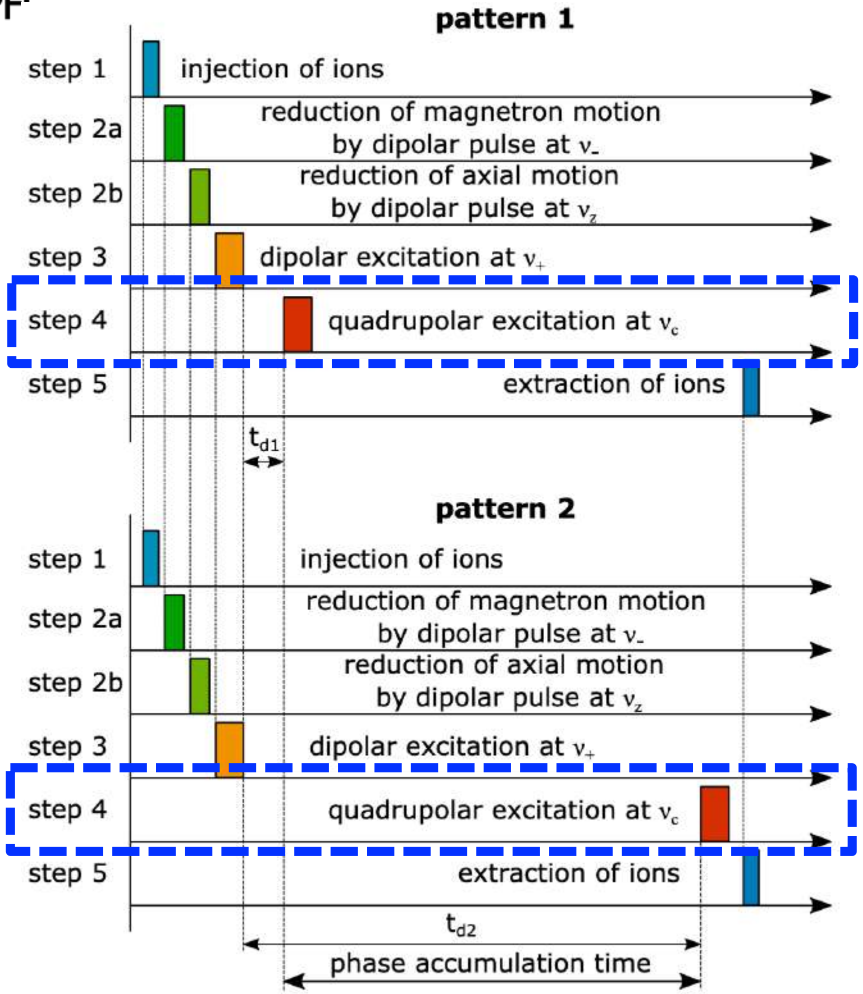
Angle between cyclotron and magnetron motion phases with respect to the center spot:

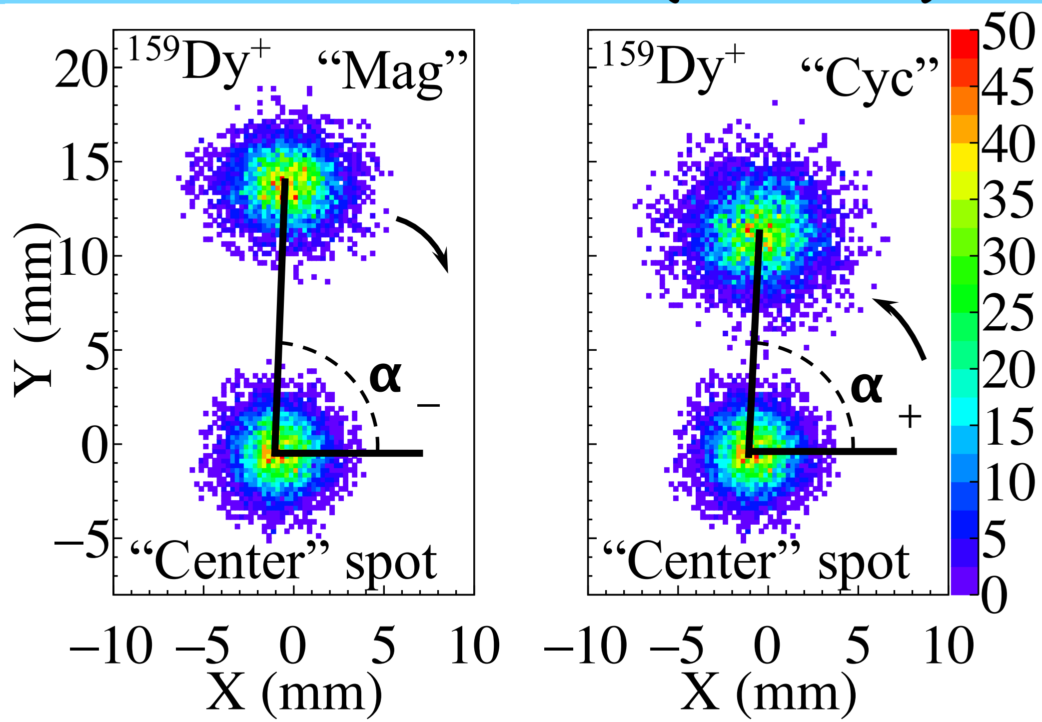
$$\alpha_c = \alpha_- + \alpha_+$$

cyclotron frequency:

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

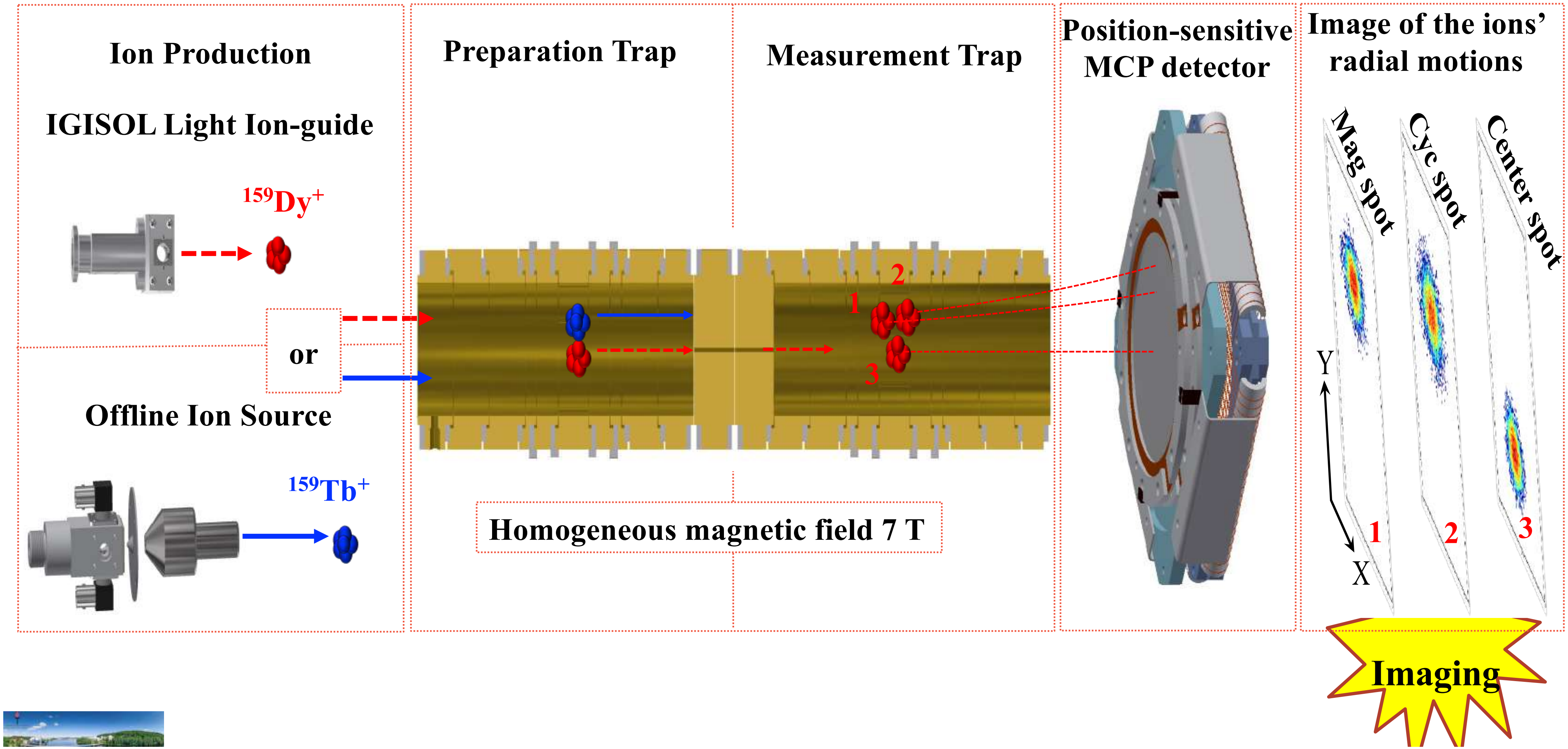
Phase-imaging Ion-Cyclotron-Resonance (PI-ICR)





- Dipolar excitation at ν_+
  - Direct conversion to magnetron motion
    - → Magnetron phase
  - Accumulation then conversion to magnetron motion
    - → Modified cyclotron phase

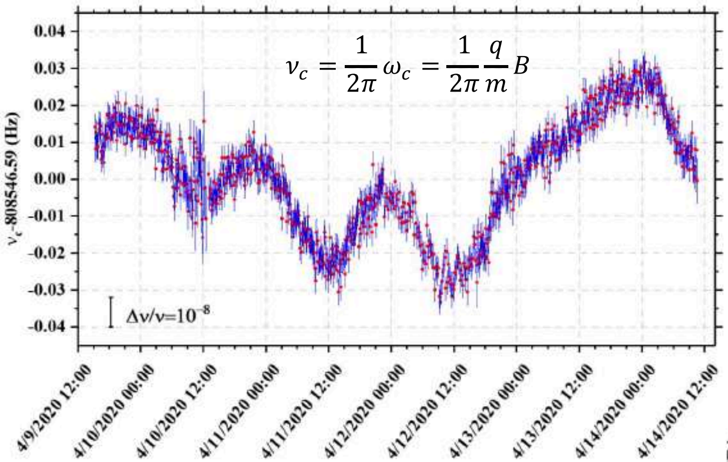
Schematic of PI-ICR for 159Dy-159Tb Q-value measurements



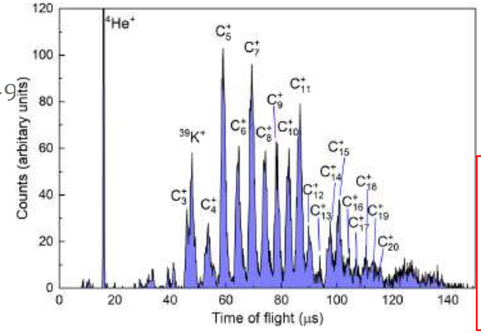
Typical systematic uncertainties

D.A. Nesterenko, T. Eronen , Z. Ge, A. Kankainen, M. Vilen, Eur. Phys. J. A (2021) 57:302

- JYFLTRAP (TOF-ICR)
  - 7.8×10^{-10} per u, residual: 1.2×10^{-8}
  - If $m - m_{ref} < 24u$:
    - 7.5×10^{-10} per u, residual: 7.9×10^{-9}

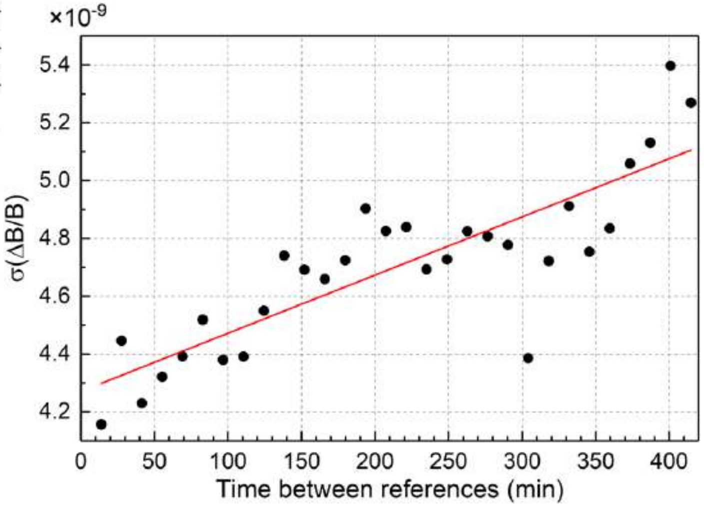


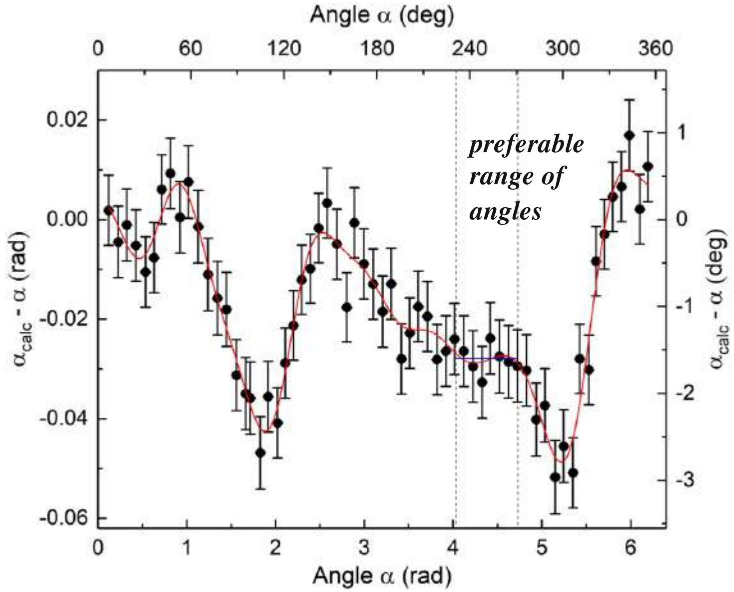
***magnetic field fluctuations*:**
δB/B = 2.01(25) x 10^{-12} /min δt



- JYFLTRAP (PI-ICR)
  - -2.35(81) $\times10^{-10}$ per u, residual: 9×10^{-9}
  - If $\mathrm{m - m_{ref} < 12u}$:
    - -2.3(21) $\times10^{-10}$ per u, residual: 5.3×10^{-9}

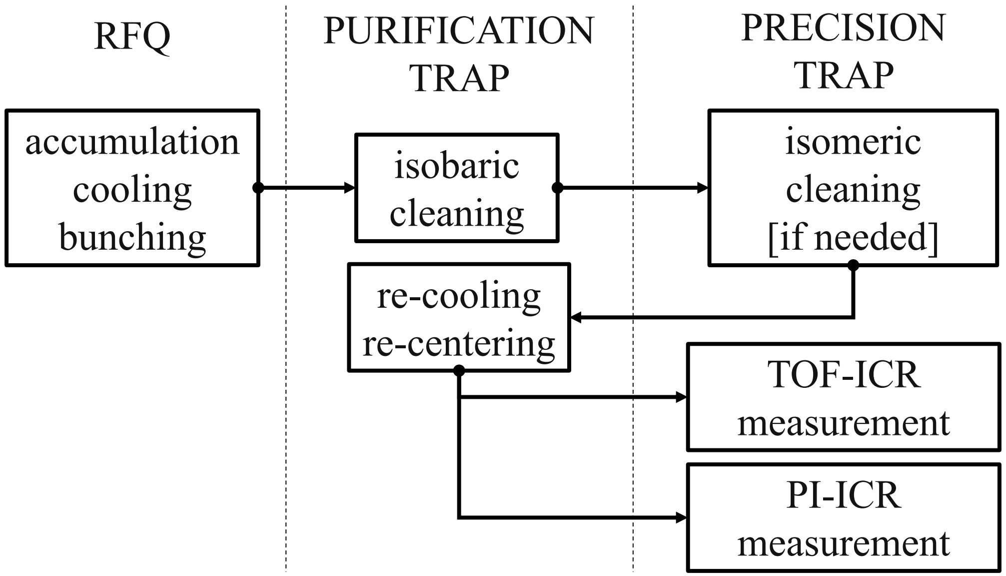
To reach the precision at the level of 10^{-10} or better, need: $|m_{ref} - m_{ioi}| \leq 2$ u or ideally *A/q* doublets.

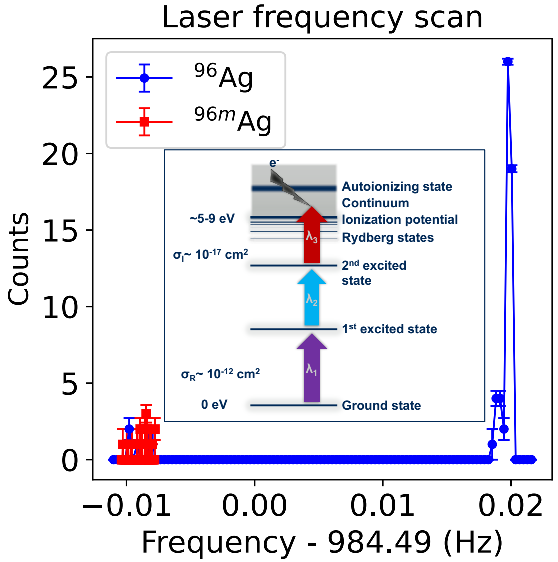


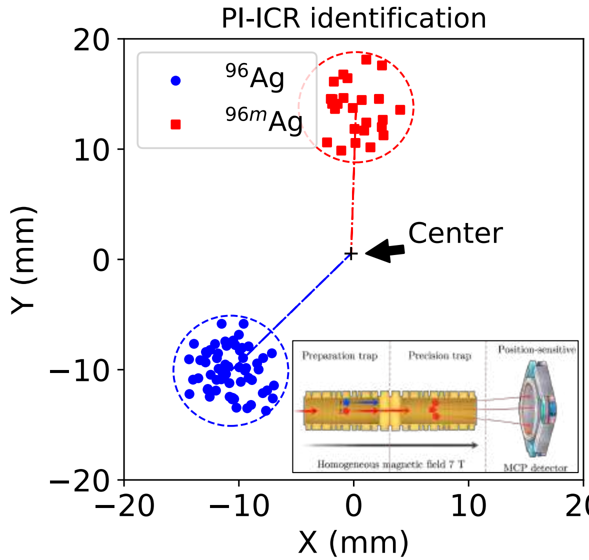


Cleaning methods coupled with PI-ICR method

Z. Ge, T. Eronen, A. de Roubin et al., Phys. Rev. C **108**, 045502 (2023)







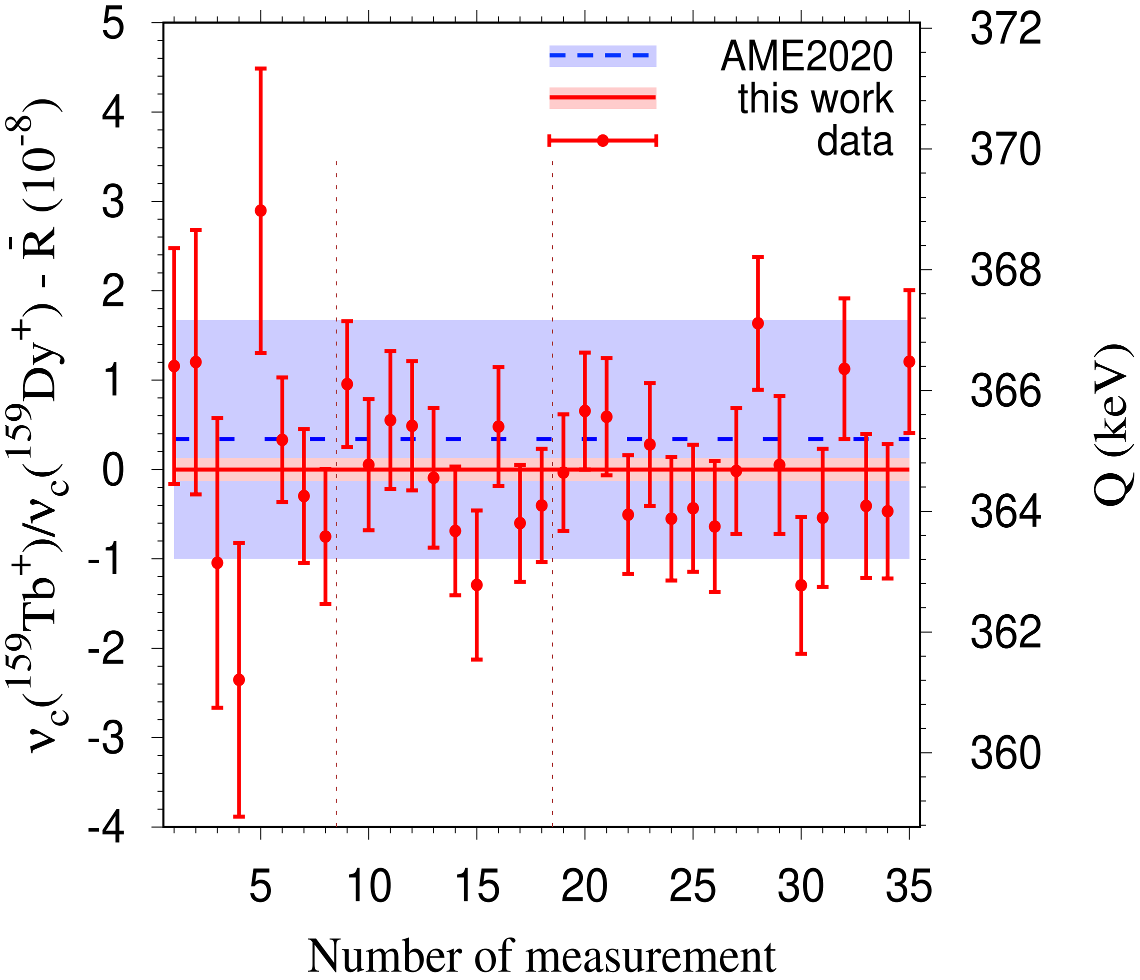
Z. Ge, M. Reponen, T. Eronen et al., arXiv:2401.07976v2 (PRL, accepted)

Conatminant-free ion sample preparation:

Coupling of Ramsey cleaning&Buffer gas cleaning&laser frequency scan and PI-ICR method for unambiguous cleaning

contaminants of 90 keV (A =136) away from ion of interest easy to clean, more than 10^6 resolving power to clean 2 or more closely lying contaminants

Q-value measurement of ^{159}Dy



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

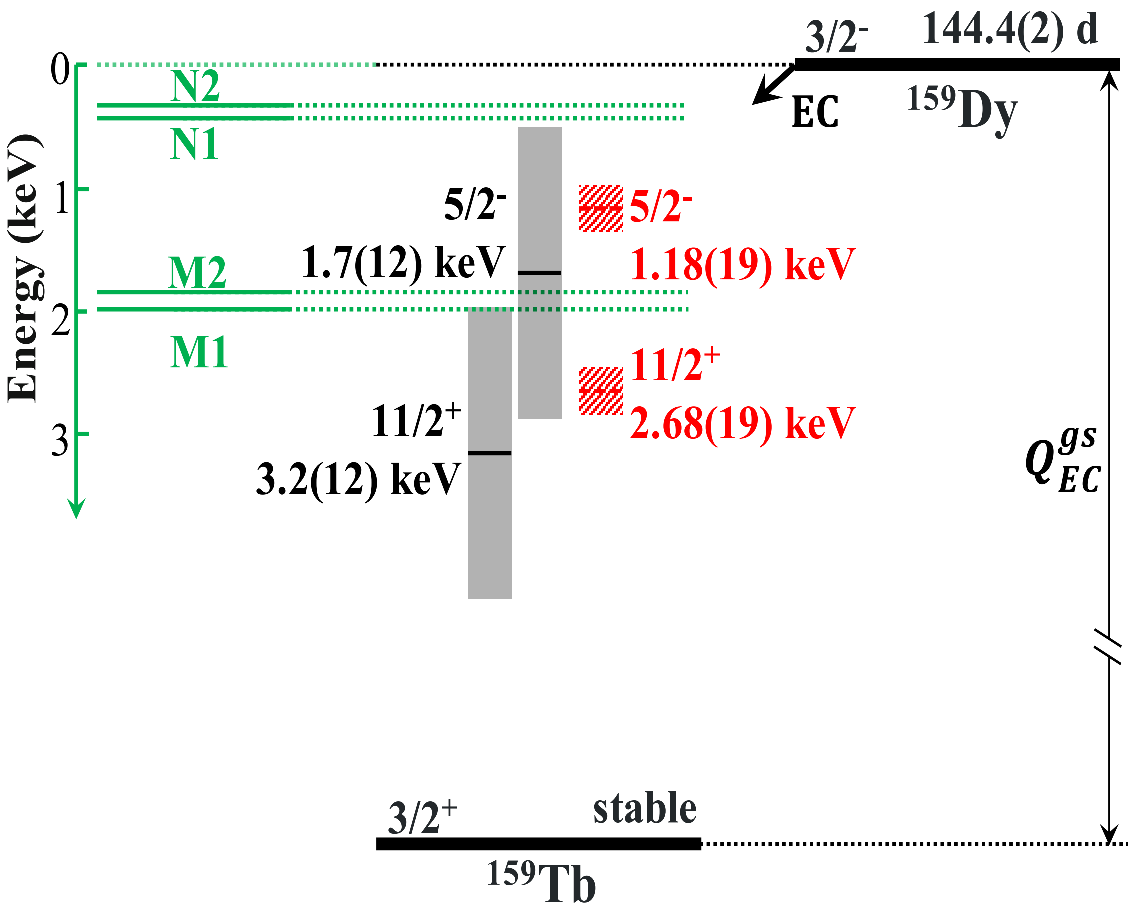
Obtained frequency ratio *r* with a precision of **1.3×10^{-9}**

$\longrightarrow$

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^*	
5/2-	363.5449(14)
11/2+	362.050(40)

\+

Binding energy e_x (allowed atomic shell x of the EC)

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

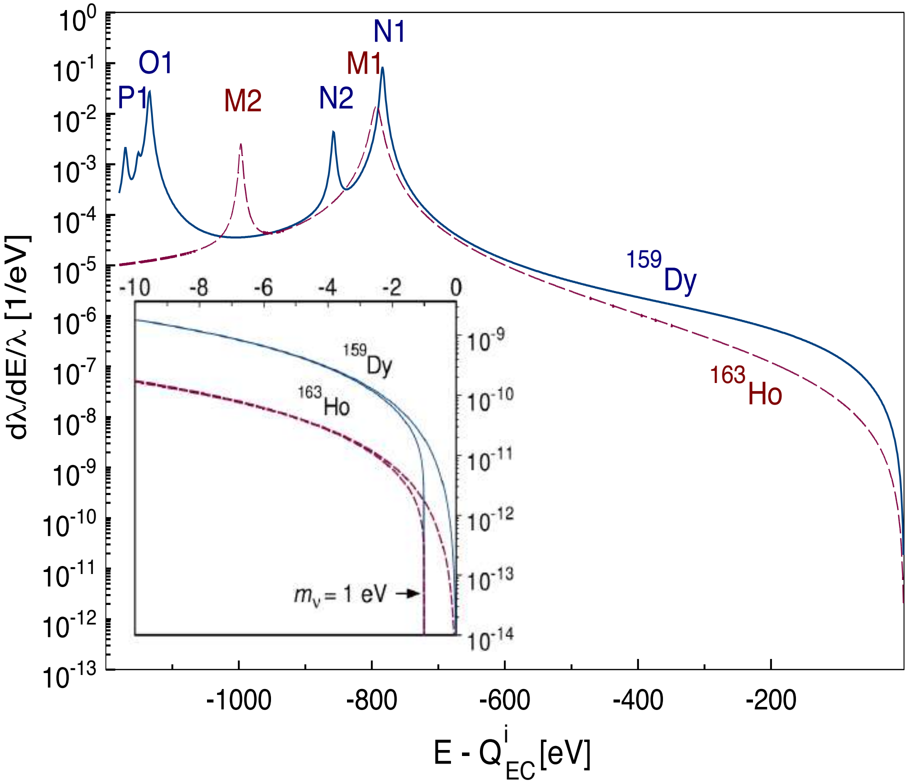
- **Captures to 5/2-**
  - only from N1 or higher orbitals
  - M2 and M1 captures forbidden at > 4σ level
- **captures to 11/2+**
  - from M1 and higher orbitals

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)

^{159}Dy($3/2^-$)$\rightarrow$^{159}Tb* ($5/2^-$),Q_{EC}^{*} = 1.18(19) keV

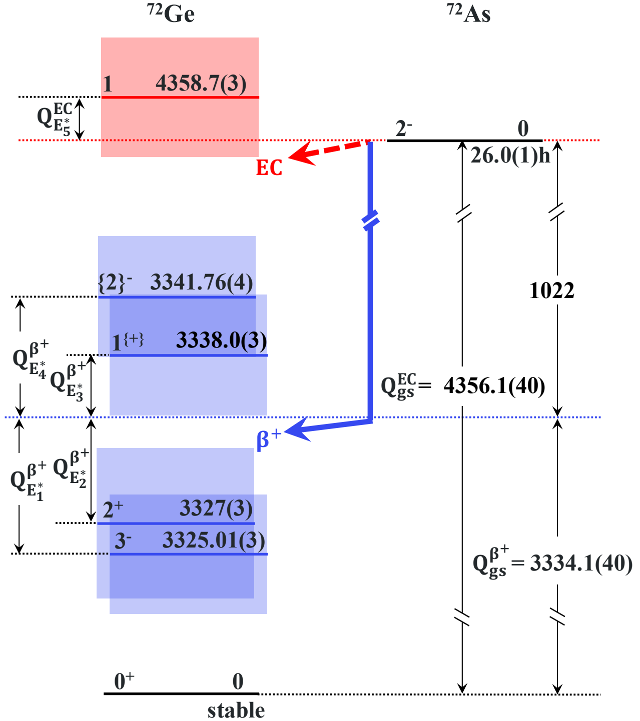
⇨ lower than the GS-to-GS Q_{EC} of ^{163}Ho (running)

- allowed transition
- known branching ratio 1.9(5) × 10^{-6}
- ultra-low distance to the atomic line M1: 0.79(19) keV

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

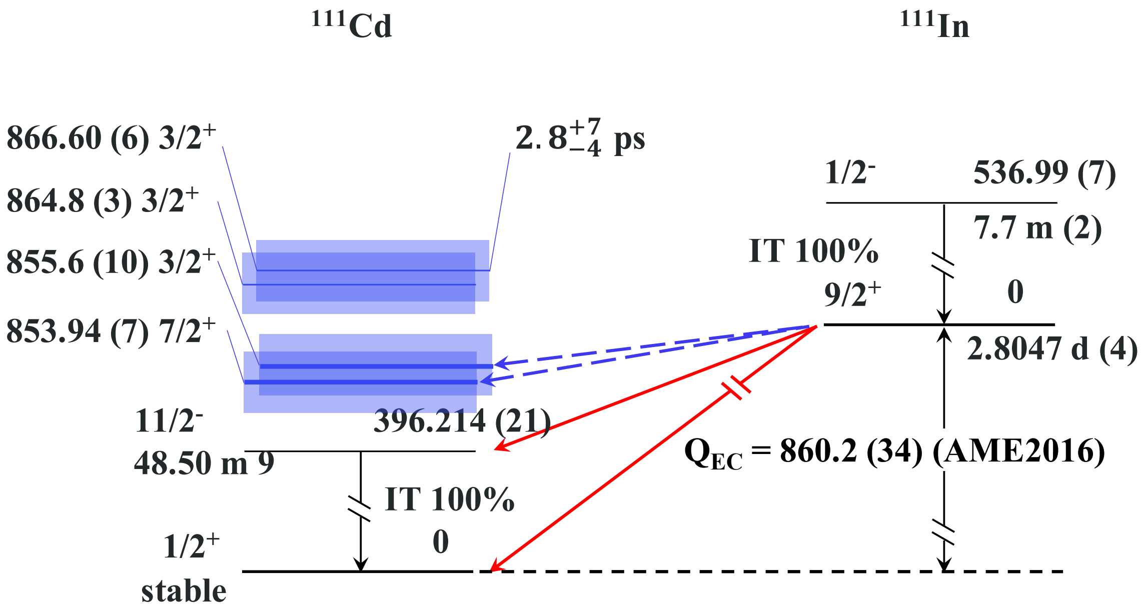
Puzzles in potential candidates ^{72}As, ^{111}In

State, i	E^* (keV)	J^π	Decay type	Q (keV)
1	3325.01(3)	3^-	β^+: Allowed	8.9(40)
2	3327(3)	2^+	β^+: 1st FNU	6.9(50)
3	3338.0(3)	$1^{\{+\}}$	β^+: 1st FNU{?}	-4.1(40)
4	3341.76(4)	$\{2\}^-$	β^+: Allowed{?}	-7.9(40)
5	4358.7(3)	1	EC: Allowed{?}	-2.8(40)
gs	0	0^+		4356(4)



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

similarly

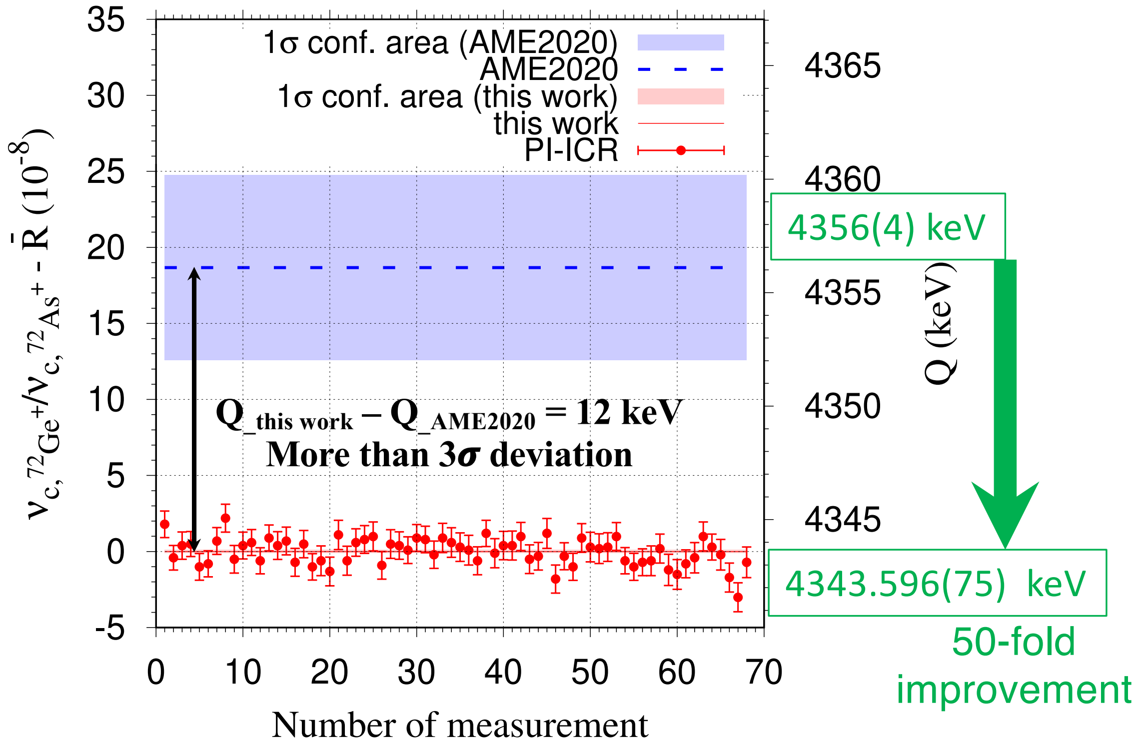


Z. Ge, T. Eronen, et al., Physics Letters B 832 (2022) 137226

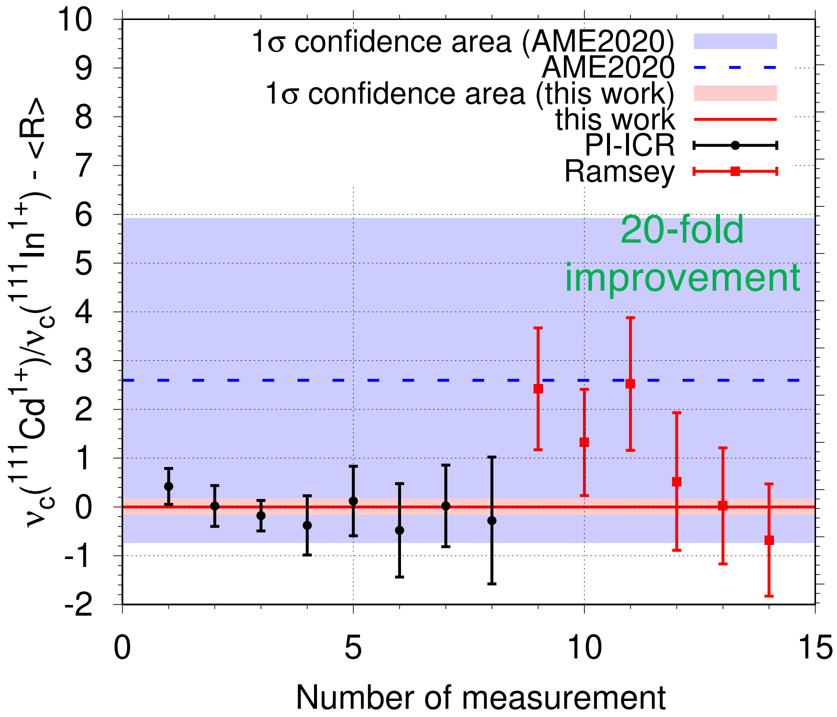
Q_0 from M. Wang et al. , Chinese Physics C 45, 030003 (2021)

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

Q-value of potential candidate ^{72}As, ^{111}In



Large discrepancy from the AME2020

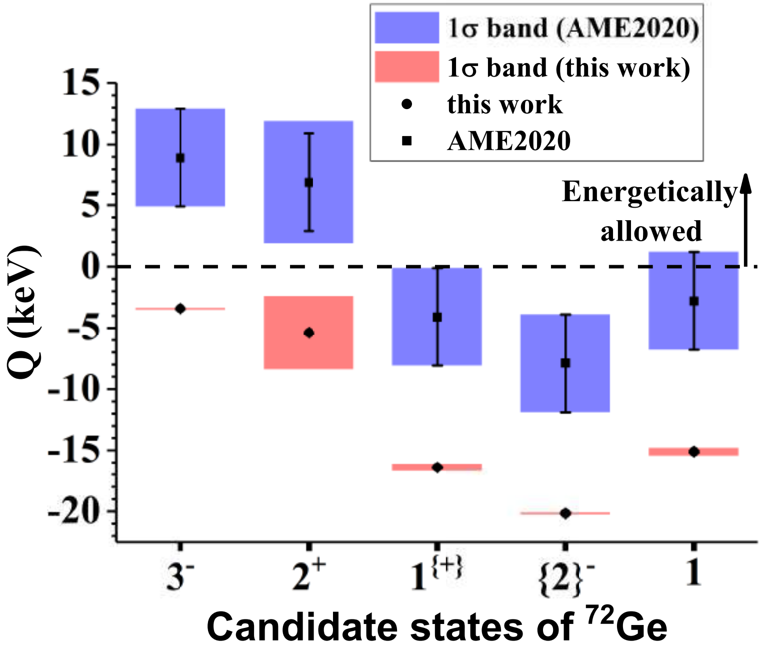


Good agreement with the AME2020

GS-to-GS *Q*-values to ~ 100 eV precision to determine whether the cases are suitable for neutrino mass determination

Required to be measured directly with high accuracy and precision

Ruling out ^{72}As as potential candidate



Q-values (in keV) for the decay candidate to the excited states of the daughter nucleus ^{72}Ge

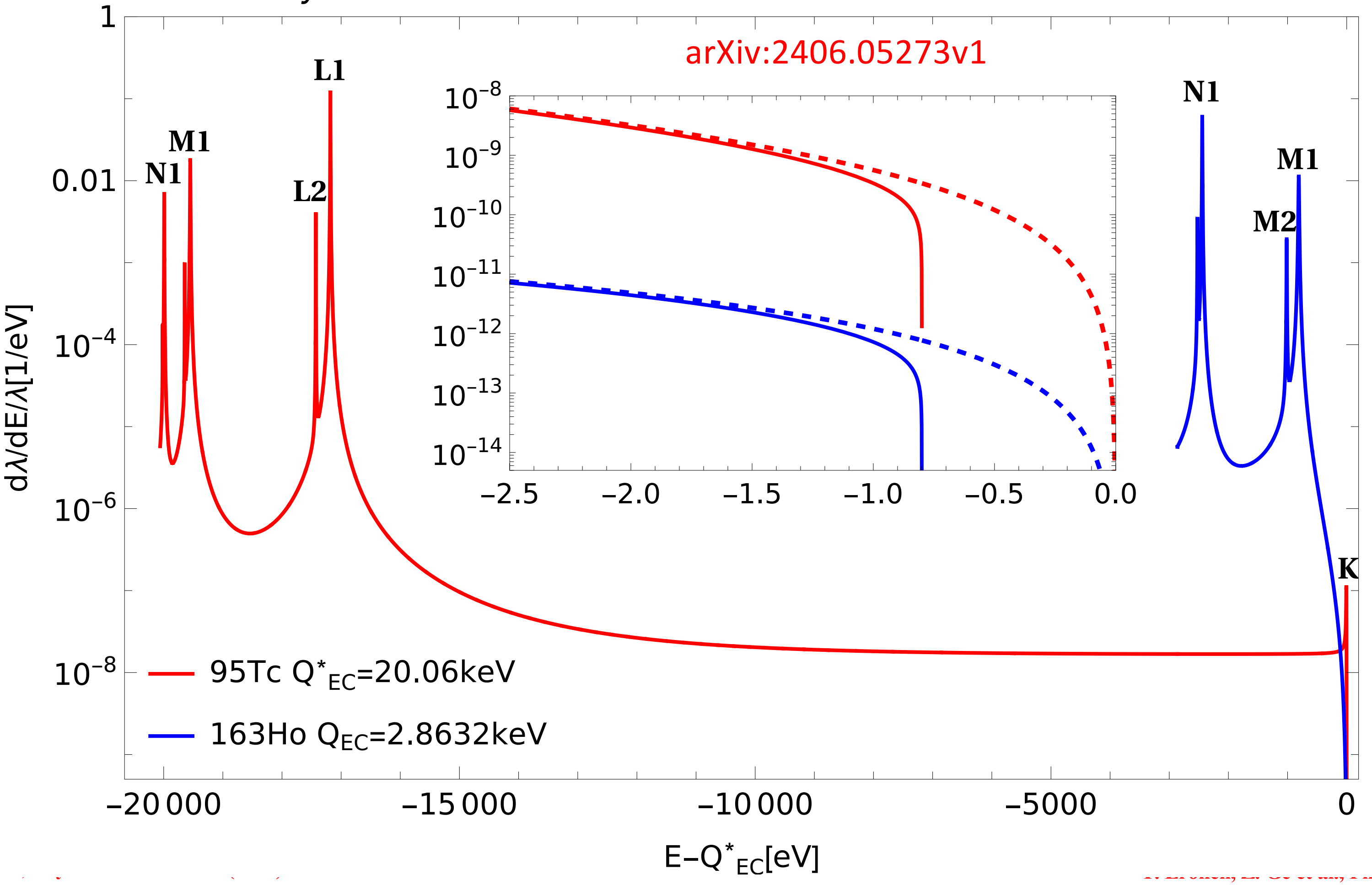
E*	Q-value (AME2020)	Q-value (This work)	$Q/\delta Q$ (This work)
3325.01(3)	8.9(40)	-3.42(8)	43
3327(3)	6.9(50)	-5.4(30)	1.8
3338.0(3)	-4.1(40)	-16.41(31)	53
3341.76(4)	-7.9(40)	-20.17(8)	238
4358.7(3)	-2.8(40)	-15.11(31)	49

five potential ultra-low Q-value β^+-decay or electron capture transitions are energetically forbidden, precluding all the transitions as possible candidates for the electron neutrino mass determination

However, the discovery of *small negative Q-values* opens up the possibility to use ^{72}As for the study of virtual β-γ transitions

Potential cases of 111In, 131I and 95Tc

Normalized distribution of the released energy (EC) and partial half-lives: atomic self-consistent many-electron Dirac–Hartree–Fock–Slater method and NSM

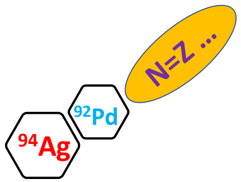


Multiple corrections are considered in the new method

Summary and Outlook

- ❖ 12 Cases being published in 9 papers by JYFLTRAP (PRLx2, PLBx2, PRCx4, EPJAx1)
  - ➢ $^{72,76,77}As$, ^{75}Se, $^{75\text{-}76}Ge$, ^{111}In, ^{131}I, $^{135},^{136}Cs$, ^{155}Tb, and ^{159}Dy
    - ✓ Neutrino mass, Neutrino capture, relic ne
  - ➢ ^{95}Tc --- submitted (PLB)

- ❖ More than 10 other Cases to be characterized for
  - ➢ The JYFLTRAP wanna some rest now --- 0-T s



- ❖ More low Q value cases to be measured
  - ➢ 14 days of beam time with Penning trap is lef
  - ➢ More …
- ❖ To do: N~Z mass measurements (recently Funded Academy project)
  - ➢ *Make JYFLTRAP great again* (PRL accepted: masses 95-97Ag, more…) Traps+Laser+Hot cavity+HIGISOL/MI
  - ➢ IGISOL MR-TOF (RIKEN MR-TOF?)
  - ➢ RIKEN storage ring + Bro-TOF
    - ✓ (9 days of beam time approved: 100Sn) x3 to measure all N=Z nuclei
  - ➢ RIKEN storage ring + Bro-TOF (9 days of beam time) x3 to measure all N=Z

Let us see how productive for this project in next PLATAN

Theory
experiment

COLLABORATION LIST

T. Eronen,[1] Z. Ge,[1] A. de Roubin,[2] D. A. Nesterenko,[1] M. Hukkanen,[1, 2] O. Beliuskina,[1] R. de Groote,[1] C. Delafosse,[1] S. Geldhof,[1], W. Gins,[1] A. Kankainen,[1] Á. Koszorús,[7] I. D. Moore,[1] H. Penttilä,[1] A. Raggio,[1] S. Rinta-Antila,[1] M. Stryjczyk,[1] V. Virtanen,[1] A. P. Weaver,[8] A. Zadvornaya,[1] A. Jokinen[1] and the IGISOL collaboration

J. Suhonen,[1] K. S. Tyrin,[3] M. I. Krivoruchenko,[3,4] J. Kostensalo,[1] J. Kotila,[5,6] P. Pirinen,[1] M. Ramalho[1]

1 Department of Physics, University of Jyväskylä, Finland
2 Centre d'Etudes Nucléaires de Bordeaux Gradignan, UMR 5797 CNRS/IN2P3 - Université de Bordeaux, France
3 National Research Centre "Kurchatov Institute", Russia
4 Institute for Theoretical and Experimental Physics, NRC "Kurchatov Institute", Russia
5 Finnish Institute for Educational Research, University of Jyväskylä, Finland
6 Yale University, USA
7 University of Liverpool, United Kingdom
8 University of Brighton, United Kingdom

Theoretical Collaborators before 2021

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Zhuang Ge[a,*], Tommi Eronen[a], Vasile Alin Sevestrean[b,c,d,*], Ovidiu Nițescu[b,d], Sabin Stoica[b], Marlom Ramalho[a], Jouni Suhonen[a,b,*], Antoine de Roubin[e,f], Dmitrii Nesterenko[a], Anu Kankainen[a], Pauline Ascher[f], Samuel Ayet San Andres[g], Olga Beliuskina[a], Pierre Delahaye[h], Mathieu Flayol[f], Mathias Gerbaux[f], Stéphane Grévy[f], Marjut Hukkanen[a,i], Arthur Jaries[a], Ari Jokinen[a], Audric Husson[f], Daid Kahl[j,2], Joel Kostensalo[k], Jenni Kotila[b,l,m], Iain Moore[a], Stylianos Nikas[a], Marek Stryjczyk[a] and Ville Virtanen[a]

[a]Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014, Jyväskylä, Finland
[b]International Centre for Advanced Training and Research in Physics (CIFRA), POB MG-12, RO-077125, Bucharest-Măgurele, Romania
[c]Faculty of Physics, University of Bucharest, 405 Atomiștilor, POB MG-11, RO-077125, Bucharest-Măgurele, Romania
[d]"Horia Hulubei" National Institute of Physics and Nuclear Engineering, 30 Reactorului, POB MG-6, RO-077125, Bucharest-Măgurele, Romania
[e]KU Leuven, Instituut voor Kern- en Stralingsfysica, B-3001, Leuven, Belgium
[f]Université de Bordeaux, CNRS/IN2P3, UMR 5797, F-33170, Gradignan, France
[g]Instituto de Fisica Corpuscular, CSIC-UV, 46980, Gradignan, Spain
[h]GANIL, CEA/DSM-CNRS/IN2P3, Bd Henri Becquerel, 14000, Caen, France
[i]Université de Bordeaux, CNRS/IN2P3, LP2I Bordeaux, UMR 5797, F-33170, Gradignan, France
[j]Extreme Light Infrastructure - Nuclear Physics, Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), 077125, Bucharest-Magurele, Romania
[k]Natural Resources Institute Finland, Yliopistokatu 6B, FI-80100, Joensuu, Finland
[l]Finnish Institute for Educational Research, University of Jyväskylä, P.O. Box 35, FI-40014, Jyväskylä, Finland
[m]Center for Theoretical Physics, Sloane Physics Laboratory, Yale University, New Haven, Connecticut 06520-8120, Connecticut, USA

New theoretical collabarators

JYFL

Thank you for your attention

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