JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Search of beta decays with ultra-low Q value for neutrino mass determination

Zhuang Ge

20210325

Department of Physics, University of Jyväskylä

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

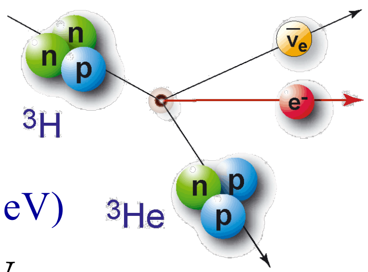
Current direct neutrino mass probes: Ground-state to ground-state (gs-to-gs) decays (β^-:Tritium, ^{187}Re; EC: ^{163}Ho)

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

Our Purpose: Search for low Q-value decays

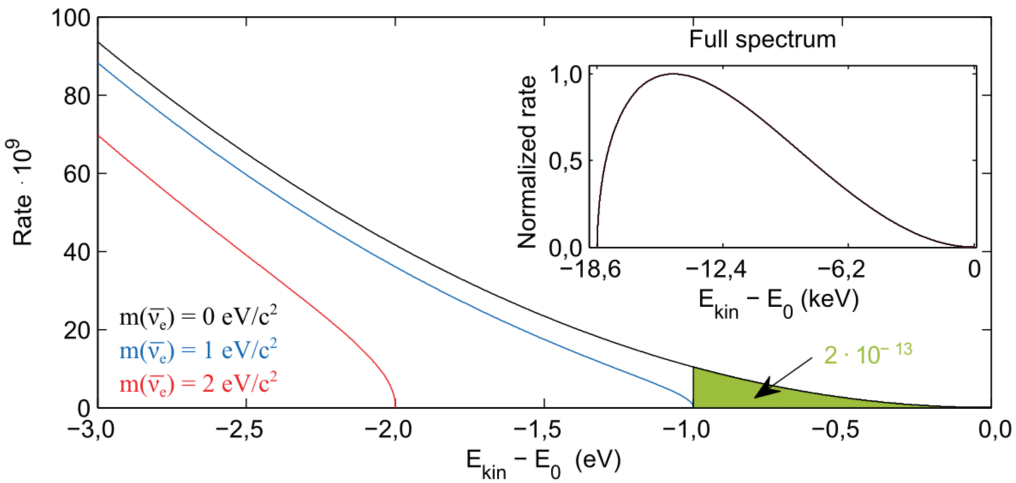
Q → 0, and Q < 1 keV (ultra-low)

Tritium (β^-decay)



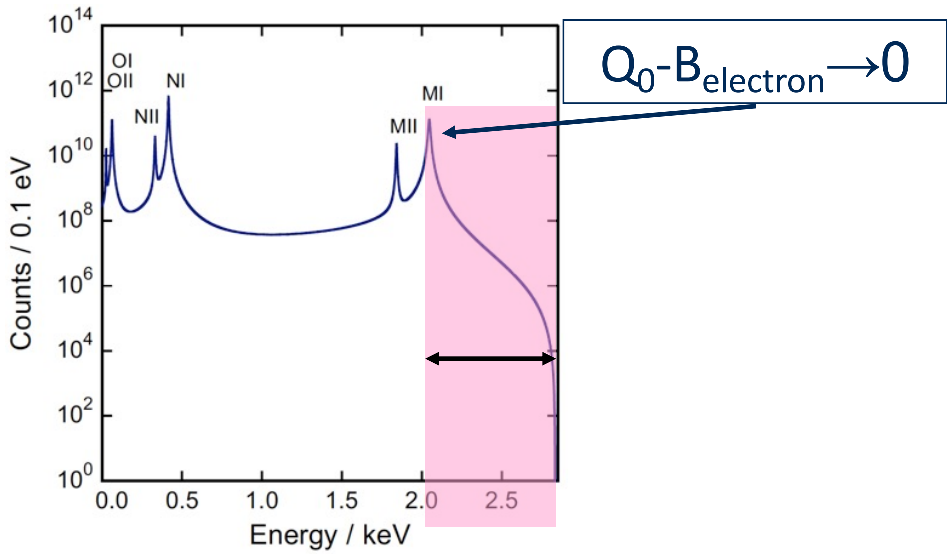
$E_0 = Q_0 - E_{rec}$ (recoil corrections: 1.72 eV)

Endpoint energy E_0 ~18.57 keV



^{163}Ho (Electron Capture)

Q_0 ~2.83 keV



Search for slightly positive Q-value decays

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

Ground-state to excited-state decay Q-value (Q^*) for potential candidates:

- **Ground-state to Ground-state (GS-to-GS) decay Q-value**

  → mass difference

  typical uncertainty > 1 keV

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**
2. β-decay of ^{187}Re: Q-value = 2.492(30)(15) keV *D. A. Nesterenko, et al , Phys. Rev. C 90, 042501(R) (2014).*	**MARE**
3. EC in ^{163}Ho: Q-value = 2.858(10)(50) keV *S. Eliseev et al , Phys. Rev. Lett. 115, 62501 (2015)*	**ECHo, HOLMES, NuMECS**

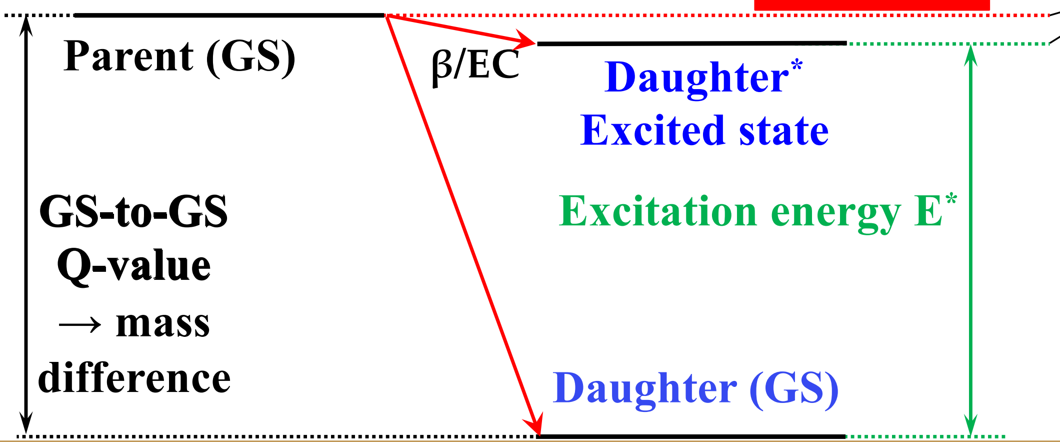
- **Excitation energy of daughter excited state**

  → From gamma spectroscopy

  typical uncertainty ~100 eV

1. β-decay of ^{115}In($9/2^+$)→^{115}Sn*($9/2^+$): Q*-value = 0.147(10) keV
   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
   A. De Roubin, J. Kostensalo, T. Eronen et al., Phys. Rev. Lett., 124 (22), 222503.

$Q^*=Q_0-E^*$



To search for other low Q-value decay candidates (especially ultra-low, <1 keV)

Ground-state to excited-state decay Q-value (Q^*) needed to be measured with a precision of ~100 eV

Relys on Penning trap spectrometer: JYFLTRAP

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

Submitted case: arXiv:2103.08729 [nucl-ex]

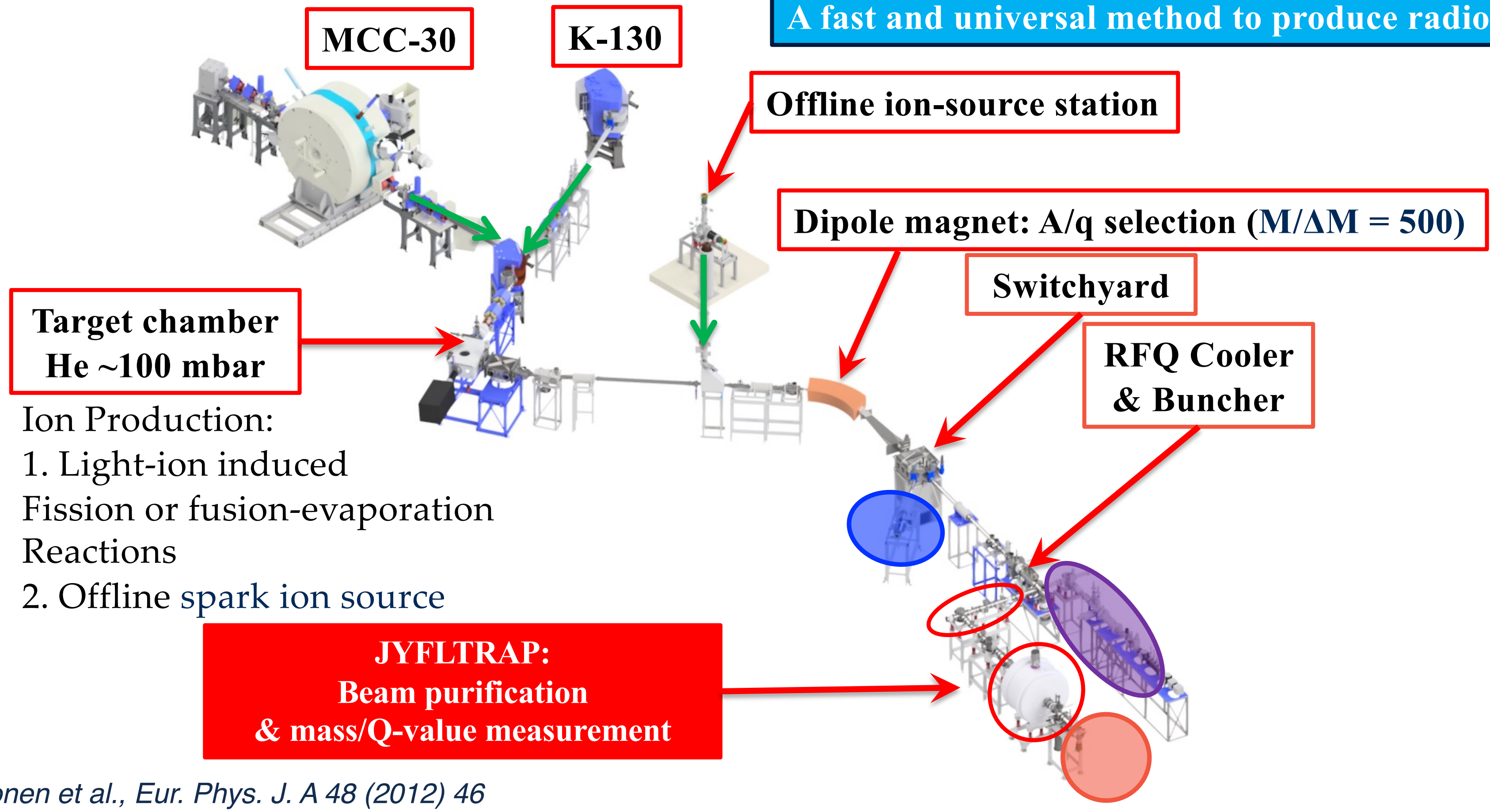
Q_0 from: *M. Wang et al. , Chinese Physics C 45, 030003 (2021)*

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

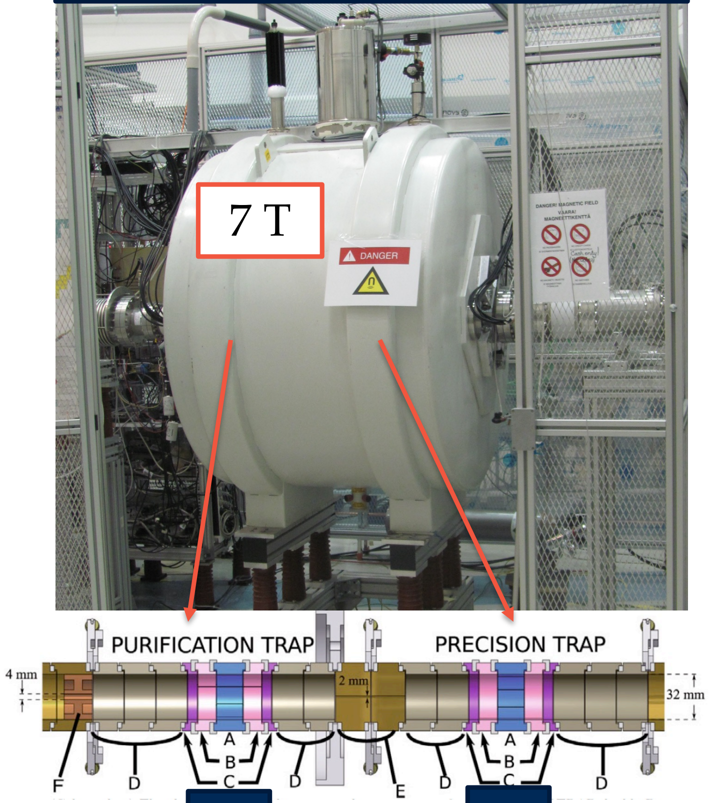


Ion Production:
1. Light-ion induced Fission or fusion-evaporation Reactions
2. Offline spark ion source

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

JYFLTRAP double Penning trap

JYFLTRAP double Penning trap

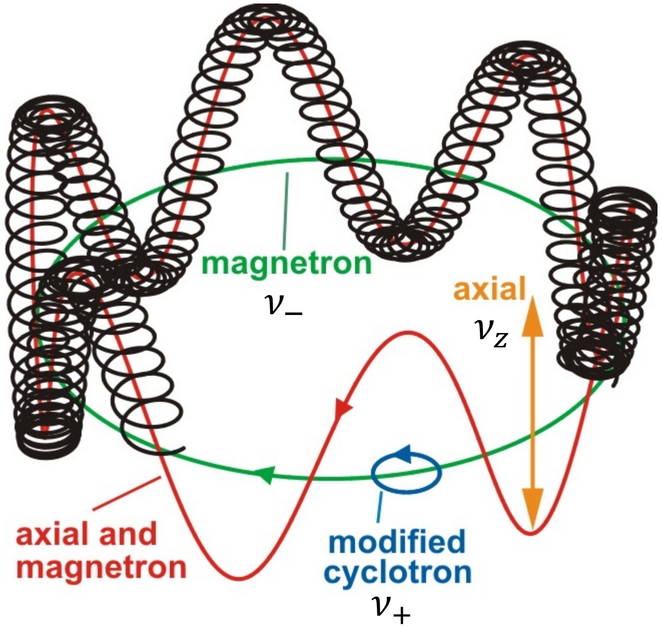


Eronen et al., EPJA 48 (2012) 46

Q-value measurements

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

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



Cyclotron frequency:

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

Frequency ratio:

$$r = \frac{\nu_{c,d}}{\nu_{c,p}}$$

***Q*-value:**

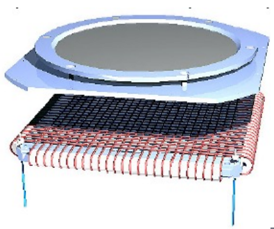
$$Q = M_p - M_d = (r-1)(M_d - m_e)c^2$$

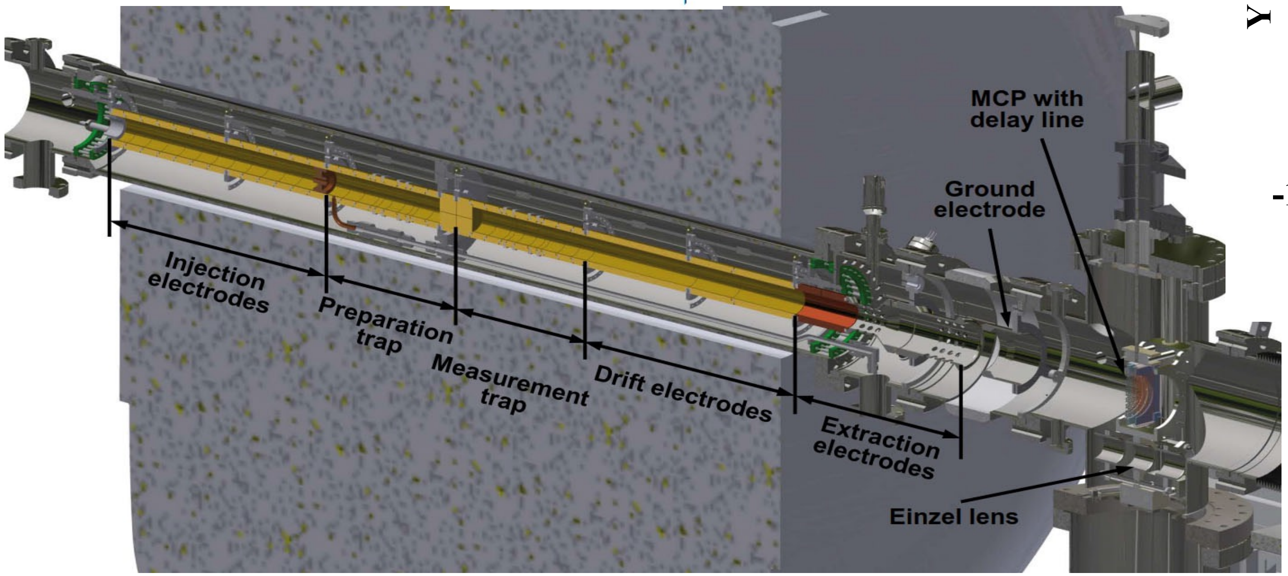
parent daughter

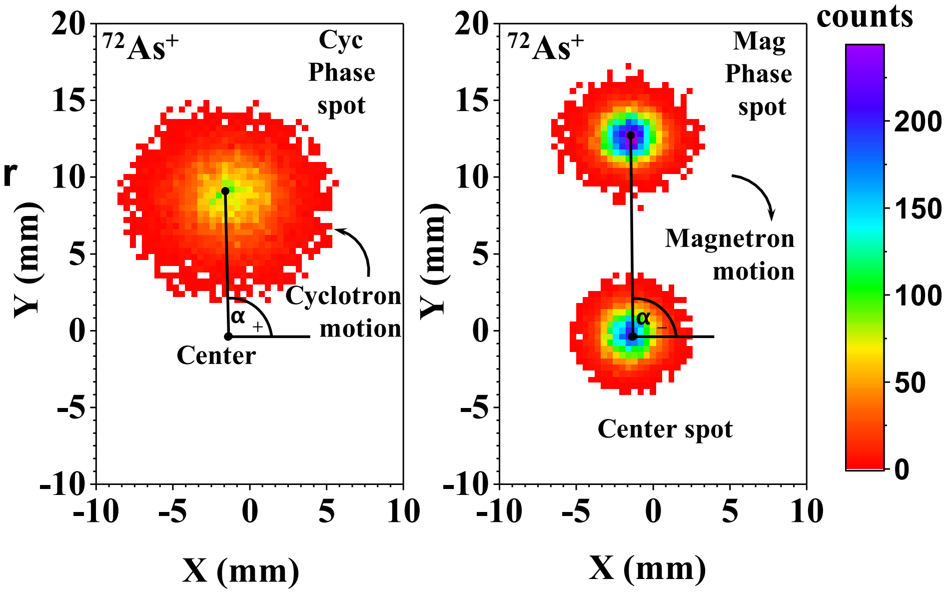
Phase-imaging Ion Cyclotron Resonance (PI-ICR)

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

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







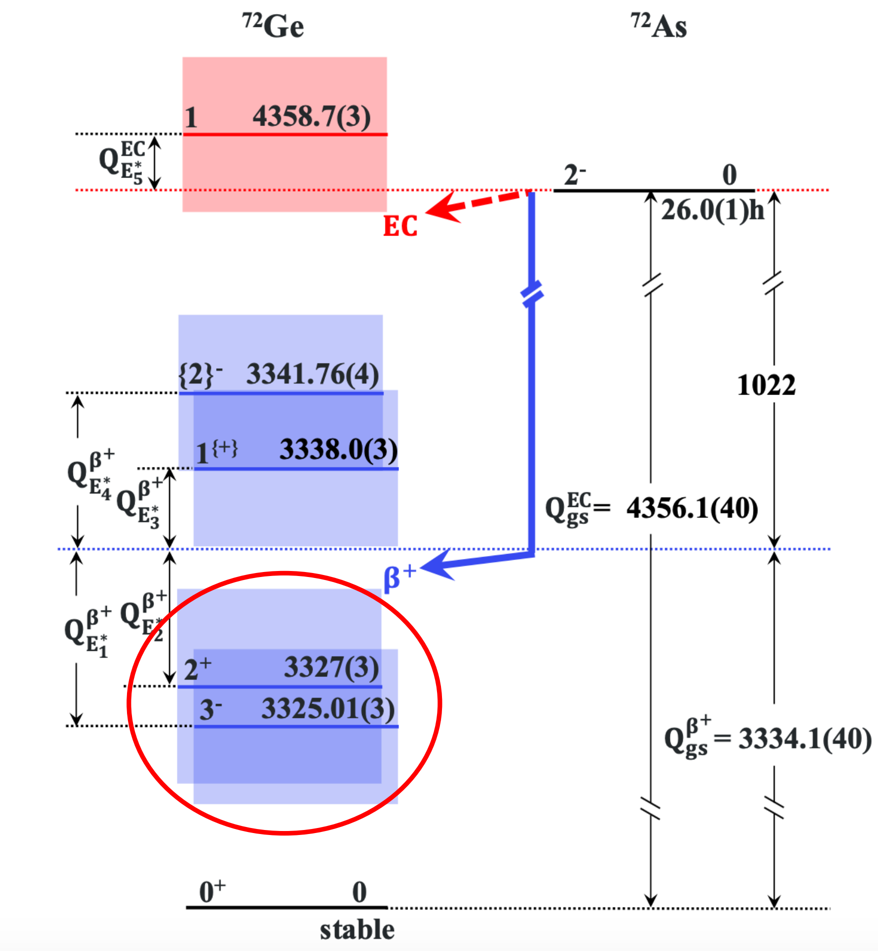
Angle between cyclotron and magnetron motion phases with respect to the center spot:

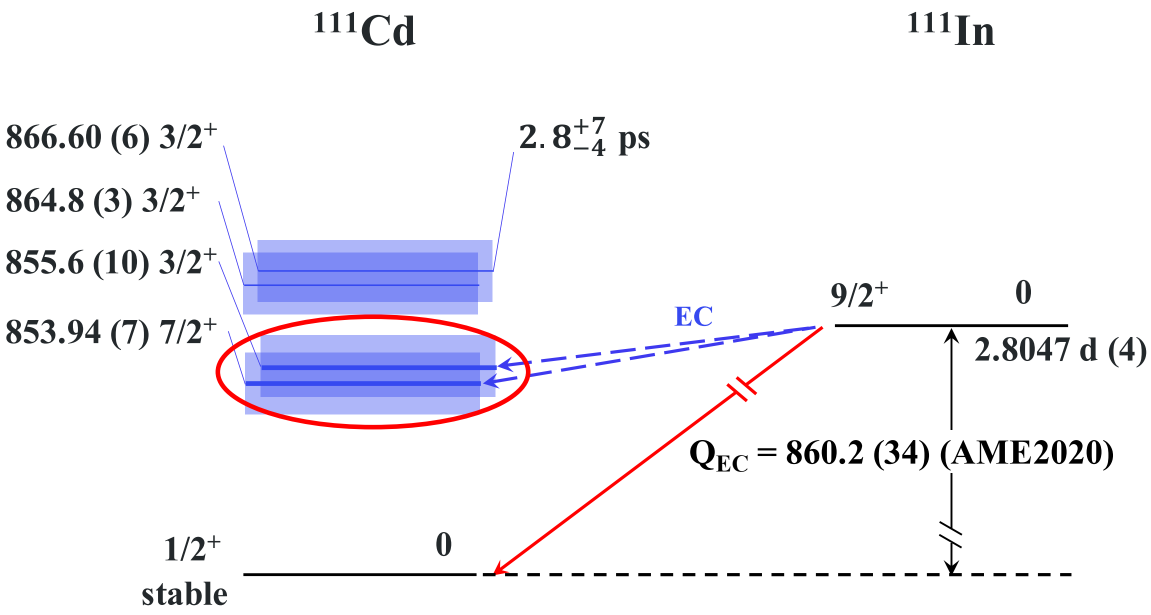
$$\alpha_c = \alpha_- + \alpha_+$$

cyclotron frequency:

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

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



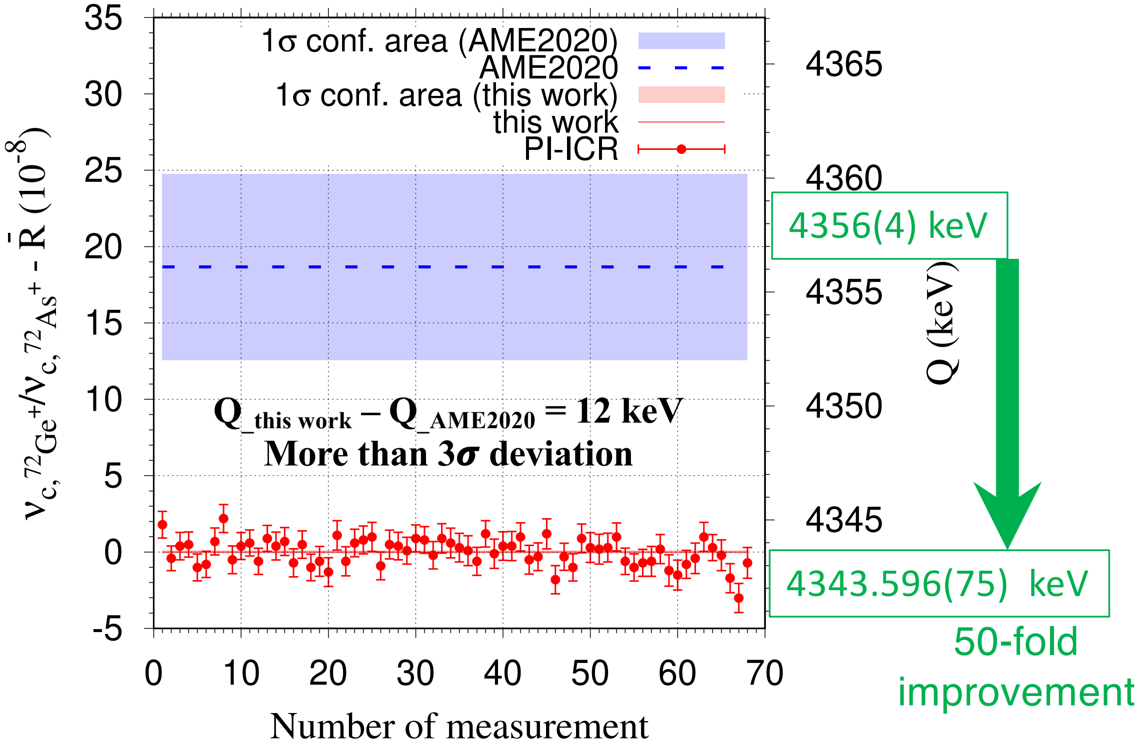


Q_0 from: *M. Wang et al. , Chinese Physics C 45, 030003 (2021)*

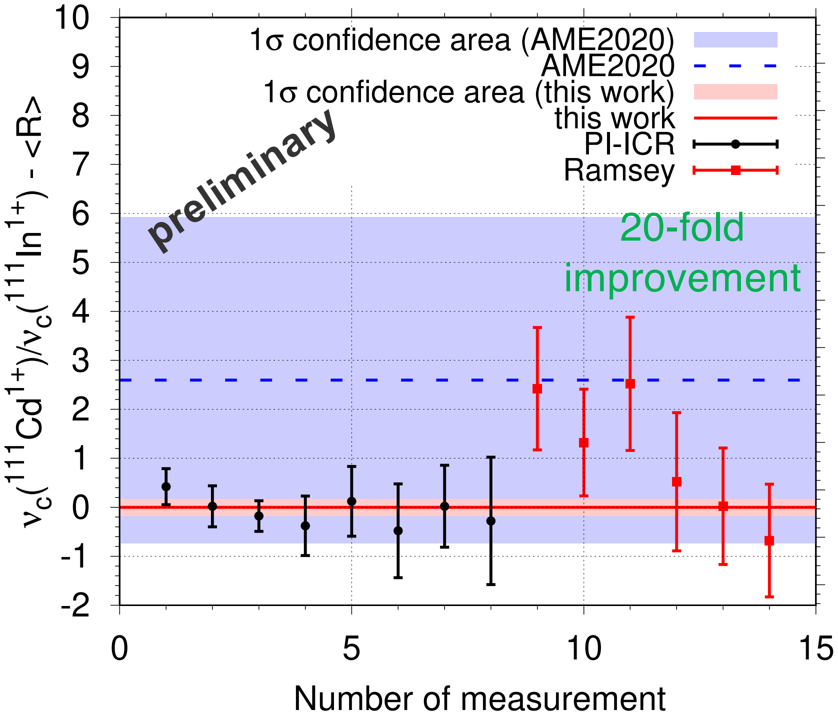
E^* from: *National nuclear data center, Available at https://www.nndc.bnl.gov*

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

arXiv:2103.08729 [nucl-ex]



Large discrepancy from the AME2020

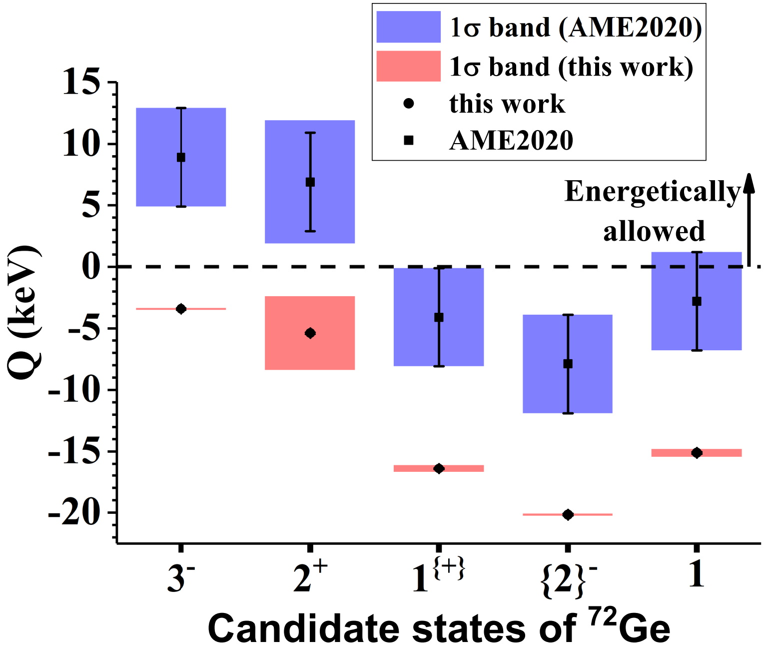


Good agreement with the AME2020

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

Results and conclusion



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

Ruling out ^{72}As as potential candidate

Confidence of being negative

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.

Collaboration list

T. Eronen,[1] Z. Ge,[1] A. de Roubin,[2] J. Kostensalo,[1] J. Kotila,[3,4] J. Suhonen,[1] 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,[5] I. D. Moore,[1] H. Penttilä,[1]
A. Raggio,[1] S. Rinta-Antila,[1] V. Virtanen,[1] A. P. Weaver,[6] A. Zadvornaya,[1] A. Jokinen[1] and the IGISOL collaboration

1 Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014, Jyväskylä, Finland
2 Centre d'Etudes Nucléaires de Bordeaux Gradignan, UMR 5797 CNRS/IN2P3 - Université de Bordeaux,
19 Chemin du Solarium, CS 10120, F-33175 Gradignan Cedex, France
3 Finnish Institute for Educational Research, University of Jyväskylä, P.O. Box 35, FI-40014, Jyväskylä, Finland
4 Center for Theoretical Physics, Sloane Physics Laboratory Yale University, New Haven, Connecticut 06520-8120, USA
5 Department of Physics, University of Liverpool, Liverpool, L69 7ZE, United Kingdom
6 School of Computing, Engineering and Mathematics, University of Brighton, Brighton BN2 4JG, United Kingdom

Thank you for your attention

Financial Support

Academy of Finland projects No. 306980, 312544, 275389, 284516, 295207, 314733 and 320062.
EU Horizon 2020 research and innovation program under grant No. 771036 (ERC CoG MAIDEN)

Acknowledgements

the staff of the accelerator laboratory of University of Jyväskylä (JYFL-ACCLAB)
J. Jaatinen and R. Seppälä, for preparing the production target