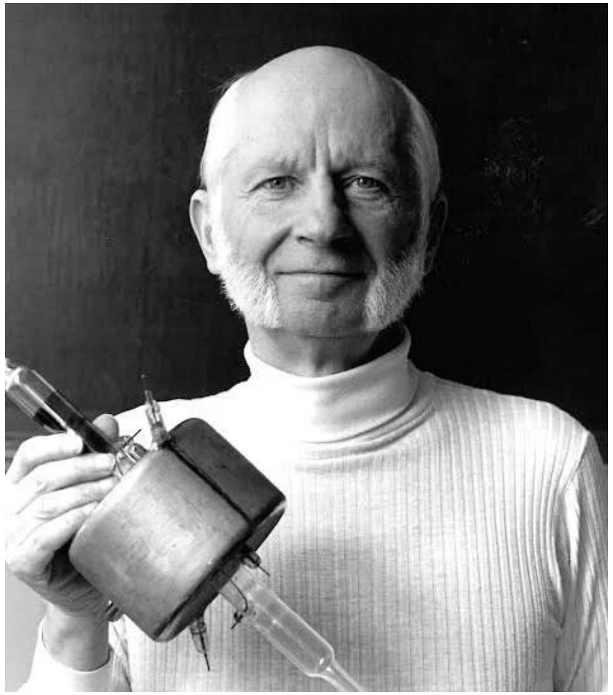
Penning Trap β-decay Q-value Measurements for BSM Physics Searches

Matthew Redshaw, Central Michigan University

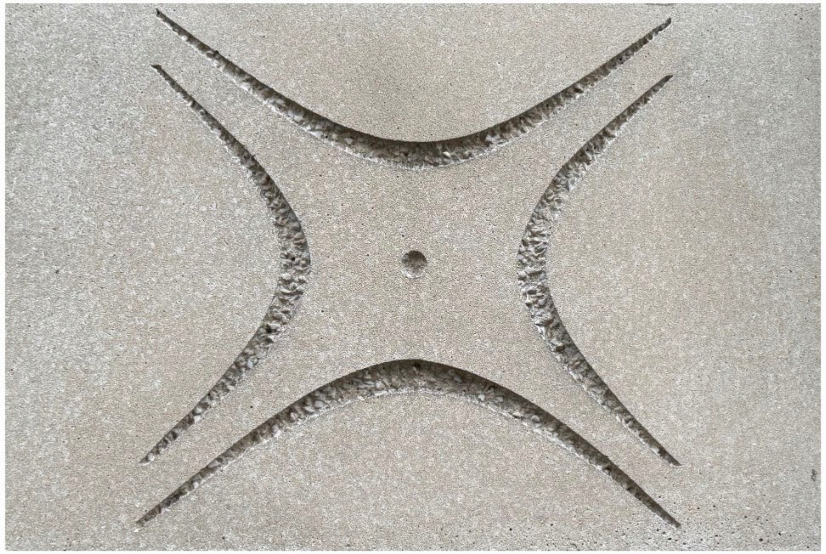
INT Workshop:
Testing the Standard Model in Charged-Weak Decays
Seattle, WA
Thursday Jan 15th 2026

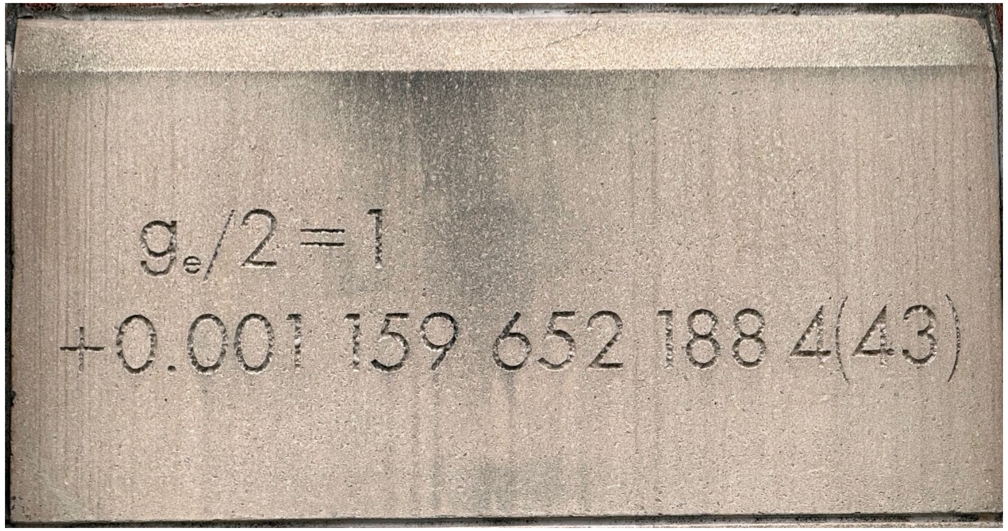
Hans Dehmelt

1989
Nobel Prize



"for the development of the ion trap technique"





(1) Introduction

(2) Method

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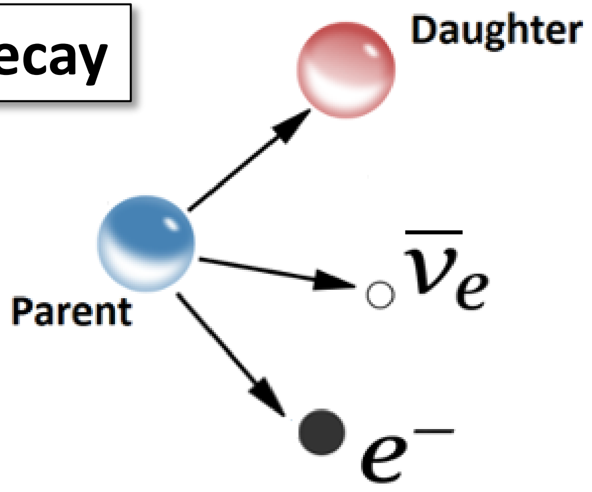
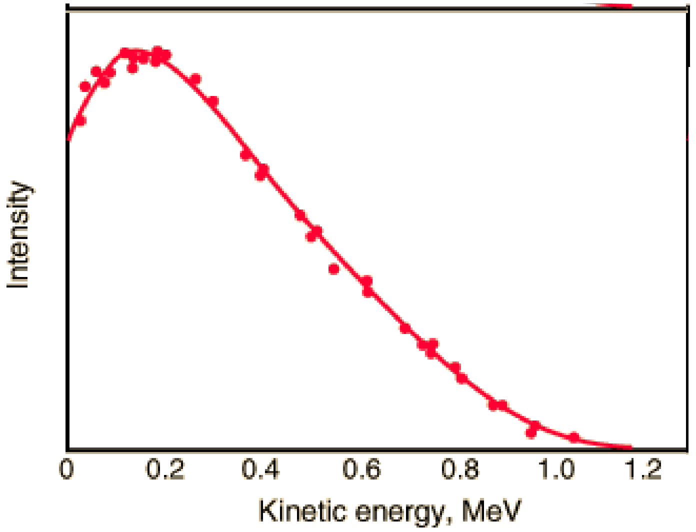
(3) Measurements & Results

β-decay Q value

Q value: the energy released as kinetic energy of the final state particles

β^- decay

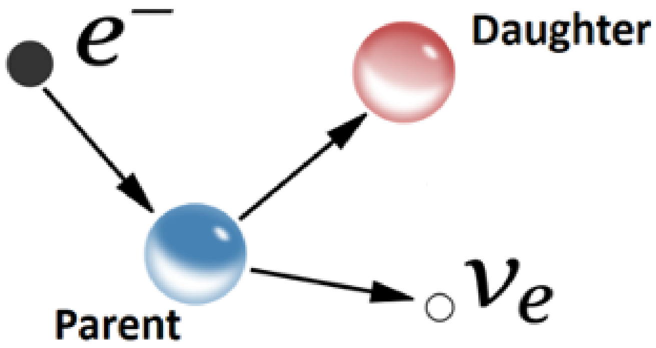


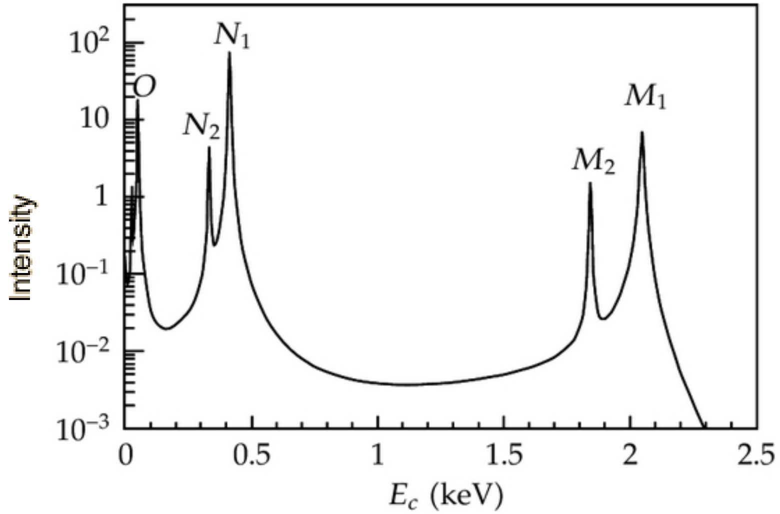


$${}^{A}_{Z}X_N \rightarrow {}_{Z+1}^{\;\;A}Y^+_{N-1} + e^- + \bar{\nu}_e$$

$$Q^{gs}_{\beta^-} = (M_X - M_Y)c^2$$

Electron capture





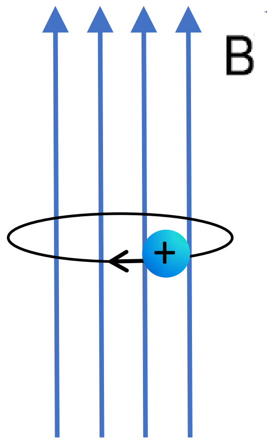
$${}^{A}_{Z}X^+_N + e^- \rightarrow {}_{Z-1}^{\;\;A}Y_{N+1} + \nu_e$$

$$Q^{gs}_{EC} = (M_X - M_Y)c^2$$

Penning Trap Measurements of Q values

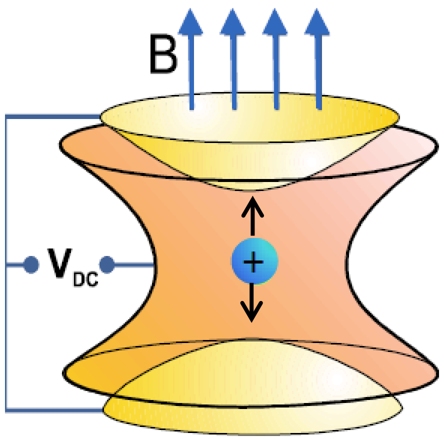
The Penning trap

Uniform B-Field



+

Quadrupole E-Field



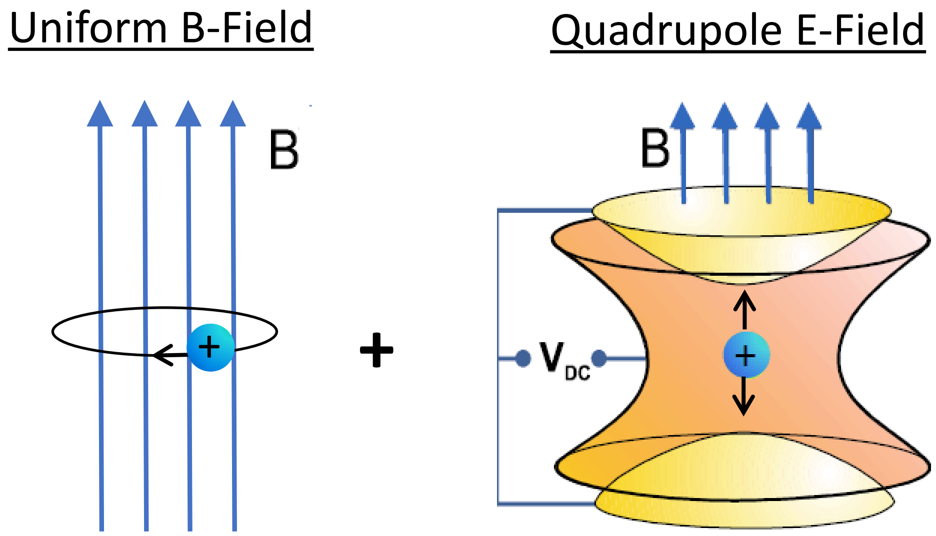
$$\nu_c = \frac{1}{2\pi}\frac{qB}{m}$$

ν_c = cyclotron frequency
m = mass
q = charge
B = magnetic field strength

Measure cyclotron frequency to determine mass

Penning Trap Measurements of Q values

The Penning trap



$$\nu_c = \frac{1}{2\pi}\frac{qB}{m}$$

ν_c = cyclotron frequency
m = mass
q = charge
B = magnetic field strength

Measure cyclotron frequency to determine mass

However, we can measure ν_c more precisely than B, so measure cyclotron frequency ratios

$$R = \frac{\nu_{c1}}{\nu_{c2}} = \frac{m_2}{m_1}$$

Do this for ions of parent, 1 → P, and daughter, 2 → D.

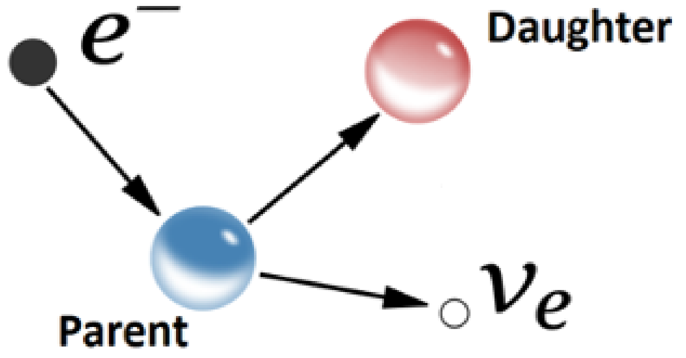
Convert mass ratio to a mass difference

$$Q = (M_P - M_D)c^2 = (M_P - m_e)(1 - R)\, c^2$$

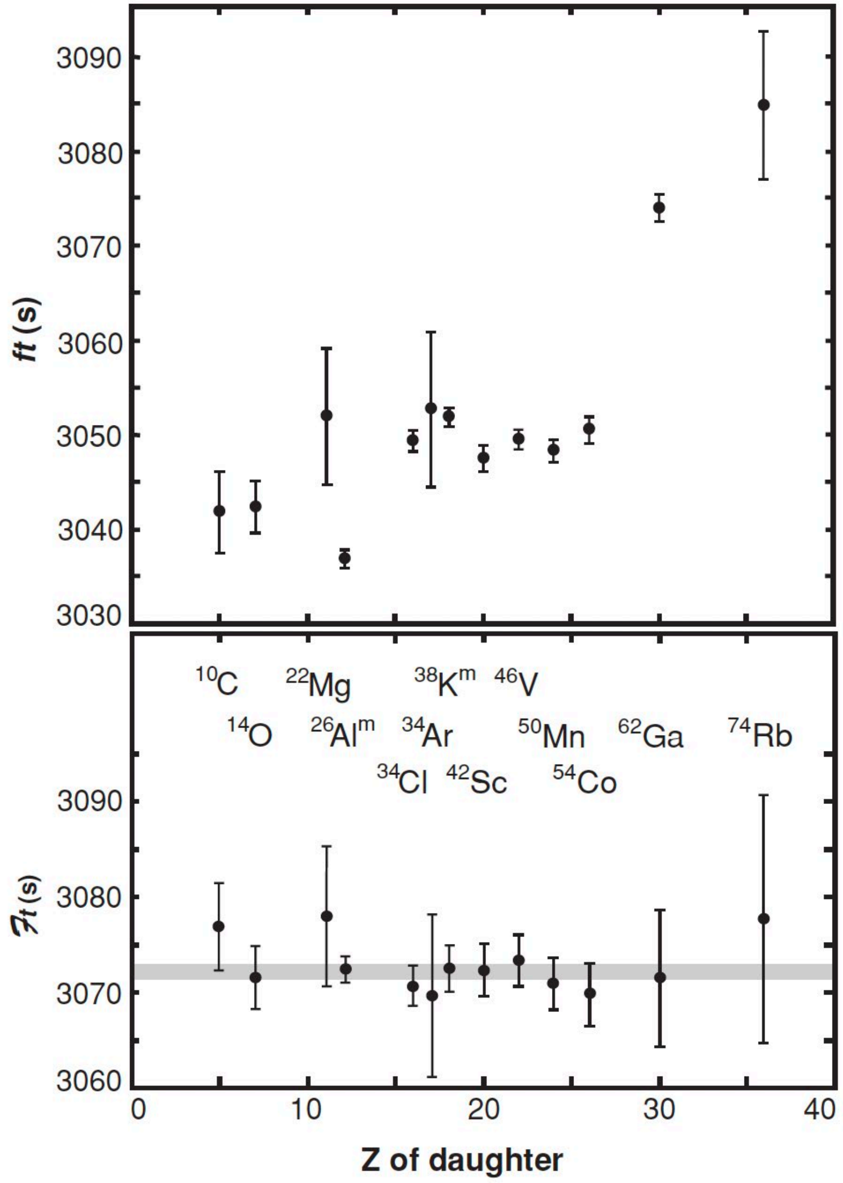
What Q values are applicable to BSM Physics?

- **Tests of CKM Matrix Unitarity**
  - Superallowed β-decays
  - T = $\frac{1}{2}$ Mirror Nuclei Mixed β-decays

- **Neutrino Physics**
  - $0\nu\beta\beta$ and 0νEC
  - Sterile ν searches
  - Direct ν mass measurements
  - Ultra-low Q value decays



CKM Matrix Unitarity: Superallowed β-decay



Superallowed β-decays:

Decays between $T = 1, J^{\pi} = 0^{+}$ nuclear analog states

ft value – statistical rate function x partial half-life

- Half-life, $t_{1/2}$
- Branching ratio, R
- Q value, Q_{EC}

$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{\mathrm{NS}}-\delta_C) = \frac{K}{2G_V^2\left(1+\Delta_R^V\right)}$$

CVC hypothesis: G_V *not renormalized in nuclear medium*

$\therefore$ *all $\mathcal{F}t$ values are the same*

Unitarity of CKM matrix:

$$V_{ud}^2 = \frac{K}{2G_F^2\left(1+\Delta_R^V\right)\overline{\mathcal{F}t}}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

CKM Matrix Unitarity: Superallowed β-decay

- **Circa. 2004 – a possible issue?**

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9966 \pm 0.0014$$

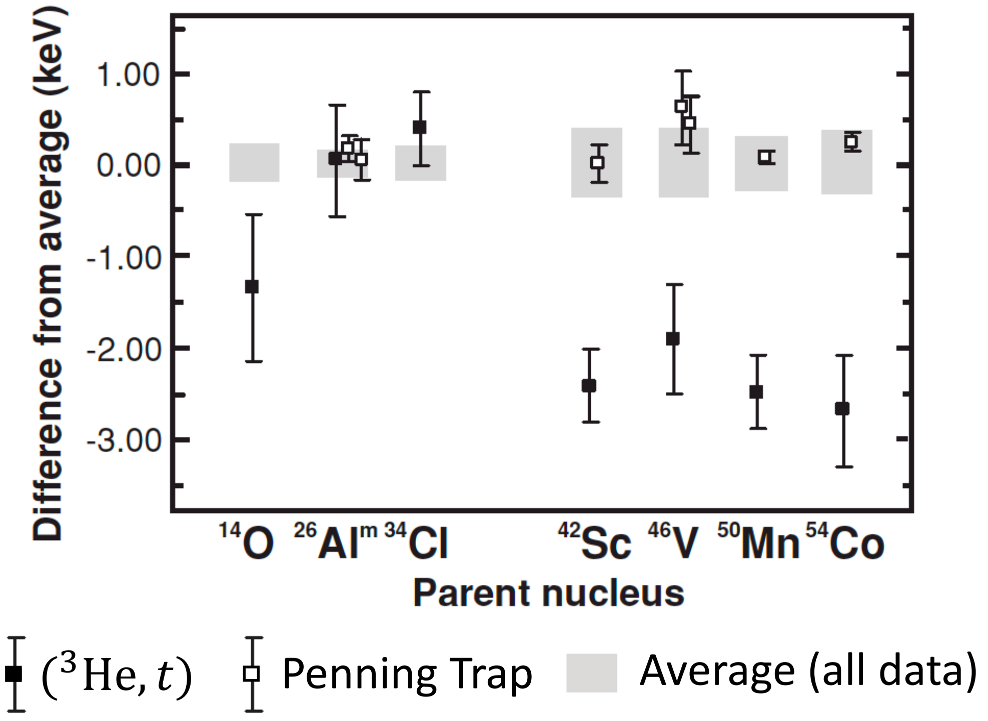
Towner and Hardy, PRC **71**, 055501 (2005)

- Penning trap measurements at rare isotope facilities taken in 2004 – 2008 showed discrepancy with $(^3\mathrm{He}, t)$ data from 1970s

CPT @ Argonne National Lab
Savard, *et al*, PRL **95**, 102501 (2005)

JYFLTRAP @ University of Jyvaskyla
Eronen, *et al*, PRL **97**, 232501 (2006)
Eronen, *et al*, PRL **100**, 132502 (2008)

ISOLTRAP @ ISOLDE, CERN
George, *et al*, E. Phys. Lett. **82**, 50005 (2008)



- Circa. 2009 – all is right with the world

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99995 \pm 0.00061$$

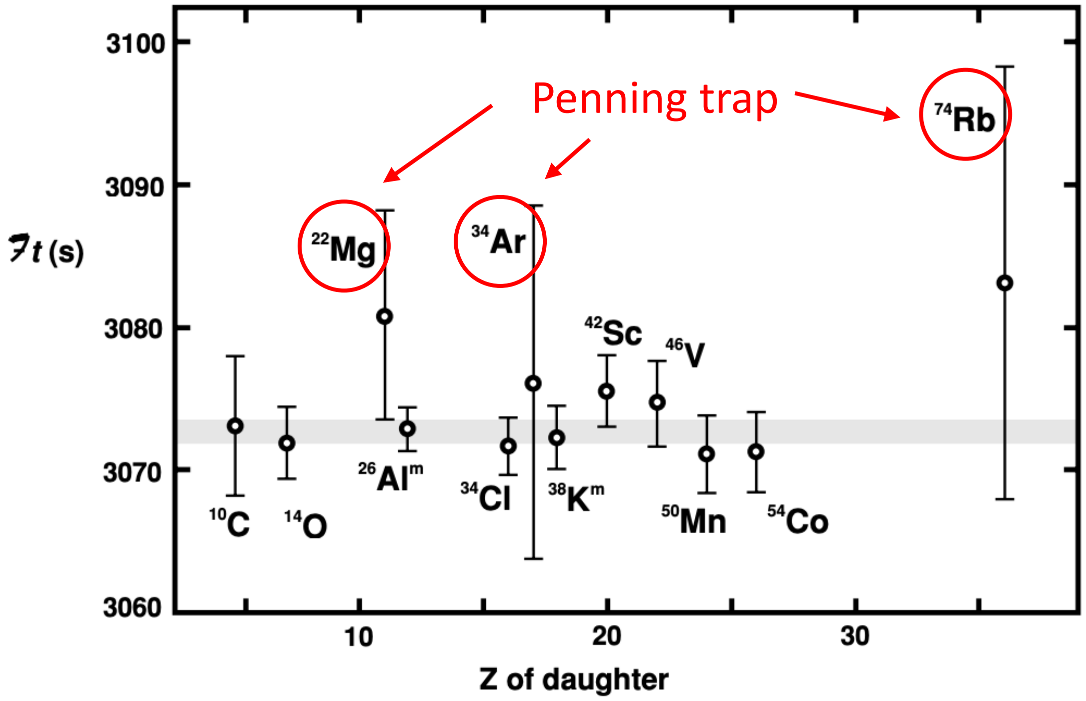
Towner and Hardy, PRC **79**, 055502 (2009)

CKM Matrix Unitarity: Superallowed β-decay

- Online Penning traps have also enabled measurements of Q_{EC} values of superallowed β-decays beyond the "standard nine" to those with unstable daughters.

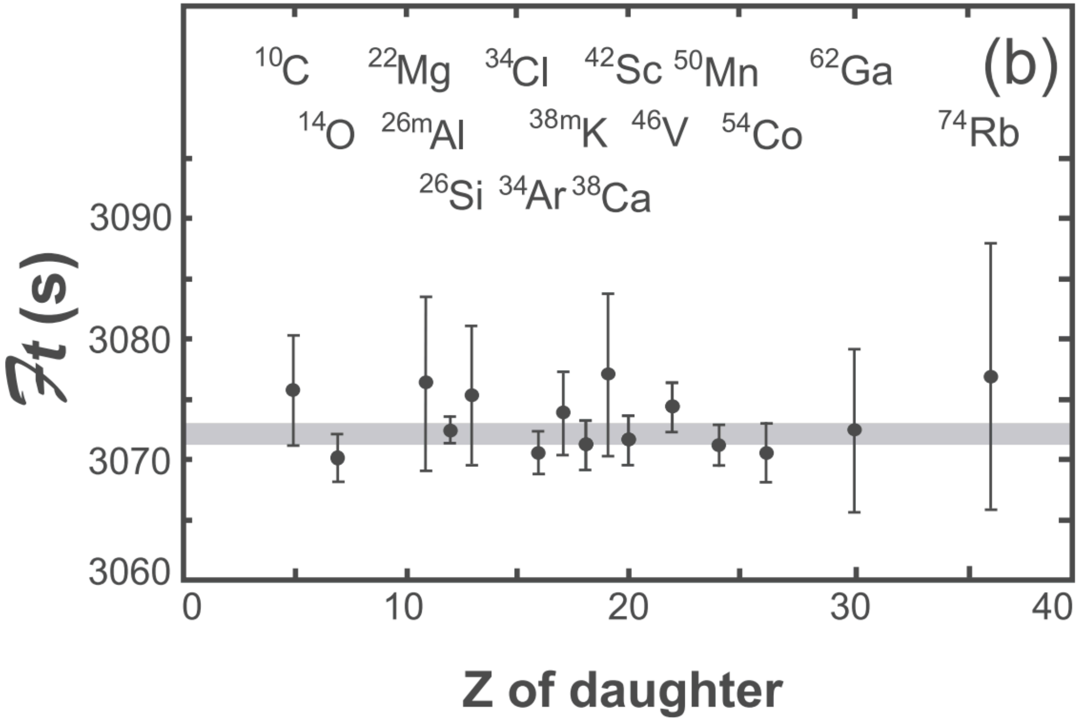
<u>Number of precisely known $\mathcal{F}t$ values that contribute to final average</u>

2005 : 12



Towner and Hardy, PRC **71**, 055501 (2005)

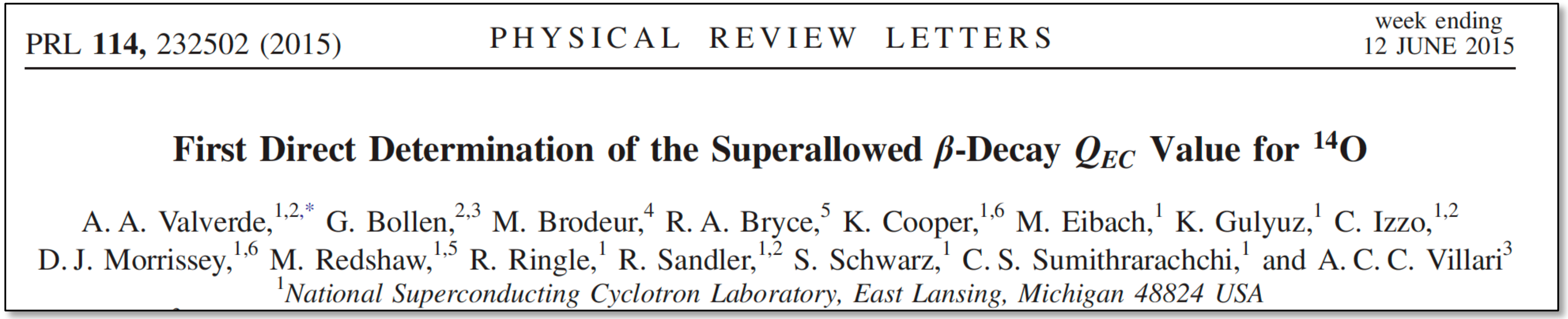
2020 : 15



Towner and Hardy, PRC **102**, 045501 (2020)

CKM Matrix Unitarity: Superallowed β-decay

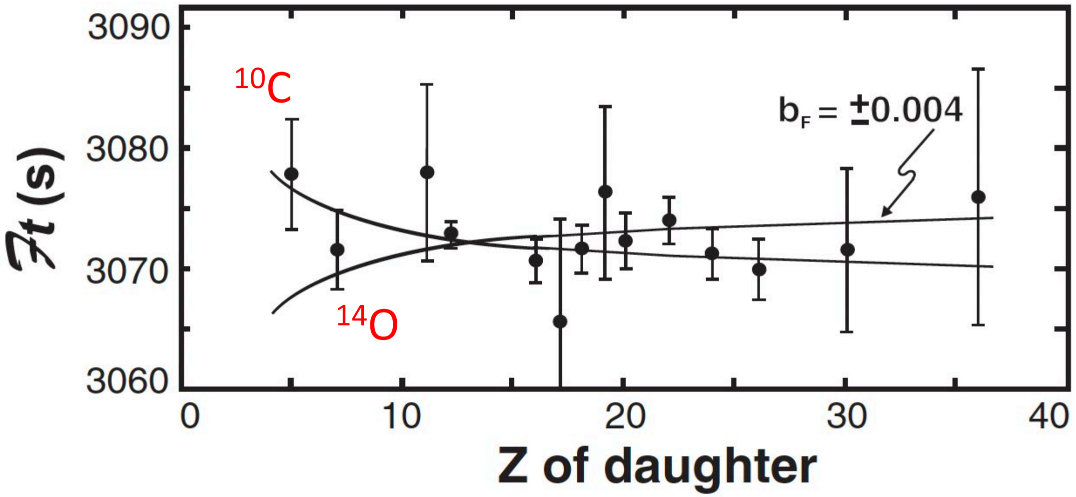
- LEBIT @ NSCL (now FRIB) measured Q_{EC} for ^{14}O, the last of the "traditional nine".
- Improved precision in Q_{EC} and ft by a factor of 10.

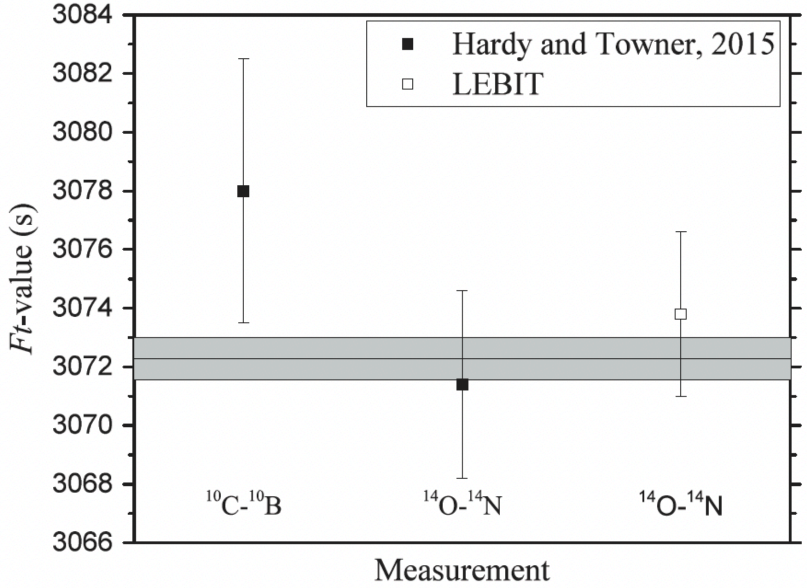

PRL **114,** 232502 (2015) PHYSICAL REVIEW LETTERS week ending 12 JUNE 2015

First Direct Determination of the Superallowed β-Decay Q_{EC} Value for ^{14}O

A. A. Valverde,[1,2,*] G. Bollen,[2,3] M. Brodeur,[4] R. A. Bryce,[5] K. Cooper,[1,6] M. Eibach,[1] K. Gulyuz,[1] C. Izzo,[1,2] D. J. Morrissey,[1,6] M. Redshaw,[1,5] R. Ringle,[1] R. Sandler,[1,2] S. Schwarz,[1] C. S. Sumithrarachchi,[1] and A. C. C. Villari[3]
[1]*National Superconducting Cyclotron Laboratory, East Lansing, Michigan 48824 USA*

- The light superallowed β-decay candidates, ^{10}C and ^{14}O are significant for setting limits on the existence of scalar currents.





CKM Matrix Unitarity: T = ½ Mirror Nuclei Decays

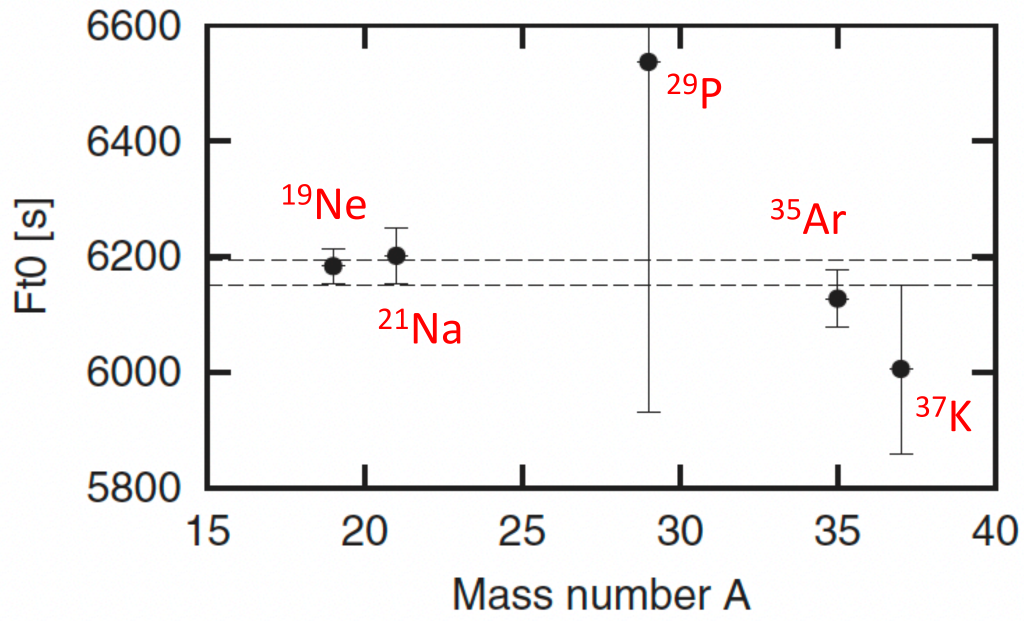
T = ½ mirror nuclei decays:

Decays between $T = \frac{1}{2}, \frac{1}{2}$ integer spin states $\Longrightarrow$ mixed Fermi/Gamow-Teller transitions

$$\mathcal{F}t^{\text{mirror}} \equiv f_V t \left(1 + \delta_R'\right)\left(1 + \delta_{\text{NS}}^V - \delta_C^V\right) = \frac{K}{G_F^2 V_{ud}^2} \frac{1}{\left(1 + \Delta_R^V\right)\left(1 + \frac{f_A}{f_V}\rho^2\right)}$$

$f_V t$ determination still requires $t_{1/2}$, R, and Q_{EC} measurements.

$\mathcal{F}t$ determination also requires Gamow-Teller to Fermi mixing ratio, ρ.



To date, ρ has been measured for only 5 systems: ^{19}Ne, ^{21}Na, ^{29}P, ^{35}Ar, ^{37}K

$$\mathcal{F}t_0^{\text{mirror}} = \mathcal{F}t^{\text{mirror}}\left(1 + \frac{f_A}{f_V}\rho^2\right)$$

Naviliat-Cuncic and Severijns, PRL **102**, 142302 (2009)

CKM Matrix Unitarity: T = ½ Mirror Nuclei Decays

- With LEBIT @ NSCL (now FRIB) measured Q_{EC} for ^{11}C, ^{21}Na, and ^{29}P.

PRL **116,** 012501 (2016) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2016

High Precision Determination of the β Decay Q_{EC} Value of ^{11}C and Implications on the Tests of the Standard Model

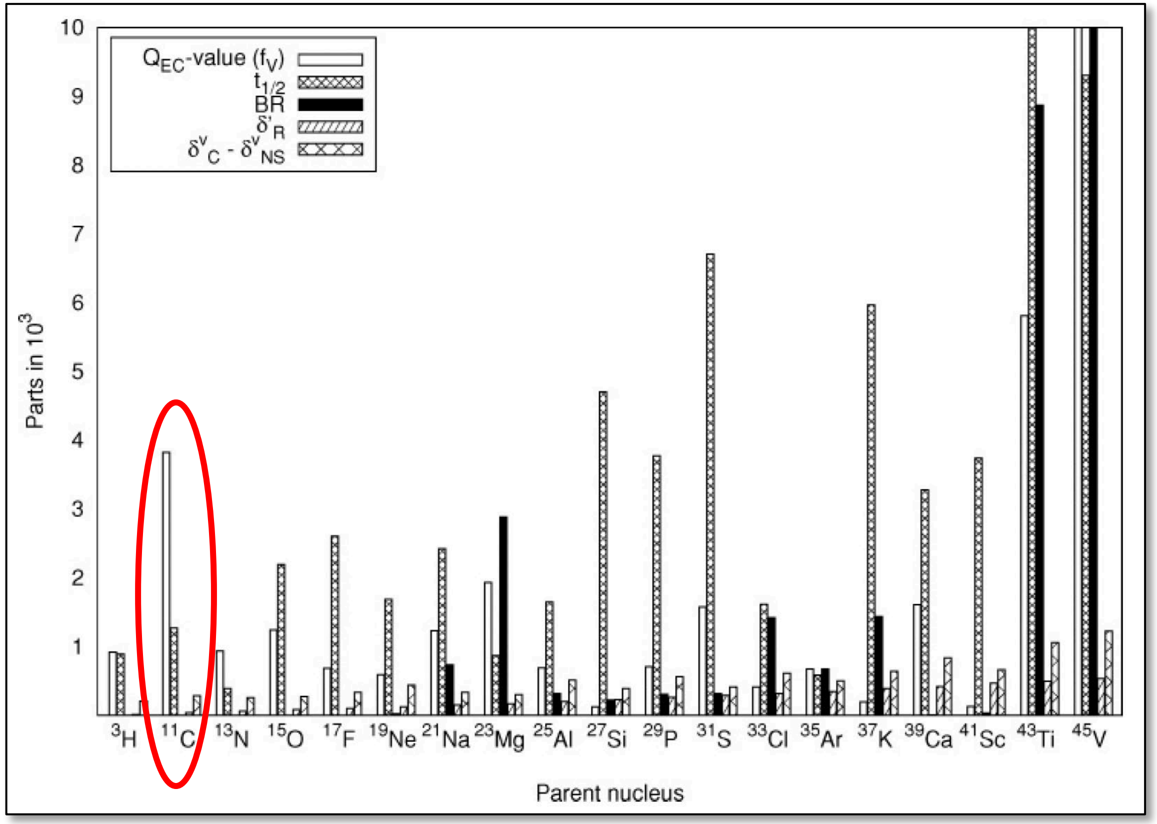
K. Gulyuz,[1,*] G. Bollen,[2,3] M. Brodeur,[4] R. A. Bryce,[5] K. Cooper,[1,6] M. Eibach,[1] C. Izzo,[1,2] E. Kwan,[1] K. Manukyan,[4] D. J. Morrissey,[1,6] O. Naviliat-Cuncic,[1,2] M. Redshaw,[1,5] R. Ringle,[1] R. Sandler,[1,2] S. Schwarz,[1] C. S. Sumithrarachchi,[1] A. A. Valverde,[1,2] and A. C. C. Villari[3]

PHYSICAL REVIEW C **92**, 045502 (2015)

Determination of the Q_{EC} values of the $T = 1/2$ mirror nuclei ^{21}Na and ^{29}P at LEBIT

M. Eibach,[1,*] G. Bollen,[2,3] M. Brodeur,[4] K. Cooper,[1,5] K. Gulyuz,[1] C. Izzo,[1,2] D. J. Morrissey,[1,5] M. Redshaw,[1,6] R. Ringle,[1] R. Sandler,[1,2] S. Schwarz,[1] C. S. Sumithrarachchi,[1] A. A. Valverde,[1,2] and A. C. C. Villari[3]

Contribution to uncertainty in $\mathcal{F}t$



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PHYSICAL REVIEW C **92**, 045502 (2015)

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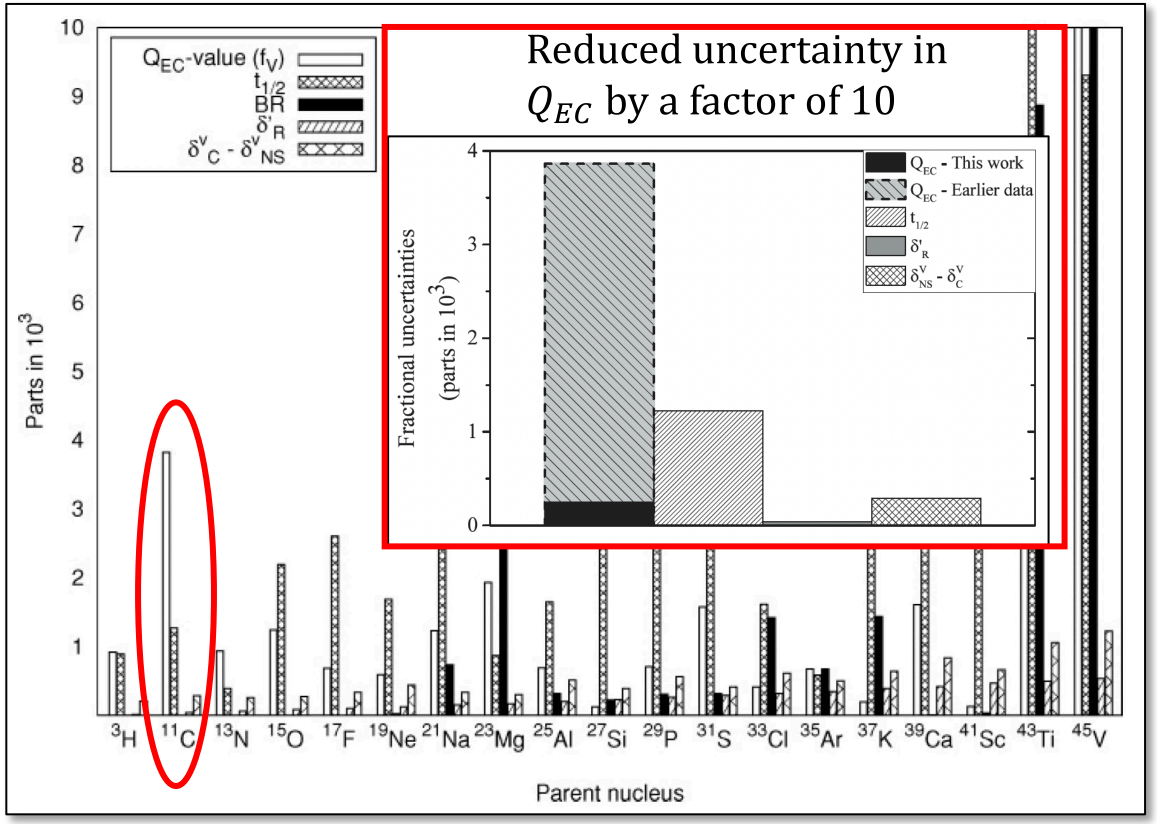

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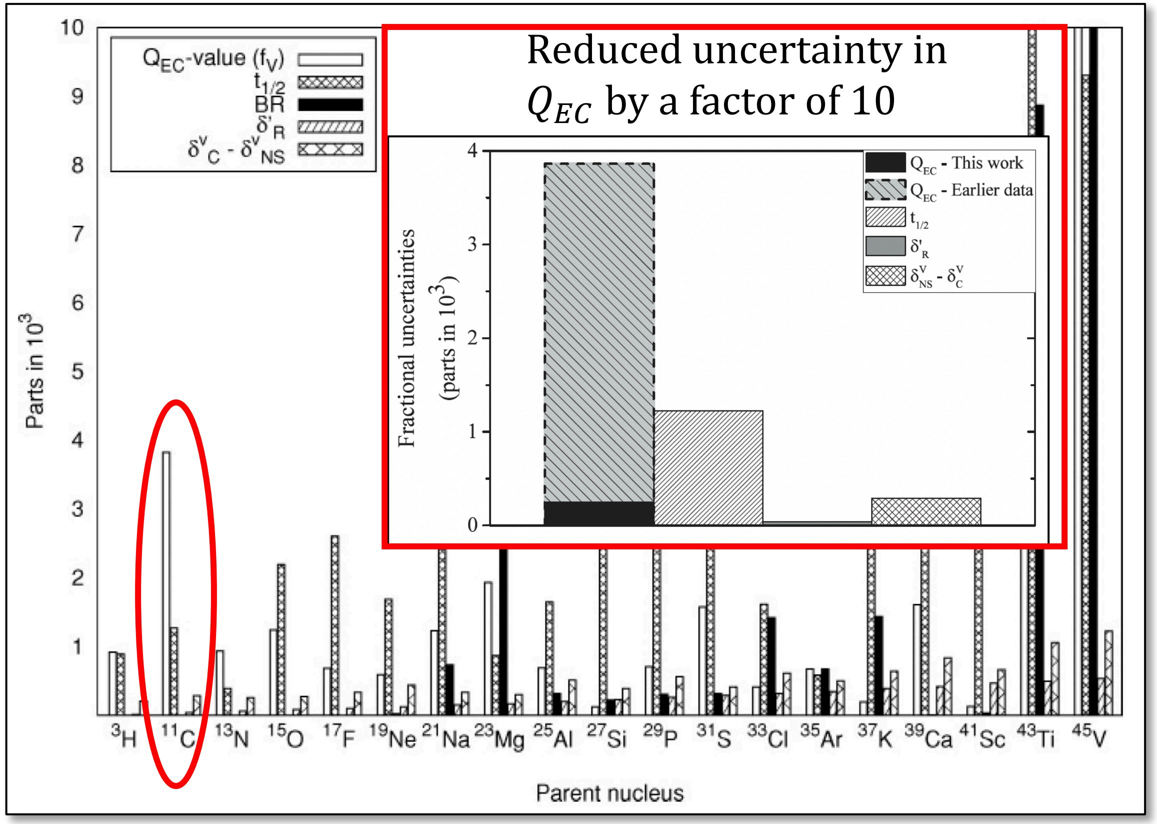
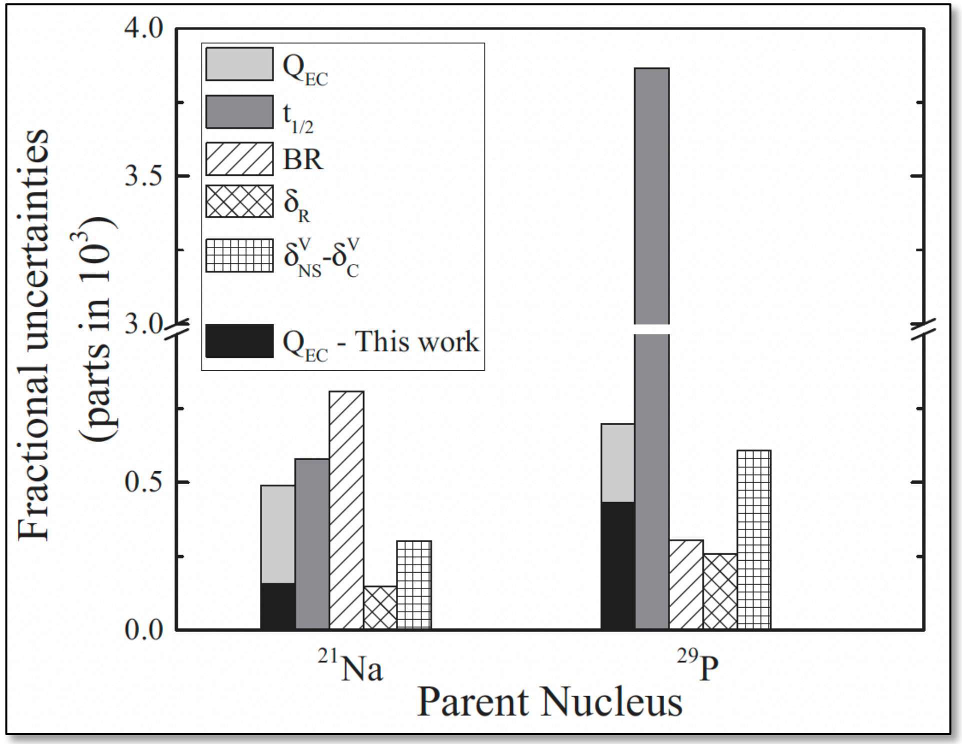
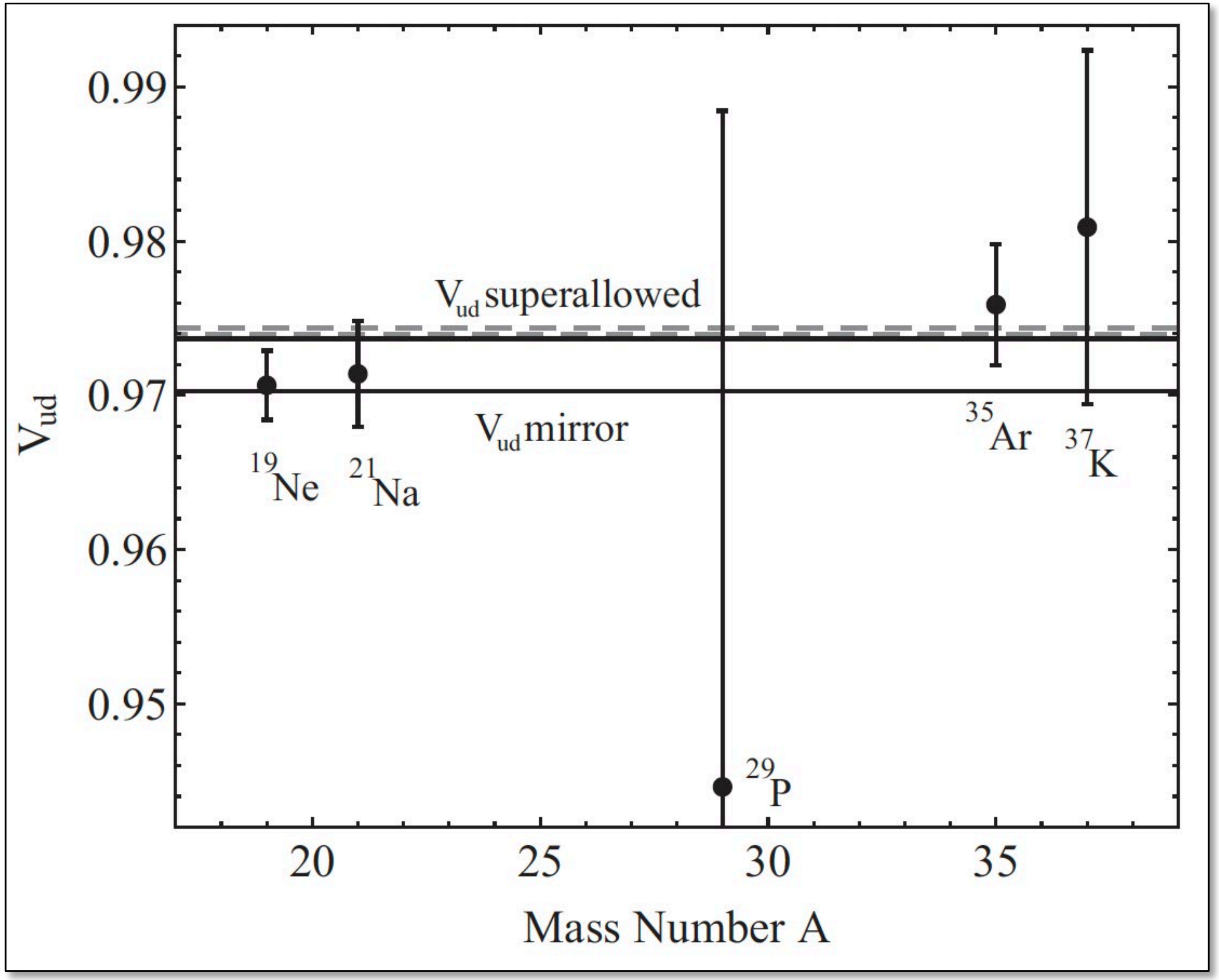




First measurements of Q_{EC} values for mirror nuclei used to determine V_{ud} with a Penning trap

CKM Matrix Unitarity



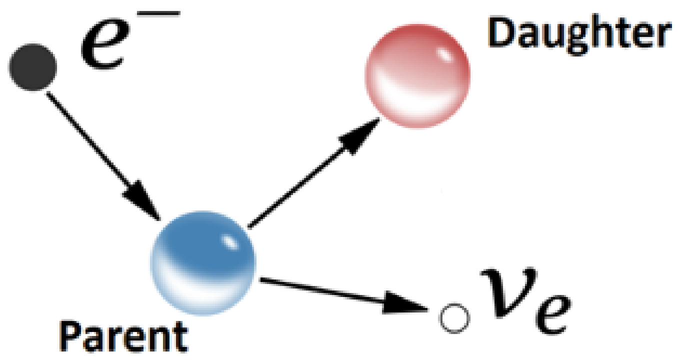
Penning traps have played an important role in contributing to the robust data set for superallowed decays.

They will continue to be important in providing Q_{EC} values for mirror decays when new Gamow-Teller to Fermi ratio (ρ) measurements become available. e.g. Q_{EC} value measurements for ^{13}N, ^{15}O, ^{17}F with CPT @ Argonne National Lab.

What Q values are applicable to BSM Physics?

- <u>Tests of CKM Matrix Unitarity</u>
  - Superallowed β-decays
  - T = $\frac{1}{2}$ Mirror Nuclei Mixed β-decays

- <u>Neutrino Physics</u>
  - $0\nu\beta\beta$ and $0\nu EC$
  - Sterile ν searches
  - Direct ν mass measurements
  - Ultra-low Q value decays



Neutrino Physics: $0\nu\beta\beta$-decay

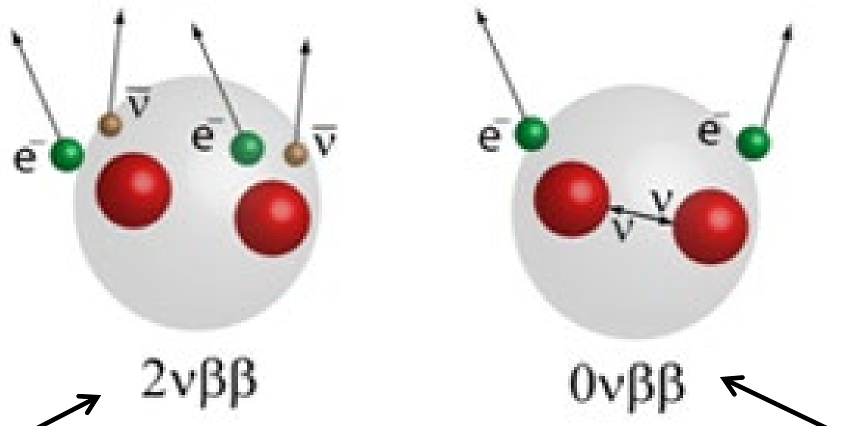
2νββ-decay

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}Y + 2e^{-} + 2\bar{\nu}_{e}$$

0νββ-decay

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}Y + 2e^{-}$$

$$Q_{\beta\beta} = \left[M({}^{A}_{Z}X) - M({}^{A}_{Z+2}Y)\right]c^{2}$$

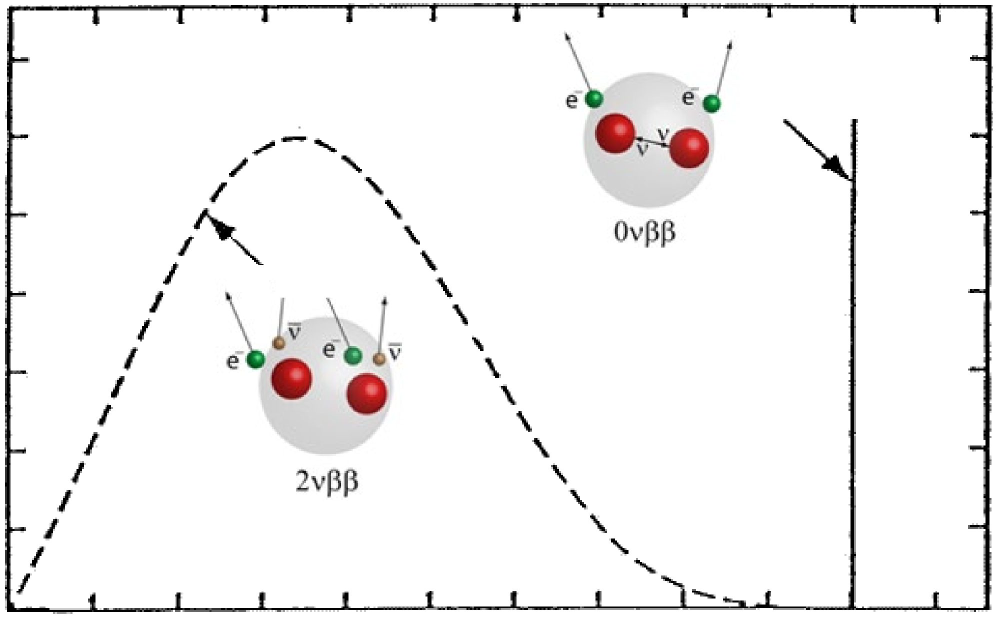


Allowed by Standard Model

<u>New Physics</u>:
- Neutrino is a Majorana particle
- Lepton number is not conserved
- Determine effective Majorana neutrino mass

$Q_{\beta\beta}$ corresponds to location of 0νββ signal

<u>Double-beta-decay total electron energy spectrum</u>



$Q_{\beta\beta}$ is required for phase space factor calculation

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^{2}\langle m_{\beta\beta}\rangle^{2}$$

$$G_{0\nu} \sim Q^{5}_{\beta\beta}$$

Signature of $0\nu\beta\beta$ in ^{76}Ge

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PHYSICS LETTERS B

Physics Letters B 586 (2004) 198–212

www.elsevier.com/locate/physletb

Search for neutrinoless double beta decay with enriched ^{76}Ge in Gran Sasso 1990–2003

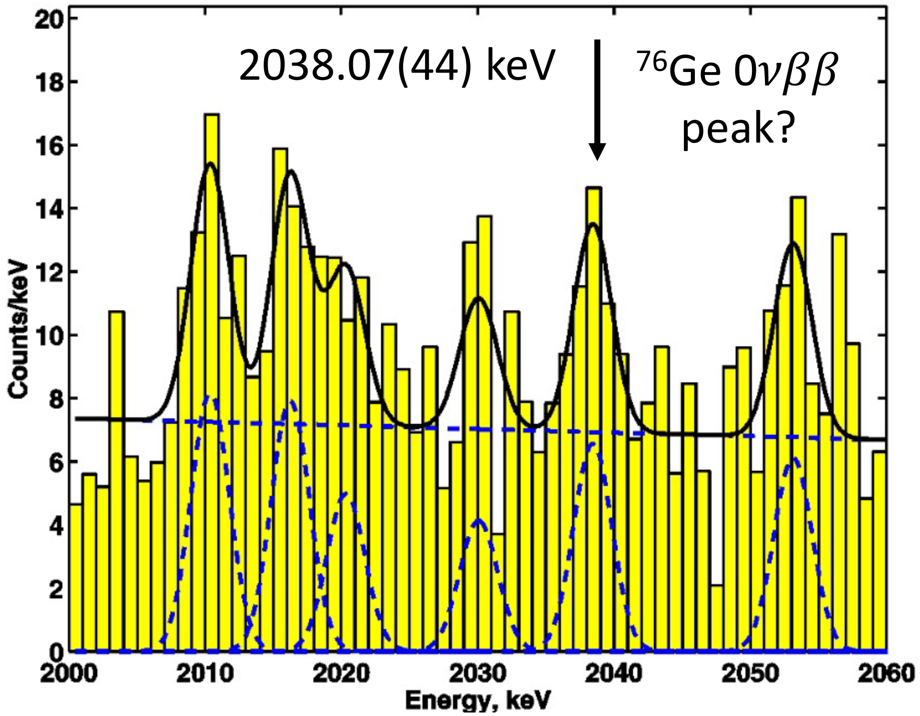
H.V. Klapdor-Kleingrothaus [*,1], I.V. Krivosheina [2], A. Dietz, O. Chkvorets

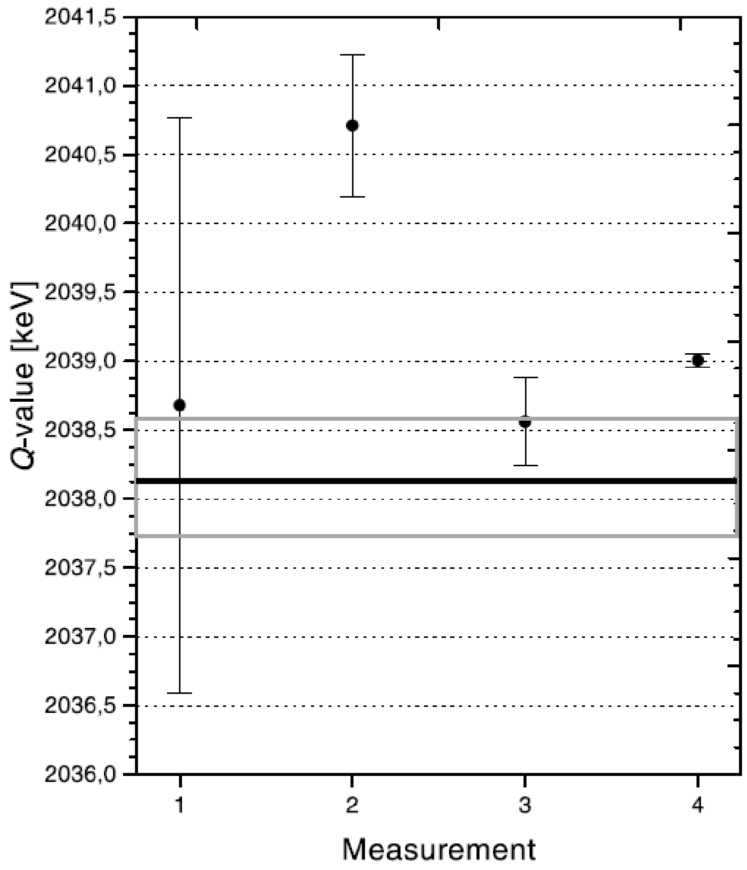
VOLUME 86, NUMBER 19 PHYSICAL REVIEW LETTERS 7 MAY 2001

Determination of the ^{76}Ge Double Beta Decay Q Value

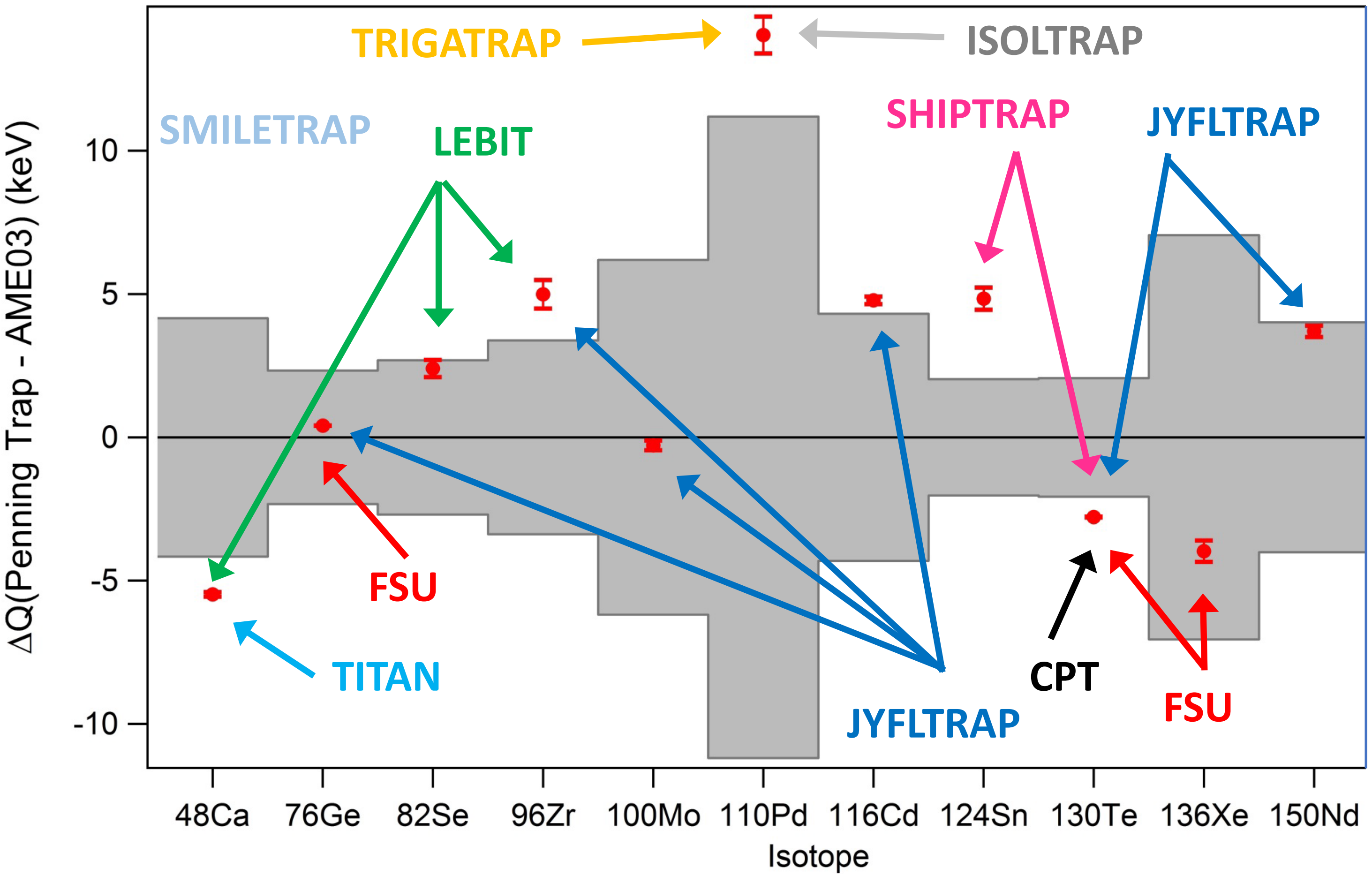
Guilhem Douysset, Tomas Fritioff, and Conny Carlberg
Atomic Physics, Stockholm University, Frescativägen 24, S-10405 Stockholm, Sweden

Ingmar Bergström and Mikael Björkhage
Manne Siegbahn Laboratory, Frescativägen 24, S-10405 Stockholm, Sweden





Q values for $0\nu\beta\beta$



$Q_{\beta\beta}$ values for all 11 most prominent $\beta\beta$-decay candidates now measured with a Penning trap.

All to a precision of < 1 keV

$0\nu 2EC$ candidates

2ν2EC

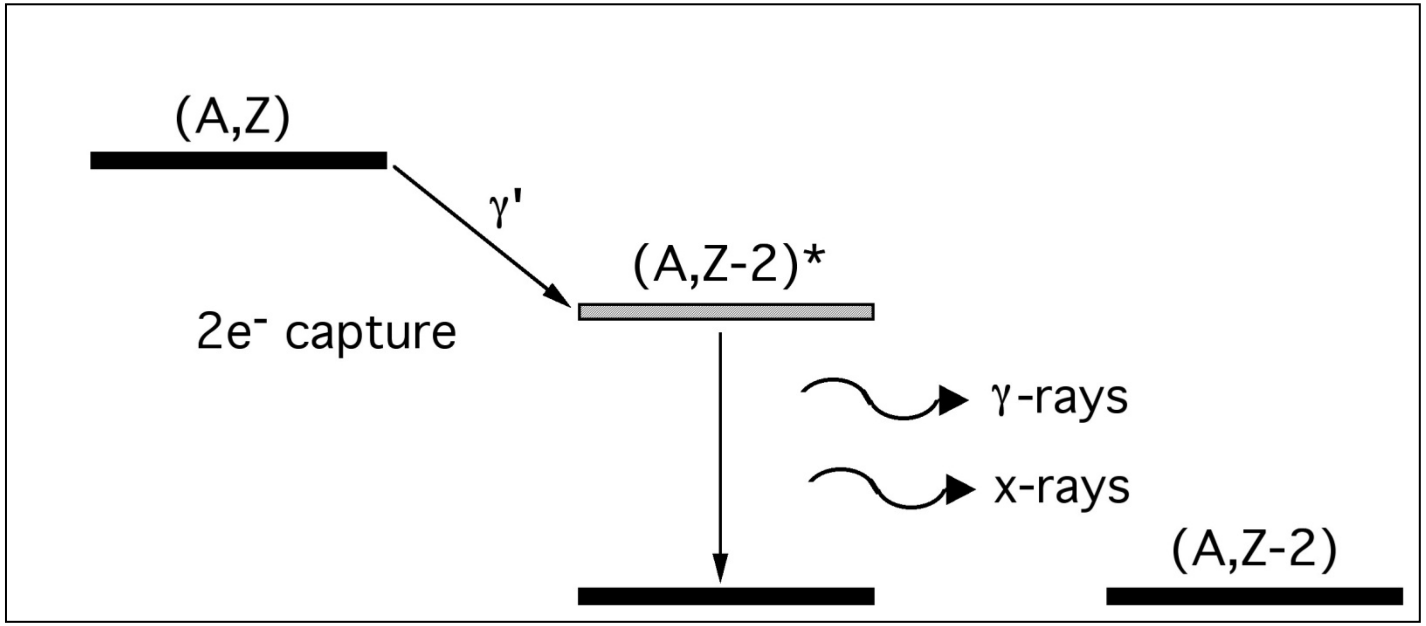
$$ {}^{A}_{Z}X + 2e^{-} \rightarrow {}_{Z-2}^{\ \ A}Y^{*} + 2\nu_e $$

0ν2EC

$$ {}^{A}_{Z}X + 2e^{-} \rightarrow {}_{Z-2}^{\ \ A}Y^{*} $$

$$ \mathrm{Q}_{2EC} = \left[M\left({}^{A}_{Z}X\right) - M\left({}_{Z-2}^{\ \ A}Y\right)\right]c^2 $$

$$ \Delta(E_{\gamma'}) = \mathrm{Q}_{2EC} - E_n - E_a $$



A resonant enhancement of the 0ν2EC rate can occur if $Q_{\beta\beta} \approx E_n + E_a$

Need Q_{2EC} to < 1 keV

0ν2EC candidates

NSCL/MSU

- 34 naturally occurring isotopes that are 2EC-decay candidates
- Many have a possibility of a resonant enhancement
- Most of these had not been measured with a Penning trap as of 2010

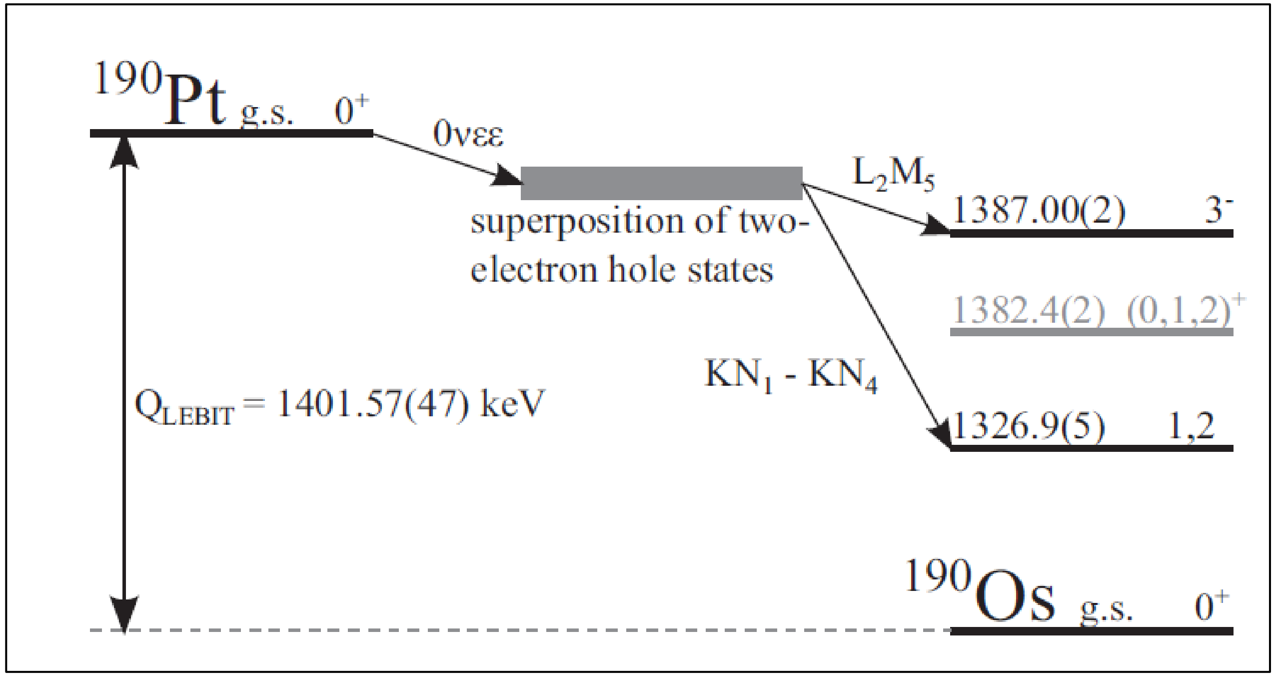
Isotope	Q-value (keV)	E^* (keV)	$Q - E^*$ (keV)		Isotope	Q-value (keV)	E^* (keV)	$Q - E^*$ (keV)
^{36}Ar	432.58(0.19)	0.00	432.6		^{126}Xe	919.76(3.89)	666.4	253.4
^{40}Ca	193.51(0.02)	0.00	193.5		^{130}Ba	2618.73(2.58)	2608.4	10.3
^{50}Cr	1168.97(0.95)	0.00	1169.0		^{132}Ba	843.97(1.06)	667.7	176.3
^{54}Fe	679.83(0.75)	0.00	679.8		^{136}Ce	2378.55(0.47)	2373.7	4.9
^{58}Ni	1926.31(0.69)	1674.7	251.6		^{138}Ce	693.12(9.89)	0.0	693.1
^{64}Zn	1094.69(0.86)	0.0	1094.7		^{144}Sm	1782.41(2.66)	1780.0	2.4
^{74}Se	1209.24(0.02)	1204.2	5.0		^{152}Gd	55.68(2.31)	0.0	55.7
^{78}Kr	2846.33(0.73)	2838.5	7.8		^{156}Dy	2005.95(2.30)	2003.7	2.3
^{84}Sr	1789.78(1.24)	881.6	908.2		^{158}Dy	282.73(3.29)	261.5	21.2
^{92}Mo	1651.80(1.99)	1495.5	156.3		^{162}Er	1846.96(2.68)	1845.5	1.5
^{96}Ru	2714.50(0.64)	2700.2	14.3		^{164}Er	25.07(2.67)	0.0	25.1
^{102}Pd	1171.90(2.85)	1106.4	65.5		^{168}Yb	1409.27(2.89)	1403.7	5.6
^{106}Cd	2775.39(1.56)	2748.0	27.2		^{174}Hf	1098.89(3.33)	889.9	209.0
^{108}Cd	271.81(1.58)	0.0	271.8		^{180}W	143.23(2.68)	93.3	49.9
^{112}Sn	1919.82(0.80)	1871.0	48.8		^{184}Os	1450.91(1.60)	1446.3	4.6
^{120}Te	1730.41(3.24)	1171.3	559.1		^{190}Pt	1384.21(6.05)	1382.4	1.8
^{124}Xe	2864.25(2.35)	2853.2	11.1		^{196}Hg	820.15(3.09)	688.7	131.5

$0\nu 2EC$ candidates

^{190}Pt

Q = 1401.57(47) keV

M. Eibach, PRC **94**, 015502 (2016).



Enhancement Factors of ~10^5 – 10^{10} possible

Improved ^{190}Pt Q-value and ^{190}Os final state energies are desirable

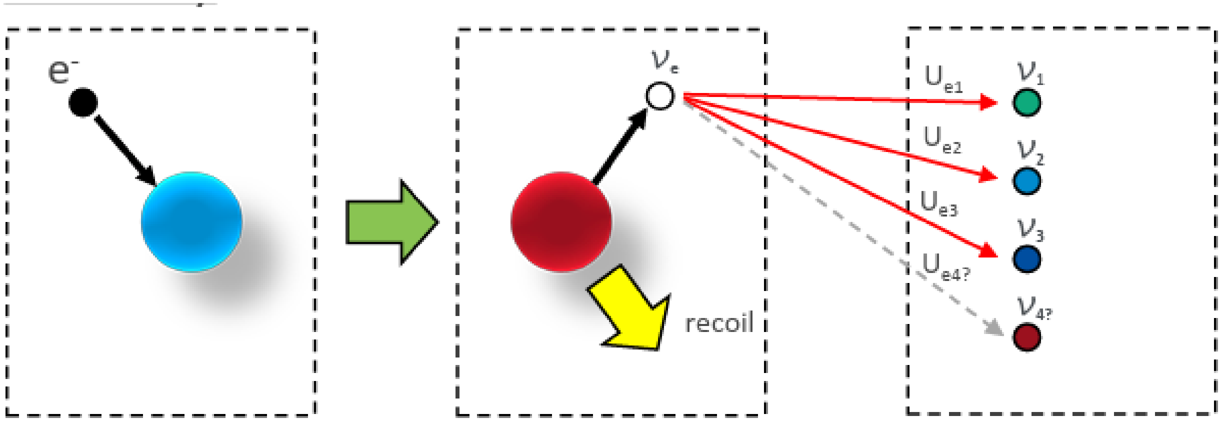
Isotopes with potential resonant enhancements:

^{152}Gd (0.20 %), ^{164}Er (1.61 %), ^{180}W(0.12 %), ^{190}Pt(0.014 %)

Eliseev, *et al*, Ann. Phys. **525**, 707 (2013)

EC Q value of ^{7}Be to aid BSM Physics Searches

BeEST: **Be**ryllium **E**lectron capture in **S**uperconducting **T**unnel junctions

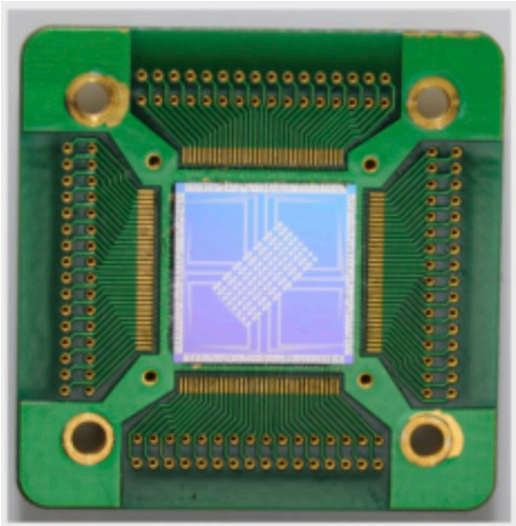


Recoil Energy

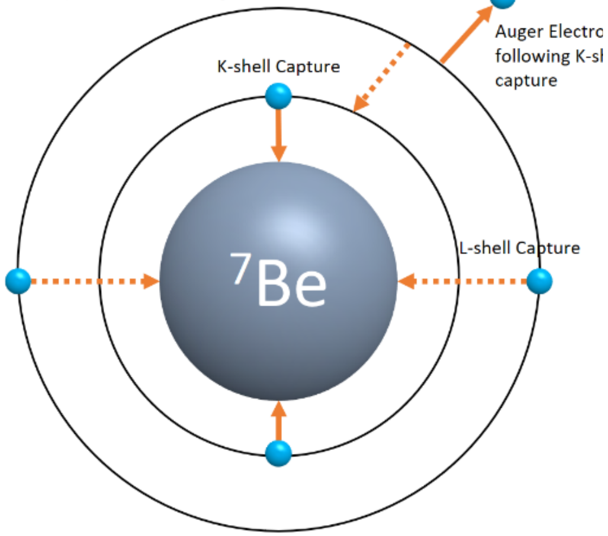
$$T_d = \frac{Q_{EC}^2 - m_\nu^2 c^4}{2\left(Q_{EC} + m_d c^2\right)}$$

$$T_d = 56.826(9)\ \mathrm{eV}$$

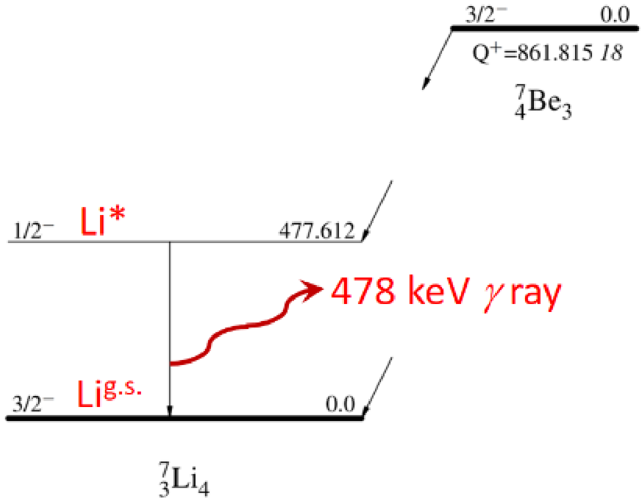
Limited by $\sigma_{M(^7Be)} = 70\ \mathrm{eV}$

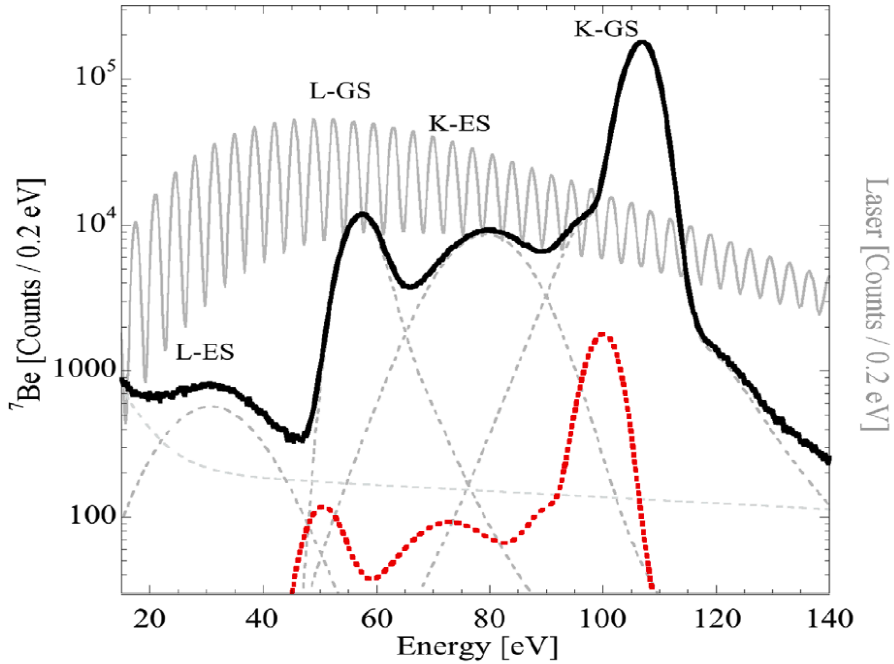


a) Atomic Capture Processes



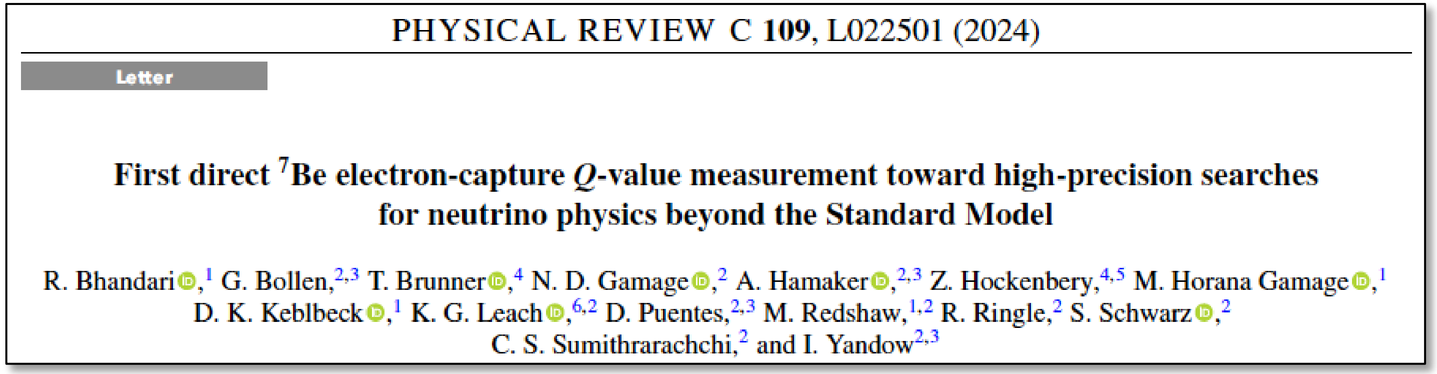
b) Nuclear Decay Process





EC Q value of ^{7}Be to aid BSM Physics Searches

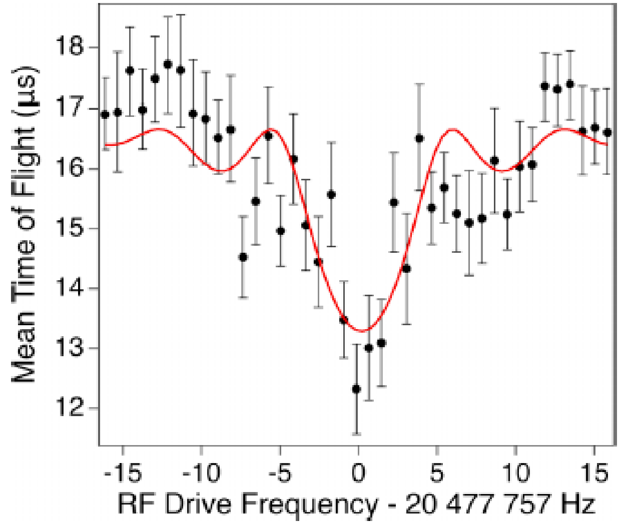
Q-value measured at LEBIT with $^{7}Be^{+}$ beam from BMIS

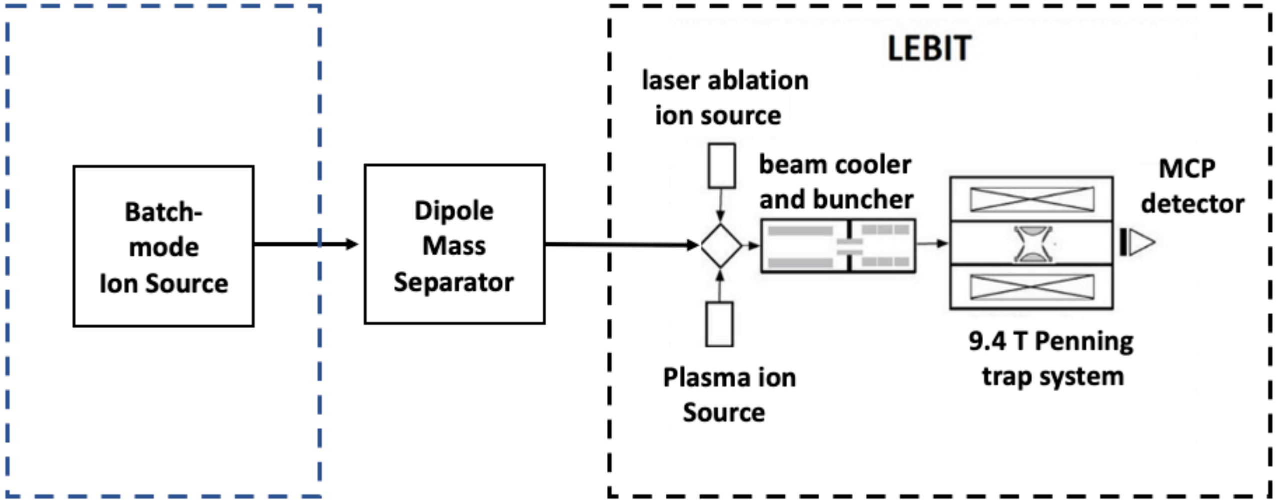

PHYSICAL REVIEW C **109**, L022501 (2024)

Letter

First direct ^{7}Be electron-capture *Q*-value measurement toward high-precision searches for neutrino physics beyond the Standard Model

R. Bhandari,[1] G. Bollen,[2,3] T. Brunner,[4] N. D. Gamage,[2] A. Hamaker,[2,3] Z. Hockenbery,[4,5] M. Horana Gamage,[1] D. K. Keblbeck,[1] K. G. Leach,[6,2] D. Puentes,[2,3] M. Redshaw,[1,2] R. Ringle,[2] S. Schwarz,[2] C. S. Sumithrarachchi,[2] and I. Yandow[2,3]





	Q_{EC} (keV)	T_d (eV)
LEBIT	861.964(23)	56.836(3)
AME	861.893(71)	56.826(9)
Diff	71(77)	10(10)

- Reduced uncertainty of ^{7}Be Q_{EC} value and ^{7}Li recoil energy by factor of 3
- Uncertainty in recoil energy similar to that of BeEST Phase I
- Future improvements could be needed.

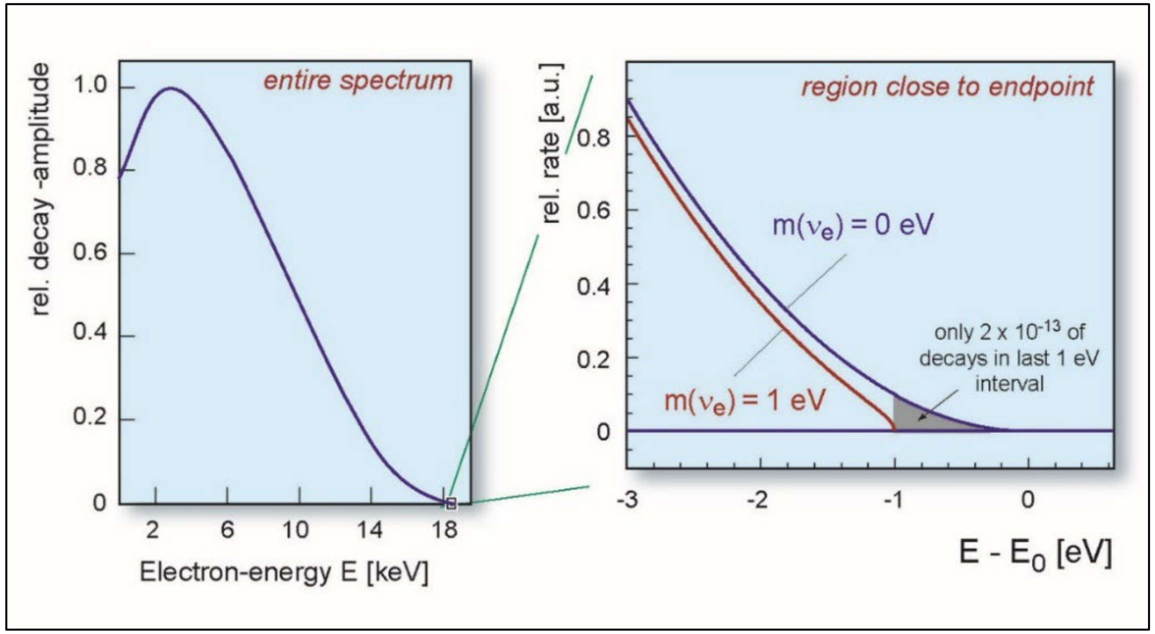
Direct neutrino mass measurements

Study the shape of β-decay energy spectrum

$$\frac{dN}{dE} = \underbrace{\left[G_F^2 \frac{m_e^5}{2\pi^3}\cos^2\theta_C\right]}_{\text{Constant}} \underbrace{|M|}_{\text{Nuclear Matrix Element}} \underbrace{F(Z,E)}_{\text{Fermi Function}} \underbrace{\sqrt{pE(E_0-E)^2 - m_\nu^2}}_{\text{Phase space factor}}$$

e.g. tritium β-decay (KATRIN)

$$\boxed{{}^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e}$$



An independent measurement of the end-point energy ($E_0 \approx$ Q) provides a check of systematics in the experiment

^{163}Ho Q value

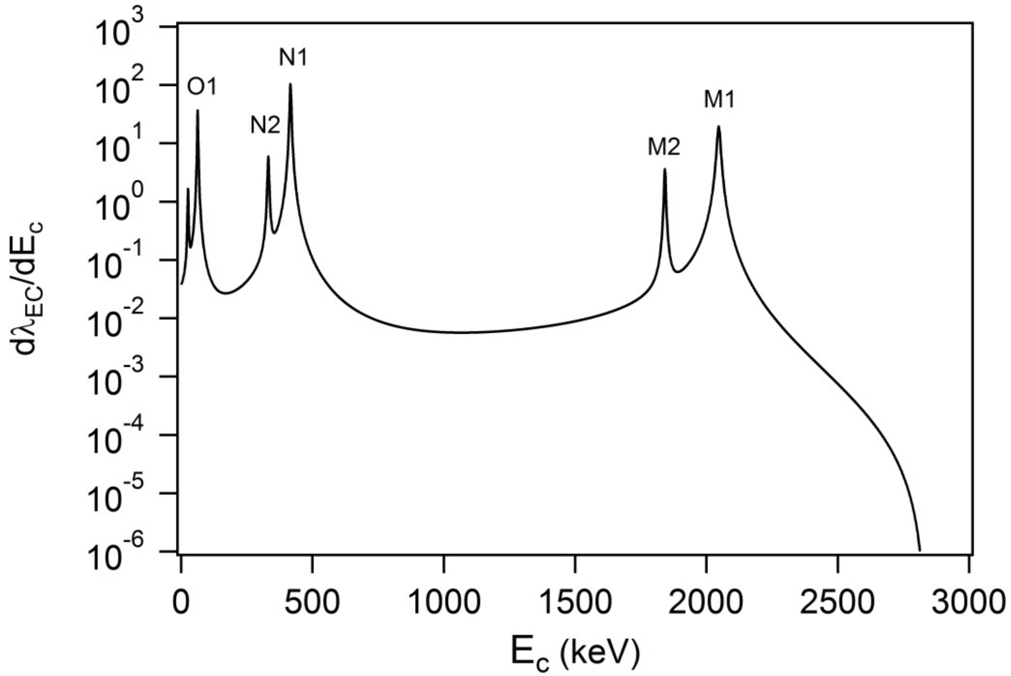
^{163}Ho – ^{163}Dy
Electron Capture

$$^{163}_{67}\mathrm{Ho} + e^- \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$
$$\hookrightarrow {}^{163}_{66}\mathrm{Dy} + E_c$$

$$\boxed{Q = 2.8632(6)\ \mathrm{keV}}$$

C. Schweiger, *et al,* Nature Phys. **20**, 921 (2024)

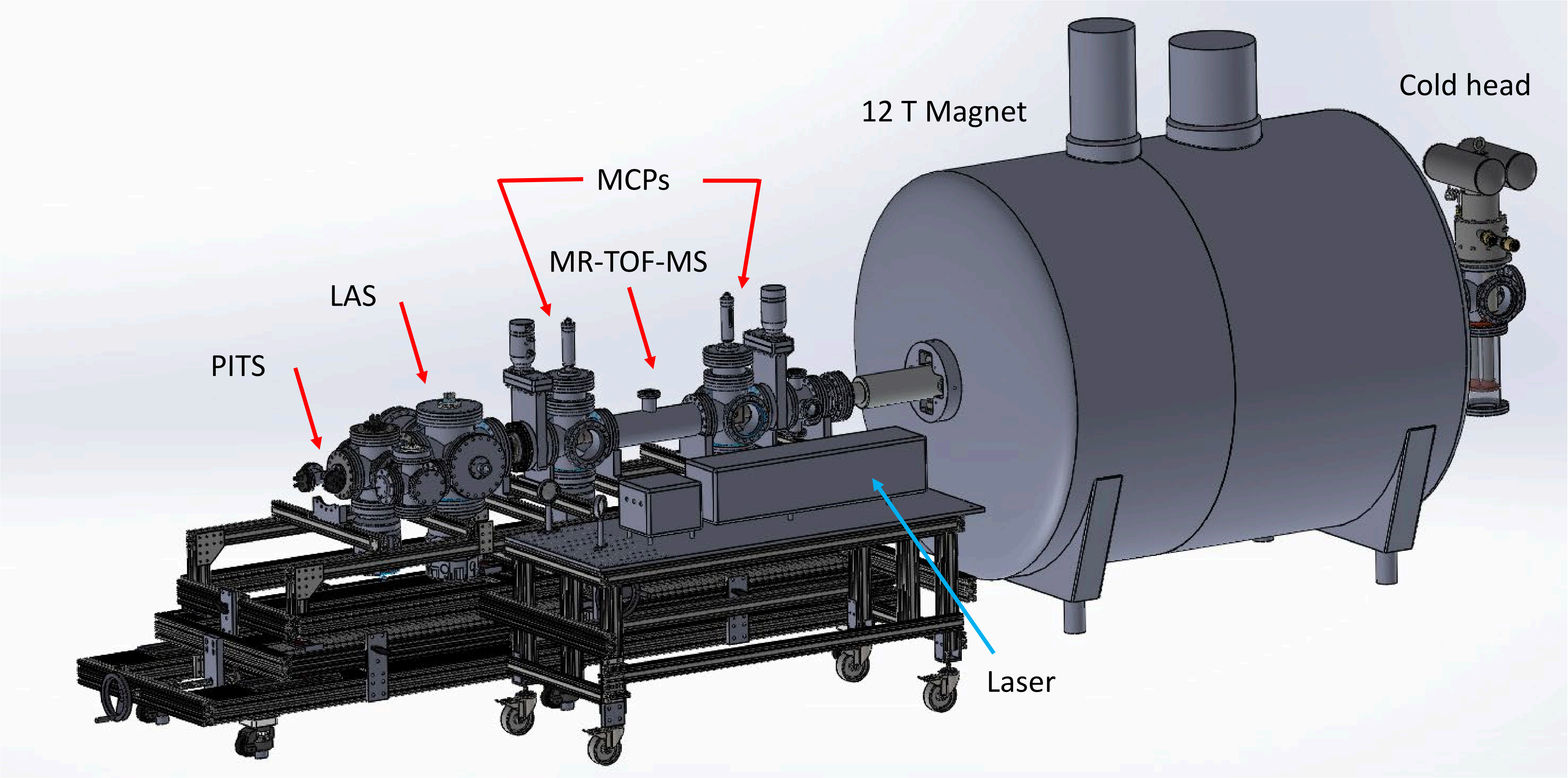
^{163}Ho de-excitation energy spectrum



Energy spectrum measurements using cryogenic microcalorimeters
Europe: ECHo, HOLMES

- Sub-eV sensitivity to m_ν expected
- ~1 eV energy resolution
- **Q-value needed to ~1 eV**

CHIP-TRAP : ^{163}Ho Q value

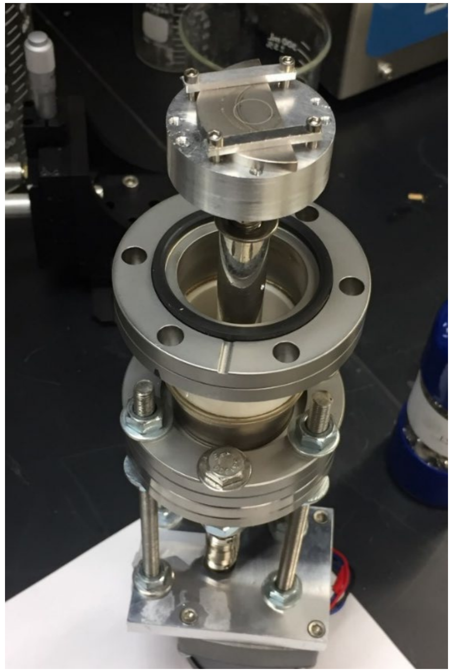


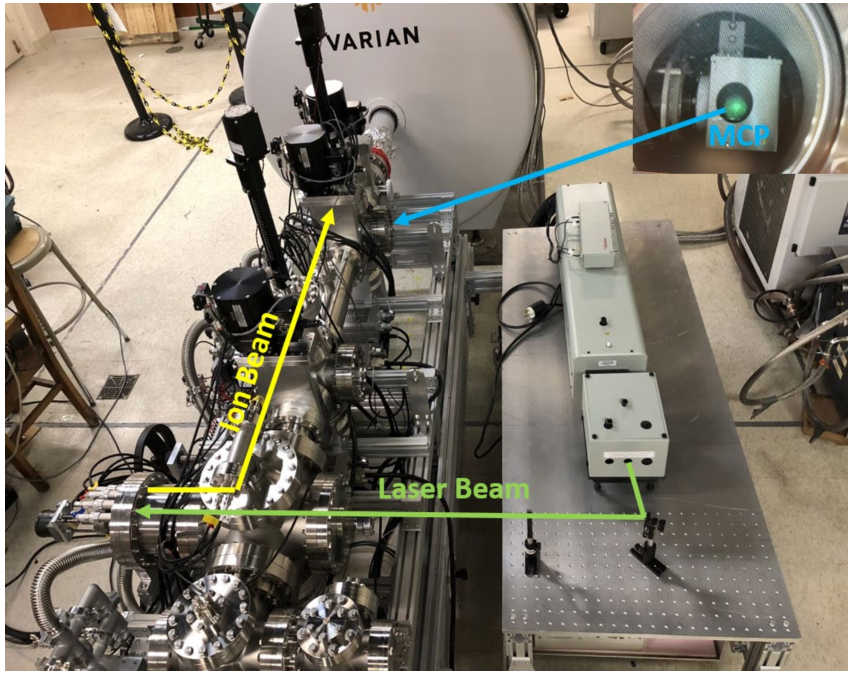
CHIP-TRAP : ^{163}Ho Q value

Investigation of Ho ion production with a laser ablation ion source

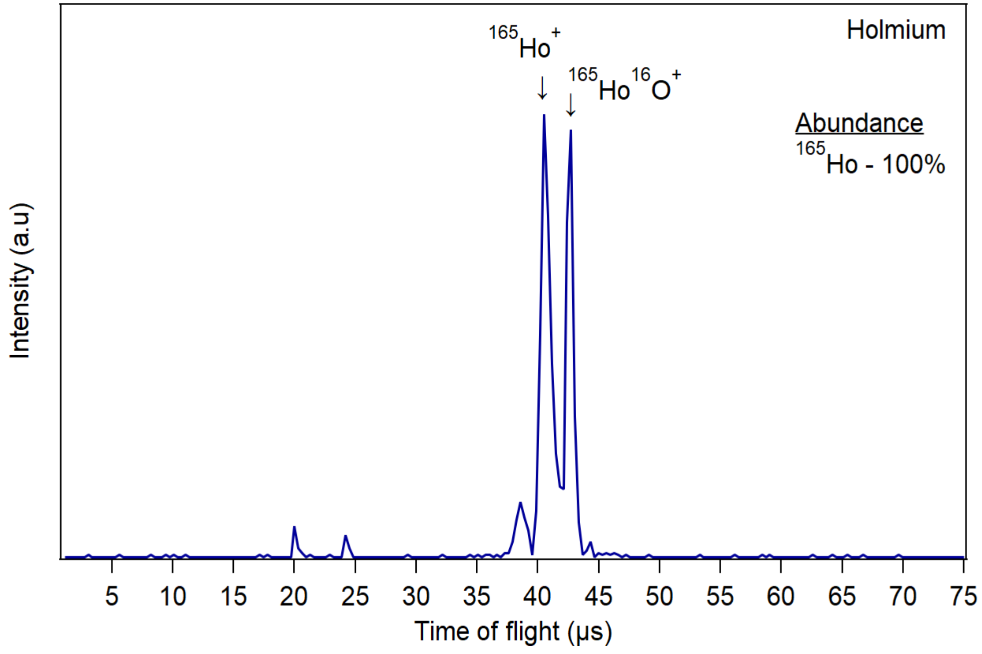
R. Bhandari[1], M. Horana Gamage[1], N. D. Gamage[1], M. Redshaw[1,2]

[1]Department of Physics, Central Michigan University, Mt. Pleasant, MI-48859,





^{165}Ho$^+$ ions from $HoNO_3$ solution



Observed ion signal with ~10^{17} Ho atoms on the LAS foil

Low Q value β-decay for ν mass measurements

Low Q value β-decays

$$ {}^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + e^{-} + \bar{\nu}_e $$

Q = 18.592 01(7) keV

$$ {}^{187}_{75}\mathrm{Re} \rightarrow {}^{187}_{76}\mathrm{Os} + e^{-} + \bar{\nu}_e $$

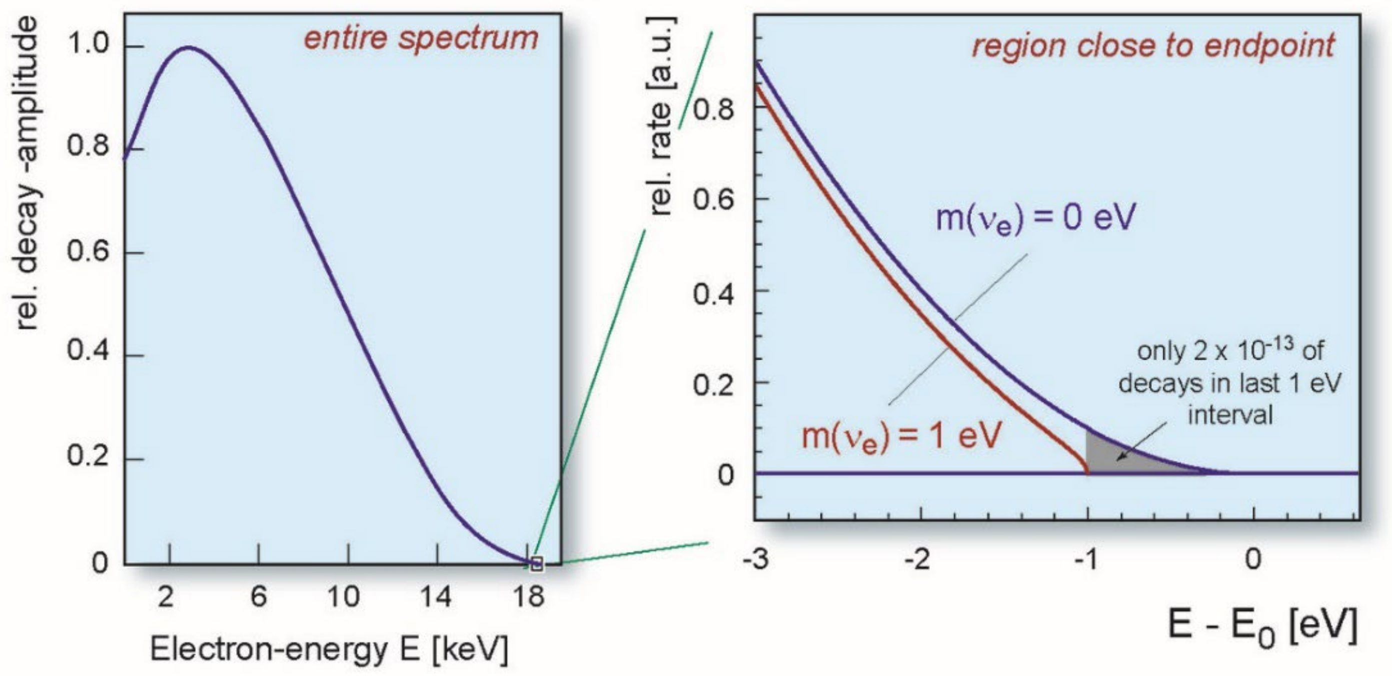
Q = 2.492(34) keV

$$ {}^{163}_{67}\mathrm{Ho} + e^{-} \rightarrow {}^{163}_{66}\mathrm{Dy} + \nu_e $$

Q = 2.863 2(6) keV

g.s. to g.s decays

Direct neutrino mass measurements



Number of counts in energy interval ΔE near end-point goes as $(\Delta E/Q)^3$

Ultra-low Q value β-decays

Low Q value β-decays

$$^{3}_{1}\mathrm{H} \rightarrow ^{3}_{2}\mathrm{He} + e^{-} + \bar{\nu}_e$$

Q = 18.592 01(7) keV

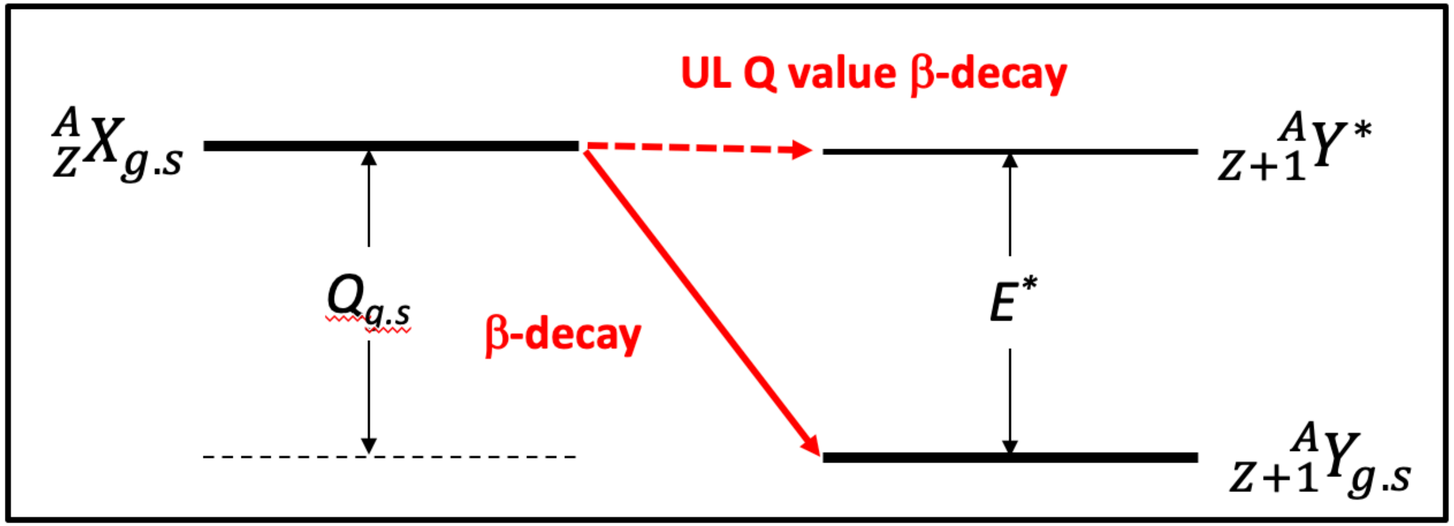
$$^{187}_{75}\mathrm{Re} \rightarrow ^{187}_{76}\mathrm{Os} + e^{-} + \bar{\nu}_e$$

Q = 2.492(34) keV

$$^{163}_{67}\mathrm{Ho} + e^{-} \rightarrow ^{163}_{66}\mathrm{Dy} + \nu_e$$

Q = 2.863 2(6) keV

g.s. to g.s decays

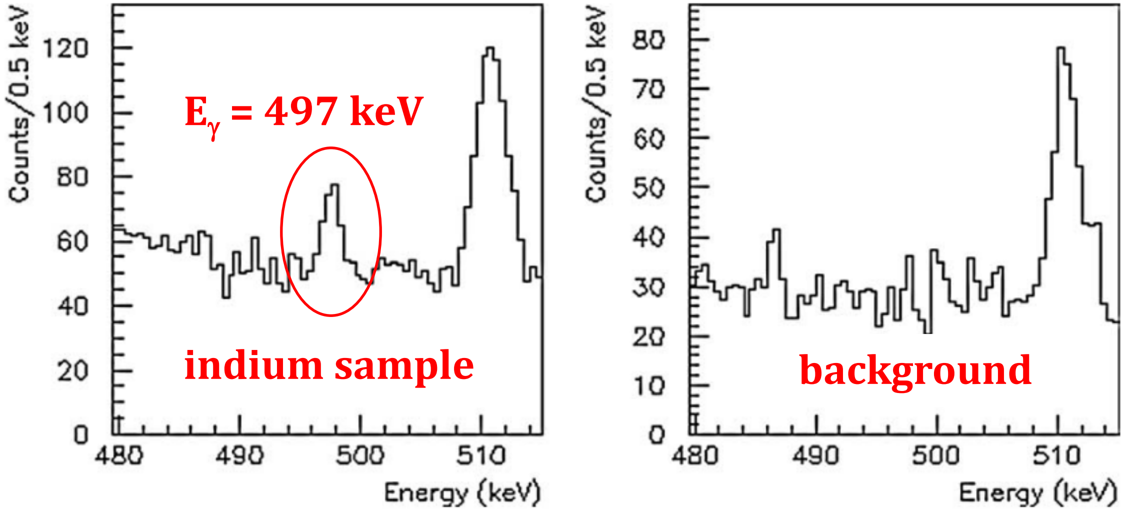


$$Q_{e.s} = Q_{g.s} - E^{*} < 1\ \mathrm{keV}$$

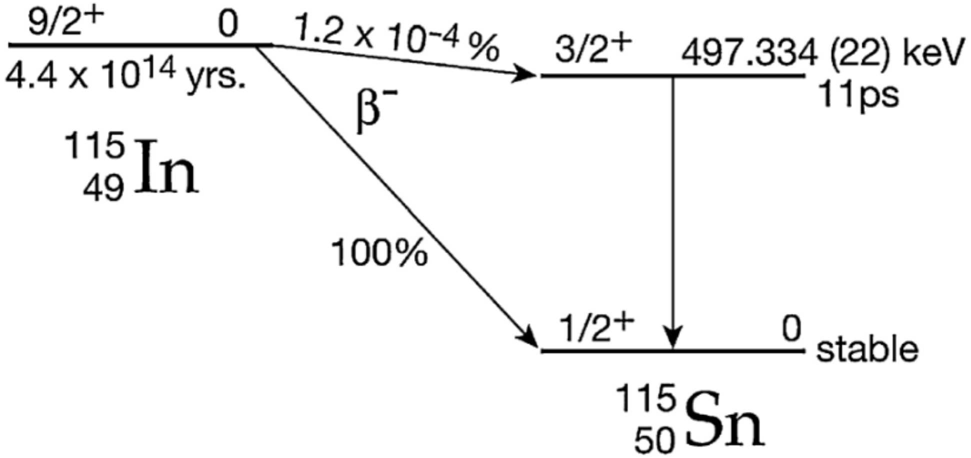
Need $Q_{g.s}$ and E^{*} to << 1 keV

Do any ultra-low Q value β-decays exist?

Observation of a 497 keV γ-ray from In sample



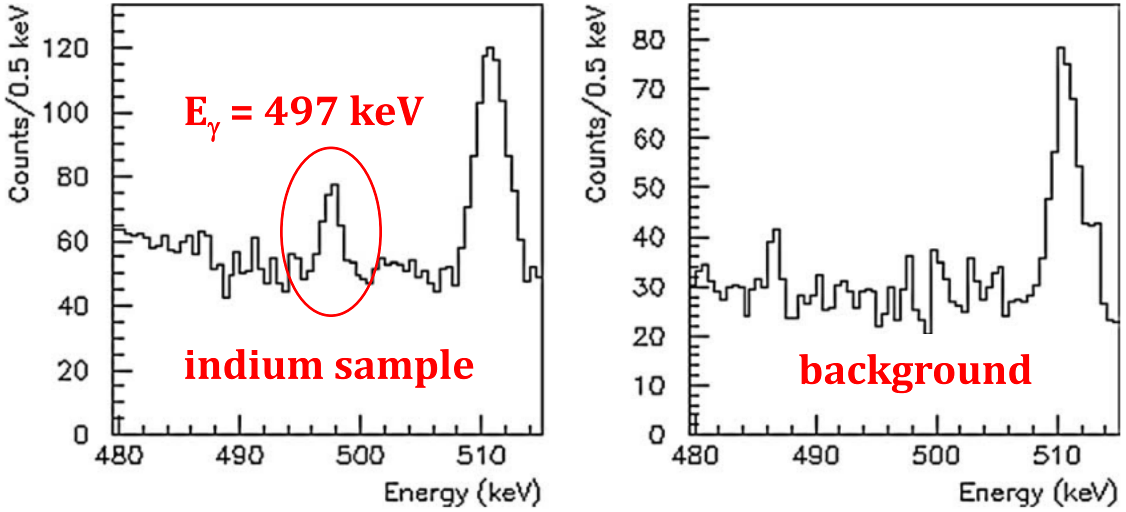
From a weak decay branch to ^{115}Sn(3/2$^+$)



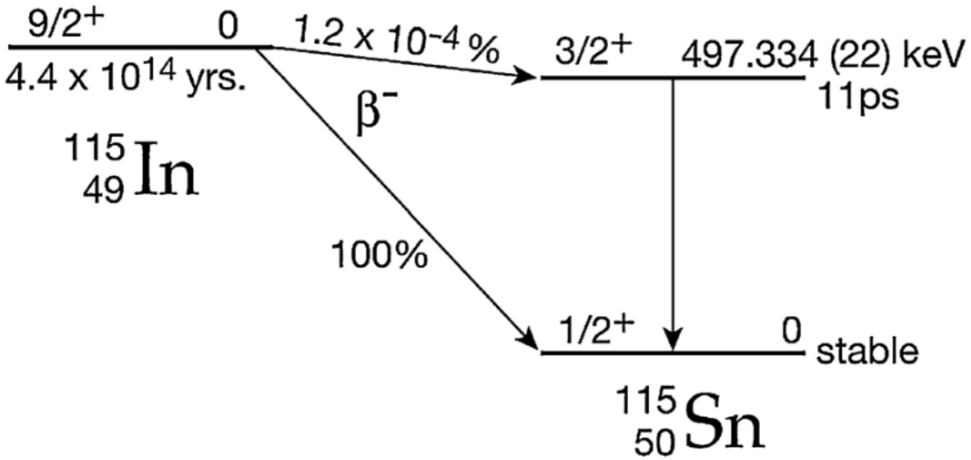
Cattadori, *et al*, Nuc. Phys. A **748**, 333 (2005)

Do any ultra-low Q value β-decays exist?

Observation of a 497 keV γ-ray from In sample



From a weak decay branch to ^{115}Sn(3/2$^+$)



Cattadori, *et al*, Nuc. Phys. A **748**, 333 (2005)

2003 Atomic Mass Evaluation

$$Q_{ES} = M(^{115}\mathrm{In}) - M(^{115}\mathrm{Sn}) - E^* = 2(4)\ \mathrm{keV}$$

PRL **103,** 122502 (2009) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2009

Q Value of ^{115}In → ^{115}Sn(3/2$^+$): The Lowest Known Energy β Decay

Brianna J. Mount, Matthew Redshaw, and Edmund G. Myers
Department of Physics, Florida State University, Tallahassee, Florida 32306-4350, USA

(Received 17 April 2009; published 16 September 2009)

$$\boxed{Q_{ES} = 155(24)\mathrm{eV}}$$

PRL **103,** 122501 (2009) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2009

Smallest Known Q Value of Any Nuclear Decay: The Rare β^- Decay of ^{115}In(9/2$^+$) → ^{115}Sn(3/2$^+$)

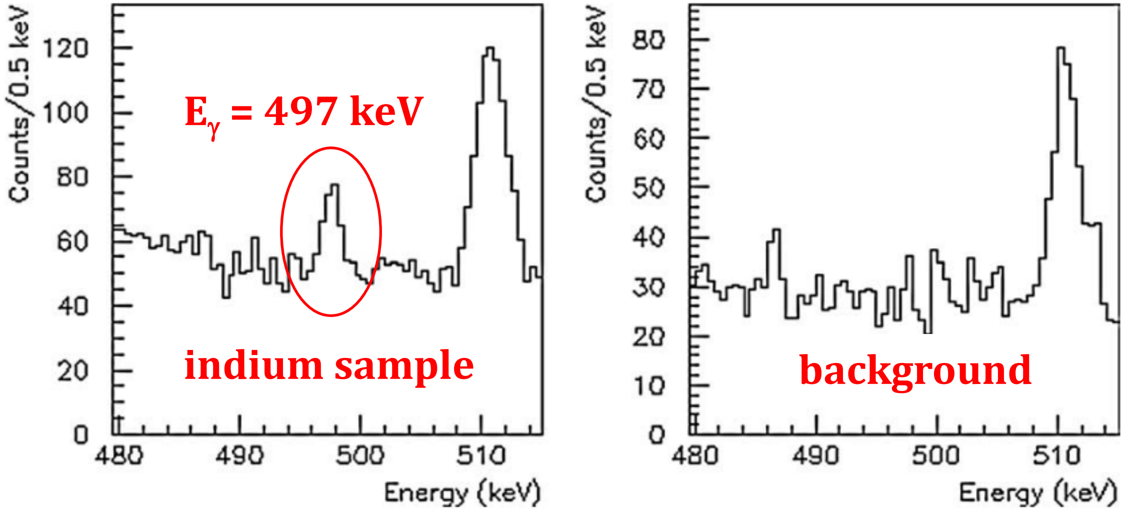
J. S. E. Wieslander,[1,2] J. Suhonen,[2] T. Eronen,[2] M. Hult,[1,‡] V.-V. Elomaa,[2] A. Jokinen,[2] G. Marissens,[1] M. Misiaszek,[3] M. T. Mustonen,[2] S. Rahaman,[2,*] C. Weber,[2,†] and J. Äystö[2]
[1]*EC-JRC-IRMM, Institute for Reference Materials and Measurements, Retieseweg 111, B-2440 Geel, Belgium*
[2]*Department of Physics, P.O. Box 35 (YFL), FIN-40014 University of Jyväskylä, Finland*
[3]*Marian Smoluchowski Institute of Physics, Jagiellonian University, ul. Reymonta 4, 30-059 Krakow, Poland*

(Received 18 March 2009; published 16 September 2009)

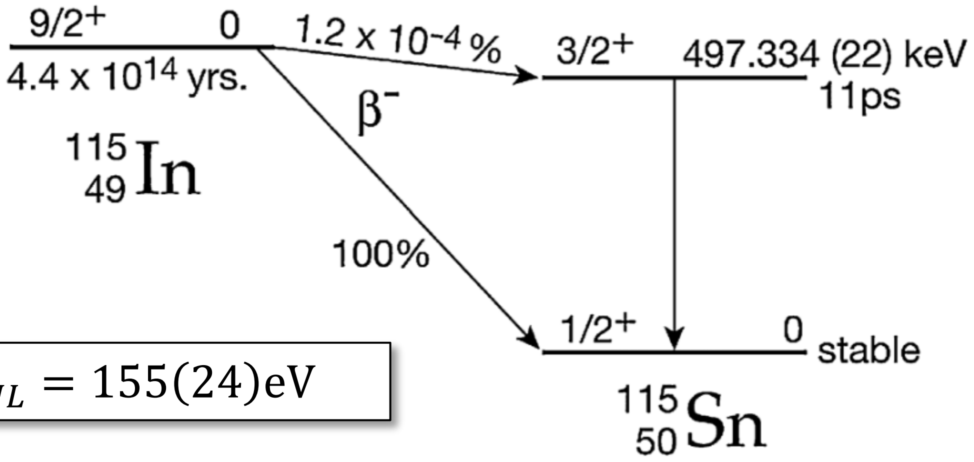
$$\boxed{Q_{ES} = 350(170)\mathrm{eV}}$$

Atomic Interference Effects

Observation of a 497 keV γ-ray from In sample



From a weak decay branch to $^{115}Sn(3/2^+)$

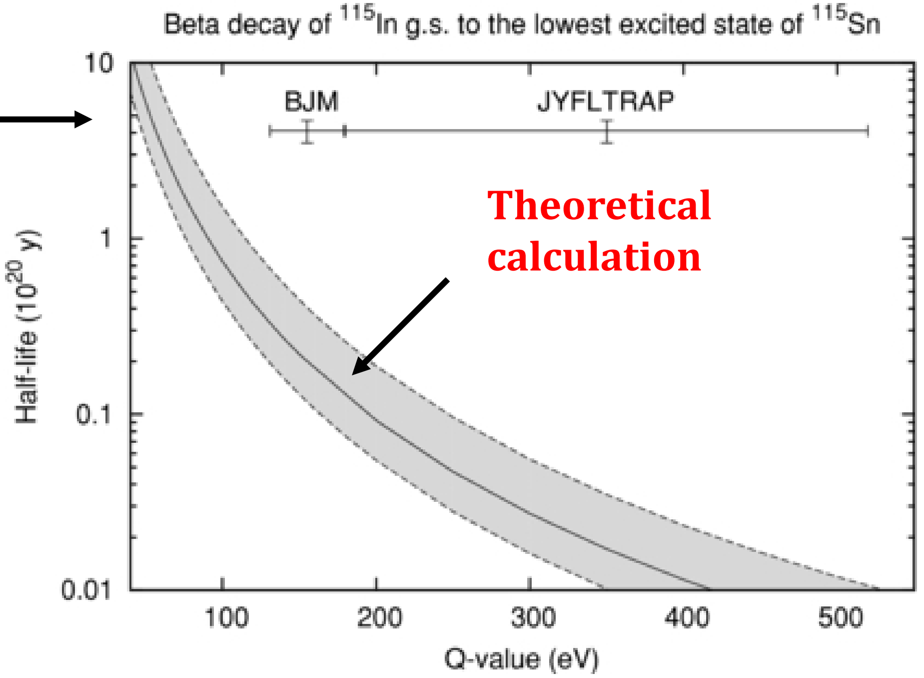


$$Q_{UL} = 155(24)\text{eV}$$

Cattadori, *et al*, Nuc. Phys. A **748**, 333 (2005)

Comparison of theoretical and measured half-life

Measurement:
$T_{1/2} = 4.1 \times 10^{20}$ yr



Discrepancy could be due to atomic interference effects.

Do other ultra-low Q value β-decay Candidates exist?

Hyperfine Interact (2019) 240:43
https://doi.org/10.1007/s10751-019-1588-5

Identification and investigation of possible ultra-low Q value β decay candidates

N. D. Gamage[1,2] · R. Bhandari[1] · M. Horana Gamage[1,2] · R. Sandler[1,2] · M. Redshaw[1,2,3]

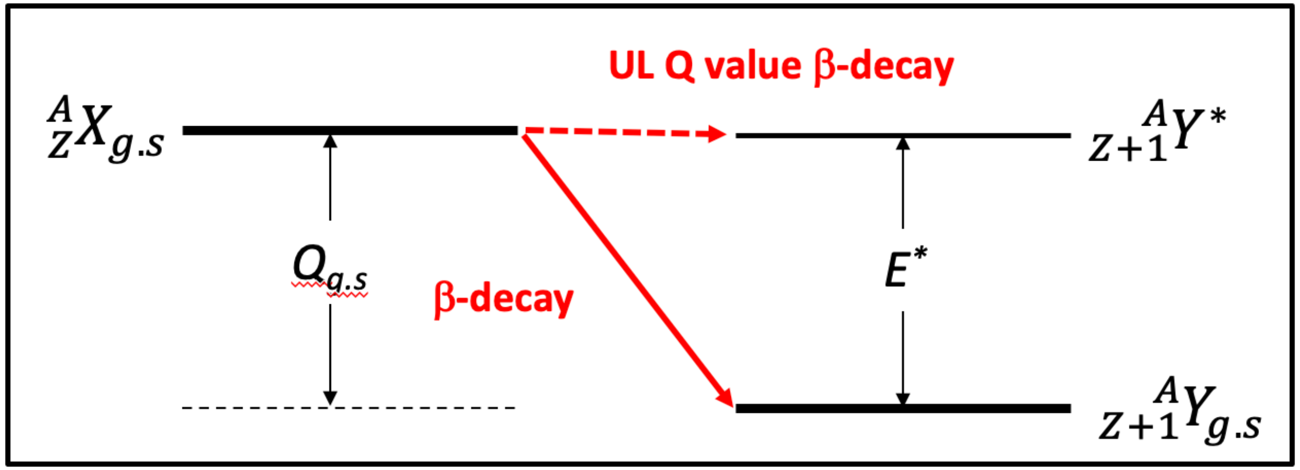
PHYSICAL REVIEW C 107, 015504 (2023)

Updated evaluation of potential ultralow Q-value β-decay candidates

D. K. Keblbeck,[1] R. Bhandari,[1] N. D. Gamage,[1,2] M. Horana Gamage,[1] K. G. Leach,[3,2] X. Mougeot,[4] and M. Redshaw[1,5,*]
[1]*Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA*
[2]*Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA*
[4]*Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel (LNE-LNHB), F-91120 Palaiseau, France*
[5]*National Superconducting Cyclotron Laboratory, East Lansing, Michigan 48824, USA*

2016 AME Data

2020 AME Data



- Calculate β-decay Q values from AME data for isotopes across nuclear chart ($t_{1/2}$ > 1 hr, 1 day)
- Look through nuclear energy level data to see if there is an E^{*} close to Q_{gs}.
- **≈100 potential candidates! More precise mass (and E^{*}) data needed.**

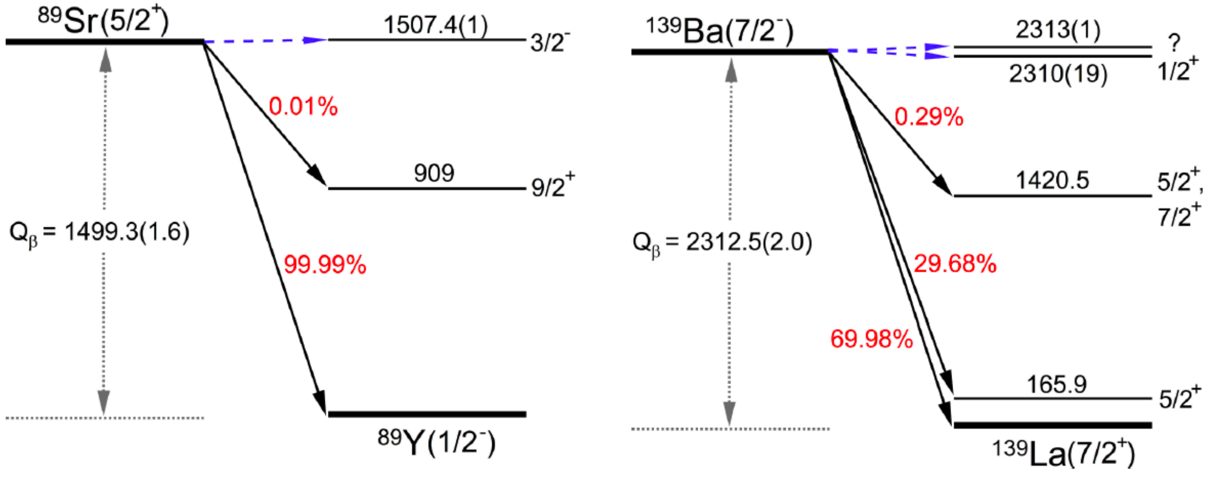
Ultra-low Q value β-decay Candidates: Stable Daughter Nuclides

PHYSICAL REVIEW C **100**, 024309 (2019)

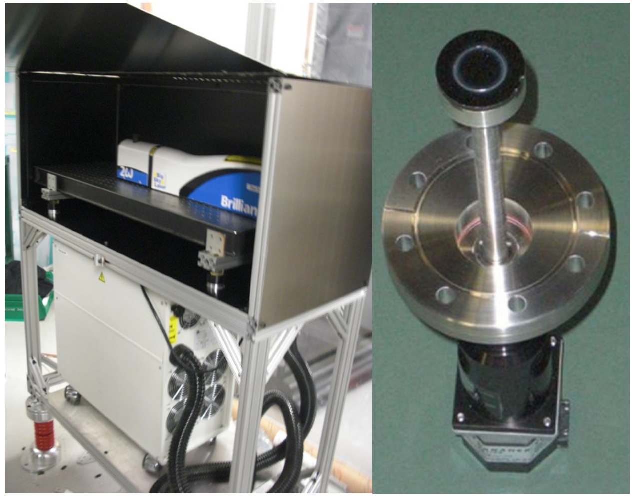
Investigation of the potential ultralow Q-value β-decay candidates ^{89}Sr and ^{139}Ba using Penning trap mass spectrometry

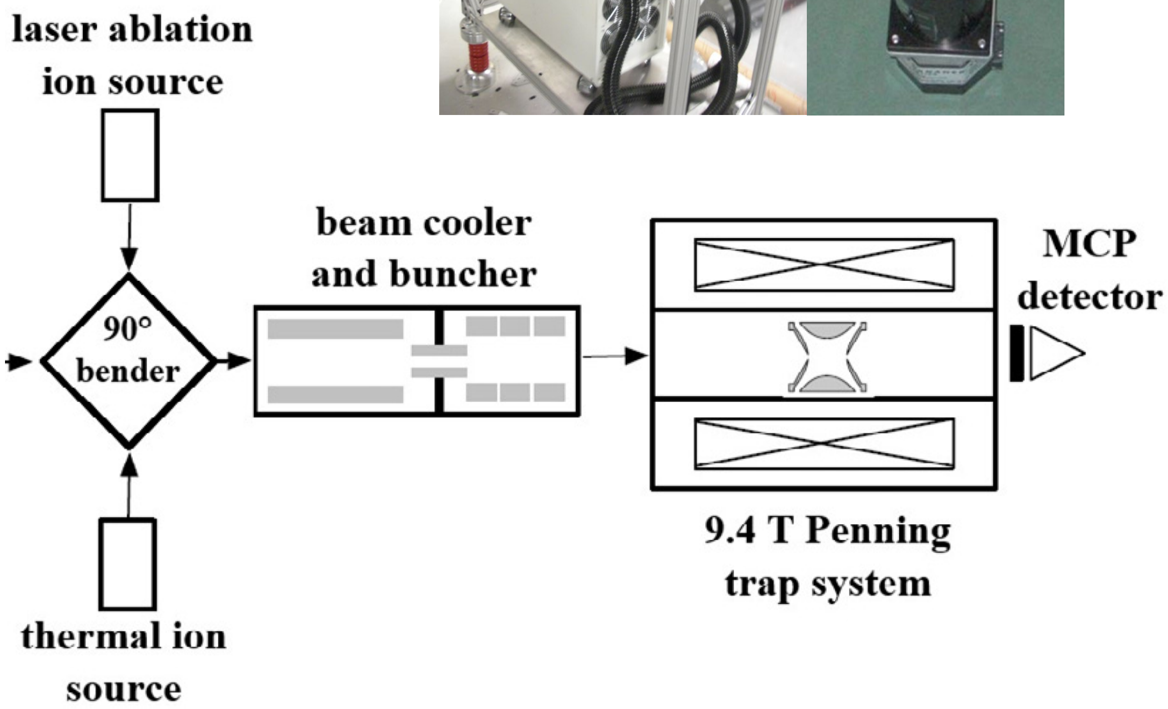
R. Sandler,[1,2,*] G. Bollen,[3,4] N. D. Gamage,[1] A. Hamaker,[2,4] C. Izzo,[2,4] D. Puentes,[2,4] M. Redshaw,[1,2] R. Ringle,[2] and I. Yandow[2,4]

Stable ^{89}Y and ^{139}La from laser source



Parent	Daughter	Q_{GS} keV	E^* keV	Q_{UL} keV
^{89}Sr	^{89}Y	1502.20(0.35)	1507.4(0.1)	−5.20(0.37)
^{139}Ba	^{139}La	2308.37(0.68)	2310(19)	$\boxed{-1.6(19.0)}$
^{139}Ba	^{139}La	2308.37(0.68)	2313(1)	−4.6(1.2)



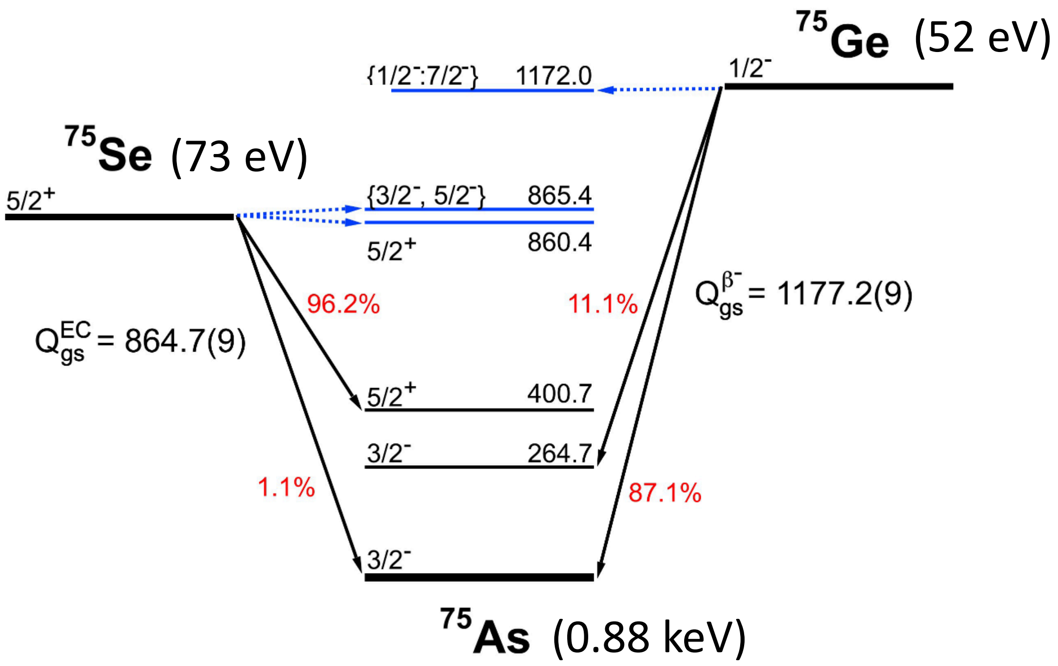


Q values measurement to evaluate potential ULQ decays of ^{75}Se and ^{75}As

PHYSICAL REVIEW C **106**, 065503 (2022)

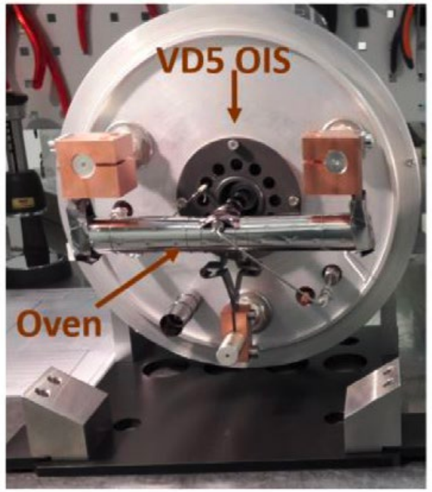
Identification of a potential ultralow-Q-value electron-capture decay branch in ^{75}Se via a precise Penning trap measurement of the mass of ^{75}As

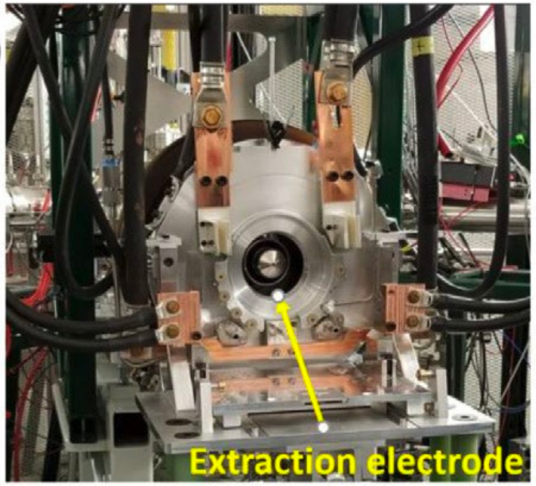
M. Horana Gamage,[1,*] R. Bhandari,[1] G. Bollen,[2,3] N. D. Gamage,[2] A. Hamaker,[4,3] D. Puentes,[4,3] M. Redshaw,[1,4] R. Ringle,[2] S. Schwarz,[2] C. S. Sumithrarachchi,[2] and I. Yandow[4,3]

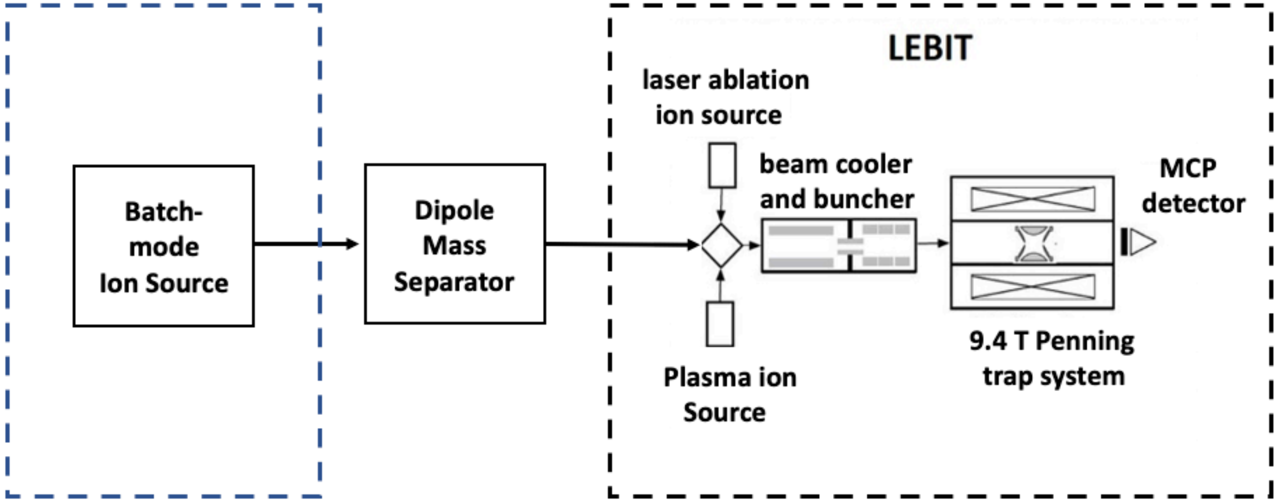


Parent	Decay	Q_{gs} (keV)	E^* (keV)	Q_{es} (keV)
^{75}Se	EC	866.50(44)	865.4(5)	$\boxed{1.10(67)}$
^{75}Se	EC	866.50(44)	860.4(4)	6.10(60)
^{75}Ge	β	1179.01(44)	1172.0(6)	7.01(74)

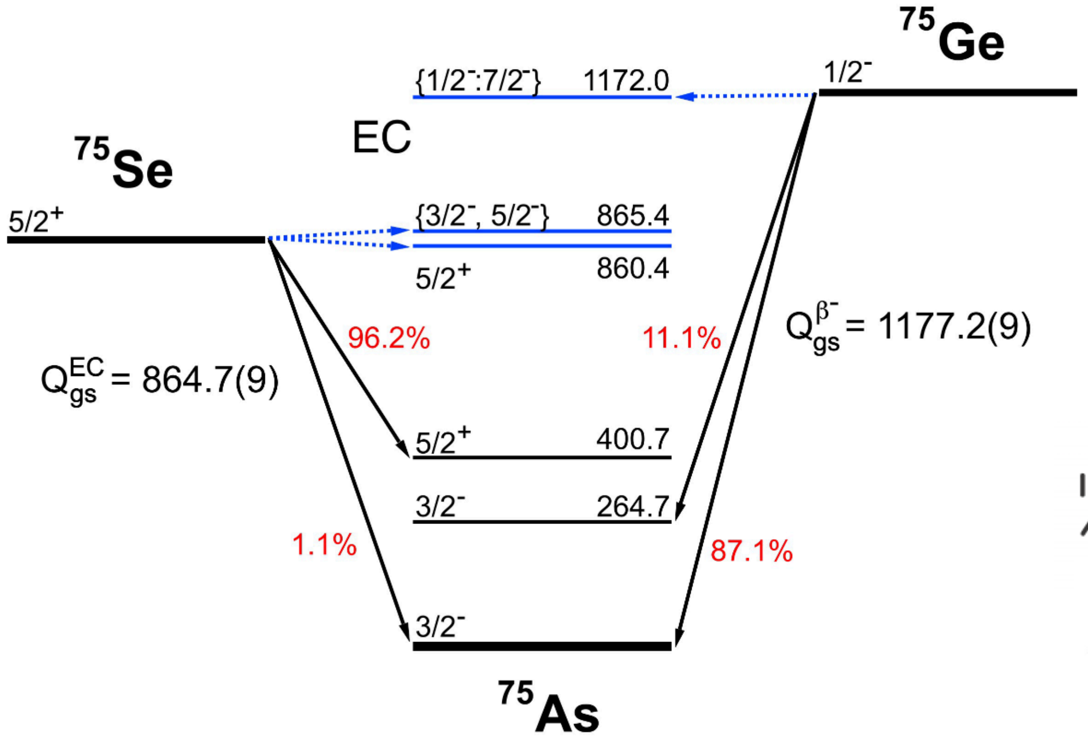
Stable ^{75}As from BMIS







Ultra-low Q value β-decay Candidates: E* Measurement



Decay	Q_{GS}	E^*	Q_{ES}	
^{75}Se$(5/2^+) \rightarrow$ ^{75}As$\{3/2^-;5/2^-\}$	866.041(81)	865.40(50)	0.64(51)	**JYFL**
	866.50(44)	865.40(50)	1.10(67)	**LEBIT**

Gamma-Ray Spectroscopy Measurement of the 865.4 keV Energy Level of ^{75}As

G. Raymond[1], M. Brodeur[2], A. Dissanayake[1], M. Hasan[1], P. O'Mally[2], D. Perera[1], W. S. Porter[2], M. Redshaw[1]

[1]*Department of Physics, Central Michigan University, Mount Pleasant, Michigan, 48859, USA*

[2]*Department of Physics and Astronomy, University of Notre Dame, South Bend, IN 46656, USA*

Coulomb Excitation: $p + {}^{75}\mathrm{As} \rightarrow {}^{75}\mathrm{As}^* \rightarrow {}^{75}\mathrm{As} + \gamma's$

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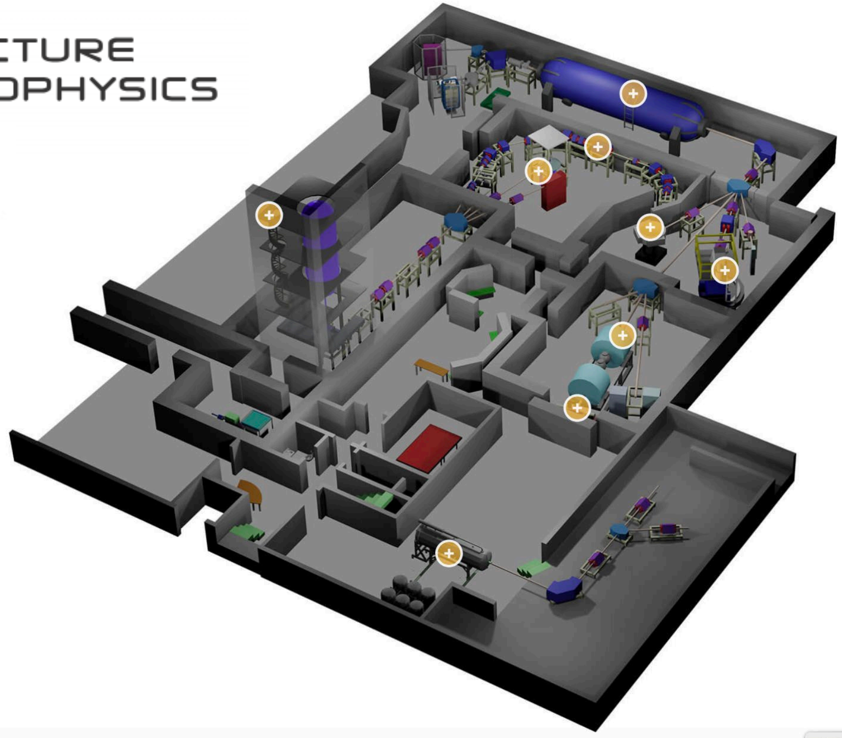
I S N A P



Preliminary Run : September 25th, 2025

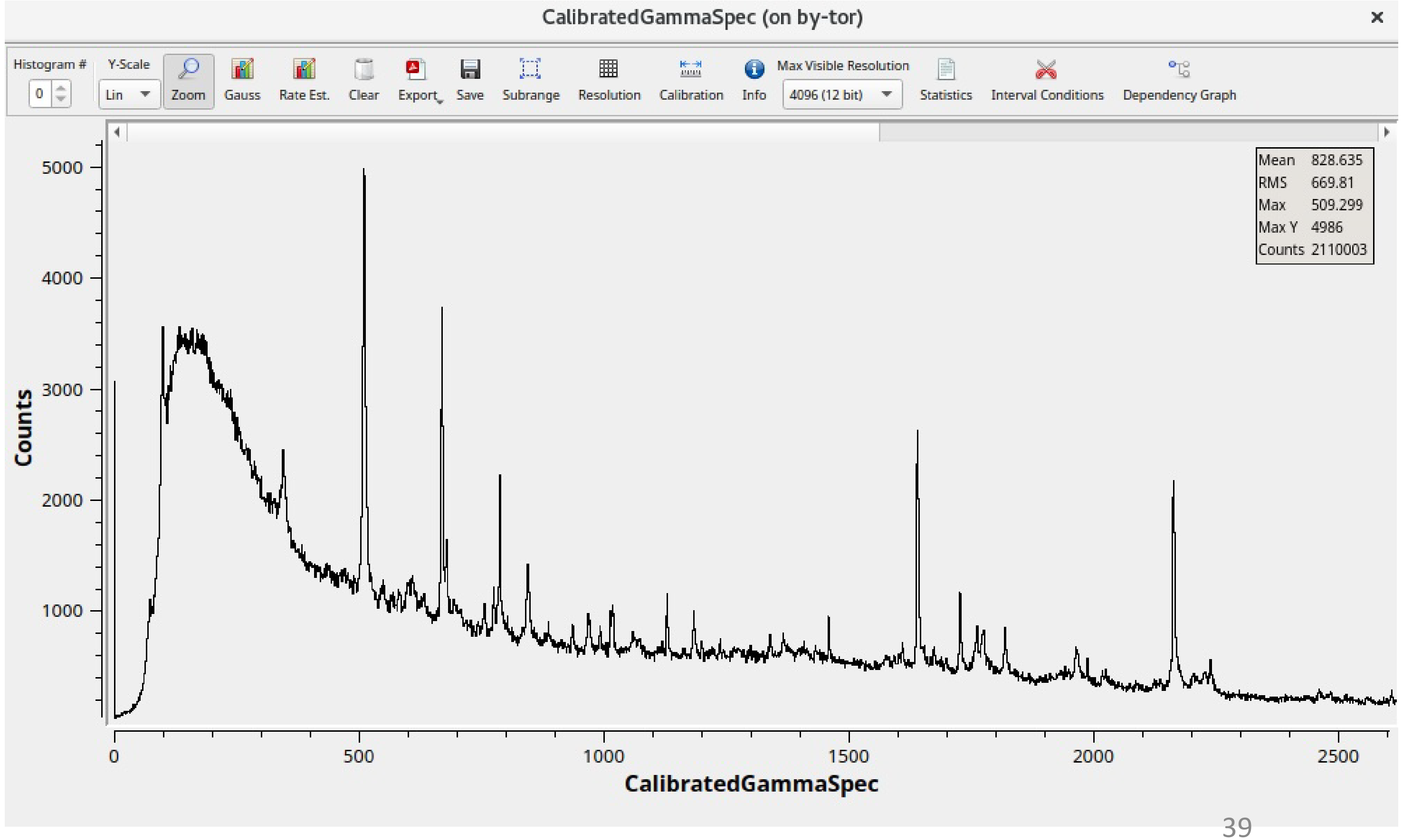
<u>Initial run:</u> 16, 14, 12 MeV proton beam on ~200 μm thick As target

- Saw high rate of γ-rays that saturated the detector.
- Likely due to proton beam impinging on and activating the aluminum target holder.

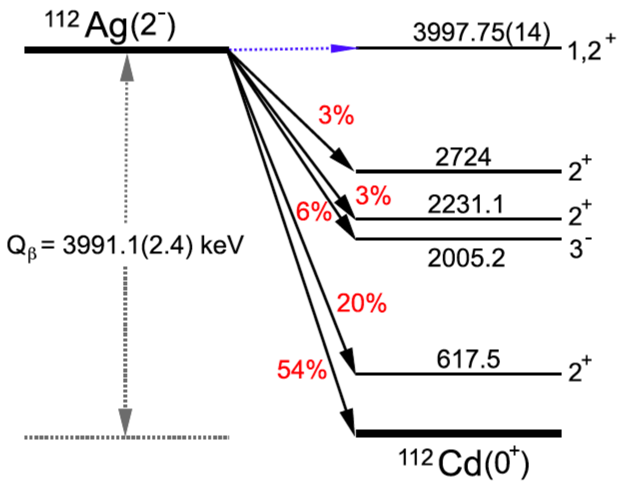
<u>Additional runs</u> : 36 MeV $^{12}C^{5+}$, 10 MeV $^{4}He^{2+}$, 60 MeV $^{16}O^{6+}$, 47 MeV $^{14}N^{5+}$ beams

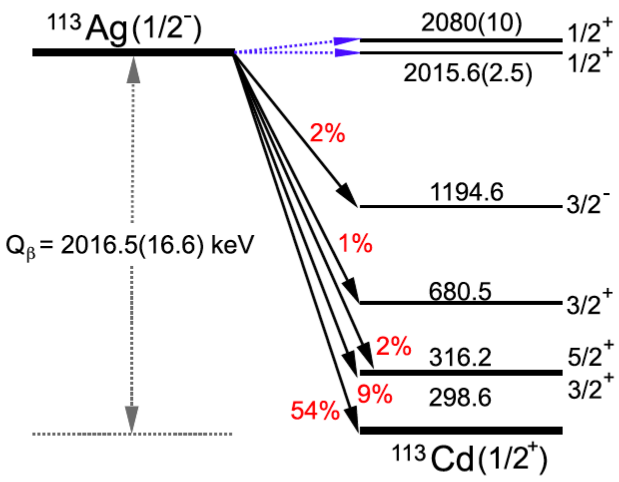
- Saw some low-lying ^{75}As peaks.

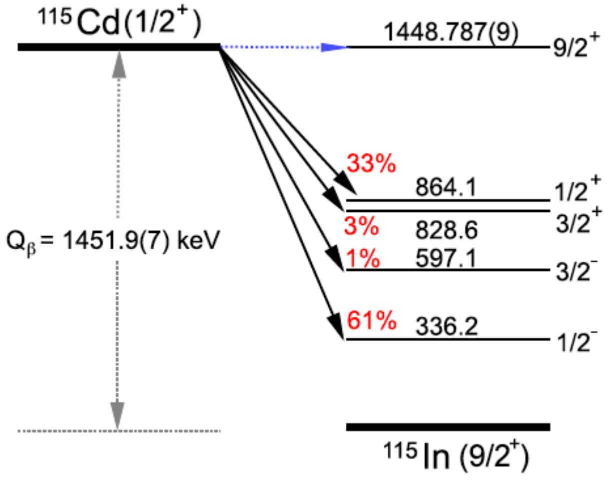
Spectrum from ^{16}O run

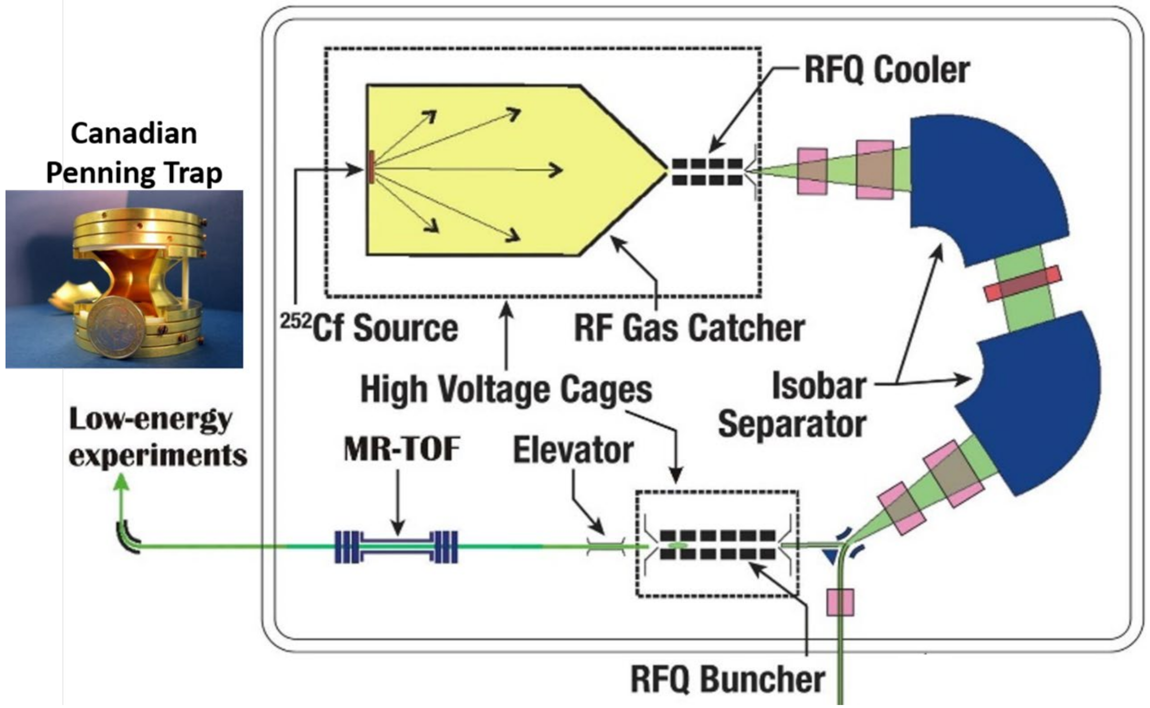


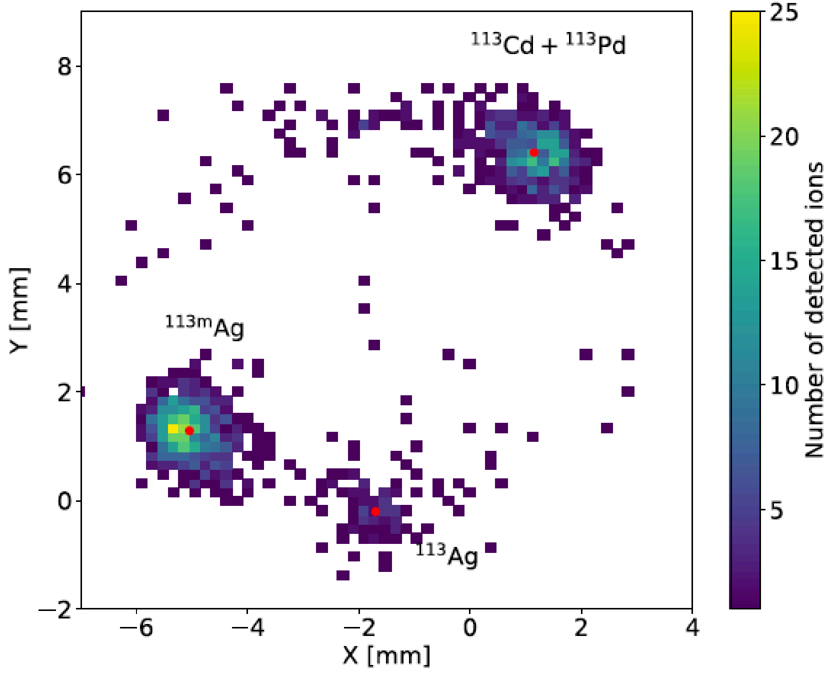
The Search for Ultra-low Q value β-decay Candidates : CPT











The Search for Ultra-low Q value β-decay Candidates : CPT

PHYSICAL REVIEW C **106**, 045503 (2022)

Precise Q-value measurements of ^{112,113}Ag and ^{115}Cd with the Canadian Penning trap for evaluation of potential ultralow Q-value β decays

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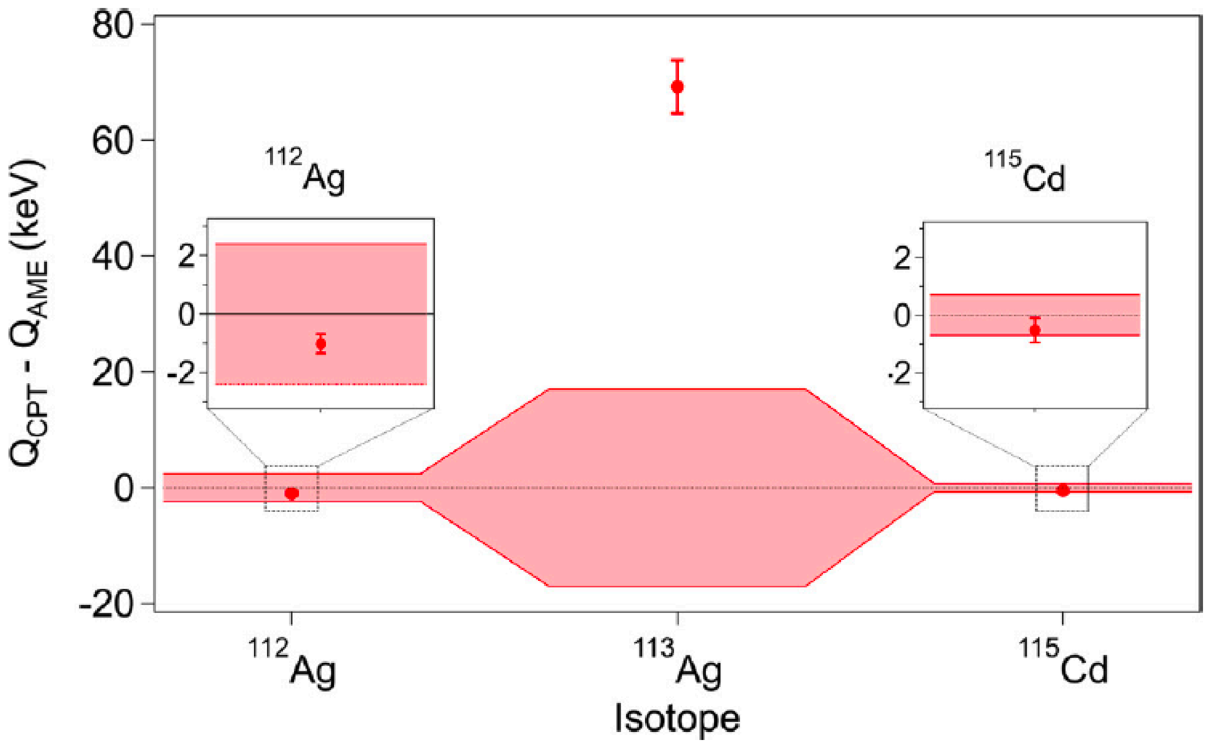

Decay	E^*	Q_{UL} CPT	Q_{UL} AME
^{112}Ag → ^{112}Cd	3997.75(14)[a]	−7.59(26)	−6.6(2.4)
^{113}Ag → ^{113}Cd	2015.6(2.5)[b]	70.1(5.2)	0.9(16.8)
	2080(10)[c]	5.7(11.0)	−63.5(19.4)
^{115}Cd → ^{115}In	1448.787(9)[d]	2.57(34)	3.1(0.7)

Summary of ULQ value decay candidate searches

LEBIT: Ruled out: ^{89}Sr, ^{139}Ba, ^{75}Ge
Identified: ^{75}Se

CPT: Ruled out: $^{112,113}Ag$, ^{115}Cd

ISOLTRAP: Ruled out: ^{131}Cs

JYFLTRAP: Ruled out: ^{72}As, ^{75}Ge, $^{76,77}As$, ^{136}Cs, ^{155}Tb
Identified: ^{75}Se, ^{111}In, ^{131}I, ^{135}Cs, ^{159}Dy
^{95}Tc, ^{110m}Ag

ULQ value β-decays provide interesting opportunities for nuclear theory and possibilities for ν-mass determination experiments.

There are many potential candidates out there, but more precise Q value (mass) data and in some cases, energy level data, is needed.

Isotope	Decay	Forbiddenness	Half-life	Q_{ES} (keV)
^{136}Cs	β^-	Allowed	13 dy	3.7(19)
^{188}W	β^-	Allowed	70 dy	-4.6(32)
^{155}Eu	β^-	1st Forbidden	5 yr	0.3(16)
^{156}Eu	β^-	1st Forbidden	15 dy	1.0(37)
^{56}Co	EC	Allowed	78 dy	4.76(55)
^{97}Tc	EC	Allowed	4.2 Myr	-0.1(42)
^{175}Hf	EC	Allowed	70 dy	1.0(26)
^{81}Kr	EC	1st Forbidden	229 kyr	3.2(15)
^{146}Pm	EC	1st Forbidden	6 yr	-0.3(45)
^{157}Tb	EC	1st Forbidden	71 yr	-2.3(14)
^{173}Lu	EC	1st Forbidden	1.5 yr	1.0(18)
^{183}Re	EC	1st Forbidden	70 dy	2.5(81)
^{195}Au	EC	1st Forbidden	186 dy	1.9(12)
^{148}Eu	β^+	Allowed	55 dy	-15(10)
^{105}Ag	β^+	1st Forbidden	41 dy	5.7(47)
^{144}Pm	β^+	1st Forbidden	1 yr	-4.8(32)
^{146}Pm	β^+	1st Forbidden	6 yr	-4.3(45)

Conclusions

Penning traps have played an important role for providing Q value data for

- Superallowed $0^+ \rightarrow 0^+$ and $T = 1/2$ mirror nuclei β-decays to help determine V_{ud}
- Searches for $0\nu\beta\beta$ and calculating phase space factors
- Evaluating potential $0\nu 2EC$ searches
- Direct neutrino mass determination experiments
- Searches for sterile neutrinos and BSM Physics
- Identifying potential candidates for new neutrino mass determination experiments

Thanks for listening!

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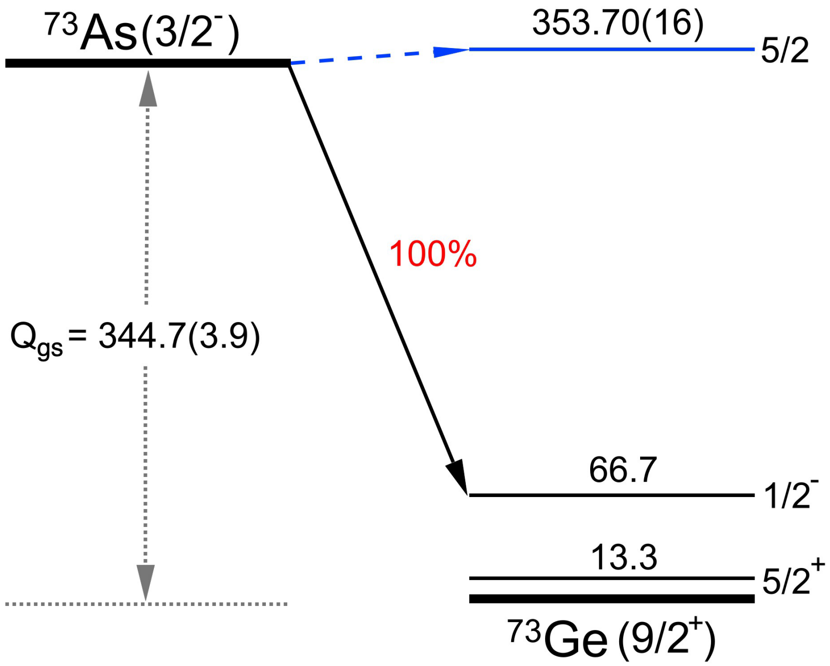
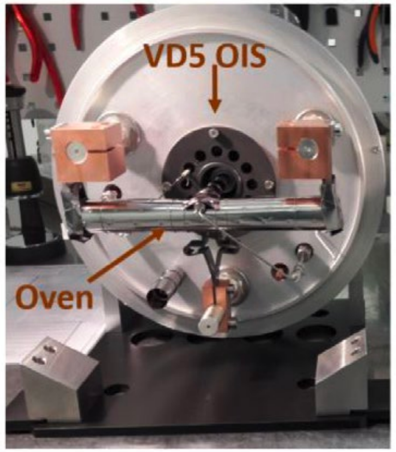
Approved ^{73}As Q value measurement at FRIB

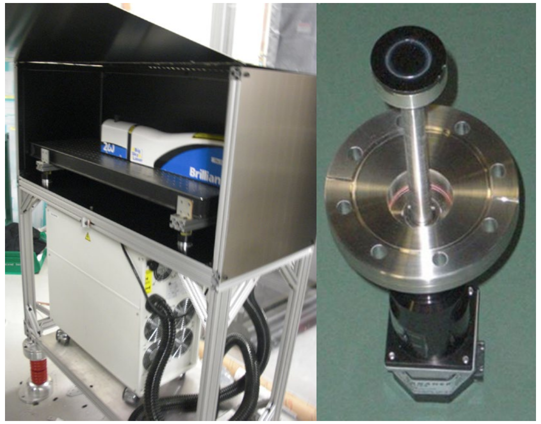
Potential allowed EC decay of ^{73}As to 354 keV state in ^{73}Ge

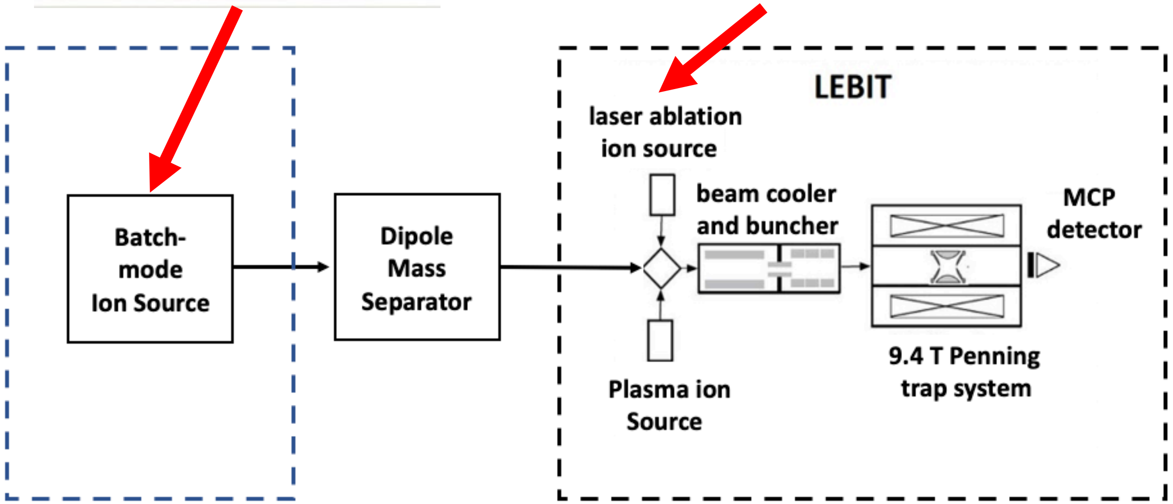


Radioactive ^{73}As from BMIS



Stable ^{73}Ge from LAS





Parent	$T_{1/2}$	Daughter	Q_{gs} (keV)	E^* (keV)	Shell	E_B (keV)	Decay type	Q_{es} (keV)
^{73}As(3/2$^-$)	80 d	^{73}Ge(5/2)	344.7(39)	353.7(16)	L	1.3	Allowed (?)	−10.3(42)