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Single and double beta decay Q-value measurements for ^{96}Zr and implications

RTG annual retreat 19—22-9-2016

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JYVÄSKYLÄN YLIOPISTO
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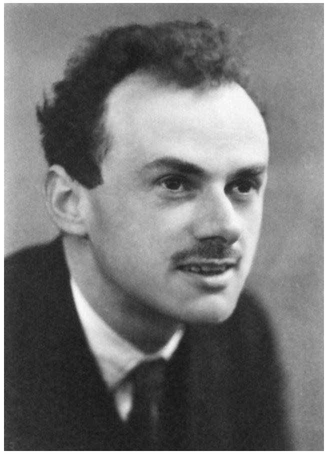
Outline

- Double beta ββ decay
  - → decay rate.
  - → neutrinoless double beta 0ν ββ decay NME.
- ^{96}Zr project
  - → the specialties of ^{96}Zr/ ^{96}Nb for β and ββ decay
- IGISOL facility
- Mass measurements using ion trap (JYFLTRAP)
- Results of experiment
- Summary
- The latest publication about ^{71} Ga/ ^{71} Ge Q-value.

Open questions in neutrino physics

- What is the absolute mass for neutrinos ?
- Are neutrinos Dirac or Majorana particles ?
- Which mass hierarchy is realized in nature ?



Paul Dirac

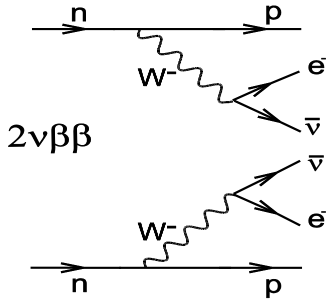
$\nu \neq \bar{\nu}$

$0\nu\beta\beta$ -decay

Ettore Majorana

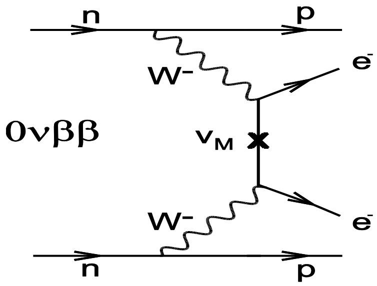
$\nu = \bar{\nu}$

Double beta decay



$$A(Z,N) \rightarrow A(Z+2,N-2)+2e^- + 2\bar{\nu}_e$$

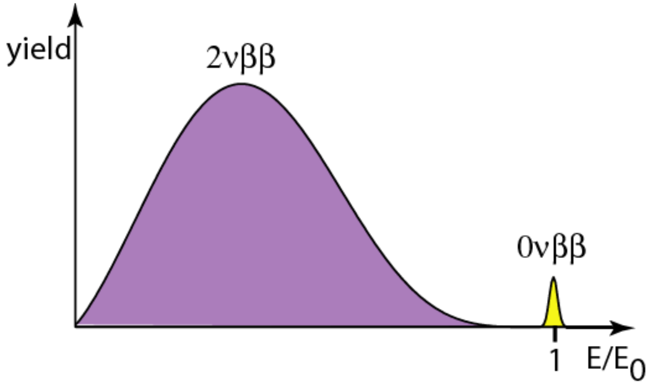
- Allowed in Standard Model ($\Delta L=0$)
- Observed experimentally
- NME is measured (charge-exchange reaction)
- No effect on the ν mass
- low-q phenomenon ($q_{tr} \sim 0.01\ \mathrm{fm}^{-1}$)



$$A(Z,N) \rightarrow A(Z+2,N-2)+2e^-$$

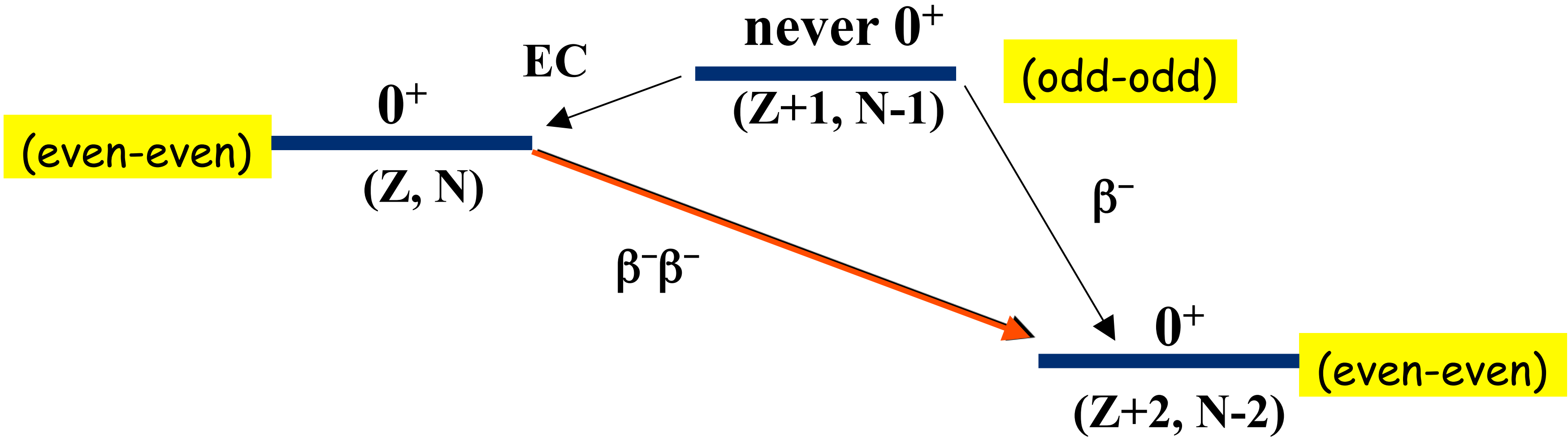
- Forbidden in Standard Model ($\Delta L=2$)
- Not observed yet
- NME is only calculated
- ν has Majorana mass
- high-q phenomenon ($q_{tr} \sim 0.5\ \mathrm{fm}^{-1}$)

2νββ-decay



0νββ-decay

$\beta^-\beta^-$ decay


never 0^+

(odd-odd)

EC

0^+

(even-even)

(Z+1, N-1)

(Z, N)

β^-

$\beta^-\beta^-$

0^+

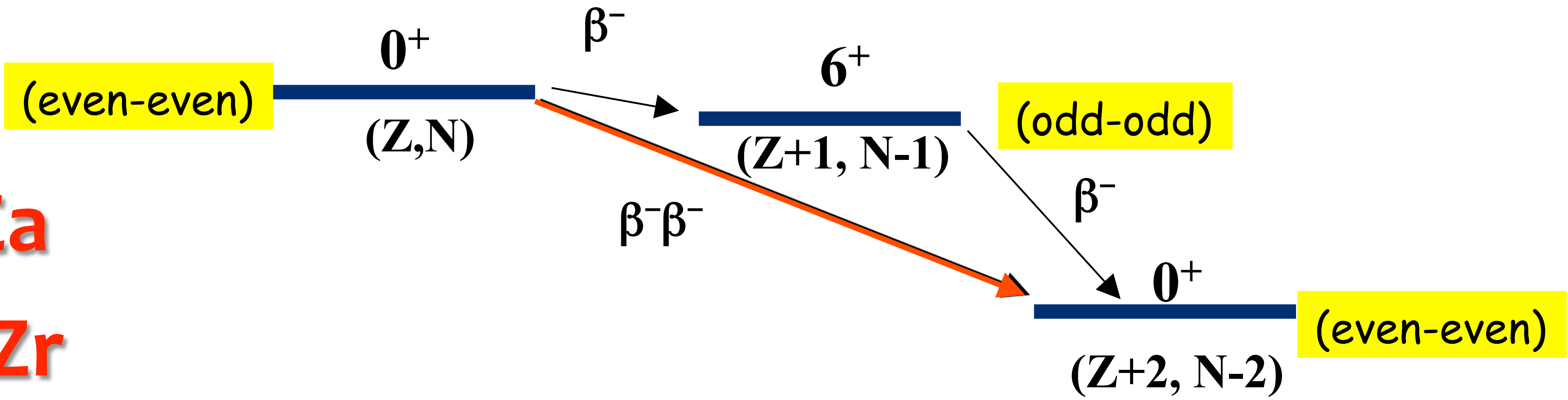
(even-even)

(Z+2, N-2)

1. ^{48}Ca
2. ^{150}Nd
3. ^{96}Zr
1. ^{100}Mo
2. ^{82}Se
3. ^{116}Cd
7. ^{130}Te
8. ^{136}Xe
9. ^{124}Sn
10. ^{76}Ge
11. ^{110}Pd

The β-β- decay candidates with highest Q-value

$\beta^-\beta^-$ decay



^{48}Ca

^{96}Zr

1. ^{48}Ca
2. ^{150}Nd
3. ^{96}Zr
1. ^{100}Mo
2. ^{82}Se
3. ^{116}Cd
7. ^{130}Te
8. ^{136}Xe
9. ^{124}Sn
10. ^{76}Ge
11. ^{110}Pd

The β-β- decay candidates with highest Q-value

$\beta^-\beta^-$ decay rate

$2\nu\beta^-\beta^-$ **decay:**

$$T_{1/2} \approx 10^{19-21}\, y$$

$$\Gamma = \underbrace{G(Q,Z)}_{\text{5-body}} \times g_A^4 \times \left| \underbrace{NME}_{\text{allowed (GT)}} \right|^2$$

$\alpha\ Q^{11}$

From charge exchange reactions

$0\nu\beta^-\beta^-$ **decay:**

$$T_{1/2} > 10^{24}\, y$$

$$\Gamma = \underbrace{G(Q,Z)}_{\text{3-body}} \times g_A^4 \times \left| NME \right|^2 \times \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2$$

$\alpha\ Q^5$

Calculated within models

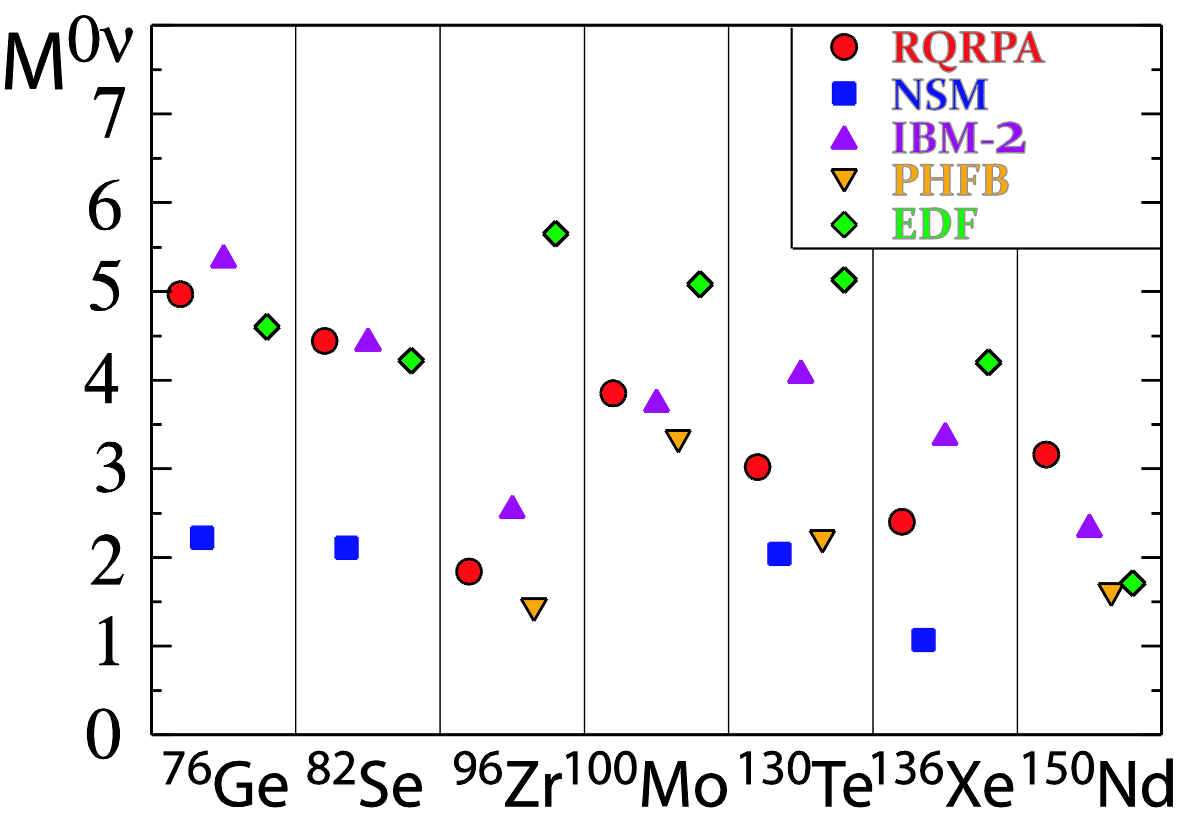
Effective Majorana ν mass, $m_{\beta\beta}$

favorable:

1. high Q-value
2. large Z

$0\nu\beta^{-}\beta^{-}$ N$_{ucl.}$ M$_{atrix}$ E$_{lement}$

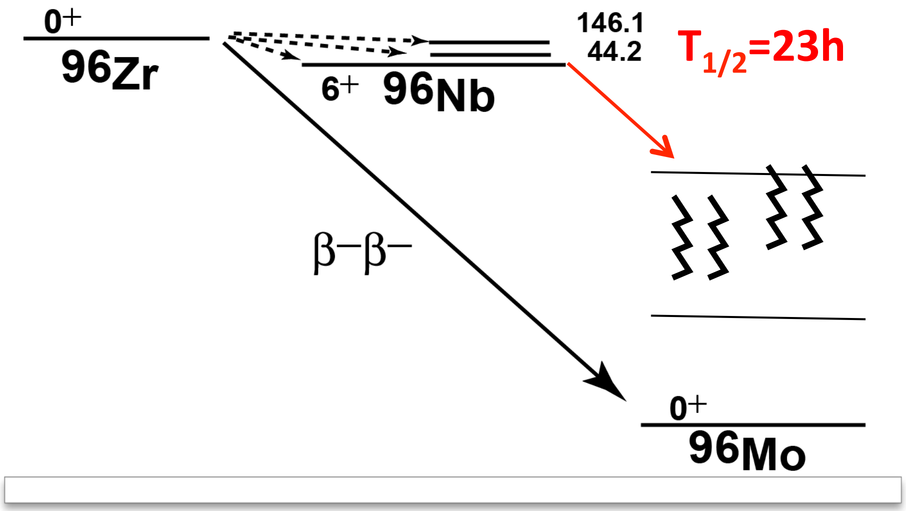
P.Vogel, J. Phys. G, NPP39, 2012



The calculated $0\nu\beta\beta$ decay NME via different models differ by more than a factor of 2-3 (i.e. half-life 4-9)

Objective of ^{96}Zr project

Why zirconium ?



- Features single β^- and $\beta^-\beta^-$ decay (only with ^{48}**Ca**)
- Single β^- decay is **4-fold forbidden** → direct test to **0$\nu\beta^-\beta^-$ NME**
- Side effect: single β^- and $2\nu\beta^-\beta^-$ decays gives handle on $\mathbf{g_A}$

Competition between β & ββ decay of ^{96}Zr

two conflicting half-lives:

NEMO-3: $T^{2\nu\beta\beta}_{1/2} = (2.3 \pm 0.2) \times 10^{19}\,\mathrm{y}$

geo-chem: $T_{1/2} = (0.94 \pm 0.32) \times 10^{19}\,\mathrm{y}$ ①

can this difference be reconciled ?
yes, if single β competes with ββ decay

$$\left(T_{1/2}\right)^{-1} = \left(T^{2\nu\beta\beta}_{1/2}\right)^{-1} + \left(T^{\beta}_{1/2}\right)^{-1}$$

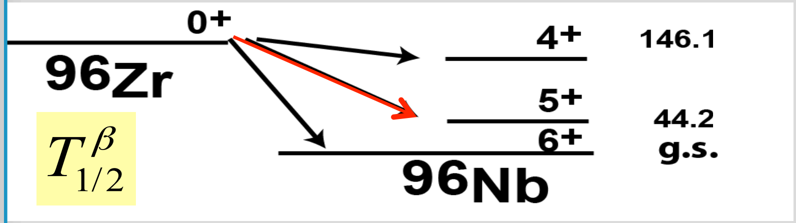
expected $T^{\beta}_{1/2} = (1.6 \pm 0.9) \times 10^{19}\,\mathrm{y}$

experiment $T^{\beta}_{1/2} > 2.6 \times 10^{19}\,\mathrm{y}$ ②

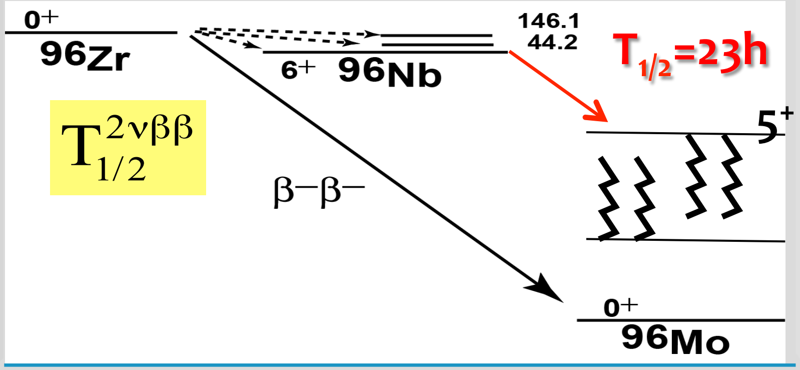
pred. (QRPA) $T^{\beta}_{1/2} = 24 \times 10^{19}\,\mathrm{y}$ ③

BUT

$$(T^{\beta}_{1/2})^{-1} \propto 0(Q^{13})\, g_A^2 \left\langle M^{4u}_{\beta} \right\rangle^2$$



$0^+ \rightarrow 6^+$ 6-fold non-unique (unobservably long)
$0^+ \rightarrow 5^+$ 4-fold unique (possible)
$0^+ \rightarrow 4^+$ 4-fold non-unique (no phase space)



Q-value $\rightarrow M^{4u}_{\beta} \rightarrow (T^{0\nu\beta\beta}_{1/2})^{-1} \propto Q^5 \left|M^{0\nu}_{\beta\beta}\right|^2 \left\langle m_{\beta\beta} \right\rangle^2$

① Wieser, PRC64,2001, ② Barabash, JPG-NPP22, 1996 ③ Heiskanen, JPG3,2007

What we have to do ?

1st

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We measure the single β and $\beta^-\beta^-$ decays Q-value of ^{96}Zr
(my thesis project)

2nd Determine the ^{96}Zr single β decay half-life:

Geo-chemically

UNIVERSITY OF
CALGARY

Counting

UNIVERSITAS COMENIANA BRATISLAVENSIS · MCMXIX ·

How to measure β decay Q-value of ^{96}Zr ?

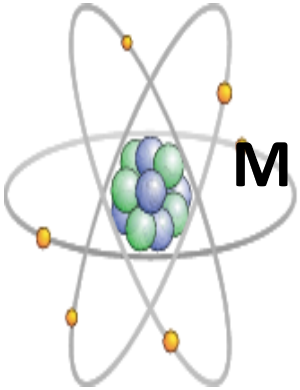
Mass measurements ^{96}Zr, ^{96}Nb & ^{96}Mo using Penning trap

$$M = A\,u + ME$$

$A = 96$, $u = 931.494\ \mathrm{MeV}/c^2$

ME = mass excess [AME12]

$$Q = M_{\mathrm{mother}} - M_{\mathrm{daughter}}$$



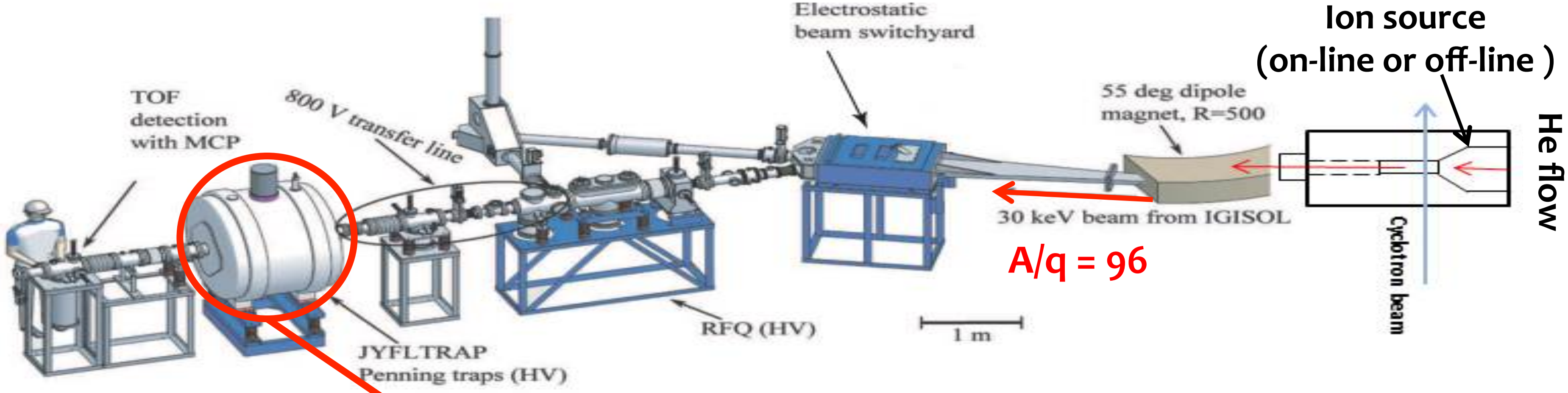
M = N·● + Z·● + Z·●

- binding energy

Jyvaskyla, Finland
July - 2015

IGISOL / JYFLTRAP setup

Figures from Eronen EPJA 48-2012

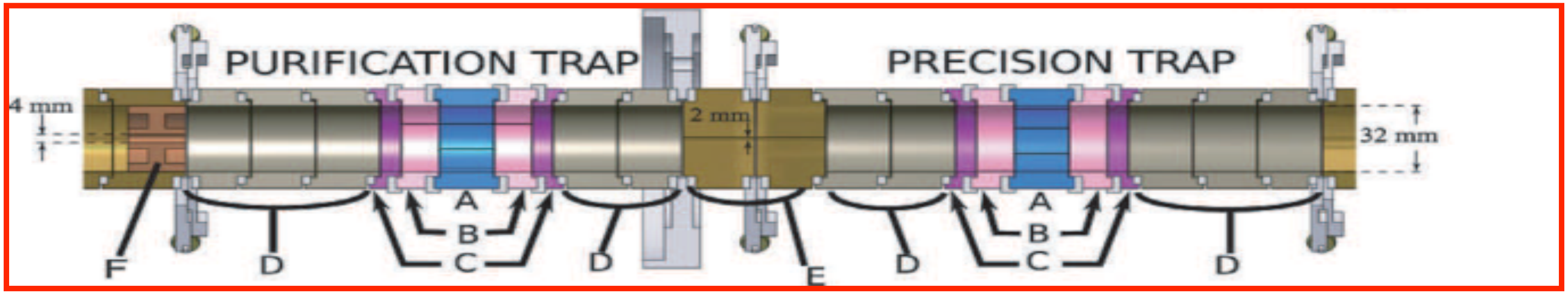


Ion source (on-line or off-line)

He flow

A/q = 96

$\Delta B/B = 8.18 \times 10^{-12}$ /min



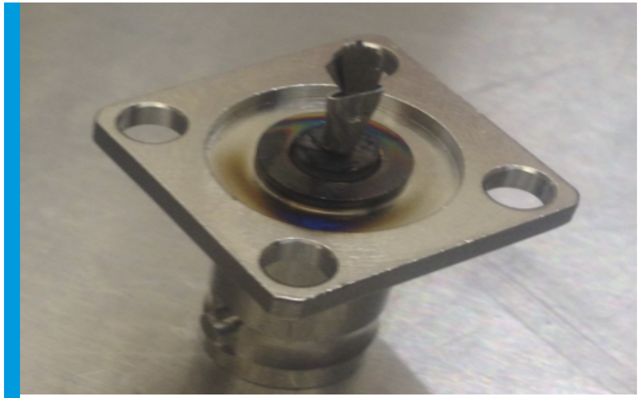
purification & isobars separation
By buffer-gas cooling tech.

mass measurement via cyclotron frequency, p. < 10^{-7} mbar.

Beam production at IGISOL

Off-line measurements

^{96}Zr and ^{96}Mo

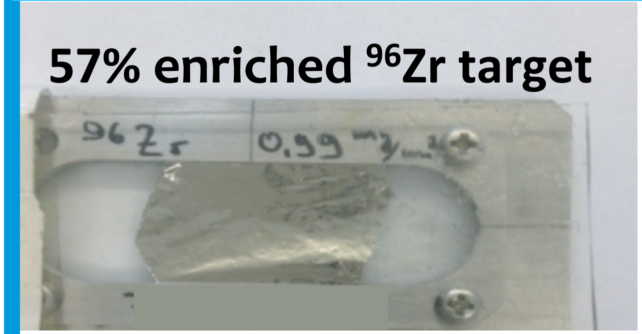


off-line ion source

On-line measurements

^{96}Zr (p, n)^{96}Nb reaction for production of ^{96}Nb

10MeV proton beam



57% enriched ^{96}Zr target

target (on-line) ion source

Note IGISOL produces on-line :

^{96}Zr ----- from target material

^{96}Nb ----- (p,n) charge-ex reaction

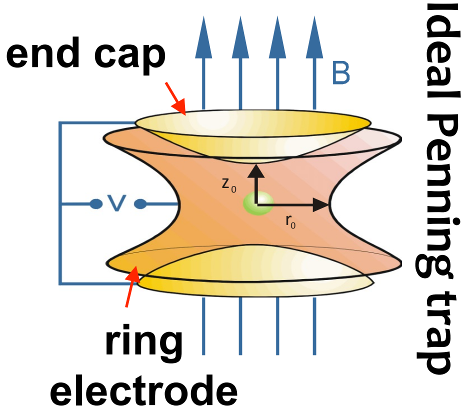
^{96}Mo----- from havar separator foil

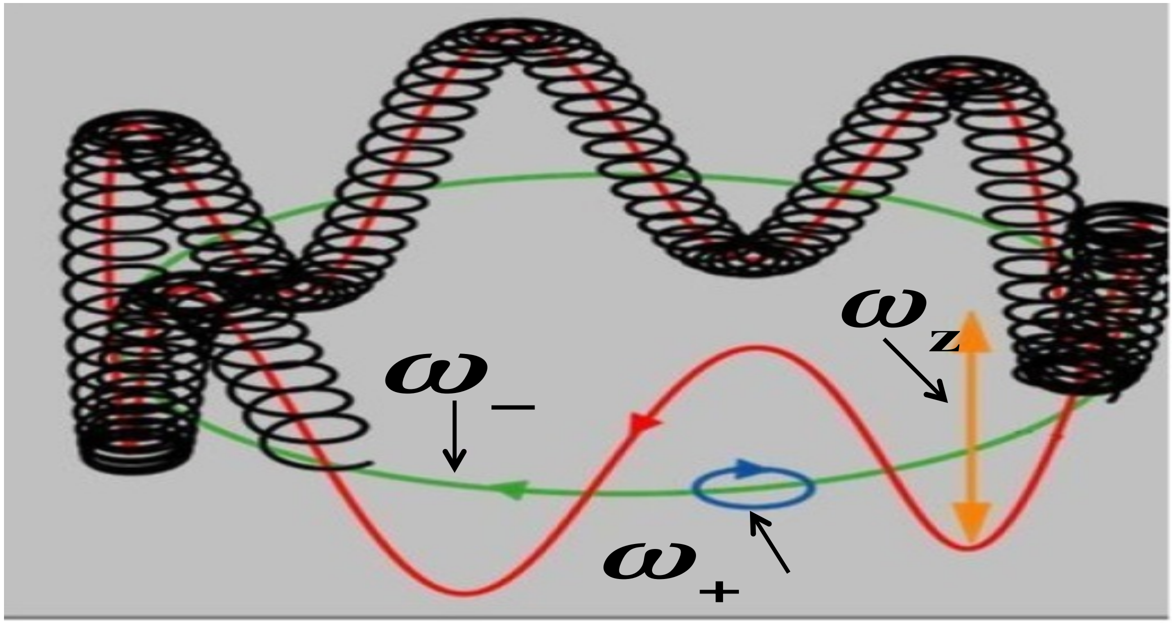
mother & daughter ions are produced at IGISOL at the same time

Ion motion in a Penning trap

Homogeneous magnetic field + static electric field provides 3D confinement results in three eigenmotions:

1. Magnetron motion ω_-
2. Reduced cyclotron motion ω_+
3. Axial motion ω_z





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

$\omega_- \approx 1$ kHz,
$\omega_+ \approx 1$ MHz

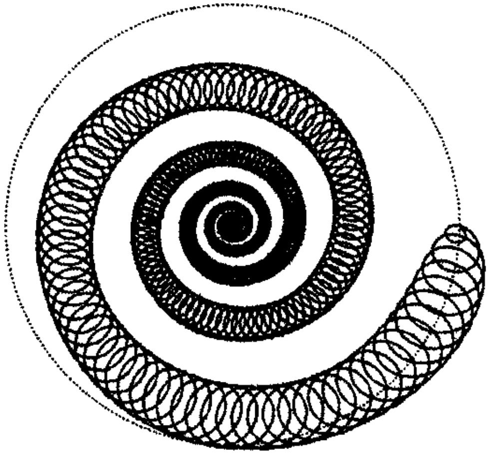
$$\boxed{\omega_c = \frac{q}{m} \cdot B}$$

Excitation of ion motion in trap

How to measure any of the ion eigenfrequencies in a Penning trap ?

- ***Excite*** the ion eigenmotion by applying a dipolar or a quadrupolar electric field with a corresponding frequency

$(\nu_- \text{ or } \nu_c)$



excitation of ion in the presence of the buffer gas (**purification trap** > 500/1)

Mass measurements in a Penning trap

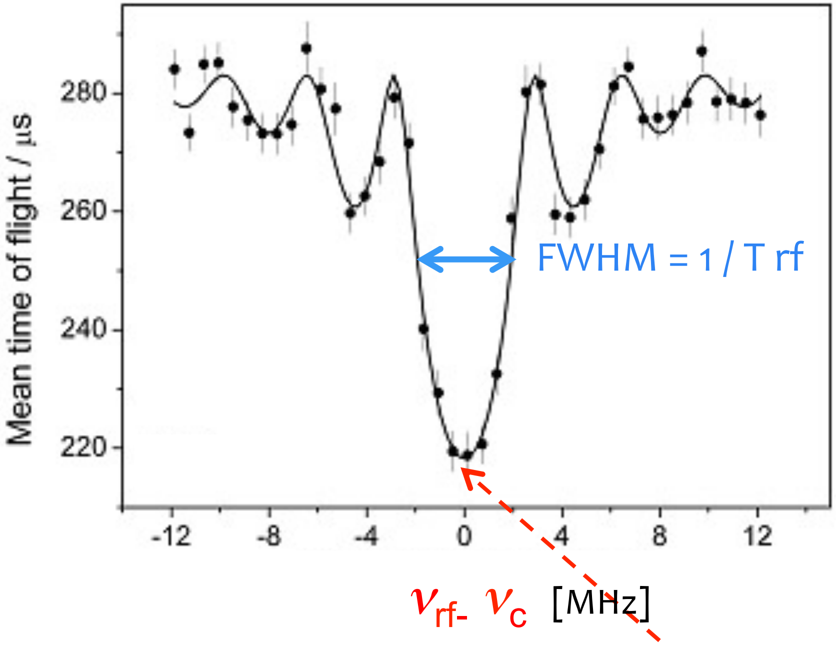
- Performing precision mass determination via **cyclotron frequency** ν_c measurement

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

$\omega_c = 2\pi\, \nu_c$

- Cyclotron frequency ν_c determination done by **TOF-ICR** technique

Typical conventional TOF spectrum



- Frequency ratio $r = \dfrac{\nu_{c\ daughter}}{\nu_{c\ mother}}$

at ν_c ion acquires extra energy $\longrightarrow$ shorter time of flight

Q-value from mass doublets

Atomic mass is:

$$M_{mother} = r\,(M_{daughter} - m_e) + m_e$$

precision required

Δm_{mother} given by Δr & $\Delta m_{daughter}$

Q-value is:

ΔQ given by Δr only

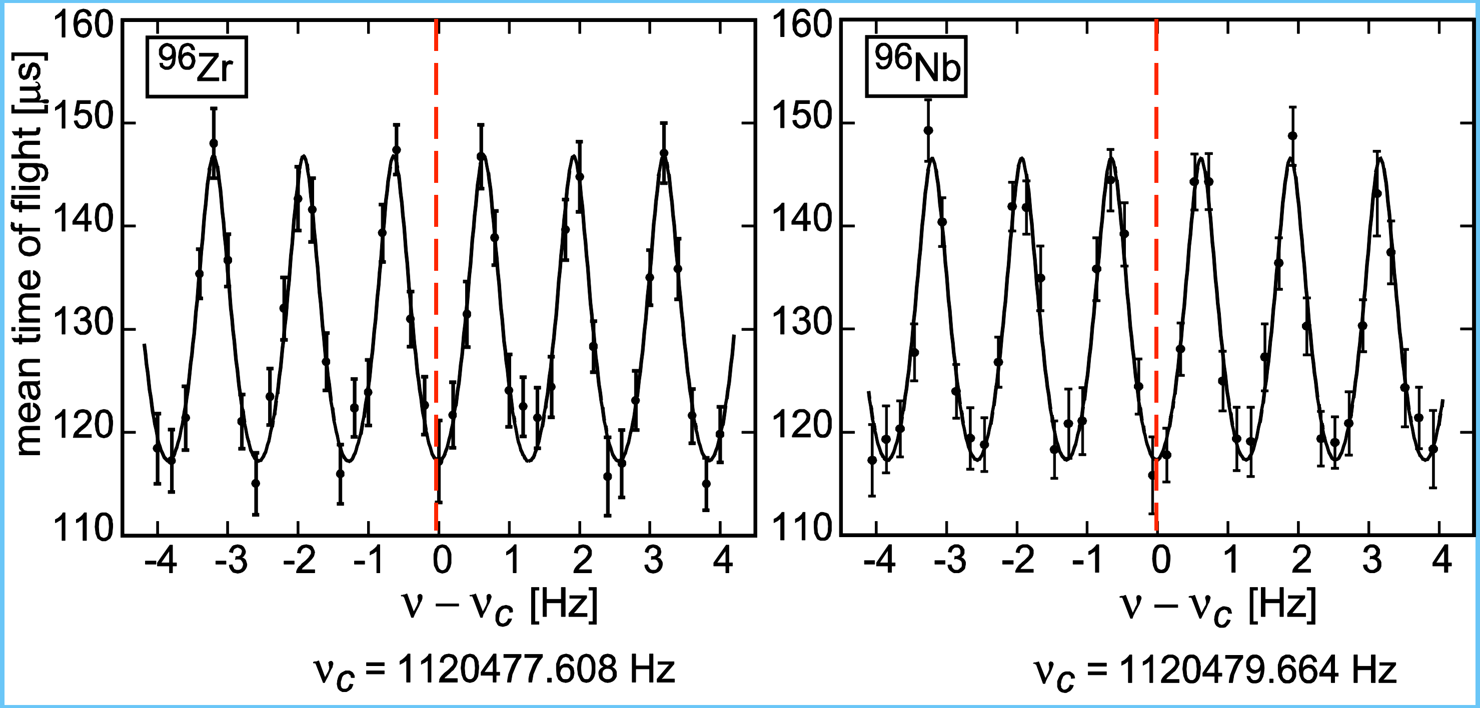
$$Q = M_{mother} - M_{daughter} = \underbrace{[r-1]}_{\approx 10^{-4}}(M_{daughter} - m_e)$$

Note:

1. Δr in order of 10^{-9}
2. The mass dependent corrections cancel out (no systematic uncertainty)

Jyvaskyla, Finland
July – 2015, at 1:00 am

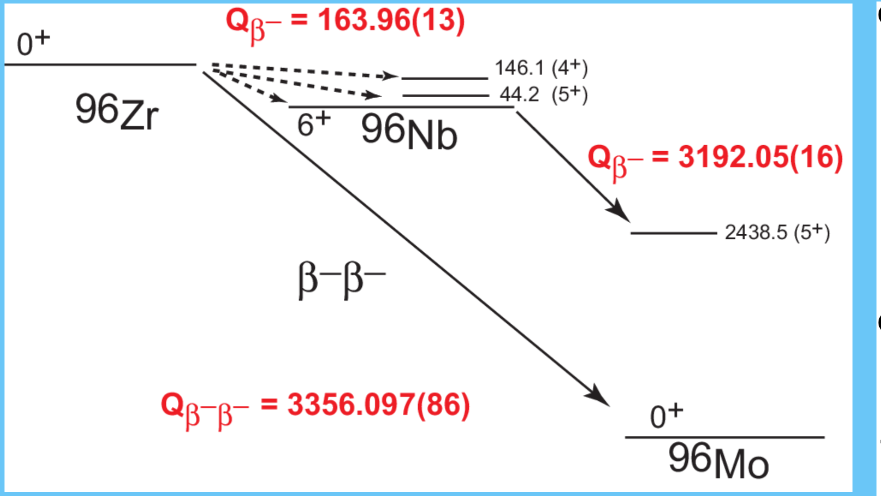
Cyclotron frequency results

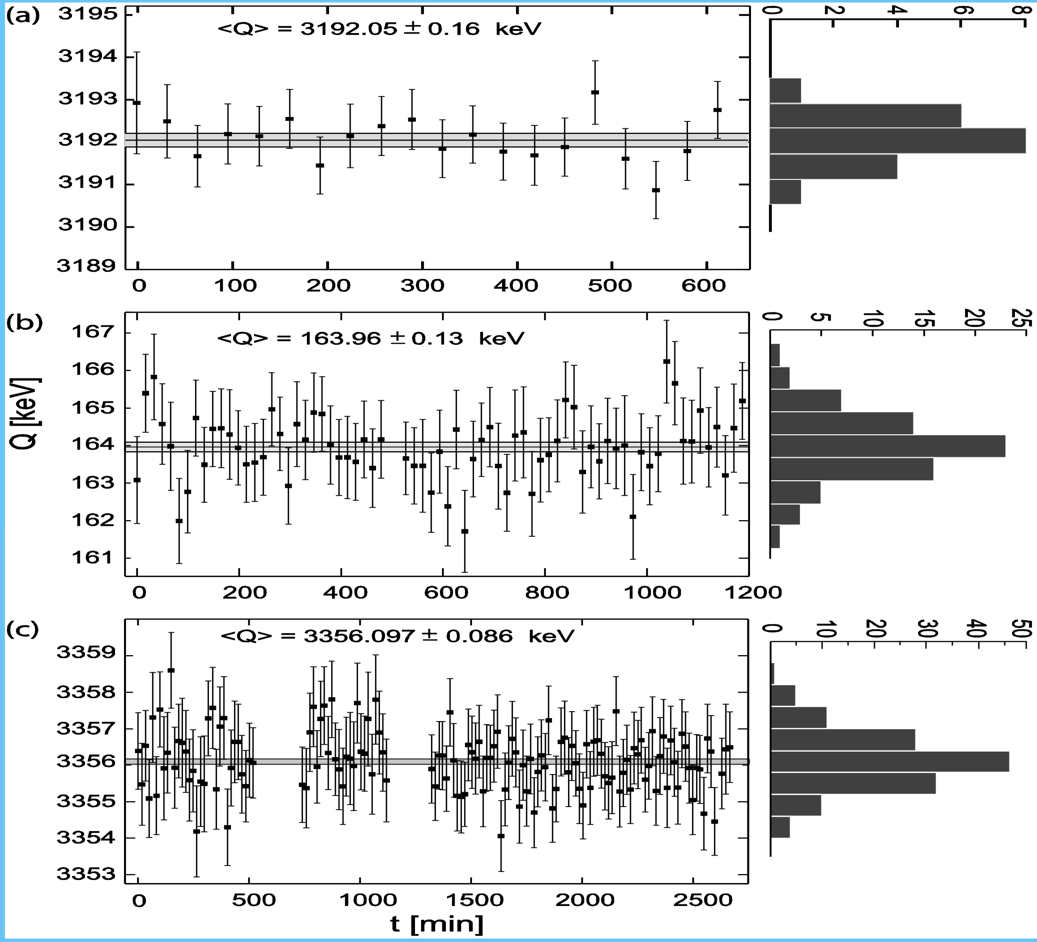


The measured cyclotron frequency of ^{96}Zr and ^{96}Nb by

Ramsey excitation pattern 25-750-25 (on-off-on)

Q-value results





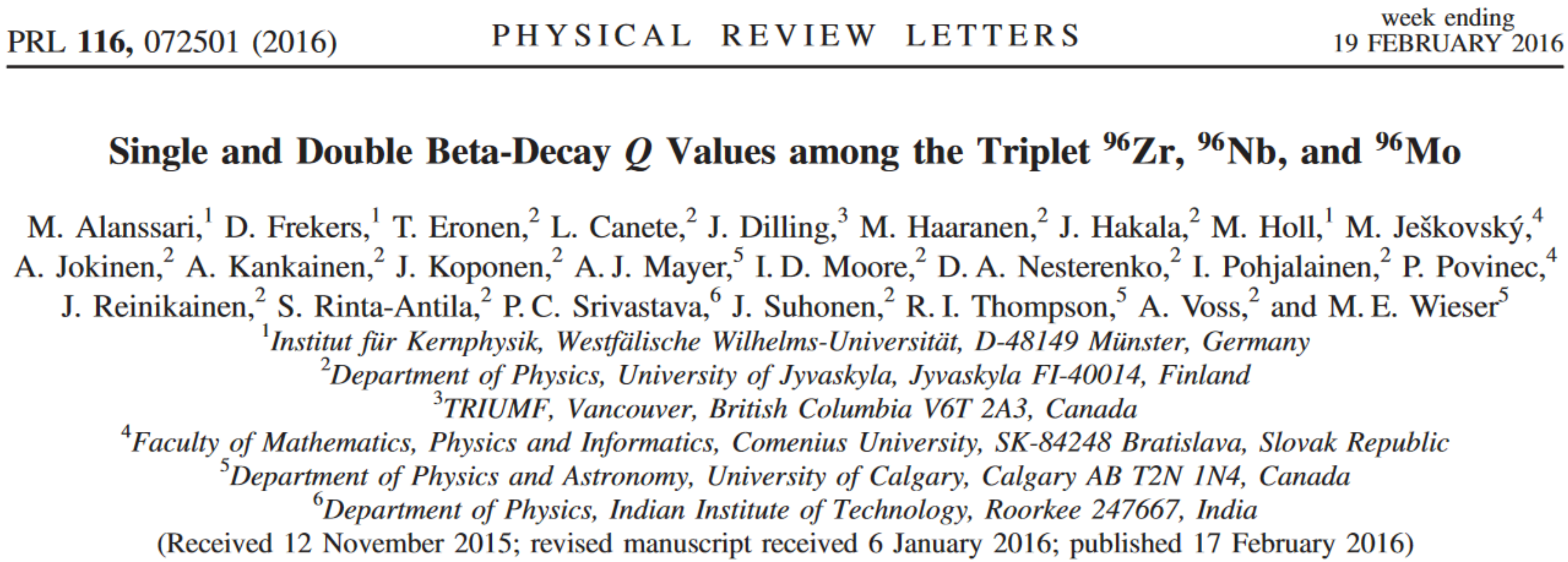
^{96}Zr

$$Q_{\beta\beta} = 3356.097 \pm 0.086\ \text{keV}$$

7.1 keV higher than AME2012

$$Q_{\beta} = 163.96 \pm 0.13\ \text{keV}$$

The measured single β^- and $\beta^-\beta^-$ decay Q-values of the A=96 triplet



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Single and Double Beta-Decay *Q* Values among the Triplet ^{96}Zr, ^{96}Nb, and ^{96}Mo

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Jyvaskyla, Finland
July – 2015

Jyvaskyla, Finland
Feb. – 2016

Summary

- Q-value of ^{96}Zr - ^{96}Nb 4-fold forbidden single β decay is measured for the first time using mass spectrometry
- Q-value sets ground for the new measurement of the ^{96}Zr-^{96}Nb half-life
- The Q-value & half-life allow extracting the NME for the 4-fold forbidden decay and comparing with theory calculations
- The comparison provides a test for the 0νββ NME calculations for the same ^{96}Zr nucleus
- The single β decay $\propto g_A^2$ while the known 2νββ decay scales with g_A^4 !!! this allows comparison of the g_A quenching within the same ^{96}Zr nucleus

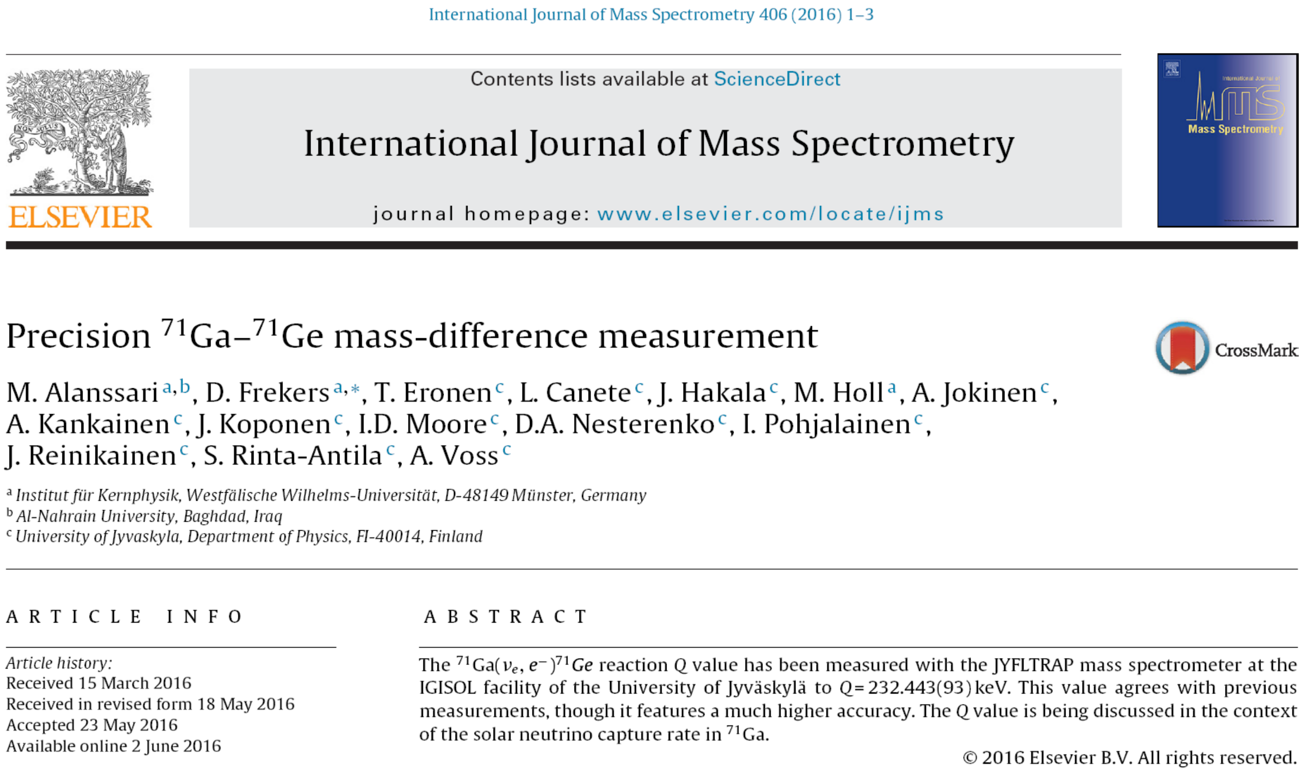
Next step: the $T_{1/2}$ of single β- decay has to be measured

^{71}Ga - ^{71}Ge Q-value

In the context of solar neutrinos

The ^{71}Ga (ν_e, e) ^{71}Ge reaction Q-value has been measured in JYFLTRAP

Q = 232.443 ± 0.093 KeV



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Precision ^{71}Ga–^{71}Ge mass-difference measurement

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ABSTRACT

The ^{71}Ga$(\nu_e, e^-)^{71}$*Ge* reaction *Q* value has been measured with the JYFLTRAP mass spectrometer at the IGISOL facility of the University of Jyväskylä to *Q* = 232.443(93) keV. This value agrees with previous measurements, though it features a much higher accuracy. The *Q* value is being discussed in the context of the solar neutrino capture rate in ^{71}Ga.

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