Geochemical measurement of the half-life of the double-beta decay of ^{96}Zr

Dr. Adam Mayer[1]

D. Frekers[2], M.E. Wieser[1], R.I. Thompson[1], J. Dilling[3]

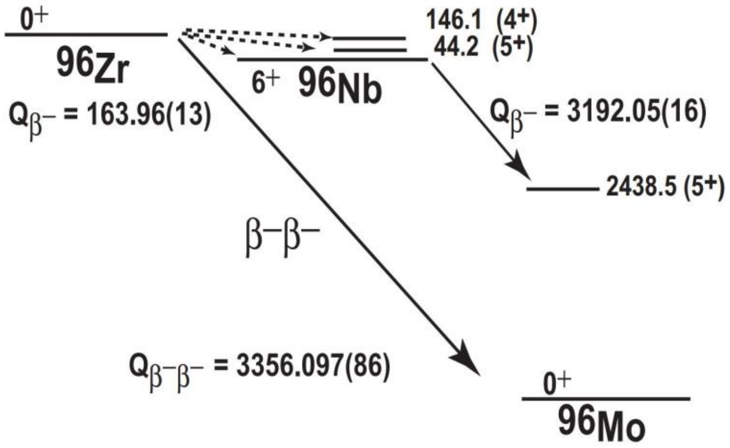
[1]Department of Physics and Astronomy, University of Calgary, Calgary, AB, Canada
[2]Institut für Kernphysik, Westfälische Wilhelms-Universität, Münster, Germany
[3]TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada

Project Overview

- Studying the decay (ββ and β) of $^{96}Zr \rightarrow {}^{96}Mo$
  - System provides unique insights into double-beta decay
- We are studying two properties:
  - Q value ***(completed 2015, published PRL 116 (2016))***
  - Half-life ***(completed 2017, publishing soon)***

^{96}Zr Decay

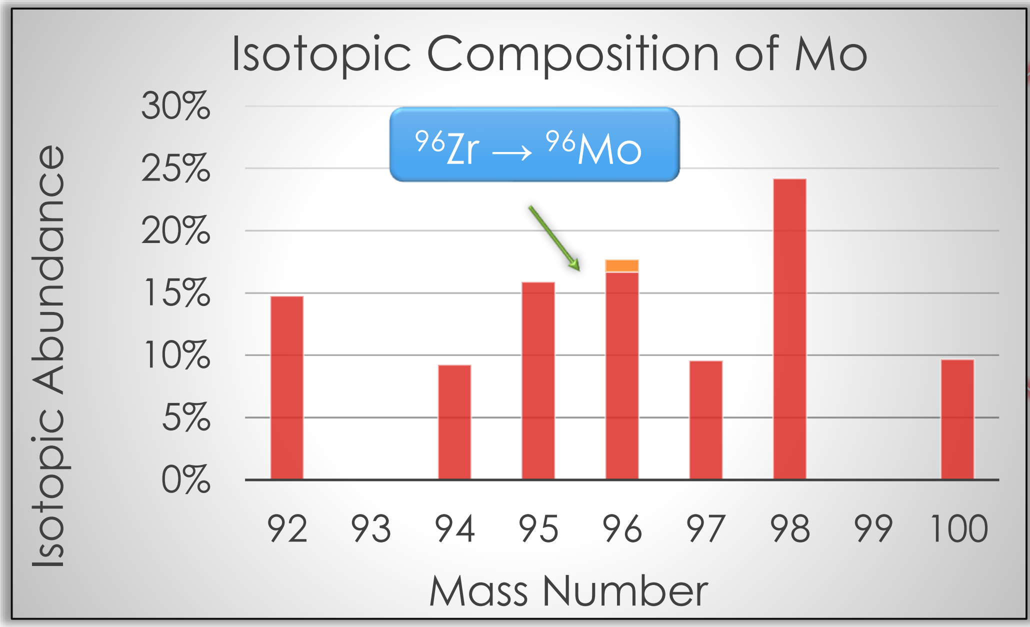
- ^{96}Zr is of particular interest:
  - One of the largest Q values and shortest half-lives
  - Unstable against single β-decay (4^{th} order forbidden)
- Previous measurements of half-life did not agree:
  - Geochemical measurements:
    - $3.9(9) \times 10^{19}$ yr (1993)
    - $0.94(32) \times 10^{19}$ yr (2001)
  - Direct count-rate measurement:
    - $2.35(30) \times 10^{19}$ yr (2010)



Zircons

- Zircon, or $ZrSiO_4$, is a highly stable mineral
- Can remain a closed system over billions of years
  - Evidenced by accurate (concordant) U-Pb ages
- Large amount of zirconium (~50 wt%)
  - ^{96}Zr is 2.80% of zirconium
- Very little molybdenum (< ppm)

Double-beta decay half-life by stable isotope geochemistry



Zircon

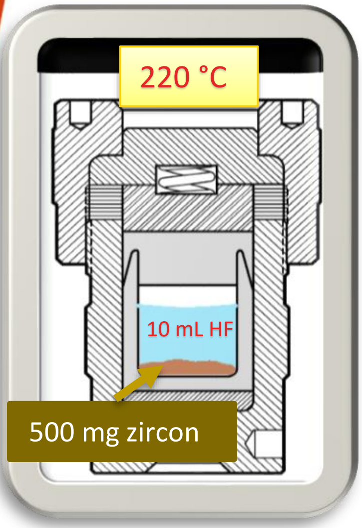
0.5 – 2.5 Ga

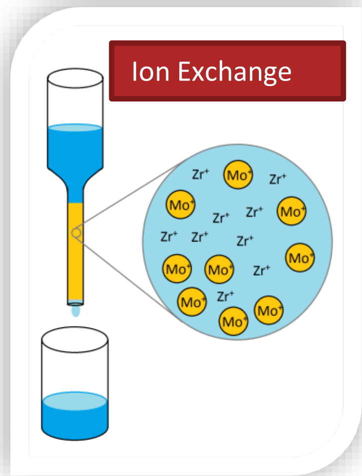
$ZrSiO_4$

2.8 % ^{96}Zr

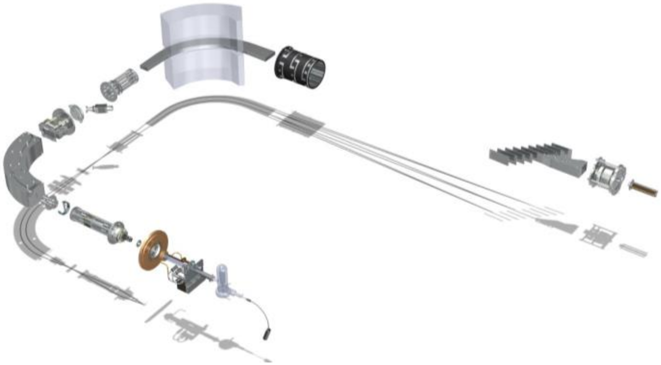
$^{96}Zr \rightarrow {}^{96}Mo + 2e^- + 2\bar{\nu}$

Zircon sample prep and analysis





Thermo Scientific Neptune: Multi-collector inductively coupled plasma mass spectrometer



Need maximum recovery (achieved >60 %)

Need $>10^7$ reduction in Zr (achieved $\sim 10^9$!)

Zr and Ru isobaric interference correction; <50 ppm precision (achieved 20 ppm)

Half-life calculation

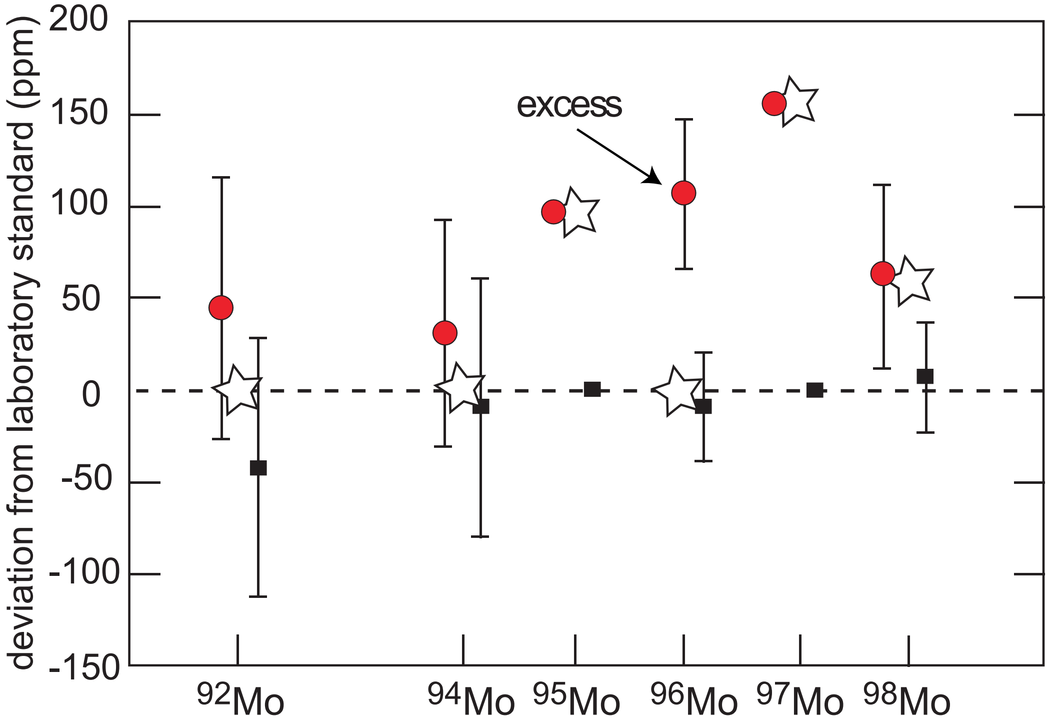
$$t_{1/2} = \frac{-t \ln(2)}{\ln(1 - n_d/n_0)}$$

n_d daughter product: $\quad n_d(^{96}\text{Mo}) = \frac{m_{\text{Mo}} N_A}{A_W(\text{Mo})} \, \text{C}(^{96}\text{Mo}) \, \delta(^{96}\text{Mo})$

n_0 parent: $\quad n_0(^{96}\text{Zr}) \cong \frac{m_{\text{Zr}} N_A}{A_W(\text{Zr})} \, \text{C}(^{96}\text{Zr})$

$$\frac{n_d}{n_0} = \frac{m_{\text{Mo}}}{m_{\text{Zr}}} \frac{A_W(\text{Zr})}{A_W(\text{Mo})} \frac{\text{C}(^{96}\text{Mo})}{\text{C}(^{96}\text{Zr})} \delta(^{96}\text{Mo})$$

Geochemical results



- Red shows 2.68 Gyr zircon
- Stars show expected U spontaneous fission decay
- Black shows 1 Gyr zircon

^{97}Mo/^{95}Mo fixed to expected U-SF decay pattery

^{96}Zr Half-life

	Nov-2017	Apr-2018
$m_{\mathrm{Mo}}/m_{\mathrm{Zr}}$ (ng/g)	173(32)	181(27)
$\delta(^{96}\mathrm{Mo})$ (ppm)	107(35)	88(19)
Half-life (10^{19} yr)	1.77(+0.71, -0.39)	2.09(+0.51, -0.34)

$$T_{1/2} = 2.03^{+0.46}_{-0.31} \cdot 10^{19}\ \mathrm{yr}$$

Compare this to NEMO $\beta\beta$ half-life of: $T_{1/2}^{\beta\beta}(2.35 \pm 0.21) \cdot 10^{19}$ yr

$$T_{1/2}^{\beta} > 5.2 \cdot 10^{19}\ \mathrm{yr}$$

Contributions to uncertainty

Parameter	Contribution
Age	0.0%
[U]	35.0%
mMo/mZr	6.2%
Zr Composition	2.7%
Mo Composition	7.1%
Delta-96Mo	49.0%

Improvements to results require better $\delta(^{96}\mathrm{Mo})$ result.
To achieve this would require a larger sample with a lower "common" Mo content.

Future endeavors

- We have resolved the discrepancy between previous geochemical measurements and counting-rate experiments
- Search for new high-quality ancient zircon samples with lower Mo content to measure.
  - A significant improvement in uncertainty is possible, and could yield the first measurement of the ^{96}Zr single-beta decay rate
- Develop technique to fully separate ruthenium from very large quantity of zirconium (>10^{10} separation required)
  - Possible to improve lower limits of ^{96}Zr quadruple-beta decay rate by **two orders of magnitude.**