Superallowed Fermi β Decay

The low-energy precision frontier of nuclear physics

EIEIOO 2024

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@gwendoesscience

Hi! I'm Gwen!

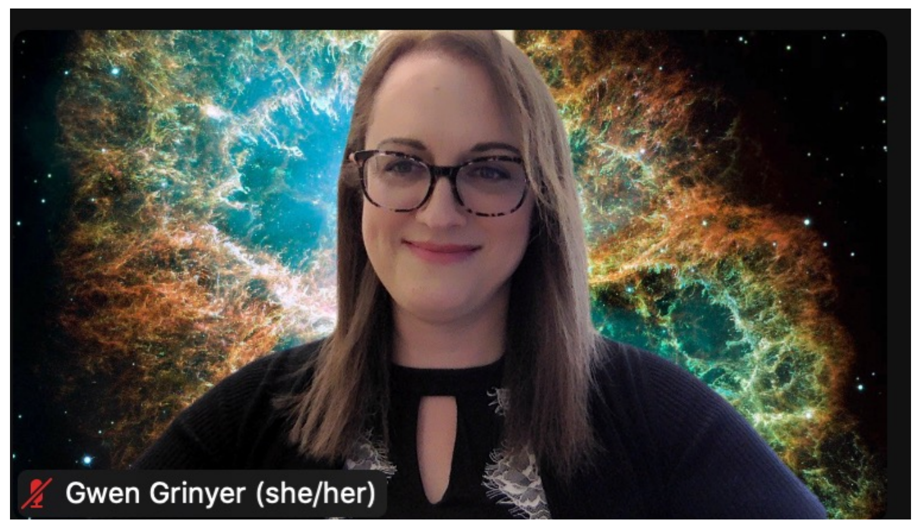
- **My academic journey:**
  - 🇨🇦 **B.Sc. McMaster University (2002)**
  - 🇨🇦 **M.Sc. University of Guelph (2004)**
  - 🇨🇦 **Ph.D. University of Guelph (2008)**
  - 🇺🇸 **PDF Michigan State (2008-2010)**
  - 🇫🇷 **Staff scientist CEA (2010-2017)**
  - 🇨🇦 **Professor U Regina (since 2017)**

- **My lived experience:**
  - **Experimental nuclear physicist**
  - **First generation academic**
  - **Mom of 3 kids (ages 8, 15, 17)**
  - **Woman and LGBT in physics**

- **Passionate about EDI in STEM**

  @gwendoesscience

Photo by Evie Johnny Ruddy



Nuclear β decay

- **A neutron turns into a proton (or vice versa)**

β⁻ $^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^{-} + \overline{\nu_{e}},$

neutron ⟶ proton

β⁺ $^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z-1}W_{N+1} + e^{+} + \nu_{e}.$

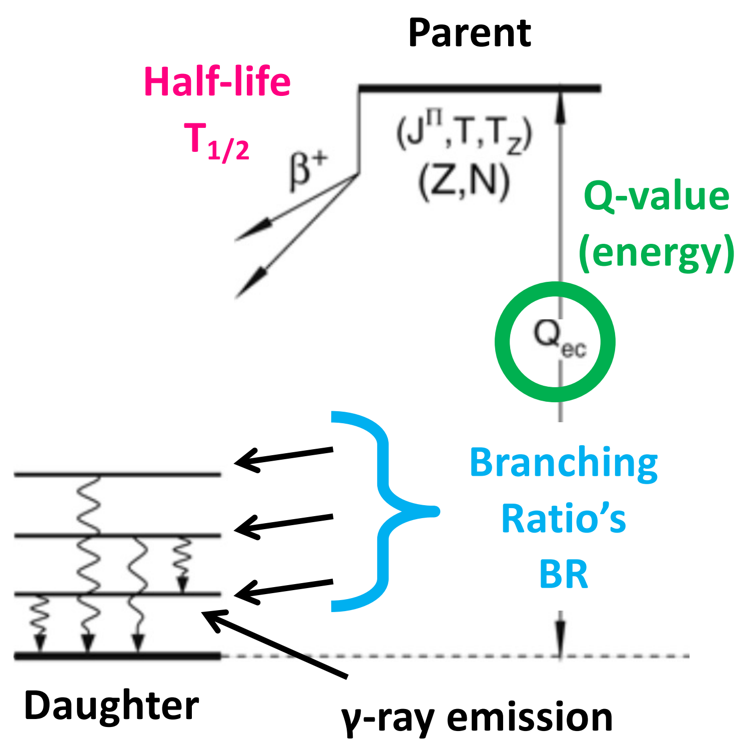
proton ⟶ neutron

- **Momentum conservation & selection rules:**

$$\vec{J}_P = \vec{J}_D + \vec{L} + \vec{S} \qquad \pi_P = \pi_D(-1)^L$$

- **Allowed decays (L=0)**
- **Forbidden decays (L=1,2,3,…)**

- **Fermi decays (S=0)**
- **Gamow-Teller decays (S=1)**



Half-lives and *ft* values

B.Singh *et al.* Nucl. Data Sheets 84, 487 (1998)

Case	J^{π} (P→D)	Classification	$T_{1/2}$	Fraction
$^{18}N \rightarrow ^{18}C$	$1^{-} \rightarrow 1^{-}$	Allowed (GT&F)	624 ms	64% "Superallowed"
$^{6}He \rightarrow ^{6}Li$	$0^{+} \rightarrow 1^{+}$	Allowed (GT only)	807 ms	
$^{10}C \rightarrow ^{10}B$	$0^{+} \rightarrow 0^{+}$	Allowed (F only)	19 s	1%
$^{38}Cl \rightarrow ^{38}Ar$	$2^{-} \rightarrow 2^{+}$	1st Forbidden	37 min	33%
$^{36}Cl \rightarrow ^{36}Ar$	$2^{+} \rightarrow 0^{+}$	2nd Forbidden	3×10^{5} years	1%
$^{40}K \rightarrow ^{40}Ca$	$4^{-} \rightarrow 0^{+}$	3rd Forbidden	1×10^{9} years	0.1%
$^{50}V \rightarrow ^{50}Cr$	$6^{+} \rightarrow 2^{+}$	4th Forbidden	1×10^{17} years	0.1%

- The *ft* value is a convenient way to characterize nuclear β decay

Half-life

Q-value →

$$ft = \frac{fT_{1/2}}{BR} = \frac{K}{g^2|M_{fi}|^2}$$

← Constants

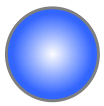
Branching Ratio →

← Matrix element

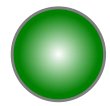
Strength

Nuclear Isotopic Spin (Isospin)

- **Introduced by Heisenberg in 1932**
  - **Protons and neutrons – (iso)spin projections of the "nucleon"**

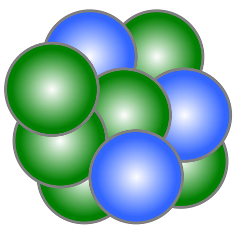


$$t_z(p) = -\frac{1}{2}$$



$$t_z(n) = +\frac{1}{2}$$

- **Total isospin (T) and isospin projection T_z of the nucleus**



$$T_z = \frac{1}{2}(N - Z) \quad \mathbf{T} = |T_z|, |T_z| + 1, \cdots, \frac{N+Z}{2}$$

- **Nuclear β decay is a neutron changing into a proton (or vice versa)**
  - **Fermi decay between "isobaric analogue states" is a ladder operator**

$$|M_F|^2 = (T \mp T_z)(T \pm T_z + 1)$$

For T = 1 decays → $|M_F|^2 = 2$

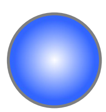
Exact!
(to extent that isospin valid)

Conserved Vector Current Hypothesis (CVC)

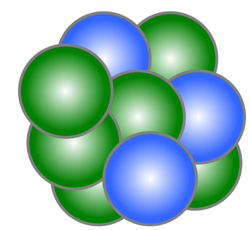
- **The *ft* values for superallowed Fermi decays… should be constant!**

$$ft = \frac{fT_{1/2}}{BR} = \frac{K}{2{G_V}^2} = \text{constant} \ \textbf{?}$$

- **CVC hypothesis (based on analogy to electrodynamics)**
  - **A universal coupling constant – the electric charge “e”**

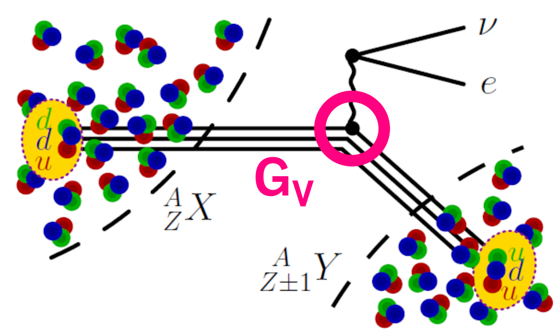


e = 1.602 176 487 x 10^{-19} C



  - **The weak interaction is also thought to have a universal coupling constant!**

G_V = 1.13621 x 10^{-5} GeV^{-2}

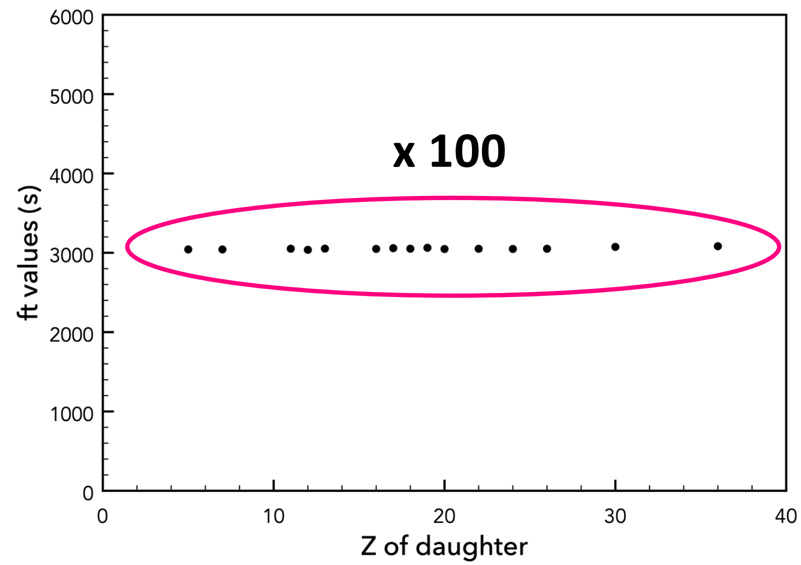


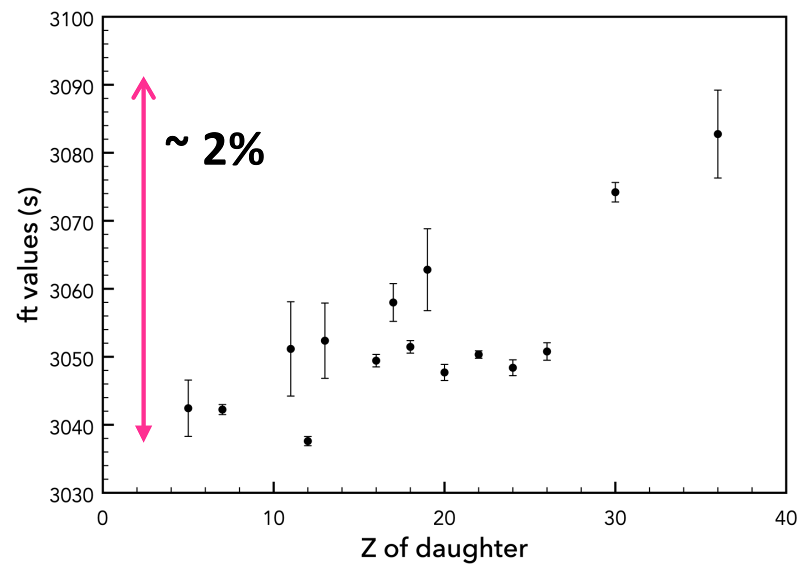
R.P.Feynman and M.Gell-Man PR 109, 193 (1958)

Superallowed *ft* values

J.C.Hardy and I.S. Towner PRC 102, 045501 (2020)

- **World survey of superallowed decays**
  - **> 220 independent measurements**
- **Superallowed *ft* values**
  - **Range from 3040 s to 3100 s (2%)**
  - **Higher-order effects (theory)**





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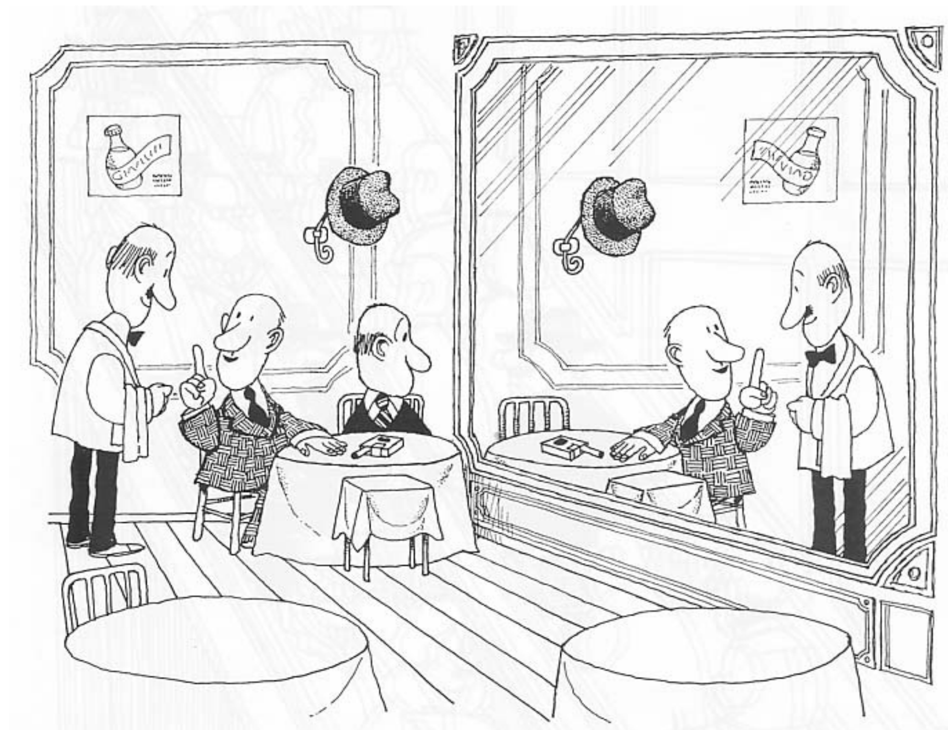
  - **Broken by charge dependent forces**

$$|M_F|^2 = 2(1 - \delta_C)$$



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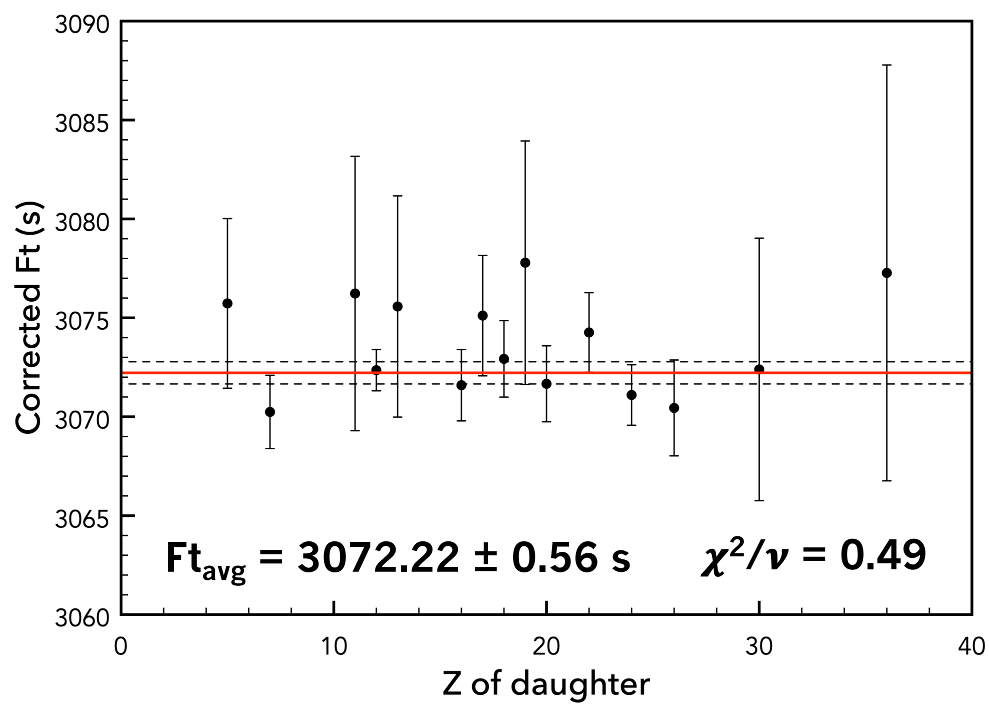
$$|M_F|^2 = 2(1 - \delta_C)$$

- **Corrected Ft values**
  - **Constant at the level of 9×10^{-5}**
  - **Validation of the CVC hypothesis**
  - **Strong constraint on "new physics"**



Wilkinson's Methods

Dhruval Shah (University of Regina)

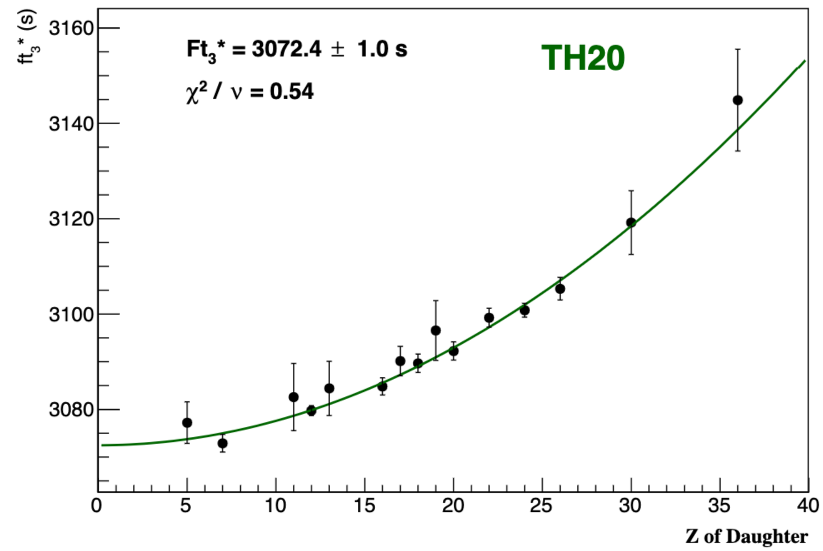
- Alternative method to extract Ft_{avg}
  - Constraint for theoretical δ_C models
- Since ISB is charge dependent
  - Remove Coulomb part of the correction
  - Perform a simple quadratic fit
  - Then extrapolate the data to Z = 0
- This works remarkably well!

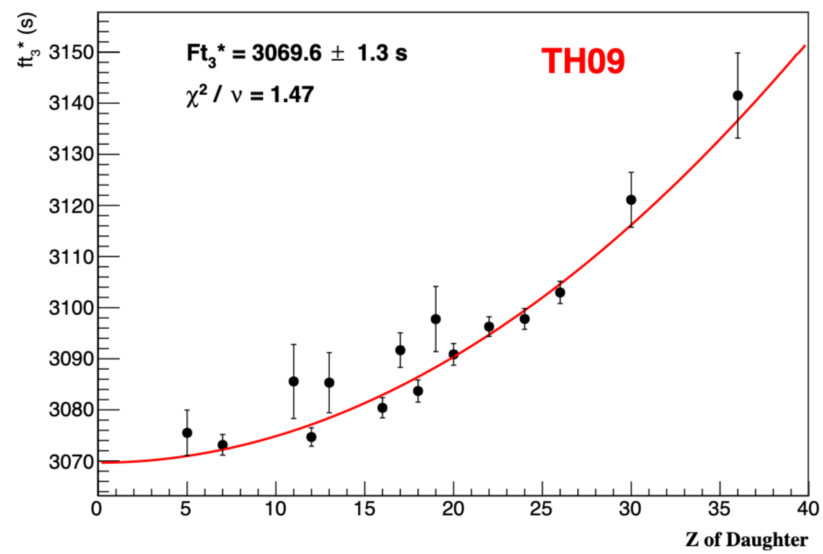
Ft_{avg} = 3071.6 ± 1.6 s D. Shah (UofR)

Ft_{avg} = 3072.2 ± 1.9 s Hardy and Towner (2020)

- Almost no change in 15 years!
  - Wilkinson analysis performed in 2010

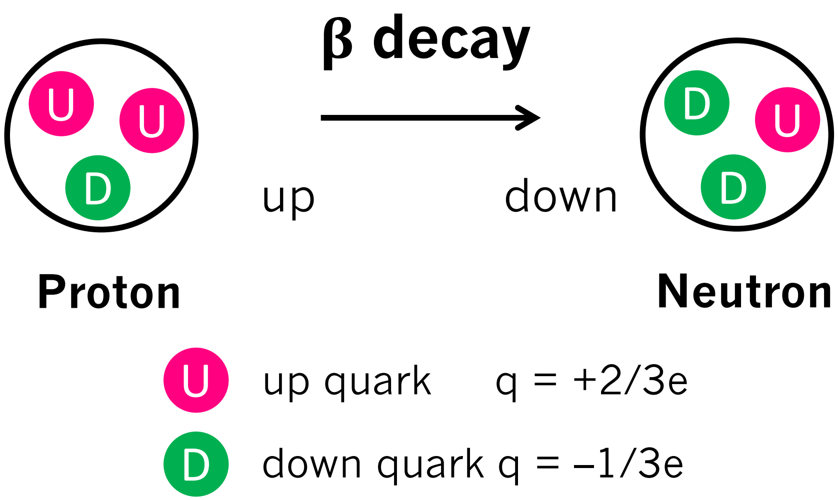
Ft_{avg} = 3071.5 ± 1.4 s Grinyer *et al.* (2010)





Cabibbo-Kobayashi-Maskawa (CKM) Matrix

- **The CKM matrix plays a central role in the Standard Model**
  - **It describes *all* quark flavour changing interactions (including β decay)**
  - **Given that there are 3 quark generations, CKM is a 3x3 matrix**



CKM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- **In the Standard Model the CKM matrix describes a *unitary* transformation**

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

CKM Unitarity Test

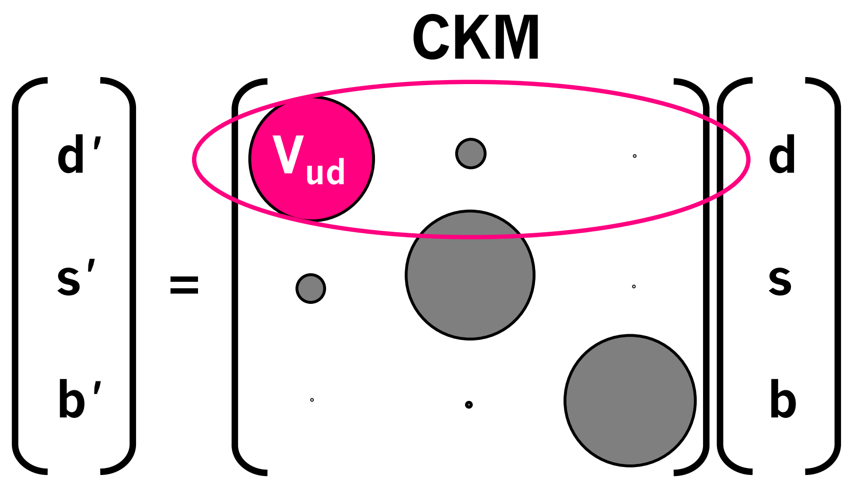
J.C.Hardy and I.S. Towner PRC 102, 045501 (2020)

- **The most precise test of CKM unitarity comes from the** *top row*
  - **V_{ud} is by far the largest and is obtained precisely from superallowed decays**

Constants

$$|V_{ud}|^2 = \frac{2912.95 \pm 0.54}{\overline{\mathcal{F}t}}$$

Average Ft value **from 15 superallowed Fermi transitions between ^{10}C and ^{74}Rb**



$|V_{ud}|$ = 0.97373(31)
$|V_{us}|$ = 0.2243(8)
$|V_{ub}|$ = 0.00382(20)

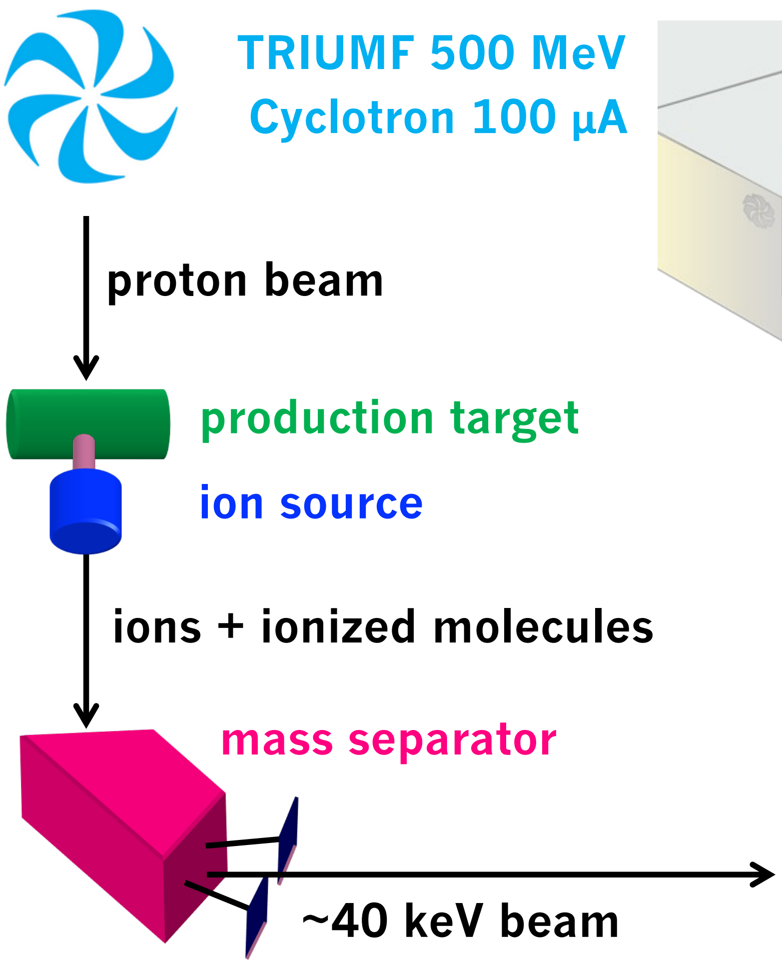
- **Present status of the test of CKM unitarity:**

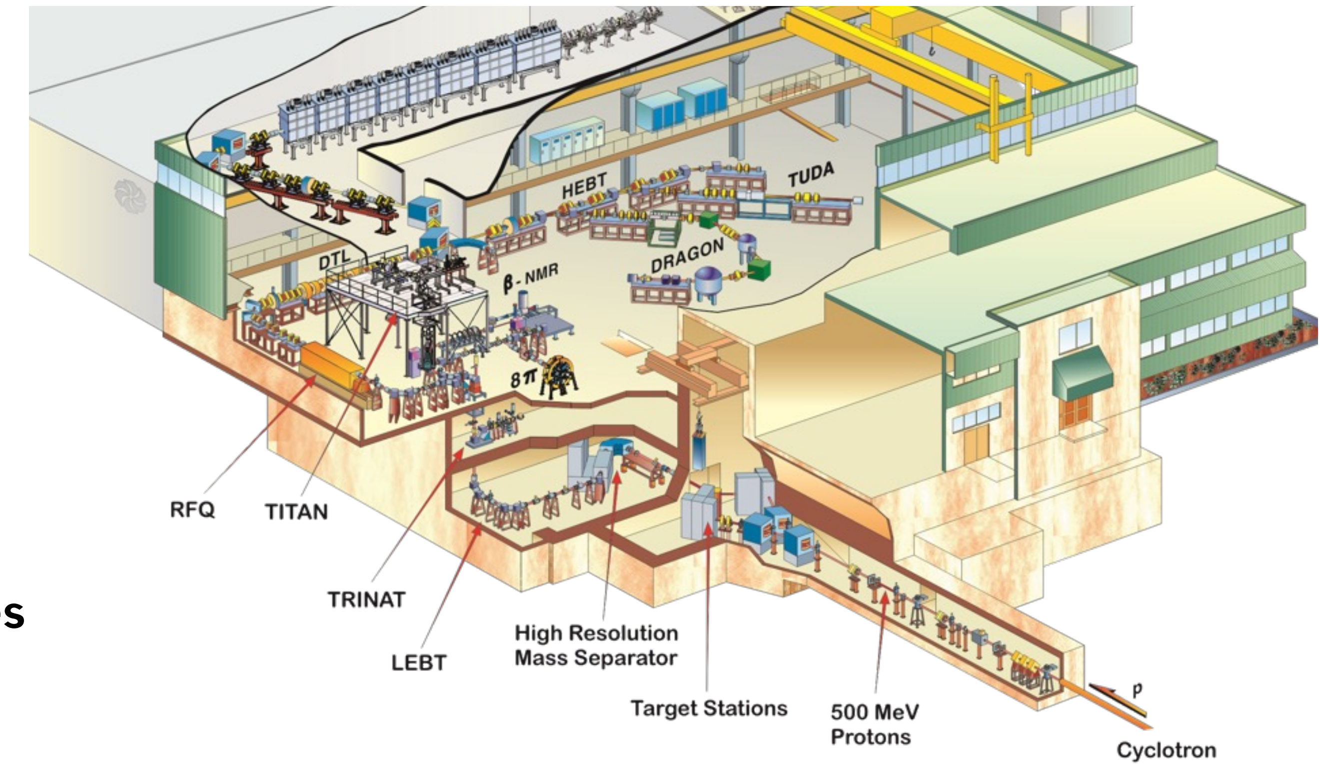
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(7)$$

2.1σ deviation from unity!!!

TRIUMF's ISAC Facility

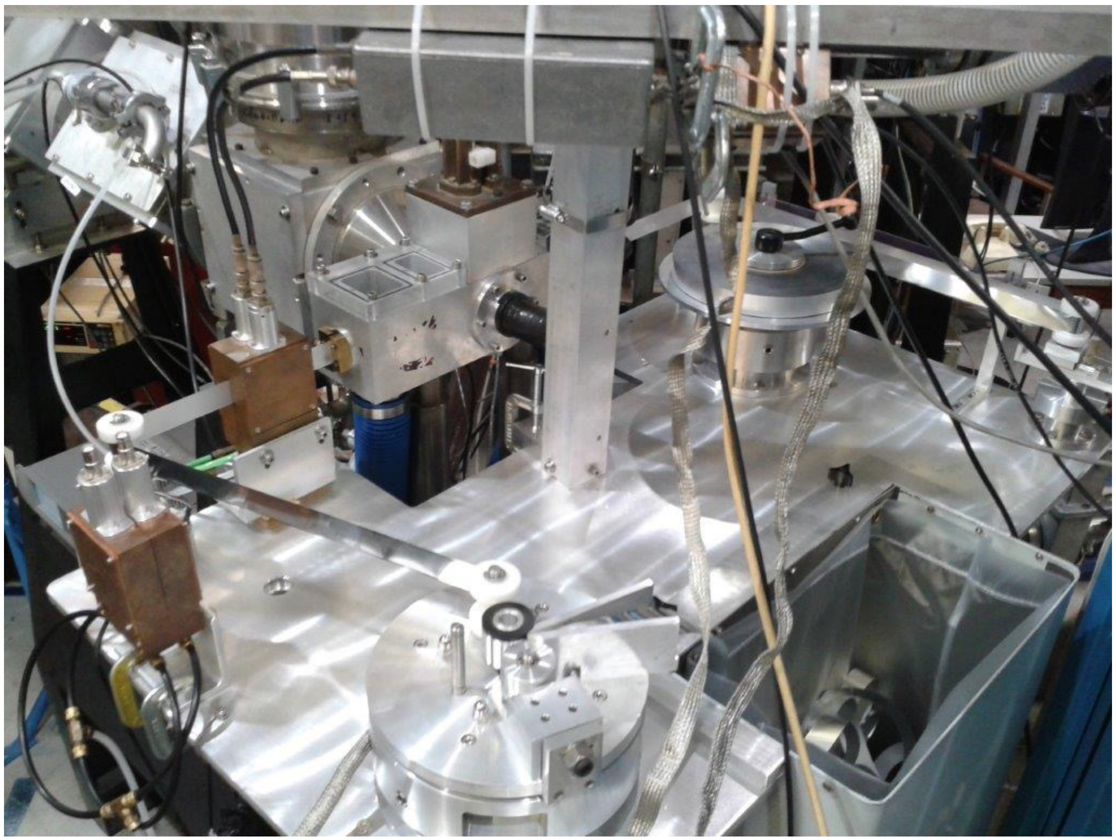
- Canada's National Laboratory for Nuclear and Particle Physics
  - Isotope Separator and Accelerator (ISAC)

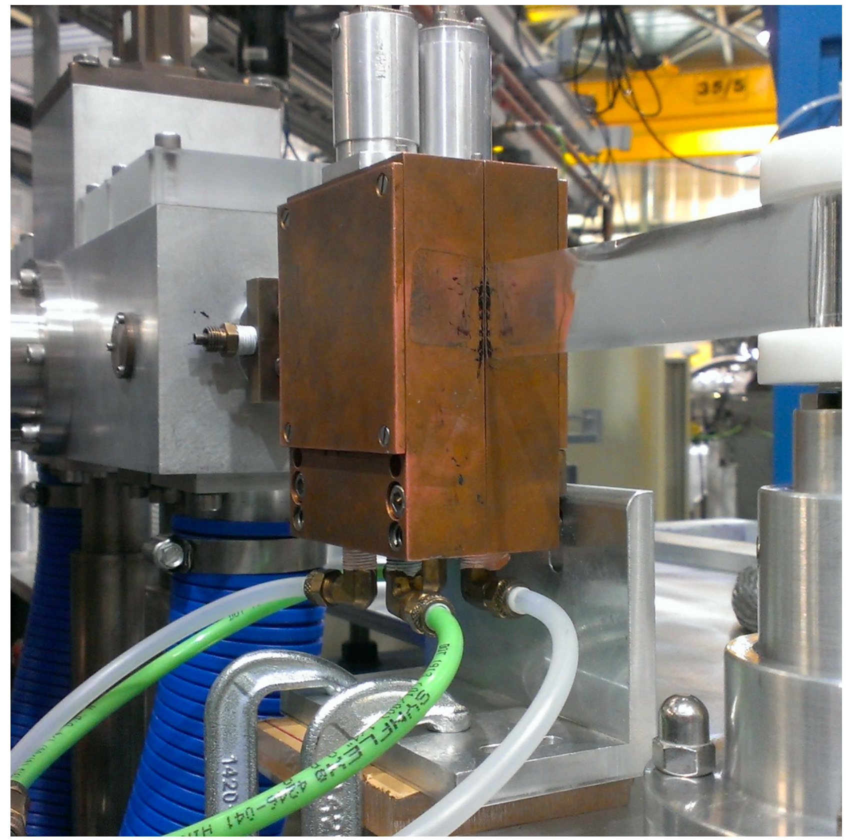




High-Precision Half-Life Measurements

- **We use a gas proportional counter and a fast tape transport system**
  - **Implant radioactive isotopes from ISAC onto a tape (collection period)**
  - **Rapidly move the sample into a gas counter (beta particles ionize the gas)**
  - **Record the radioactive decay of the sample (exponential decay law)**

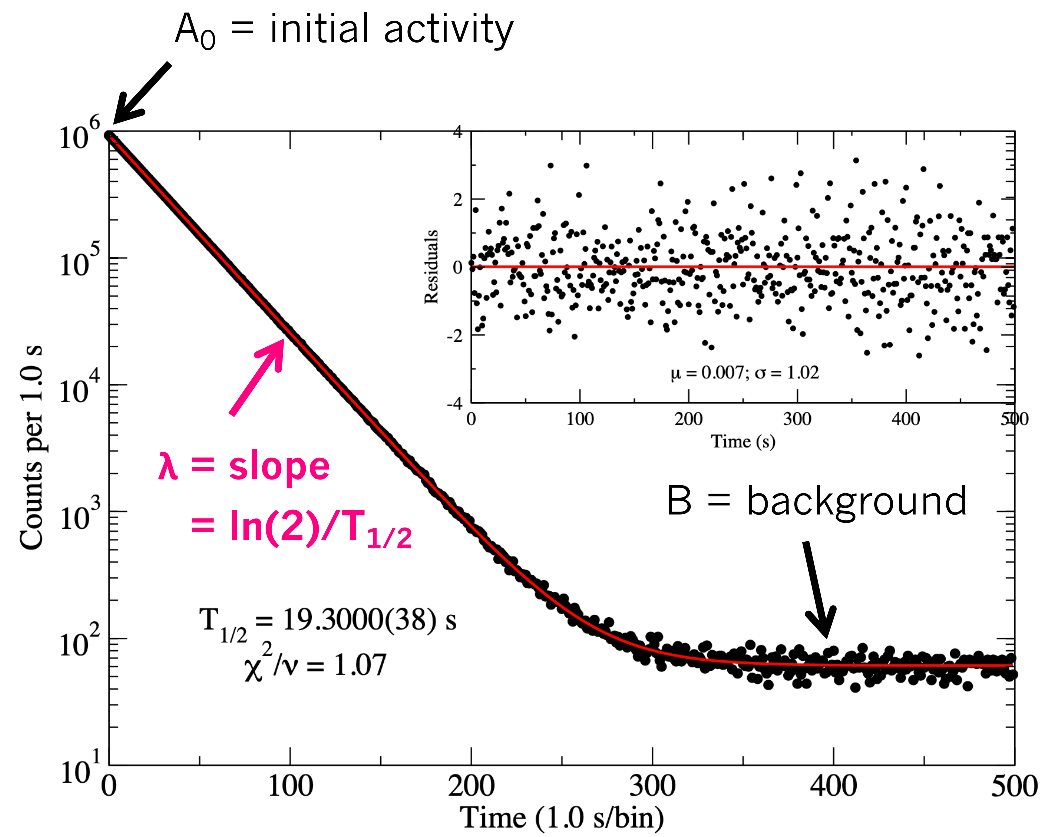




Half-life of ^{10}C

M.R.Dunlop *et al.* PRL 116, 172501 (2016)

- **Beam of radioactive ^{10}C**
  - **Intensity ~10^5 ions/s**
- **Data from 1 cycle (~ 8 mins)**
  - **Precision ± 0.07%**
- **Total of 550 cycles (4 days)**
  - **$T_{1/2}$ = 19.3009(17) s**



$$A(t) = A_0 e^{-\lambda t} + B$$

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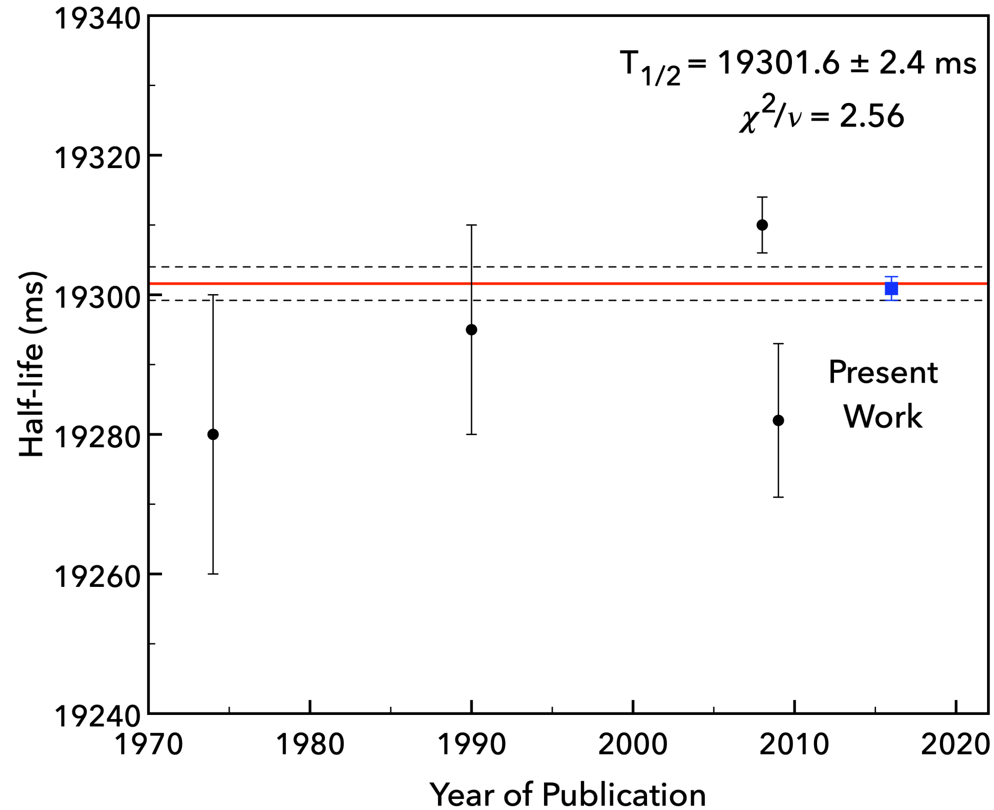
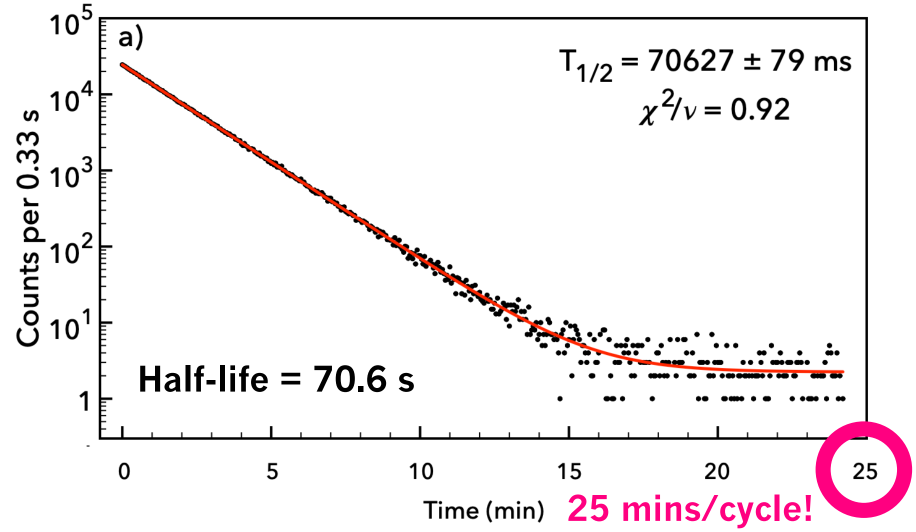
- **Total of 550 cycles (4 days)**
  - **$T_{1/2}$ = 19.3009(17) s**
- **Systematic uncertainties**
  - **The most important part!**
- **Half-life of ^{10}C @ TRIUMF**
  - **Overall precision ± 0.009%**
  - **Most precise $T_{1/2}$ ever reported!**

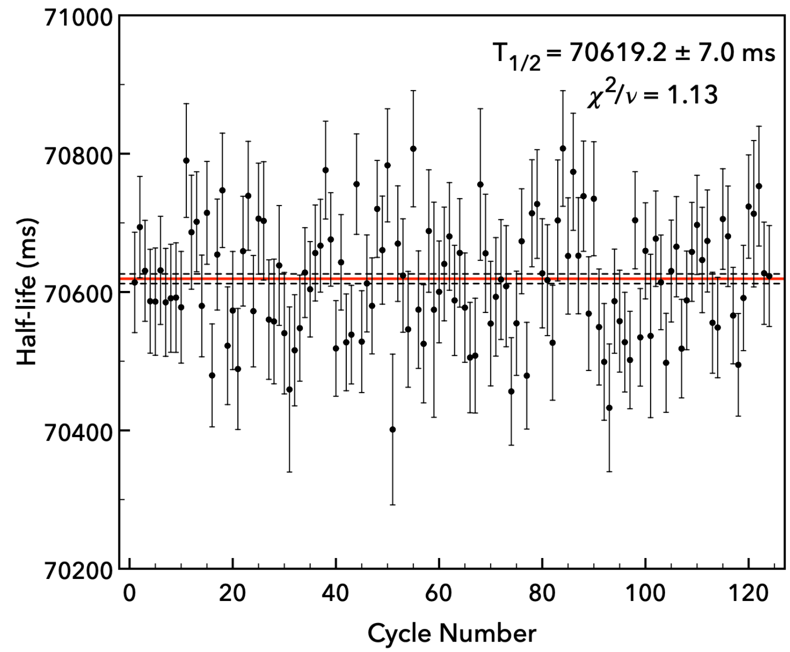


Half-life of ^{14}O

S.Sharma *et al.* E. Phys. J. A 58, 83 (2022)

- **Beam of radioactive ^{14}O**
  - **Intensity ~10^5 ions/s**
- **Data from 1 cycle (~ 25 mins)**
  - **Precision ± 0.10%**
- **Total of 124 cycles (3 days)**
  - **$T_{1/2}$ = 70.6192(76) s**





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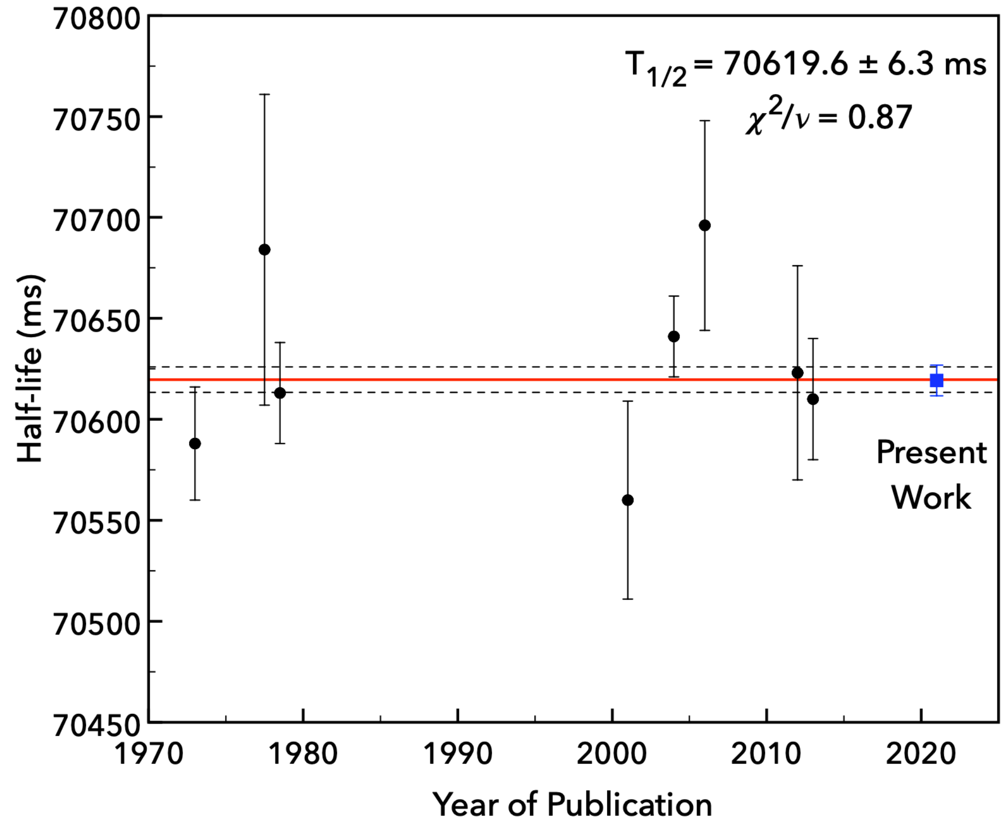
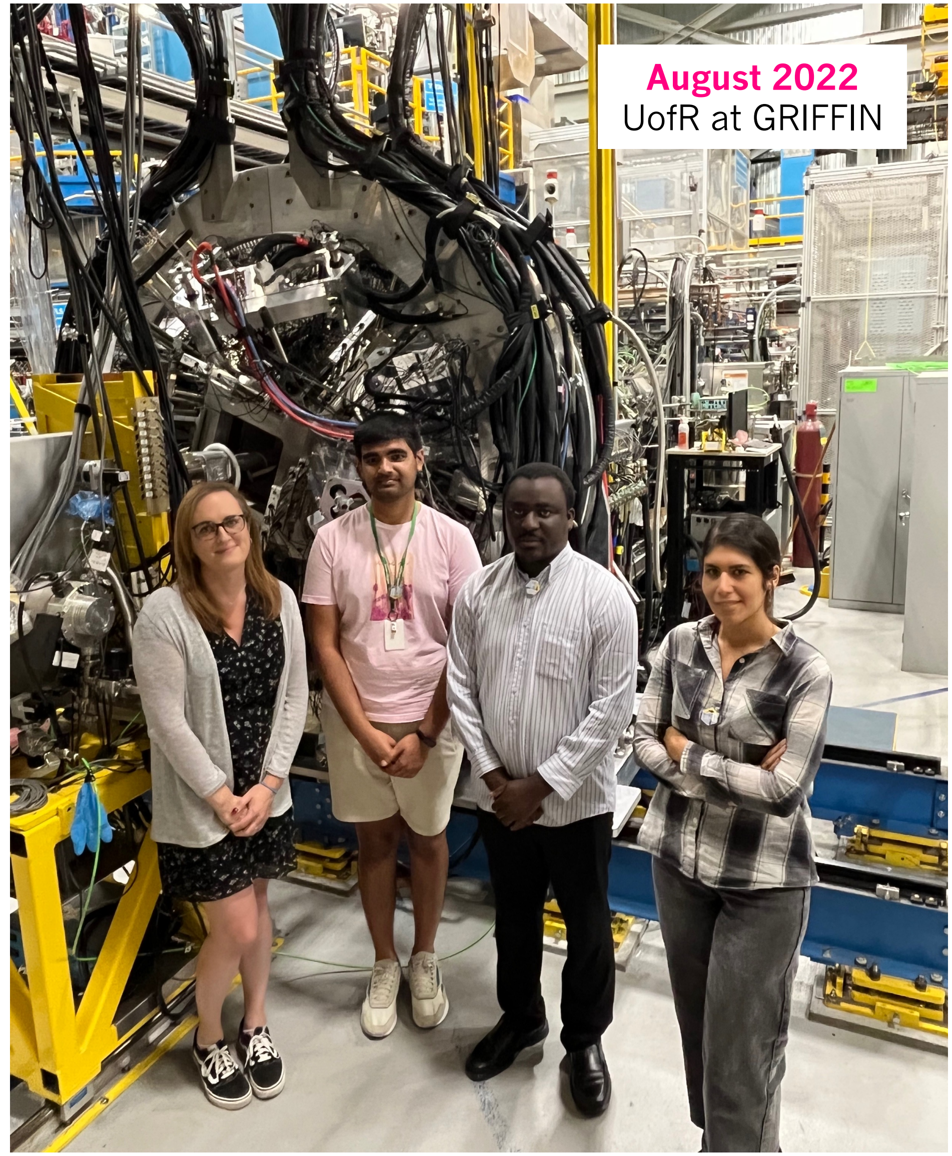
  - **Precision ± 0.10%**
- **Total of 124 cycles (3 days)**
  - **$T_{1/2}$ = 70.6192(76) s**
- **Half-life of ^{14}O @ TRIUMF**
  - **Overall precision ± 0.010%**
  - **Comparable precision to ^{10}C!**
- **Article published in 2022!**
  - **Shivani Sharma, U of R**
  - **Now at Sunnybrook Hospital**



Next generation: GRIFFIN

TRIUMF

- **New HPGe γ-ray spectrometer**
  - **16 large volume "clover" detectors**
  - **Fully operational since 2015**
- **Experiment S1140: Half-life of ^{14}O**
  - **Statistical precision ± 0.03%**
- **Regina students lead the analysis!**
  - **Ugrad Dhruval Shah**
  - **M.Sc. Nastaran Saei**
  - **M.Sc. Jizhong Liu**
  - **Ph.D. Eric Gyabeng Fuakye**
- **Experiment S1848: BR of ^{34}Ar**
  - **New experiment at ISAC!**
  - **Performed in June/July 2023**
  - **M.Sc. Mira Rupert**



August 2022
UofR at GRIFFIN

My newest adventure!

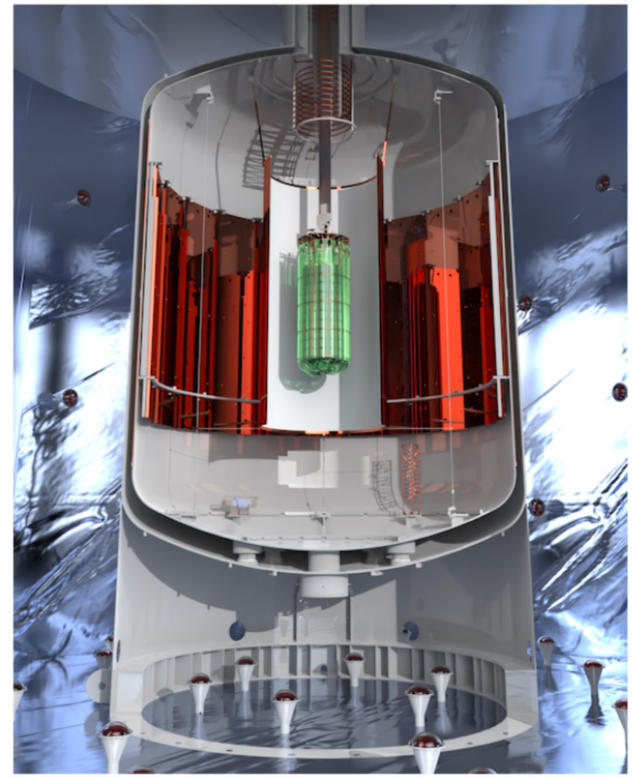
- **Large Enriched Germanium Experiment for Neutrinoless Double β decay**
  - **Deep underground ton-scale detector**

2νββ $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^- + 2\overline{\nu_e}$

0νββ $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^- + 0\overline{\nu_e}$

- **Physics program**
  - **Search for 0νββ decay in ^{76}Ge**
  - **Are neutrinos their own antiparticle?**
  - **Baryon asymmetry (matter/antimatter)**
  - **Lepton number violation (beyond SM)**

- **Legend 1000 baseline design**
  - **To probe 0νββ with 99.7% discovery CL**
  - **For a ^{76}Ge half-life > 10^{28} years**
  - **Background : 1 count per FWHM ton year!**
  - **Considering SNOLAB as a possible site**



LEGEND PCDR arXiv: 2107.11462 (2021)

LEGEND Canada

Queen's, Regina, SFU, SNOLAB

Thank you so much!

- **Superallowed Fermi β Decay**
  - **The low-energy precision frontier**
  - **Constrain the Standard Model**
  - **Demanding test of CKM unitarity**

- **Experiments at TRIUMF-ISAC**
  - **The best place for these studies**
  - **World-leading detectors/expertise**

- **Many other projects in my group!**
  - **Looking for students (Fall 2025)**

- **Please contact me if interested!!**

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