University of Regina

Superallowed Fermi β Decay

The low-energy precision frontier of nuclear physics

THIRD ANNUAL
summer particle
(astro) physics
workshop

Dr. Gwen Grinyer she/her/hers

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@gwendoesscience

Hi! I'm Gwen!

- A brief history of time:
  - 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) 🇫🇷
  - Asst. Prof. U Regina (since 2017) 🇨🇦

- A glimpse of who I am:
  - Experimental nuclear physicist
  - Builder of radiation detectors
  - Mom to 3 amazing kids
  - Passionate about EDI in STEM

- I post science stuff on Instagram:

  @gwendoesscience

Nuclear β decay

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

β⁻ $\quad {}^{A}_{Z}X_N \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^- + \overline{\nu_e},$

neutron ⟶ proton

β⁺ $\quad {}^{A}_{Z}X_N \rightarrow {}^{A}_{Z-1}W_{N+1} + e^+ + \nu_e.$

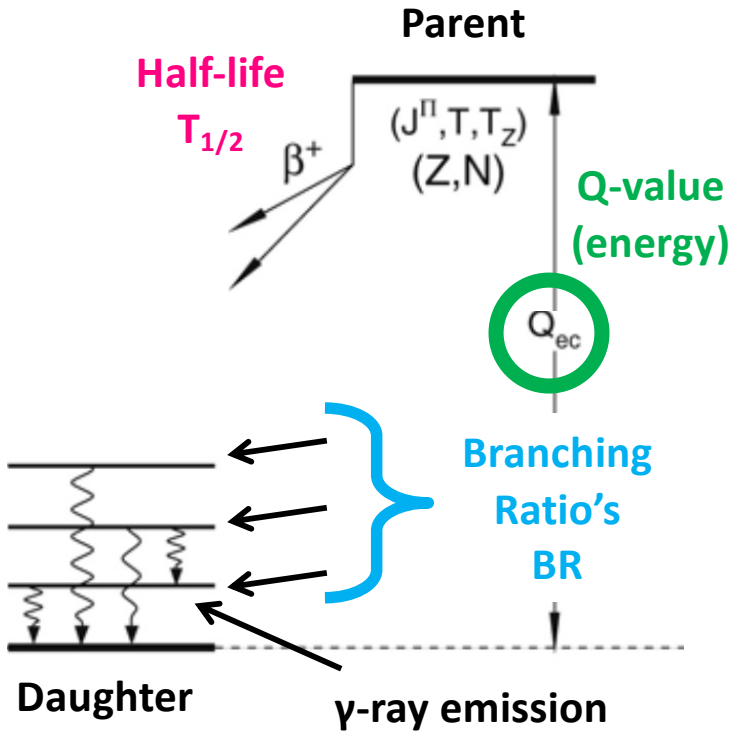
proton ⟶ neutron

- **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

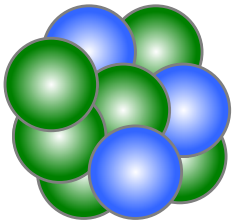
Nuclear Isotopic Spin (Isospin)

- **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 → $|M_F|^2 = 2$

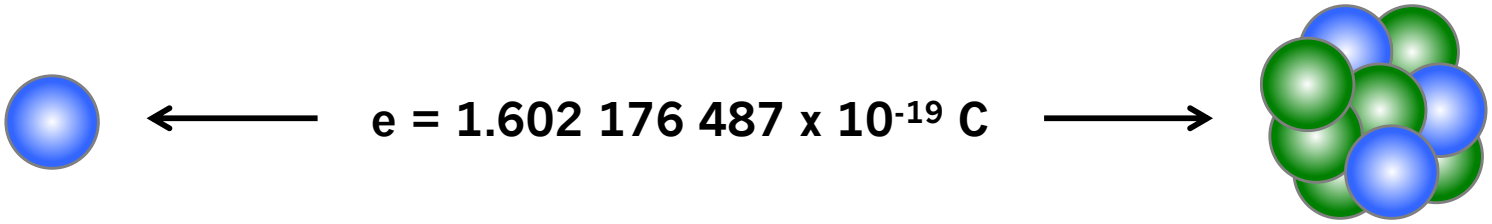
Exact!
(to extent that isospin valid)

Conserved Vector Current Hypothesis (CVC)

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

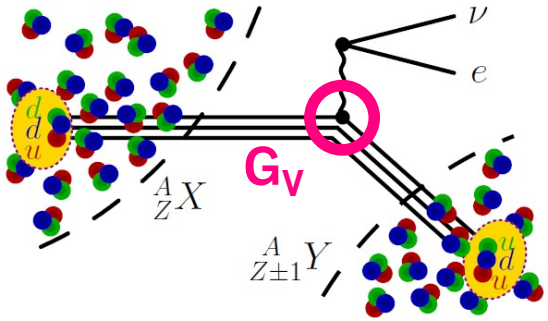
$$ft = \frac{fT_{1/2}}{BR} = \frac{K}{2{G_V}^2} = \text{constant}\ ?$$

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



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

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

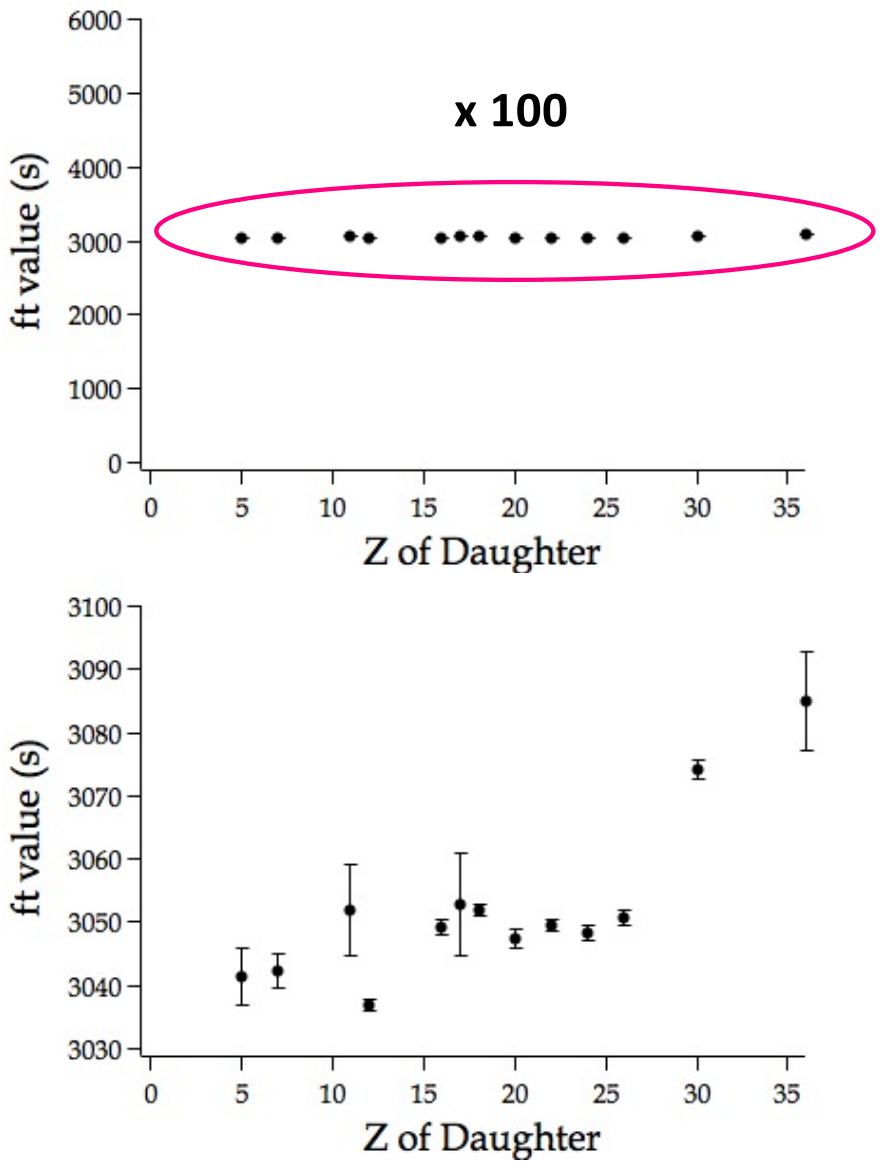


R.P.Feynman and M.Gell-Man PR 109, 193 (1958)

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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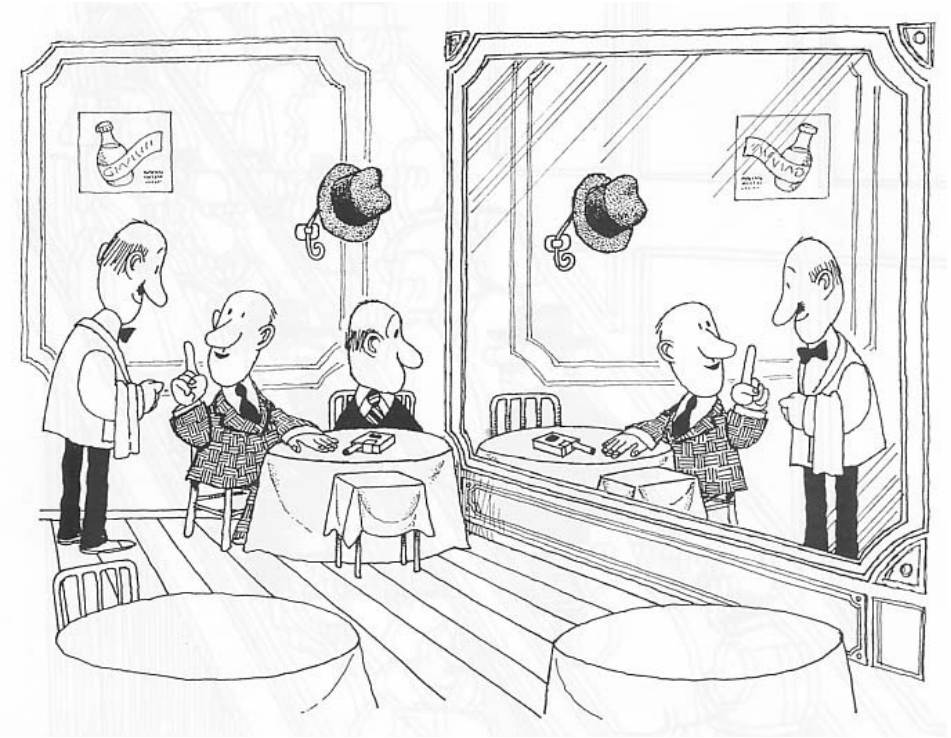
- **Isospin symmetry is not exact**
  - **Broken by charge dependent forces**

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



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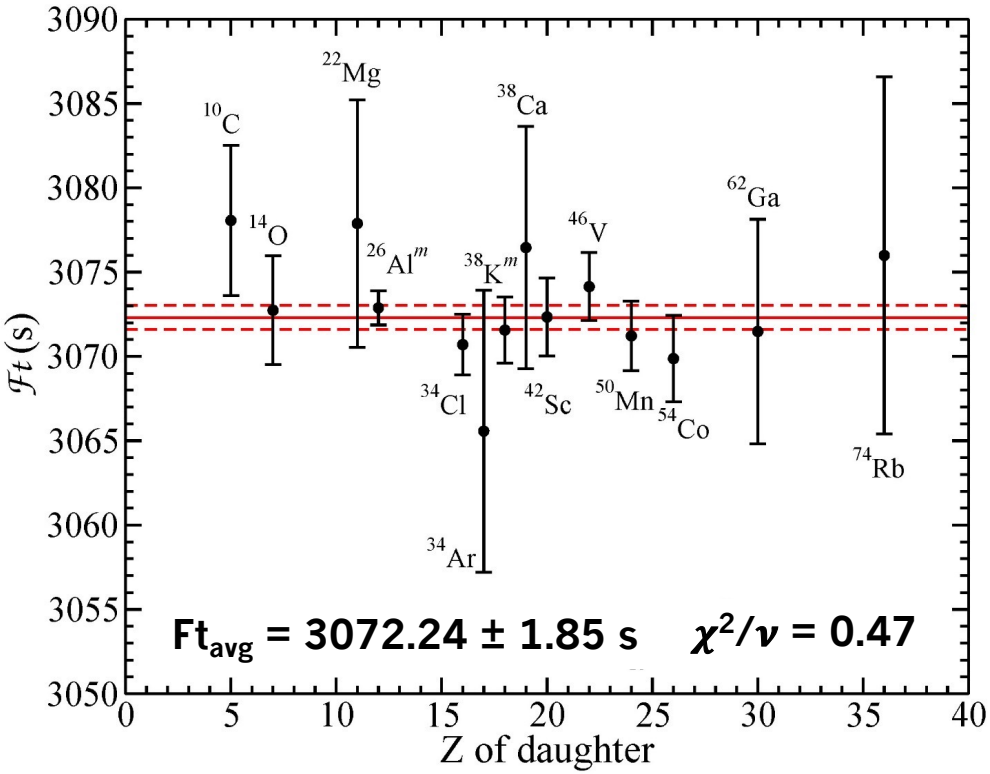
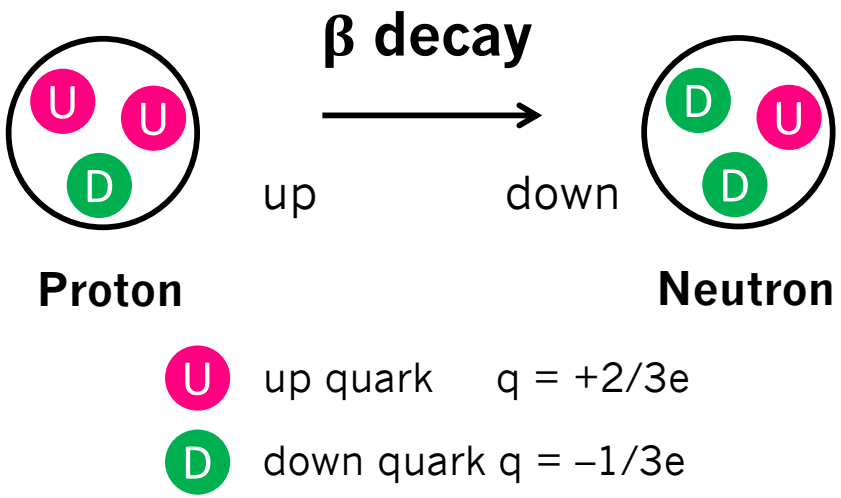
$$|M_F|^2 = 2(1 - \delta_C)$$

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



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**



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

- **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**

CKM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$|V_{ud}| = 0.97373(31)$
$|V_{us}| = 0.2243(5)$
$|V_{ub}| = 0.00394(36)$

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

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(6)$$

2.5σ deviation from unity!!!

TRIUMF's ISAC Facility

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

TRIUMF 500 MeV
Cyclotron 100 μA

proton beam

production target

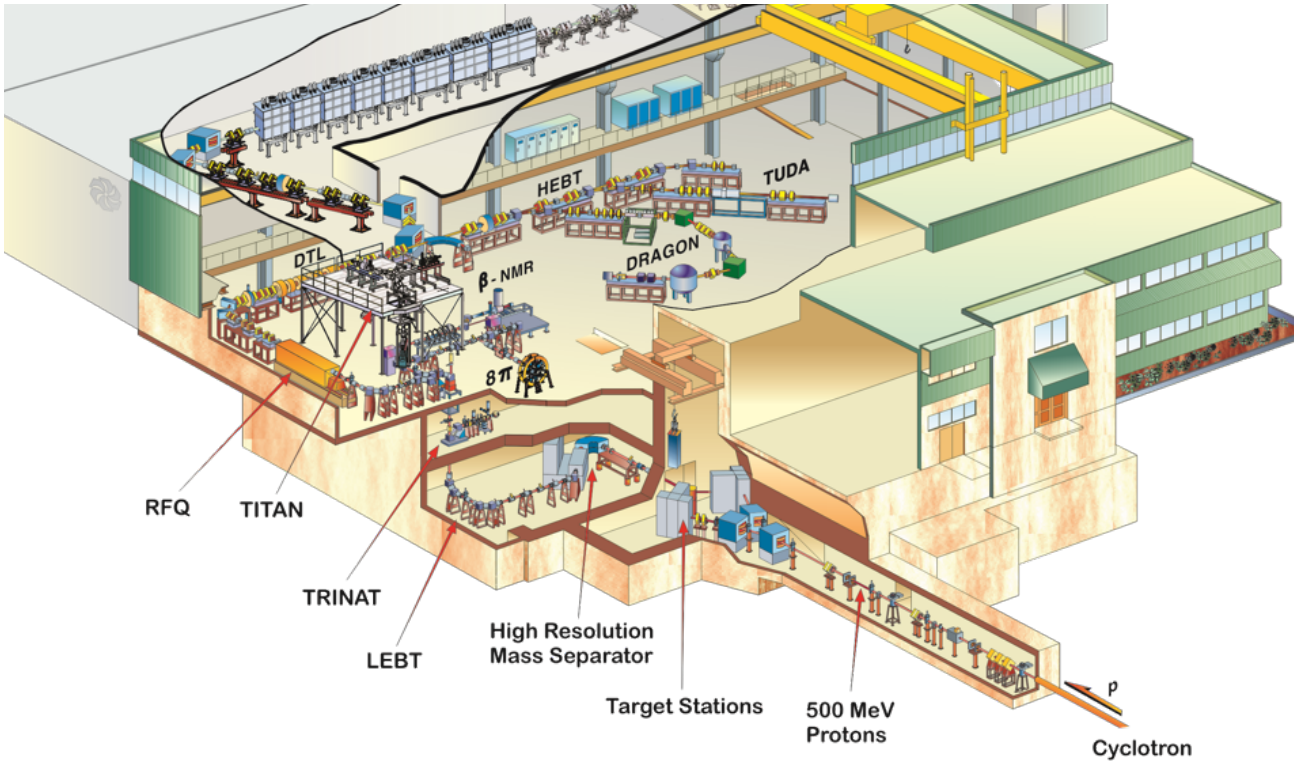
ion source

ions + ionized molecules

mass separator

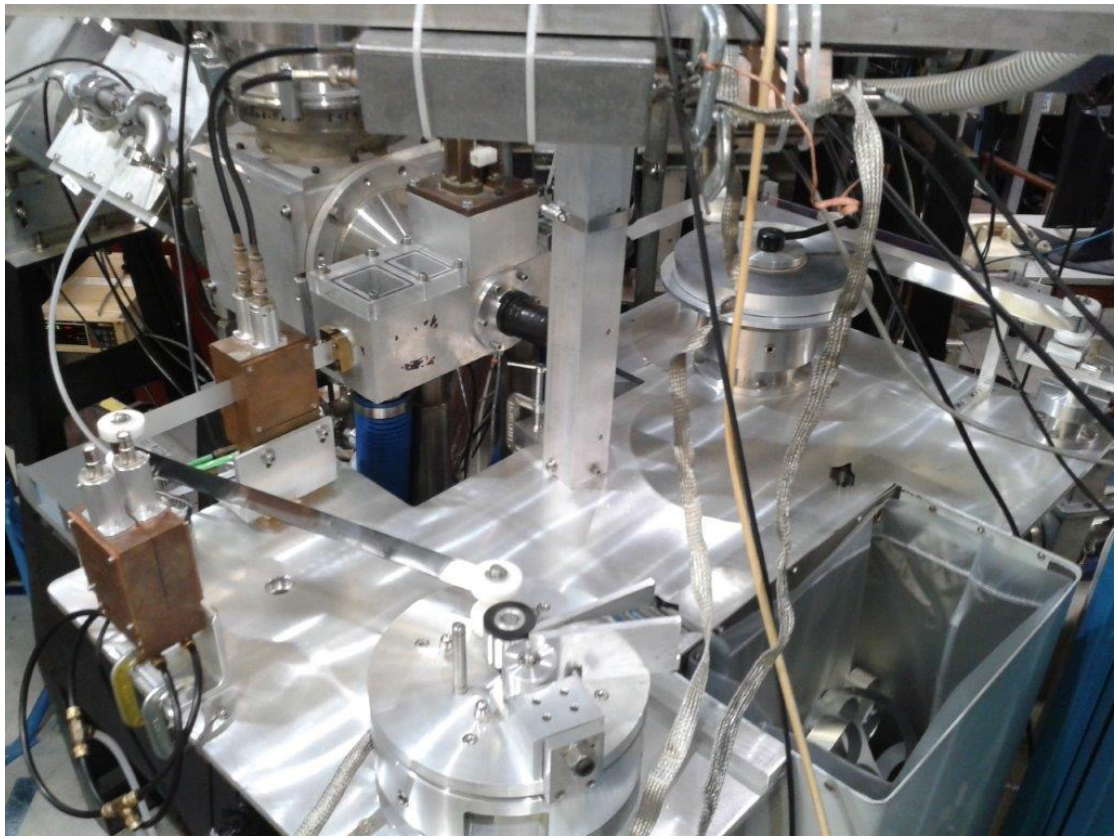
~40 keV beam

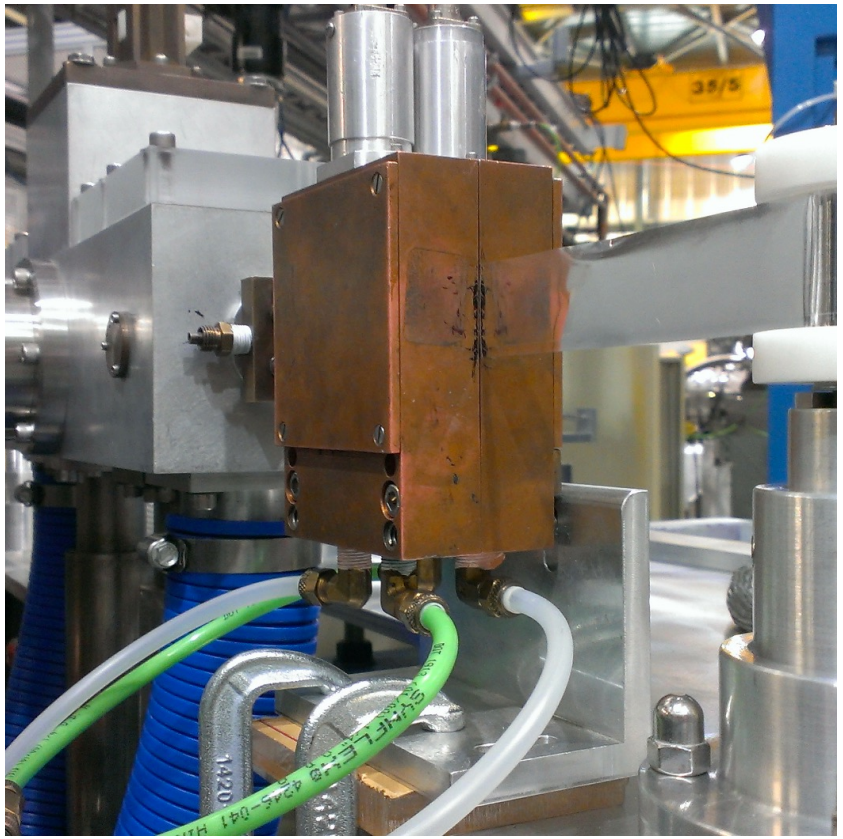
experimental area



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)

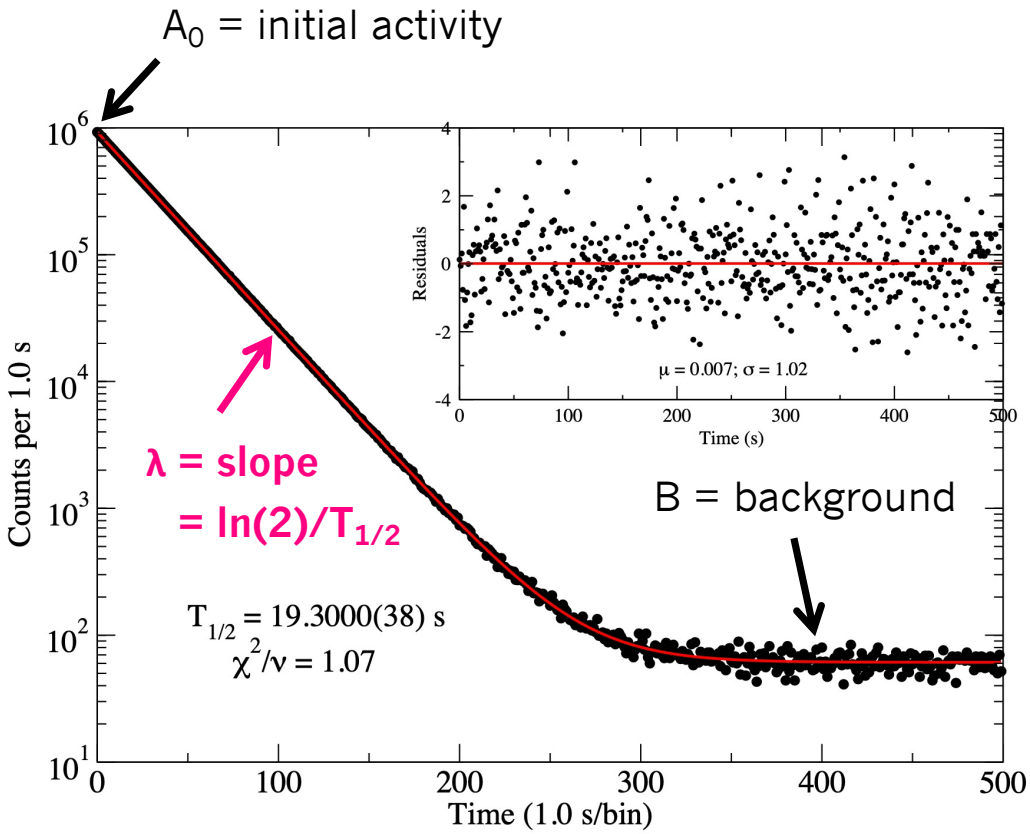




Half-life of ^{10}C

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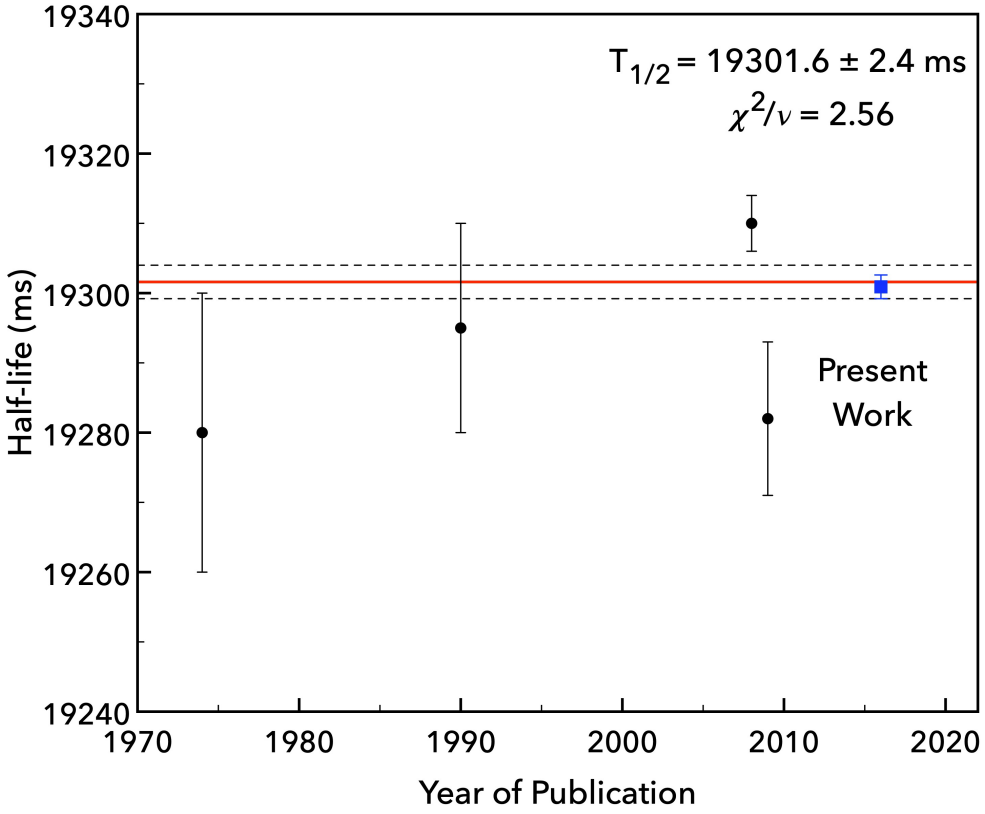
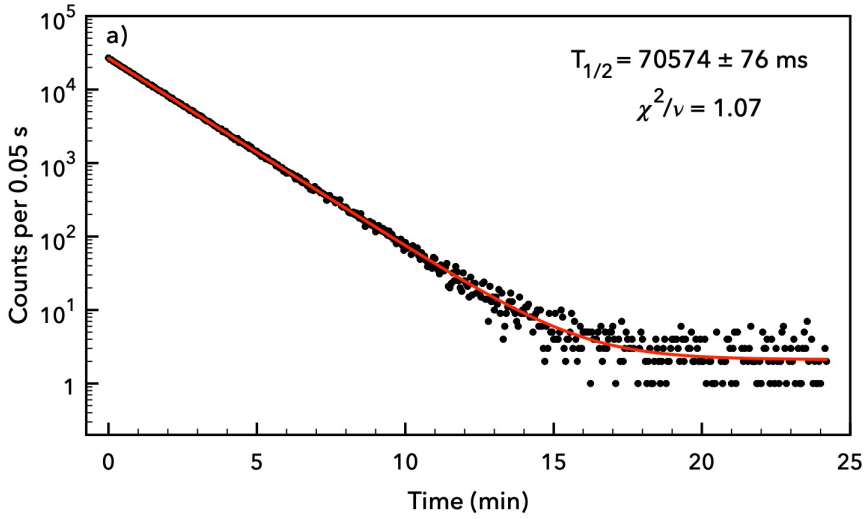
- Total of 550 cycles (4 days)
  - $T_{1/2}$ = 19.3009(17) s
- Systematic uncertainties
  - The most important part!
- Half-life of ^{10}C @ TRIUMF
  - Overall precision ± 0.009%
  - Most precise $T_{1/2}$ ever reported!

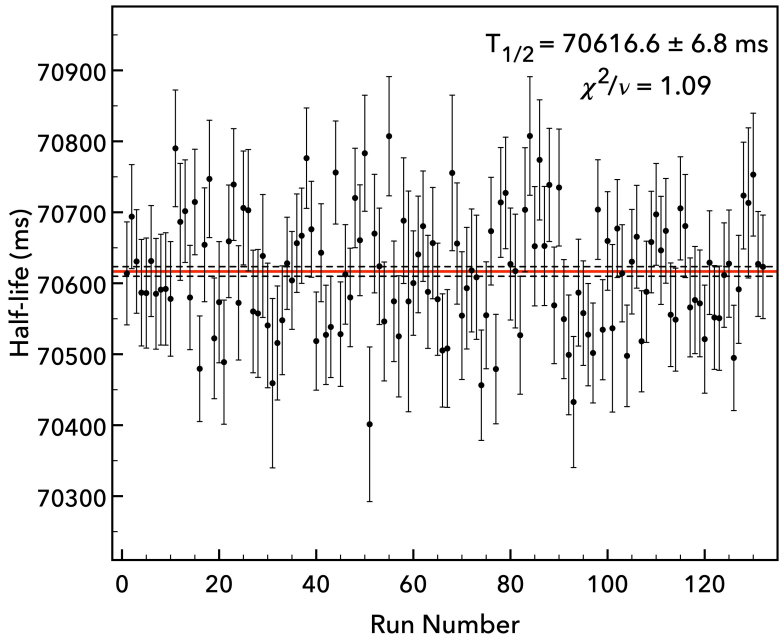


Half-life of ^{14}O

Shivani Sharma, submitted PRC

- Beam of radioactive ^{14}O
  - Intensity ~10^5 ions/s
- Data from 1 cycle (~ 25 mins)
  - Precision ± 0.10%
- Total of 132 cycles (3 days)
  - $T_{1/2}$ = 70.6166(78) s





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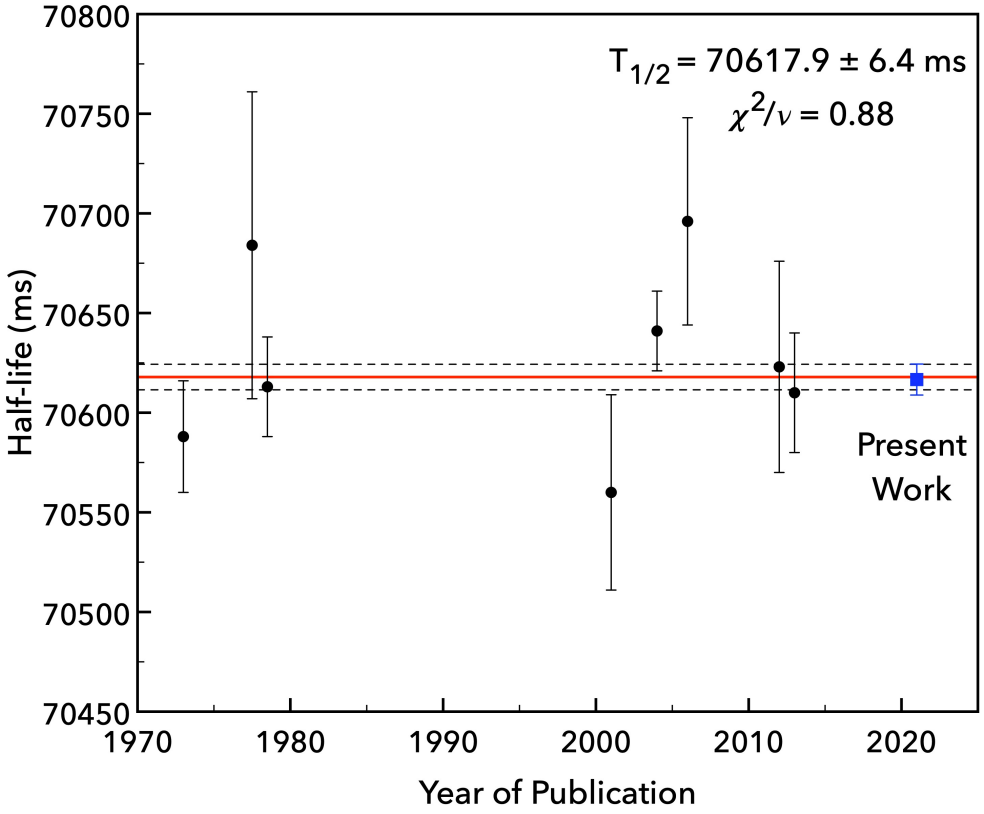
- Half-life of ^{14}O @ TRIUMF
  - Overall precision ± 0.010%
  - Comparable precision to ^{10}C!



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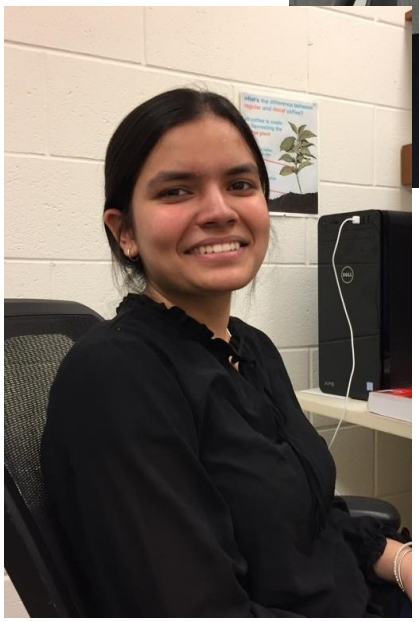
  - Comparable precision to ^{10}C!
- Article submitted on Monday!
  - Shivani Sharma, U of R



Shivani Sharma
M.Sc. University of Regina
(2018 – 2020)

Next generation: GRIFFIN

- 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!
  - M.Sc. Nastaran Saei
  - Ph.D. Eric Gyabeng Fuakye
- Experiment S1848: BR of ^{34}Ar
  - New experiment at ISAC!
  - To be scheduled in 2022
  - Looking for interested students!

Thank you so much!

- Superallowed Fermi β Decay
  - The precision frontier of NP
  - Crucial constraints on the SM
  - Demanding test of CKM unitarity
- Experiments at TRIUMF-ISAC
  - Best place for these studies
  - World-leading detectors/expertise
- Many other projects in my group!
  - I am always looking for students!
  - Please contact me if interested!!

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