High Precision Half-Life Measurements for the Superallowed Fermi β^+ Emitter ^{14}O

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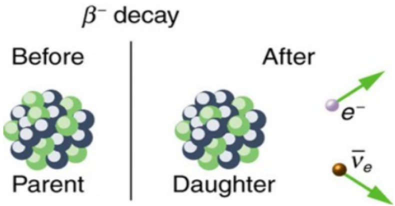
Nuclear β Decay

Two Types: Beta Minus Decay, Beta Plus Decay

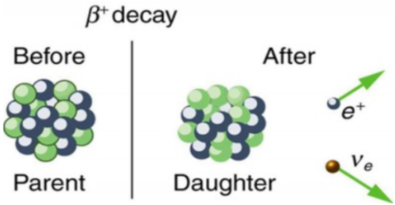
- **Beta Minus Decay:** Conversion of neutron into proton.

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^{-} + \bar{\nu}_{e} $$



- **Beta Plus Decay:** Conversion of a proton into neutron

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



Nuclear β Decay

- Beta Decay from parent nuclei can populate several daughter states

- Momentum conservation & selection rules:

$$\overrightarrow{J_P} = \overrightarrow{J_D} + \overrightarrow{L} + \overrightarrow{S} \qquad \pi_P = \pi_D\,(-1)^L$$

Momentum **Parity**

- Allowed decays $L = 0$

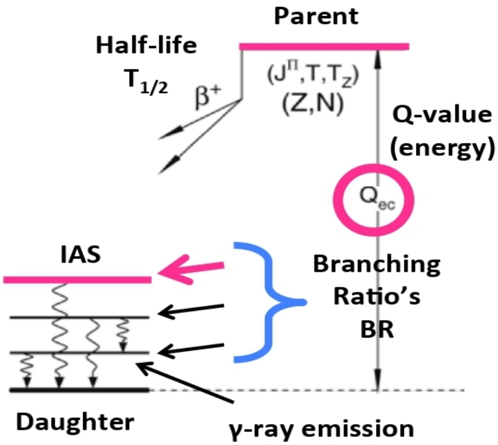
- Forbidden decays $L = 1, 2, 3, \ldots$

- Fermi decays $S = 0$ & Gamow-Teller decays $S = 1$

Superallowed Fermi Beta Decay

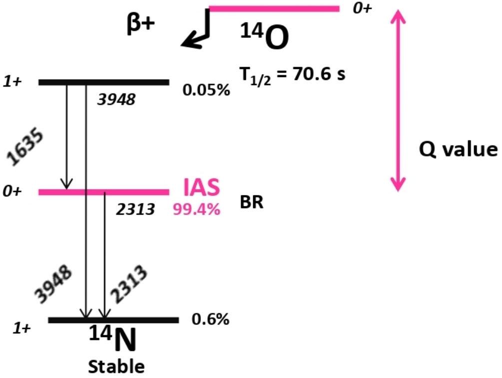
Superallowed Fermi β decays are beta decays between isobaric analogue states.

- $L = 0$, $\Delta\pi$=no, $S = 0$
- Allowed and pure Fermi decay (no GT)
- States have identical wave functions
- Isospin symmetry (neutrons = protons)



Key Quantities to be Measured

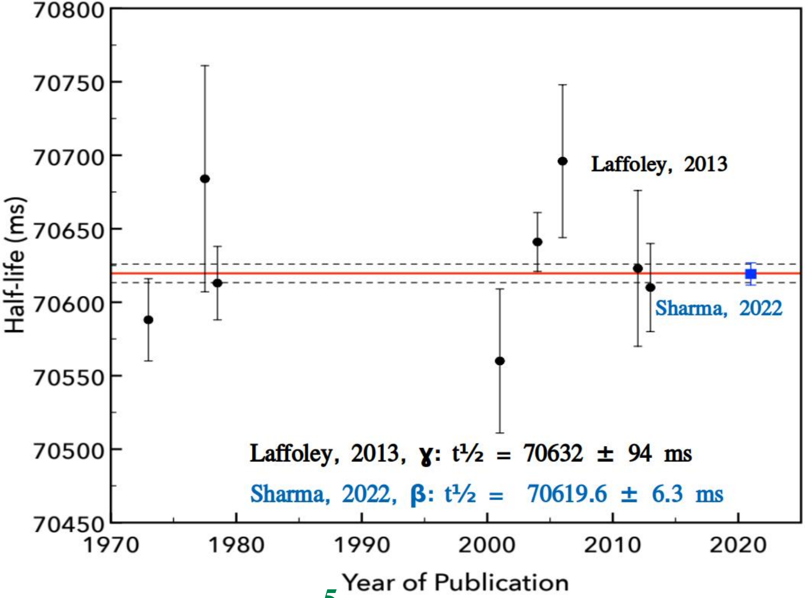
① Half life $T_{\frac{1}{2}}$ of the parent state **(focus of this work).**
② Total transition energy Q value
③ Branching ratio (BR) to the state of interest



- These quantities are combined into the ft value of the β transition
- f = statistical rate function, depends on Q value
- t = partial half life , depends on $T_{\frac{1}{2}}$ and the branching ratio.

(Grinyer, 2021)

Previous Half-Life measurements of ^{14}O



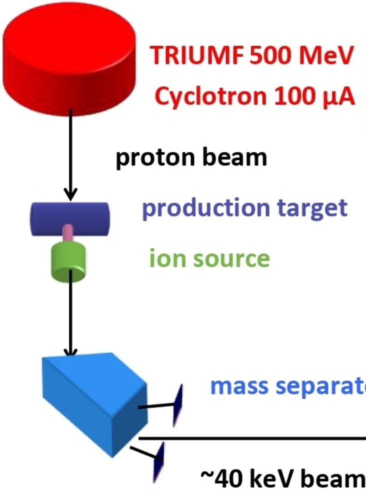
Our Goal:

1. To provide half-life measurement for ^{14}O from γ-ray counting that can be compared to the recent high precision β counting result (Sharma, 2022).

2. To search for any possible systematic effects between β and γ counting techniques. (eg. ^{34}Ar experiment scheduled in June, 2023 at TRIUMF, Vancouver).

3. To place further constraints on possible extensions of the Standard Model: ft value precision $\leq 0.1\%$ → β decay half-life precision $\leq 0.05\%$.

TRIUMF ISAC (Isotope Separator and Accelerator)



TRIUMF 500 MeV
Cyclotron 100 μA

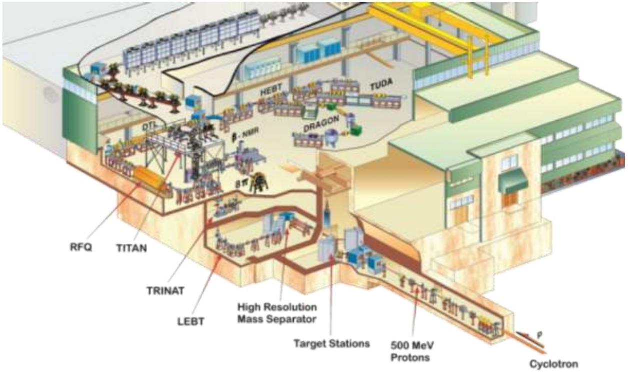
proton beam

production target

ion source

mass separator

~40 keV beam

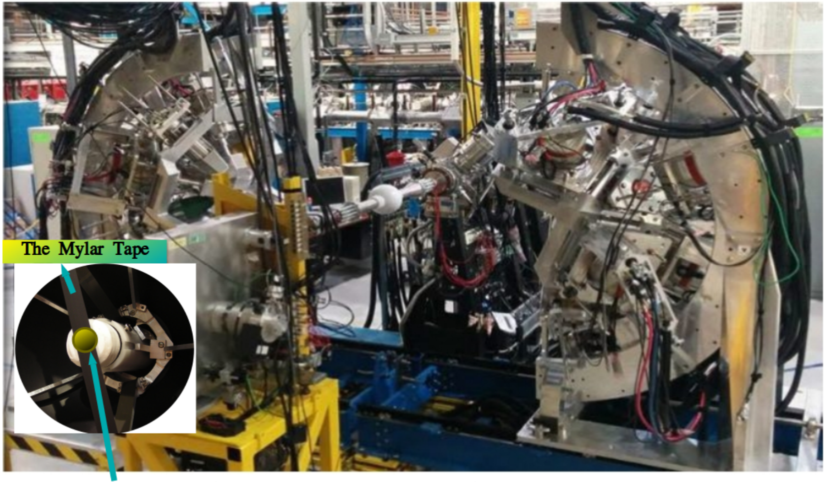


experimental area

$^{12}C^{14}O$ beam at ~10^5 ions/s

^{26}Na at $\sim 10^5$ ions/s (well-known test case)

γ Counting — The GRIFFIN Spectrometer



- The radioactive beam is then implanted into the tape.
- **Spherical array of 16 Clover detectors each consists of 4 HPGe Crystals**
- **~9.1% photopeak efficiency at 1.3 MeV**

Half-Life of ^{26}Na

- We performed half-life measurement of ^{26}Na as a first experimental test of GRIFFIN for high-precision work.

- Developed pile-up fitting and correction techniques in GRIFFIN.

- $\sim$ 99% of all β decays yield the 1809 keV γ-ray (Grinyer, 2008).

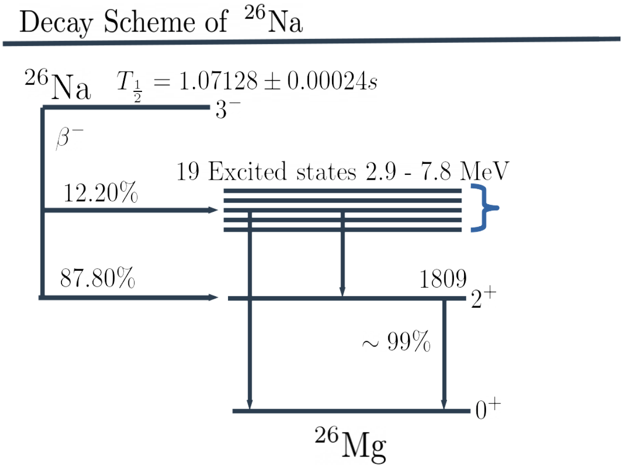
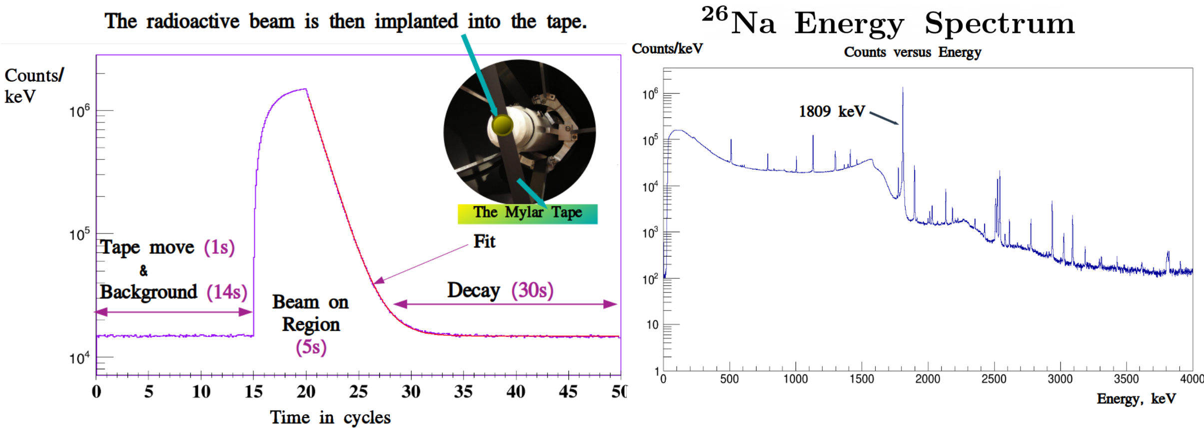


Figure 1: A simplified ^{26}Na β^- decay scheme to the stable daughter ^{26}Mg.

Half-Life of ^{26}Na



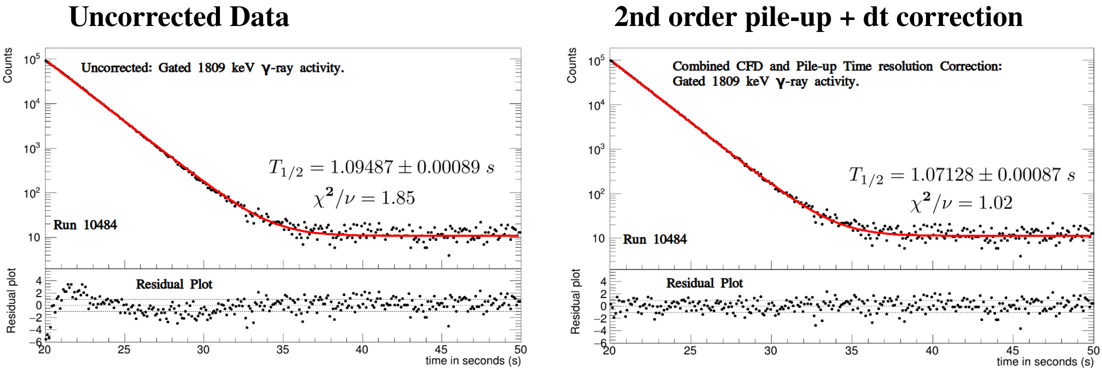
The radioactive beam is then implanted into the tape.

^{26}Na Energy Spectrum

Figure 2: Left: Data collected in cycles and Right: γ-ray singles spectrum for ^{26}Na with all the trigger events for a single run (40 mins)

Half-Life Analysis

^{26}Na Gated 1809keV Activity with total decay time of 30s.

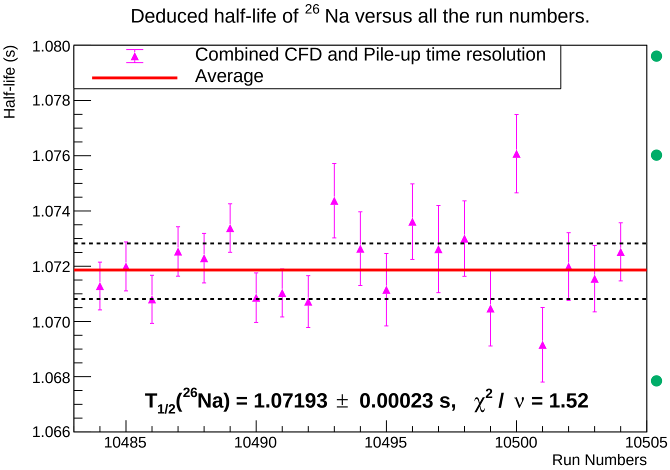


Uncorrected Data

2nd order pile-up + dt correction

Figure 3: Non-corrected decay curve (left) and Combined CFD and Pile-up time resolution correction decay curve(right) obtained from a single run following a gate on the 1809-keV transition in ^{26}Mg.

Half-Life Analysis: Previous works on ^{26}Na



- Current Result (γ-counting):
  $T_{\frac{1}{2}}(^{26}\text{Na}) = 1.07193 \pm 0.00023$ s
- Previous Result:
  Grinyer et al. (2005, 2007)

  $T_{\frac{1}{2}}(^{26}\text{Na}, \beta) = 1.07128 \pm 0.00025$ s
  $T_{\frac{1}{2}}(^{26}\text{Na}, \gamma) = 1.07167 \pm 0.00055$ s
- Good agreement with previous high-precision measurements.

1D γ-ray singles spectrum for ^{14}O

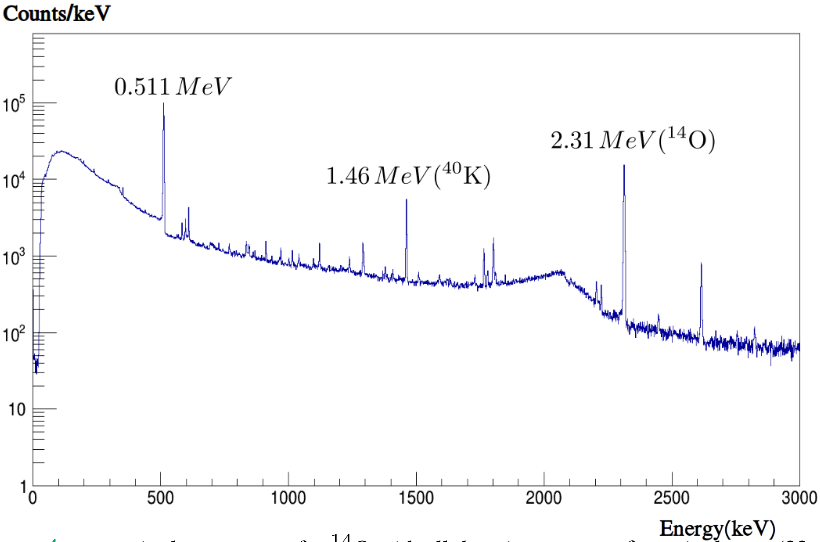


Figure 4: γ-ray singles spectrum for ^{14}O with all the trigger events for a single run (22 mins).

Energy gate on the 2.3 MeV photopeak in ^{14}N

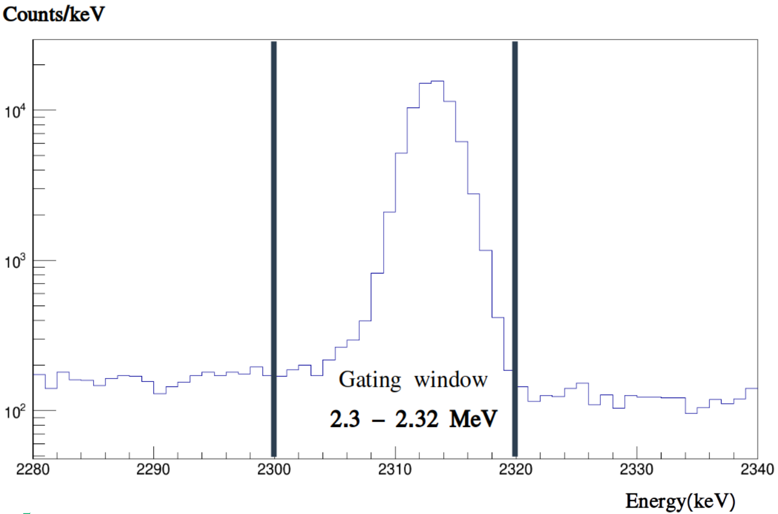


Figure 5: Typical zoomed in region (2280 - 2340 keV) from the γ-ray singles spectrum of ^{14}O.

Looking at the Pile Up and Single Events Spectra

Not Pile-up Events (blue) & Pile up Events(Red).

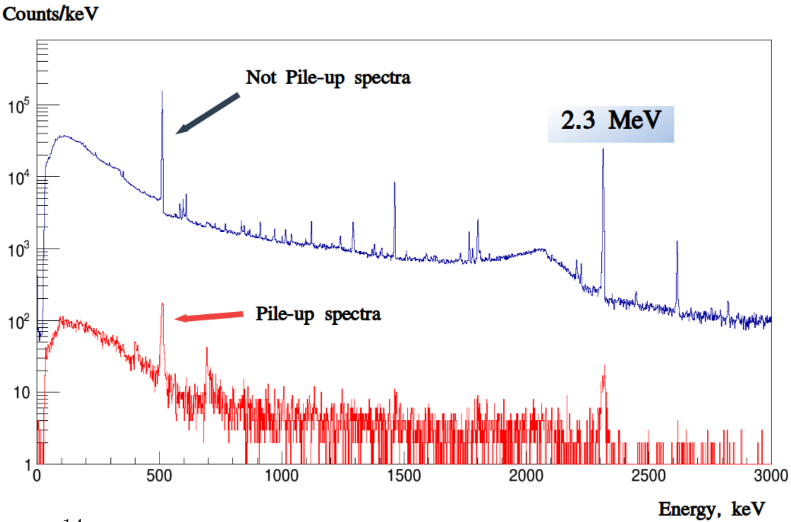
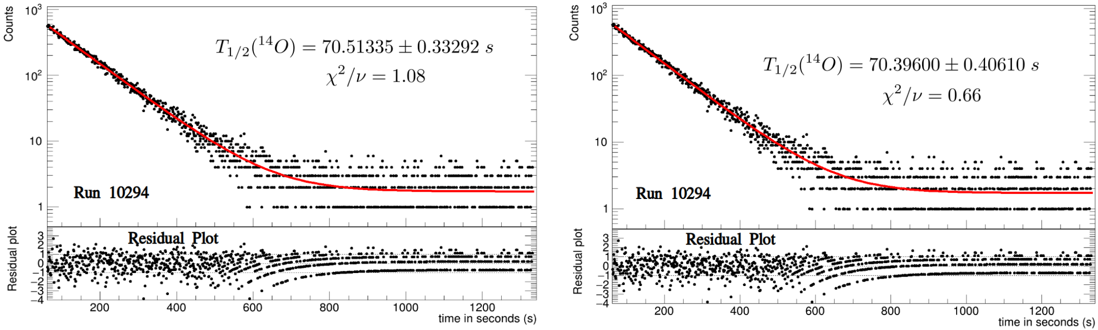


Figure 6: ^{14}O Energy spectra to distinguish between not pile-up and pile-up events.

Half-Life Analysis: ^{14}O Gated 2.3MeV Activity

Preliminary Results: ^{14}O Gated 2.3MeV Activity with total decay time of 1280s.



Uncorrected Data

1st order pile-up + dt correction

Figure 7: Non-corrected decay curve (left) and 1st order pile-up and dead-time (dt) correction decay curve(right) obtained from a single run following a gate on the 2.3-MeV transition in ^{14}N.

Half-Life Analysis: ^{14}O Gated 2.3MeV Activity

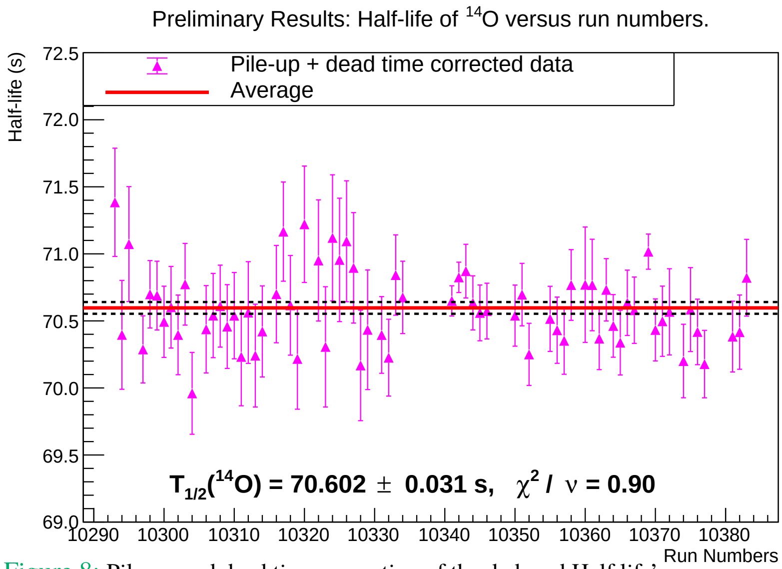


Figure 8: Pile-up and dead time correction of the deduced Half life's versus run numbers.

Summary and Future Work

1. We performed a half-life measurement of ^{26}Na as a first experimental test of GRIFFIN for high-precision work.

2. The Half life for the 2.3MeV activity from ^{14}O has been determined and was found to be $T_{\frac{1}{2}}$(avg) = 70.602 $\pm$ 0.031 s.

3. Sharma et al. (2022) measured the high-precision half-life of ^{14}O via β-counting. The half-life of ^{14}O was determined to be $T_{\frac{1}{2}}$ = 70.6196 $\pm$ 0.0063 s.

4. At this time, the analysis is in its preliminary stages and further extensive work is required in the upcoming weeks.

5. Future Work: Studies of ^{34}Ar as a superallowed Fermi β decay experiment scheduled in June, 2023 at TRIUMF, Vancouver.

Collaborators & References

COLLABORATORS

Thank you very much for your support !

S. Sharma[1], G.F. Grinyer[1a], G.C. Ball[2], J.R. Leslie[3], C.E. Svensson[4], F.A. Ali[4b], C. Andreoiu[5], N. Bernier[2,6c], S.S. Bhattacharjee[2], V. Bildstein[4], C. Burbadge[4], R. Caballero-Folch[2], R. Coleman[4], A. Diaz Varela[4], M.R. Dunlop[4], R. Dunlop[4], A.B. Garnsworthy[2], E. Gyabeng Fuakye[1], G.M. Huber[1], B. Jigmeddorj[4], K. Kapoor[1], A.T. Laffoley[4], K.G. Leach[7], J. Long[8], A.D. MacLean[4], C.R. Natzke[2,7], B. Olaizola[2d], A.J. Radich[4], N. Saei[1], J.T. Smallcombe[2e], A. Talebitaher[1], K. Whitmore[5], and T. Zidar[4]

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① Grinyer, G. (2008). High-precision half-life measurements for superallowed Fermi β decays (Doctoral dissertation).

② Sharma, S., Grinyer, G. F., Ball, G. C., Leslie, J. R., Svensson, C. E., Ali, F. A., ... & Zidar, T. (2022). High-precision half-life determination of 14 O via direct β counting. The European Physical Journal A, 58(5), 83.

③ Laffoley, A. T., Svensson, C. E., Andreoiu, C., Austin, R. A. E., Ball, G. C., Blank, B., ...& Unsworth, C. (2013). High-precision half-life measurements for the superallowed Fermi β^+ emitter 14 O. Physical Review C, 88(1), 015501.

④ Grinyer, G. F., Svensson, C. E., Andreoiu, C., Andreyev, A. N., Austin, R. A. E., Ball, G. C., ... & Zganjar, E. F. (2007). Pile-up corrections for high-precision superallowed β decay half-life measurements via γ-ray photopeak counting. .

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TRIUMF

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GRIFFIN

A.B. Garnsworthy et al.,

Regina GRIFFIN Group

Photo Credit: Shafakat Arifeen

L to R: J. Liu, Dr. Grinyer, N. Saei, D. Shah, E. Gyabeng Fuakye (me!)

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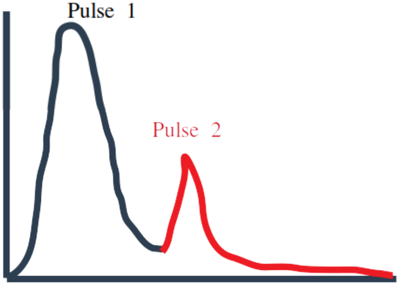
Any Questions ?

Backup Slides

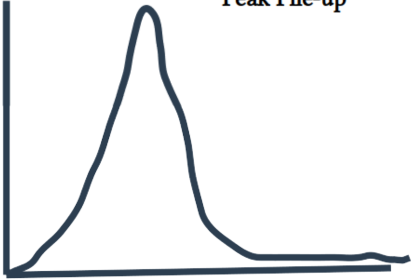
Detector Pulse pile-up

Tail Pile-up



First order pulse pile-up where **pulse 2 is riding on the tail of pulse 1.**

Peak Pile-up



If the pulses **are very close in time**, the system will simply record the two pulses as a single event with a **combined pulse amplitude**.

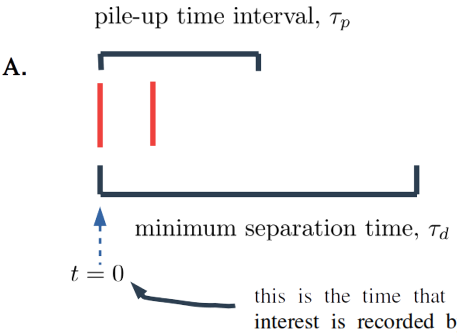
- The number of pile-up events depend strongly on the count rate of the system.

Detector Pulse pile-up

Common types of Pile-up

Post-piled-up

- Post pile-up is defined as the probability that the pile-up is caused by events arriving after the events of interest has been recorded.



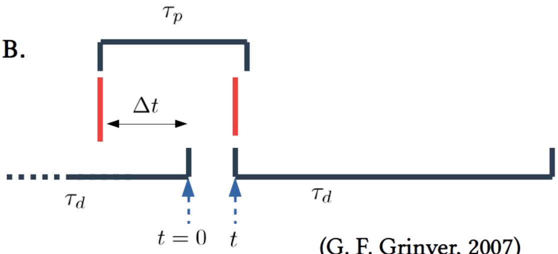
(G. F. Grinyer, 2007)

Detector Pulse pile-up

Common Types of Pile-up

II. Pre-piled-up

- The possibility that the event of interest is piled-up by an event that came before, in a process defined as "pre-pile-up"



(G. F. Grinyer, 2007)

1st Order Pile-up Corrections

Step-by-Step Correction

1. Deadfraction Correction

$$N_i' = \frac{N_i}{1 - D_i}$$

$$D_i = \text{Dead fraction}$$

Deadtime is the total period of time during which hit detection cannot be processed even if they are present.

2. 1st Order Pile-up Correction

$$N_i'' = \frac{N_i'}{1 - P_i}$$

$$P_i = \frac{\text{Pile-up Events}}{\text{All Events}}$$

$$N_i'' = \frac{N_i}{(1 - D_i) \times (1 - P_i)}$$

★ RATE DEPENDENT CORRECTIONS

Higher Order Pile-up Corrections

Bin-by-bin pile-up correction

1. Deadfraction Correction

$$D_i = \text{Dead fraction}$$

$$N_i' = \frac{N_i}{1 - D_i}$$

Deadtime is the total period of time during which hit detection cannot be processed even if they are present.

2. Higher Order Pile-up Corrections

RATE DEPENDENT CORRECTIONS

$$N_i'' = \frac{N_i}{(1 - D_i) \times (1 - P_{\text{fit-total}})}$$

Higher Order Pile-up Corrections

Analytical Expressions by (G. F. Grinyer, 2007)

$$P = 1 - e^{-(2-a_4)x}\left[e^{a_4 x} + (1-a_4)x\right] \qquad \mathbf{1}$$

$$P = 1 - e^{-2x}(1+\alpha x) \qquad \mathbf{2}$$

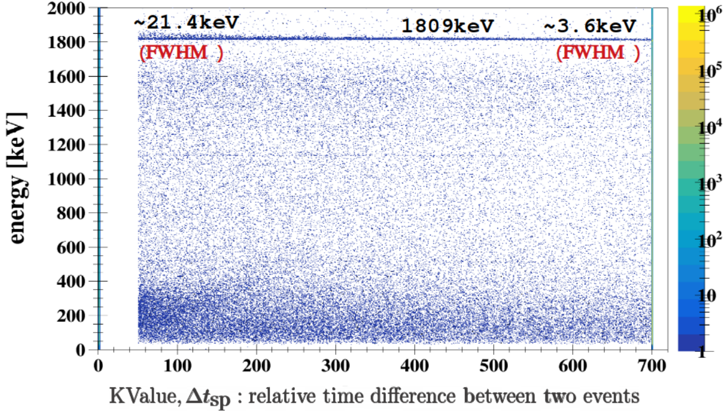
$$P = \epsilon_p\left[1 - e^{-2x}(1+x)\right] \qquad \mathbf{3}$$

The probability of pile up with a **non zero time resolution**, **CFD** and **detection efficiency** in 1, 2 and 3 respectively.

$$P_{\text{fit-total}} = a_6\left(1 - e^{-(2-a_4)x}\left[e^{a_4 x} + a_5(1-a_4)x\right]\right) \qquad \mathbf{4}$$

Dead-time and Detector Pulse Pile-up Corrections

Signal pile-up occurs when more than one energy deposition from different physics events is present in a detector element during the processing time of the initial interaction.



One can clearly see the dependence of the energy resolution on the k-value. The energy resolution worsens with decreasing integration length as expected and vice versa.

1st Order Pile-up Corrections

1. Deadfraction Correction

$$N_i^{'} = \frac{N_i}{1 - D_i}$$

$$D_i = \text{Dead fraction}$$

0.53%

2. 1^{st} Order Pile-up Correction

$$N_i^{''} = \frac{N_i^{'}}{1 - P_i}$$

$$P_i = \frac{\text{Pile-up Events}}{\text{All Events}}$$

0.78%

$$N_i^{''} = \frac{N_i}{(1 - D_i) \times (1 - P_i)}$$

★ RATE DEPENDENT CORRECTIONS

Future Work

Rate-Dependent Refinements

➤ Trigger-Energy Threshold

- Corrects for **pile-up** caused by sub threshold energy events.

➤ Pile-up Time Resolution

- Corrects for **pile-up** events not resolved (in time) by the **pile-up circuitry**.

Data Selection Criteria - Previous works on ^{26}Na

Selection Criteria Utilized

1

Decay data for the Na-26 experiment were collected in cycles**(1, 14, 5, 30 s)**.★

- The first selection criterion: **REJECT those cycles that had very few, or even zero, total counts recorded during the decay measurement.**

2

Apply an energy gate on the 1809-keV transition in 26-Mg

3

Remove Pile Up Events using a gate on the K-Values

★ The precise values of the tape move, background, beam-on time and decay measurement were varied on a **run-by-run basis.**