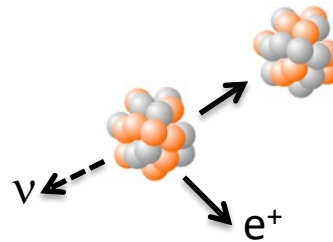


Precision half-life measurements of mirror transitions at the Nuclear Science Laboratory



Maxime Brodeur
University of Notre Dame

Unitarity test of the SM



- The Standard Model (SM) can be tested via the CKM matrix unitarity.
- CKM matrix: relates the quark weak and regular eigenstates.

$$\begin{pmatrix} |d_w\rangle \\ |s_w\rangle \\ |b_w\rangle \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} |d_s\rangle \\ |s_s\rangle \\ |b_s\rangle \end{pmatrix}$$

- SM: CKM matrix should be unitary $\sum_i |V_{ui}|^2 = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- Non-unitarity could lead to new physics:
 - Extra quark generation
 - Extra Z boson
 - Supersymmetry
 - ... Or erroneous experimental data or theoretical corrections...
- V_{ud} : largest element and *obtained from beta decays*

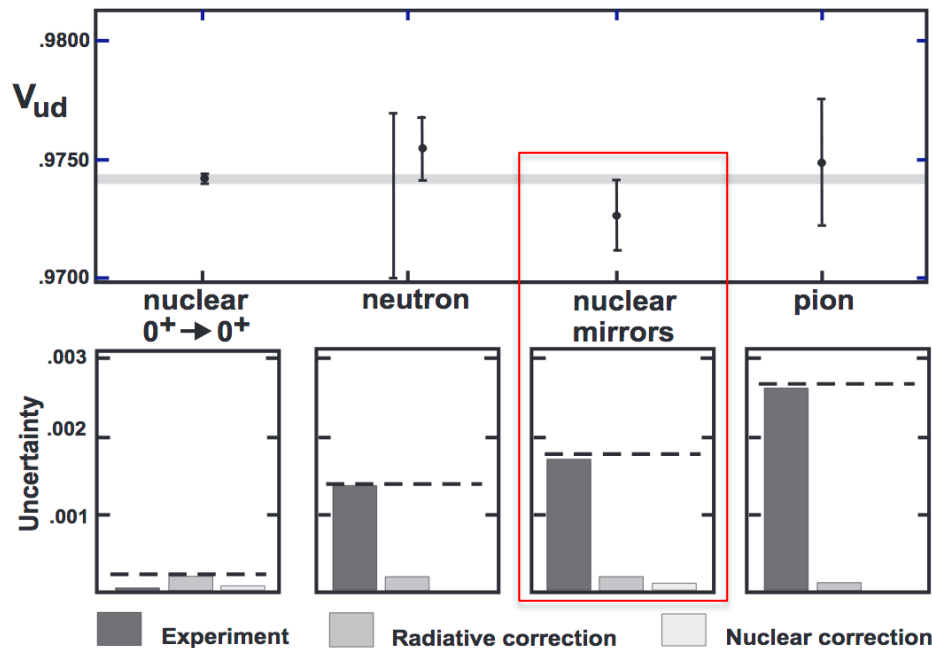
$$+ |V_{ux}|^2$$



Obtaining the V_{ud} element



- For a reliable CKM matrix unitarity test, V_{ud} need to be precise and accurate.
- Accuracy tested by a determination of V_{ud} using multiple systems.



J.C. Hardy and I.S. Towner, arXiv:1807.01146v1
[nucl-ex] (2018)

- Pure Fermi transitions
 - Most precise determination
 - Need nuclear corrections
- Pion decay
 - No nuclear corrections
 - Very low branching ratio
- Neutron decay
 - No nuclear corrections
 - Lifetime issues
 - Need Fermi-GT mixing ratio
- Mixed transitions

Currently fall short from unitarity by 3σ .

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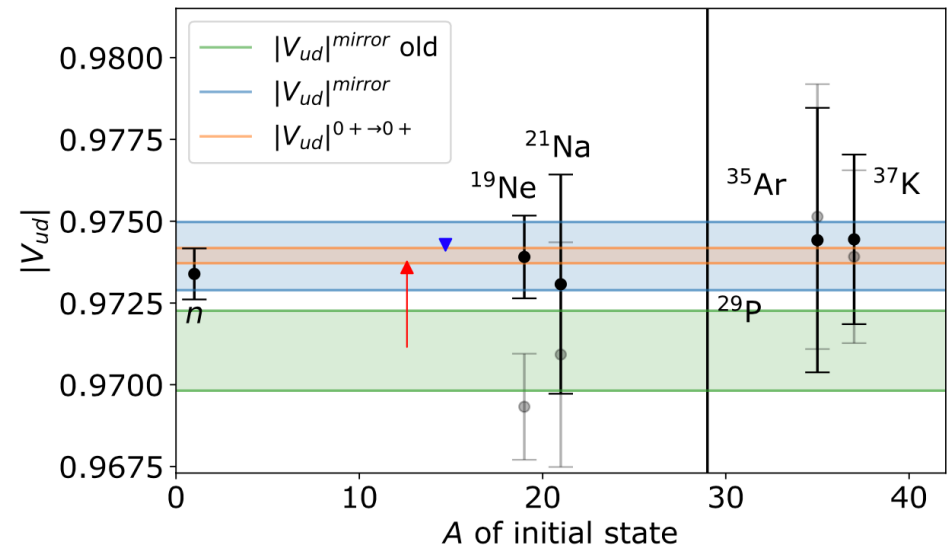


V_{ud} from mixed transitions



- Only 5 nuclei
- One more parameter needed than pure Fermi:

- ✓ Half-life
 - ✓ Branching ratios
 - ✓ Q-values
 - ✓ Fermi-to-Gamow
Teller mixing ratio ρ
- } ft-value



L. Hayen, PRD **103**, 113001 (2021)

$$\mathcal{F}t_0 = ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C) [1 + (f_A/f_V)\rho^2]$$

$$= \frac{K}{G_F^2 V_{ud}^2 (1 + \Delta_R^V)},$$

ρ determined by
measuring either:

- β asymmetry parameter A_β
- ν asymmetry parameter B_ν
- β - ν angular correlation $a_{\beta\nu}$

V_{ud} from mirror transitions is currently 6x less precise than $0^+ \rightarrow 0^+$



- To do:
- Long term: expand the list of transitions from which V_{ud} can be extracted
 - Short term: reduce sources of uncertainties in the ft-values

Need to improve ft-values

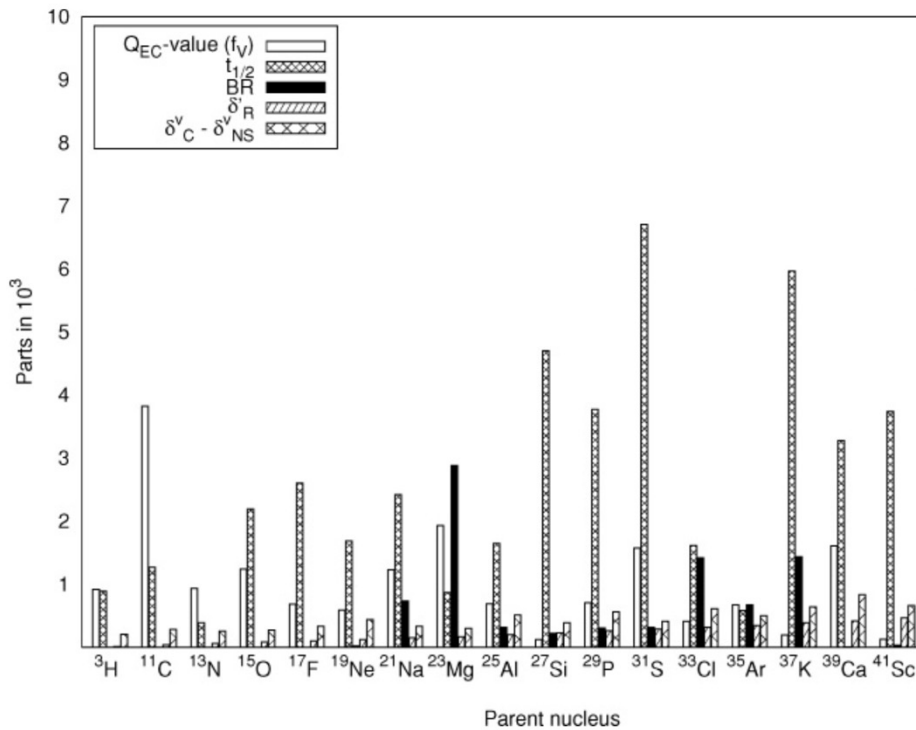


$$\mathcal{F}t_0 = ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C) [1 + (f_A/f_V)\rho^2]$$

$$= \frac{K}{G_F^2 V_{ud}^2 (1 + \Delta_R^V)},$$

$$a_{SM} = \frac{1 - \rho^2/3}{1 + \rho^2}$$

Assuming 0.5% uncertainty on a



Parent nucleus	ΔV_{ud}	a	
		$(\Delta V_{ud})^{\text{limit}}$	Factor $\Delta \mathcal{F}t$
^3H	0.0011	0.0010	2.1
^{11}C	0.0025	0.0016	4.0
^{13}N	0.0017	0.0017	1.0
^{15}O	0.0020	0.0016	2.4
^{17}F	0.0019	0.0013	3.1
^{19}Ne	0.0011	0.0010	1.5
^{21}Na	0.0022	0.0017	2.7
^{23}Mg	0.0025	0.0018	3.1
^{25}Al	0.0019	0.0018	1.7
^{27}Si	0.0029	0.0018	4.1
^{29}P	0.0026	0.0018	3.4
^{31}S	0.0038	0.0018	5.9
^{33}Cl	0.0021	0.0018	2.0
^{35}Ar	0.0019	0.0018	1.1
^{37}K	0.0034	0.0017	5.8
^{39}Ca	0.0024	0.0016	3.5
^{41}Sc	0.0029	0.0022	2.7

N. Severjins et al., PRC **78**, 055501 (2008)

N. Severjins & O. Naviliat-Cuncic, Phys. Scr. T**152**, 014018 (2013)



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Half-life measurements @ ND

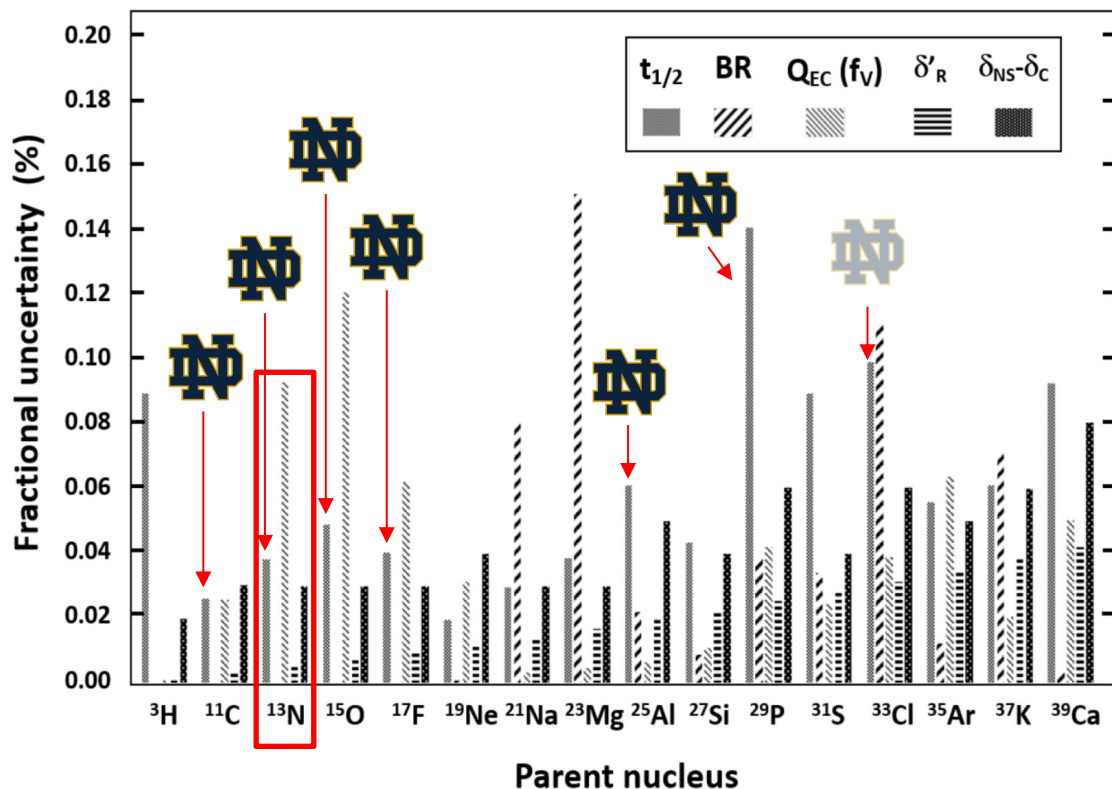
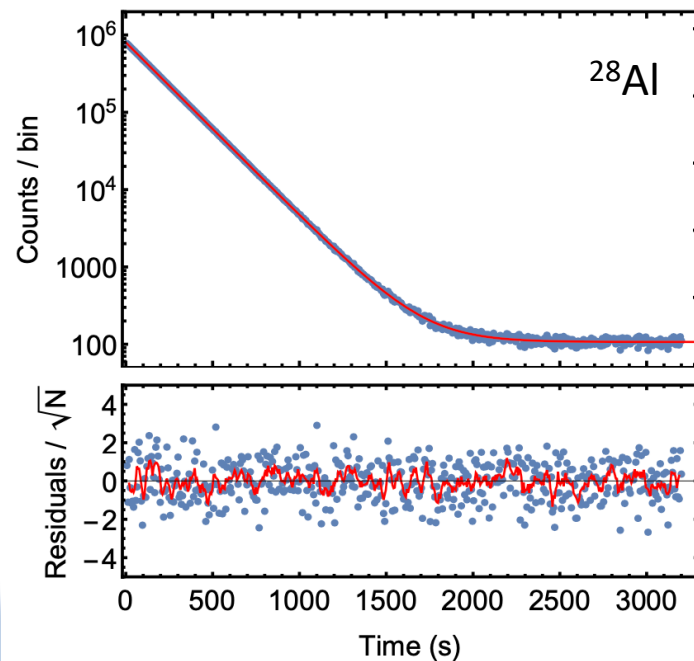
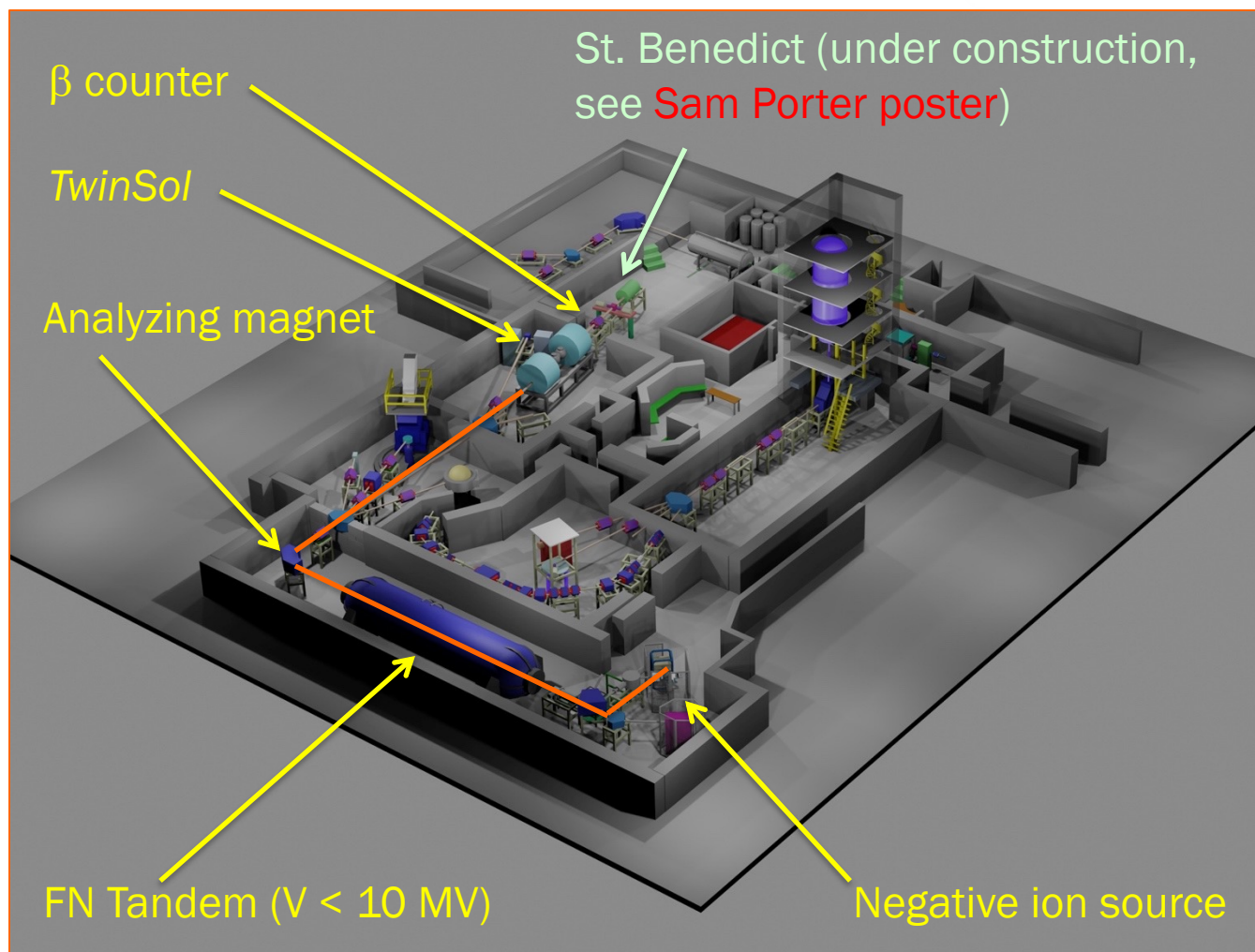


Figure from N. Severjins et al., arXiv:2109.08895 [nucl-ex] (2021)

- ^{17}F : M. Brodeur *et al.* PRC **93** 025503 (2016).
- ^{25}Al : J. Long *et al.* PRC **96**, 015502 (2017).
- ^{11}C : A. Valverde *et al.* PRC **97**, 035503 (2018).
- ^{20}F : D.P. Burdette *et al.* PRC **99**, 015501 (2019).
- ^{15}O : D.P. Burdette *et al.* PRC **101** 055504 (2020).
- ^{29}P : J. Long *et al.* PRC **101**, 015501 (2020).
- ^{13}N : J. Long *et al.* PRC **106**, 045501 (2022).
- ^{28}Al : B. Liu *et al.* In preparation.
- ^{33}Cl : P.D. O'Malley *et al.* under analysis.



Nuclear Science Laboratory



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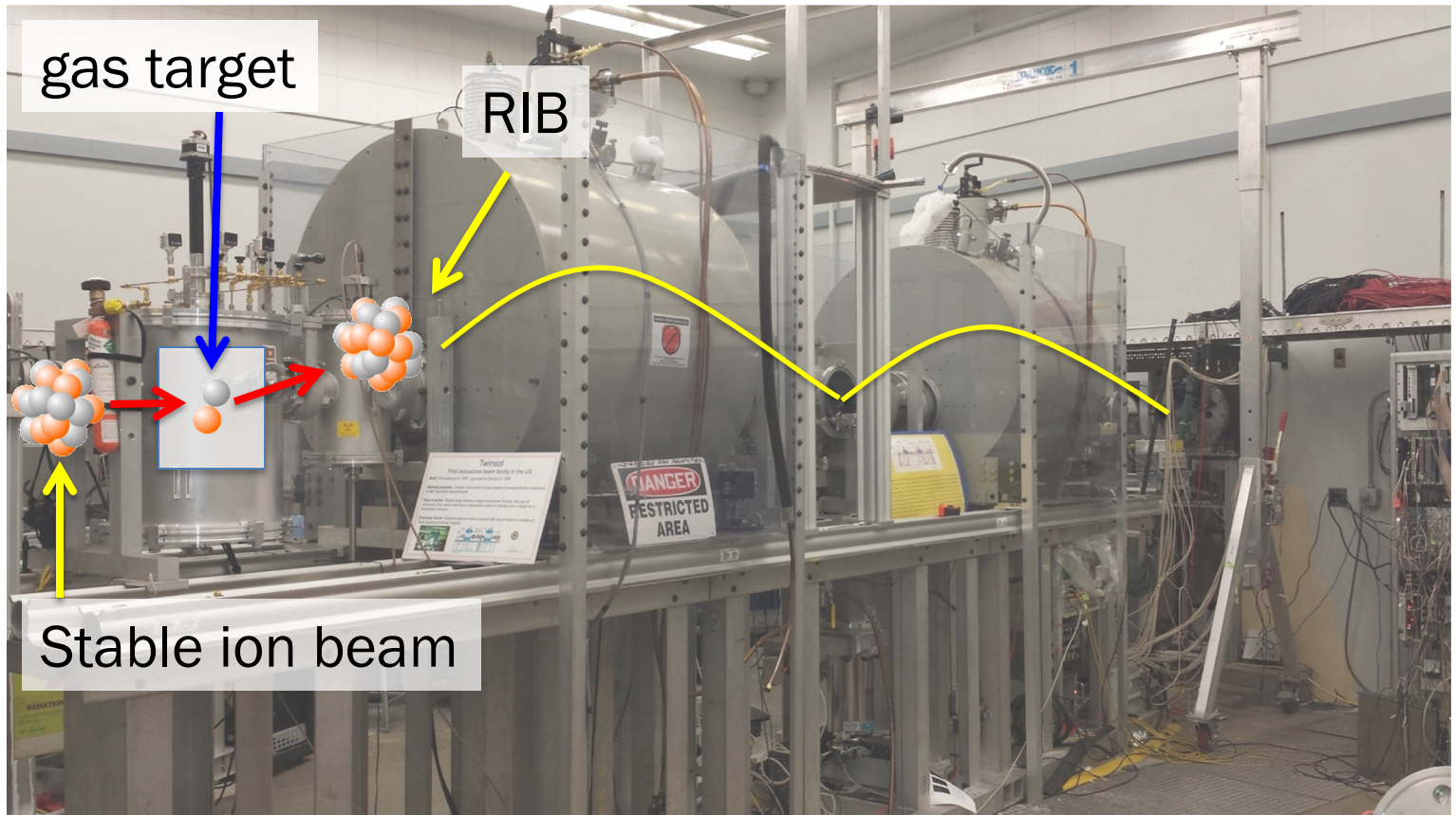


TwinSol facility



Oldest RIB facility still operational

F.D. Becchetti *et al.*, NIM A **505**, 377 (2003)



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RIBs at the NSL



Stable
primary
beam

TwinSol

St. Benedict for determination of ρ

Beam from
TwinSol

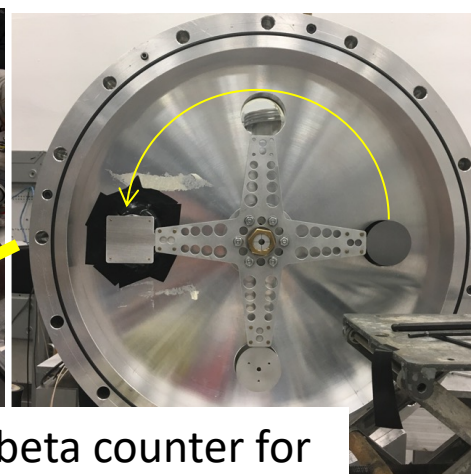
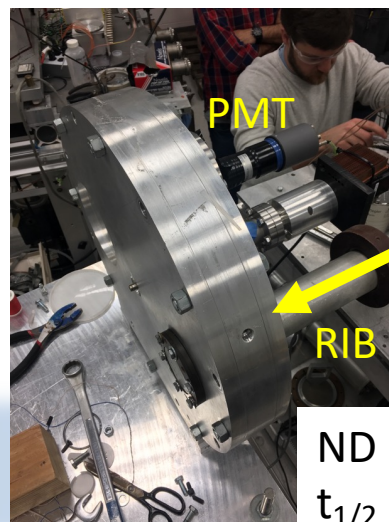
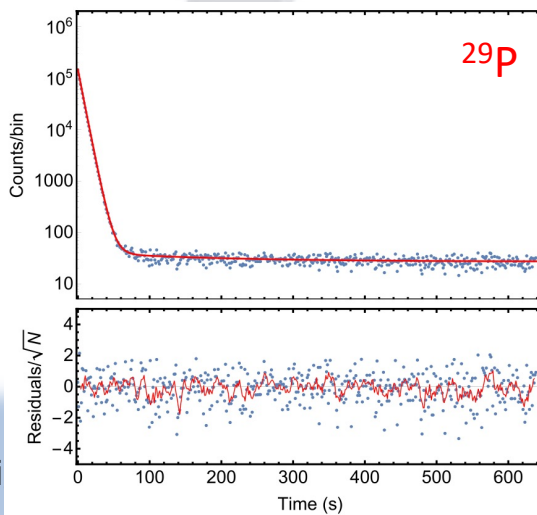
Gas Catcher

Cooler-Buncher

RF Carpet & RFQ

Paul Trap

TriSol

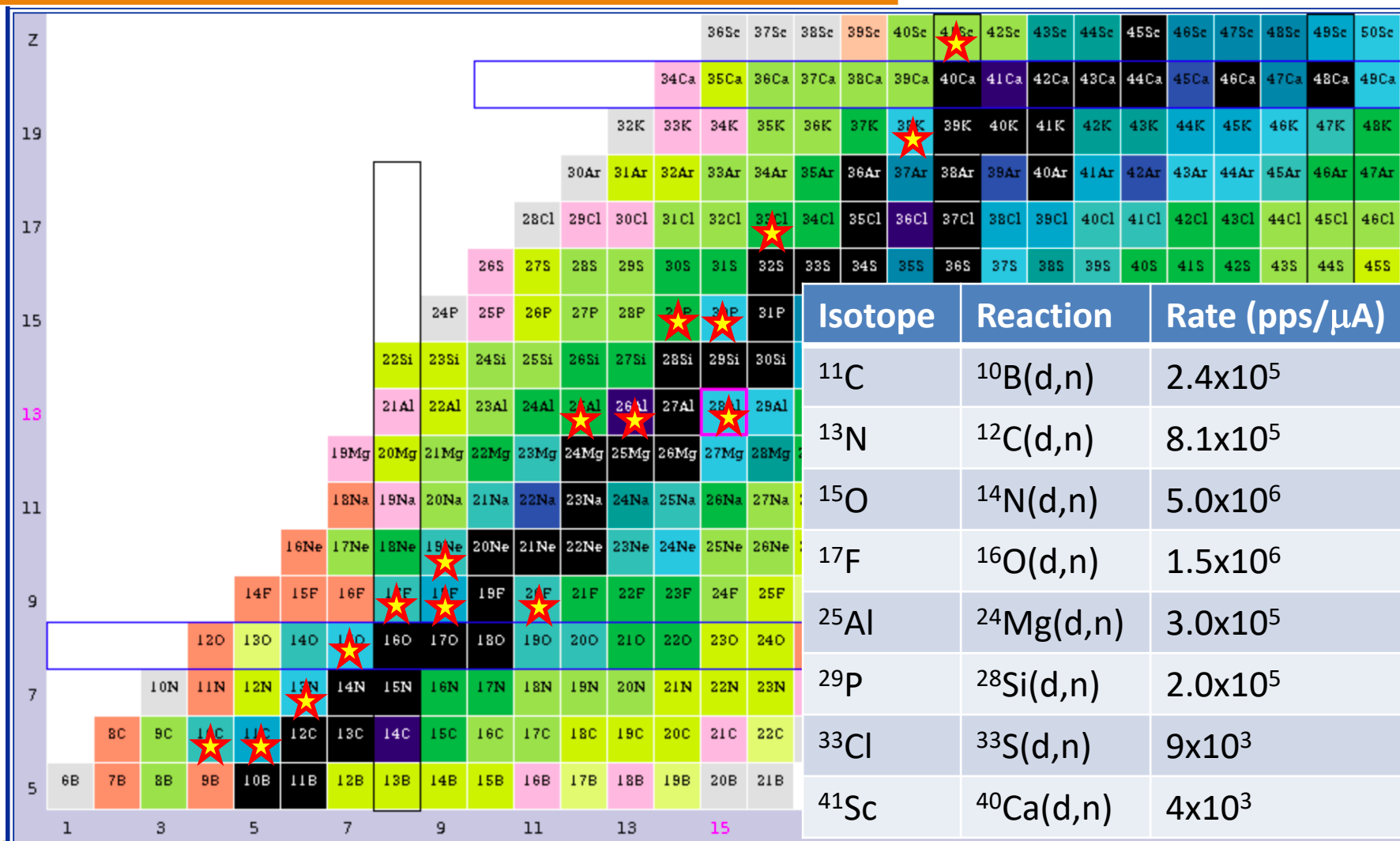


ND beta counter for
 $t_{1/2}$ measurements



ARIS 2023, Avi

RIB produced at *TwinSol*



ARIS 2023, Avignon, June 6, 2023



Energy choice



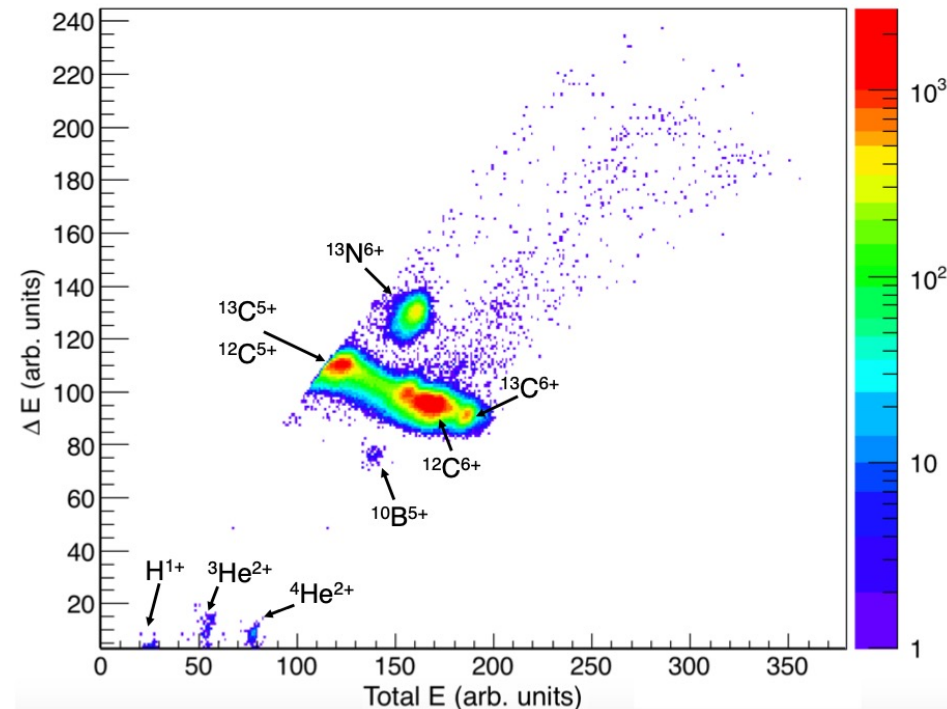
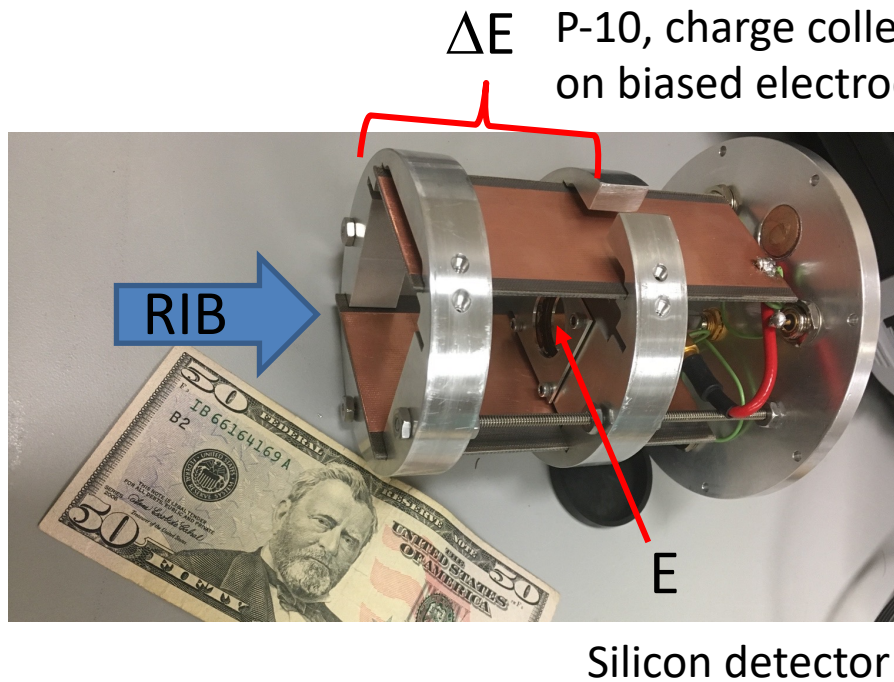
^{13}N

- Tandem operated at 6.8 MV
- $^{12}\text{C}^{4+}$ primary beam at 34 MeV
- $E(\text{after foil}) = 29.6 \text{ MeV}$ →
- Deuterium target at 832 torr
- No major radioactive contaminant to be expected

Reaction Products	Q-Value (keV)		Threshold (keV)	
$^{14}\text{N} + \gamma$	10272.3		0	
$^{13}\text{C} + \text{p}$	2721.7		0	
$^{12}\text{C} + \text{d}$	0.0		0	
$^{13}\text{N} + \text{NN}$	-281.1	3	1965.6	21
$^{10}\text{B} + \alpha$	-1339.8		9368.5	
$^{12}\text{C} + \text{NN} + \text{p}$	-2224.6		15555.4	
$^6\text{Li} + 2\alpha$	-5801.0		40563.1	
$\alpha + \text{d} + 2\alpha$	-7274.7		50867.8	
$^8\text{Be} + \text{d} + \alpha$	-7366.6		51510.4	
$^9\text{Be} + \text{p} + \alpha$	-7926.6	1	55426.2	7



Particle identification with “Akbar”

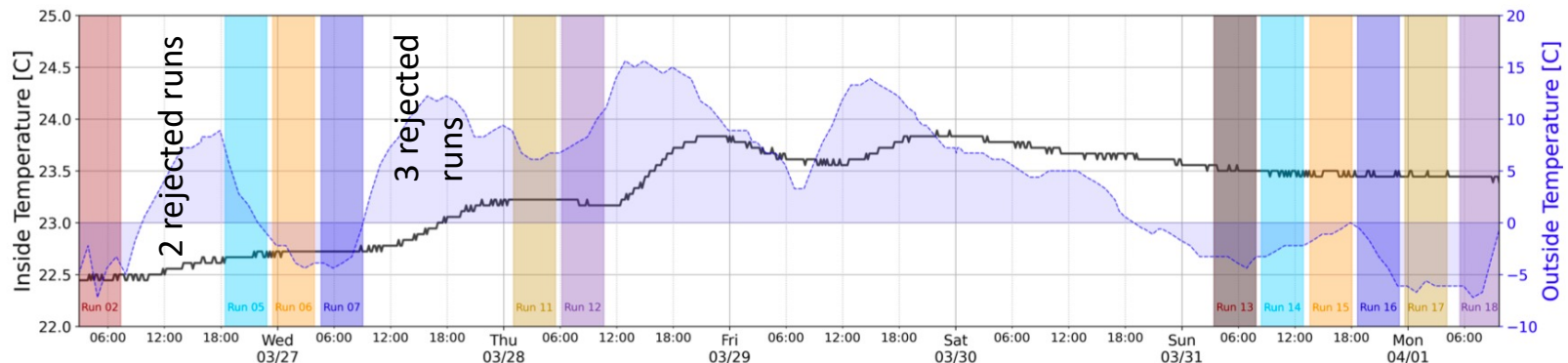
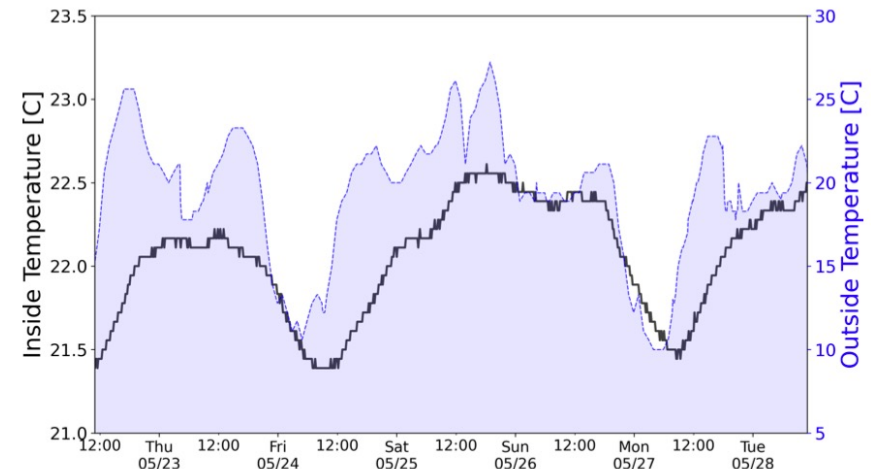
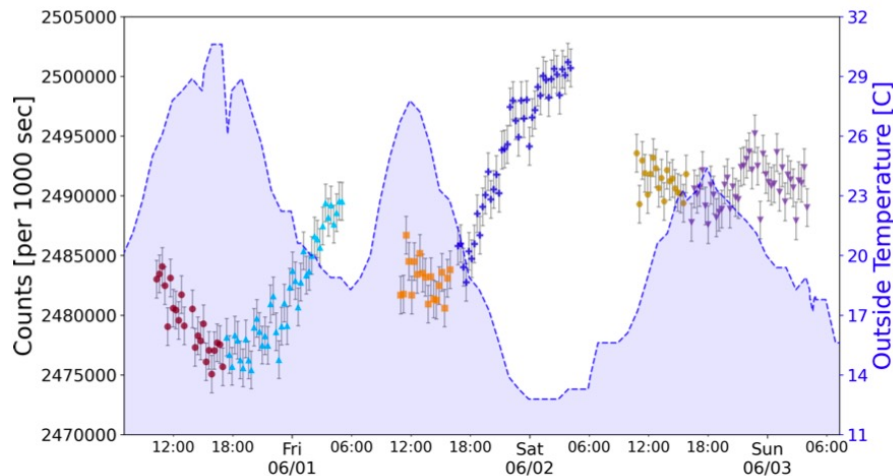


No sign of radioactive contamination

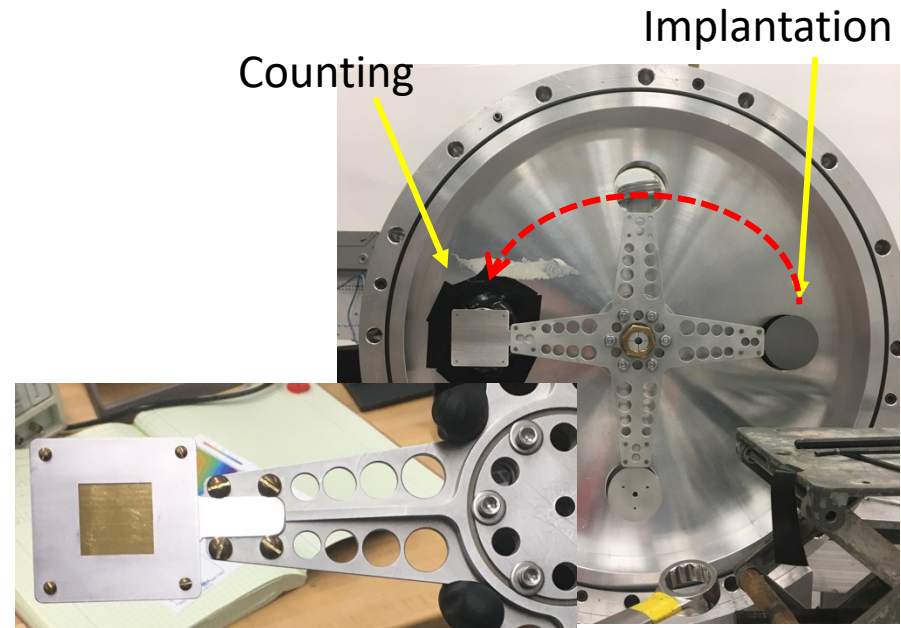
PMT stability



- With the ^{13}N $t_{1/2} \sim 10$ minutes, need to ensure that measured count rate is stable over periods of time on order of 2-3 hours.
- Recorded rate from ^{90}Sr ($t_{1/2} \sim 28.9$ y) source over several days.
- Saw strong correlation between measured rate and temperature.
- As result, only kept in analysis runs for which temperature varied by $< 0.1\text{C}$.



Measurement procedure



Typical procedure:

- 1) Implant ion beam on a Ta foil for $\sim 3 t_{1/2}$.
- 2) Deflect beam entering tandem.
- 3) Rotate foil in front of 1 mm plastic scintillator coupled to a PMT.
- 4) Count for $\sim 25 t_{1/2}$.
- 5) Rotate back to implant position, turn on the beam and repeat.

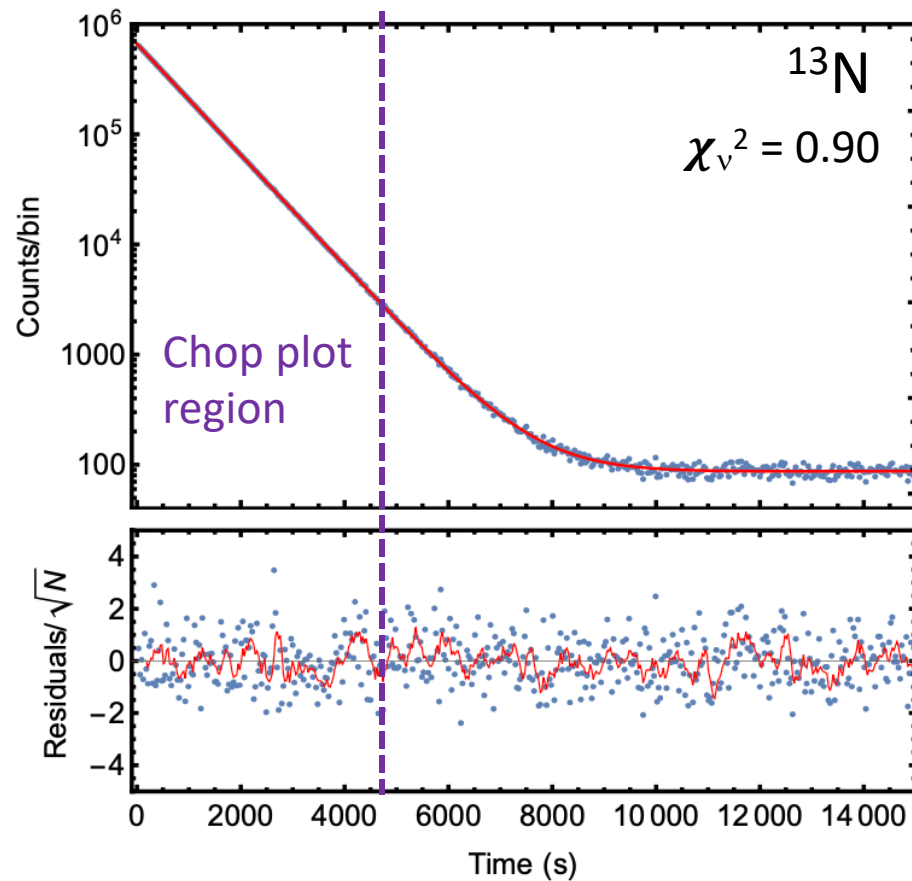


Sum fit & chop plot

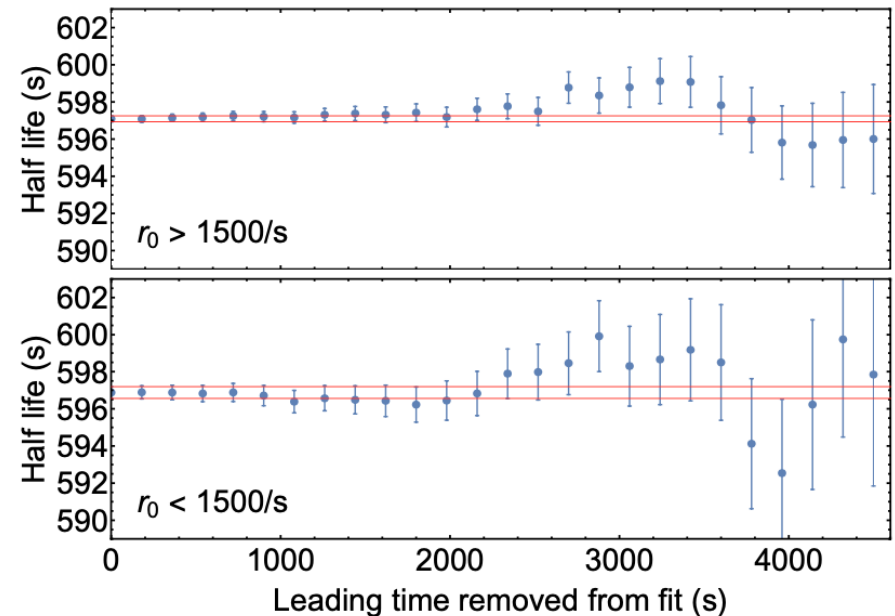


Fitted using techniques from:

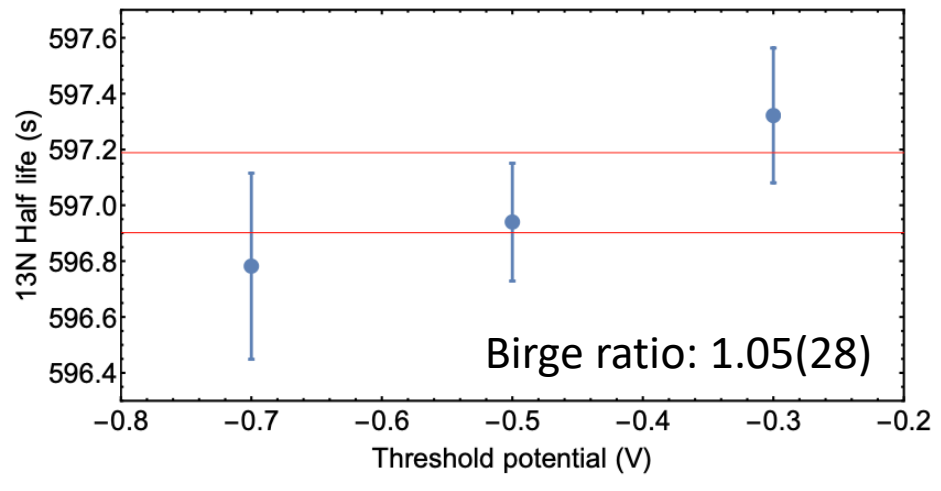
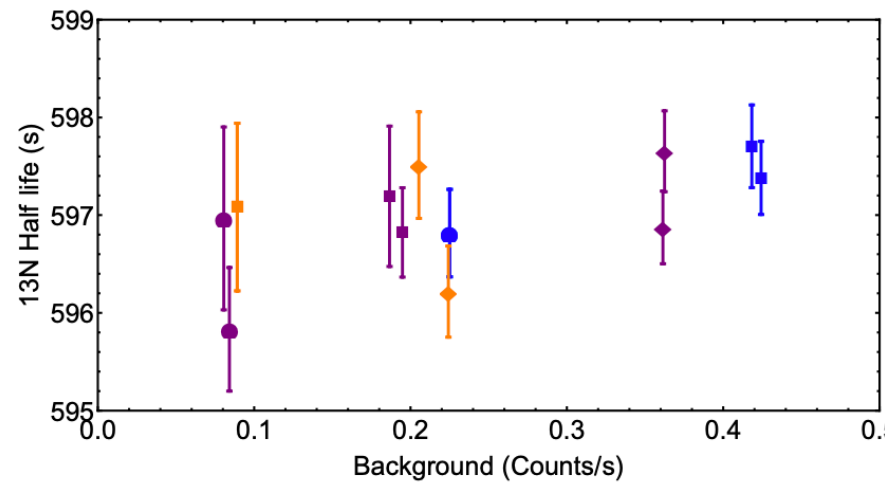
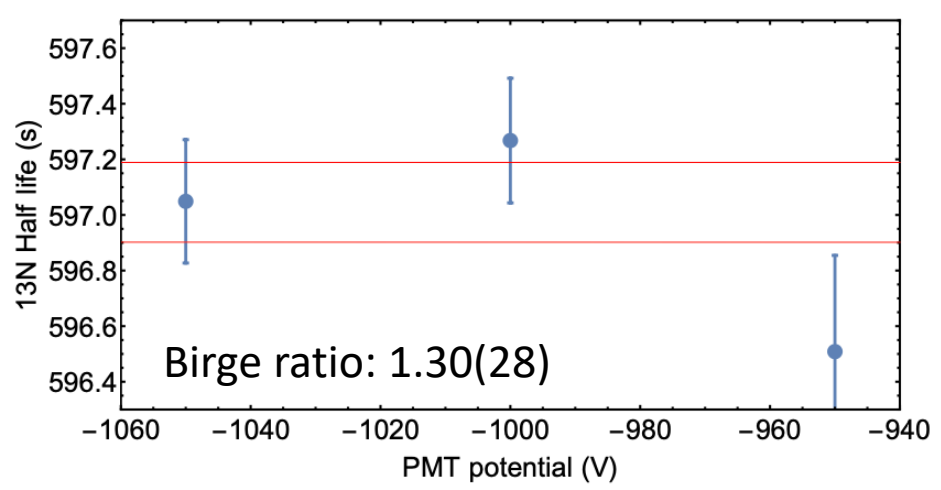
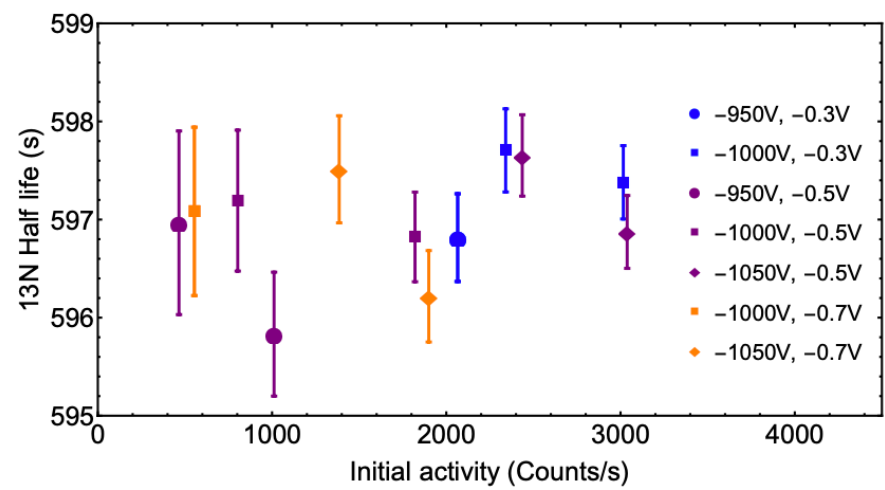
- V.T. Koslowsky *et al.*, NIM A **401**, 289 (1997)
- G. Grinyer *et al.*, PRC **71**, 044309 (2005)



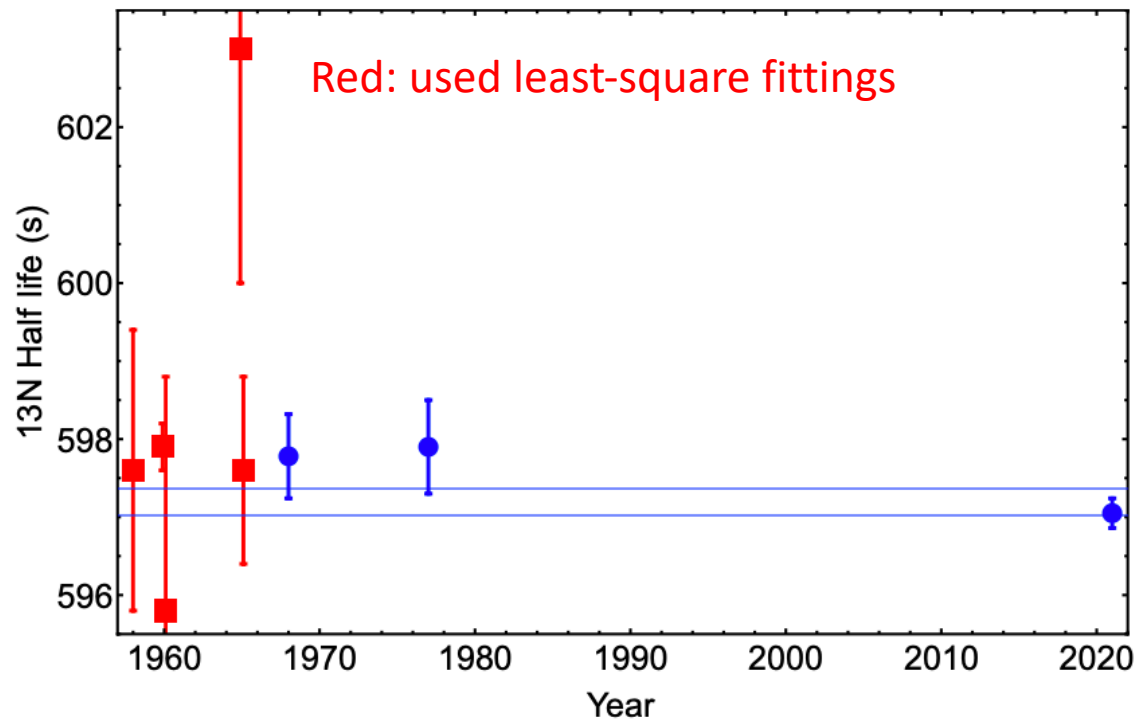
Chop plot



Individual runs & grouping by setting



Past ^{13}N half-lives measurements



ND measurement



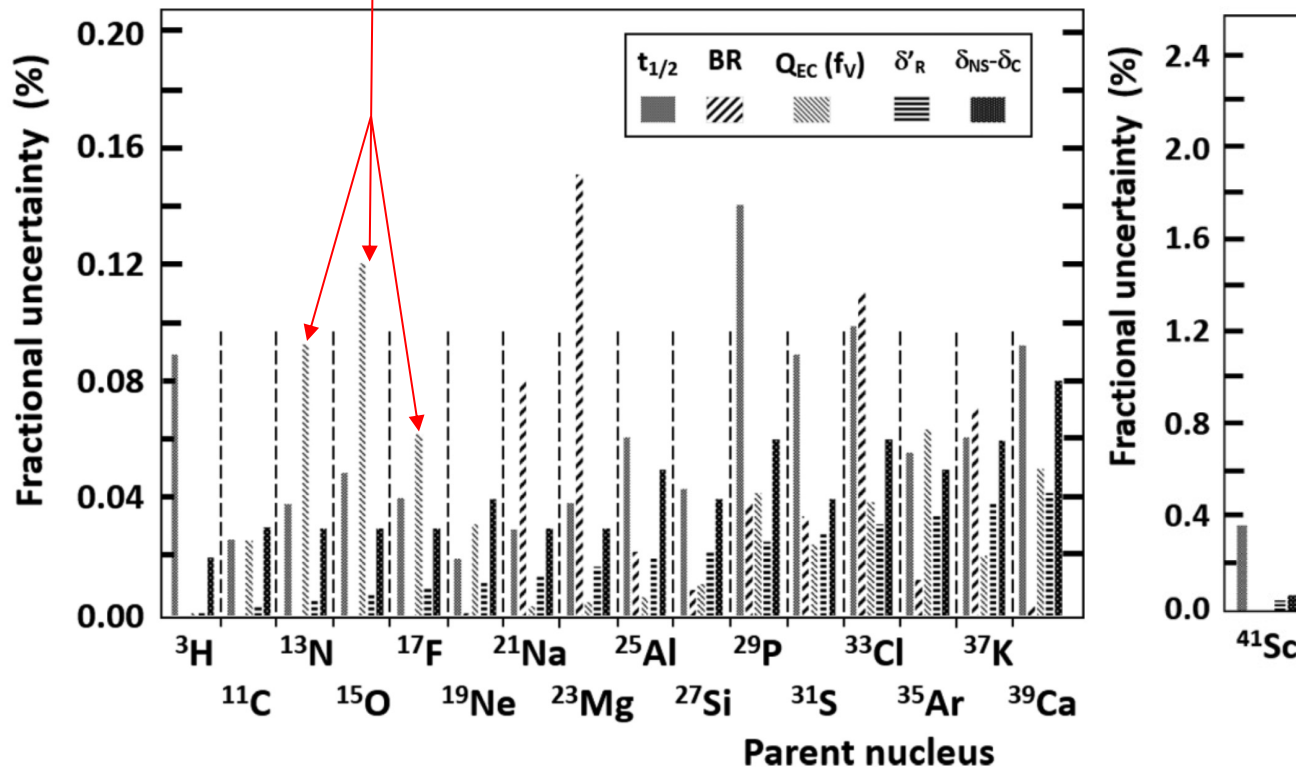
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Future ft-value measurements



Plan to measure Q_{EC} -values using TITAN Penning trap



Half-lives at ND:

- Finish analysis of ^{33}Cl
- Measure ^{31}S , ^{41}Sc

N. Severjins, PRC 107, 015502 (2023)



V_{ud} from mirror transitions

O. Naviliat-Cuncic & N. Severijns, PRL **102**, 142302 (2009)

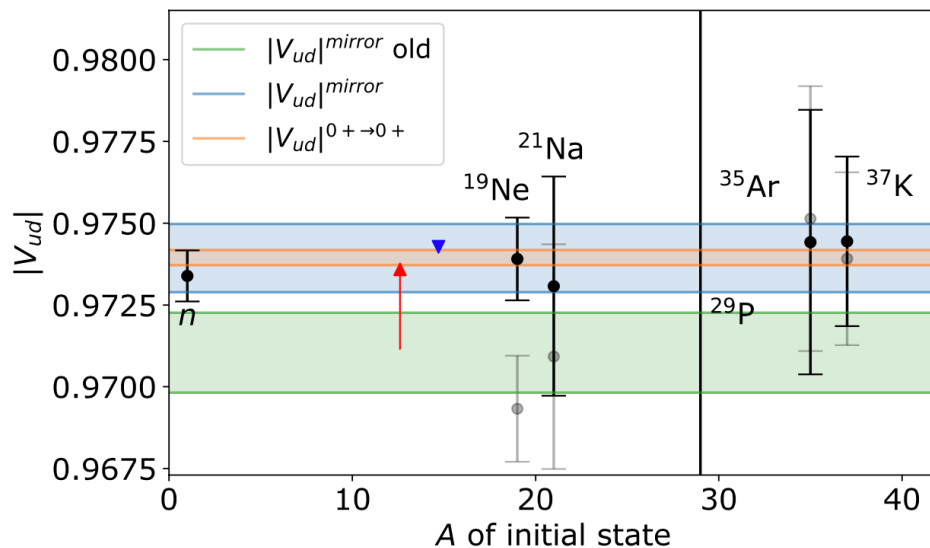
- V_{ud} : 0.9739(10)
- 6 times less precise than pure Fermi



- Only 5 nuclei
- One more parameter needed:

- ✓ Half-life
- ✓ Branching ratios
- ✓ Q-values
- ✓ Fermi-to-Gamow
Teller mixing ratio ρ

determined by measuring either:



L. Hayen, PRD **103**, 113001 (2021)

- β asymmetry parameter A_β
- ν asymmetry parameter B_ν
- β - ν angular correlation $a_{\beta\nu}$

To do:

- Long term: expand the list of transitions from which V_{ud} can be extracted
- Short term: reduce sources of uncertainties in the ft-values

Need to determine ρ



$$\mathcal{F}t_0 = \frac{ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C) [1 + (f_A/f_V)\rho^2]}{K} \rightarrow a_{SM} = \frac{1 - \rho^2/3}{1 + \rho^2}$$

$$= \frac{K}{G_F^2 V_{ud}^2 (1 + \Delta_R^V)},$$

Sensitivity of ρ to $a_{\beta\nu}$

Nucleus	n	³ H	¹¹ C	¹³ N	¹⁵ O	¹⁷ F	¹⁹ Ne
ρ	-2.20	-2.10	0.75	0.56	-0.63	-1.28	1.60
J	1/2	1/2	3/2	1/2	1/2	5/2	1/2
$\delta A_\beta/A_\beta$	4.0	5.1	0.04	0.04	0.7	-0.06	-12.6
$\delta a_{\beta\nu}/a_{\beta\nu}$	3.6	4.6	-1.2	-0.7	-0.9	-3.6	-13.1

Table I. Calculated sensitivities to $\delta\rho/\rho$ for the lowest mass mirrors, with approximate ρ values taken from [10] and the leading order expressions.

L. Hayen & A.R. Young, arXiv:2009.11364 (2020)

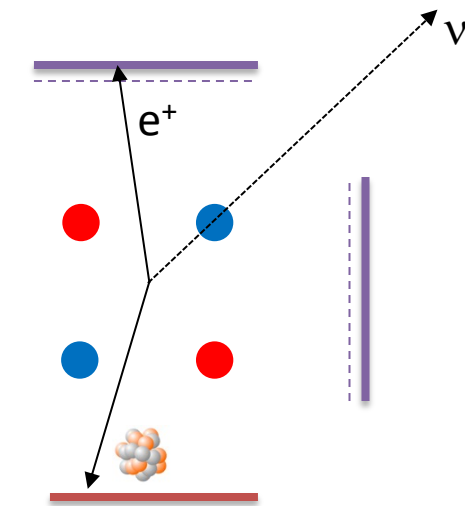
- The ¹⁷F ρ has a similar sensitivity to $a_{\beta\nu}$ as the neutron.
- TwinSol produce 2×10^6 pps of ¹⁷F
- Will be able to greatly improve on the previous determination of ρ (N. Severijns et al., PRL **63**, 1050 (1989)) based on a measurement of A (poor sensitivity to ρ (O. Navviliat-Cuncic & N. Severijns, PRL **102**, 142302 (2009))
- Choice of first isotope will depend on chemistry in the gas cell...



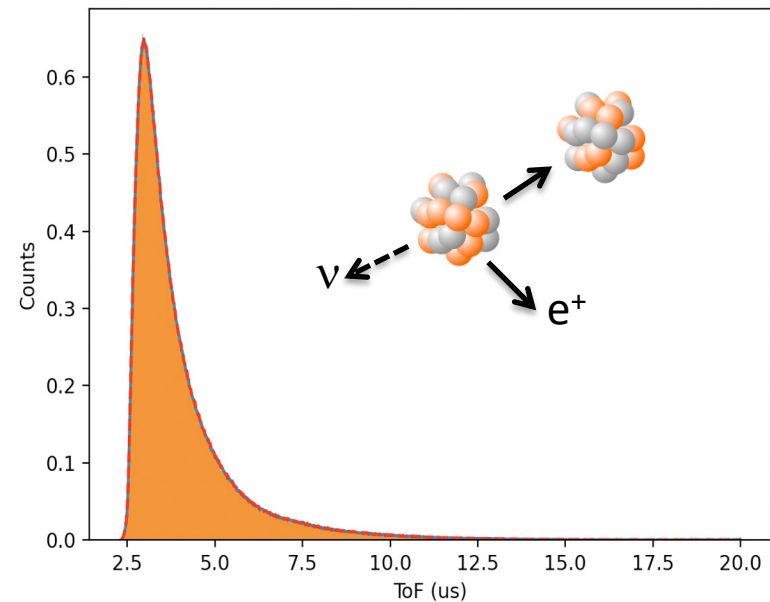
Measuring $a_{\beta\nu}$ using a Paul trap



- ρ will be determined from a measurement of $a_{\beta\nu}$
- $a_{\beta\nu}$ can be inferred from shape of energy spectra of positron and the TOF of recoil after decay of trapped nuclei.
- A Paul trap holds any kind of ions in well-defined region of space.

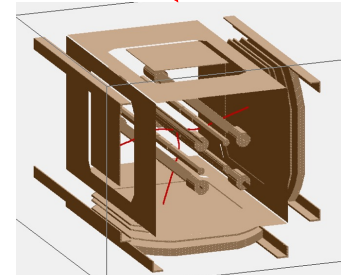
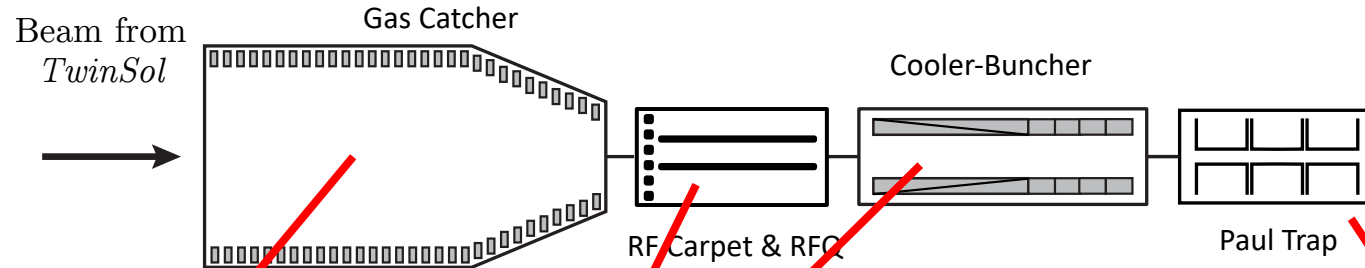


DSSD / Plastic : purple
Position sensitive MCP: red

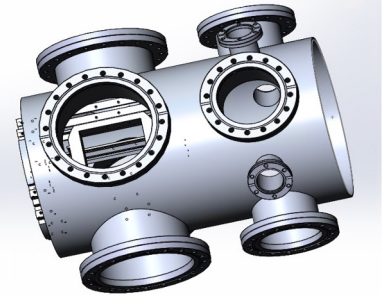


Superalloyed Transistor Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict)

See Sam Porter's poster!



Lawrence Livermore National Laboratory



- Gas catcher from ANL: transport commissioning completed
- RF carpet and ion guide completed
- Cooler/buncher commissioning completed
- Paul trap on its way to ND from LLNL

Summary



- CKM matrix unitarity is one possible test of the SM.
- There is currently a 3σ tension with unitarity.
- Superaligned mixed beta transitions can be used to improve accuracy on V_{ud} .
- Measured the half-life of 7 different such transitions at ND including ^{13}N resulting in an improvement of their ft-values.
- Future half-life measurements will include ^{31}S and ^{41}Sc .
- St. Benedict currently under construction at ND. Aim to measure $a_{\beta v}$ in many superallowed mixed transition for the first time.



Acknowledgements



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Aaron Gallant

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Patrick O'Malley

Sam Porter

Caleb Quick

Ryan Ringle

Fabio Rivero

Guy Savard

Adrian Valverde

Abe Yeck

Regan Zite

+ rest of TwinSol
collaboration

Thank you!

UG students

G students

Former G students



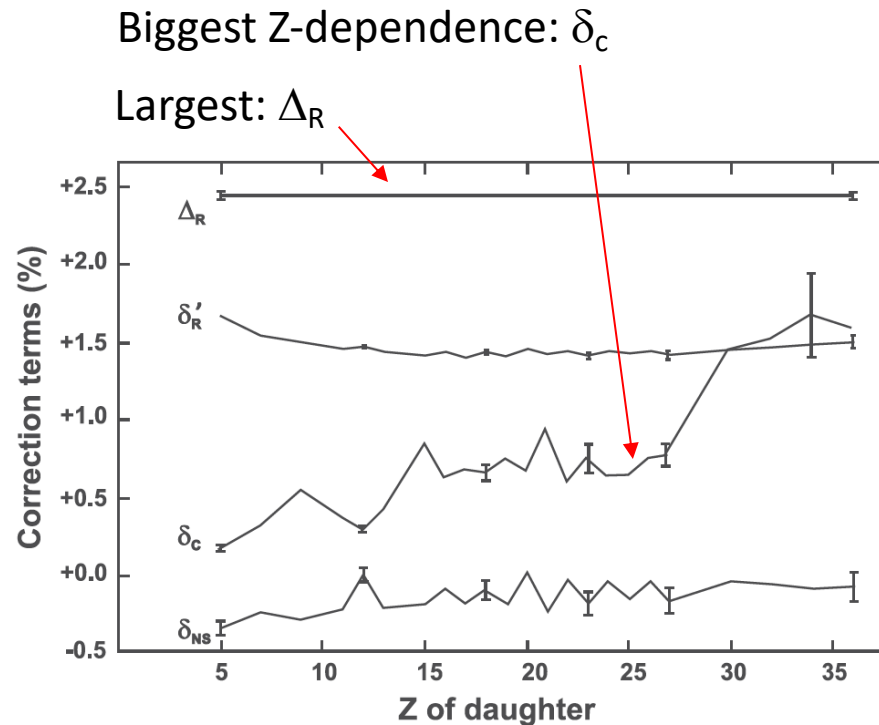
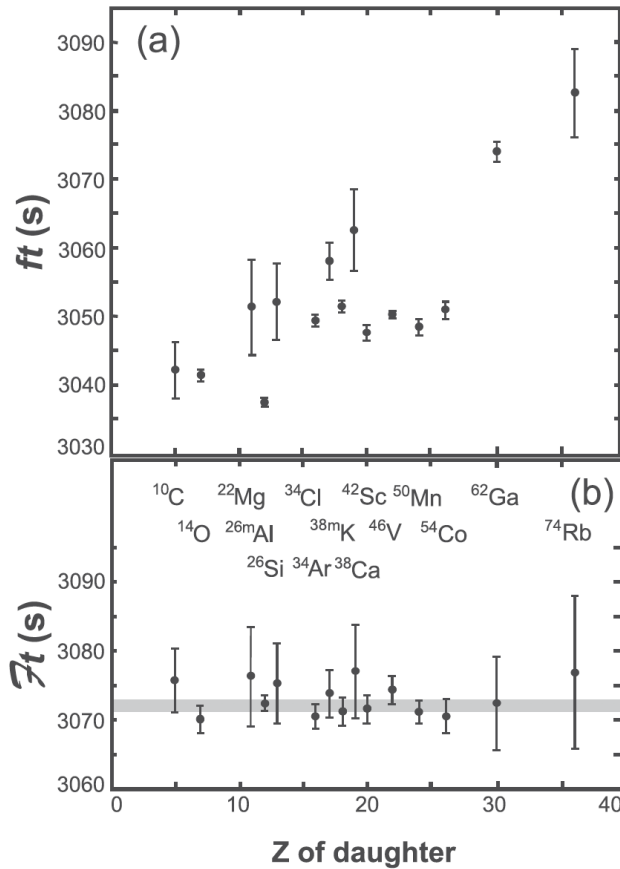
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Superaligned pure Fermi



$$\mathcal{F}t \equiv ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_c) = \frac{K}{2G_F^2 |V_{ud}|^2 (1 + \Delta_R^V)}$$



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



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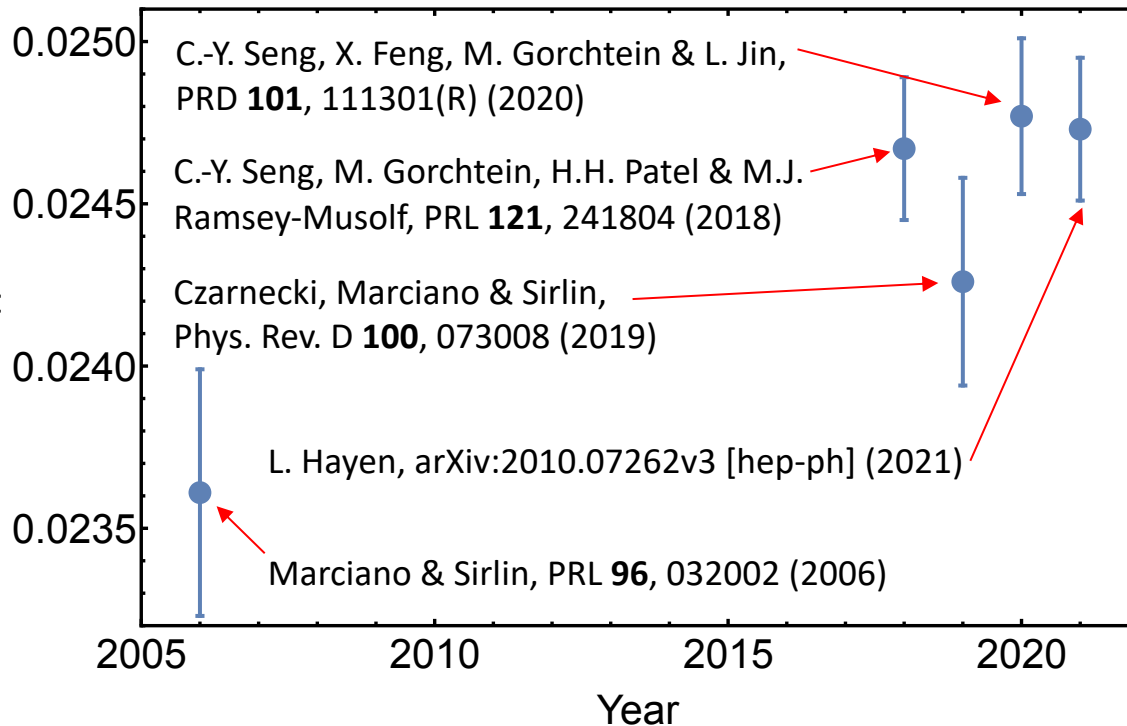
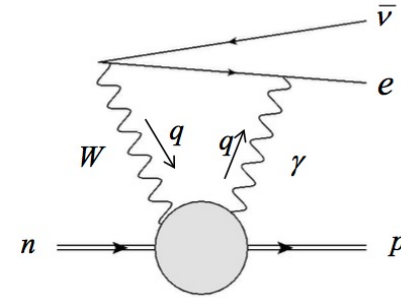


Issues with Δ_R



Recent transition-independent radiative corrections results are systematically higher than previous calculations.

$$\mathcal{F}t \equiv ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_c) = \frac{K}{2G_F^2 |V_{ud}|^2 (1 + \Delta_R^V)}$$



$$V_{ud} = 0.97370(25) \rightarrow 2020 \text{ H\&T}$$

$$\left. \begin{aligned} V_{us} &= 0.2245(8) \\ V_{ub} &= 0.00382(24) \end{aligned} \right\} 2020 \text{ PDG}$$

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

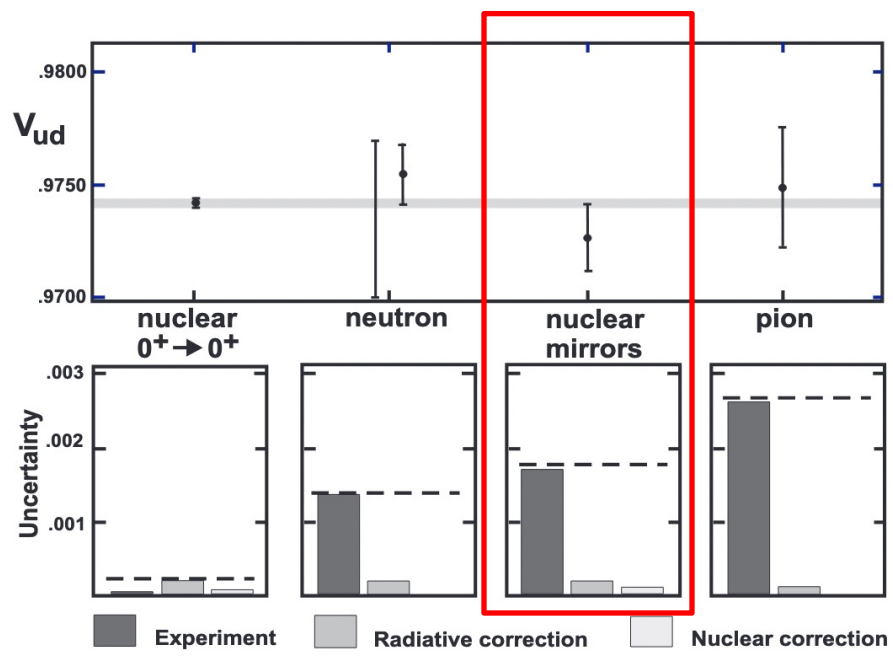
2.5 σ tension with unitarity



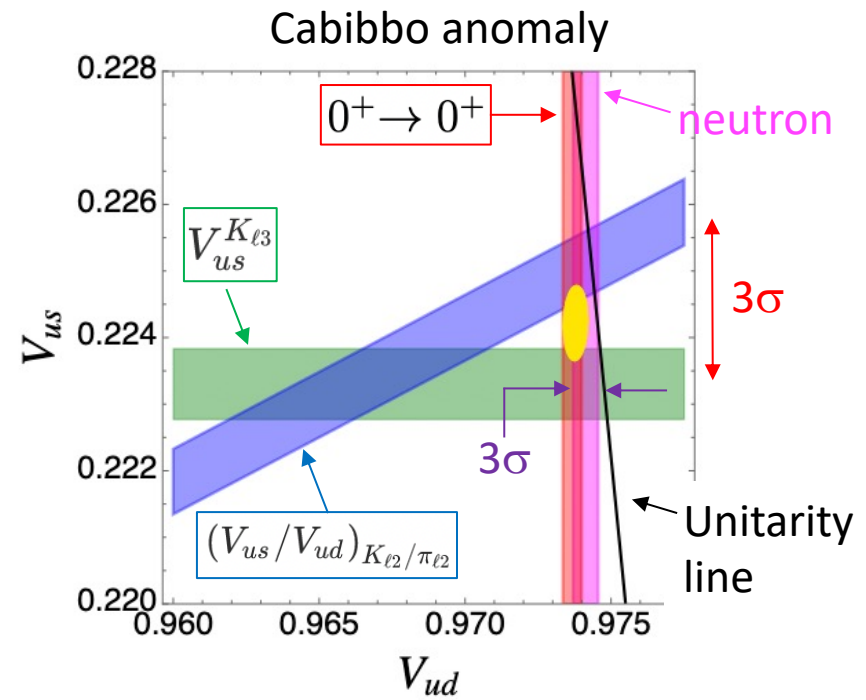
Cabibbo anomaly



- Via the CKM matrix unitarity test.
- $$\sum_i |V_{ui}|^2 = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$
- $$\begin{pmatrix} |d_w\rangle \\ |s_w\rangle \\ |b_w\rangle \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} |d_s\rangle \\ |s_s\rangle \\ |b_s\rangle \end{pmatrix}$$



J.C. Hardy and I.S. Towner,
arXiv:1807.01146v1 [nucl-ex] (2018)



V. Cirigliano *et al.*, PLB **838**, 137748 (2023)



Aside



Besides being one more system that can be used to extract V_{ud} and improve its accuracy, mirror decays can also be used to:

- Search for scalar and tensor currents
- If right-handed neutrinos are introduced, then C_S , C_T are no longer equal to C_S' and C_T' , and adding mirror nuclei data to the global beta-decay fit improve the results appreciably.

$$v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98501_{(-114)}^{(+75)} \\ -1.2544_{(-11)}^{(+14)} \\ -0.0007_{(-14)}^{(+29)} \\ -0.0010_{(-22)}^{(+33)} \end{pmatrix}, \quad \begin{pmatrix} v^2 |C_V^-| < 0.053 \\ v^2 |C_A^-| < 0.063 \\ v^2 |C_S^-| < 0.050 \\ v^2 |C_T^-| \in [0.072, 0.099] \end{pmatrix}$$

Here, adding the mixed decay data was vital in obtaining meaningful fit results and improves the uncertainty on the various coefficients by a factor of 2.

There is a hint of a BSM tensor coupling to RH neutrinos at the 3.2σ -level.

A. Falkowski, M. Gonzalez-Alonso & O. Naviliat-Cuncic, JHEP **04**, 126 (2021)



Table of uncertainties



Source	Uncertainty (ms)
Dead time	35
Contamination	41
Clock time	6
Binning	11
Total Systematic Uncertainty	55
Statistical Uncertainty	144



Effect of ft-value parameters



Parameter	This work	With Previous $t_{1/2}$
$t_{1/2}$	597.19(22) s	597.88(23) s
$f_v t$	4616.3(45) s	4621.3(47) s
$\mathcal{F}t^{mirror}$	4676.3(48) s	4681.4(49) s
ρ	0.5591(14)	0.5578(14)
a_{SM}	0.6825(12)	0.6836(13)
A_{SM}	-0.33308(4)	-0.33304(4)
B_{SM}	-0.6506(13)	-0.6495(13)

