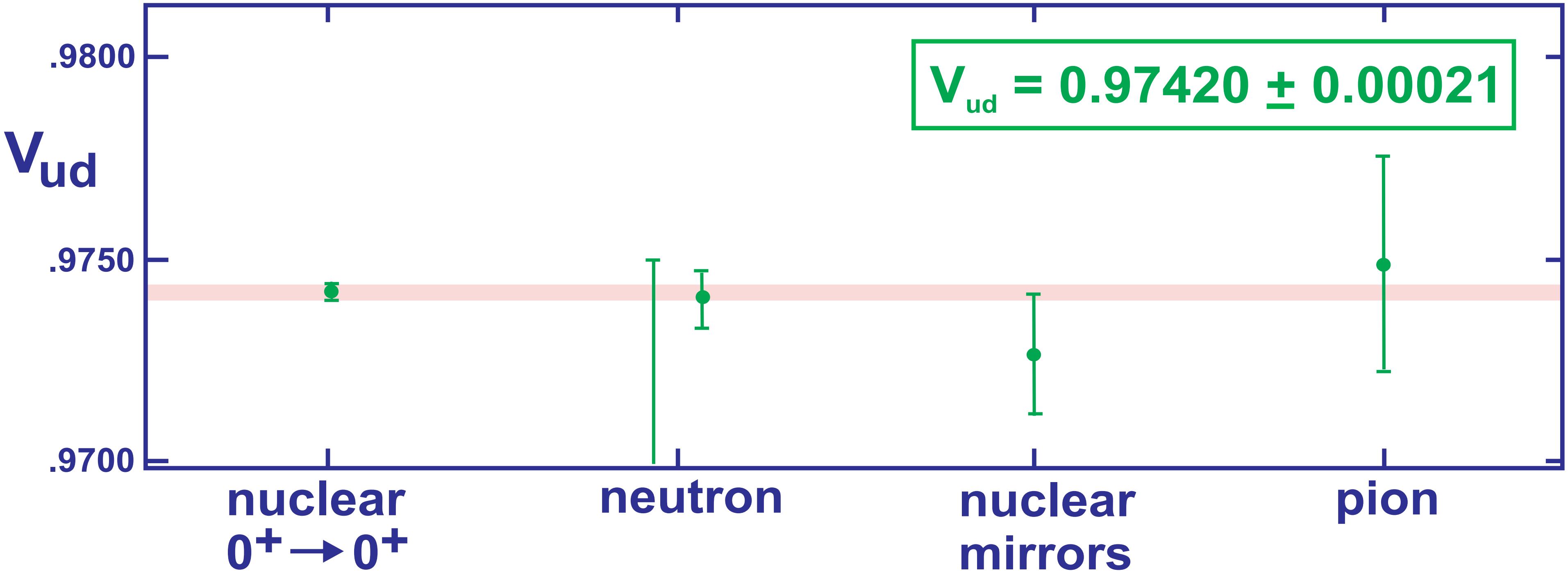
Measuring $|V_{ud}|$ and testing CKM unitarity: past, present & future

J.C. Hardy

Cyclotron Institute
Texas A&M University

CURRENT STATUS OF V_{ud}

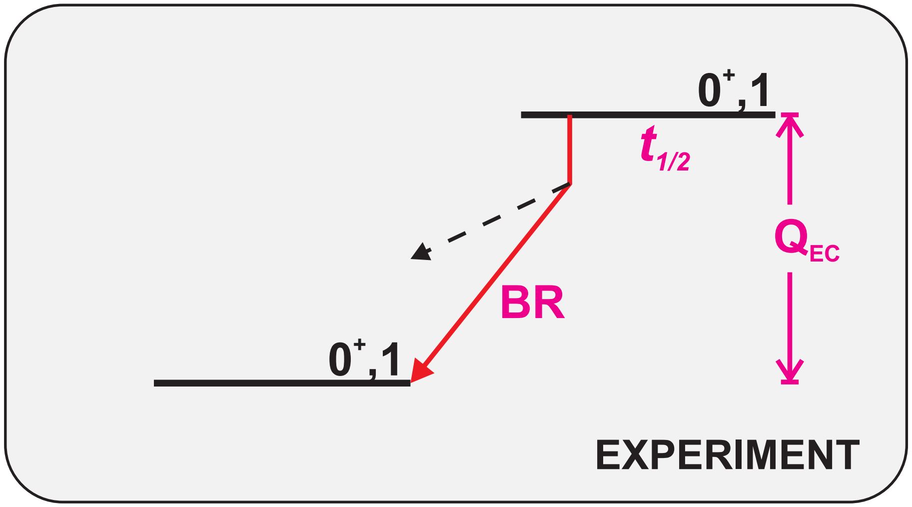


SUPERALLOWED $0^+ \rightarrow 0^+$ BETA DECAY

BASIC WEAK-DECAY EQUATION

$$ft = \frac{K}{G_V^{\,2} \langle \tau \rangle^2}$$

f = statistical rate function: $f(Z, Q_{EC})$
t = partial half-life: $f(t_{1/2}, BR)$
G_V = vector coupling constant
$\langle \tau \rangle$ = Fermi matrix element



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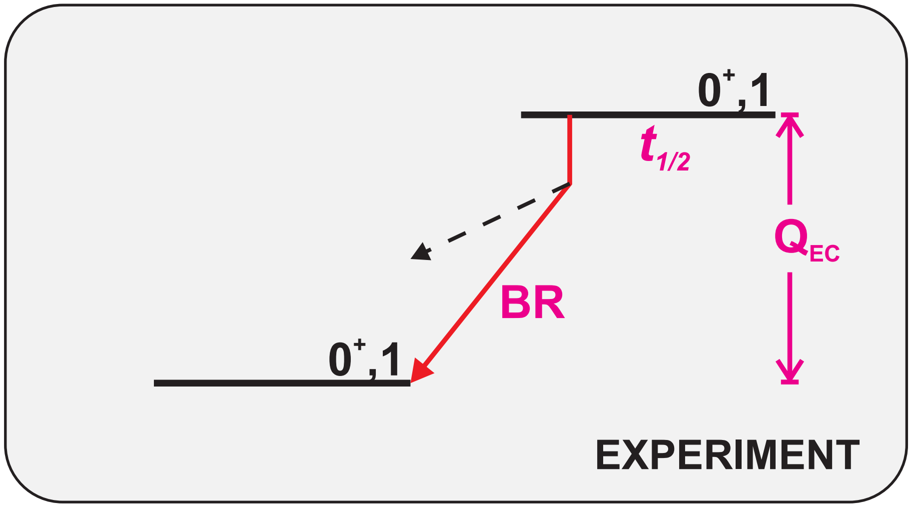

INCLUDING RADIATIVE AND ISOSPIN-SYMMETRY-BREAKING CORRECTIONS

$$\mathcal{F}t = ft\,(1 + \delta_R')[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$

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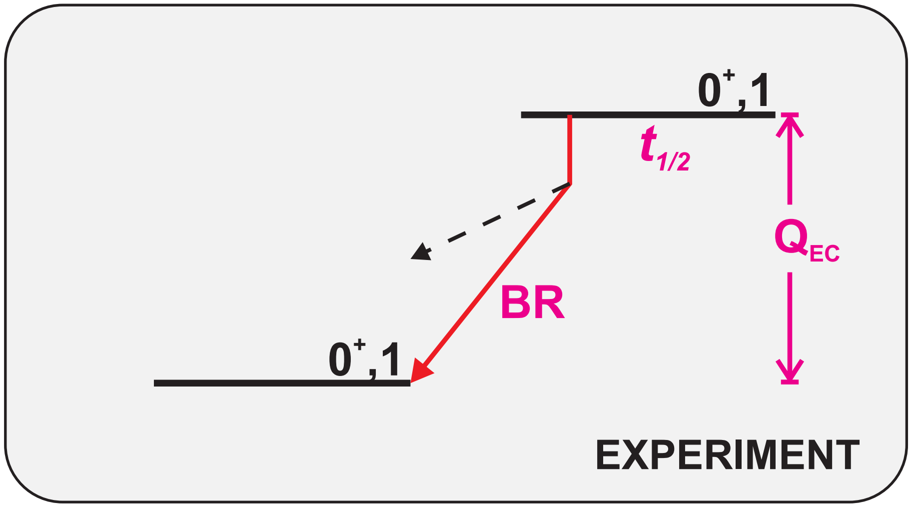

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δ_R': $f(Z, Q_{EC})$ ~1.5%

$\delta_C - \delta_{NS}$: f(nuclear structure) 0.3-1.5%

Δ_R: f(interaction) ~2.4%

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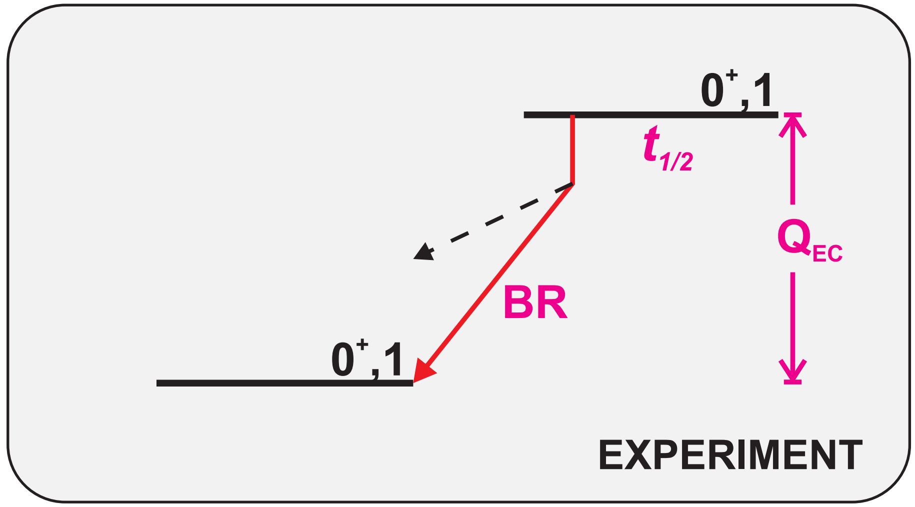

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$f(Z, Q_{EC})$ ~1.5%

f(nuclear structure) 0.3-1.5%

f(interaction) ~2.4%

THEORETICAL UNCERTAINTIES

0.05 – 0.10%

THE PATH TO V_{ud}

FROM A SINGLE TRANSITION

Experimentally determine $G_V^2 (1 + \Delta_R)$

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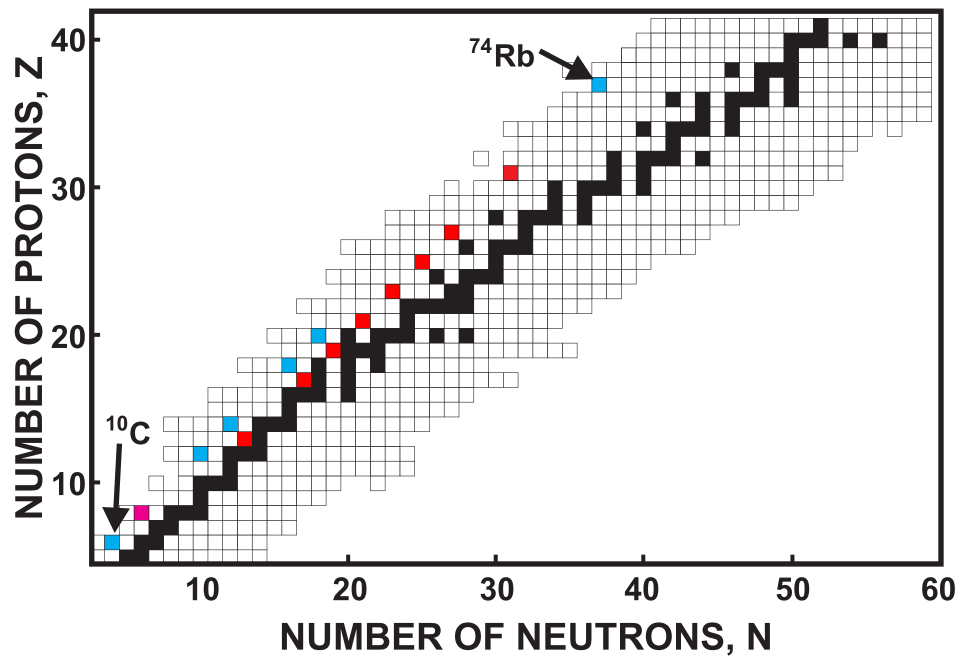
FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

Validate the correction terms



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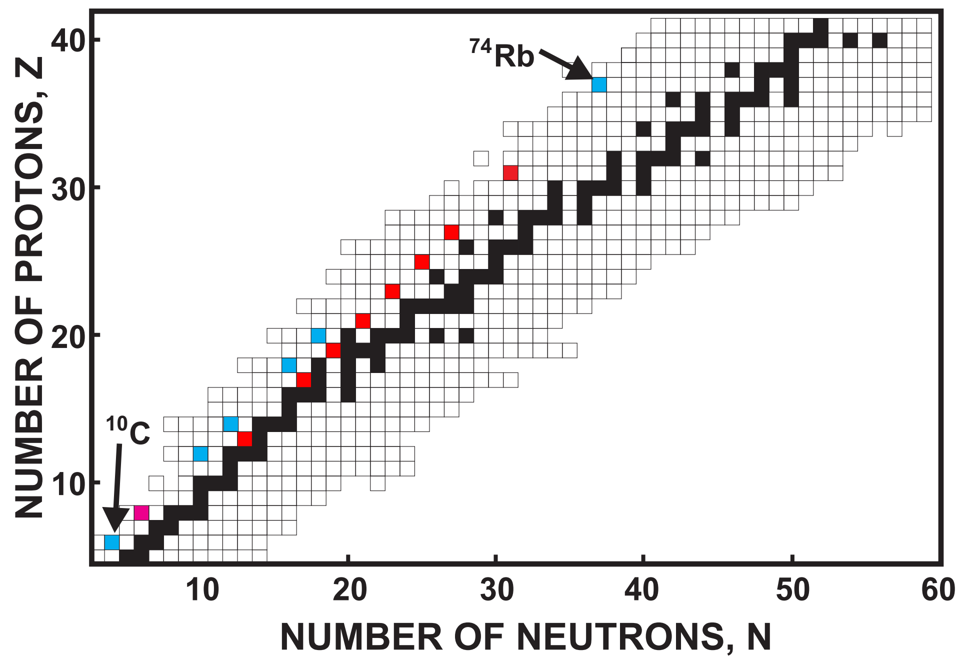

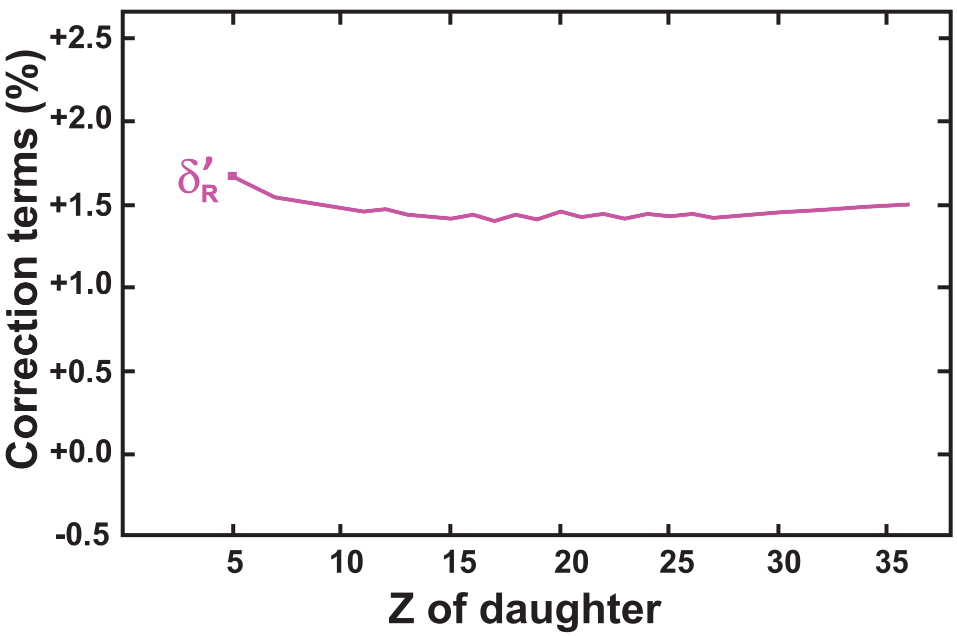

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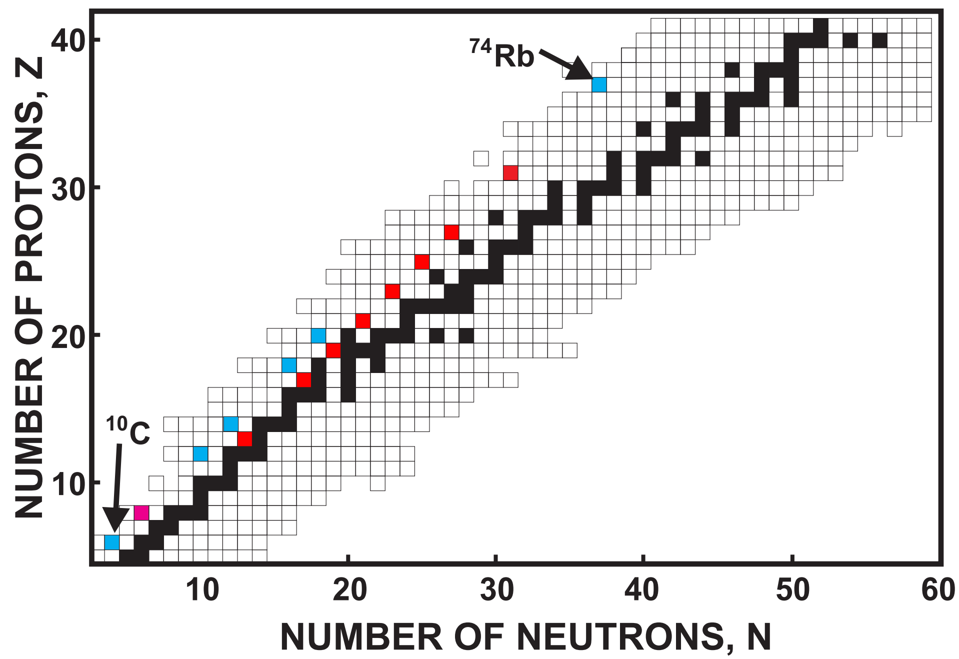

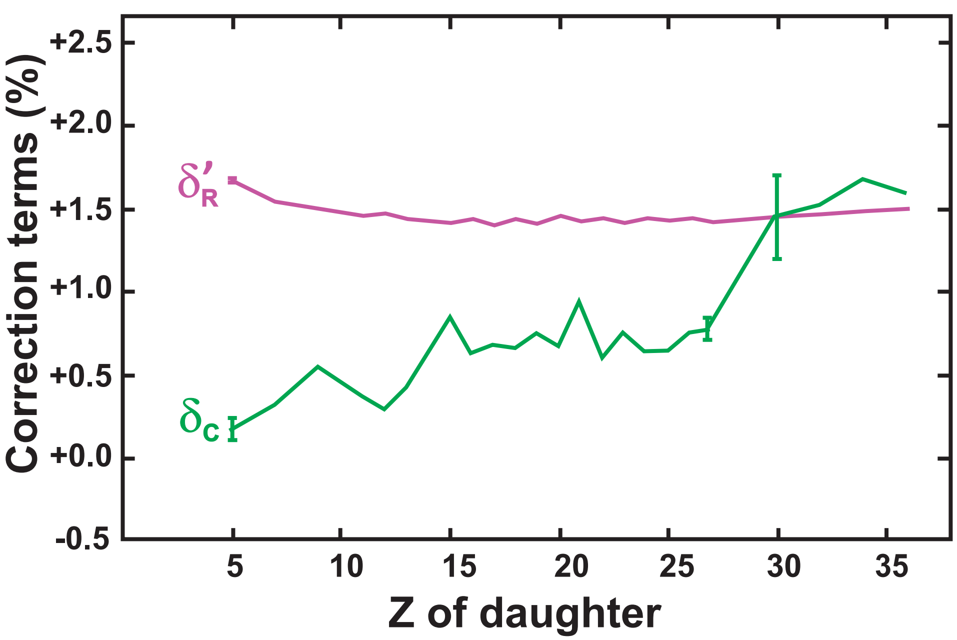

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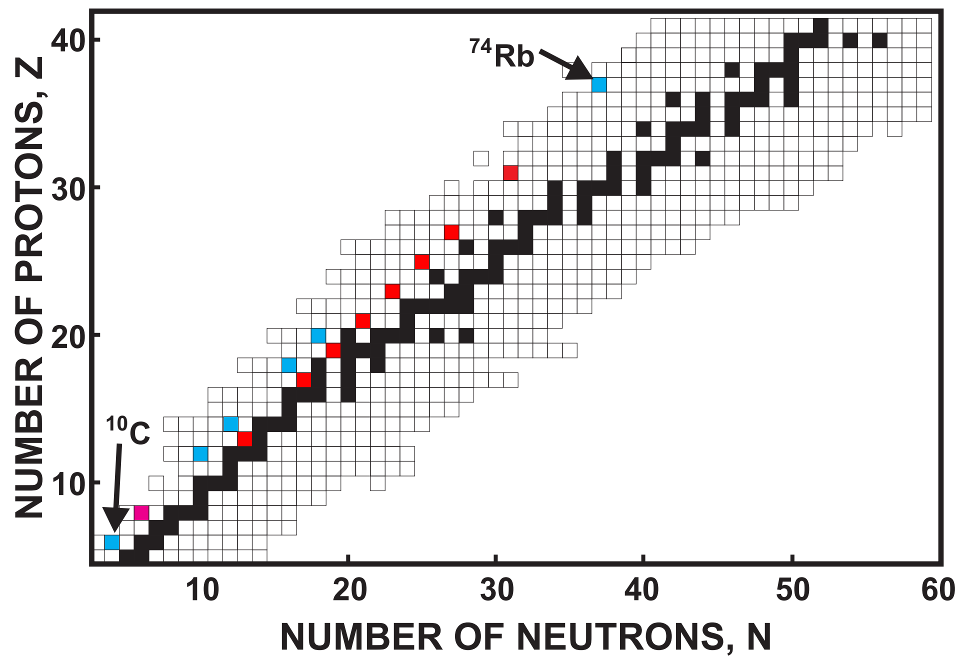

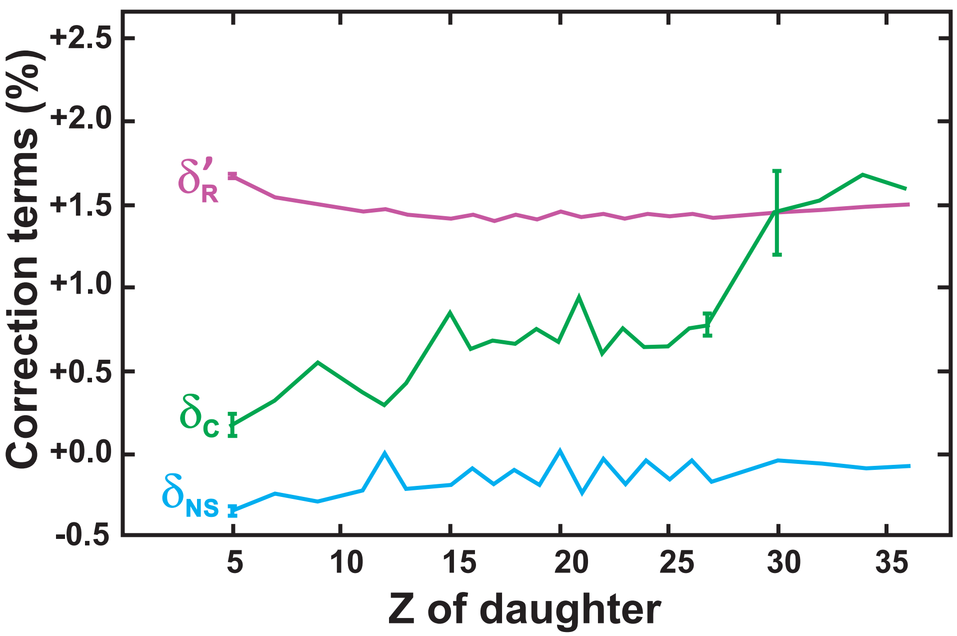

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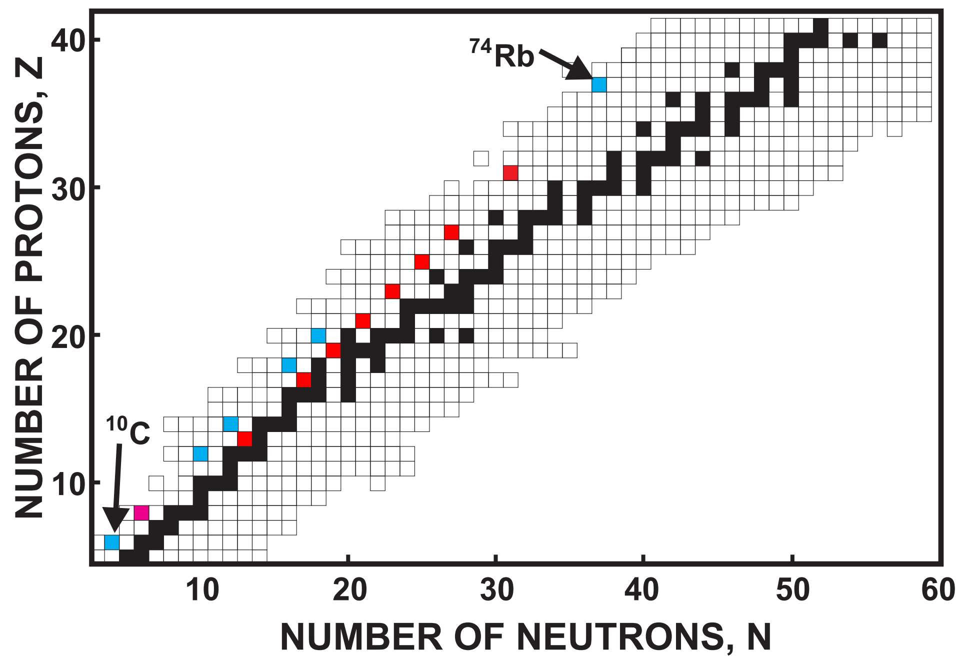

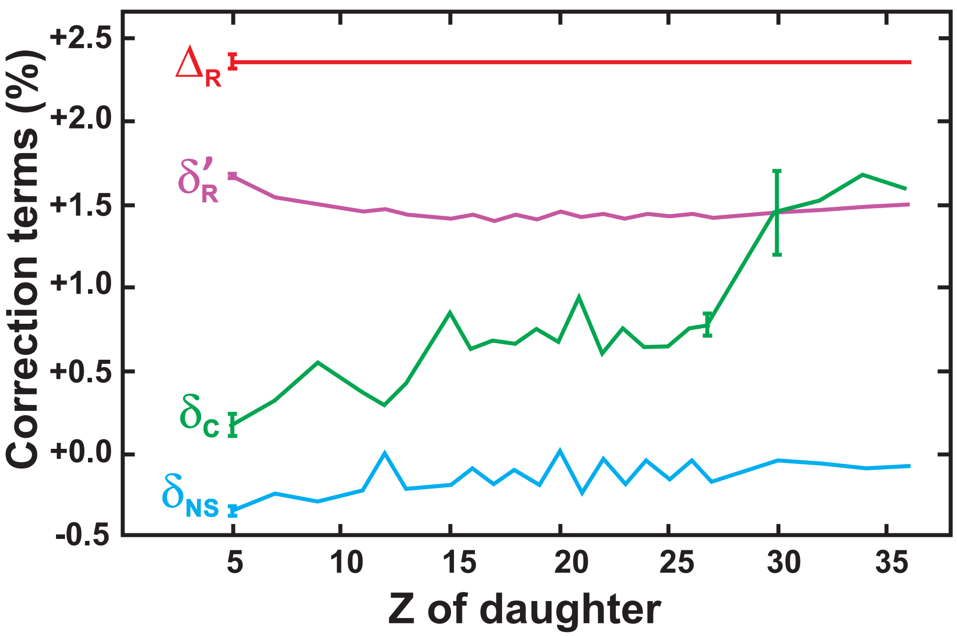

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WITH CVC VERIFIED

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

weak eigenstates — Cabibbo Kobayashi Maskawa (CKM) matrix — mass eigenstates

Obtain precise value of $G_V^2(1 + \Delta_R)$

Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G_\mu^2$$

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Test CKM unitarity

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

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weak eigenstates

Cabibbo Kobayashi Maskawa (CKM) matrix

mass eigenstates

Obtain precis… V (1 + Δ_R)

Determin…

T… unitarity

ONLY POSSIBLE IF PRIOR CONDITIONS SATISFIED

$$V_{ud}^2 = G_V^2/G_\mu^2$$

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

SUPERALLOWED-DECAY WORK INVOLVING TAMU GROUP

^{30}S
$t_{1/2}$: PRC **97**, 035501 (2018)

^{34}Ar
$t_{1/2}$,: PRC **74**, 055502 (2006)
Q_{EC}: PRC **83**, 055501 (2011)
BR: to be published (2019)

^{38}Ca
$t_{1/2}$: PRC **84**, 065502 (2011)
Q_{EC}: PRC **83**, 055501 (2011)
BR: PRL **112**, 102502 (2014)
PRC **92**. 015502 (2015)

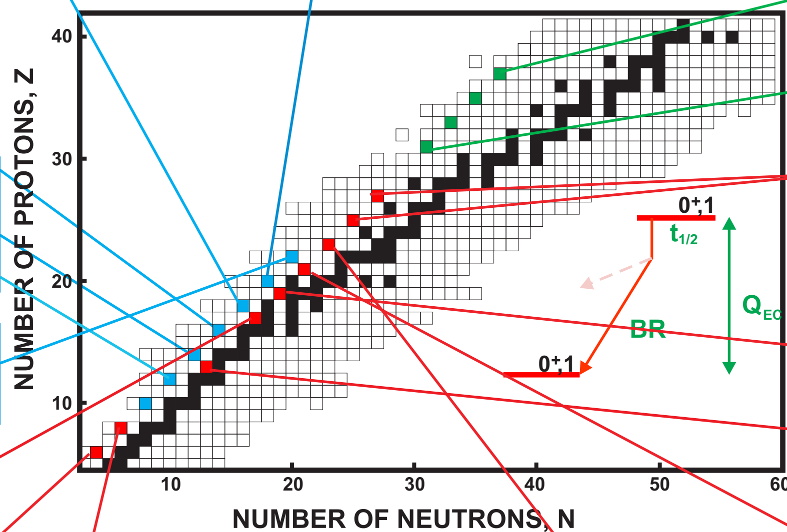
^{74}Rb
$t_{1/2}$: PRL **86**, 1454 (2001)
BR: PRC **67**, 051305R (2003)

^{62}Ga
$t_{1/2}$,BR: PRC **68**, 015501 (2003)

^{26}Si
$t_{1/2}$: PRC **82**, 035502 (2010)
BR: to be published (2019)

^{22}Mg
$t_{1/2}$: BR: PRL **91**, 082501 (2003)
Q_{EC}: PRC **70**, 042501(R) (2004)

^{42}Ti
$t_{1/2}$: data being analyzed



^{50}Mn, ^{54}Co
Q_{EC}: PRL **100**, 132502 (2008)

^{38}K^{m}
$t_{1/2}$: PRC **82**. 045501 (2010)
Q_{EC}: PRL **103**, 252501 (2009)

^{26}Al^{m}
Q_{EC}: PRL **97**, 232501 (2006)

^{42}Sc
Q_{EC}: PRC **95**, 025501 (2017)

^{34}Cl
$t_{1/2}$: PRC **74**, 055502 (2006)
Q_{EC}: PRL **103**, 252501 (2009)

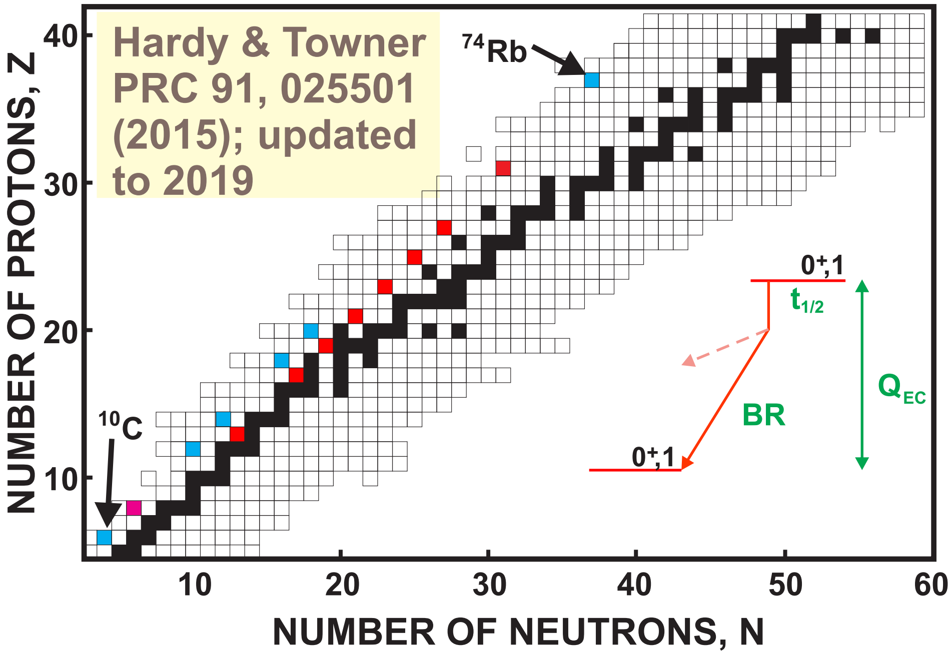
^{10}C
$t_{1/2}$: PRC **77**, 045501 (2008)
Q_{EC}: PRC **83**, 055501 (2011)
BR: data being analyzed

^{14}O
BR: PRC **72**, 055501 (2005)

^{46}V
$t_{1/2}$: PRC **85**, 035501 (2012)
Q_{EC}: PRL **95**, 102501 (2005)
PRL **97**, 232501 (2006)
PRC **83**, 055501 (2011)

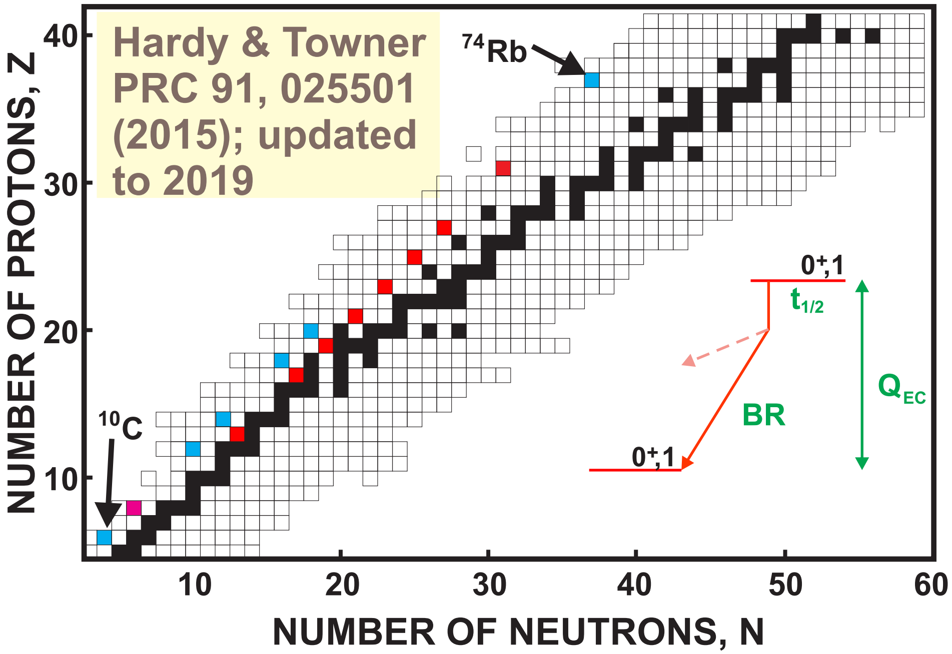
Theory/Reviews
(δ_C - δ_{NS}) calculations: PRC **77**, 025501 (2008)
Recent critical survey: PRC **91**, 025501 (2015)
Measurement & interpretation of $0^+ \rightarrow 0^+$: J. Phys G 41, 114004 (2014)
Numerous reviews of CVC and CKM-unitarity tests
Comparative tests of δ_C calculations: PRC **82**, 065501 (2010)
Parameterization of *f* function: PRC **91**, 015501 (2015)

WORLD DATA FOR $0^+ \rightarrow 0^+$ DECAY, 2019



- 9 cases with *ft*-values measured to <0.05% precision; 6 more cases with 0.05-0.23% precision.
- ~220 individual measurements with compatible precision

WORLD DATA FOR $0^+ \rightarrow 0^+$ DECAY, 2019



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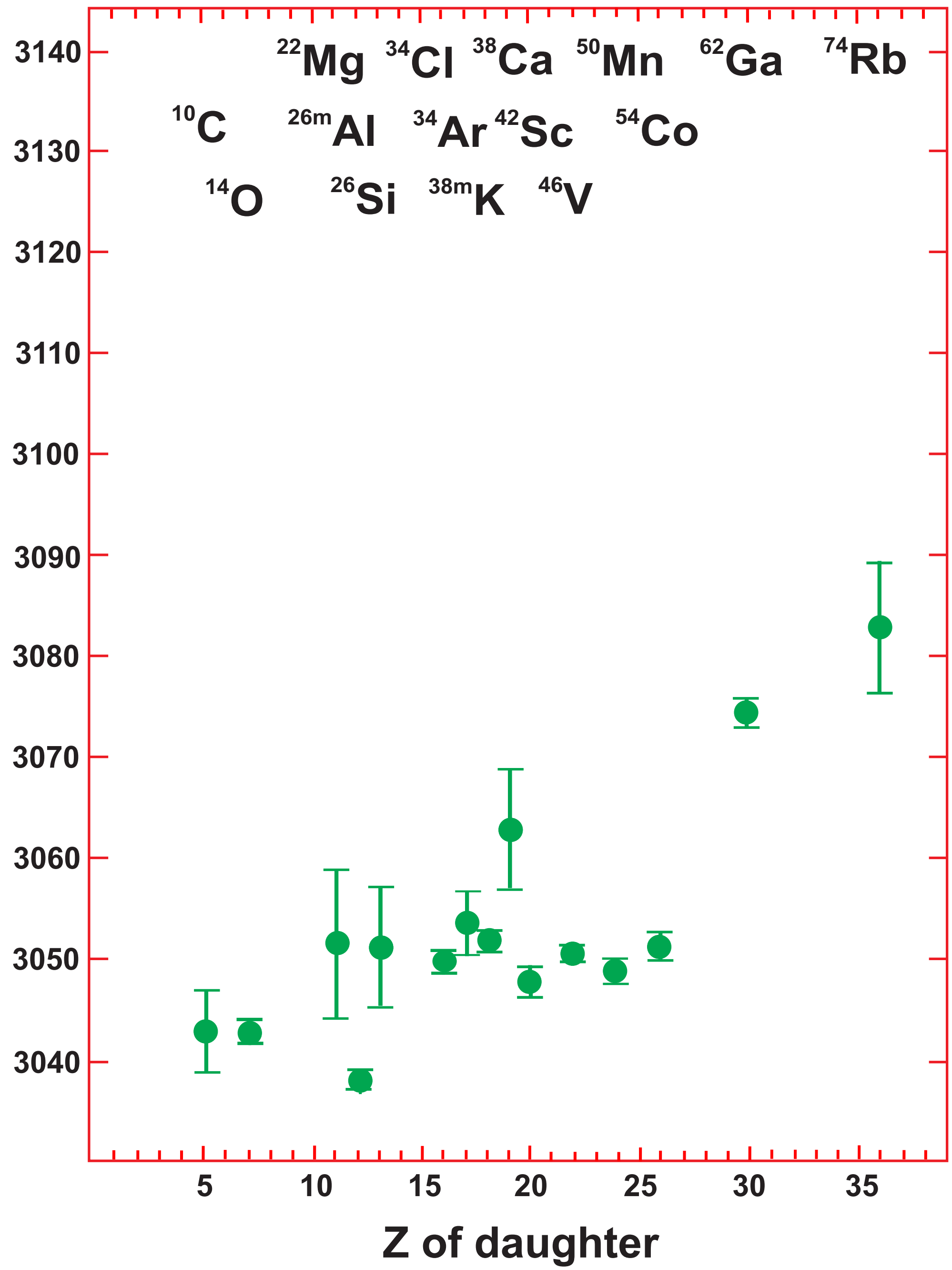
ft →



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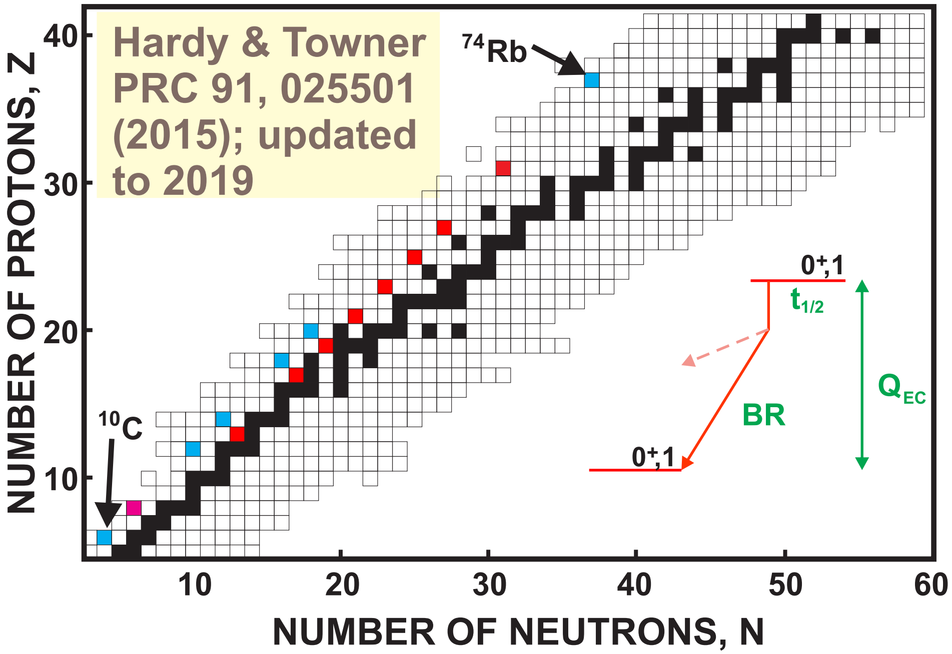

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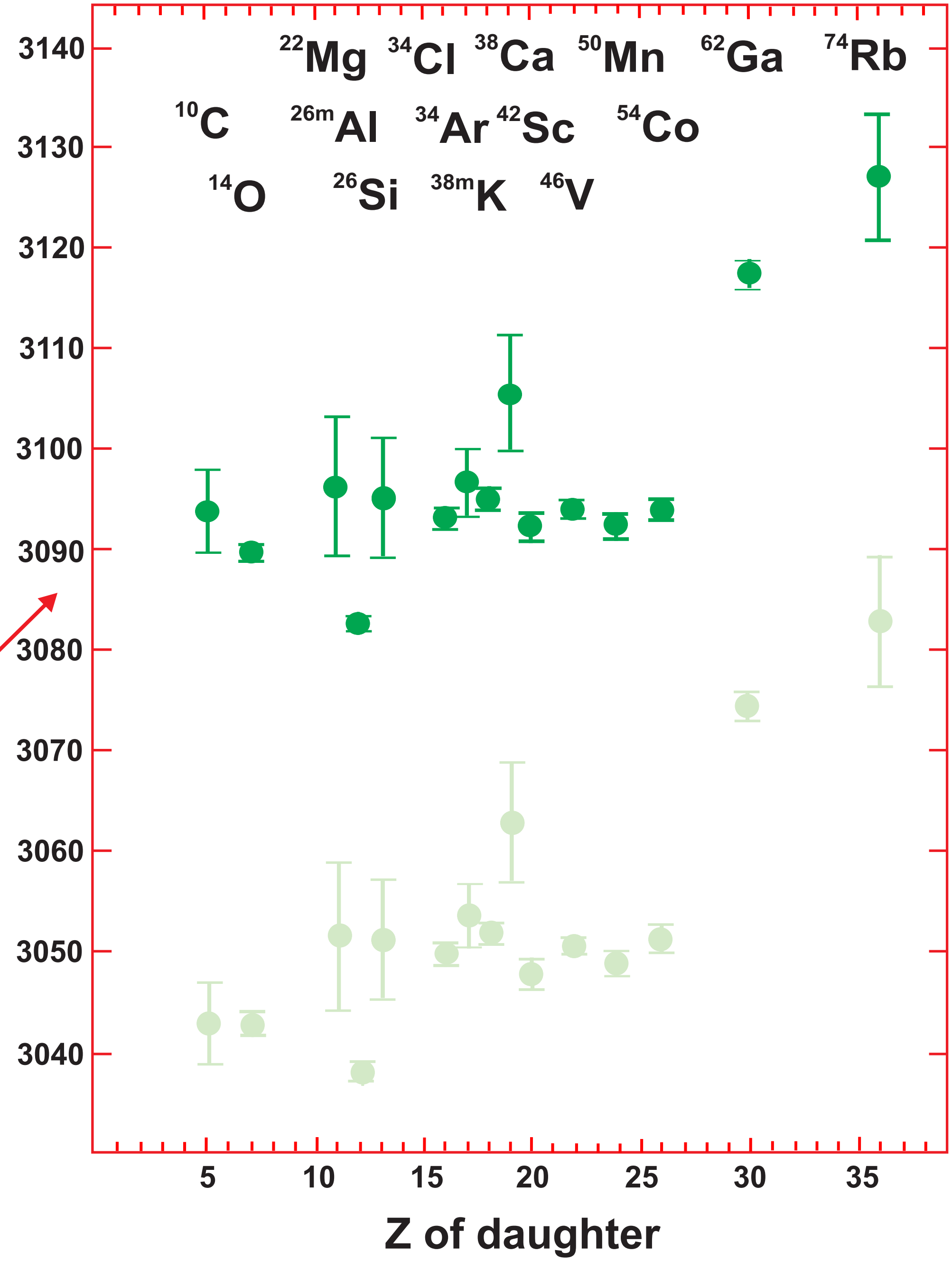
$$ft\,(1 + \delta'_R)$$



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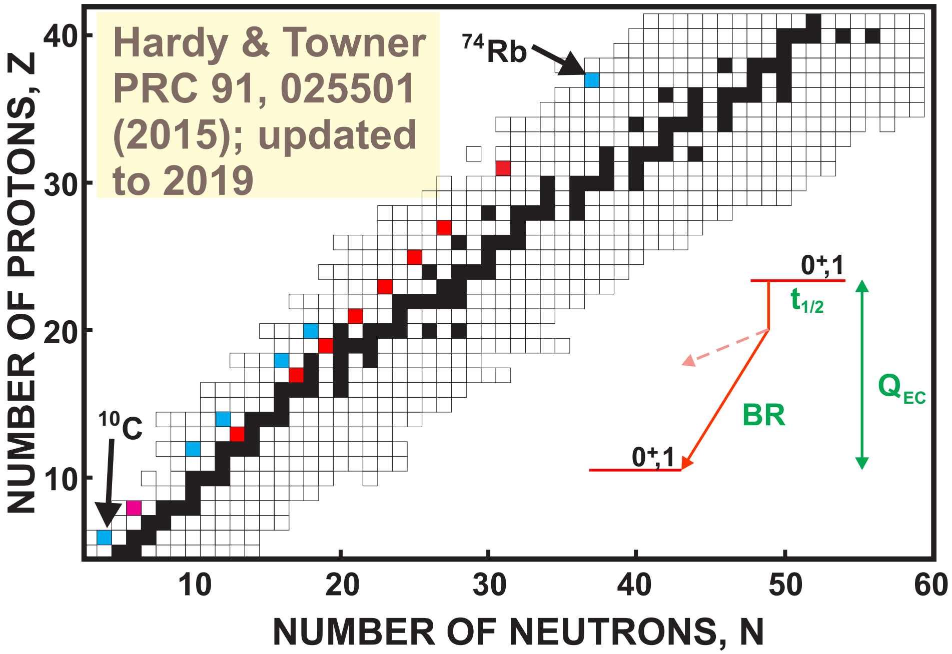

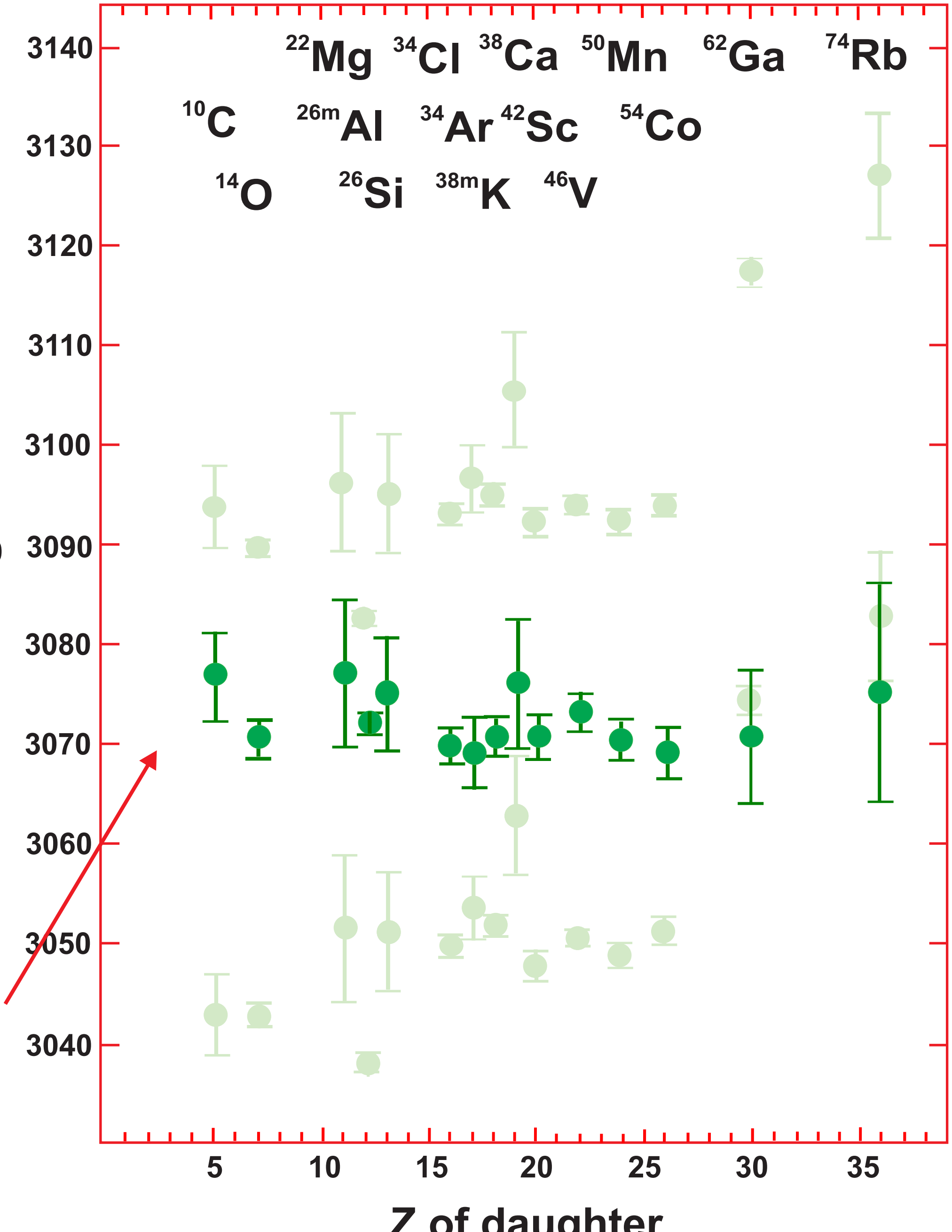

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$$ft\,(1 + \delta_R')\left[1 - (\delta_C - \delta_{NS})\right]$$

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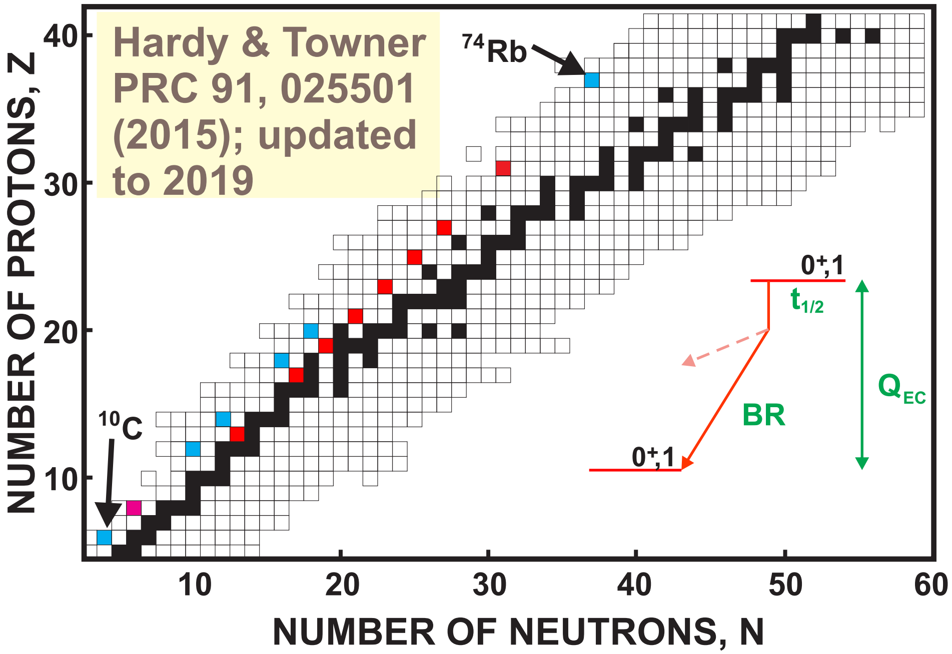

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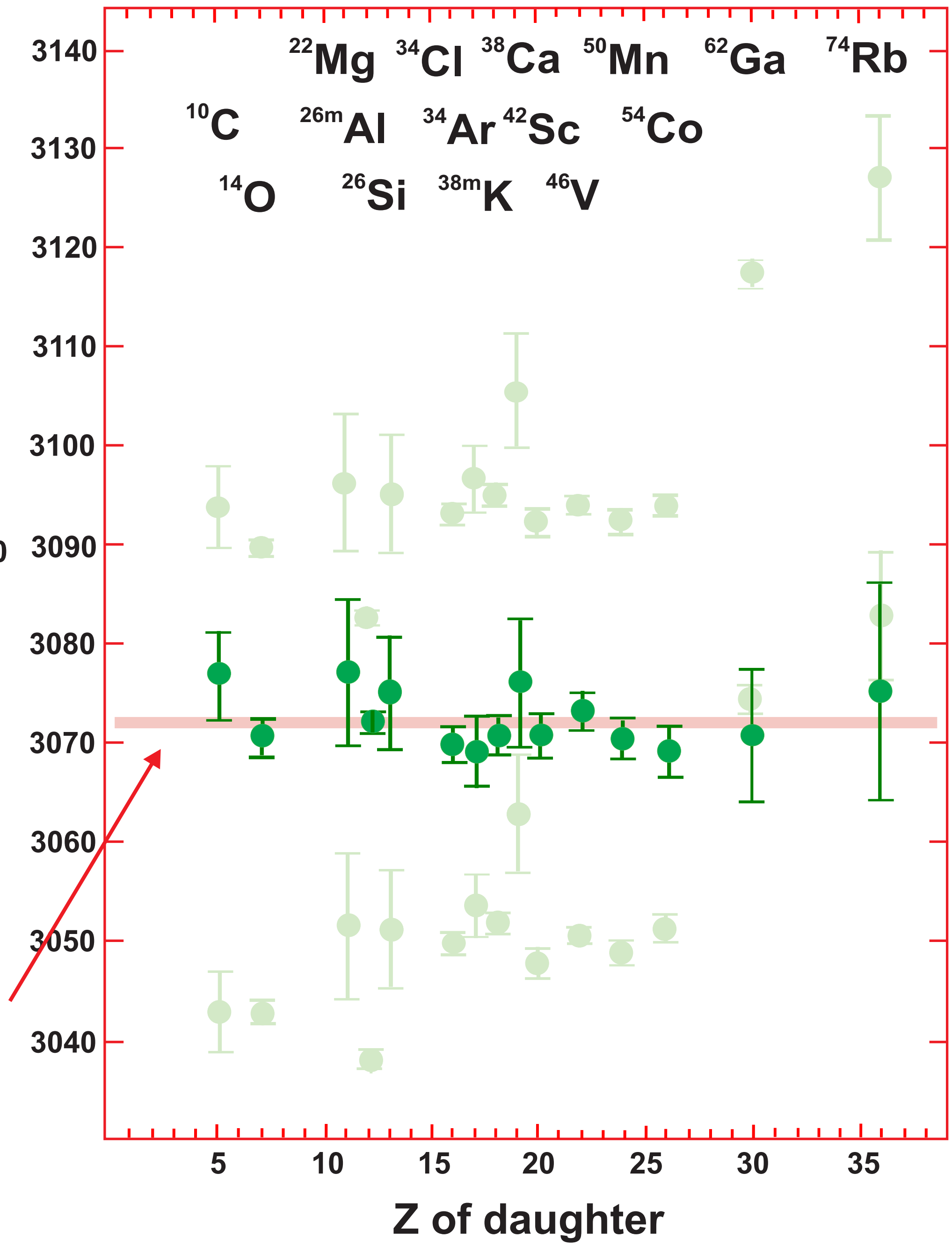

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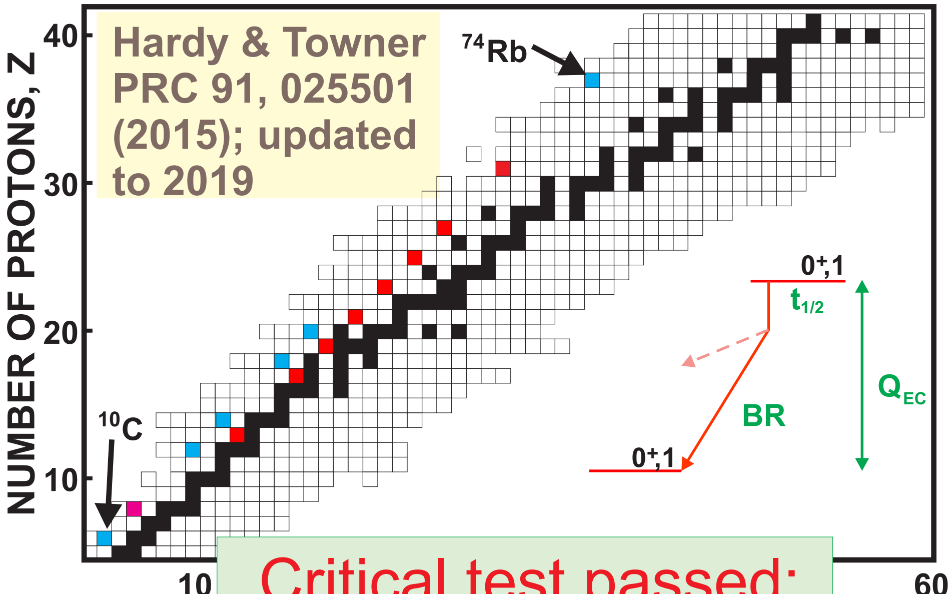

Critical test passed:
$\mathcal{F}t$ values consistent
$\chi^2/n = 0.6$

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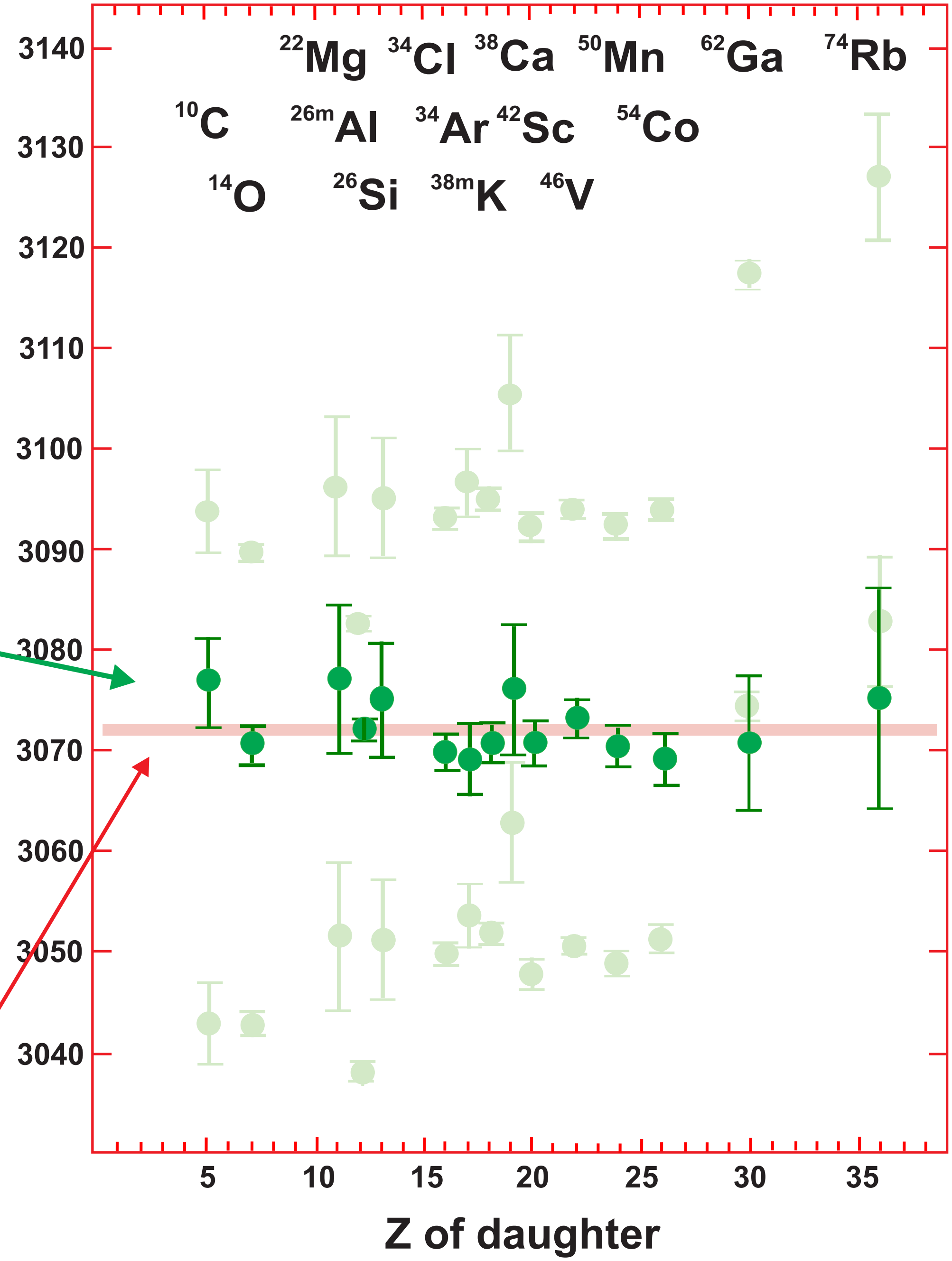

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1. Radiative corrections

$$\delta_R' = \frac{\alpha}{2\pi}\left[g(E_m) + \delta_2 + \delta_3 + \ldots\right]$$ One-photon brem. + low-energy γW-box [Serlin]

α $Z\alpha^2$ $Z^2\alpha^3$

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$$\Delta_R = \frac{\alpha}{2\pi}[4\ln(m_Z/m_p) + \ln(m_p/m_A) + 2C_{Born} + \ldots]$$ High-energy γW-box +ZW-box [Marciano & Serlin]

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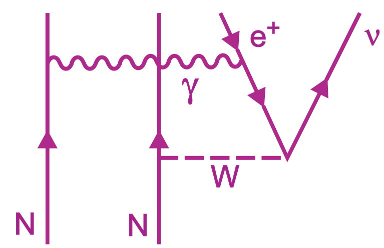
universal

δ_{NS} Order-α axial-vector photonic contributions [Towner]



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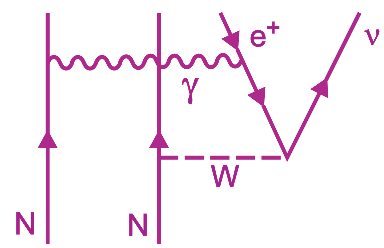

2. Isospin symmetry-breaking corrections

δ_C Charge-dependent mismatch between parent and daughter analog states (members of the same isospin triplet). [Towner & Hardy]

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1. Radiative corrections

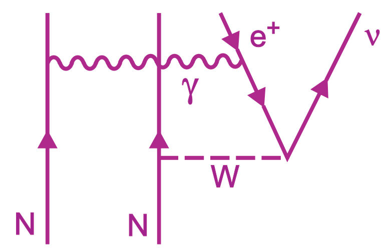
$$\delta_R' = \frac{\alpha}{2\pi}[g(E_m) + \delta_2 + \delta_3 + \dots]$$ One-photon brem. + low-energy γW-box [Serlin]

($g(E_m) \leftarrow \alpha$; $\delta_2 \leftarrow Z\alpha^2$; $\delta_3 \leftarrow Z^2\alpha^3$)

$$\Delta_R = \frac{\alpha}{2\pi}[4\ln(m_Z/m_p) + \ln(m_p/m_A) + 2C_{Born} + \dots]$$ High-energy γW-box +ZW-box [Marciano & Serlin]

universal

δ_{NS} Order-α axial-vector photonic contributions [Towner]



Dependent on nuclear structure

2. Isospin symmetry-breaking corrections

δ_C Charge-dependent mismatch between parent and daughter analog states (members of the same isospin triplet). [Towner & Hardy]

ISOSPIN SYMMETRY BREAKING CORRECTIONS

$$\delta_C = \delta_{C1} + \delta_{C2}$$

δ_{C1}

Difference in configuration mixing between parent and daughter.

- Shell-model calculation with well-established 2-body matrix elements.
- Charge dependence tuned to known single-particle energies and to measured IMME coefficients.
- Results also adjusted to measured non-analog 0^+ state energies.

δ_{C2}

Mismatch in radial wave function between parent and daughter.

- Full-parentage Saxon-Woods wave functions for parent and daughter.
- Matched to known binding energies and charge radii as obtained from electron scattering.
- Core states included based on measured spectroscopic factors.

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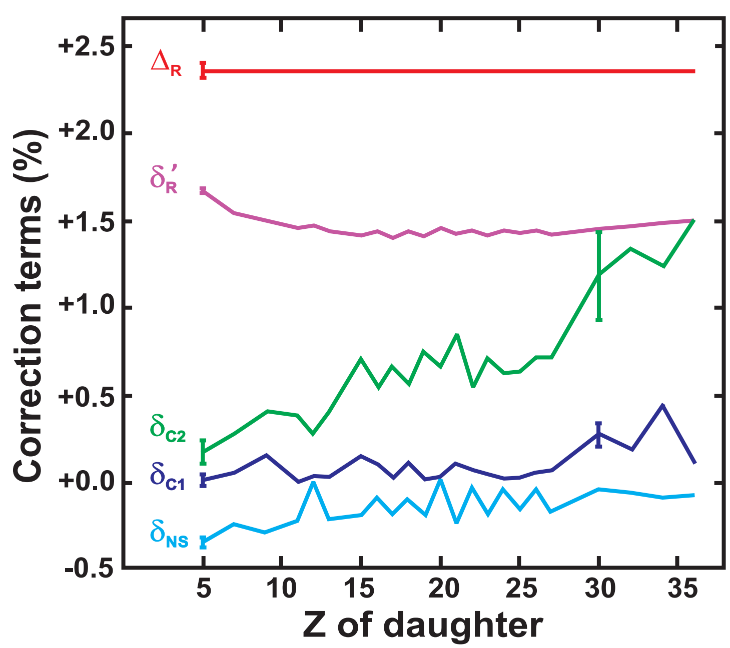

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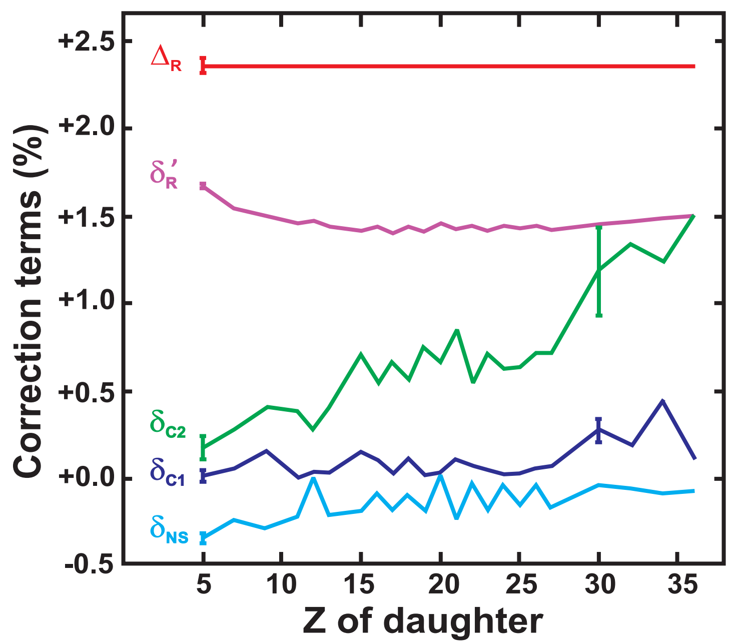

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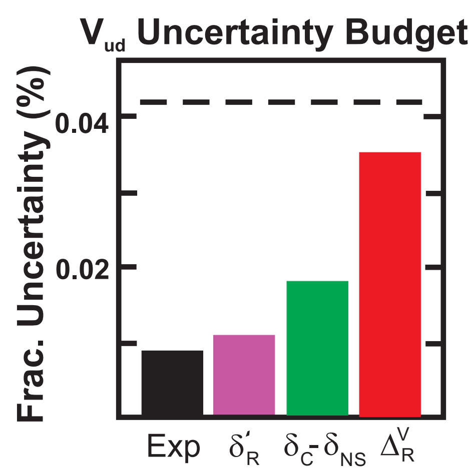

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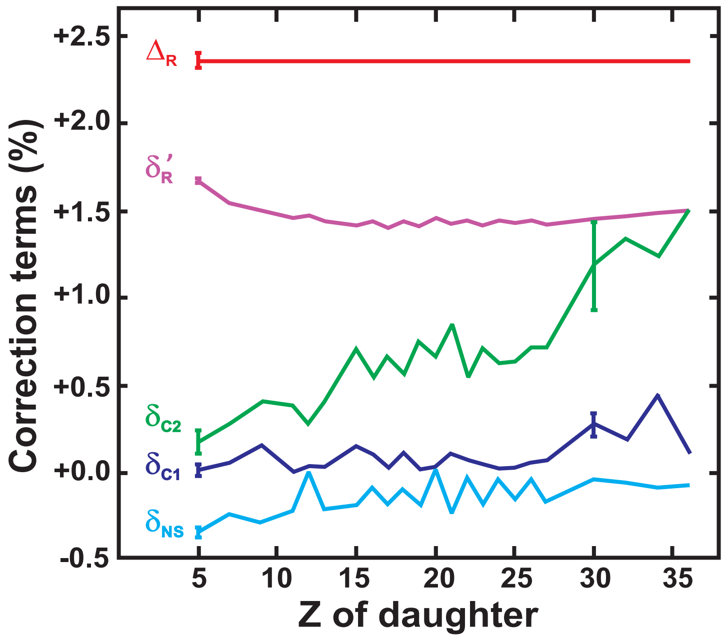

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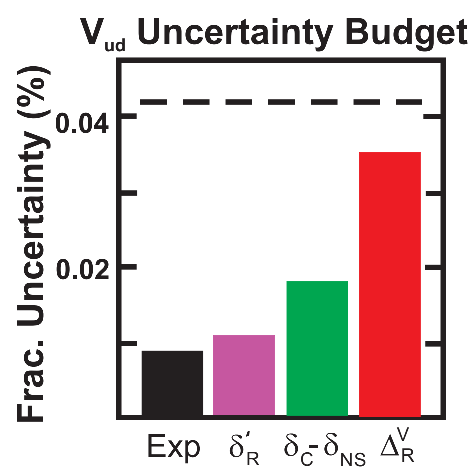

Only $\delta_C - \delta_{NS}$ can be tested experimentally.

TESTS OF (δ_C-δ_{NS}) CALCULATIONS

A. Test how well the transition-to-transition differences in δ_C-δ_{NS} match the data: *i.e.* do they lead to constant $\mathcal{F}t$ values, in agreement with CVC?

B. Measure the ratio of *ft* values for mirror $0^+ \rightarrow 0^+$ superallowed transitions and compare the results with calculations.

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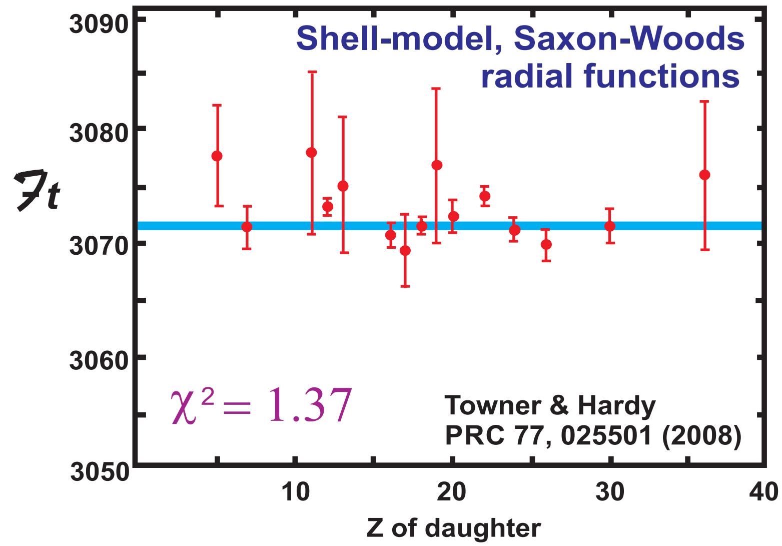
Model	χ^2/N	CL(%)
SM-SW	1.37	17



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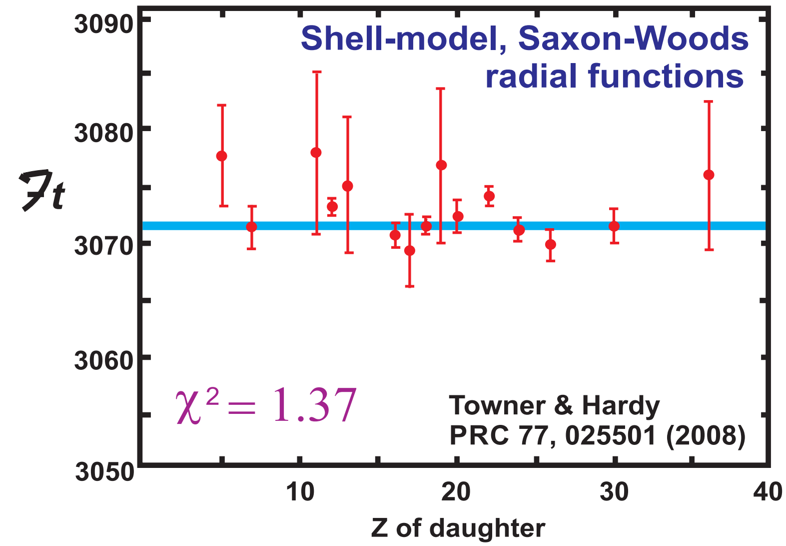

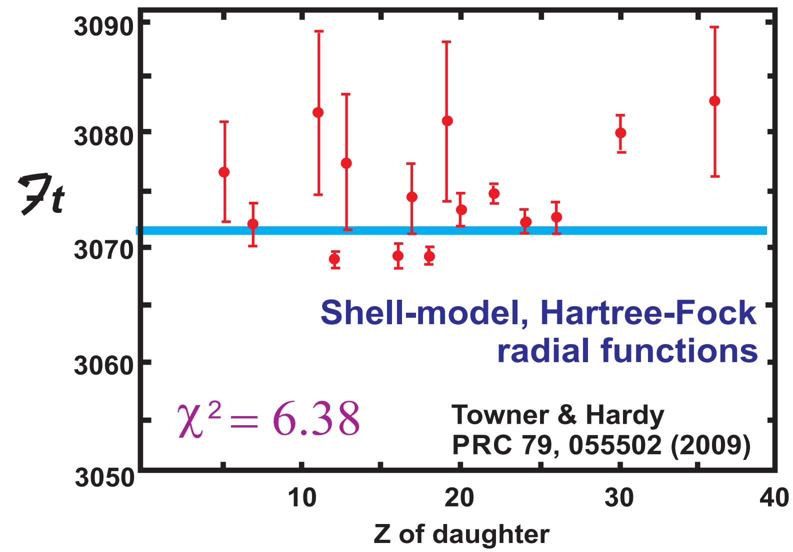

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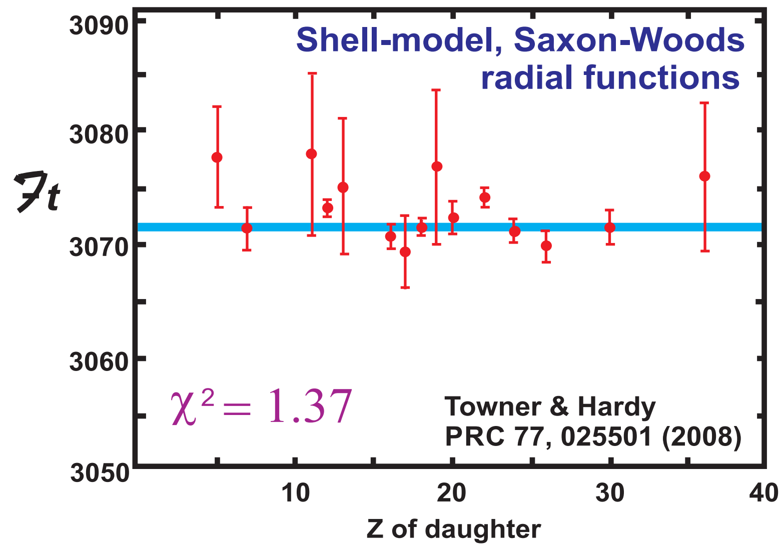

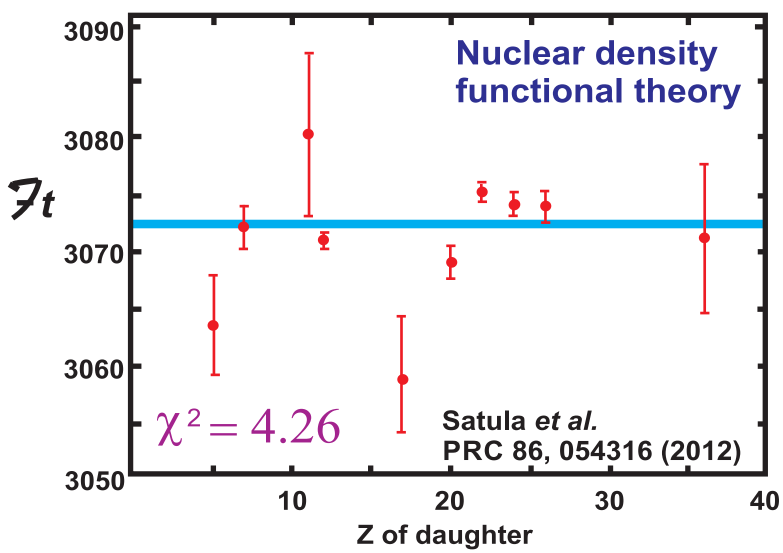

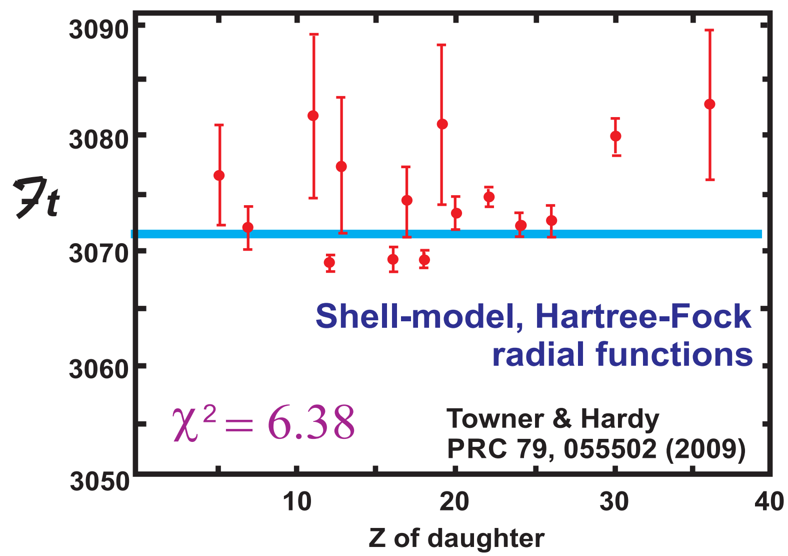

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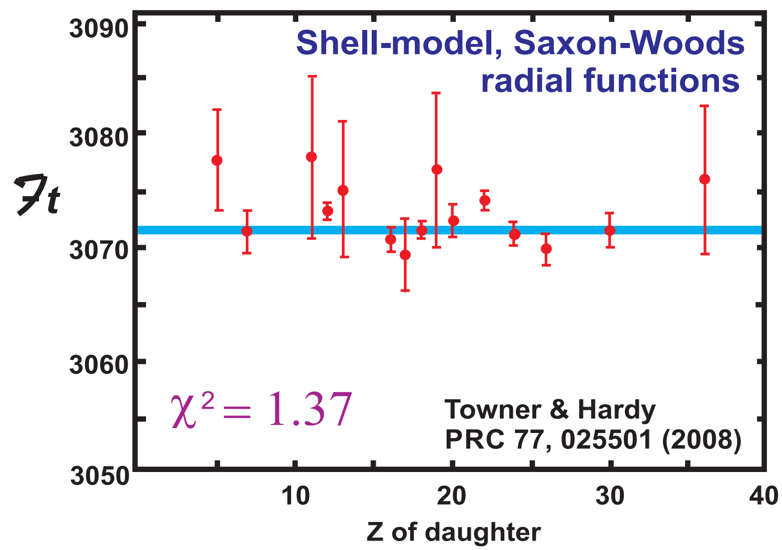

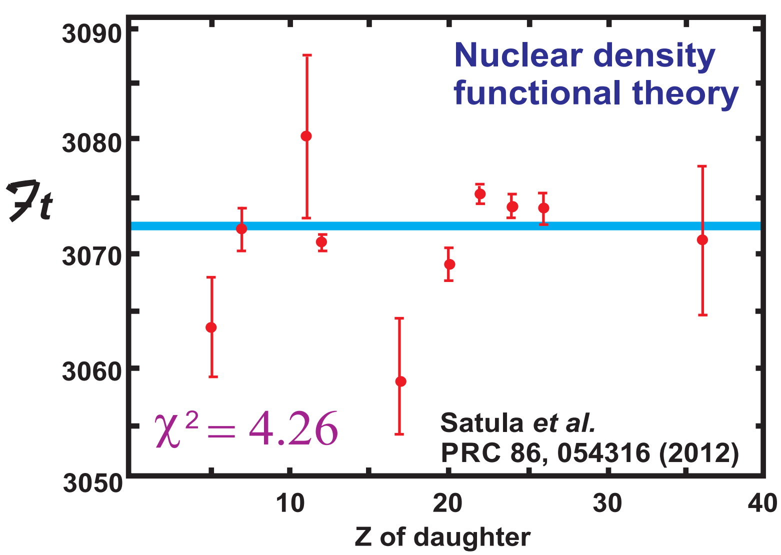

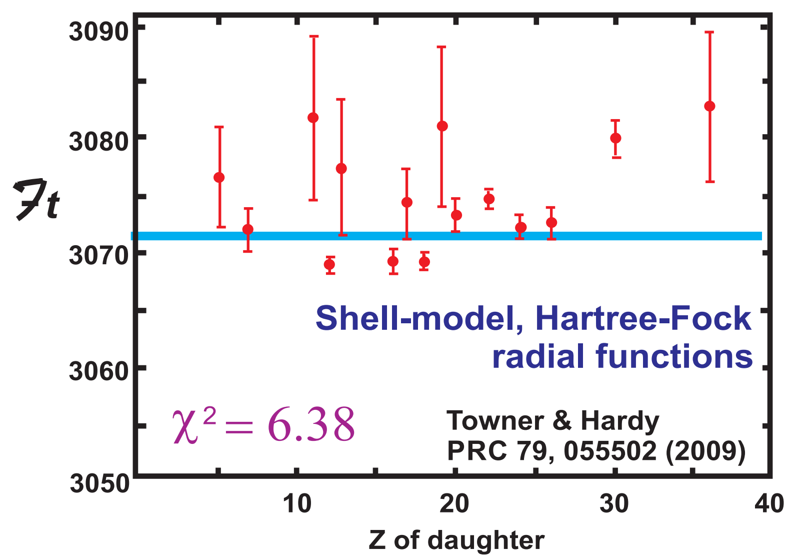

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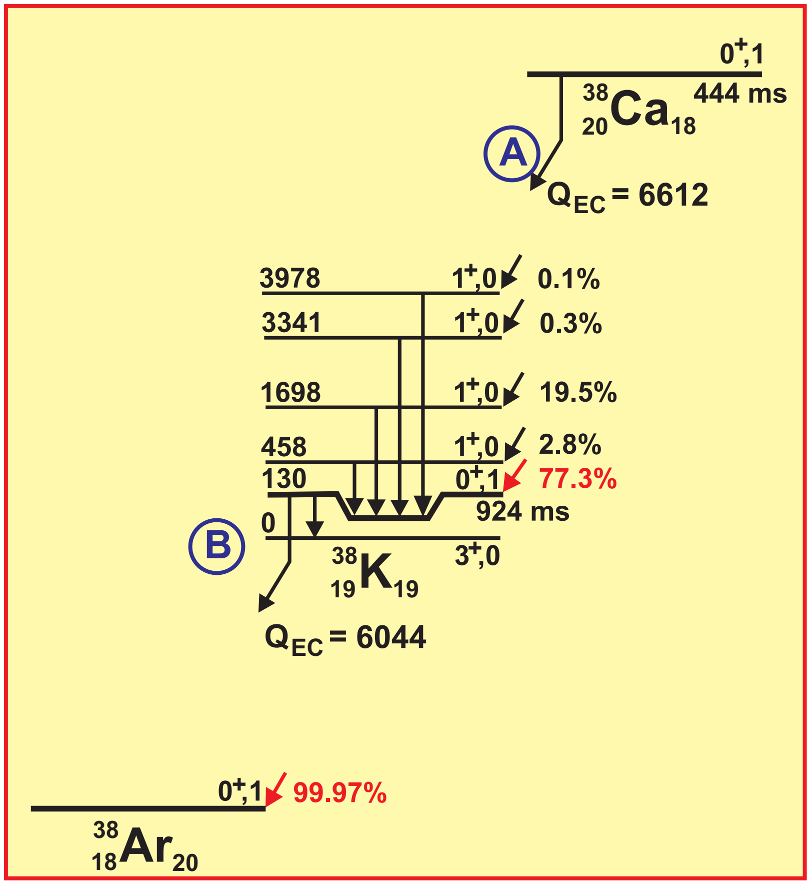
$$\mathcal{F}t = ft\,(1 + \delta'_R)\left[1 - (\delta_C - \delta_{NS})\right]$$



$$\frac{ft_A}{ft_B} = \frac{(1 + \delta_R'^B)[1 - (\delta_C^B - \delta_{NS}^B)]}{(1 + \delta_R'^A)[1 - (\delta_C^A - \delta_{NS}^A)]}$$

$$= 1 + (\delta_R'^B - \delta_R'^A) + (\delta_{NS}^B - \delta_{NS}^A) - (\delta_C^B - \delta_C^A)$$

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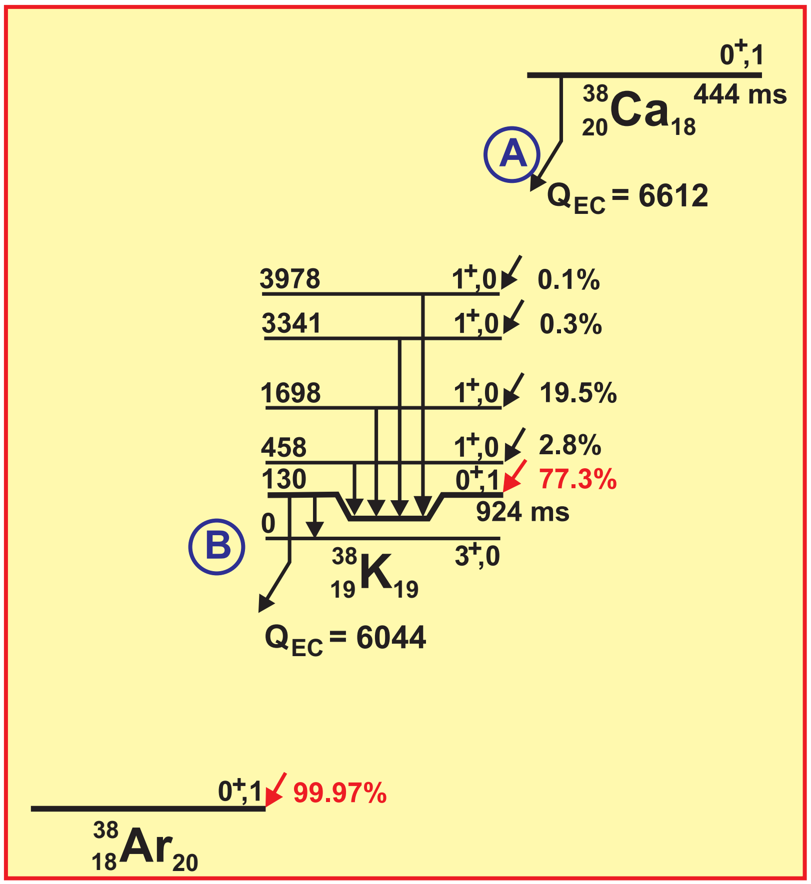

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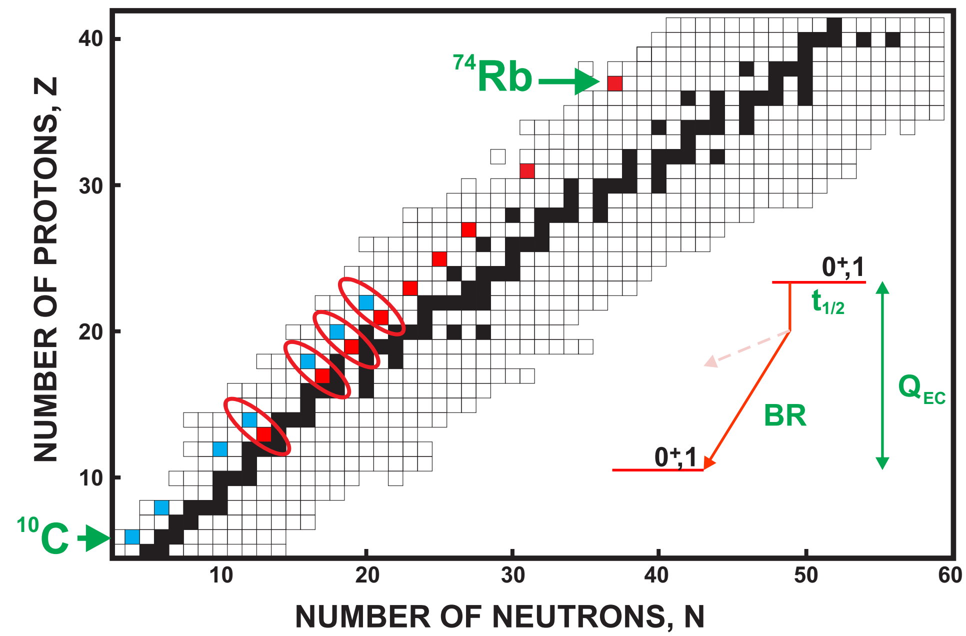
$$= 1 + (\delta'^{B}_R - \delta'^{A}_R) + (\delta^B_{NS} - \delta^A_{NS}) - (\delta^B_C - \delta^A_C)$$



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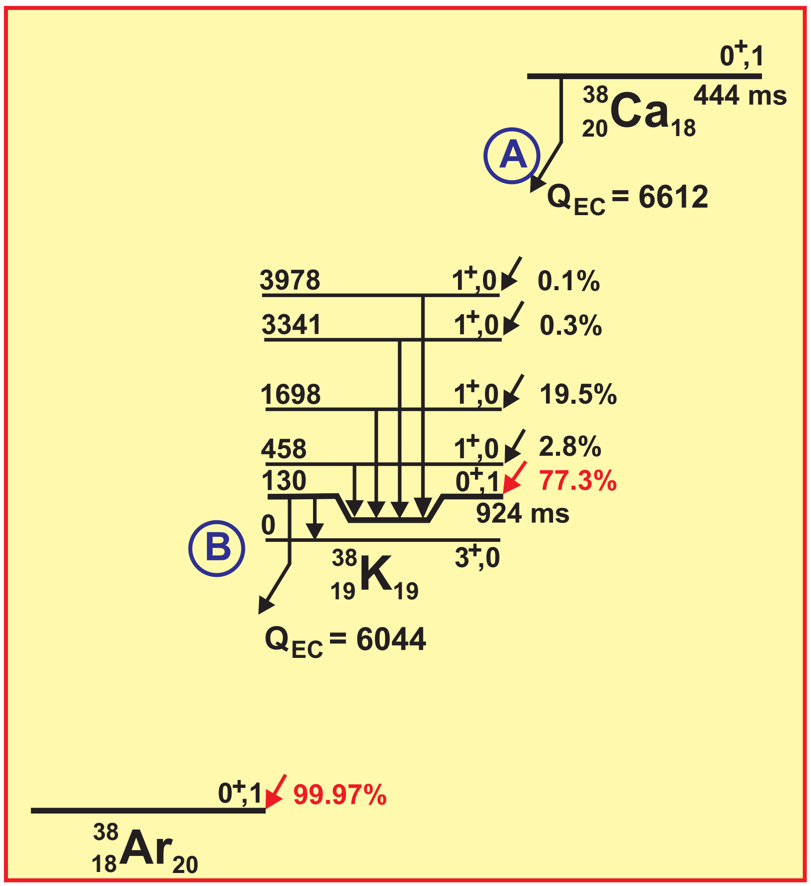

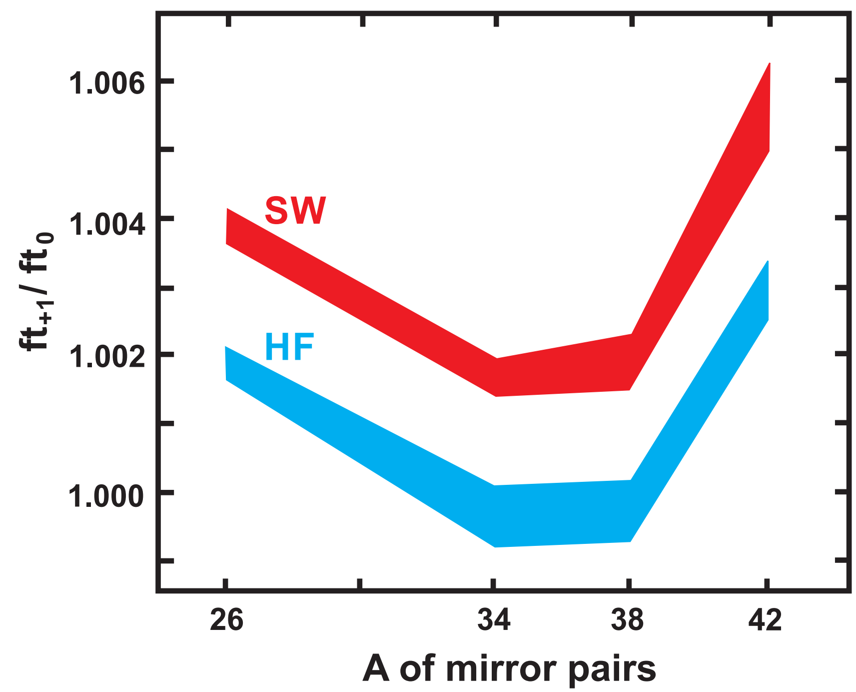

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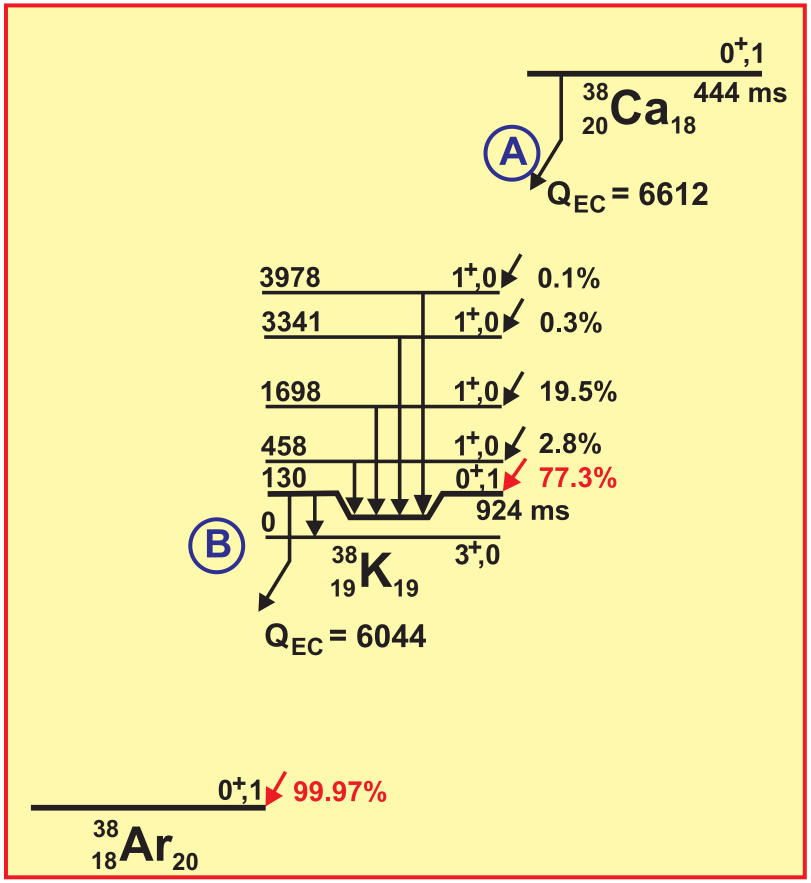

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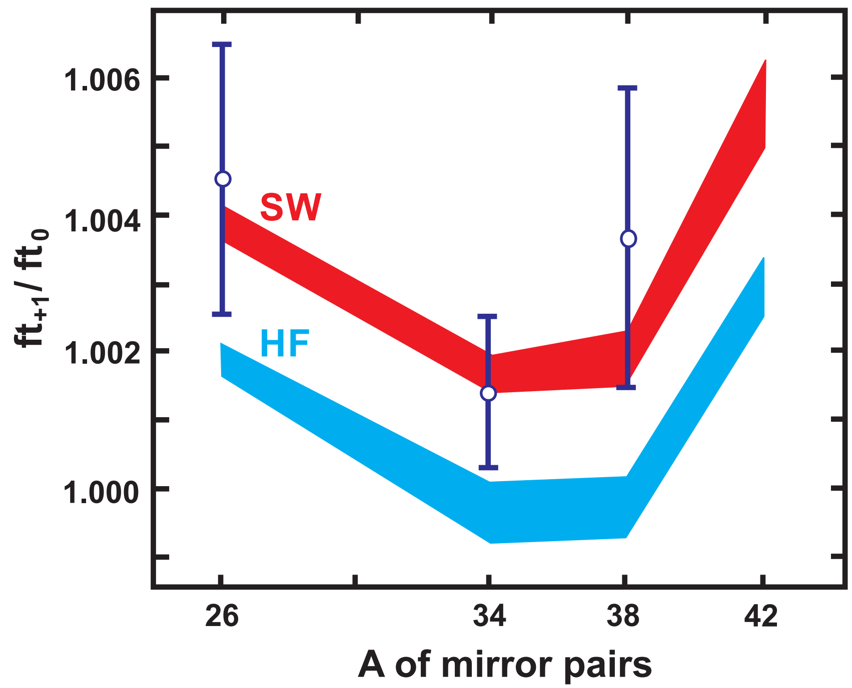

RESULTS FROM $0^+ \rightarrow 0^+$ DECAY

FROM A SINGLE TRANSITION

Experimentally determine $G_V^2(1 + \Delta_R)$

$$\mathcal{F}t = ft\,(1 + \delta_R')\left[1 - (\delta_C - \delta_{NS})\right] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$

FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

RESULTS FROM $0^+ \rightarrow 0^+$ DECAY

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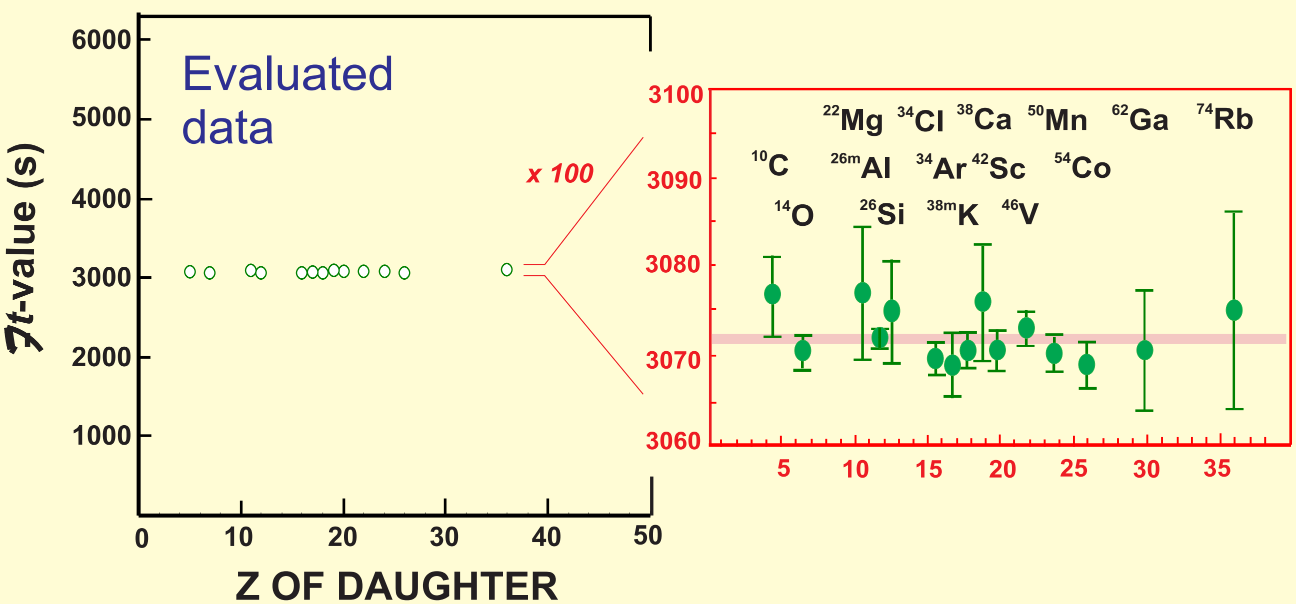
FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

G_V constant to ± 0.011%



$\mathcal{F}t$ = 3072.1(7)

$G_V(1+\Delta_R)^{1/2}/(\hbar c)^3 = 1.14962(13) \times 10^{-5}$ GeV^{-2}

$\chi^2/\nu = 0.6$

RESULTS FROM $0^+ \rightarrow 0^+$ DECAY

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FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

Validate correction terms

G_V constant to ± 0.011%

RESULTS FROM $0^+ \rightarrow 0^+$ DECAY

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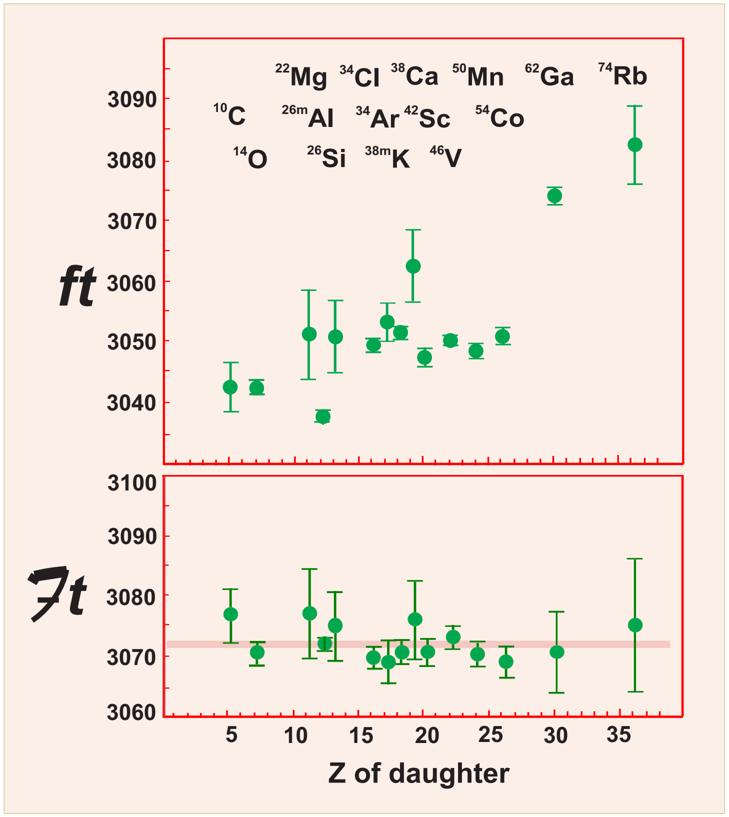

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FROM MANY TRANSITIONS

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G_V constant to ± 0.011%

Validate correction terms ✔

Model	χ^2/N	CL(%)
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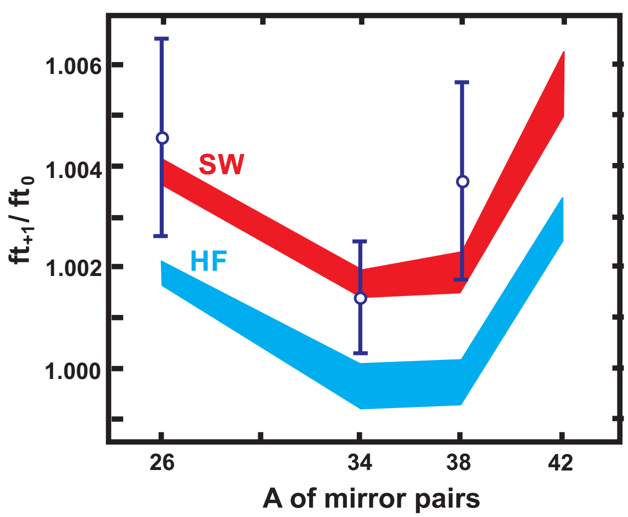

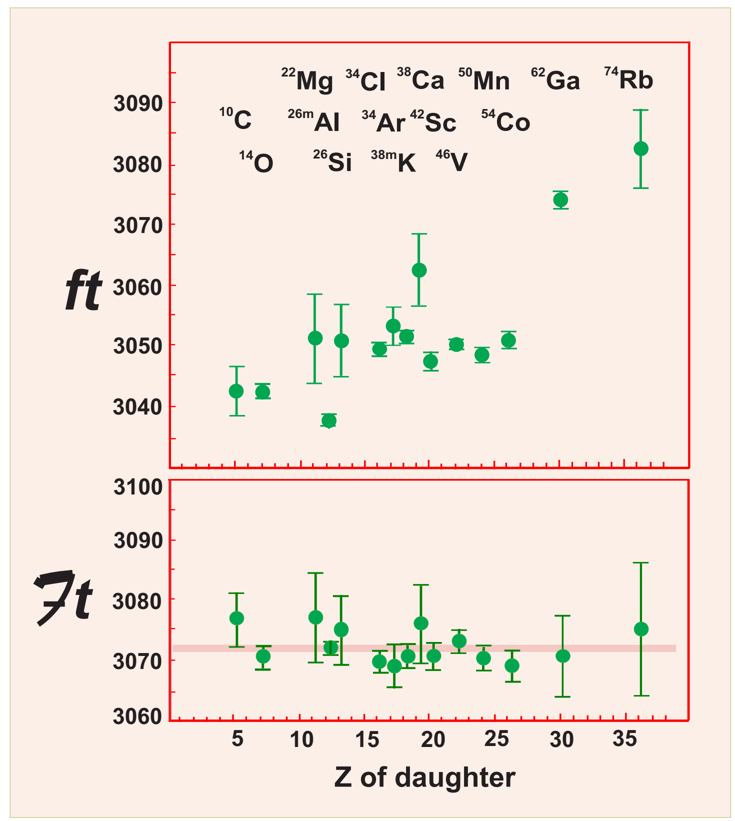

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FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

Validate correction terms ✔

Test for Scalar current

G_V constant to ± 0.011%

RESULTS FROM $0^+ \rightarrow 0^+$ DECAY

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Experimentally determine $G_V^2(1 + \Delta_R)$

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FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

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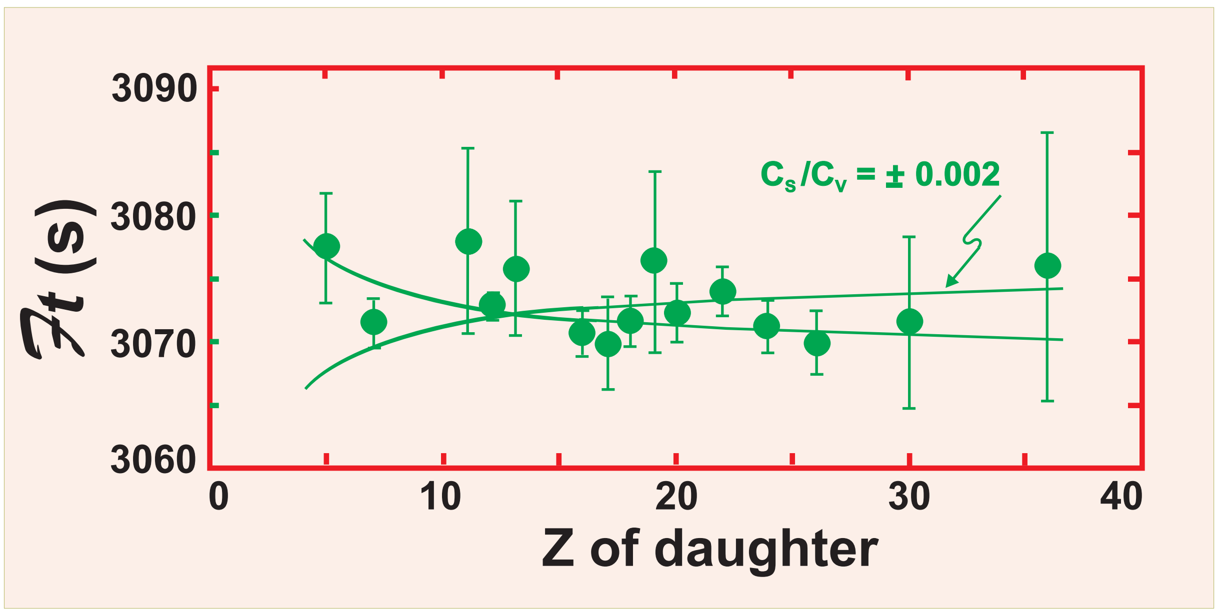
Validate correction terms ✔

Test for Scalar current

limit, $C_S/C_V = 0.0012\,(10) = b/2$



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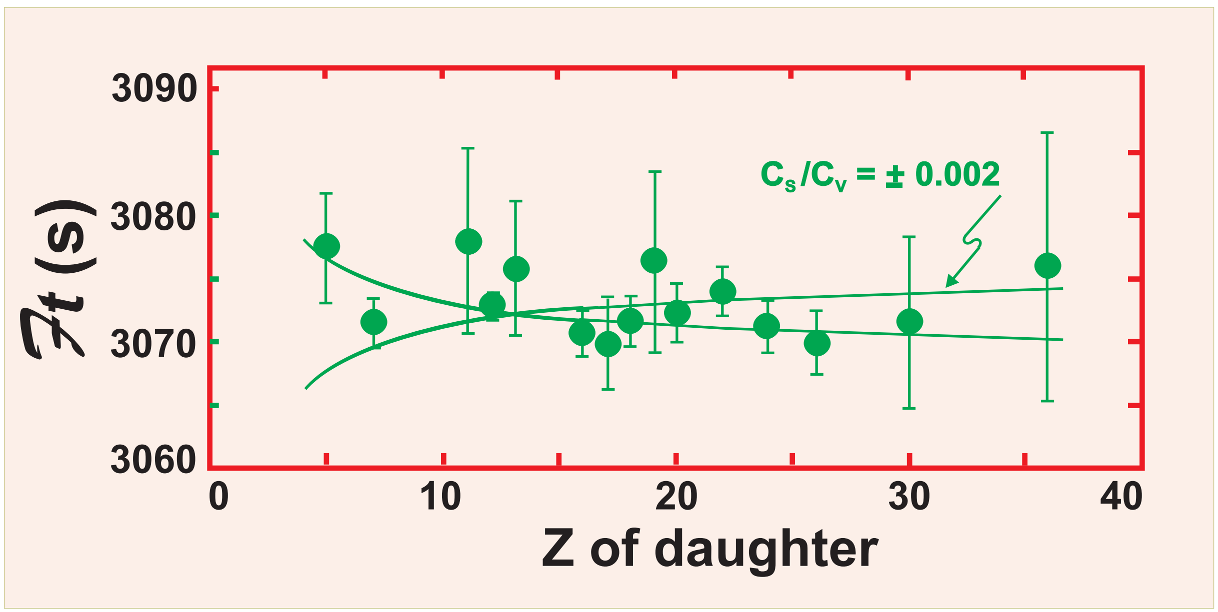

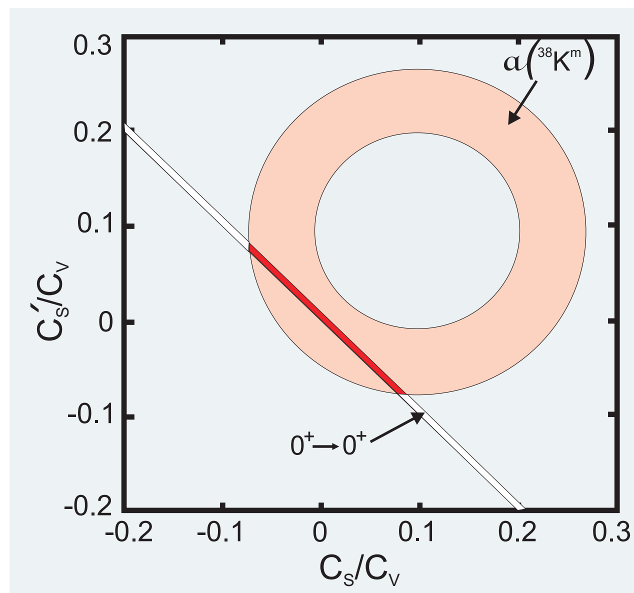

RESULTS FROM $0^+ \rightarrow 0^+$ DECAY

FROM A SINGLE TRANSITION

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FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

Validate correction terms ✔

G_V constant to ± 0.011%

Test for Scalar current

limit, $C_S/C_V = 0.0012\ (10) = b/2$

WITH CVC VERIFIED

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

weak eigenstates (left), mass eigenstates (right)

Cabibbo-Kobayashi-Maskawa matrix

Obtain precise value of $G_V^2(1+\Delta_R)$

Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G_\mu^2 = 0.94907 \pm 0.00041$$

RESULTS FROM $0^+ \rightarrow 0^+$ DECAY

FROM A SINGLE TRANSITION

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FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

Validate correction terms ✔

Test for Scalar current

G_V constant to ± 0.011%

limit, $C_S/C_V = 0.0012\,(10) = b/2$

WITH CVC VERIFIED

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

weak eigenstates — mass eigenstates

Cabibbo-Kobayashi-Maskawa matrix

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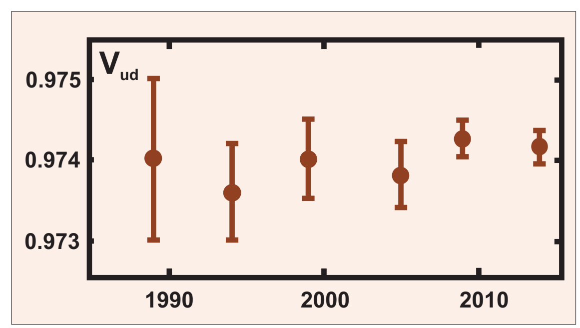
Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G_\mu^2 = 0.94907 \pm 0.00041$$



RESULTS FROM $0^+ \rightarrow 0^+$ DECAY

FROM A SINGLE TRANSITION

Experimentally determine $G_V^2(1 + \Delta_R)$

$$\mathcal{F}t = ft\,(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$

FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

Validate correction terms ✔

G_V constant to ± 0.011%

Test for Scalar current

limit, $C_S/C_V = 0.0012\ (10) = b/2$

WITH CVC VERIFIED

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

weak eigenstates

mass eigenstates

Cabibbo-Kobayashi-Maskawa matrix

Obtain precise value of $G_V^2(1 + \Delta_R)$

Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G_\mu^2 = 0.94907 \pm 0.00041$$

Test CKM unitarity

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99939 \pm 0.00047$$

T=1/2 SUPERALLOWED BETA DECAY

BASIC WEAK-DECAY EQUATION

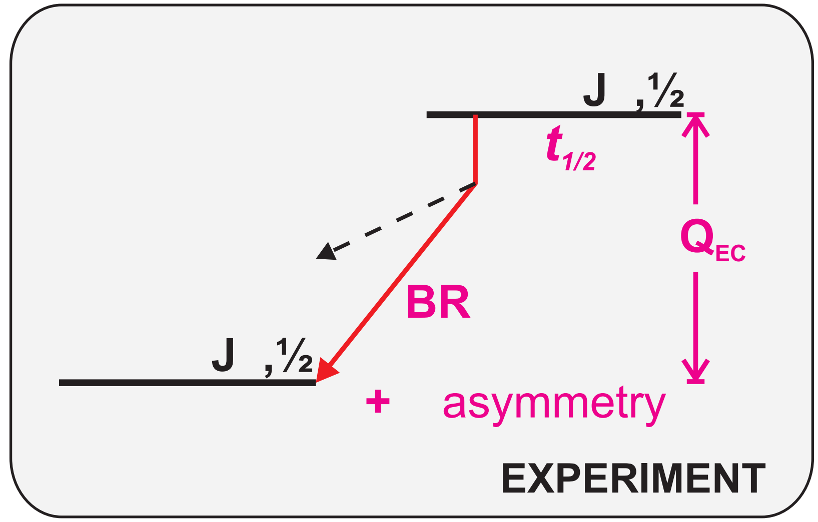
$$ft = \frac{K}{G_V^2 \langle \quad \rangle^2 + G_A^2 \langle \qquad \rangle^2}$$

f **= statistical rate function: f(Z, Q_{EC})**

t **= partial half-life: f($t_{1/2}$, BR)**

$G_{V,A}$ = coupling constants

< > = Fermi, Gamow-Teller matrix elements



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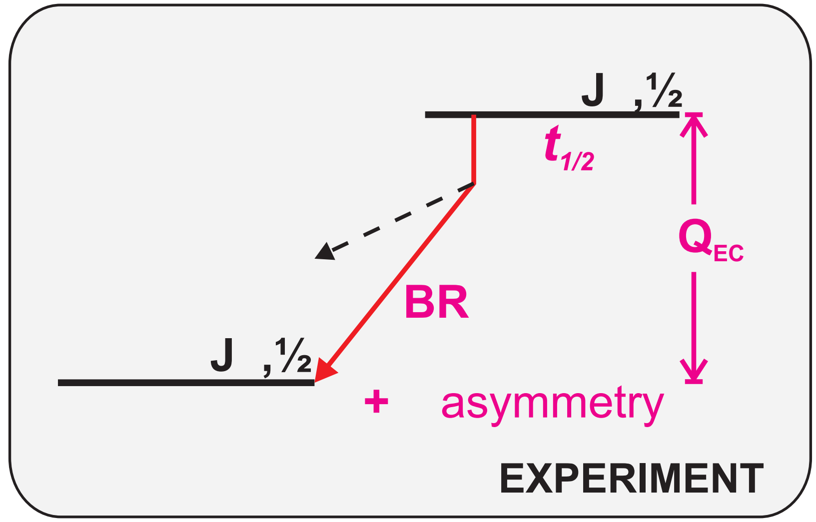

INCLUDING RADIATIVE CORRECTIONS

$$\mathcal{F}t = ft\,(1 + \ '_R)[1 - (\ _C - \ _{NS})] = \frac{K}{G_V^2\,(1 + \ _R)(1 + \ ^2 \langle \qquad \rangle^2)}$$

$= G_A/G_V$

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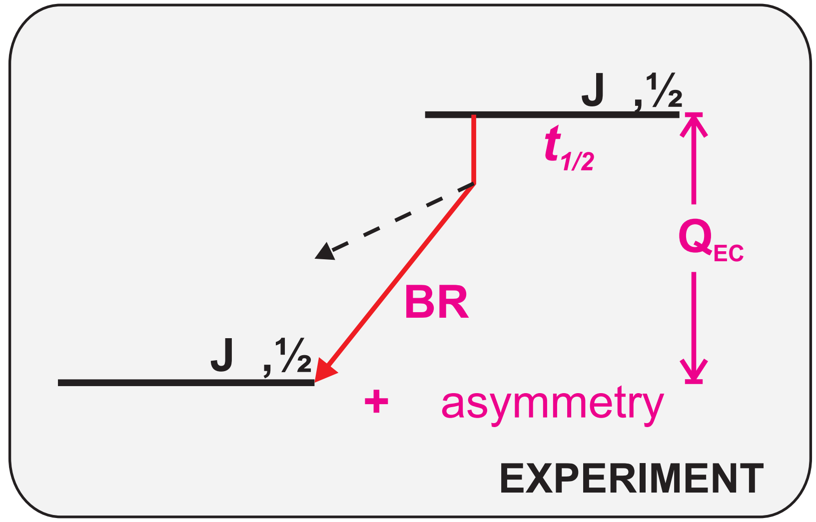

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Requires additional experiment:
for example, asymmetry (*A*)

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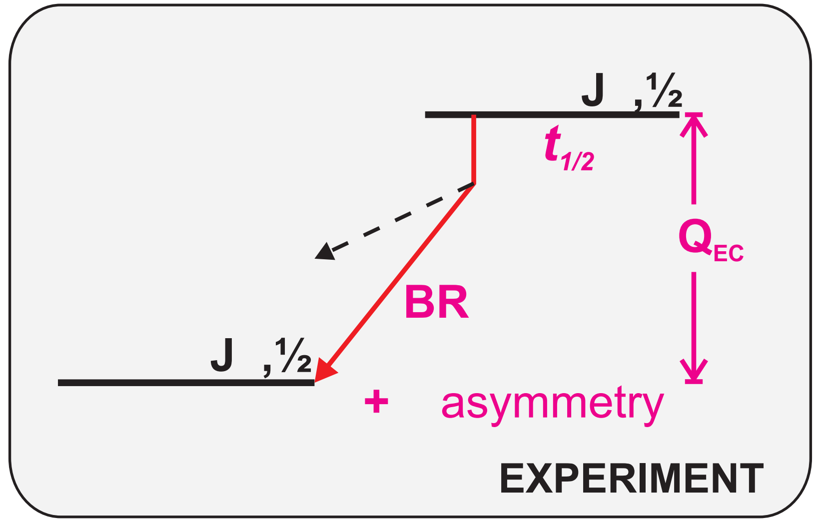

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NEUTRON DECAY

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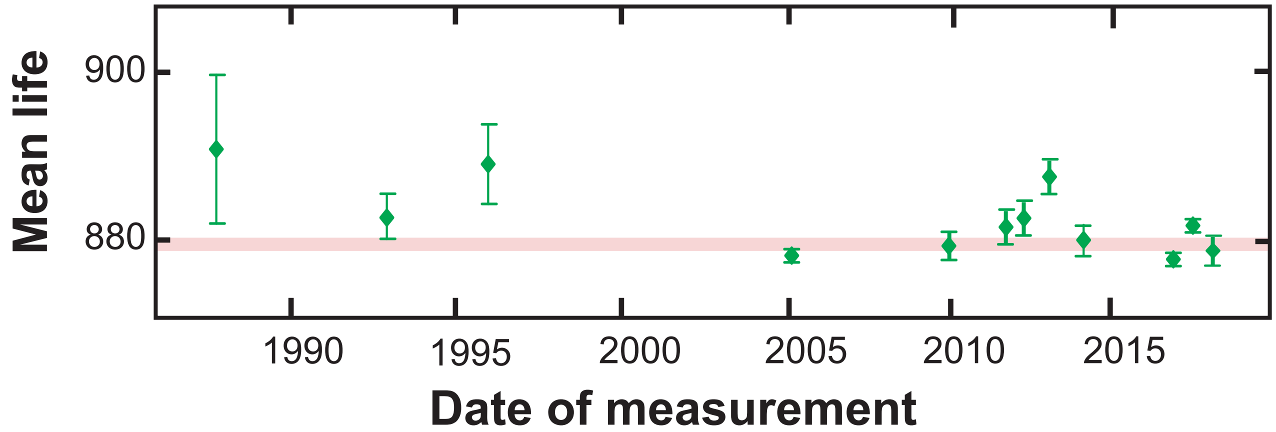
NEUTRON DECAY DATA 2019

Mean life:

τ **= 879.7 ± 0.8 s**

χ^2/N **= 3.8**



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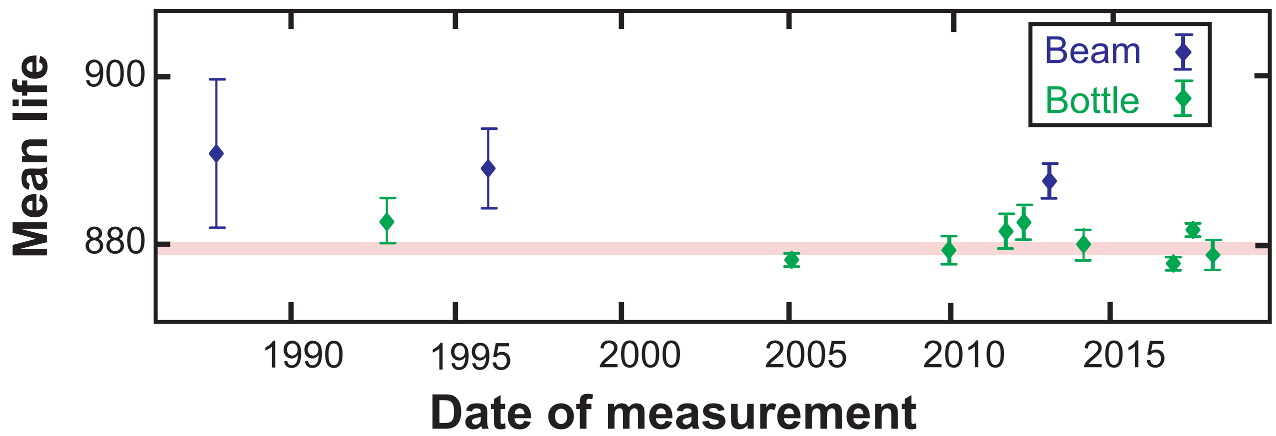


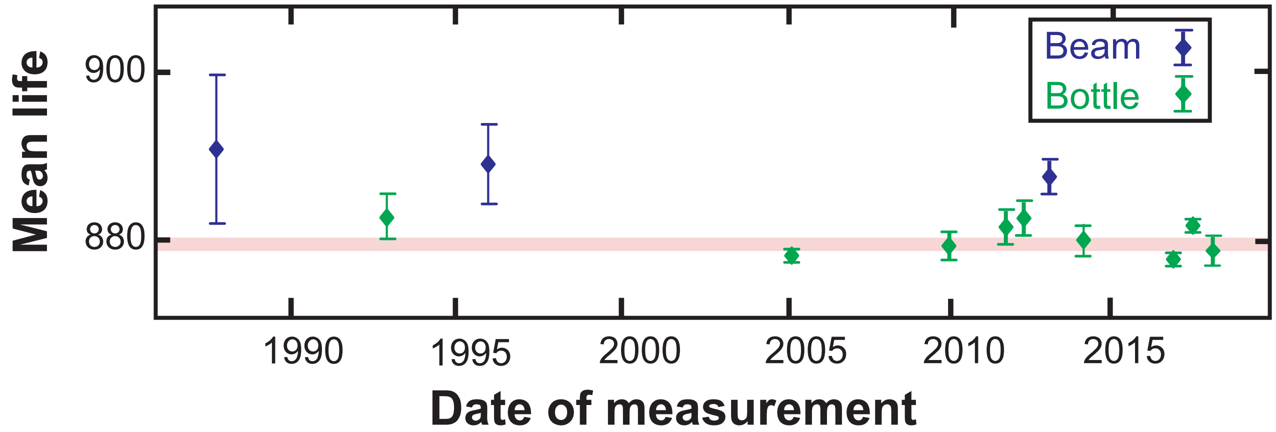
NEUTRON DECAY DATA 2019

Mean life:

τ = **879.7 ± 0.8 s**

χ^2/N = **3.8**

Beam: 888.1 ± 2.0 s
Bottle: 879.4 ± 0.6 s



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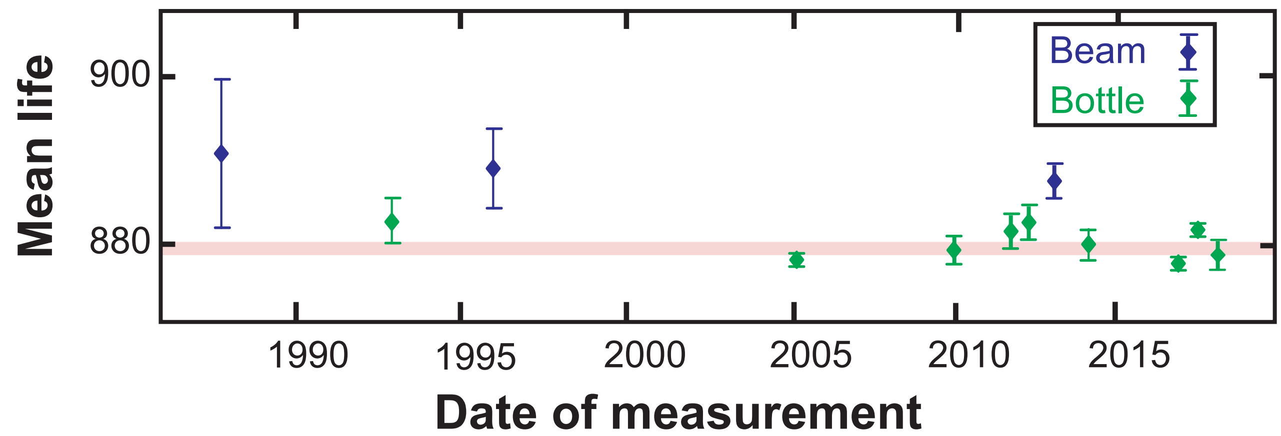
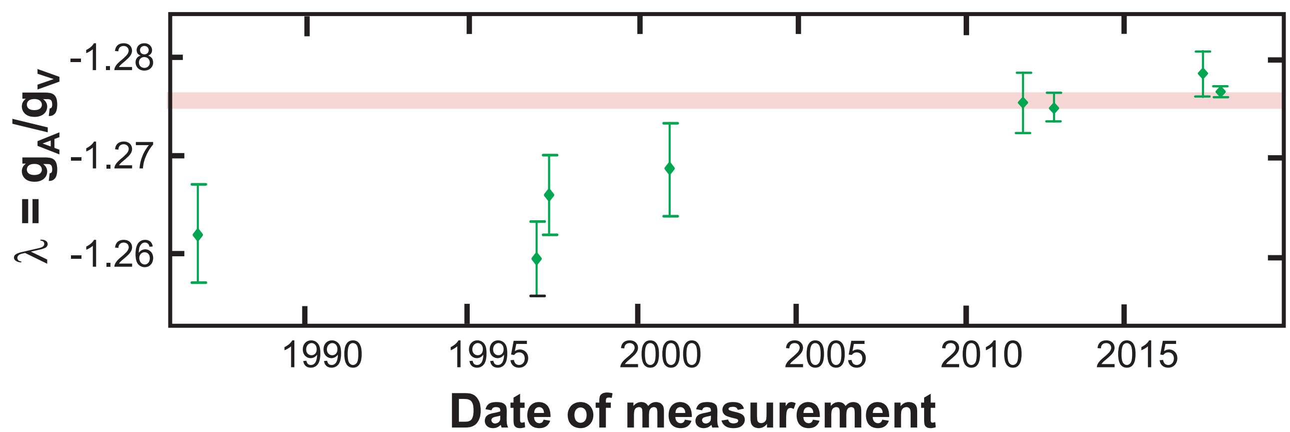


β **asymmetry:**

λ **= -1.2756 ± 0.0009**

χ^2/N **= 3.2**



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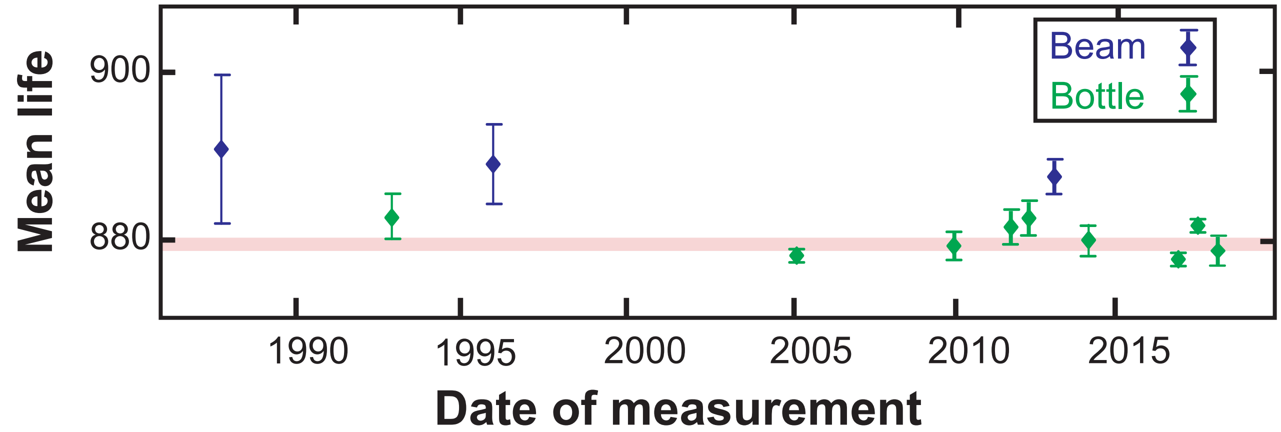

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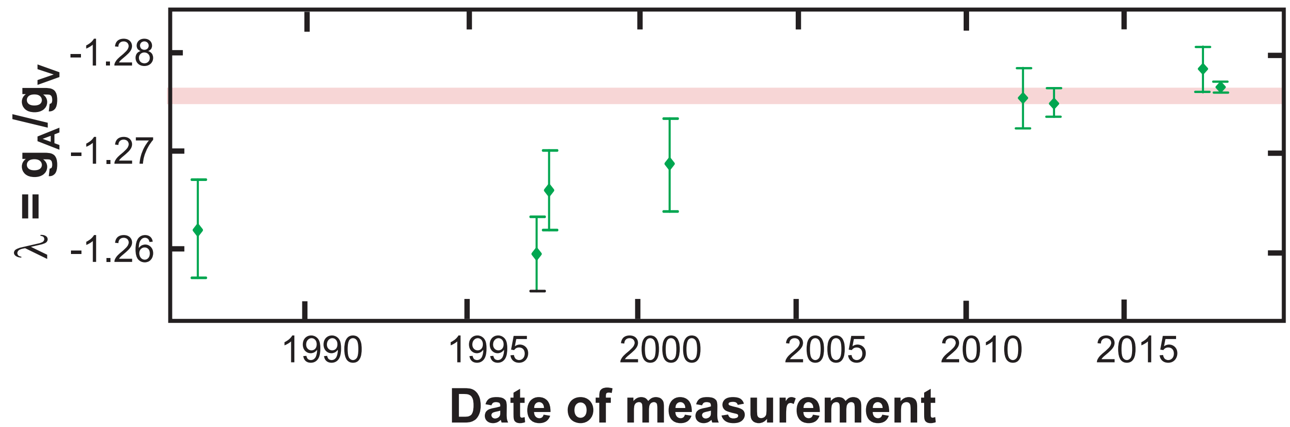

V_{ud} = 0.9740 ± 0.0007

NEUTRON DECAY DATA 2019

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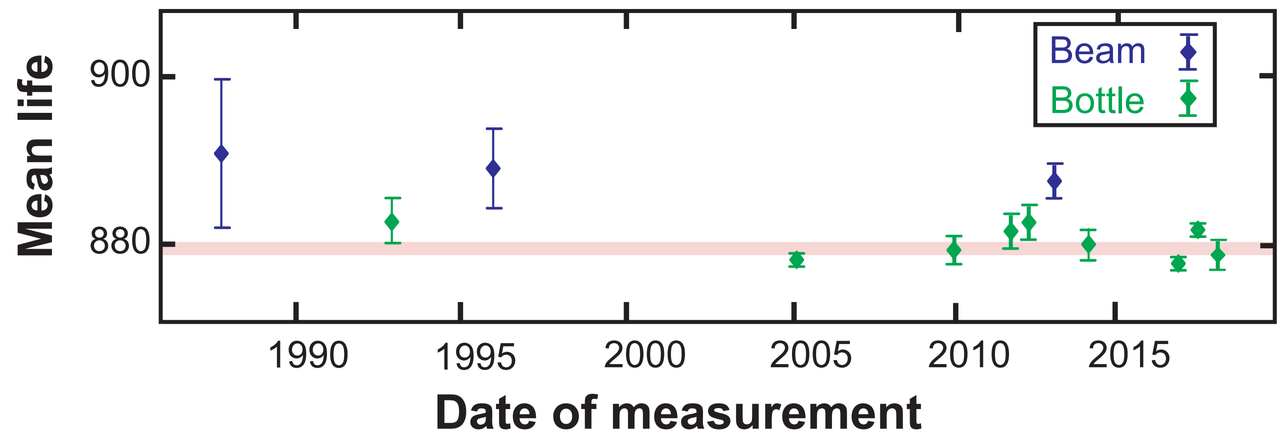

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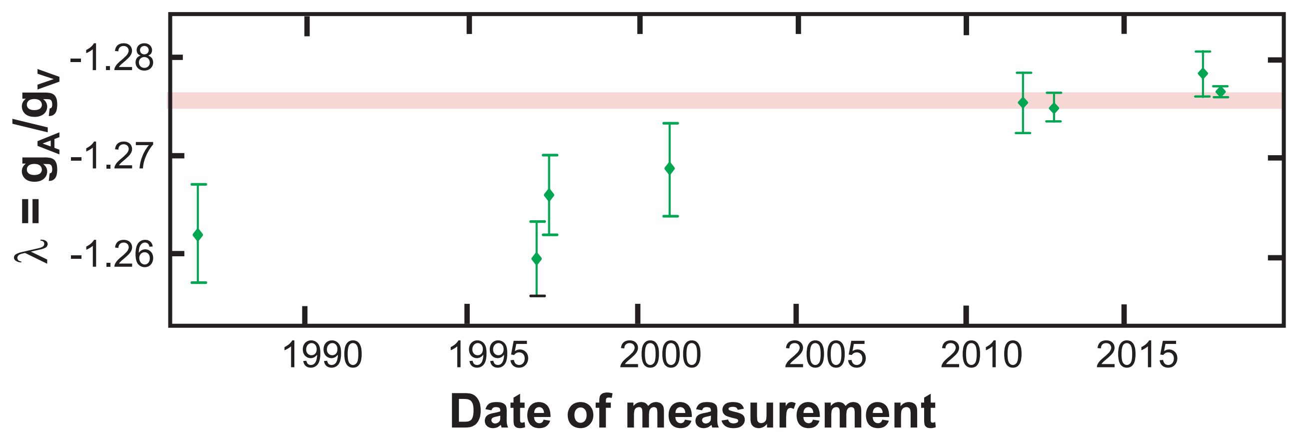

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Beam-bottle span
$0.9680 \leq V_{ud} \leq 0.9750$

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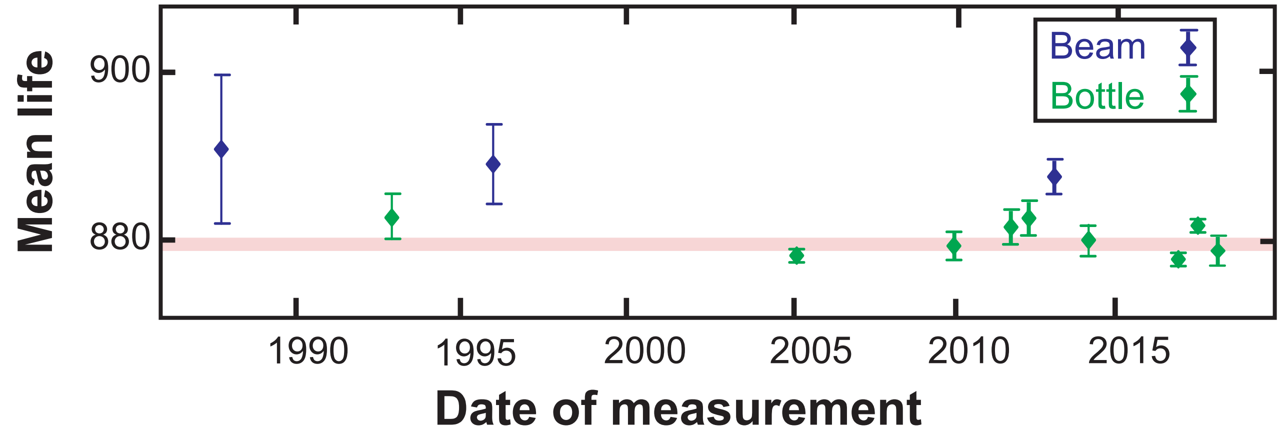

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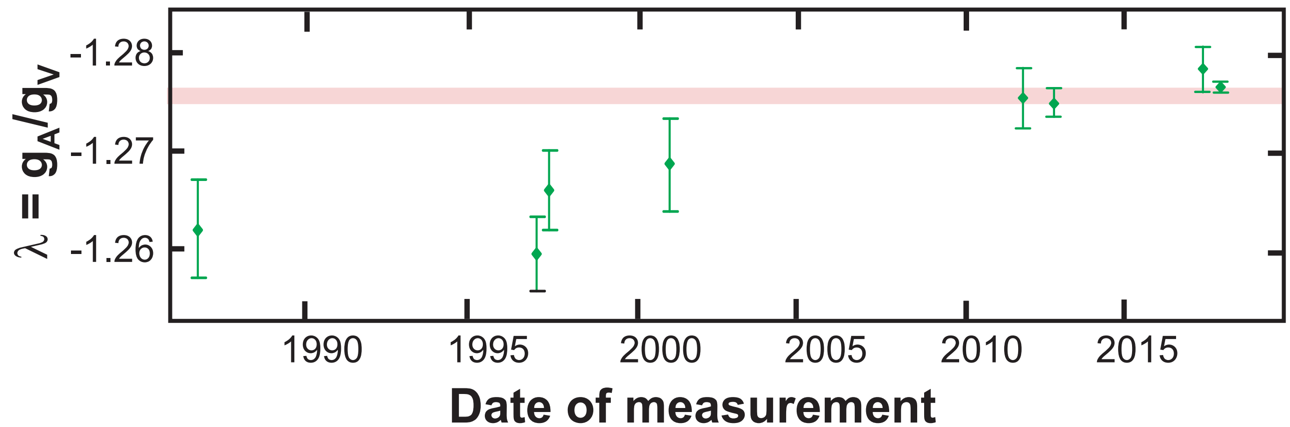

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nuclear $0^+ \rightarrow 0^+$
$V_{ud} = 0.9742 \pm 0.0002$

NUCLEAR T=1/2 MIRROR DECAY DATA 2018

$$\mathcal{F}t = ft\,(1 + \delta_R')\left[1 - (\delta_C - \delta_{NS})\right] = \frac{K}{G_V^2\,(1 + \Delta_R)(1 + \lambda^2 \langle\sigma\tau\rangle^2)}$$

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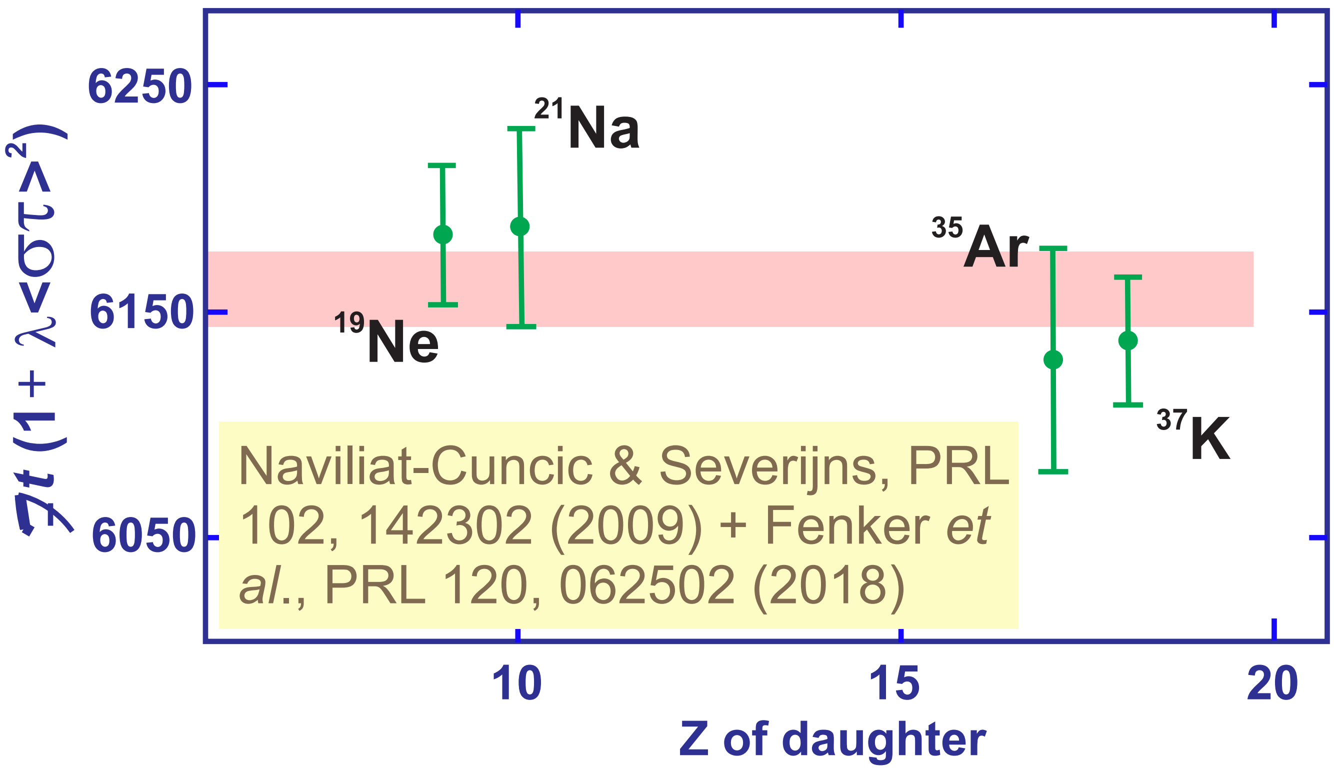

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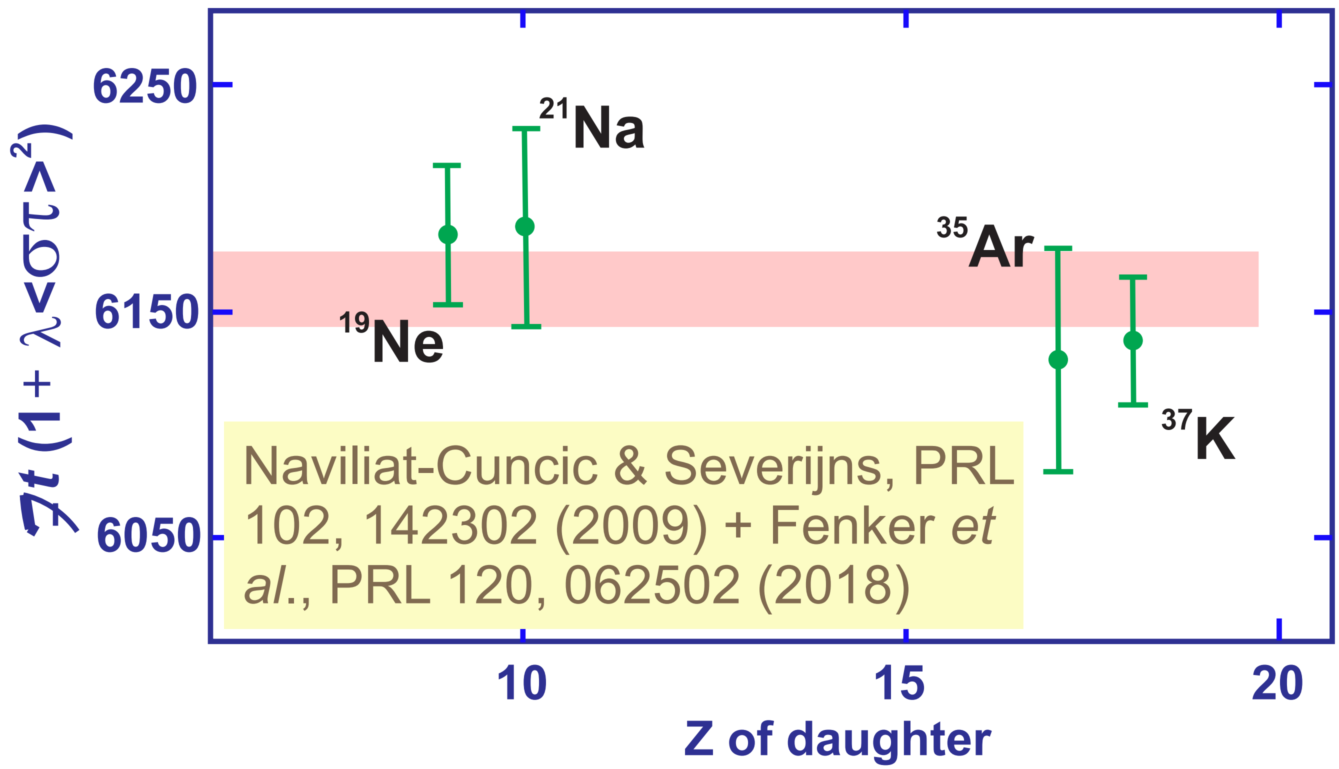

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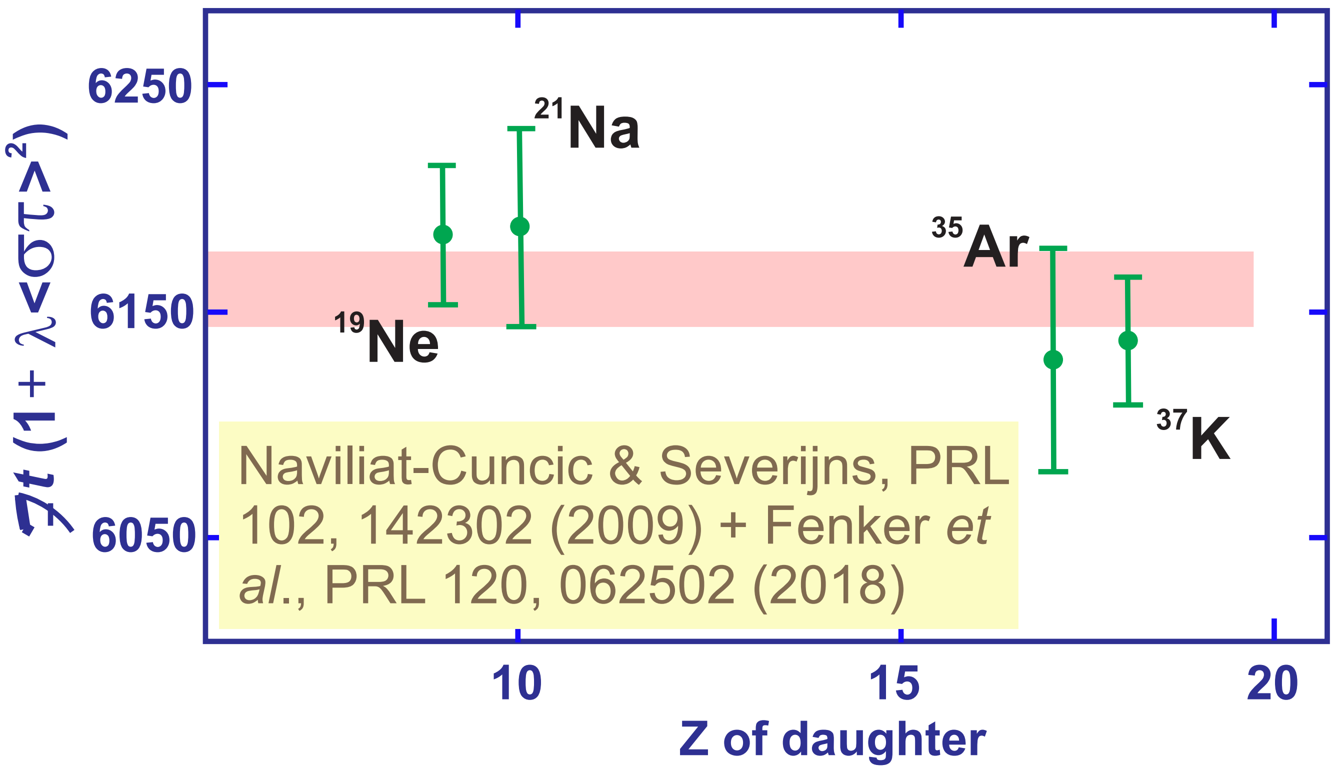

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PION BETA DECAY

Decay process:

$$^{+} \longrightarrow \; ^{0}\, e^{+} \;\; _{e}$$

$$0^{-},1 \longrightarrow 0^{-},1$$

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Experimental data:

$$\tau = 2.6033 \pm 0.0005 \times 10^{-8} \text{ s}$$ (PDG 2017)

$$BR = 1.036 \pm 0.007 \times 10^{-8}$$

Pocanic *et al*,
PRL 93, 181803 (2004)

Result:

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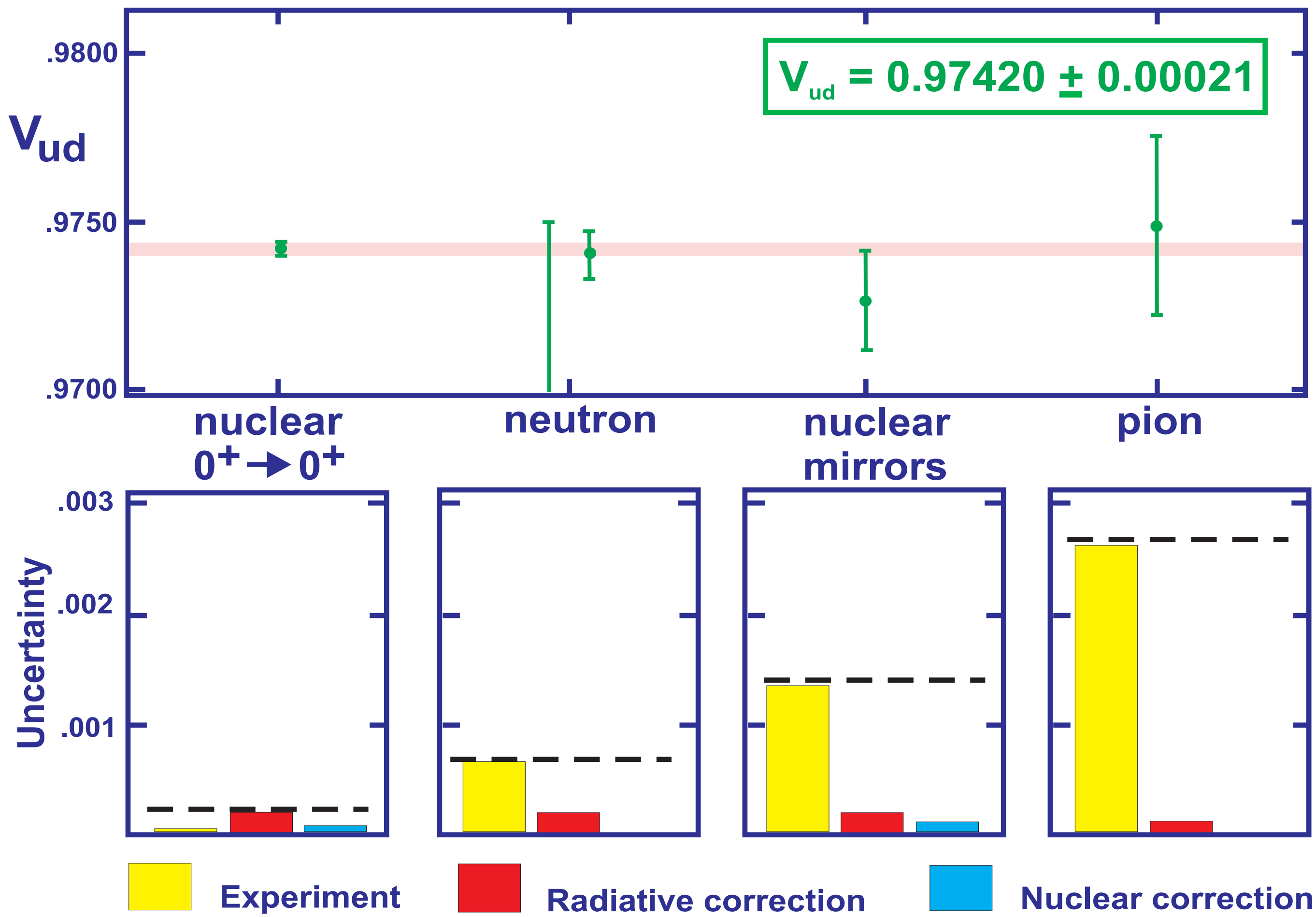
CURRENT STATUS OF V_{ud} AND CKM UNITARITY



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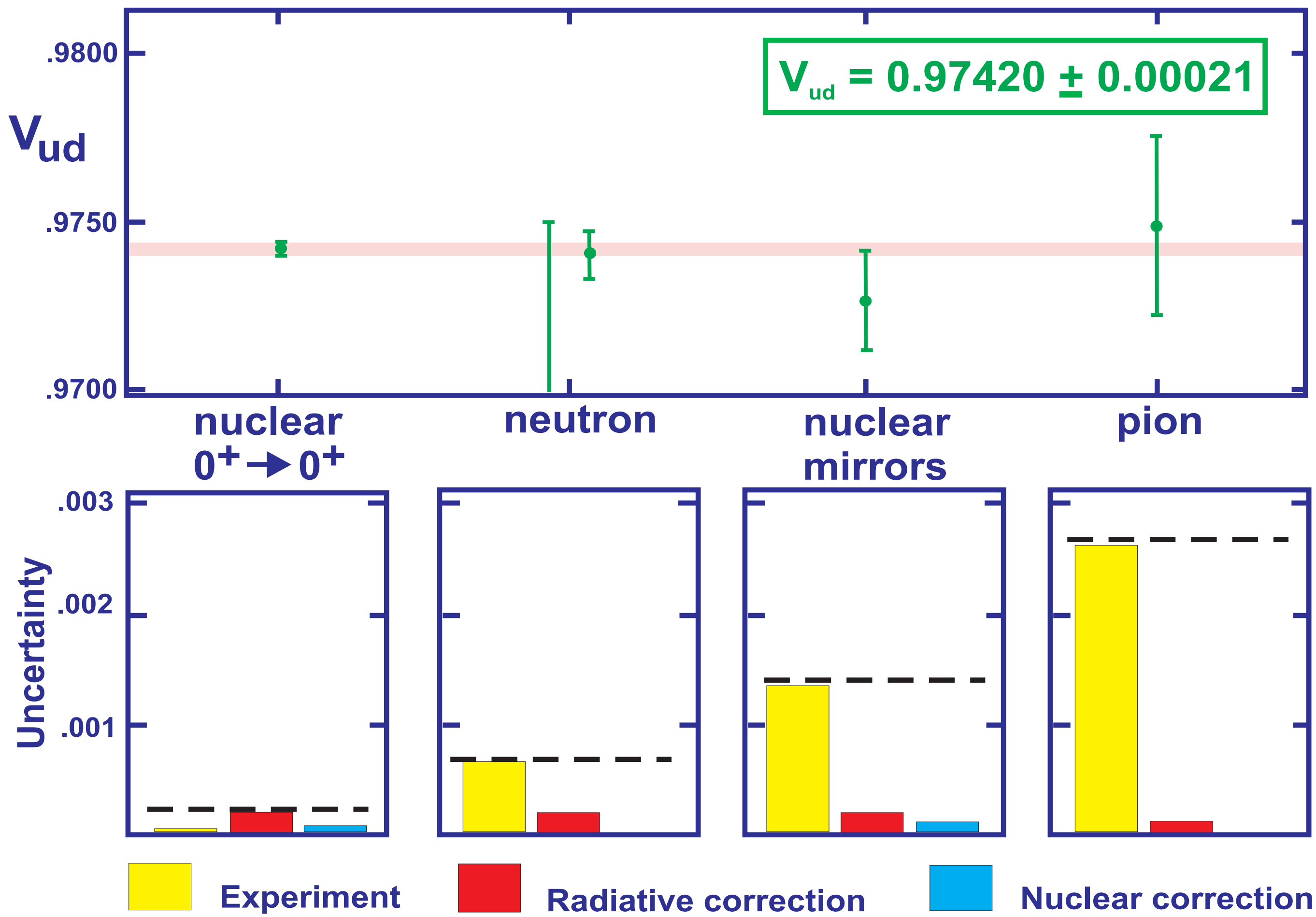

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99939 \pm 0.00047$$

V_{ud}^2 nuclear decays, muon decay: **0.94907 ± 0.00041**

V_{us}^2 PDG, kaon decays: **0.05031 ± 0.00022**

V_{ub}^2 B decays: **0.00002**

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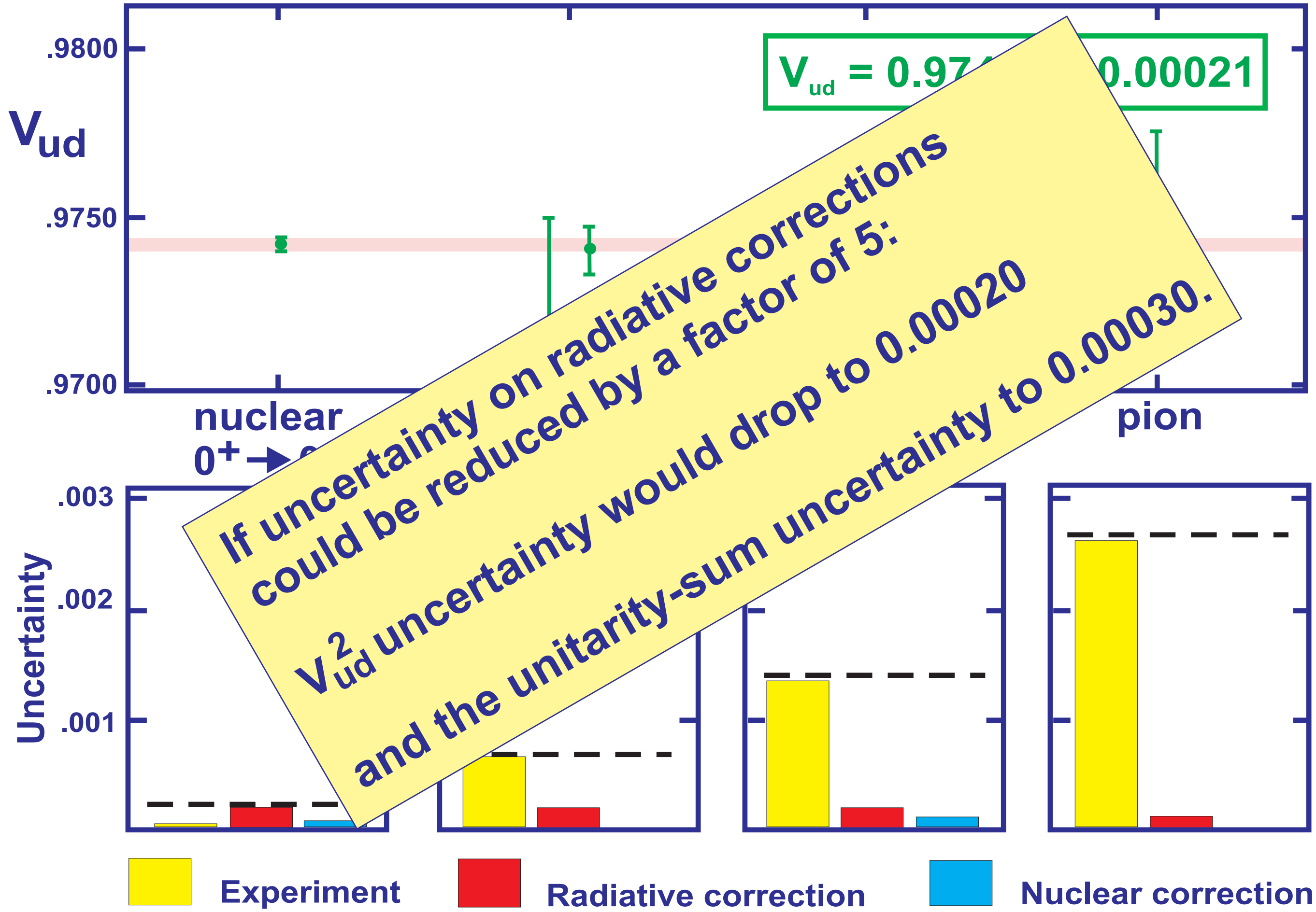

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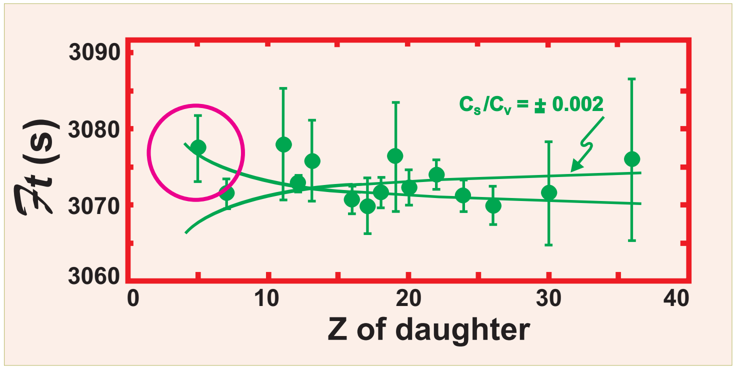

To limit or identify scalar current

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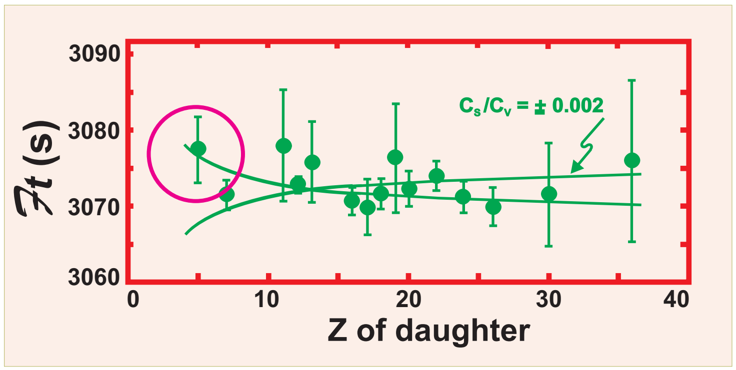
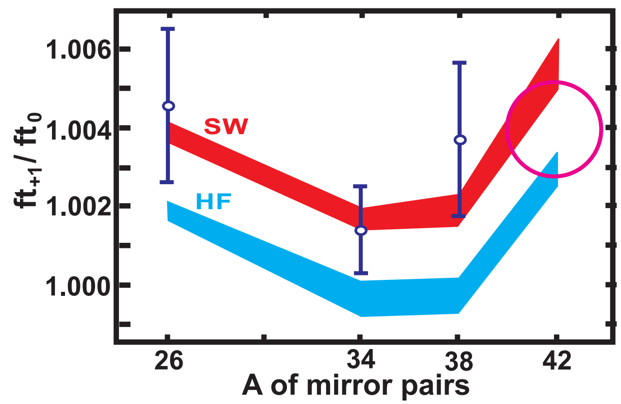


To limit or identify scalar current

2. Complete *A* = 42 mirror pair



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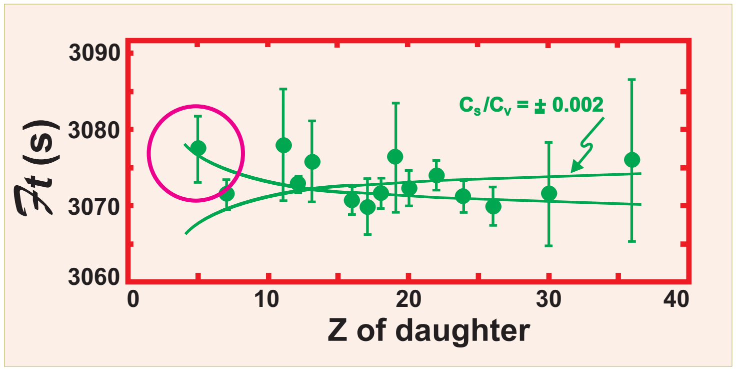

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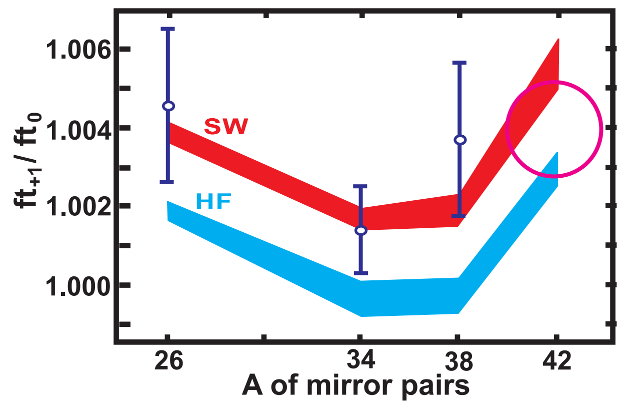

To constrain δ_C correction terms

3. Reduce uncertainty in calculated Δ_R

If uncertainty on radiative corrections could be reduced by a factor of 5:

V_{ud}^2 uncertainty would drop to 0.00020

and the unitarity-sum uncertainty to 0.00030.

To improve unitarity test

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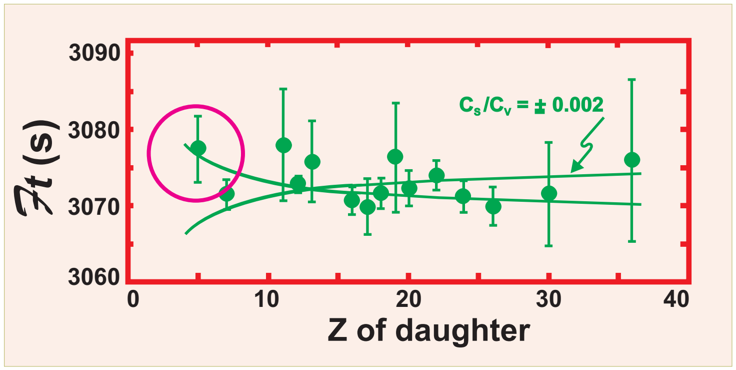

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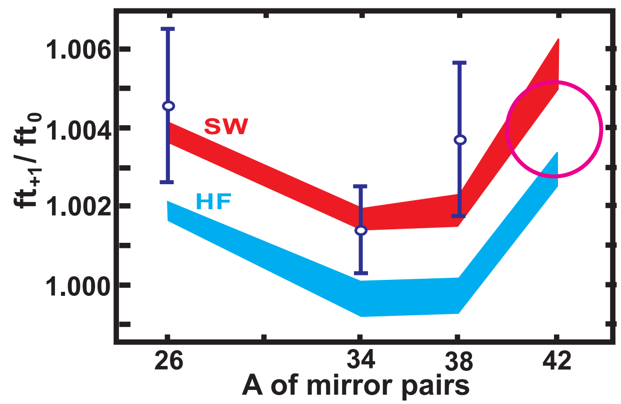

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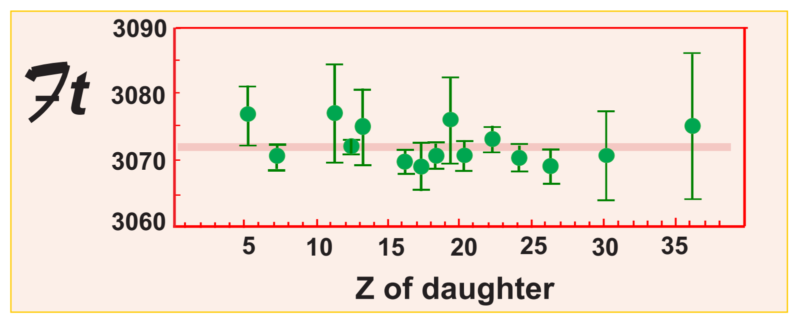
4. Revisit all calculated corrections. If transition-dependence is altered, improve all measured *ft* values to verify that CVC is preserved.



SUMMARY AND OUTLOOK

1. Analysis of superallowed $0^+ \rightarrow 0^+$ nuclear β decay confirms CVC to ±0.011% and thus yields V_{ud} = 0.97420(21).
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It's been a fun way to make a living

The people who helped make it fun (since 1997)

Ian Towner

TAMU

Victor Iacob
Ninel Nica
Hyo In Park
Vladimir Horvat
Lixin Chen
Vladimir Golovko
Maria Sanchez-Vega
Peter Lipnik
Russell Neilson
John Goodwin
Miguel Bencomo

Livius Trache
Brian Roeder
Evgeny Tereshatov
Dan Melconian
Bob Tribble
Carl Gagliardi

External

Gordon Ball (TRIUMF)
Dick Helmer (INEEL)
Guy Savard (ANL)
Subramanian Raman (ORNL)
Malvina Trzhaskovskaya (St. Petersburg)
Tommi Eronen (Jyvaskyla)
Juha Aysto (Jyvaskyla)
Maxime Brodeur (Notre Dame)