Testing CVC and CKM unitarity via superallowed nuclear β decay

J.C. Hardy

Cyclotron Institute
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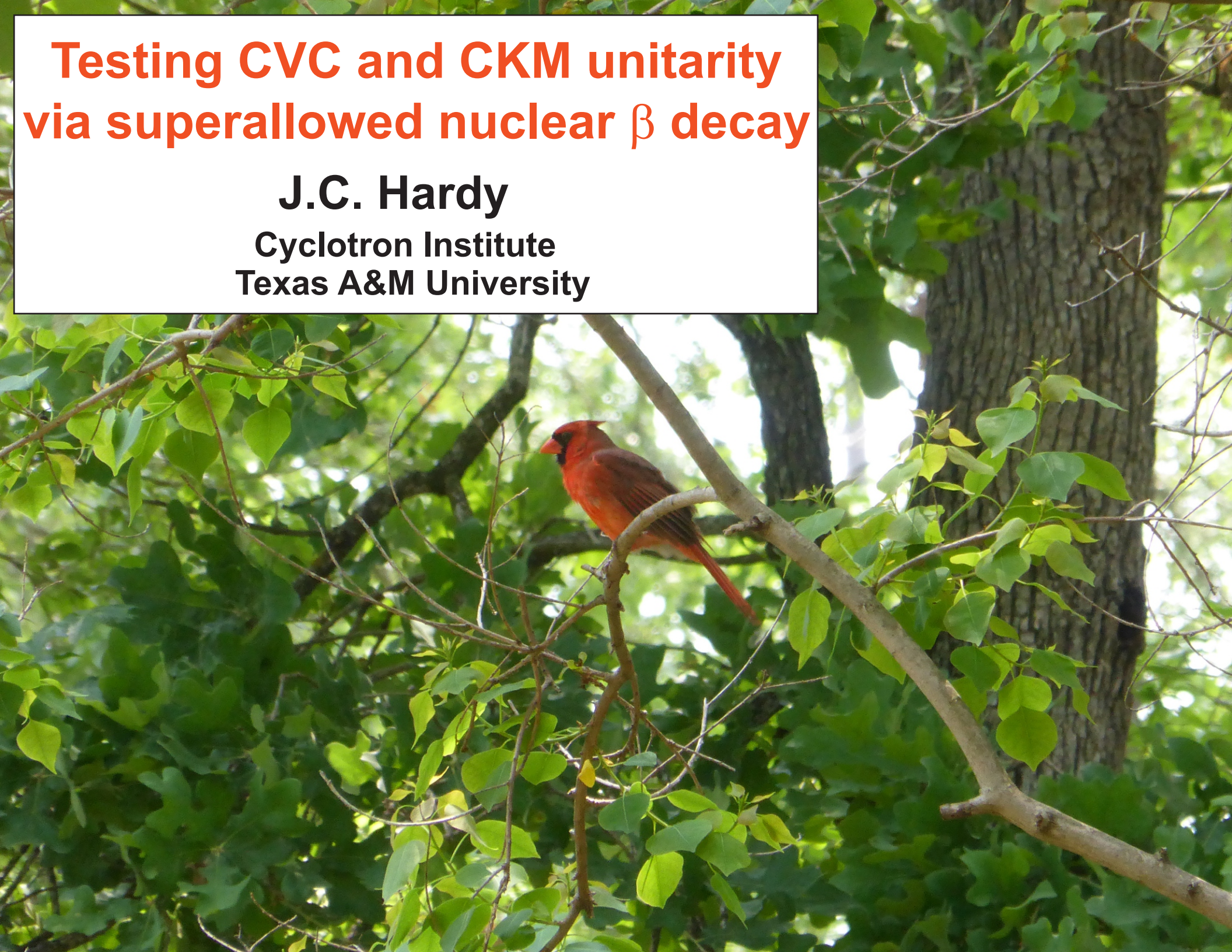


SUPERALLOWED $0^+ \rightarrow 0^+$ BETA DECAY

BASIC WEAK-DECAY EQUATION

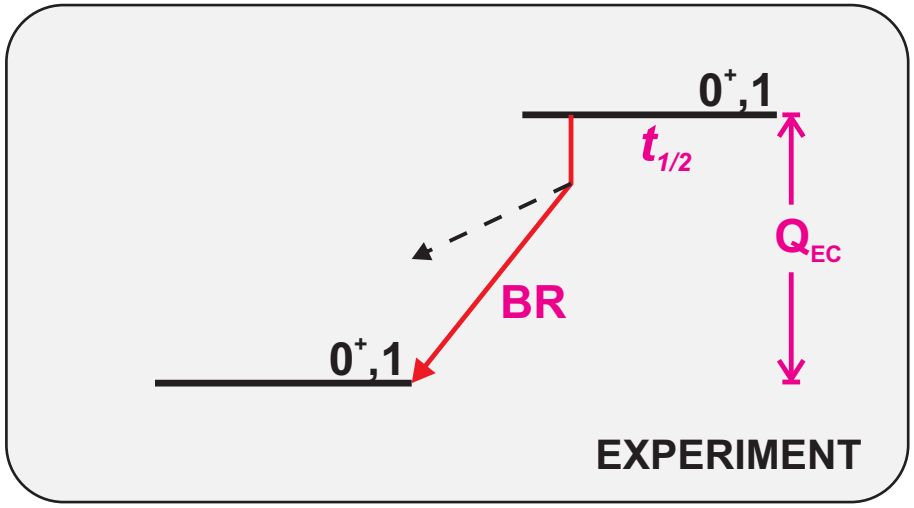
$$ft = \frac{K}{G_V^2 \langle \tau \rangle^2}$$

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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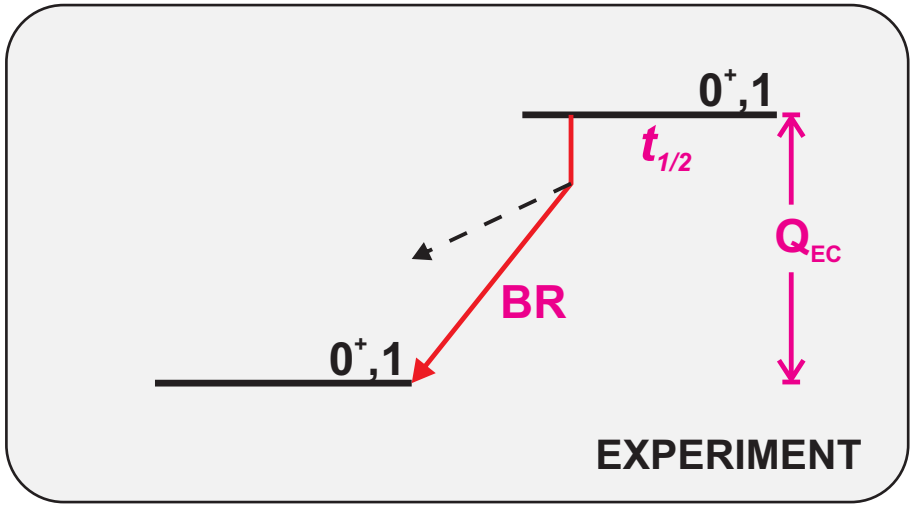

INCLUDING RADIATIVE AND ISOSPIN-SYMMETRY-BREAKING CORRECTIONS

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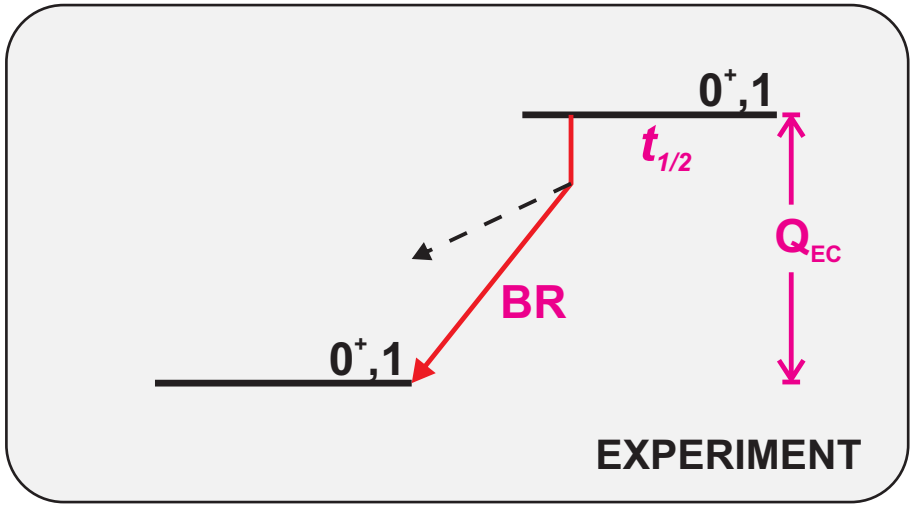

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f(nuclear structure) 0.3-1.5%

f(interaction) ~2.4%

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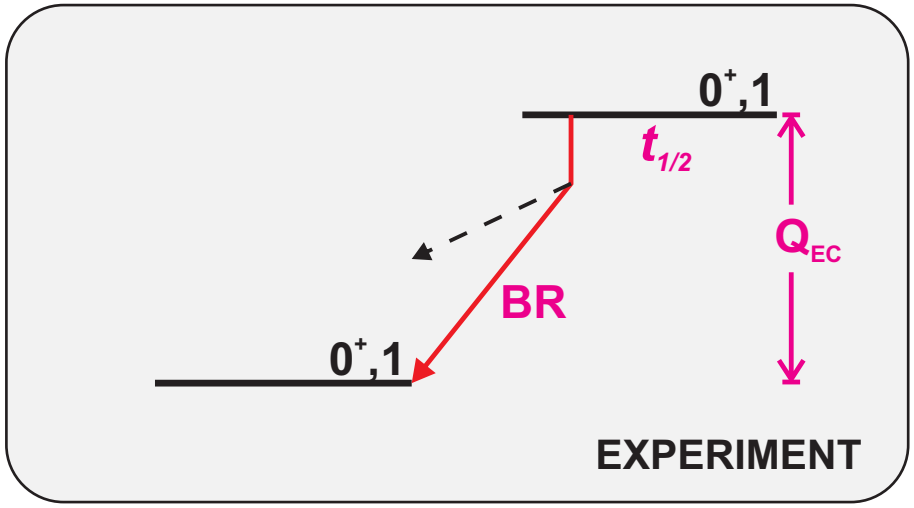

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THEORETICAL UNCERTAINTIES 0.05 – 0.10%

CALCULATED CORRECTIONS TO $0^+ \rightarrow 0^+$ DECAYS

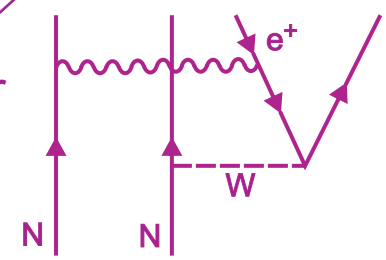
$$\mathcal{F}t = ft\,(1 + {}'_R)\left[1 - ({}_C - {}_{NS})\right] = \frac{K}{2G_V^2\,(1 + {}_R)}$$

1. Radiative corrections

$${}'_R = \frac{}{2}\left[g(E_m) + {}_2 + {}_3 + \ldots\right]$$

$${}_R = \frac{}{2}\left[4\ln(m_Z/m_p) + \ln(m_p/m_A) + 2C_{Born} + \ldots\right]$$

${}_{NS}$ — Order- axial-vector universal photonic contributions



2. Isospin symmetry-breaking corrections

${}_C$ — Charge-dependent mismatch between parent and daughter analog states (members of the same isospin triplet).

Dependent on nuclear structure

ISOSPIN SYMMETRY BREAKING CORRECTIONS

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

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.

0.01 – 0.3 %

Mismatch in radial wave function between parent and daughter.

- Full-parentage Saxon-Woods wave function also matched to known binding energy and charge radius from electron scattering.
- Compared with Hartree-Fock calculation matched to known binding energy.
- Core states included based on measured spectroscopic factors.

0.4 – 1.5 %

WHAT CAN WE LEARN?

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FROM A SINGLE TRANSITION

Experimentally determine $G_V^2(1 + {}_R)$

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FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

Validate the correction terms

Test for presence of a Scalar current

$\mathcal{F}t$ values constant

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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 $G_V^2(1 + {}_R)$

Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G^2$$

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Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G^2$$

Test CKM unitarity

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

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Obtain precis (1 + ${}_R$)

Determin

unitarity

ONLY POSSIBLE IF PRIOR CONDITIONS SATISFIED

$$V_{ud}^2 = G_V^2/G^2$$

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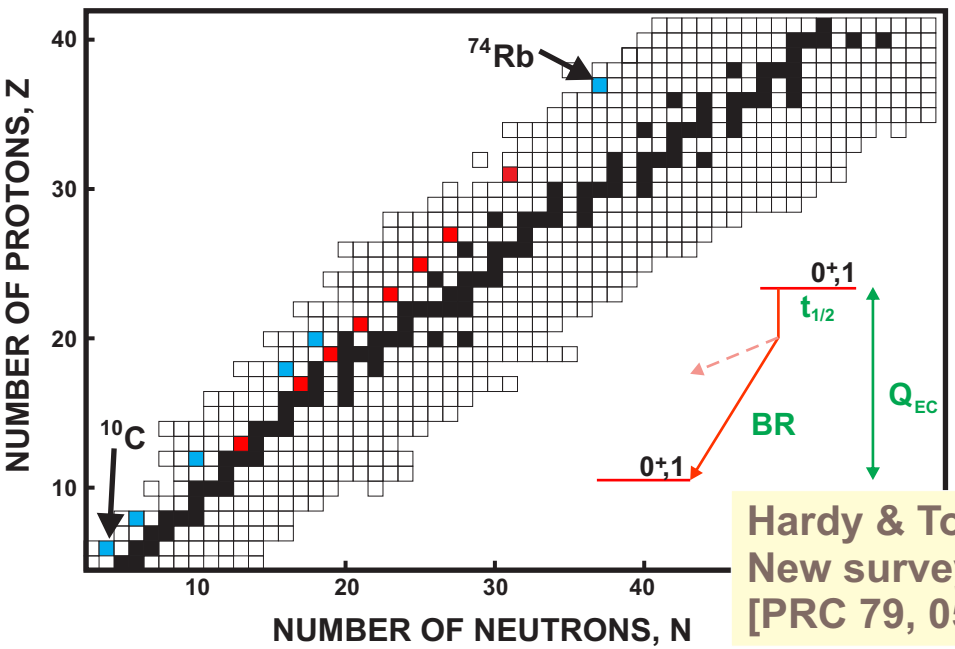
WORLD DATA FOR $0^+ \rightarrow 0^+$ DECAY, 2014



Hardy & Towner
New survey (2014)
[PRC 79, 055502 (2009)]

- 8 cases with *ft*-values measured to <0.05% precision; 6 more cases with 0.05-0.3% precision.
- ~220 individual measurements with compatible precision

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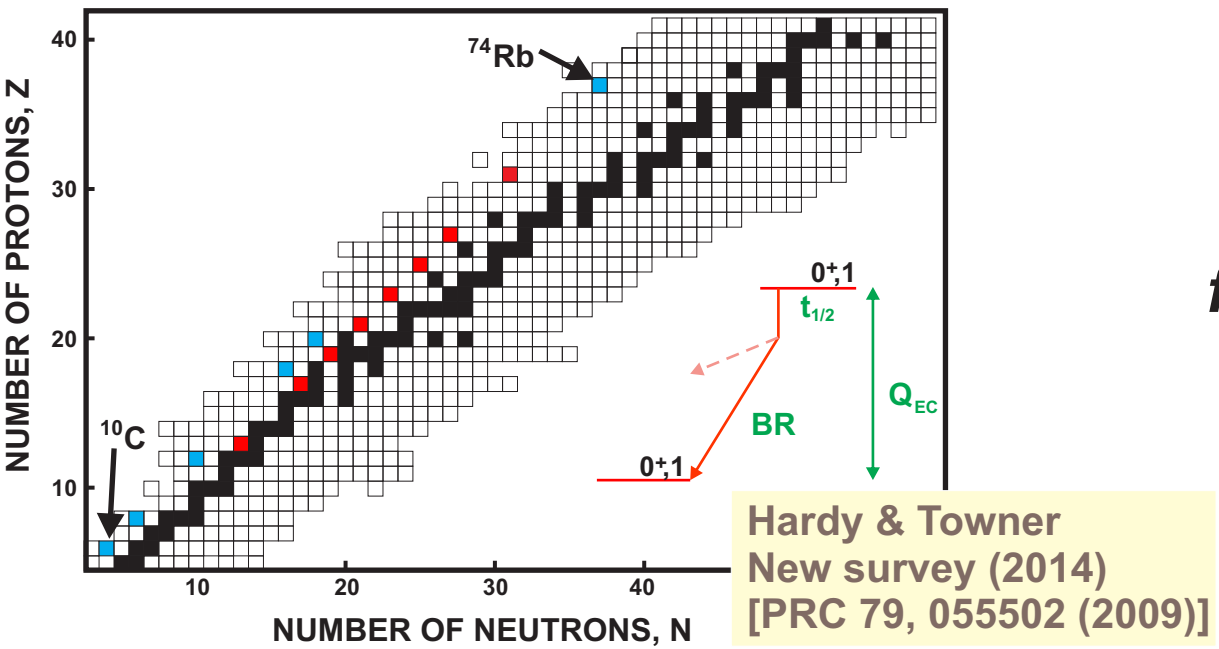

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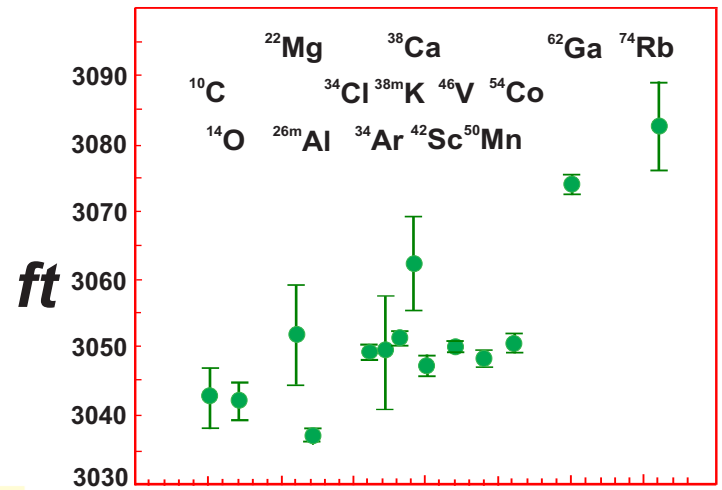

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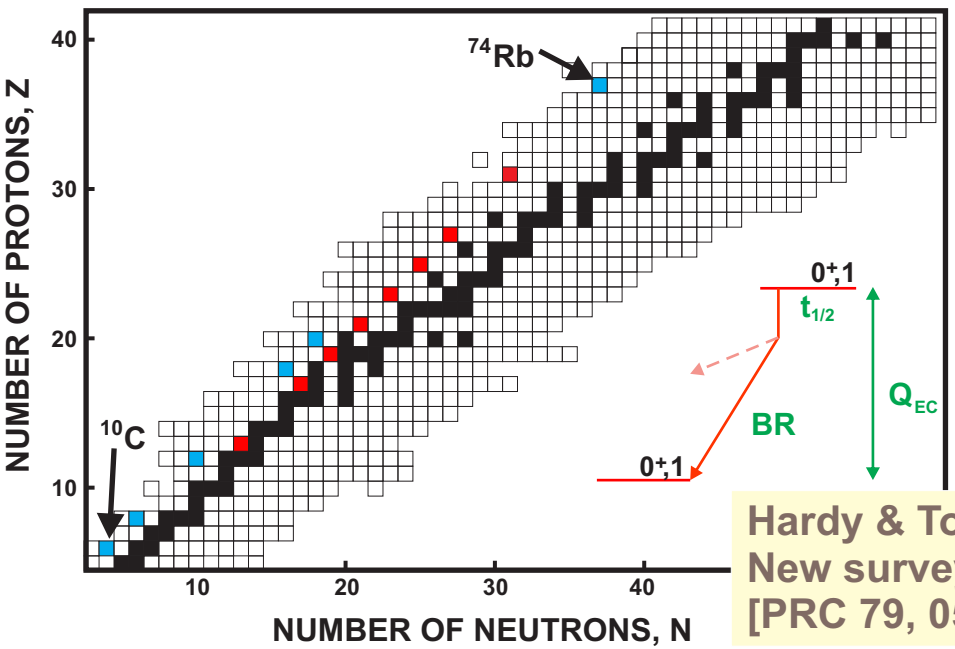

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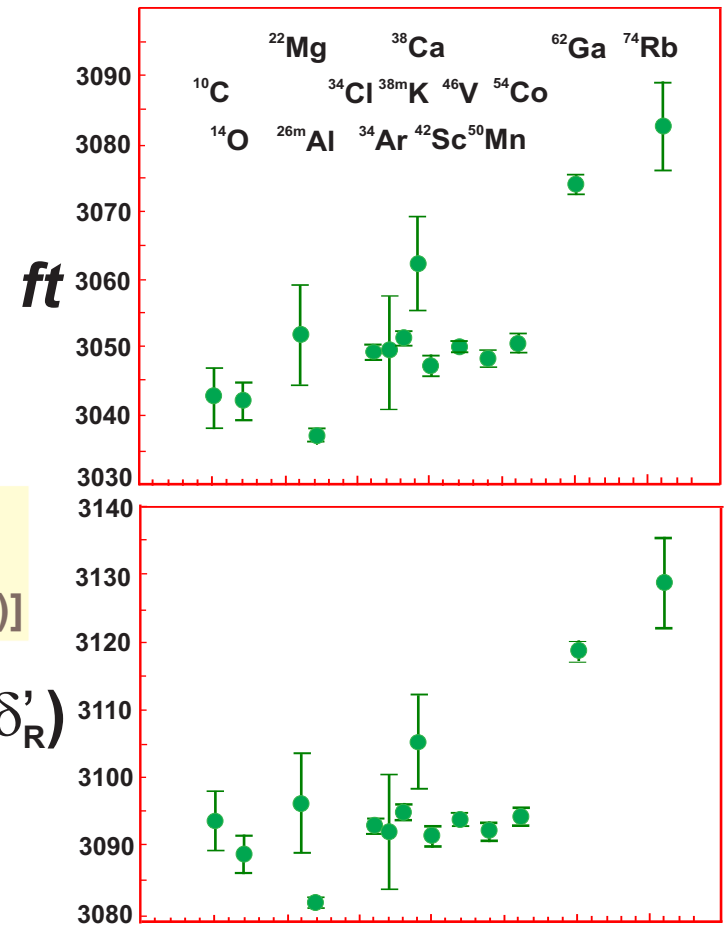

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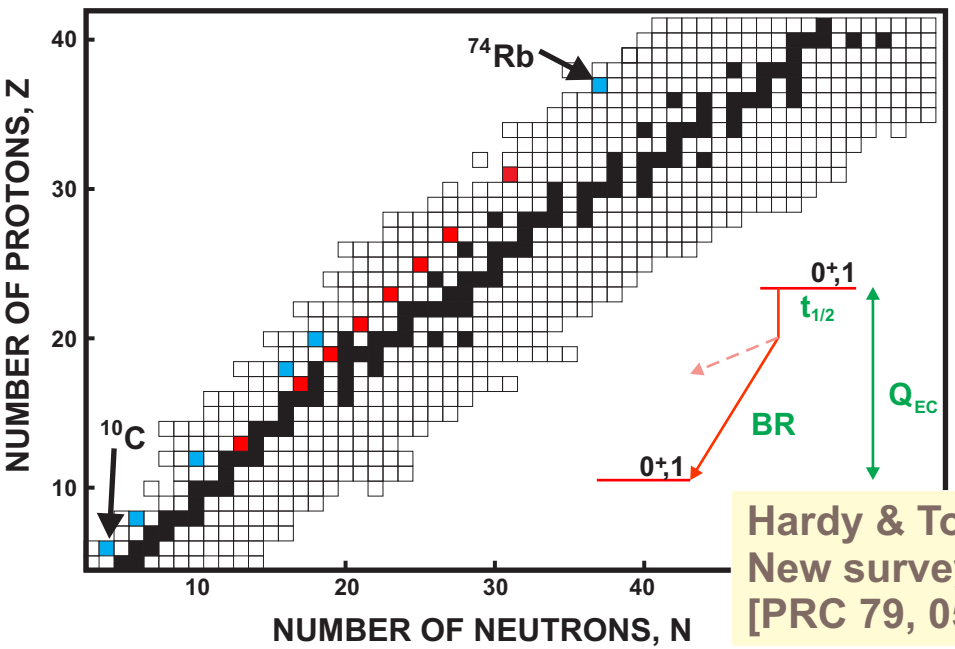

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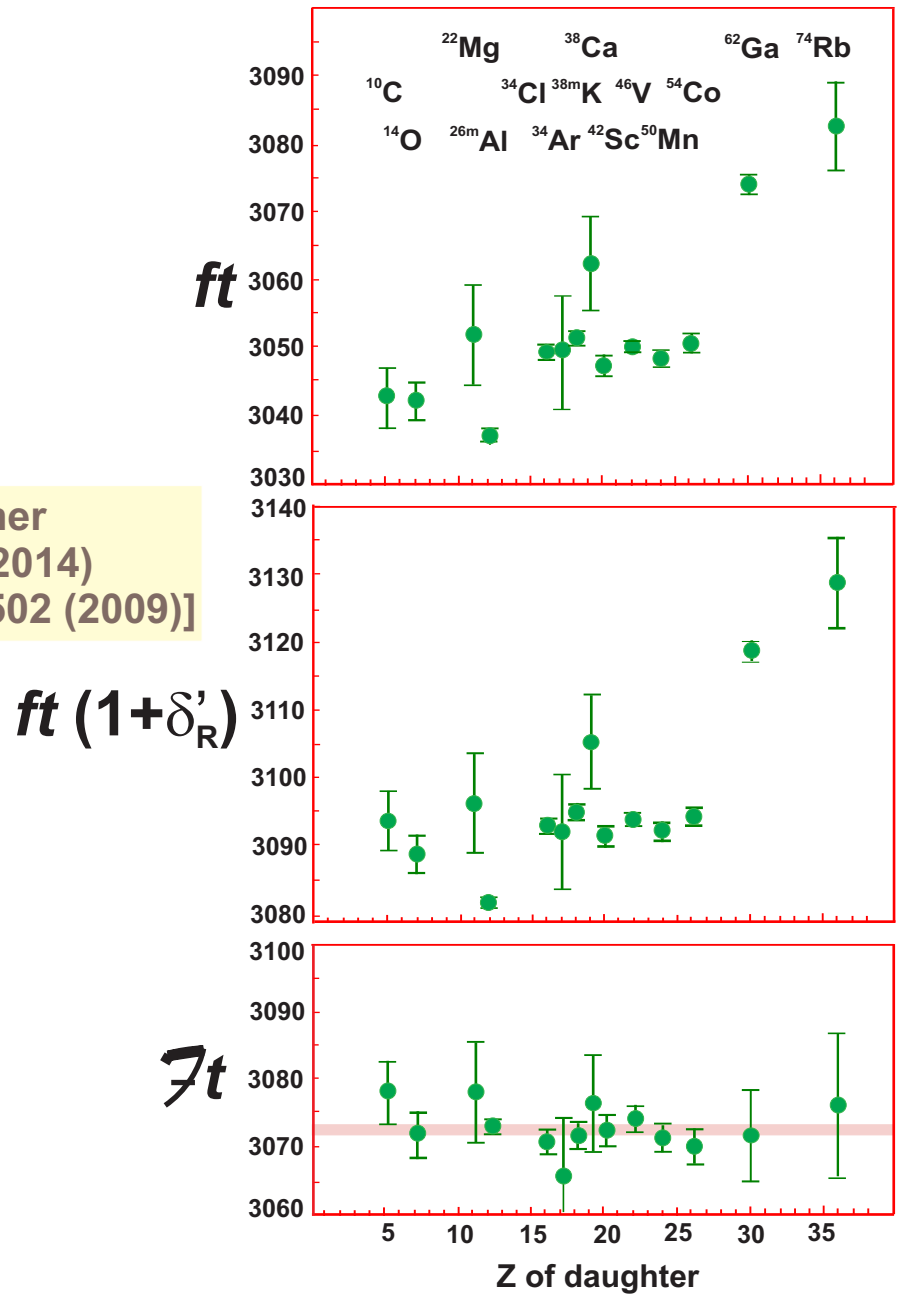

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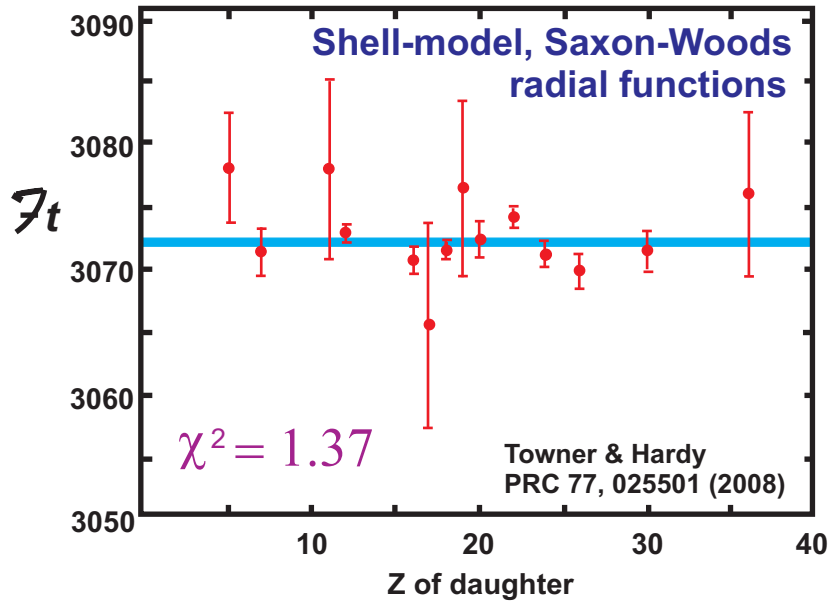
TESTS OF δ_c CALCULATIONS

A. Agreement with CVC:

$\mathcal{F}t$ values have been calculated with different models for δ_c, then tested for consistency. Normalized χ^2 and confidence levels are shown.

Model	χ^2/N	CL(%)
SM-SW	1.37	17



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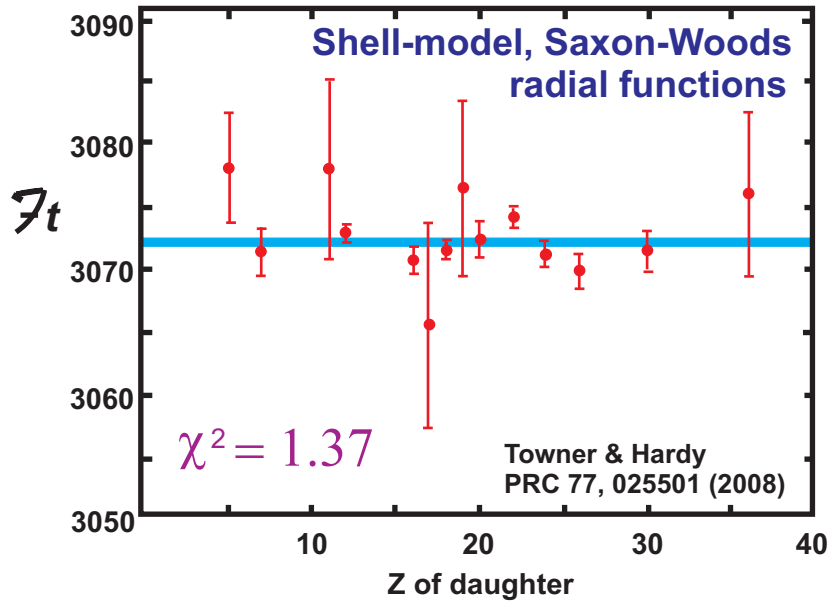

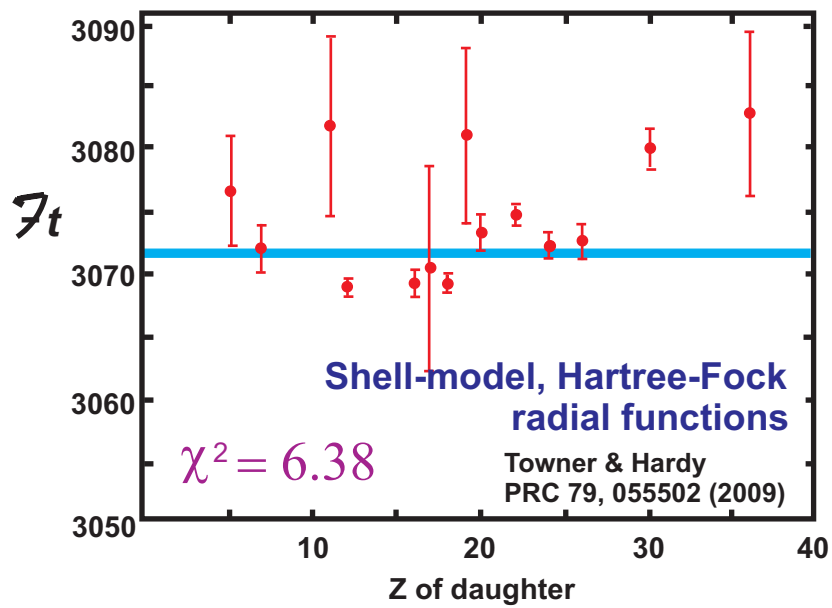

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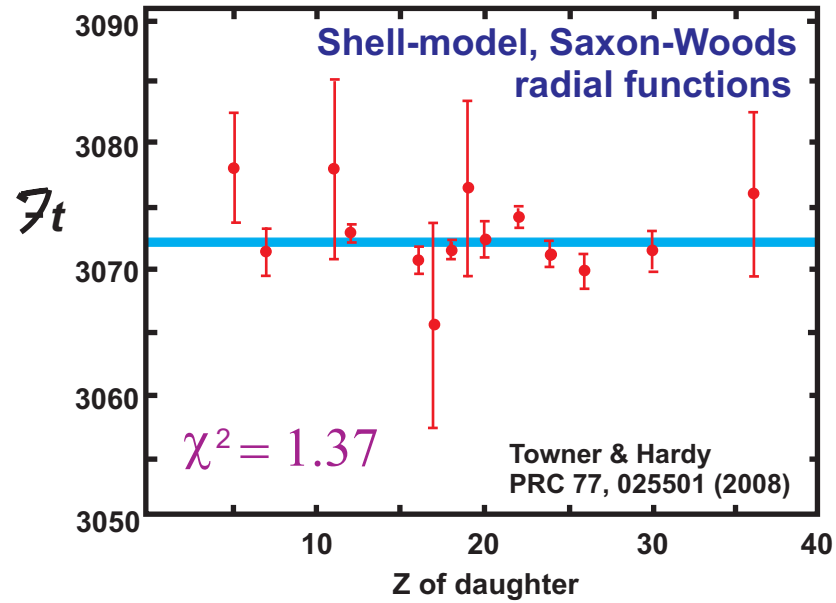

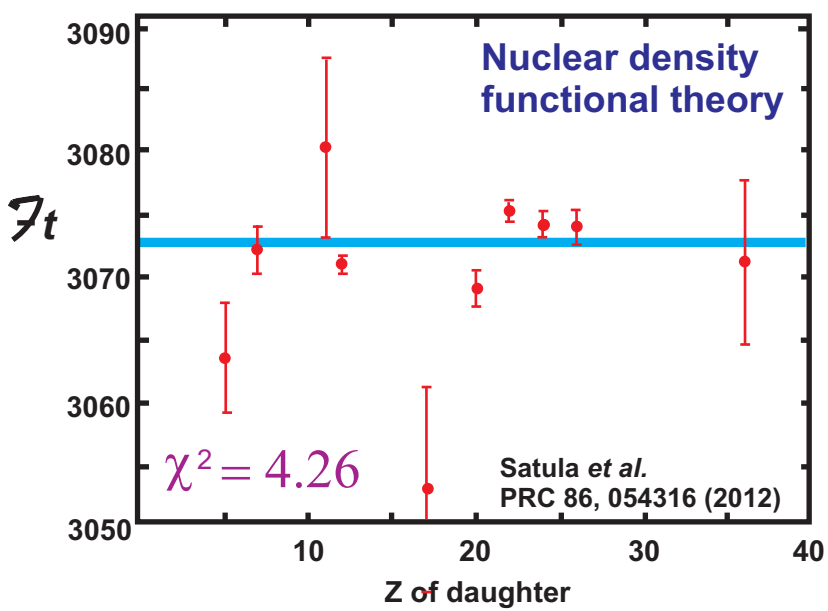

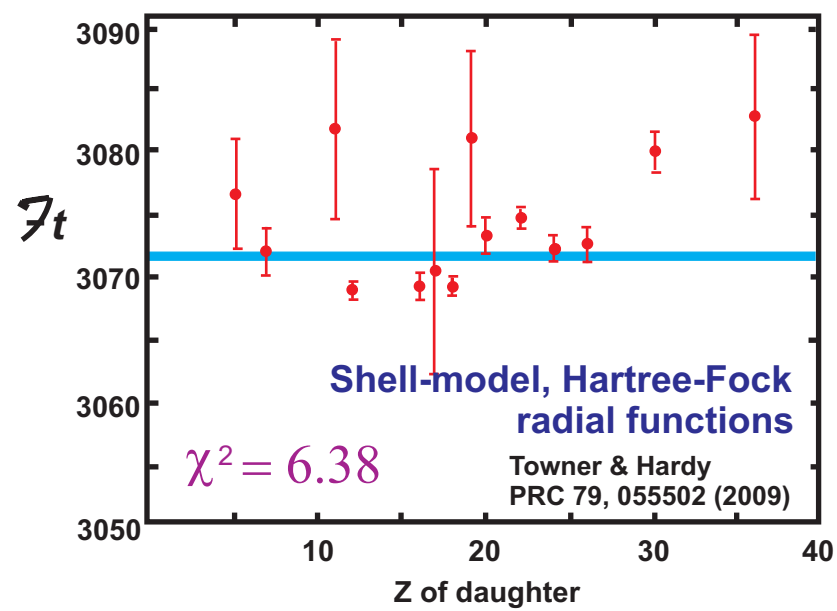

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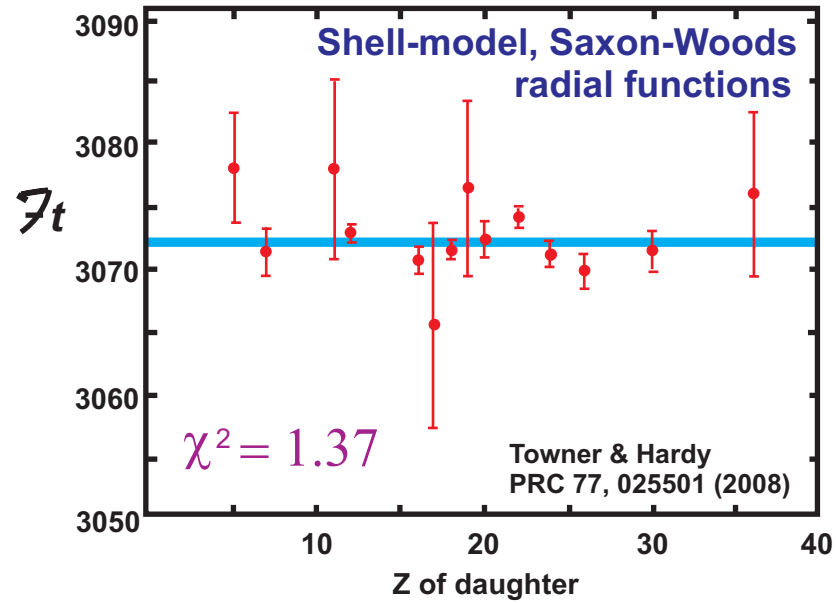
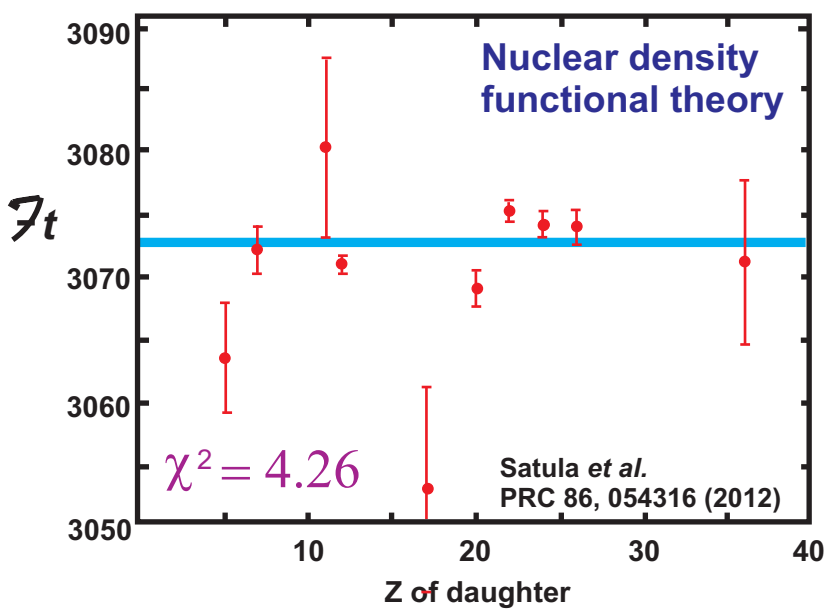
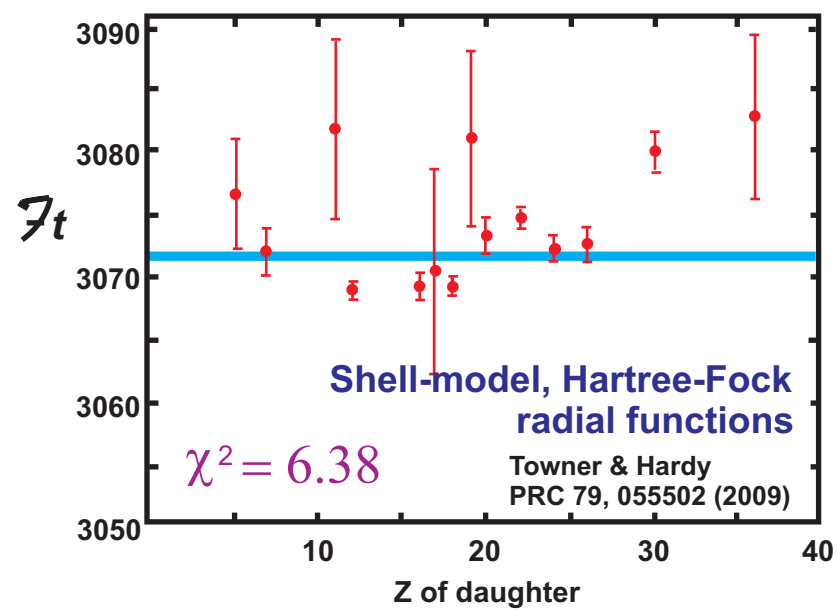
RHF-RPA	4.91	0
RH-RPA	3.68	0







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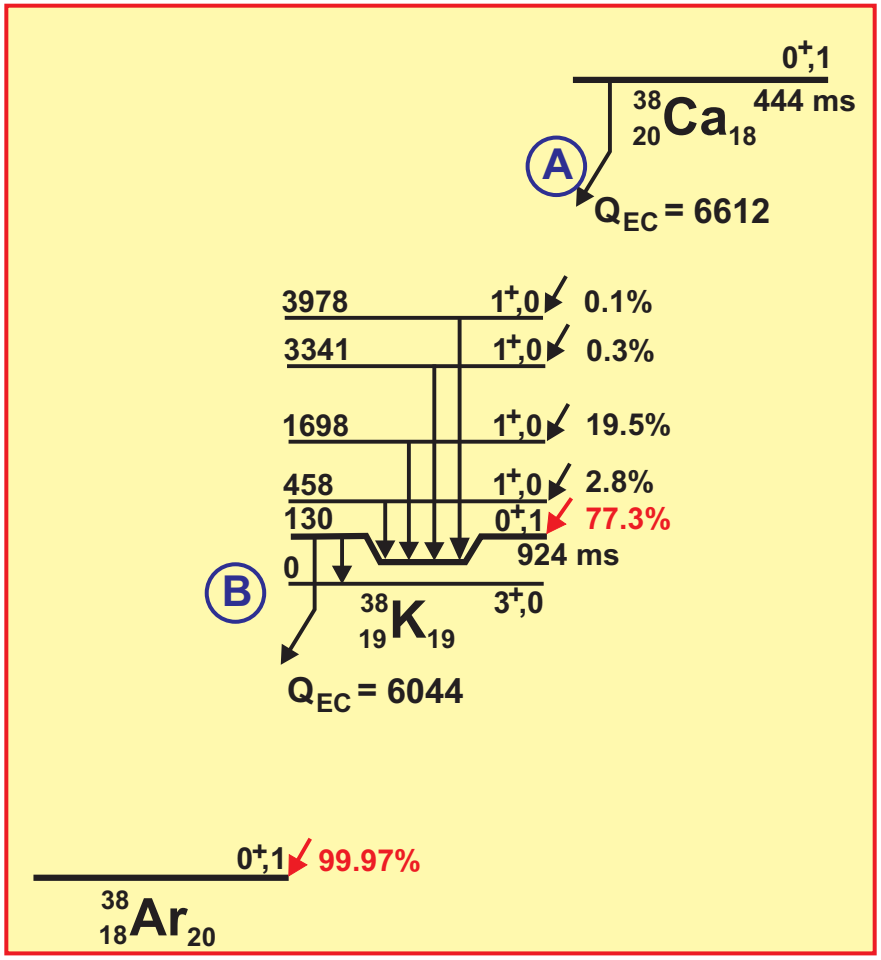

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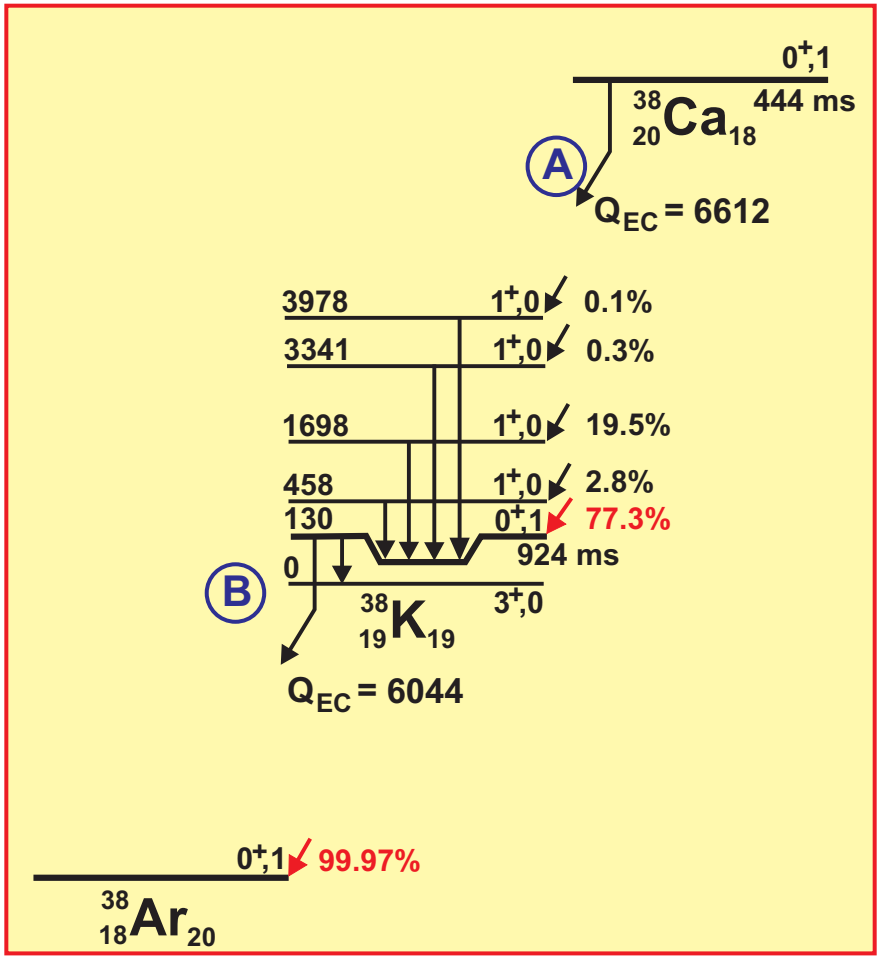

$$\frac{ft_A}{ft_B} = \frac{(1 + \delta'^{B}_R)[1 - (\delta^{B}_C - \delta^{B}_{NS})]}{(1 + \delta'^{A}_R)[1 - (\delta^{A}_C - \delta^{A}_{NS})]}$$

$$= 1 + (\delta'^{B}_R - \delta'^{A}_R) + (\delta^{B}_{NS} - \delta^{A}_{NS}) - (\delta^{B}_C - \delta^{A}_C)$$

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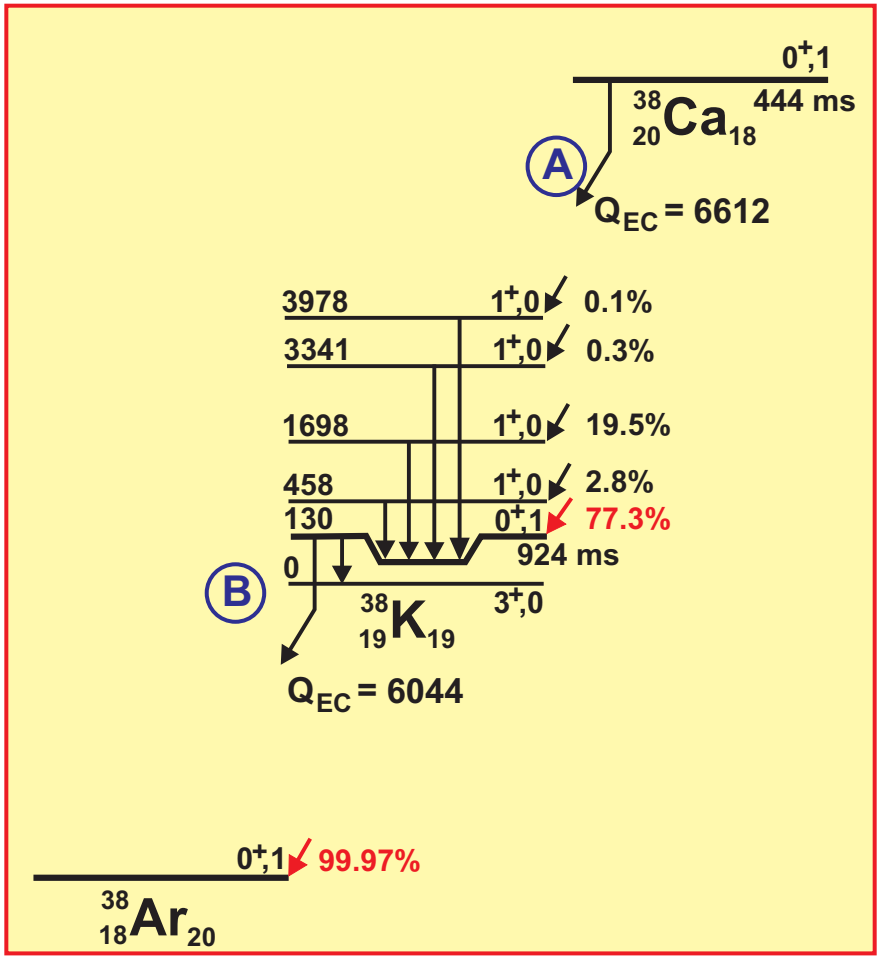

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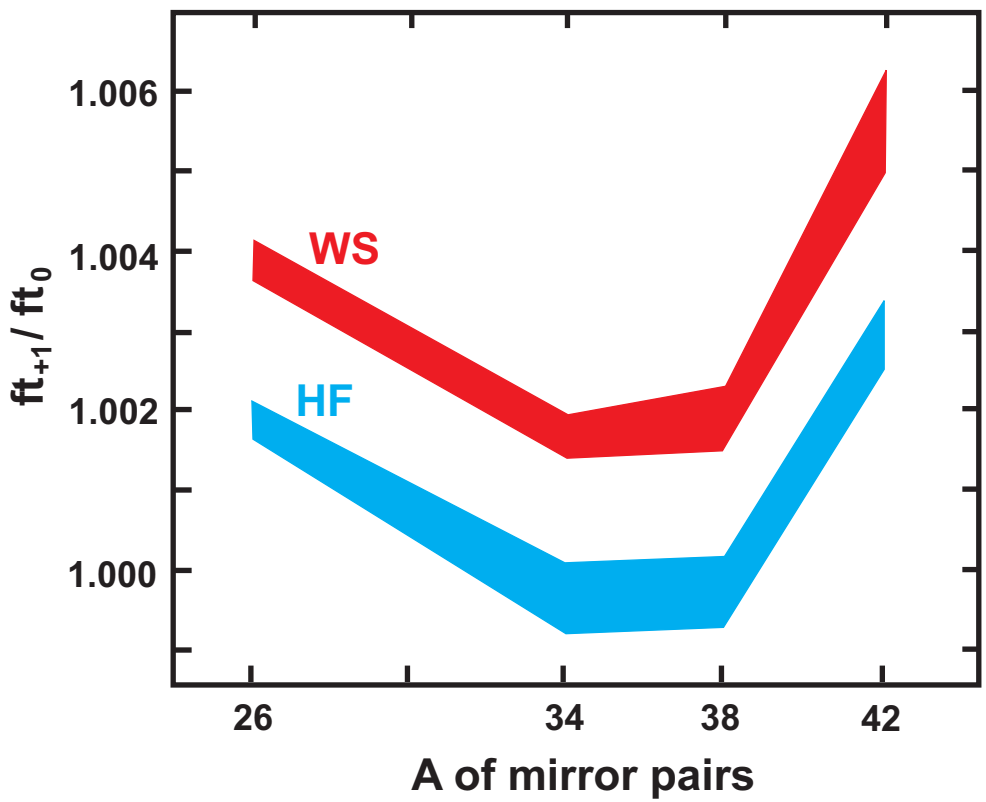
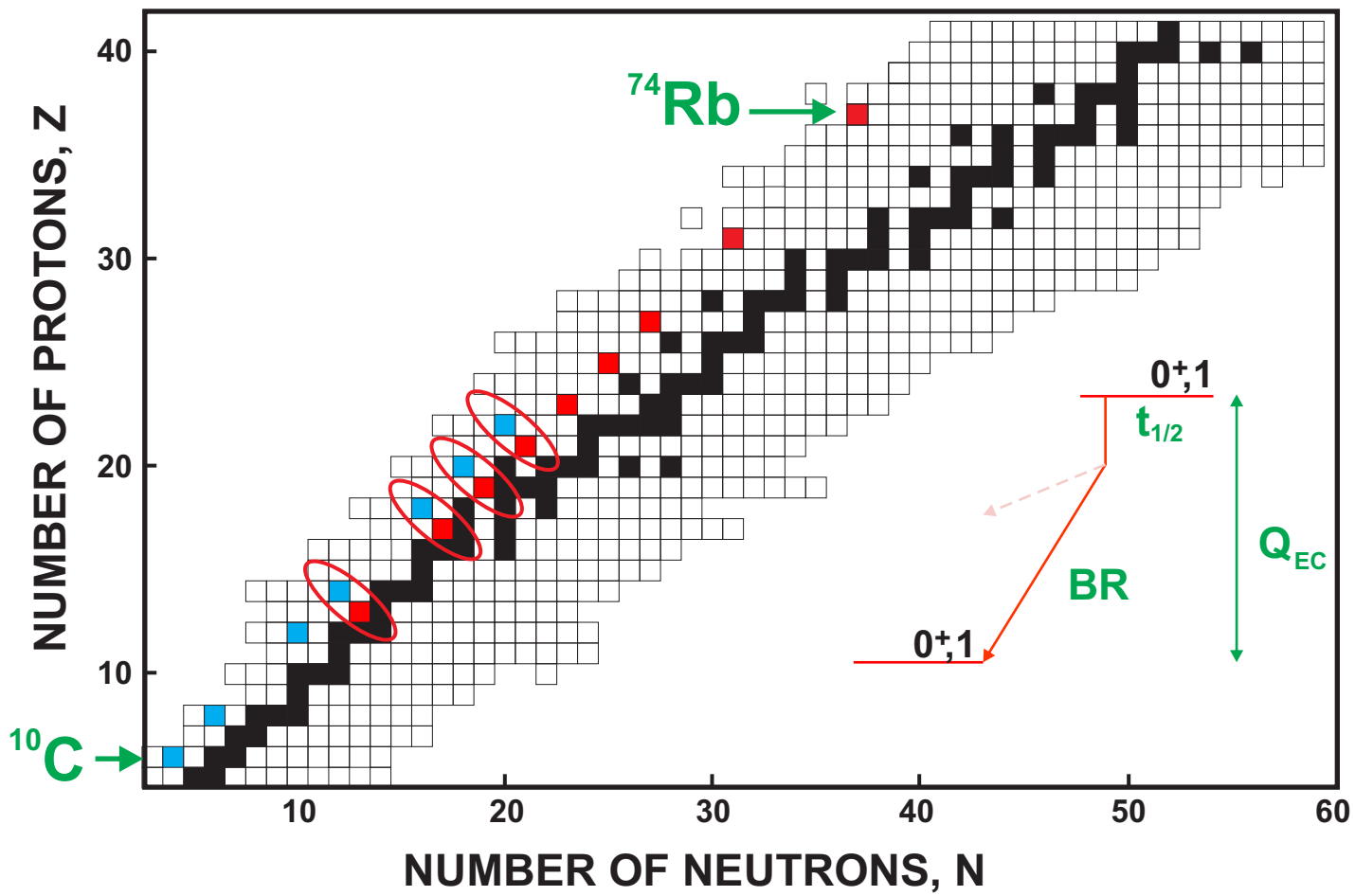


ACCESSIBLE MIRROR PAIRS OF SUPERALLOWED DECAYS



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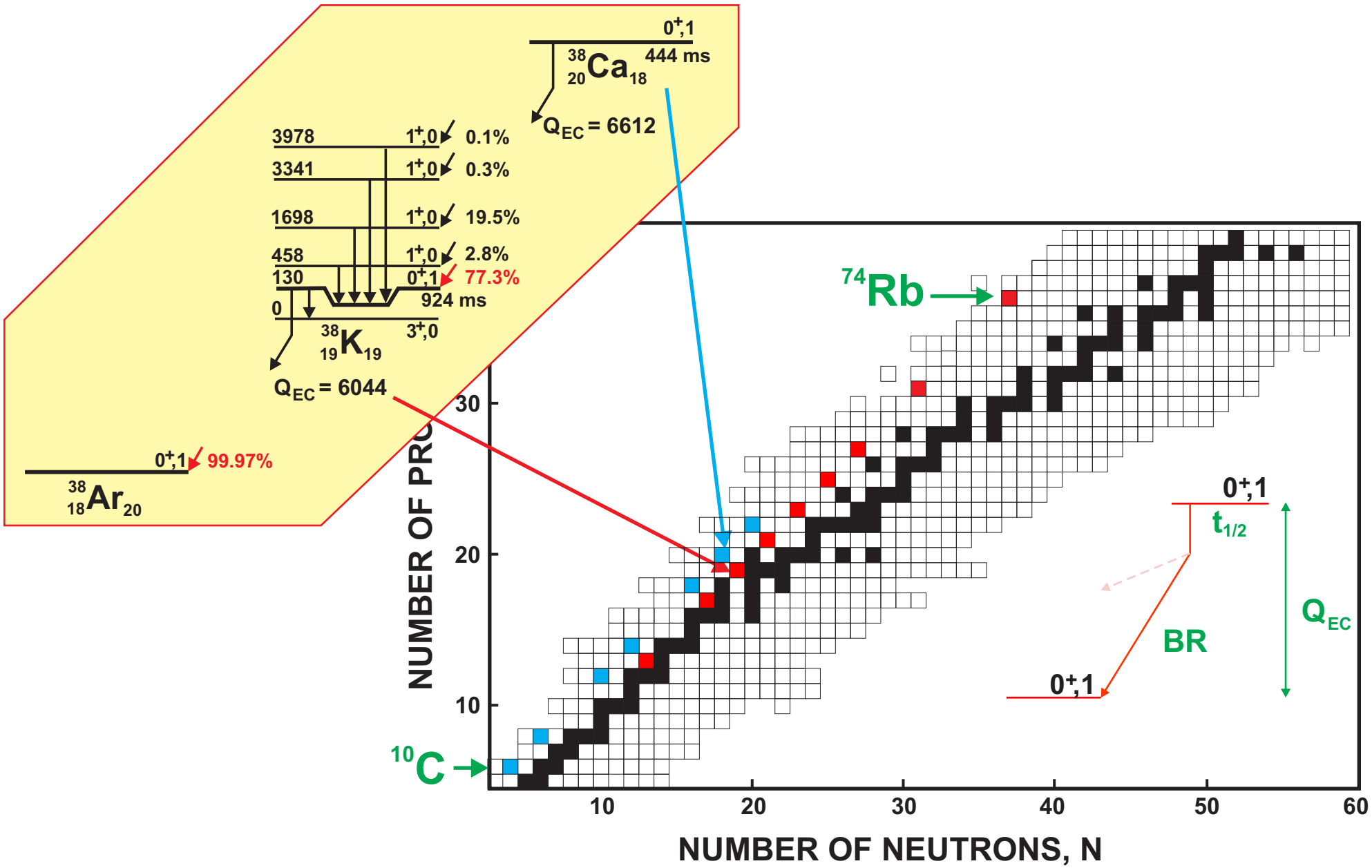
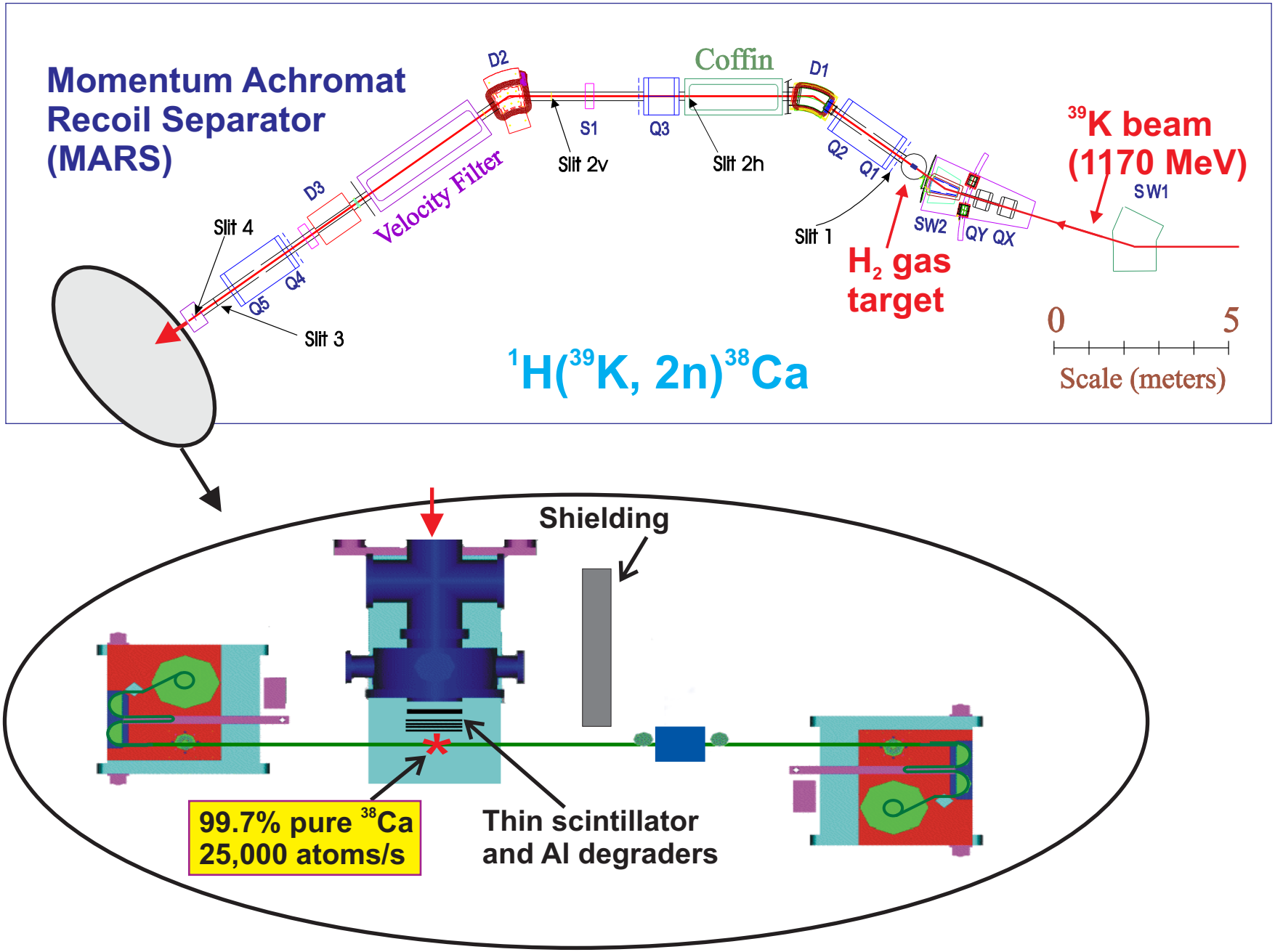


PRECISION DECAY MEASUREMENTS AT TAMU



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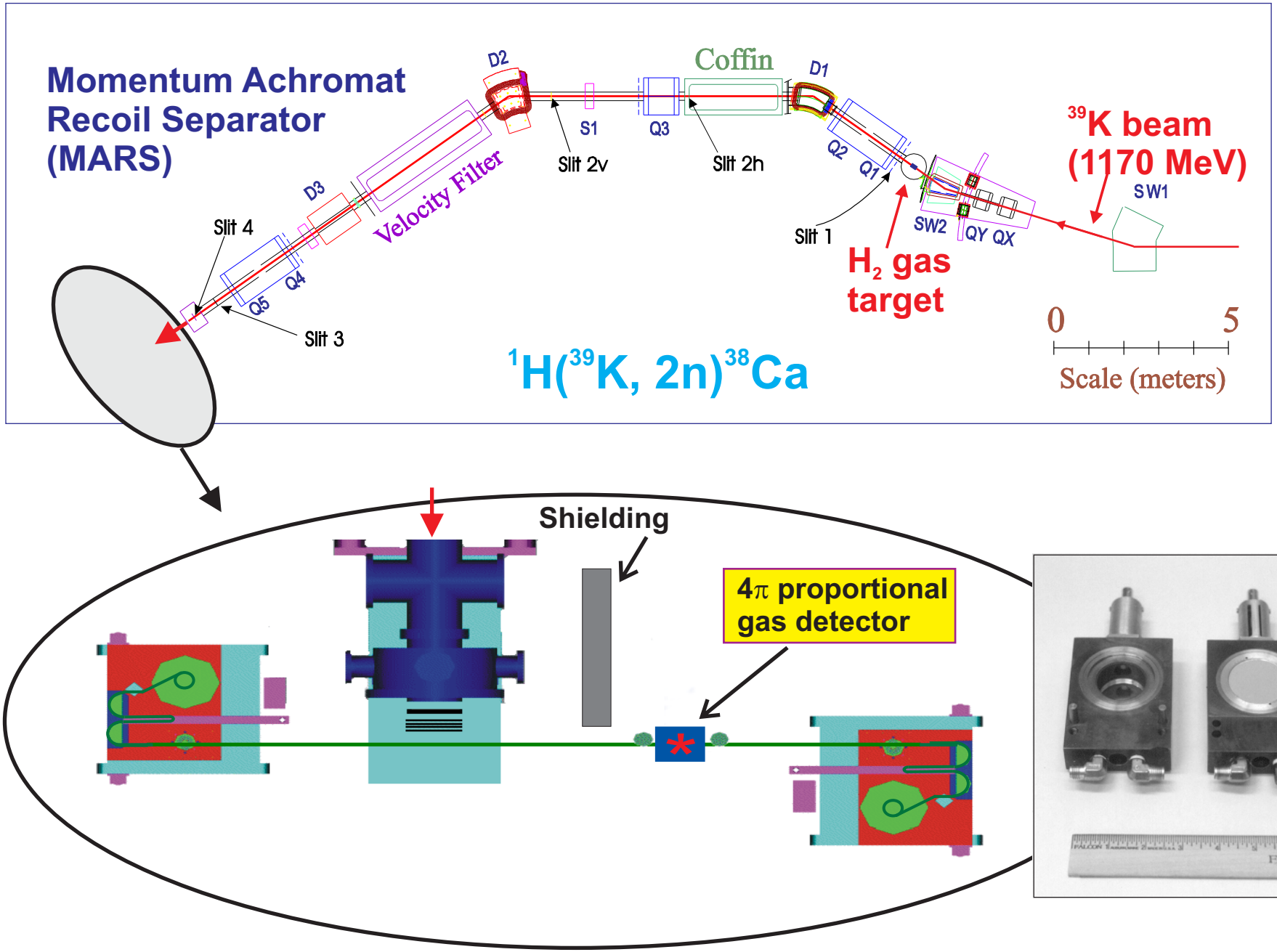

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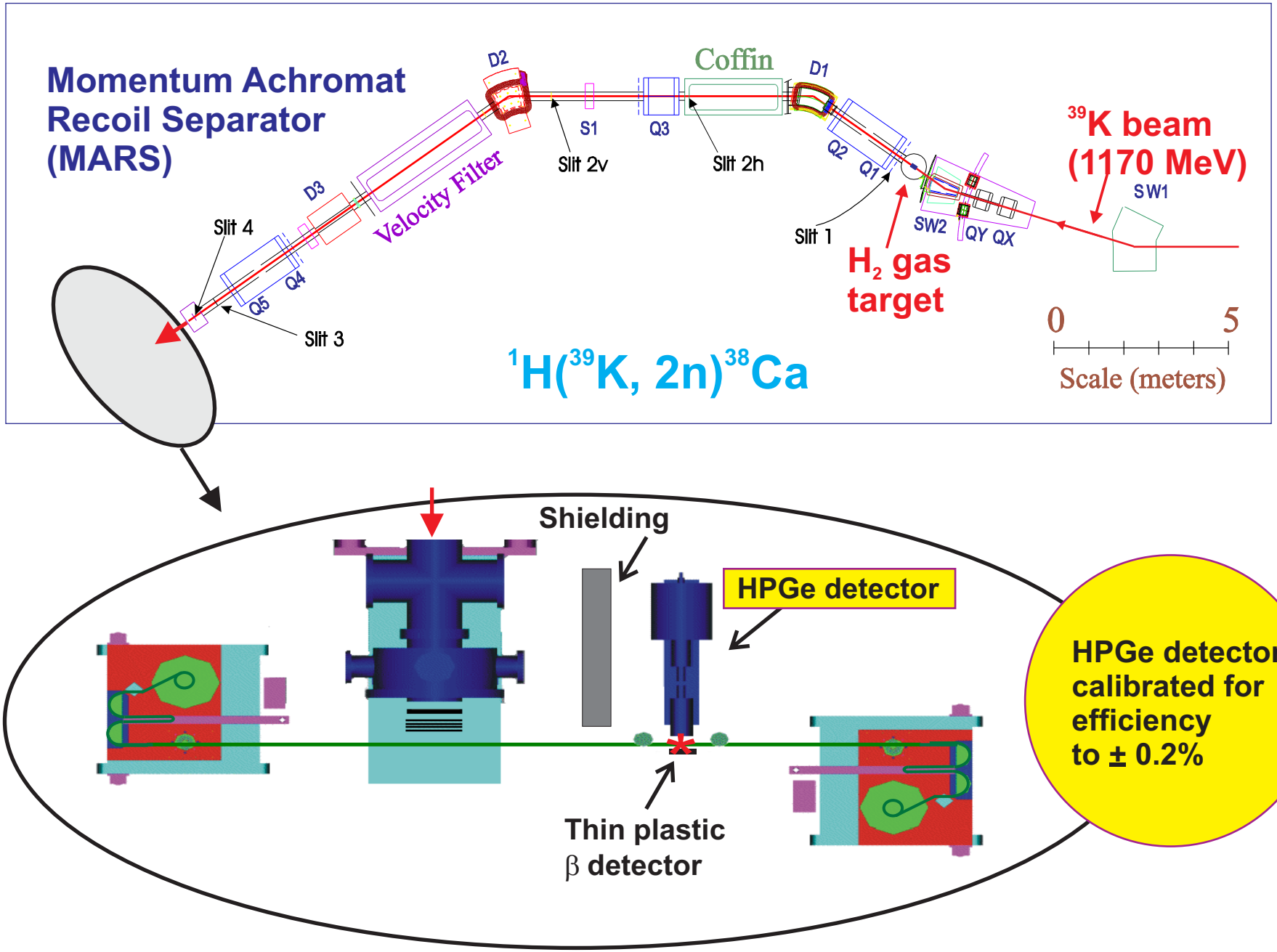
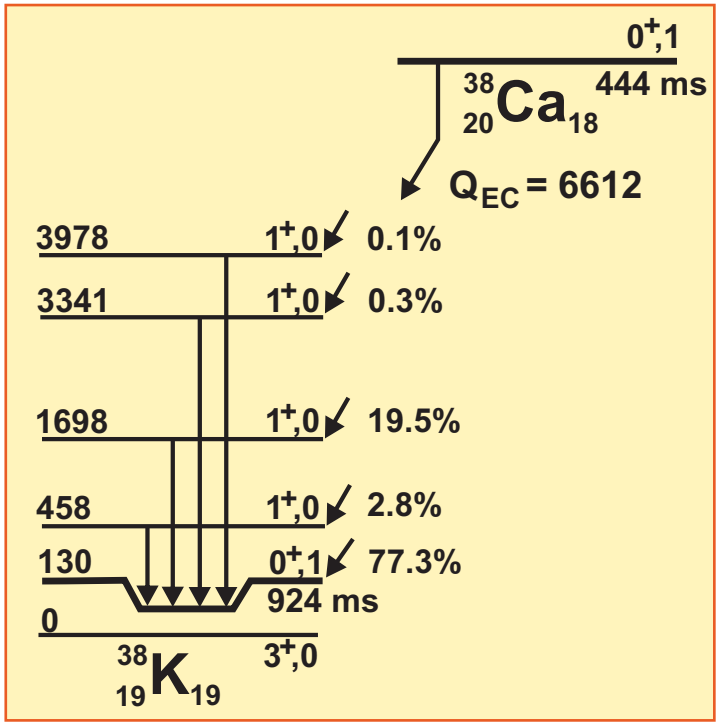
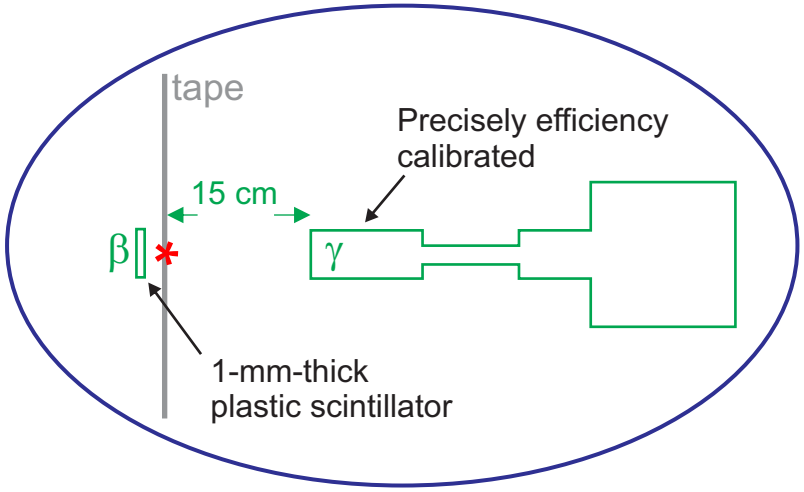
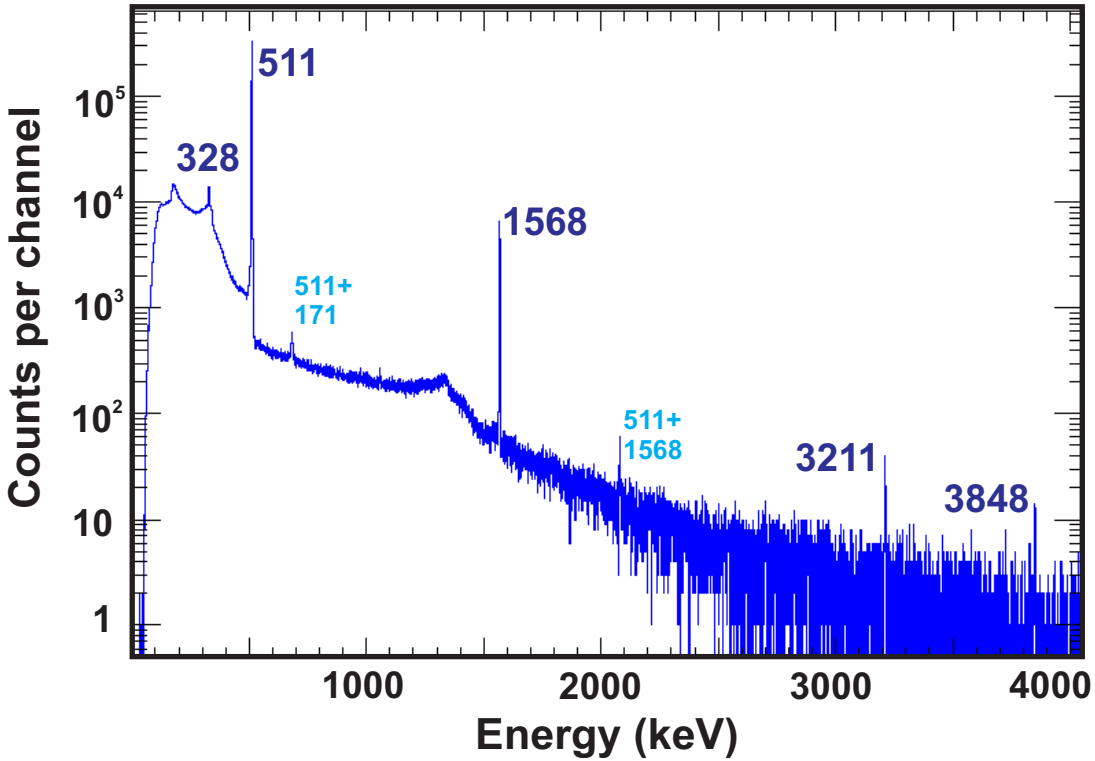


BETA-DECAY BRANCHING OF ^{38}Ca



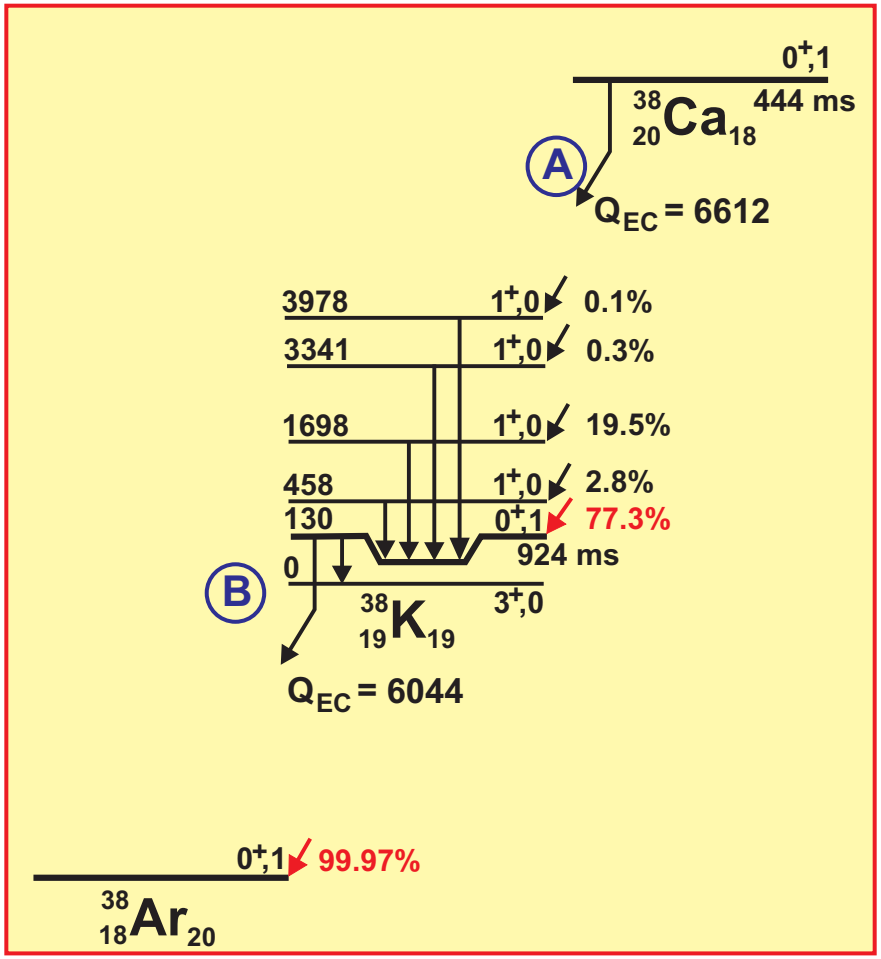




TESTS OF δ_c CALCULATIONS

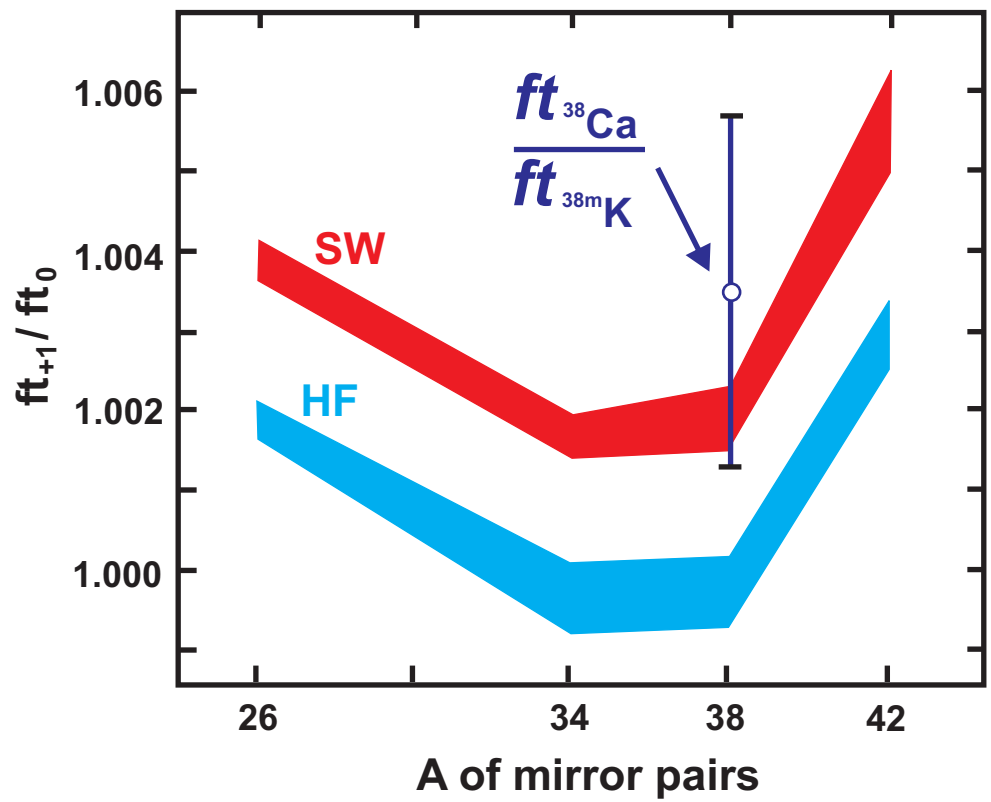
B. Measurements of mirror superallowed transitions:

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



$$\frac{ft_A}{ft_B} = \frac{(1 + \delta'^{B}_R)[1 - (\delta^{B}_C - \delta^{B}_{NS})]}{(1 + \delta'^{A}_R)[1 - (\delta^{A}_C - \delta^{A}_{NS})]}$$

$$= 1 + (\delta'^{B}_R - \delta'^{A}_R) + (\delta^{B}_{NS} - \delta^{A}_{NS}) - (\delta^{B}_C - \delta^{A}_C)$$



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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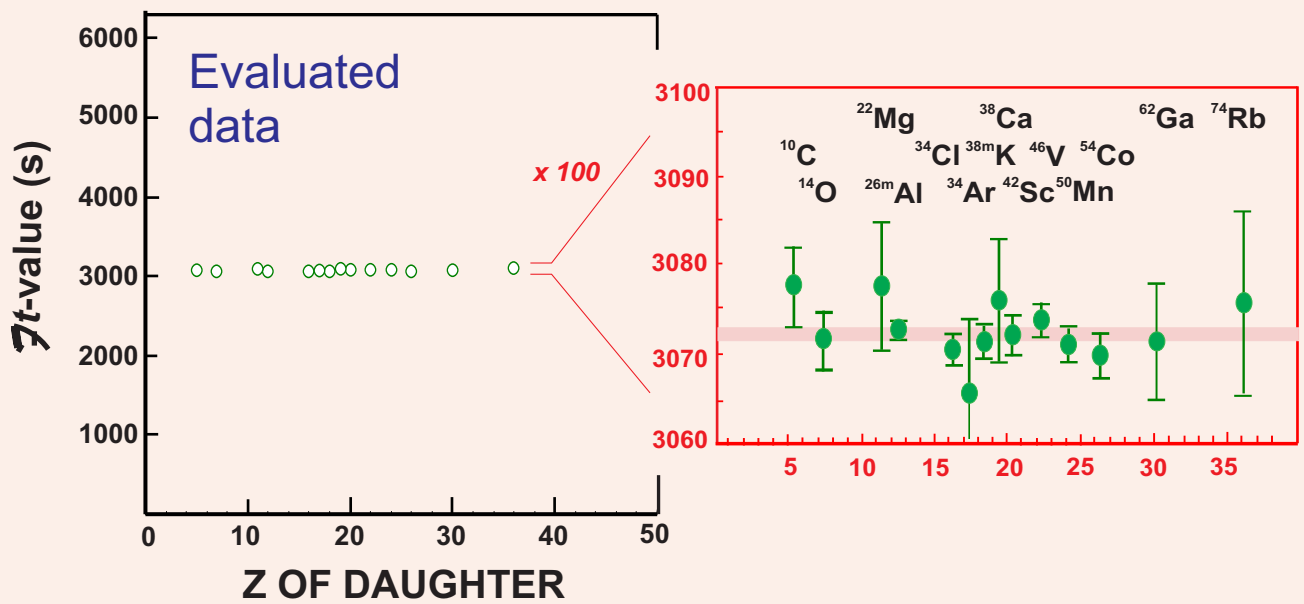
G_V constant to ± 0.013%



$\mathcal{F}t$ = 3072.3(7)

$G_V(1+\Delta_R)^{1/2}/(hc)^3$ = 1.14958(15) x10^{-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

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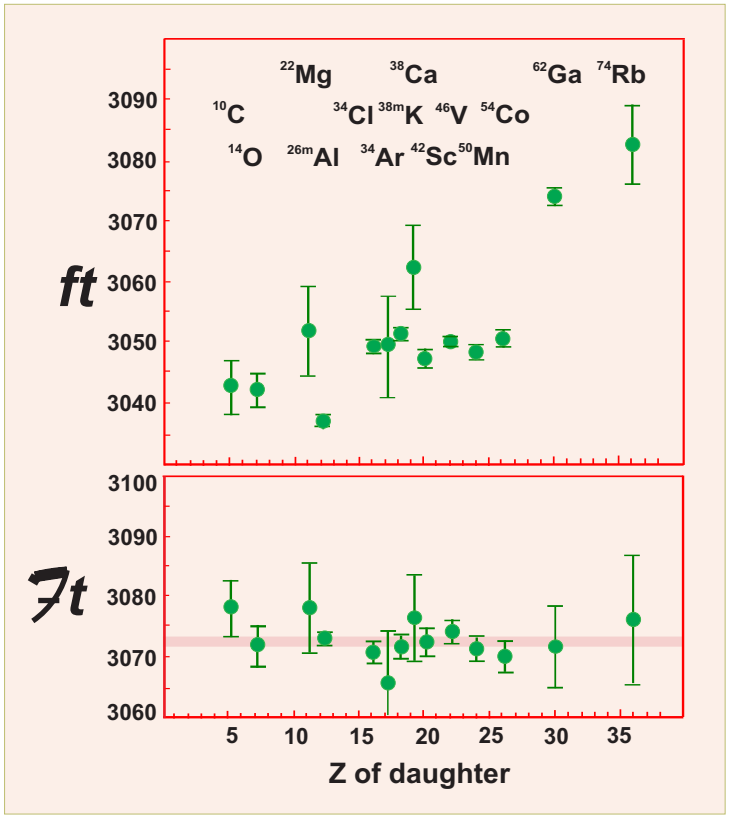

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Validate correction terms ✔

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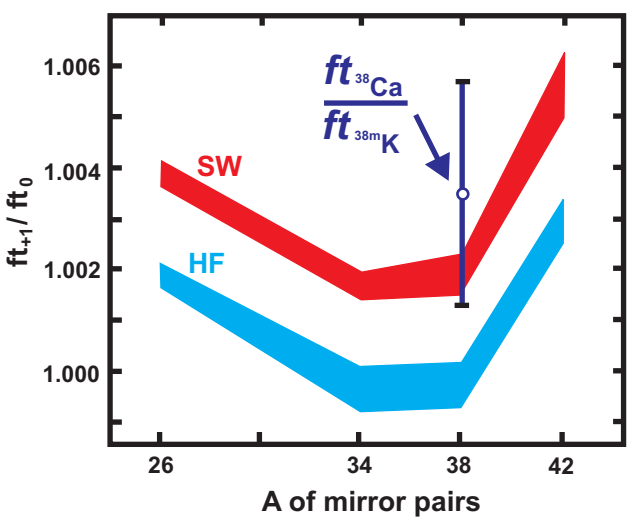
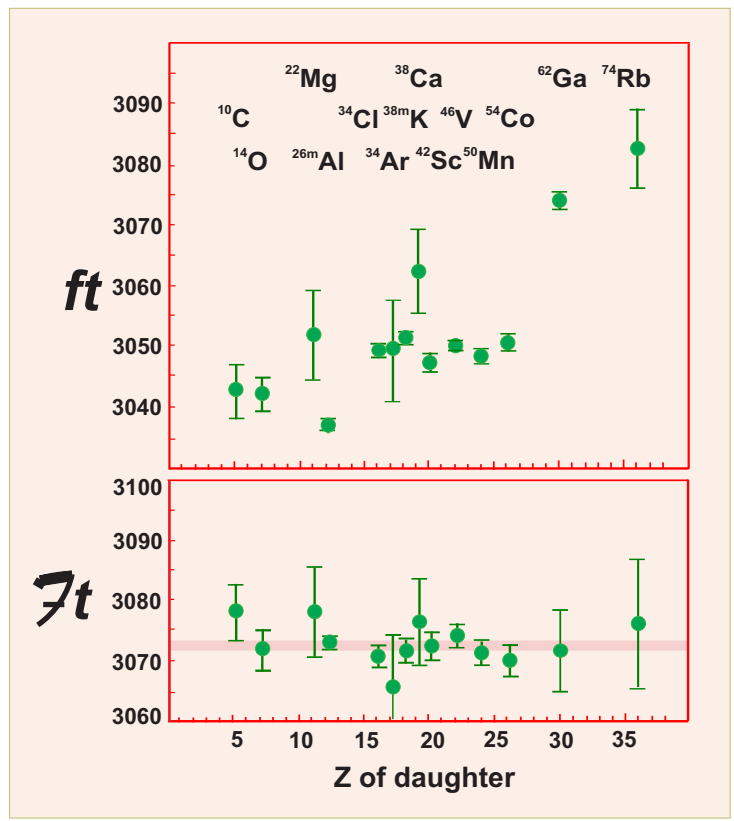
Model	χ^2/N	CL(%)
SM-SW	1.37	17
SM-HF	6.38	0
DFT	4.26	0
RHF-RPA	4.91	0
RH-RPA	3.68	0





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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 ± 0.013%

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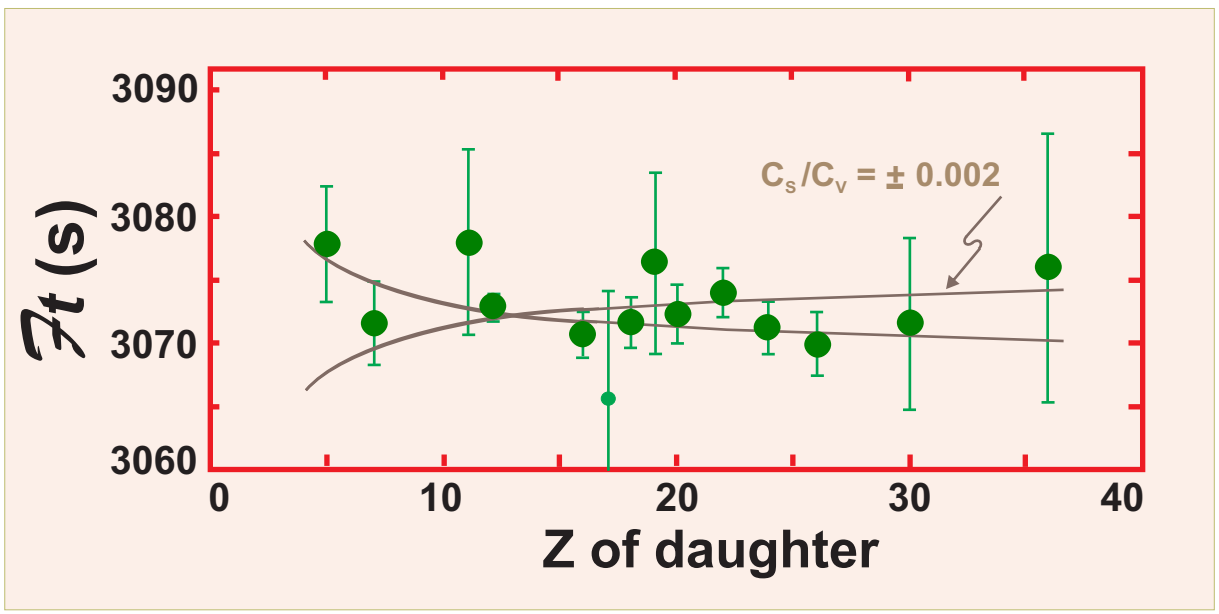

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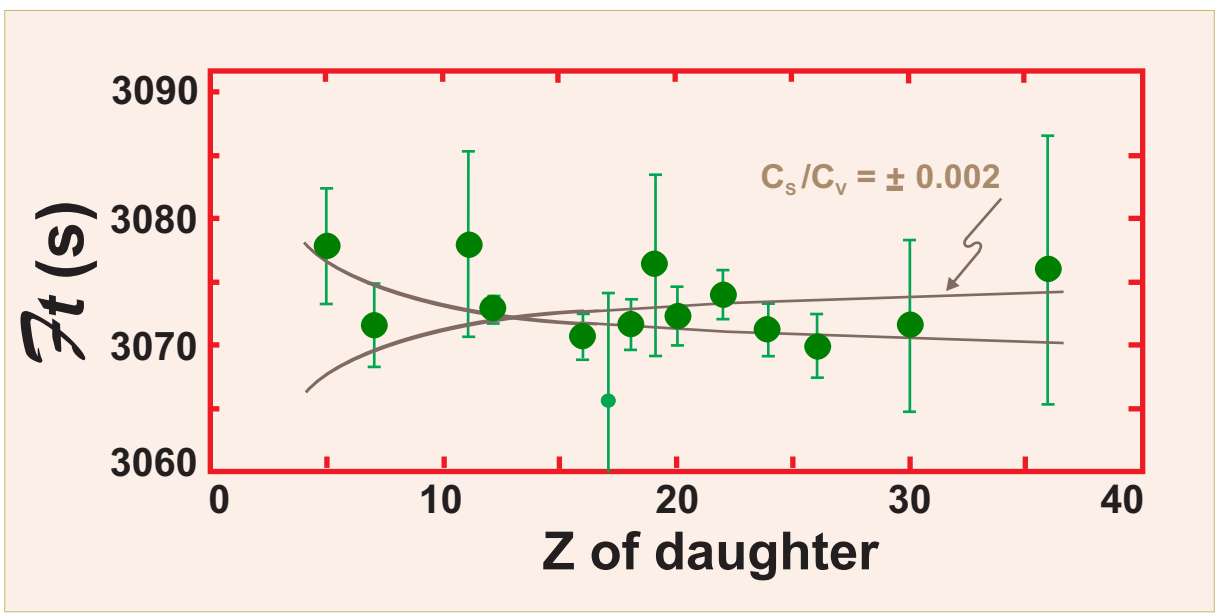

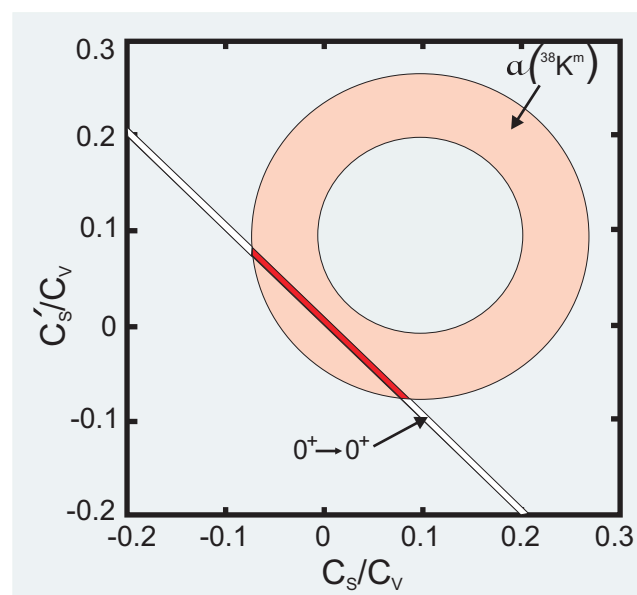

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WITH CVC VERIFIED

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

weak eigenstates

mass eigenstates

Cabibbo-Kobayashi-Maskawa matrix

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

Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G_\mu^2 = 0.94900 \pm 0.00042$$

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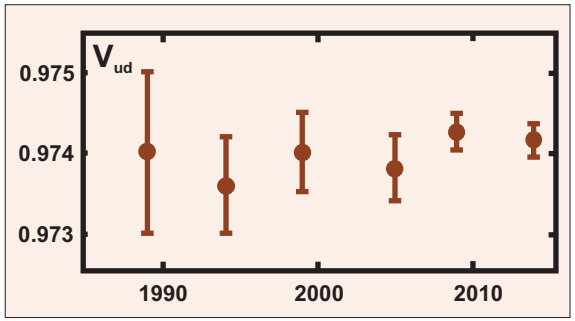

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Test CKM unitarity

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99992 \pm 0.00048$$

CURRENT STATUS OF CKM UNITARITY

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99992 \pm 0.00048$$

V_{ud}^2 nuclear decays
muon decay
0.94900 ± 0.00042

V_{us}^2 kaon decays
0.05090 ± 0.00022

V_{ub}^2 B decays
0.00002 ± 0.00001

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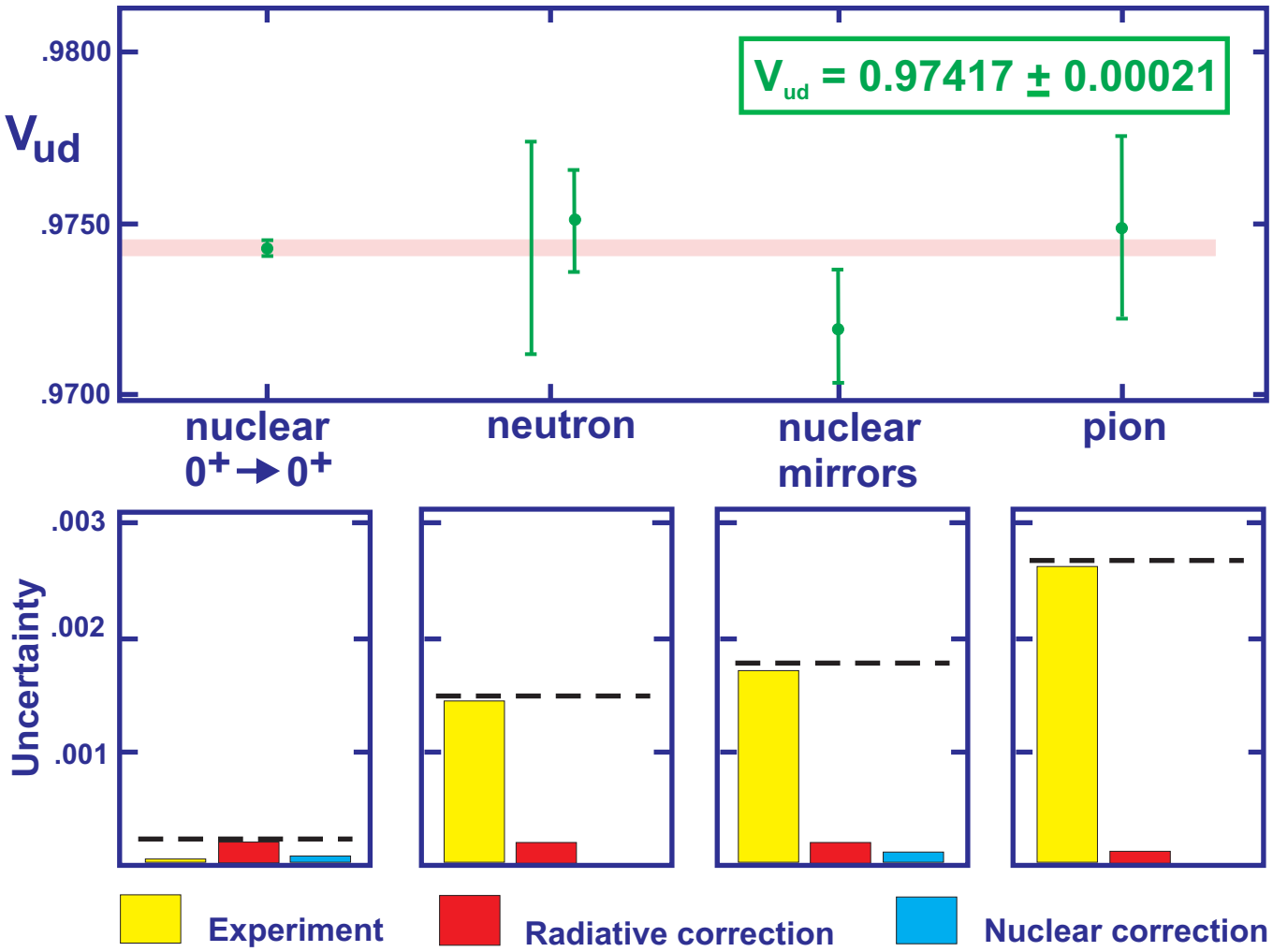

REMARK ON STATUS OF V_{us}

Kaon decay yields two independent determinations of V_{us}:

1) Semi-leptonic $K \rightarrow \pi \ell \nu_\ell$ decay ($K_{\ell 3}$) yields $|V_{us}|$.

2) Pure leptonic decays $K^+ \rightarrow \mu^+ \nu_\mu$ and $\pi^+ \rightarrow \mu^+ \nu_\mu$ together yield $|V_{us}| / |V_{ud}|$.

Both require lattice calculations of form factors to obtain their result.
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BUT, Bazavov et al. [PRL 112, 112001 (2014)] produced a new lattice calculation of the form factor used for $K_{\ell 3}$ decays.

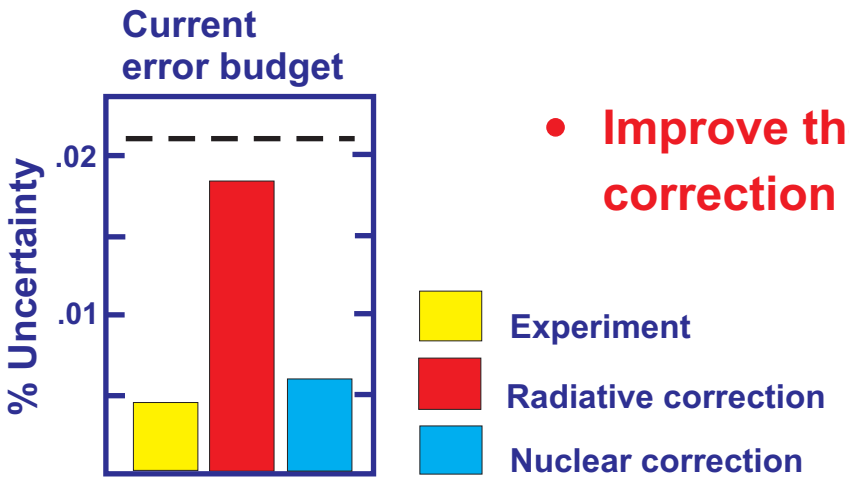
Their new result for $|V_{us}|$ is inconsistent with the $|V_{us}|/|V_{ud}|$ result and, when combined with the superallowed result for $|V_{ud}|$, leads to a unitarity sum over two standard deviations below 1.

Stay tuned ...

THE PATH FORWARD

THE PATH FORWARD

1. Improving V_{ud} and CKM Unitarity



- **Improve the calculation of the "inner" radiative correction Δ_R.**

Currently Δ_R = 2.361(38) %
Marciano & Sirlin, PRL **96,** 032002 (2006)

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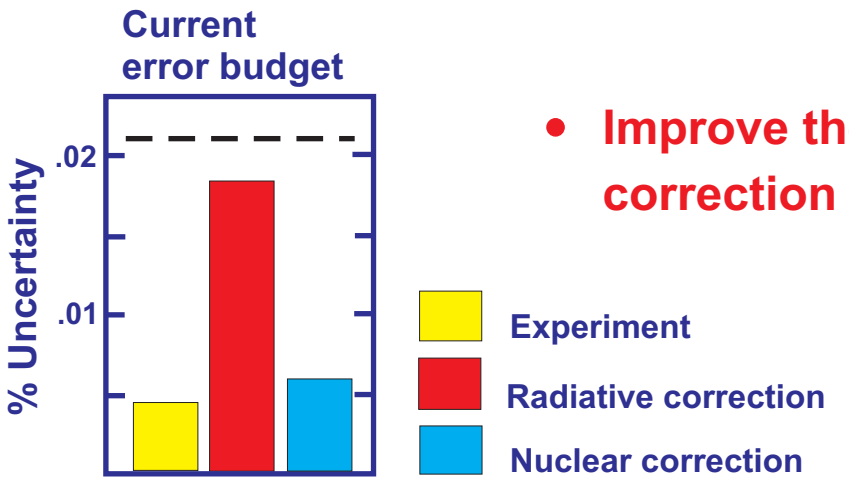

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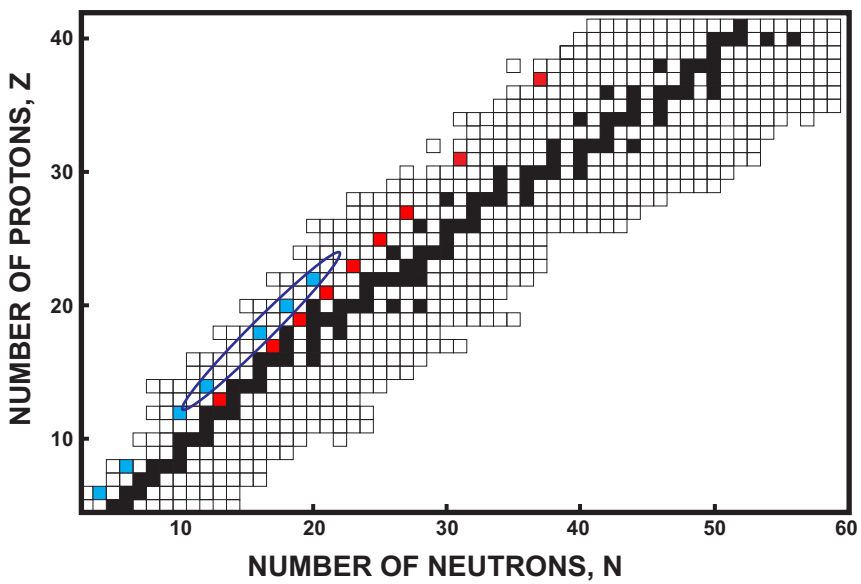

- **Potentially improve nuclear correction by completing the pairs of mirror superallowed decays with A ≤ 42.**

^{38}Ca done
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^{26}Si, ^{34}Ar and ^{42}Ti remain

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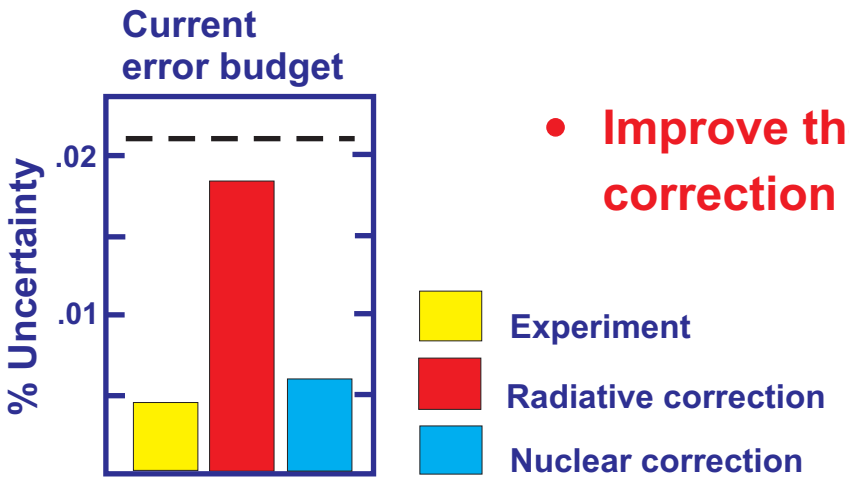

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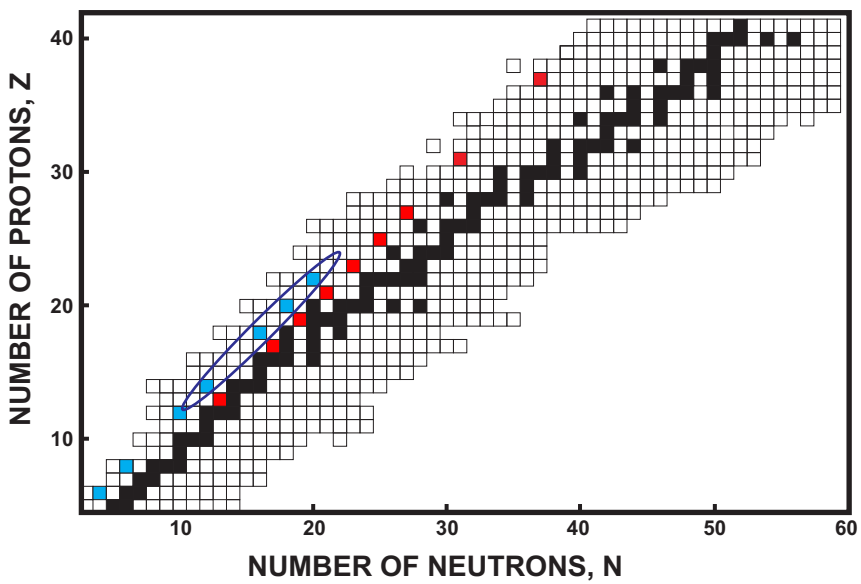

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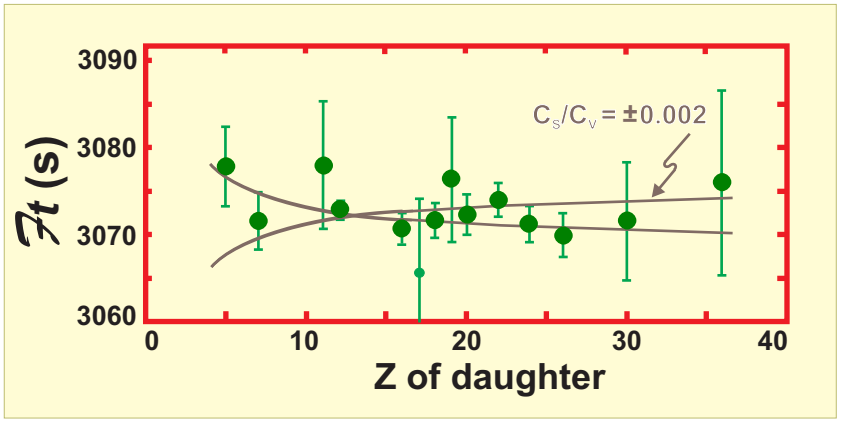
- **If theory improves, broadly improve all experimental *ft* values**

THE PATH FORWARD

2. Search for scalar current



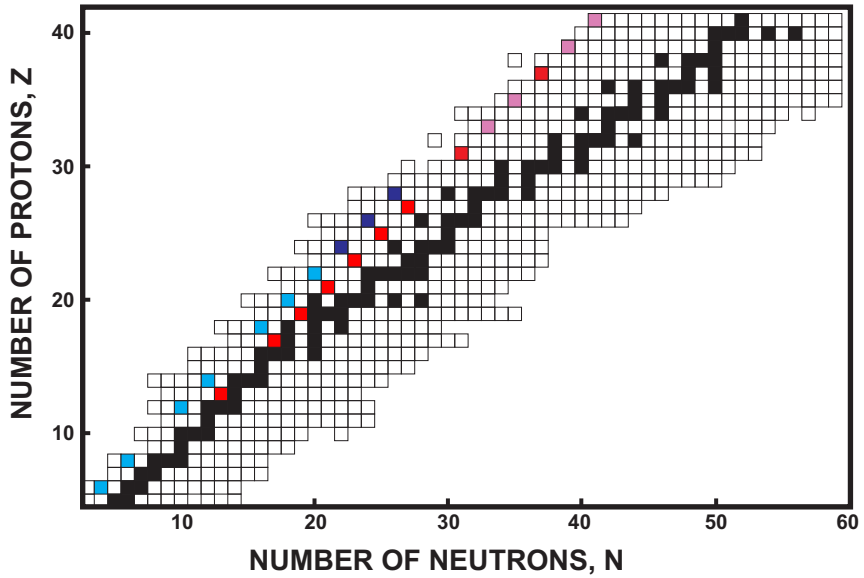
limit, $C_S/C_V = 0.0014\ (13)$

- Tighten uncertainties on the *ft* values for ^{10}C and ^{14}O

Require (order of priority):
- ^{10}C branching ratio
- ^{14}O branching ratio
- ^{14}O Q_{EC} value
- ^{10}C half-life

THE PATH FORWARD

3. Expand the number of transitions



- Potential FRIB measurements
- Complete more pairs of mirror superallowed transitions: ^{46}Cr, ^{50}Fe, ^{54}Ni ...

Tests δ_C, δ_{NS} calculations in $f_{7/2}$ shell nuclei

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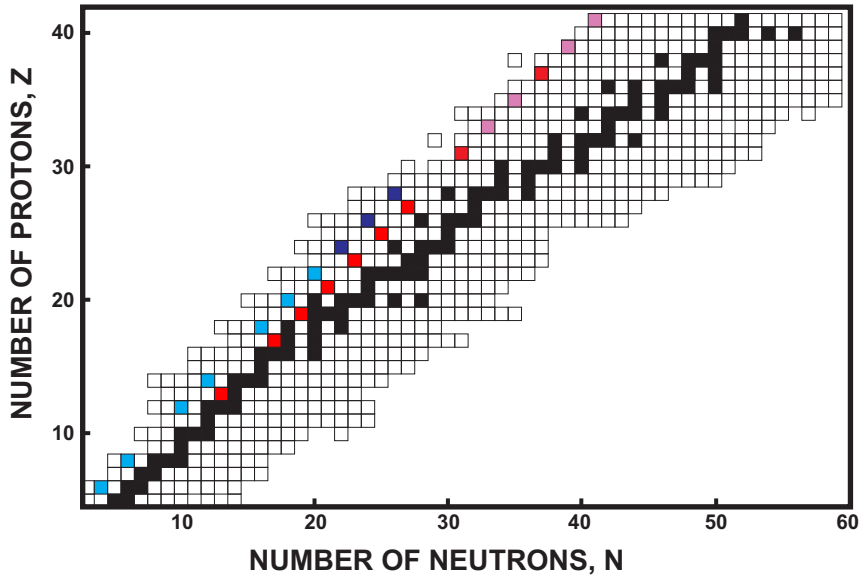

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Tests δ_C, δ_{NS} calculations in $f_{7/2}$ shell nuclei

- Add new heavy $T_z = 0$ superallowed emitters: ^{66}As, ^{70}Br, ^{78}Y ...

Probably most useful for studying isospin mixing

Challenges:

Complex decays (Pandemonium effect)
Need spectroscopic data to constrain structure model
Need $T_z = -1$ masses to determine IMME coefficients

SUMMARY AND OUTLOOK

1. Analysis of superallowed $0^+ \rightarrow 0^+$ nuclear β decay is shown to confirm CVC and thus yield V_{ud} = 0.97417(21).
2. The three other experimental methods for determining V_{ud} yield consistent results, but are less precise by a factor of 8 or more.
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3. The current value for V_{ud}, when combined with V_{us} and V_{ub}, satisfies CKM unitarity to 0.05%.

4. The largest contribution to the V_{ud} uncertainty is from the inner radiative correction. Improving it is the highest priority requirement if uncertainty is to be reduced.
5. Isospin symmetry-breaking corrections in nuclei are the second largest contributor to V_{ud} uncertainty. These may be improved by studying mirror superallowed transitions and by improving all experimental *ft* values.
6. Potential FRIB experiments can expand the number of superallowed transitions and be useful for studying isospin mixing.