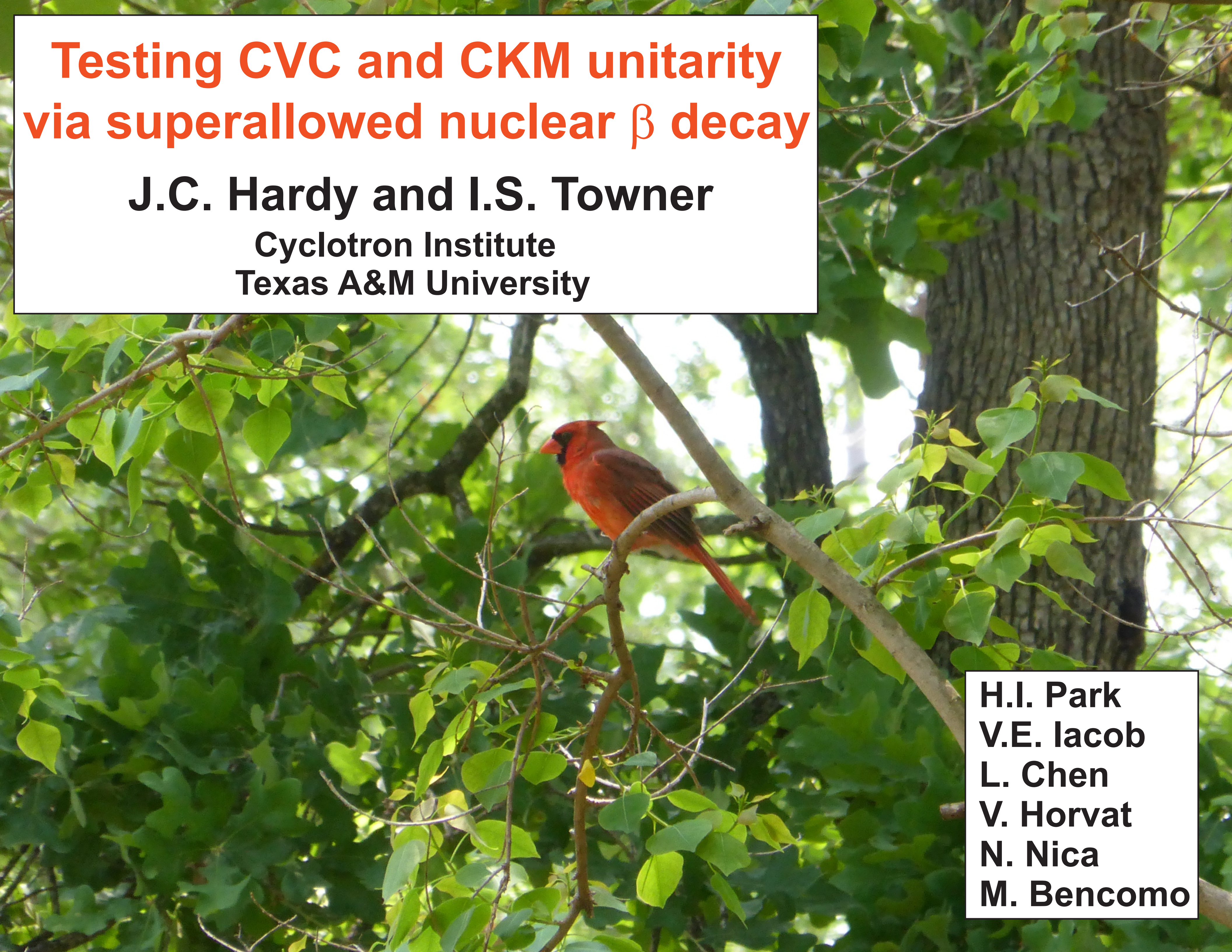
Testing CVC and CKM unitarity via superallowed nuclear β decay

J.C. Hardy and I.S. Towner

Cyclotron Institute
Texas A&M University



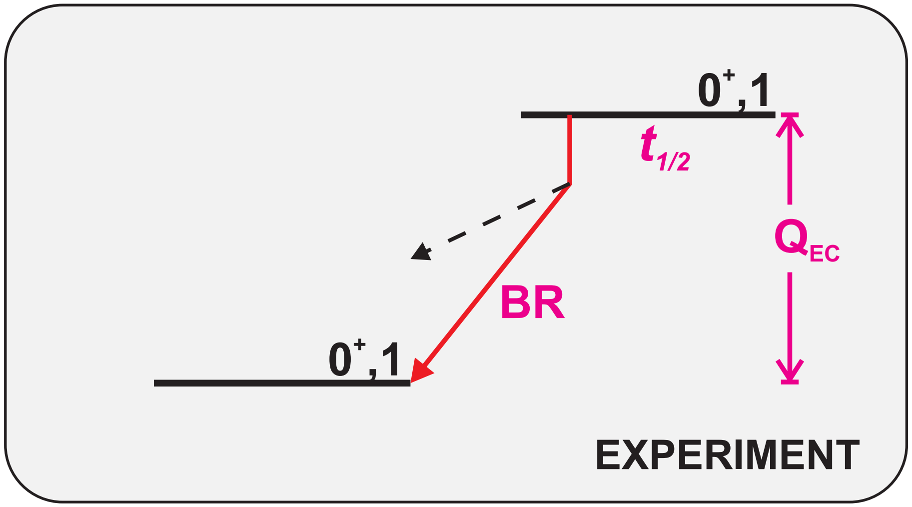
H.I. Park
V.E. Iacob
L. Chen
V. Horvat
N. Nica
M. Bencomo

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

BASIC WEAK-DECAY EQUATION

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

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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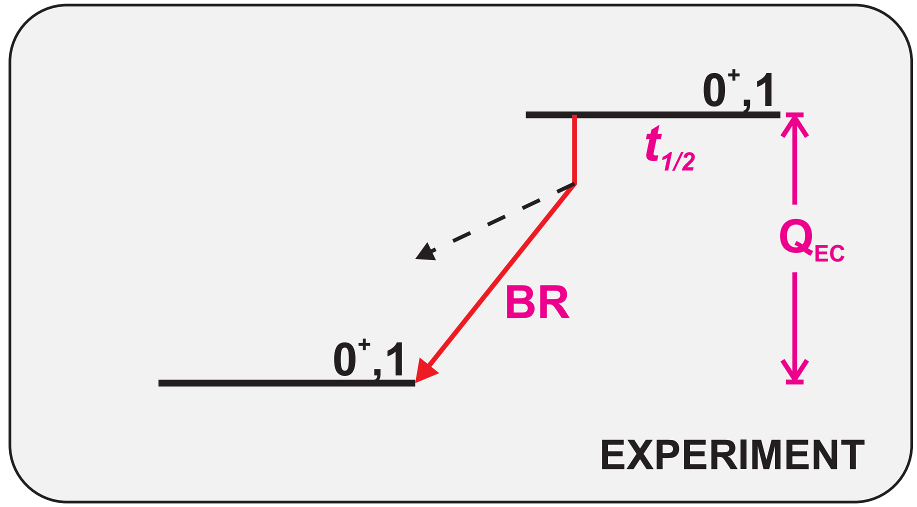

INCLUDING RADIATIVE AND ISOSPIN-SYMMETRY-BREAKING CORRECTIONS

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

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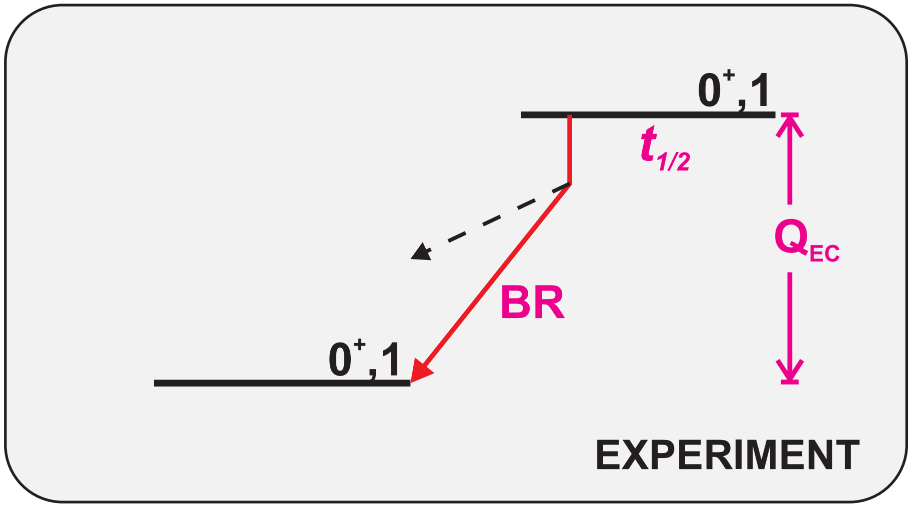

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$f(Z, Q_{EC})$
~1.5%

f(nuclear structure)
0.3-1.5%

f(interaction)
~2.4%

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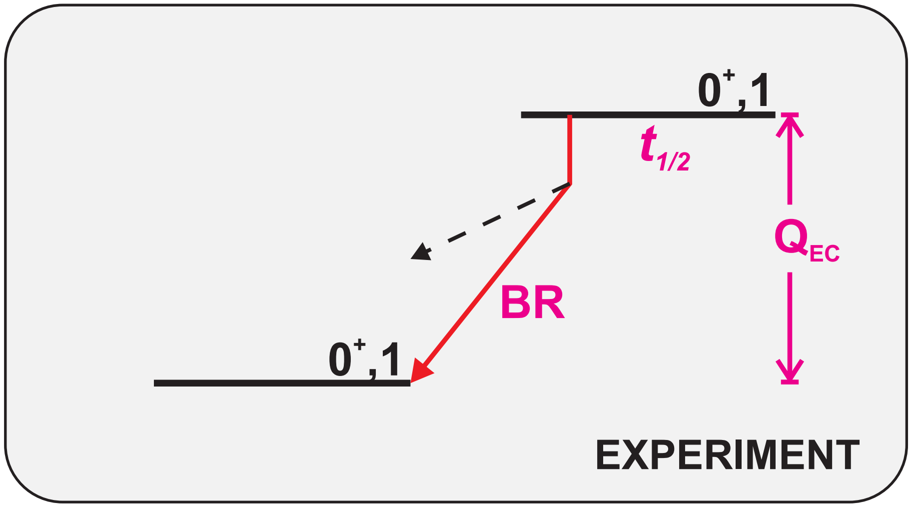

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THEORETICAL UNCERTAINTIES
0.05 – 0.10%

WHAT CAN WE LEARN?

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FROM A SINGLE TRANSITION

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

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

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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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Test CKM unitarity

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

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Obtain precis… (1 + ${}_R$)

Determin…

…unitarity

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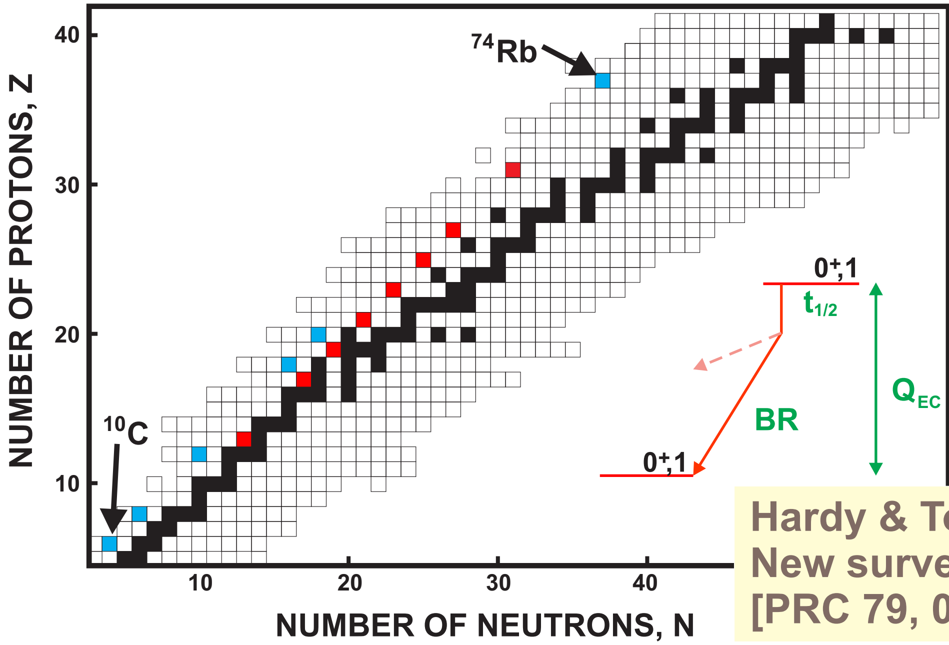
$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

ONLY POSSIBLE IF PRIOR CONDITIONS SATISFIED

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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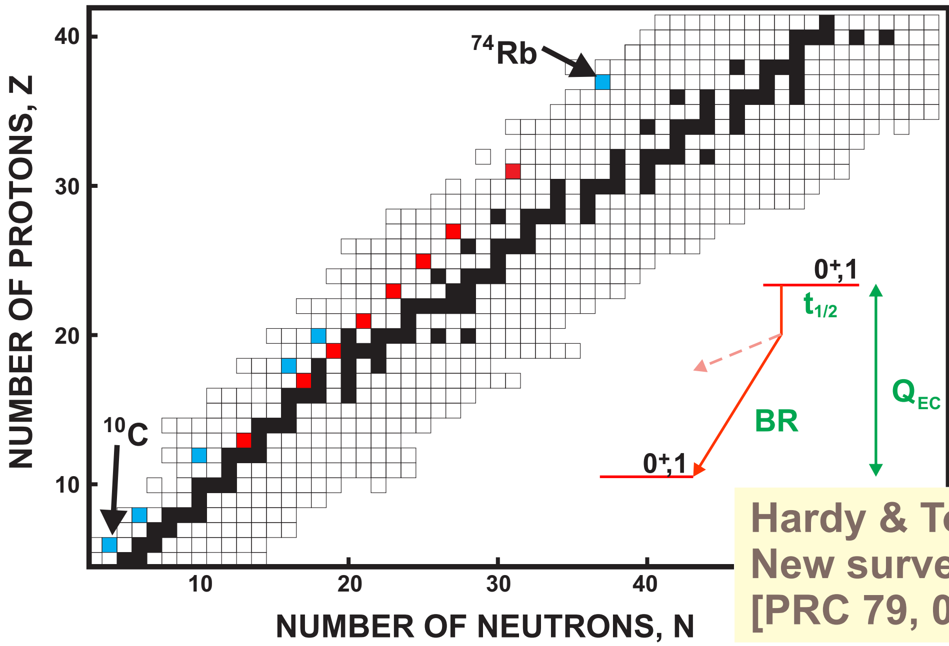

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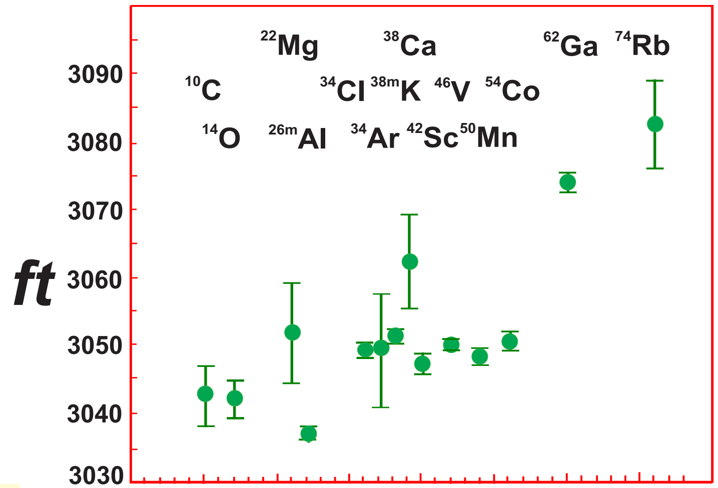

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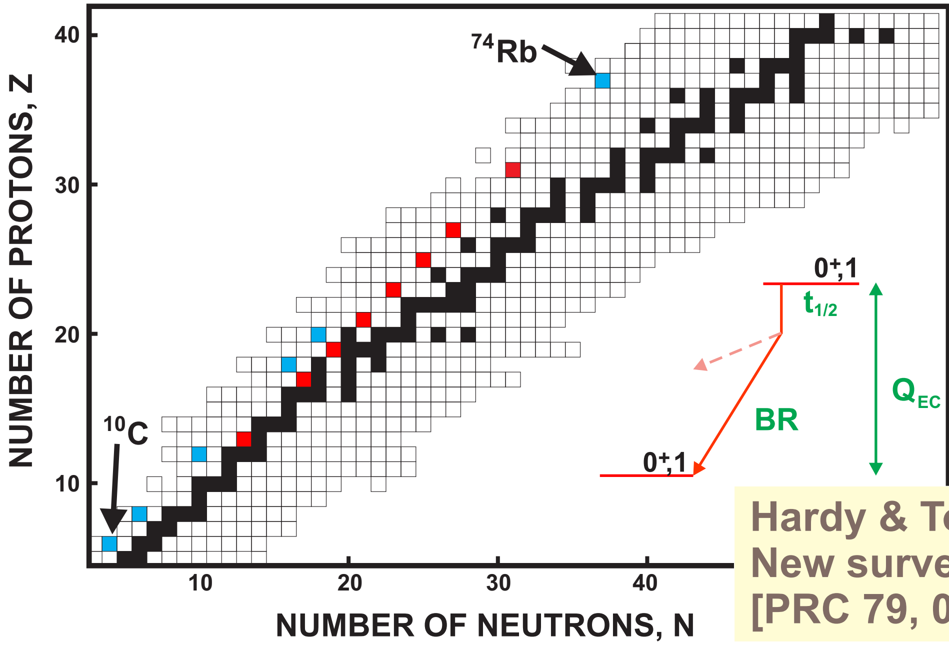

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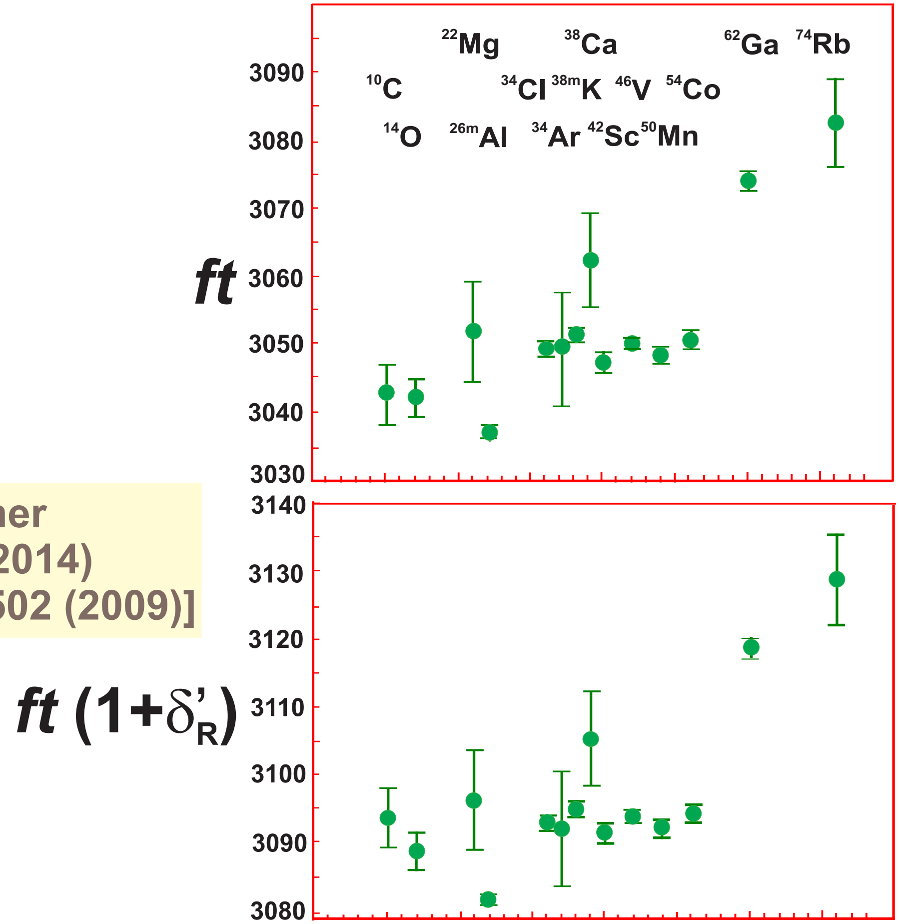

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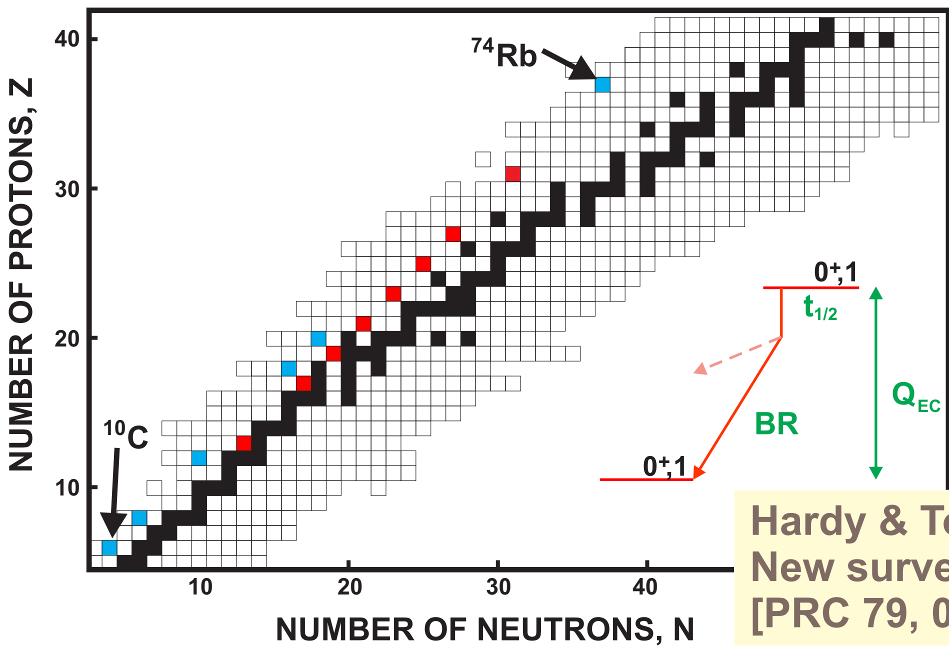

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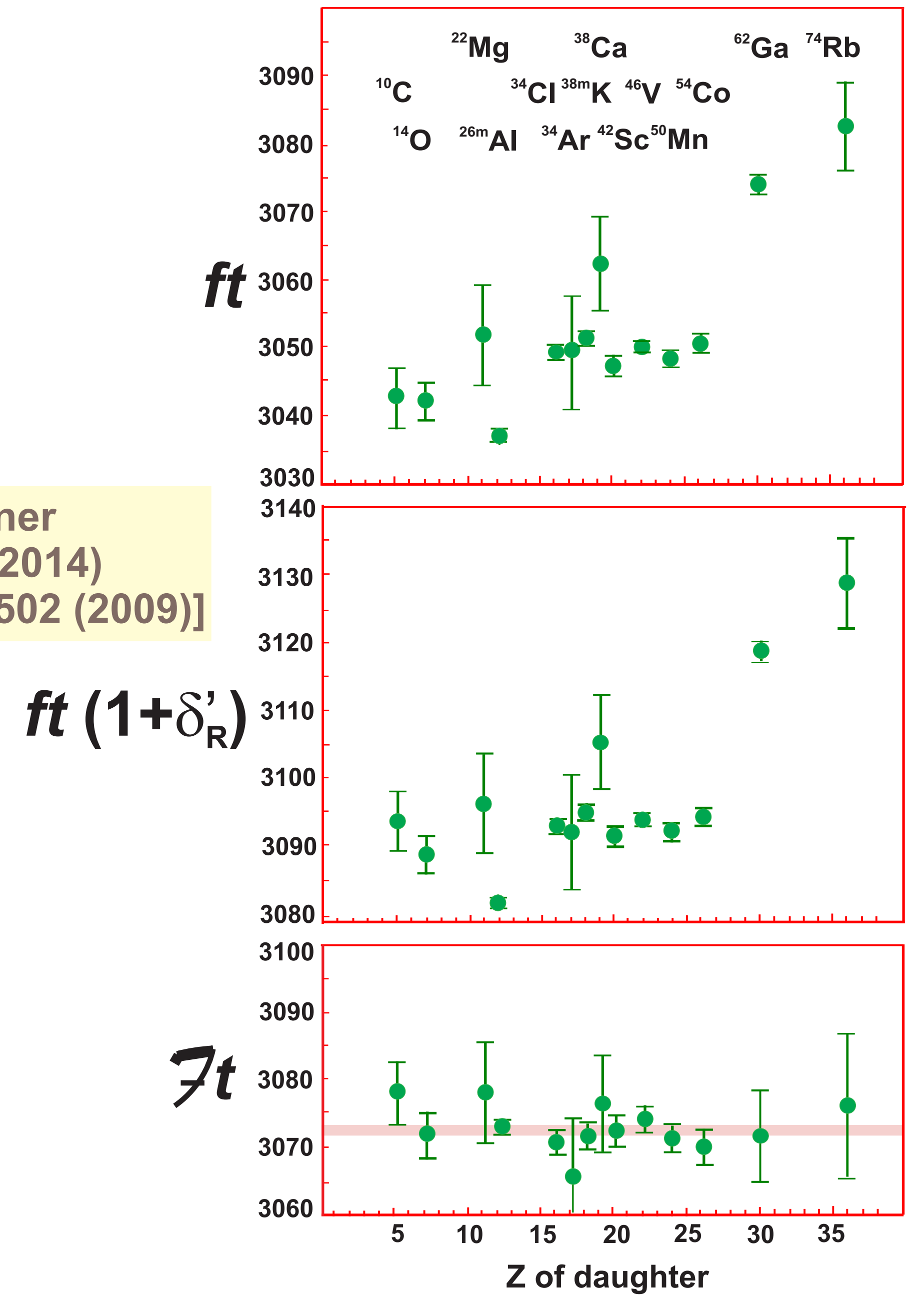

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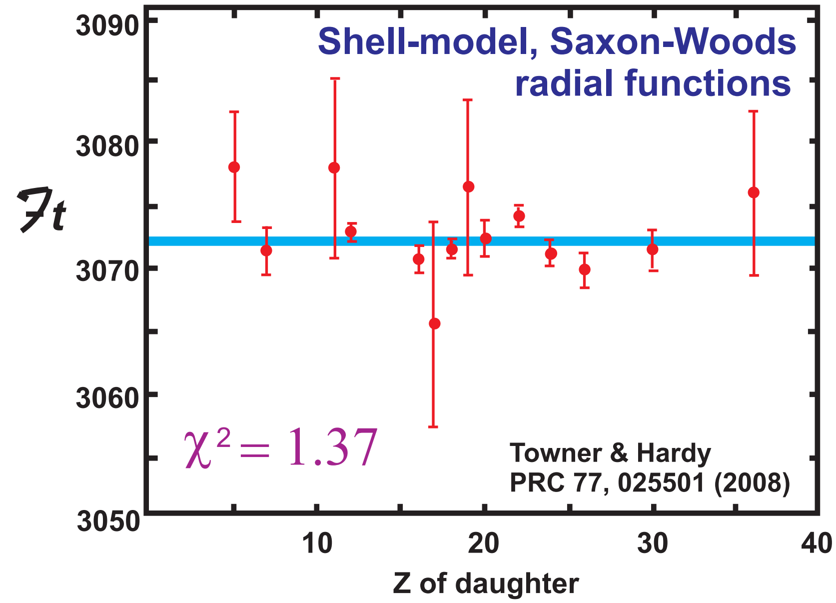
TESTS OF δ_c CALCULATIONS

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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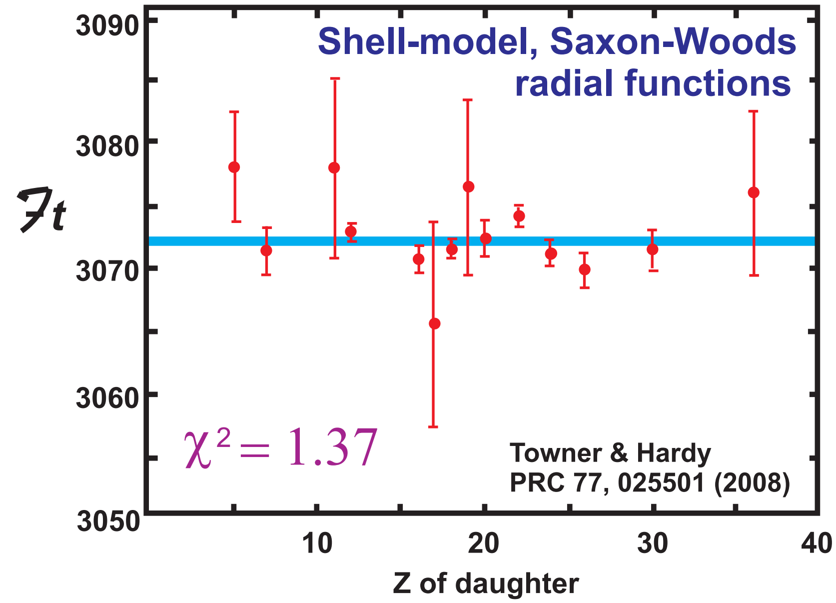

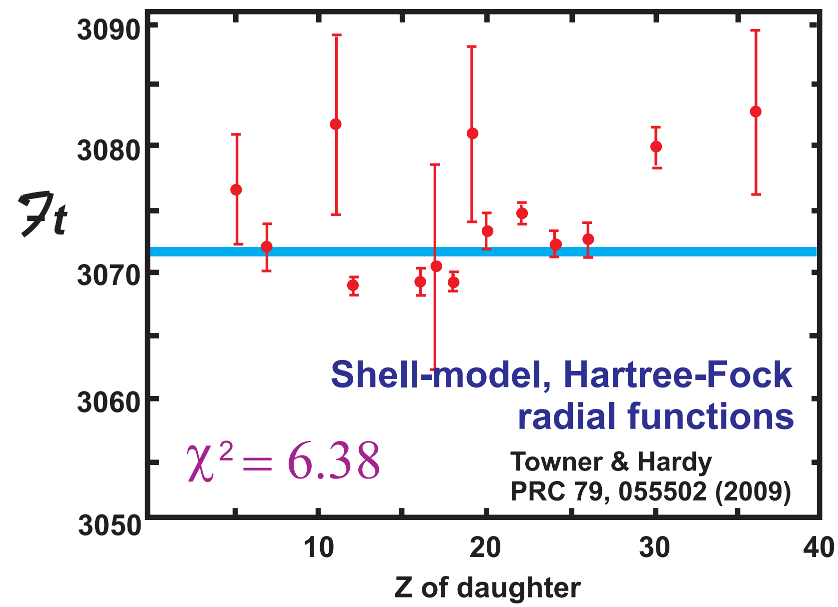

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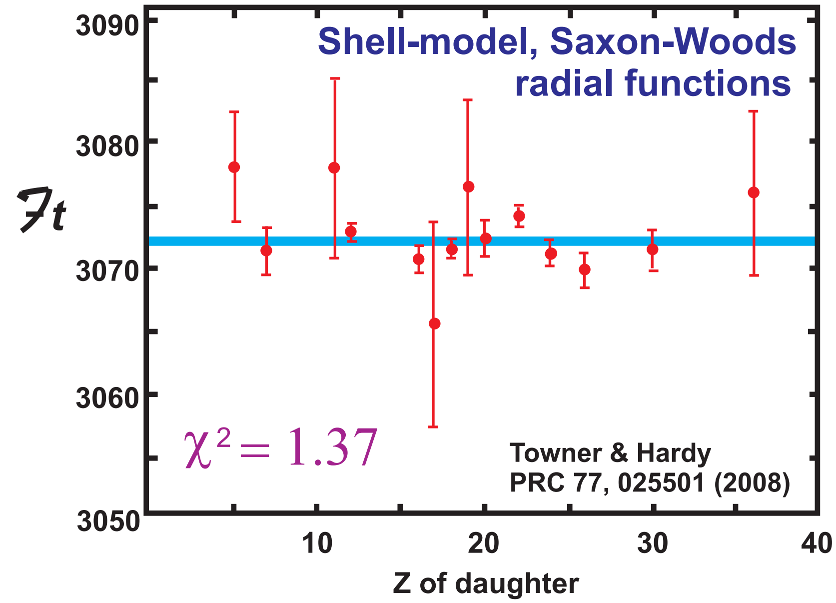

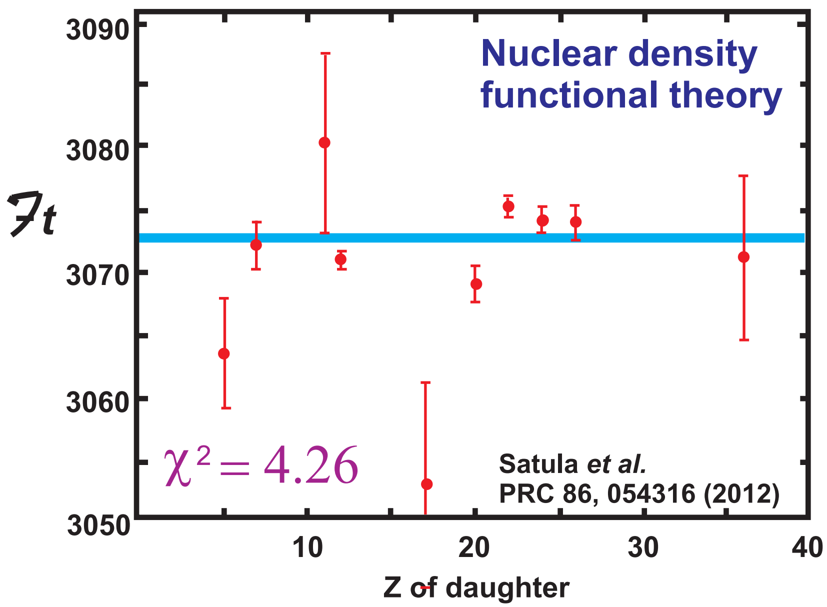

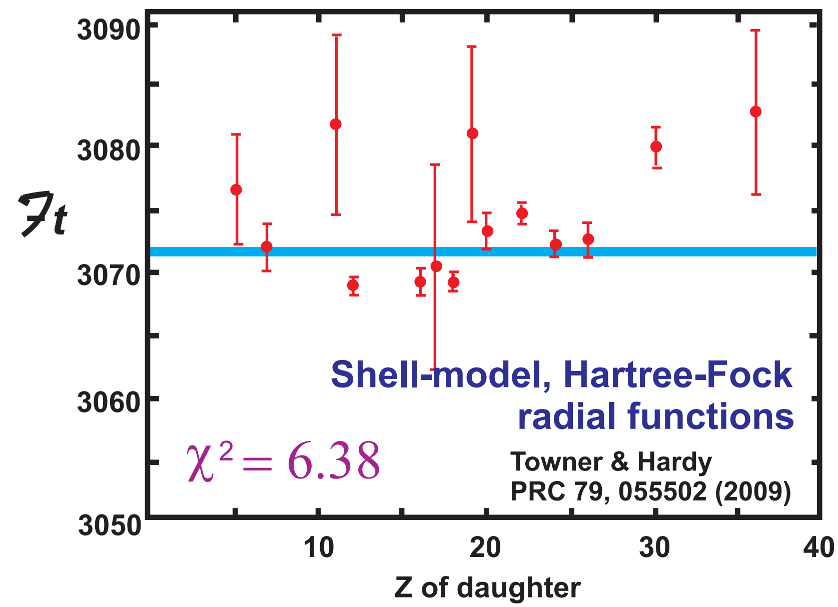

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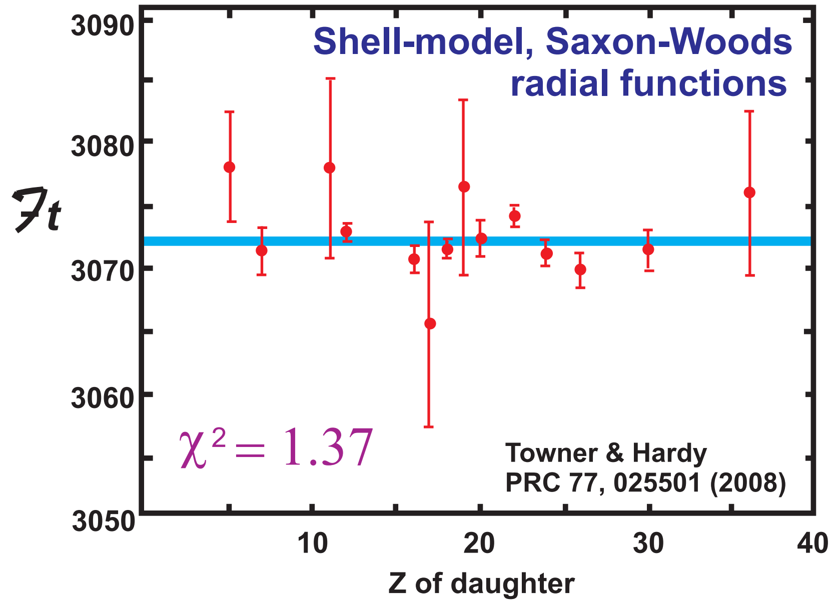
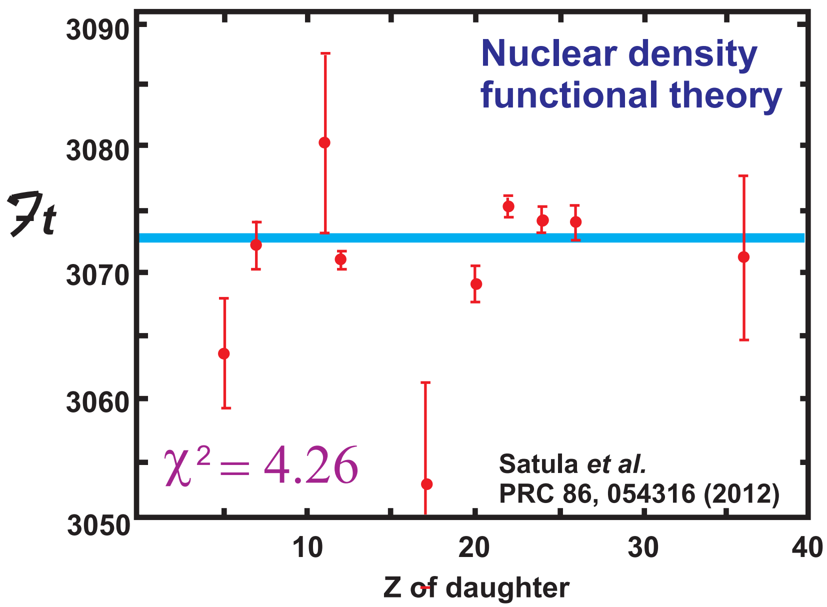
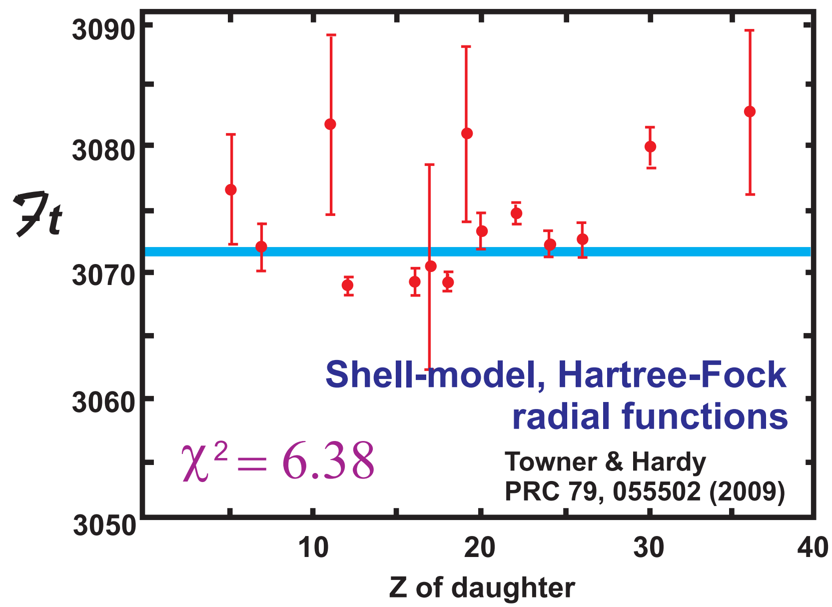
RHF-RPA	4.91	0
RH-RPA	3.68	0

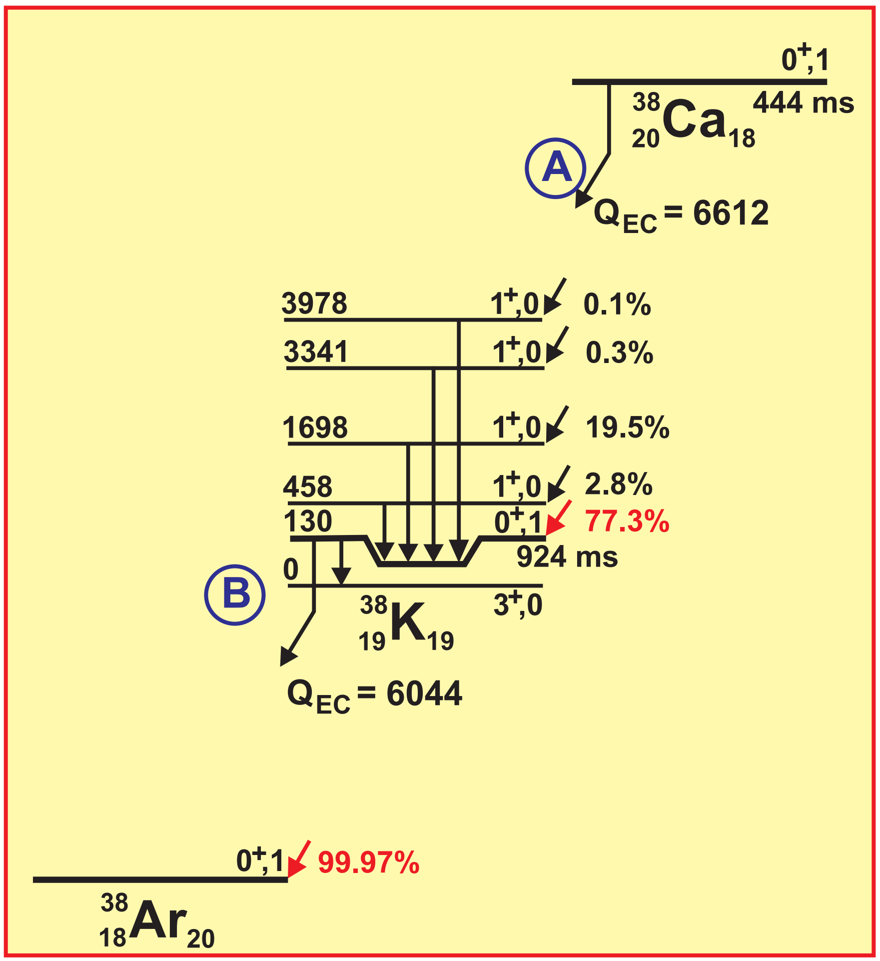






TESTS OF δ_c CALCULATIONS

B. Measurements of mirror superallowed transitions:



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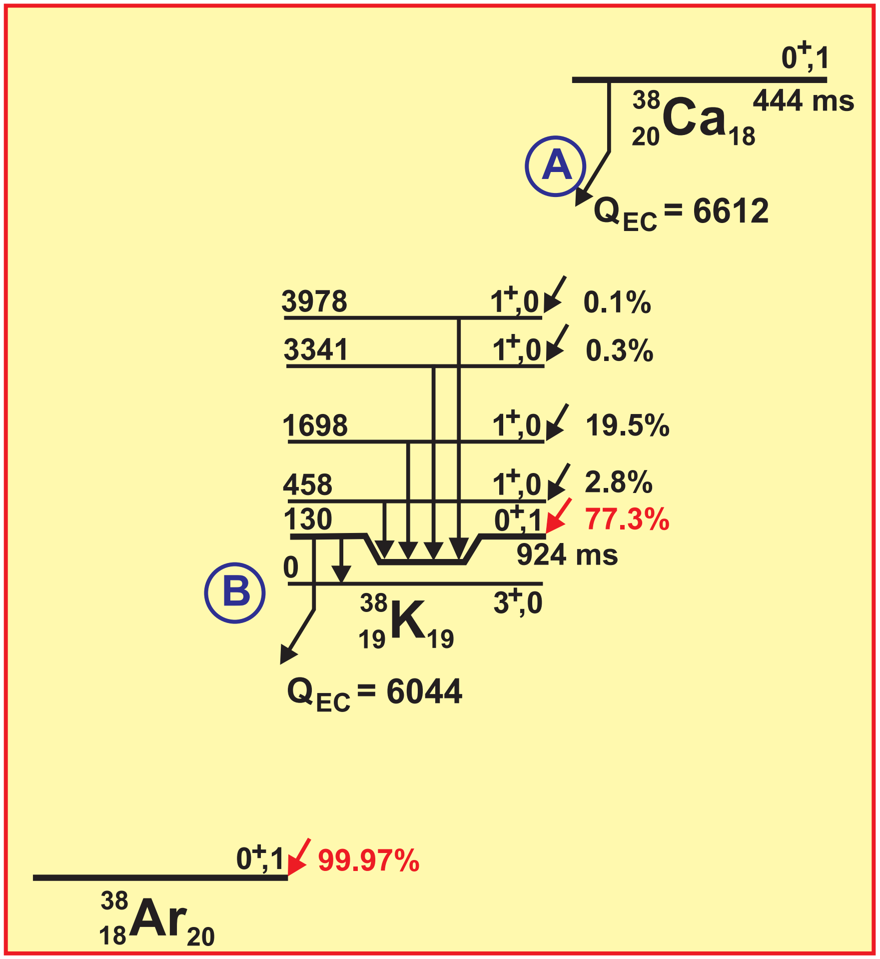

$$\frac{ft_A}{ft_B} = \frac{(1 + \delta_R'^B)[1 - (\delta_C^B - \delta_{NS}^B)]}{(1 + \delta_R'^A)[1 - (\delta_C^A - \delta_{NS}^A)]}$$

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

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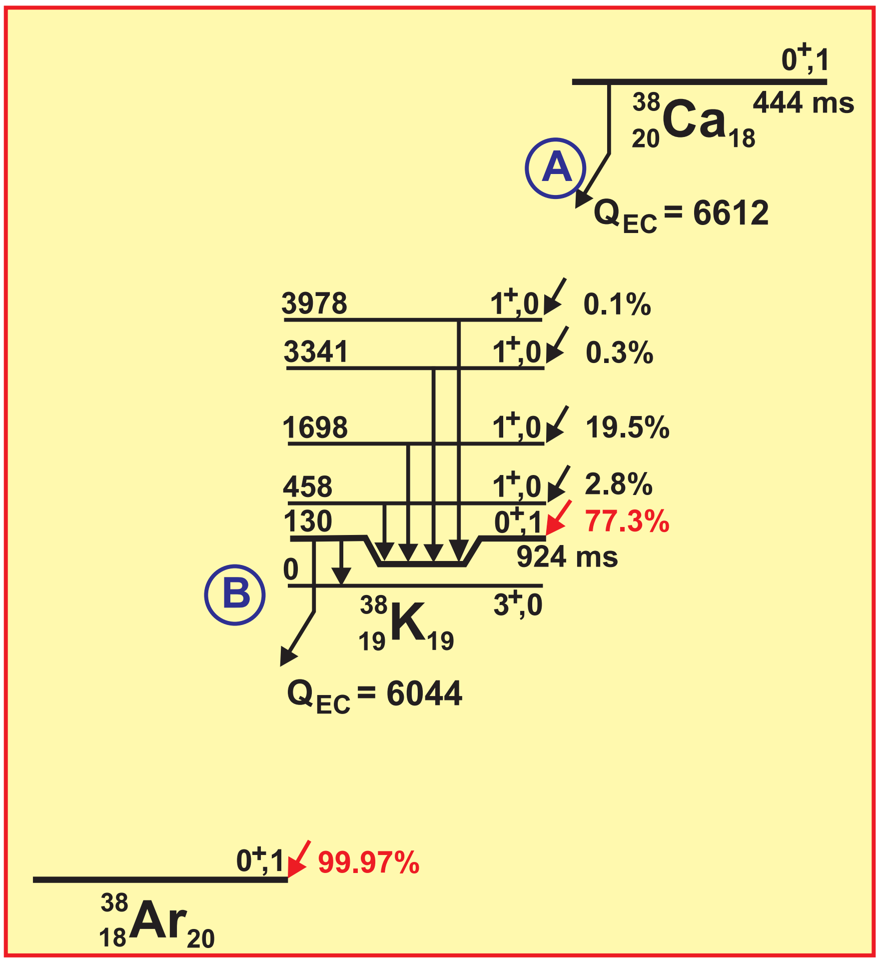

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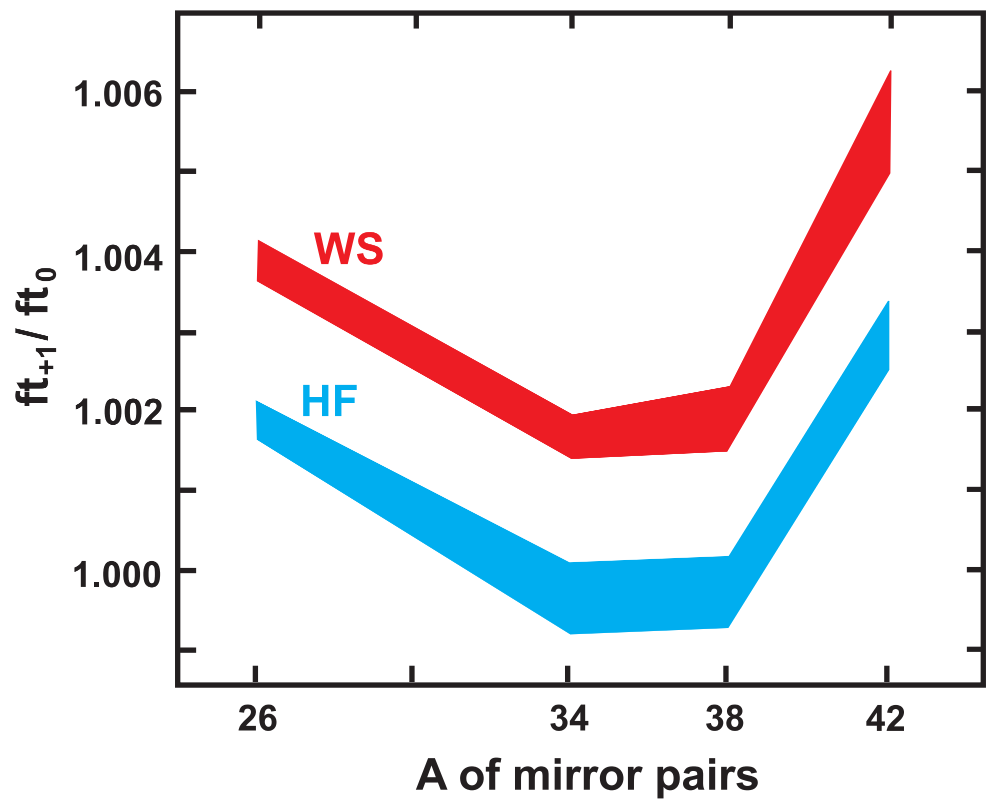
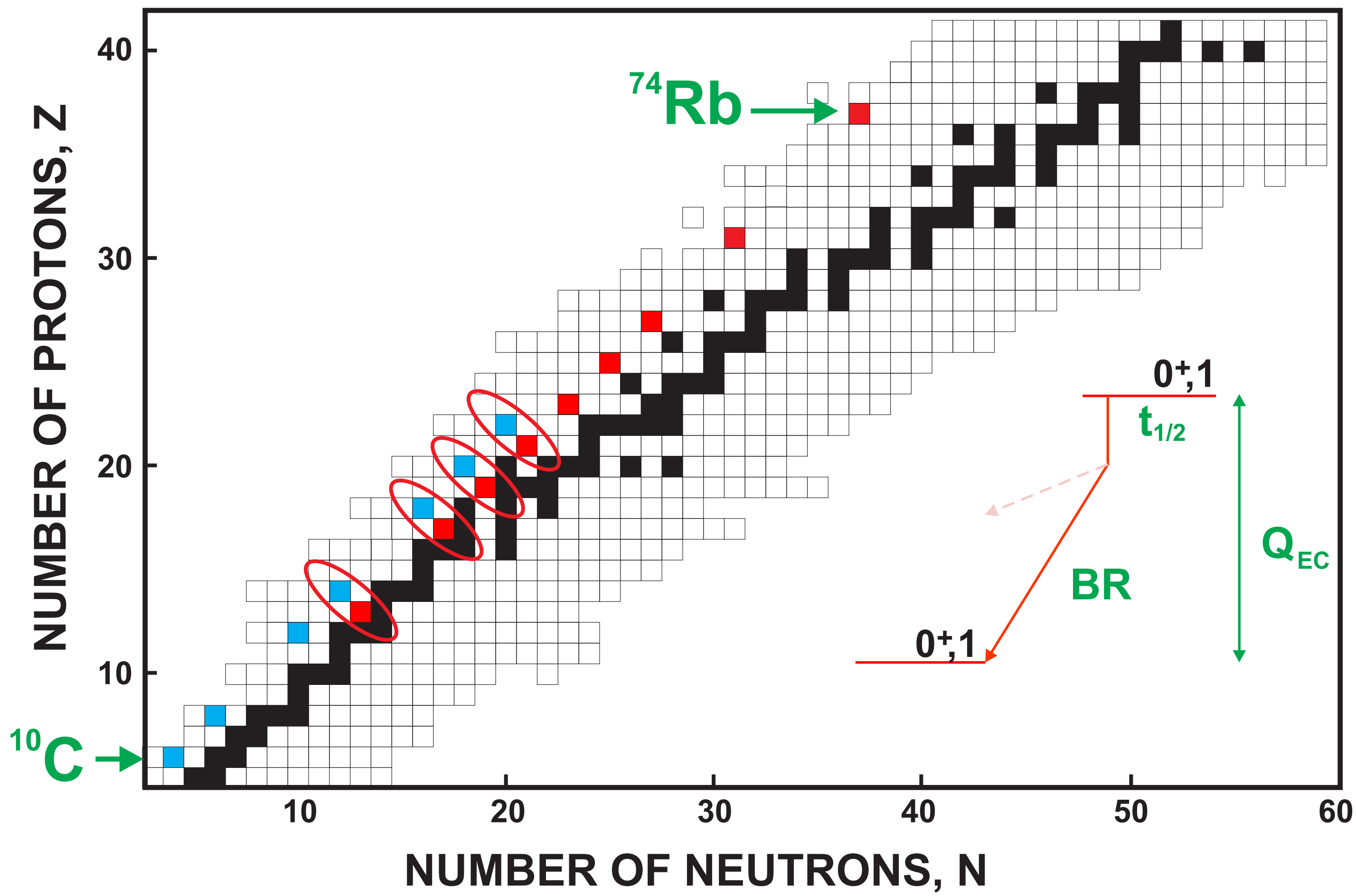


ACCESSIBLE MIRROR PAIRS OF SUPERALLOWED DECAYS



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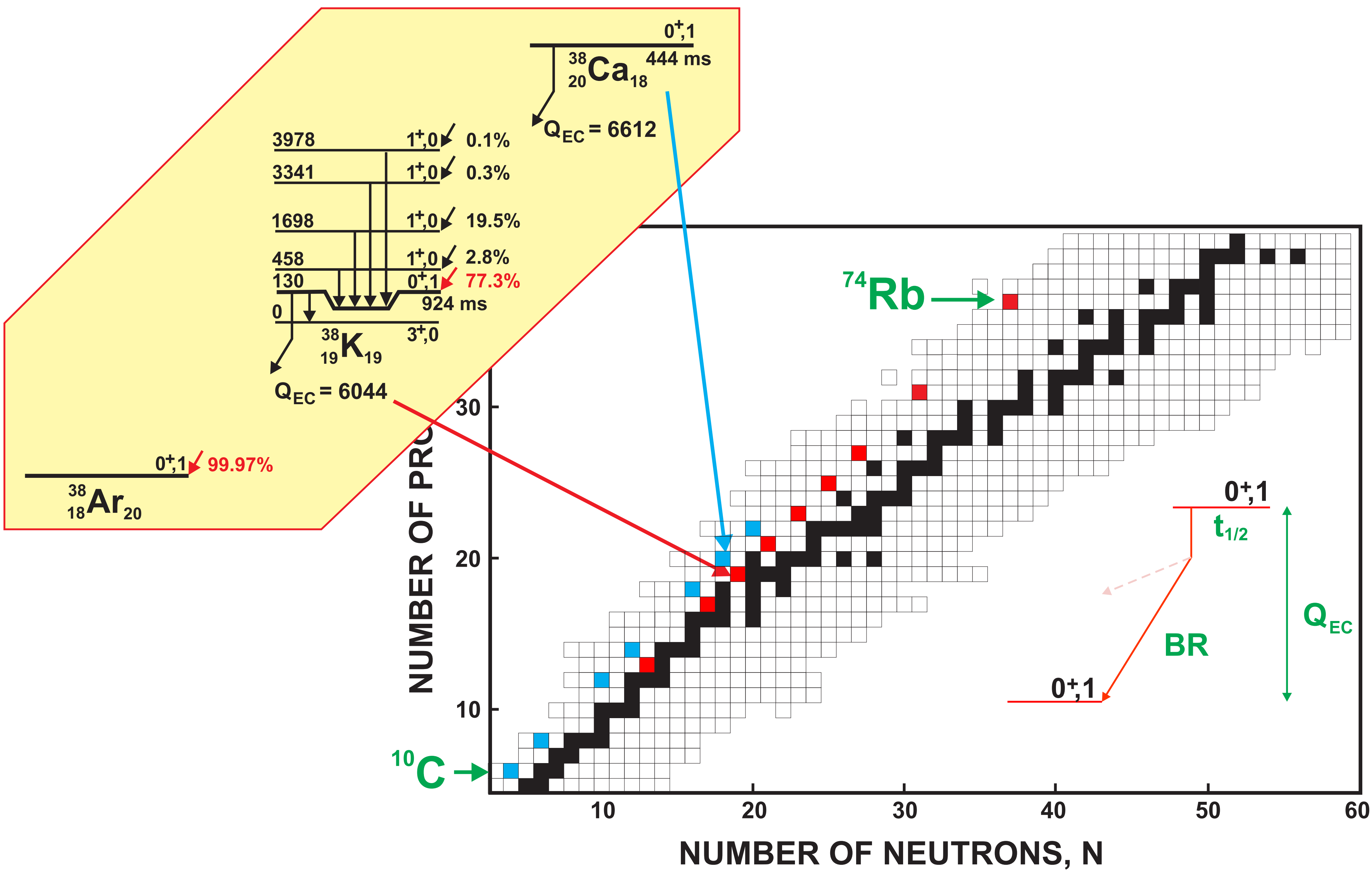
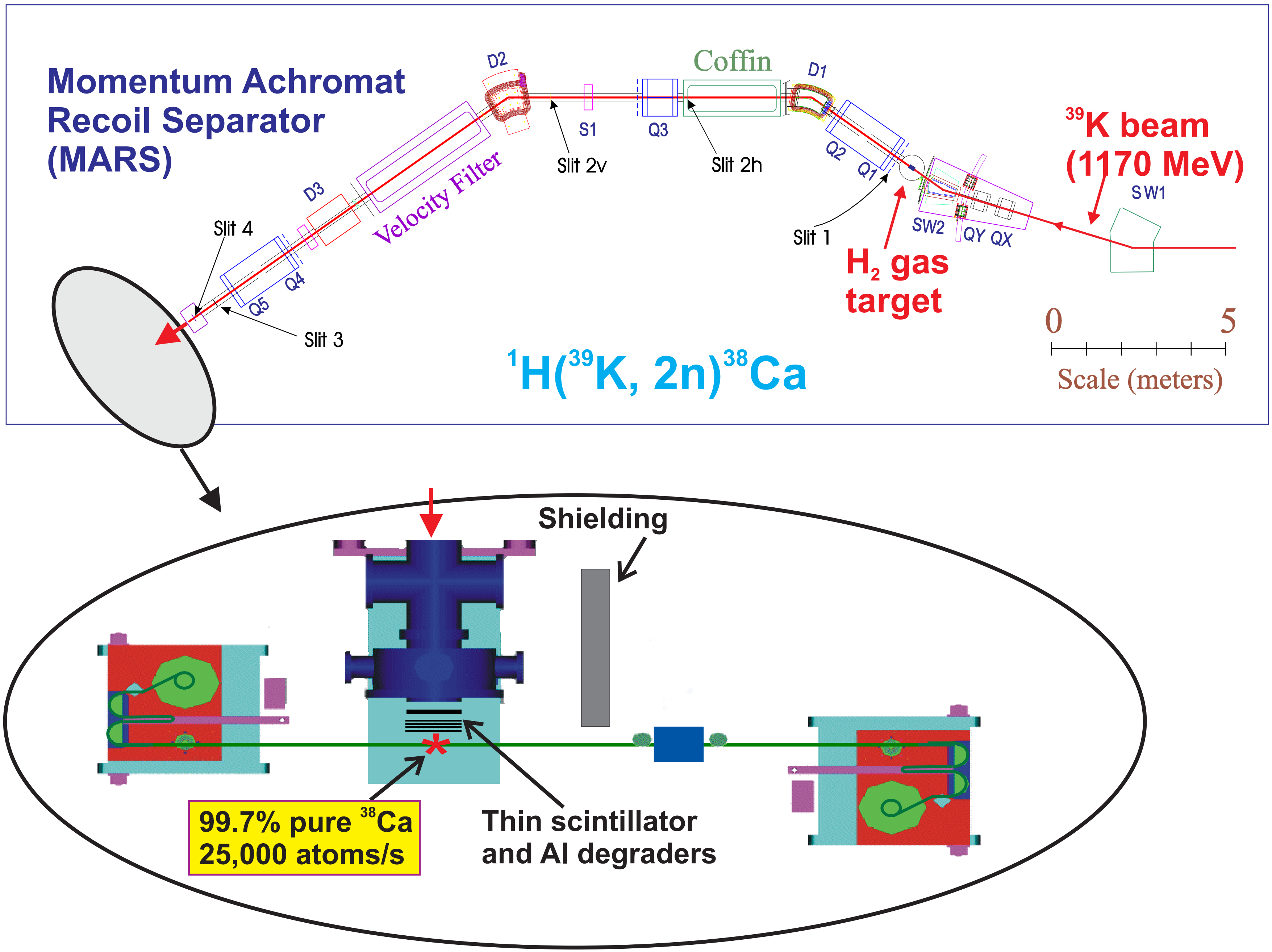


PRECISION DECAY MEASUREMENTS AT TAMU



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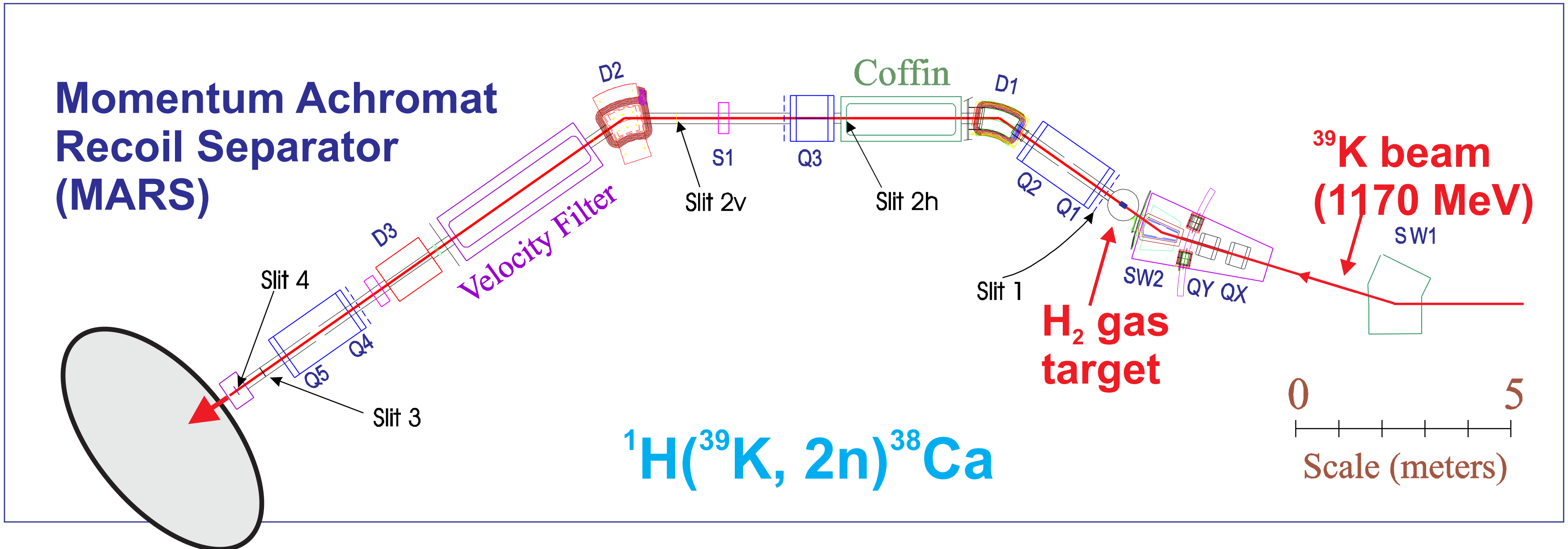

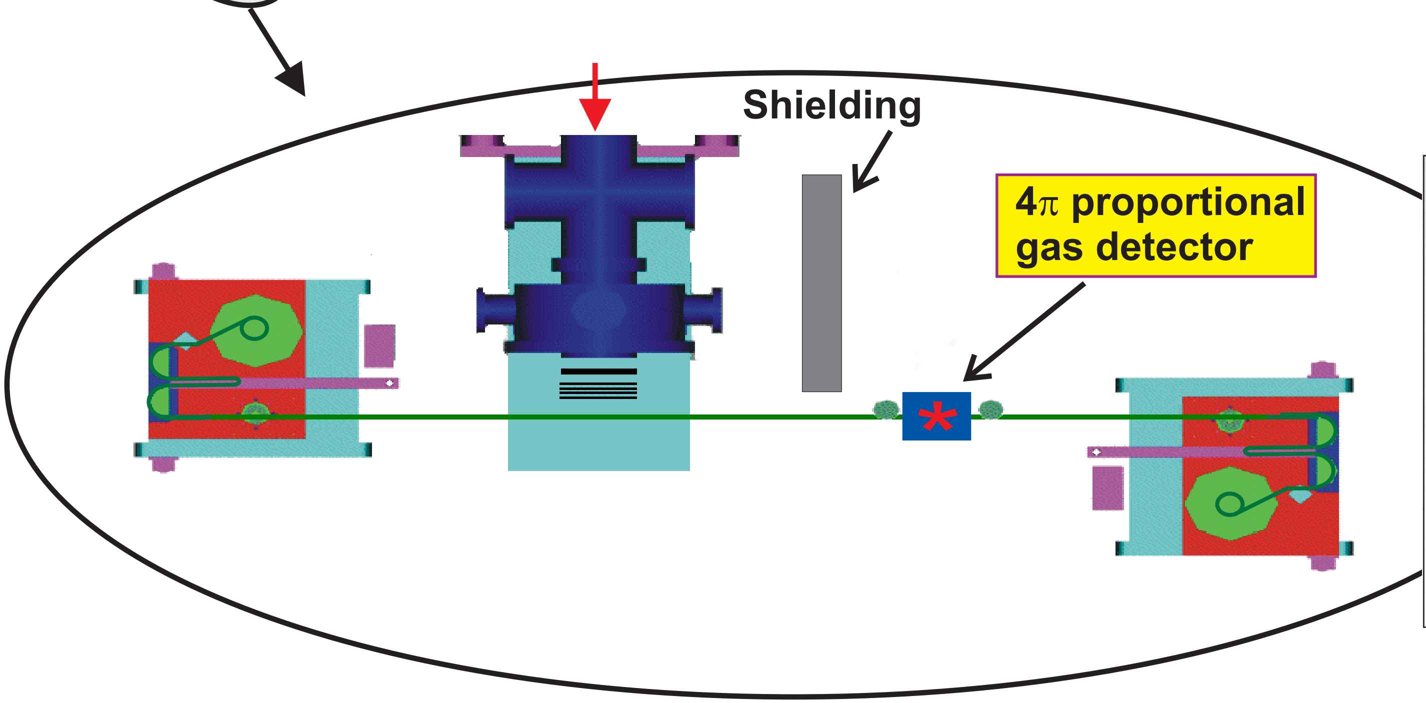

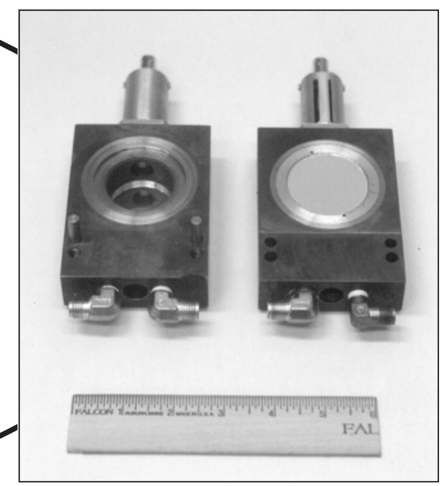

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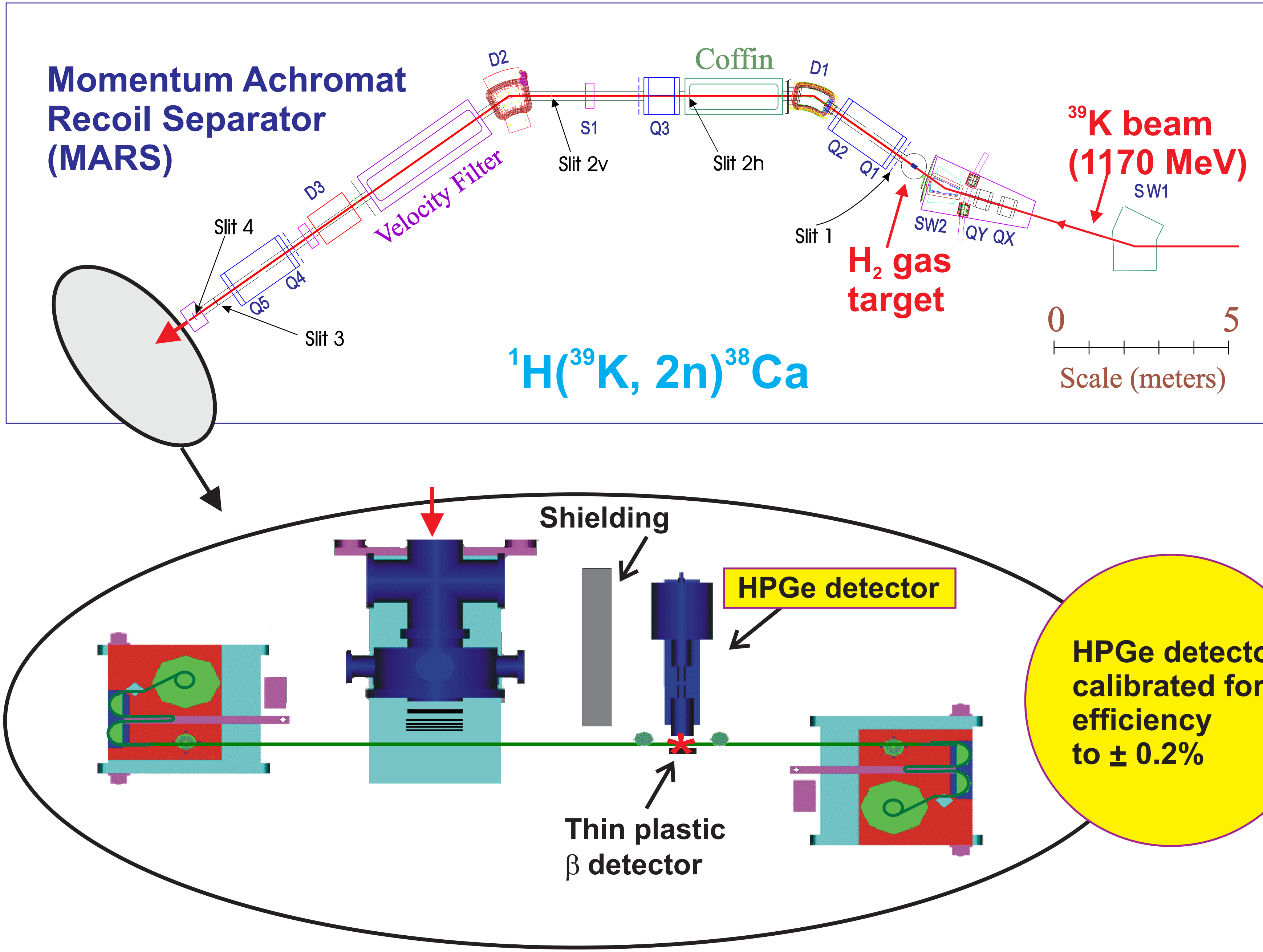
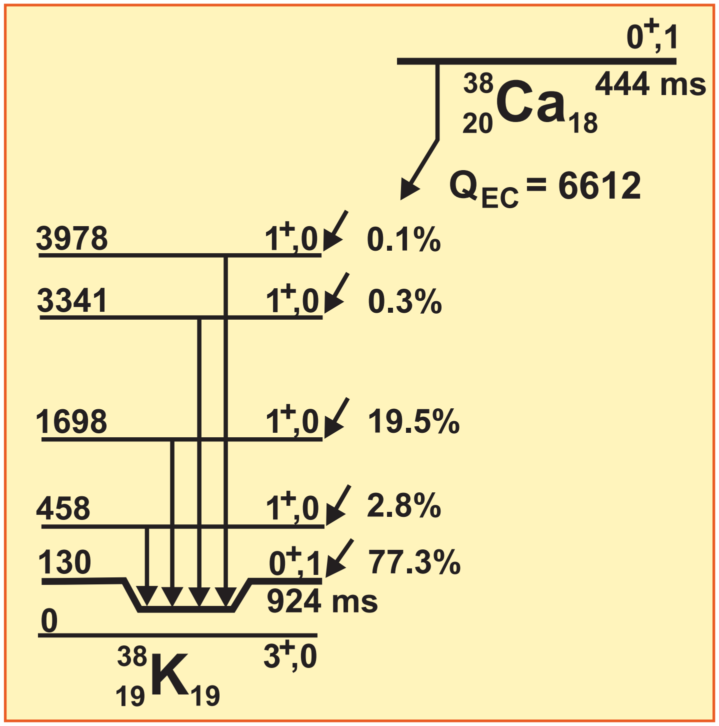
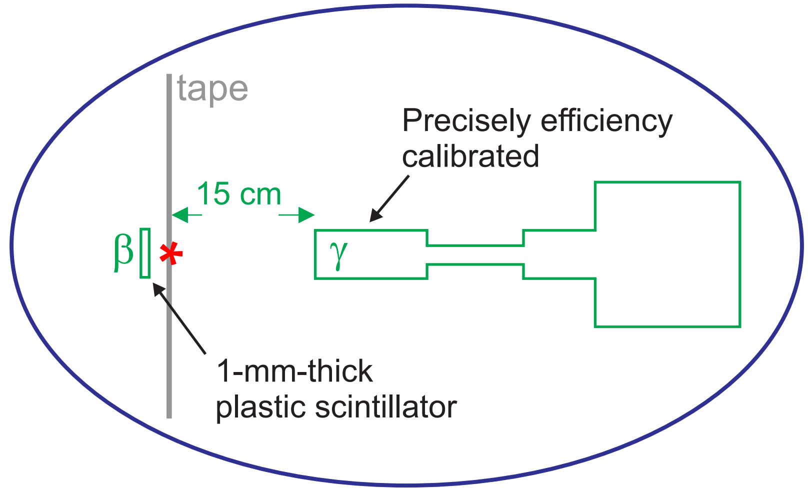
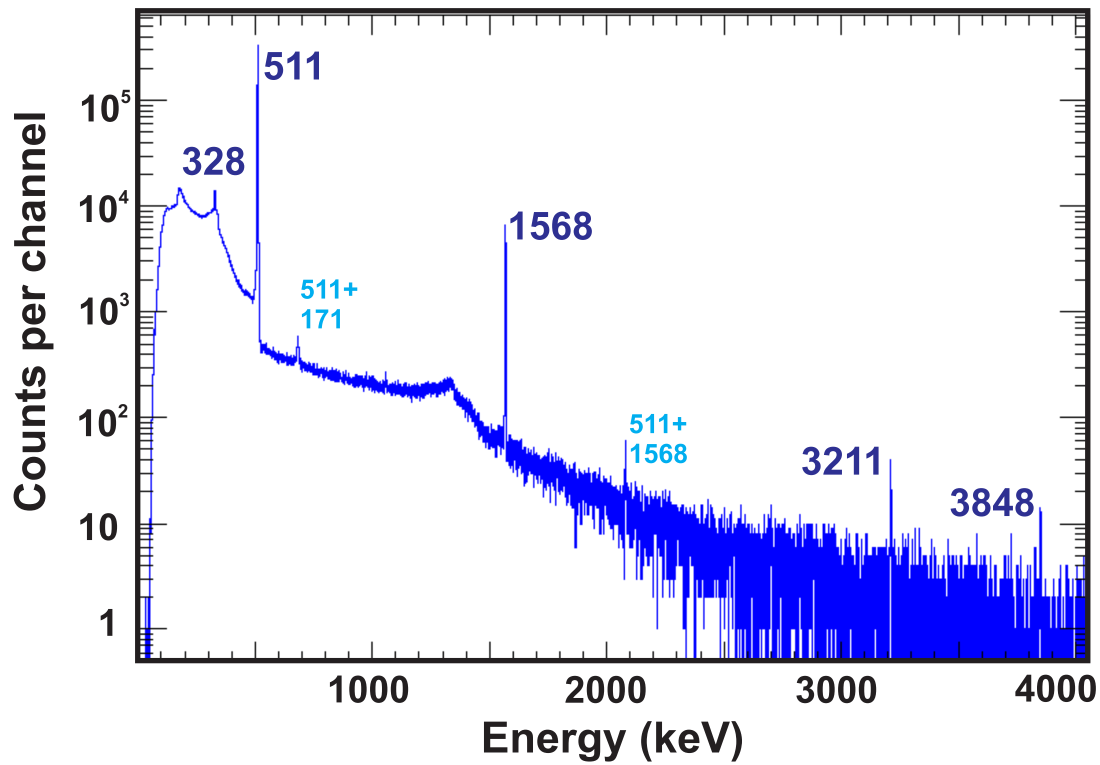


HPGe detector calibrated for efficiency to ± 0.2%

BETA-DECAY BRANCHING OF ^{38}Ca







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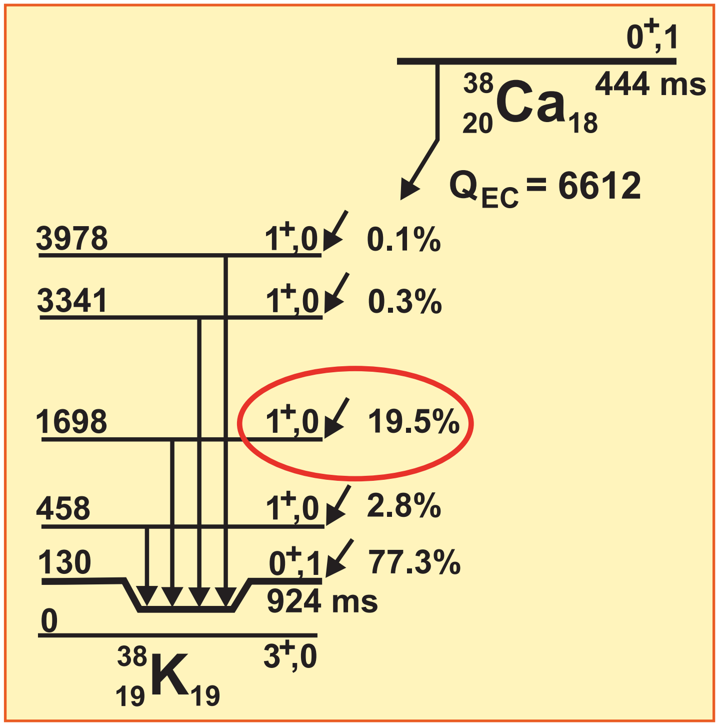

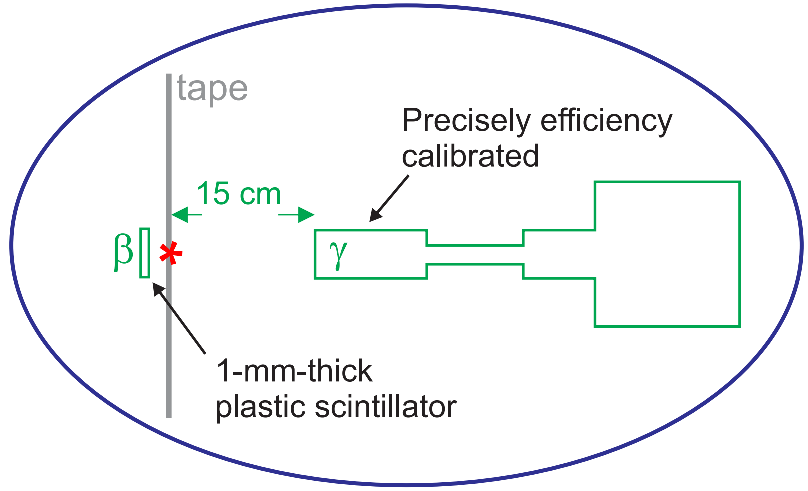

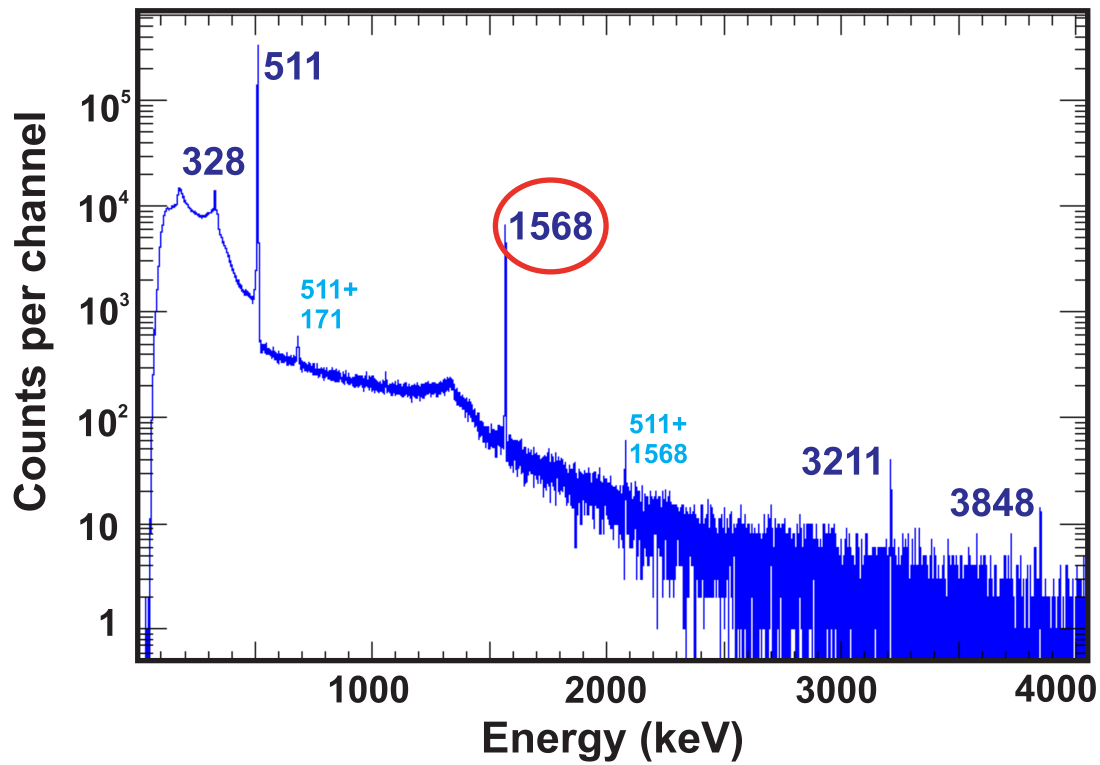

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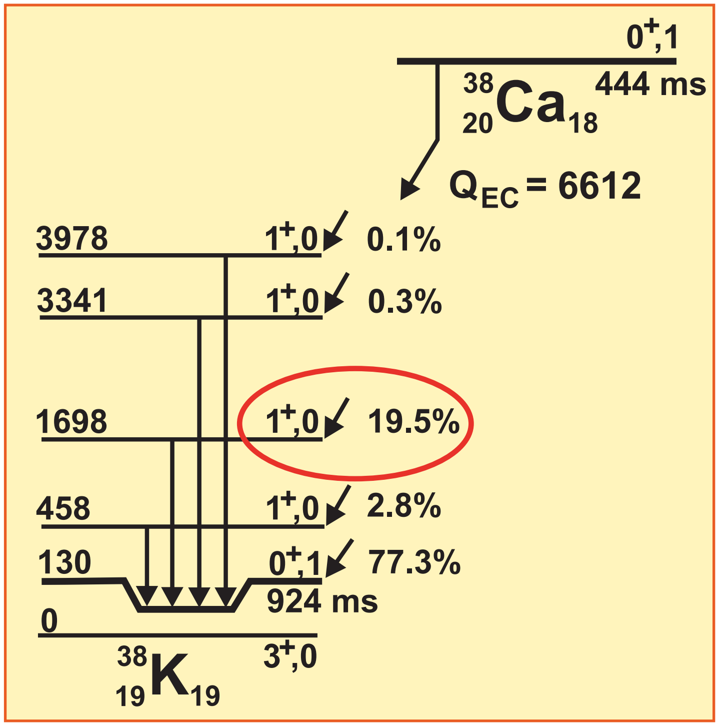
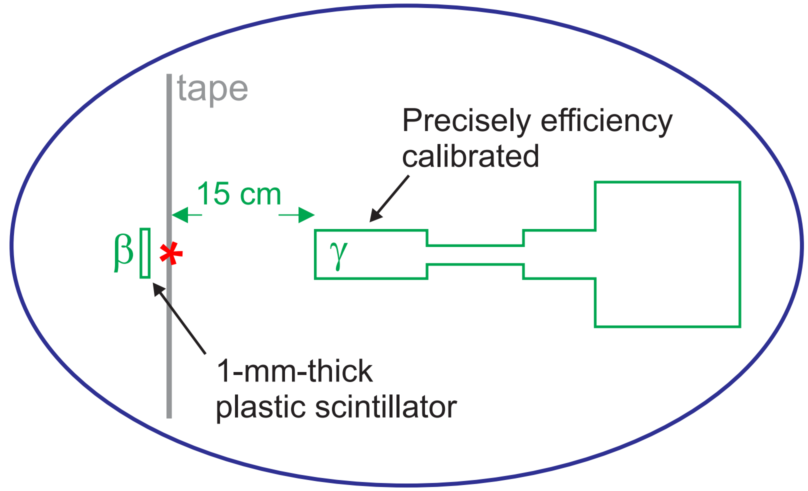
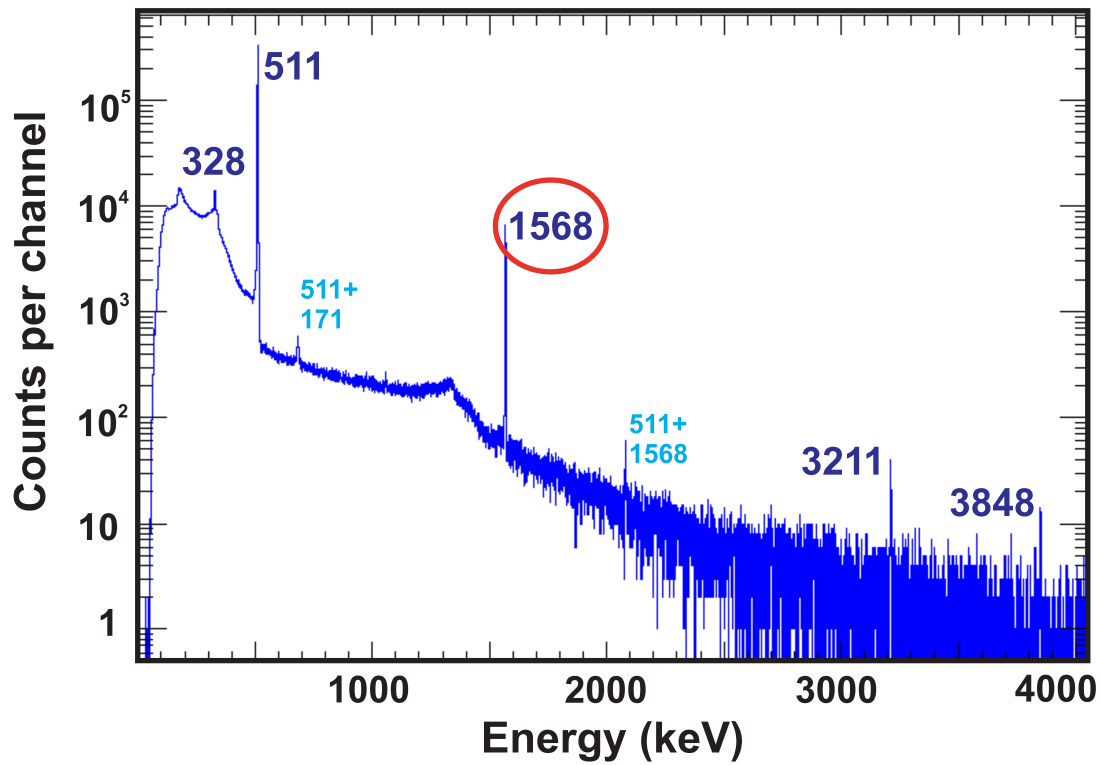




$$\frac{N_{\gamma_1\beta}}{N_\beta} = \frac{N_0 R_1 \varepsilon_{\beta_1} \varepsilon_{\gamma_1}}{N_0 \varepsilon_{\beta_{tot}}}$$



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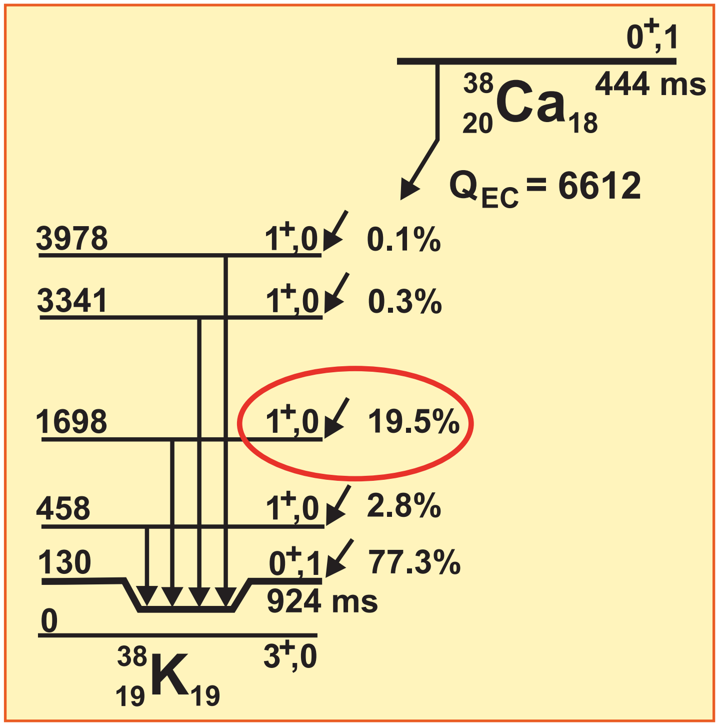
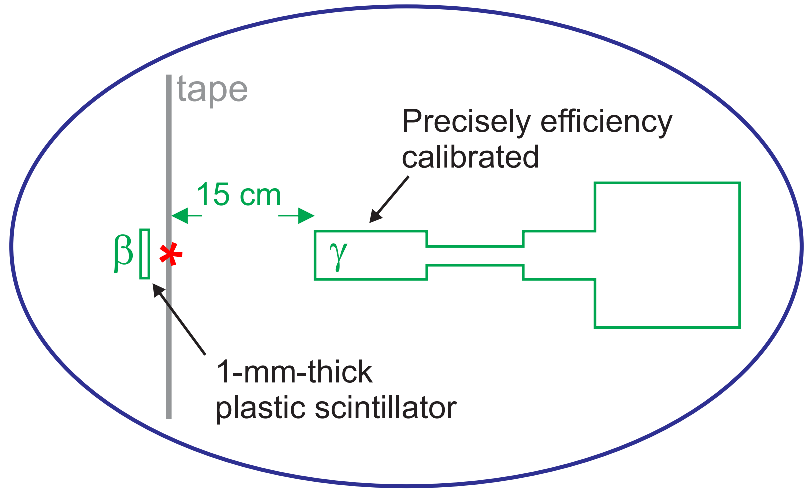
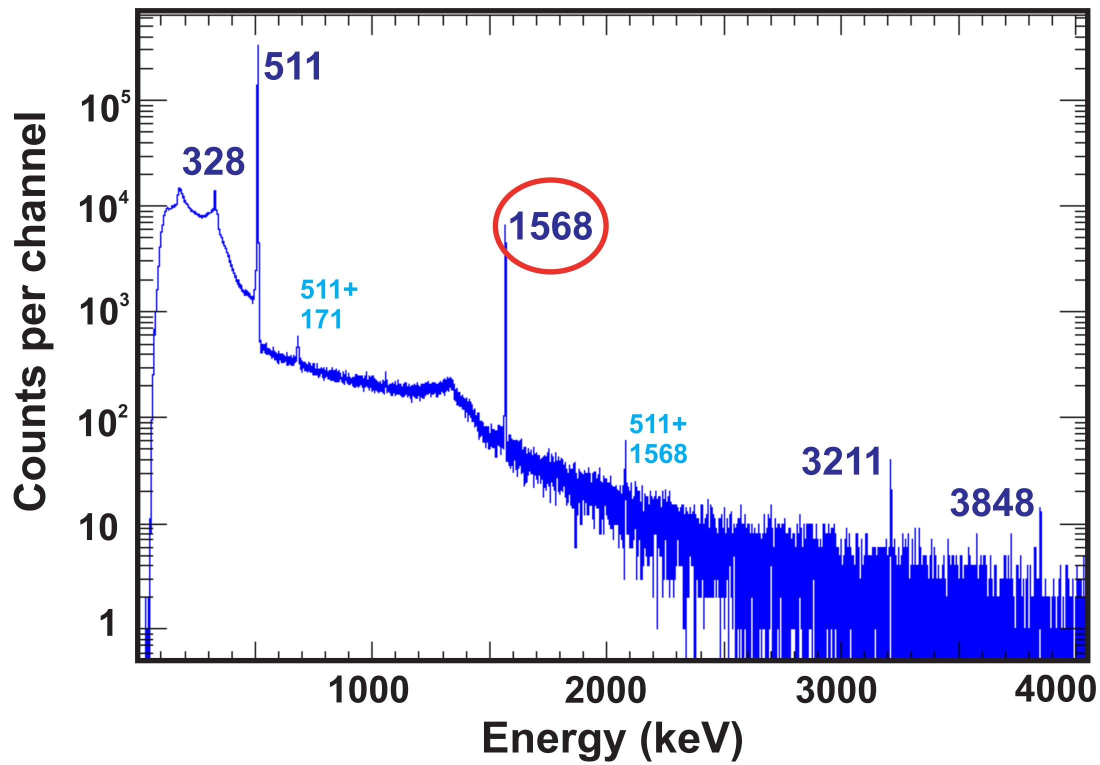


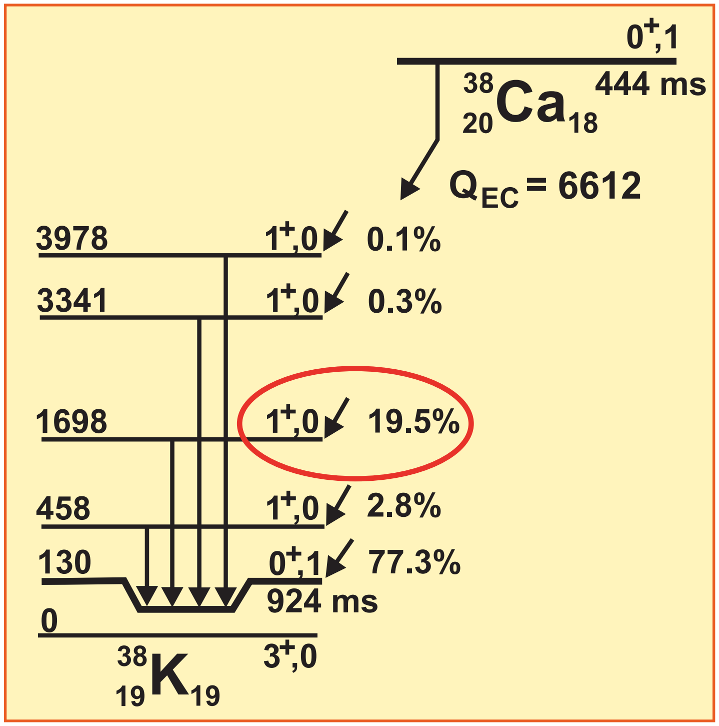


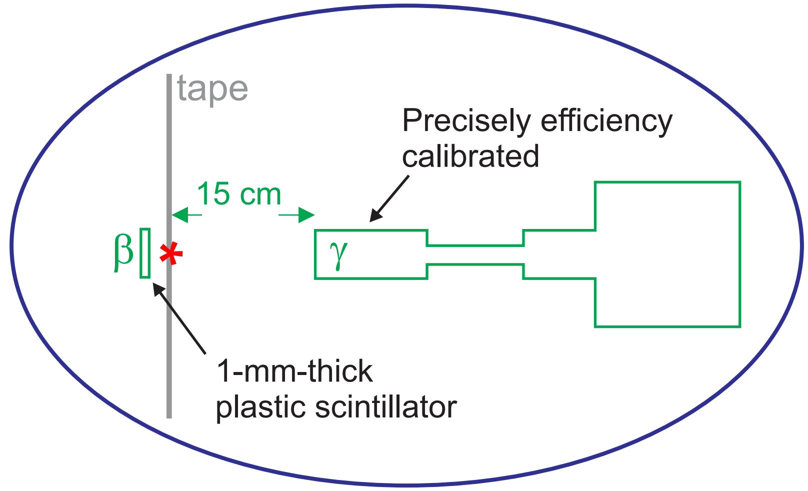
$$\frac{N_{\gamma_1\beta}}{N_\beta} = \frac{\cancel{N_o} R_1 \varepsilon_{\beta_1}\varepsilon_{\gamma_1}}{\cancel{N_o}\,\varepsilon_{\beta_{tot}}}$$

$$R_1 = \frac{N_{\gamma_1\beta}}{N_\beta \varepsilon_{\gamma_1}} \frac{\varepsilon_{\beta_{tot}}}{\varepsilon_{\beta_1}} k$$



BETA-DECAY BRANCHING OF ^{38}Ca

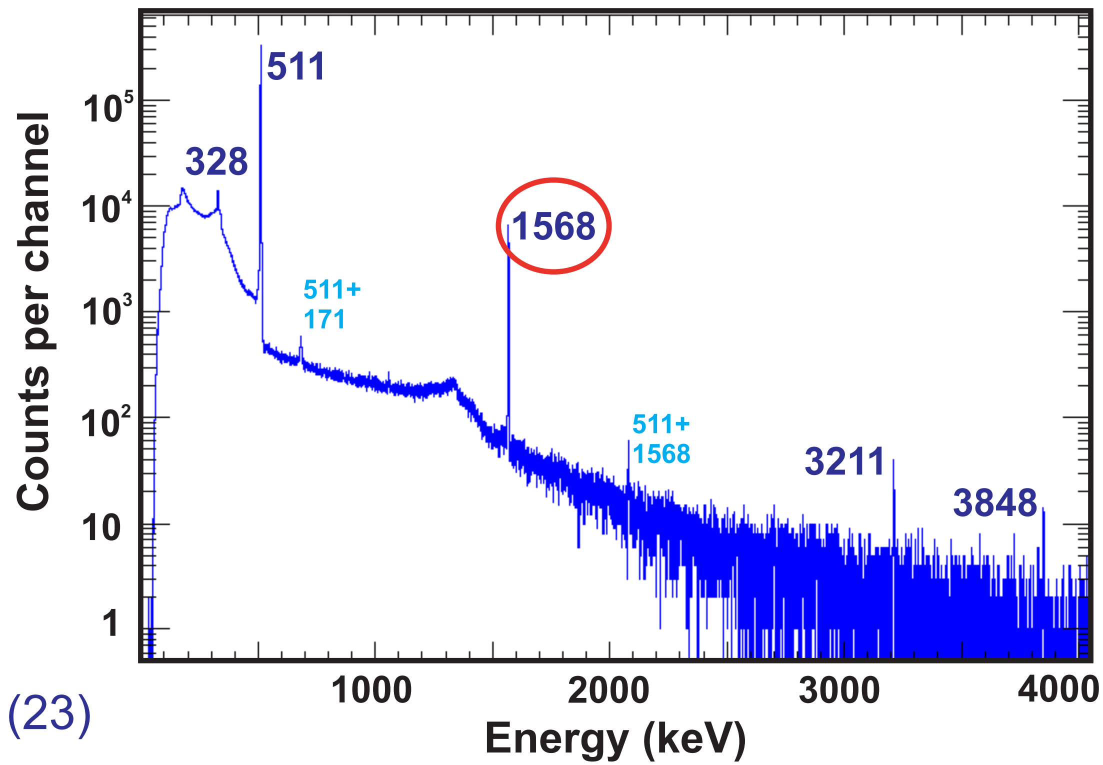




$$\frac{N_{\gamma_1\beta}}{N_\beta} = \frac{\cancel{N_o}\, R_1\, \varepsilon_{\beta_1}\varepsilon_{\gamma_1}}{\cancel{N_o}\, \varepsilon_{\beta_{tot}}}$$

$$R_1 = \frac{N_{\gamma_1\beta}}{N_\beta\, \varepsilon_{\gamma_1}}\, \frac{\varepsilon_{\beta_{tot}}}{\varepsilon_{\beta_1}}\, k$$

$k = f$(dead-time, pile-up, coincidence summing) = 1.0391(23)



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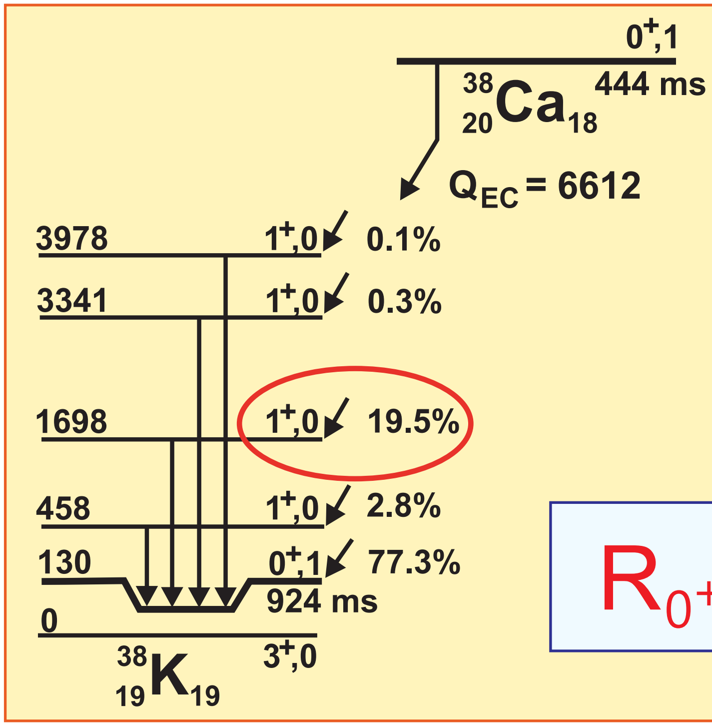

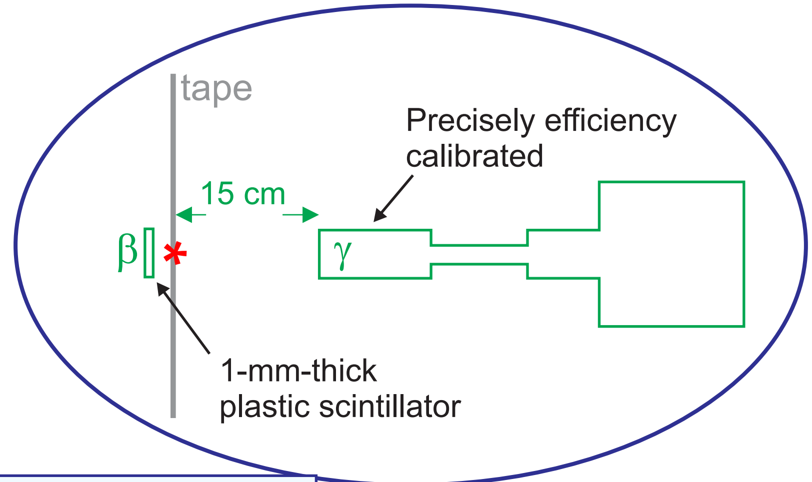

$$R_{0^+} = 77.28(16)\%$$

$$\frac{N_{\gamma_1\beta}}{N_\beta} = \frac{\cancel{N_0}\, R_1\, \varepsilon_{\beta_1}\varepsilon_{\gamma_1}}{\cancel{N_0}\, \varepsilon_{\beta_{tot}}}$$

$$R_1 = \frac{N_{\gamma_1\beta}}{N_\beta\, \varepsilon_{\gamma_1}}\, \frac{\varepsilon_{\beta_{tot}}}{\varepsilon_{\beta_1}}\, k$$

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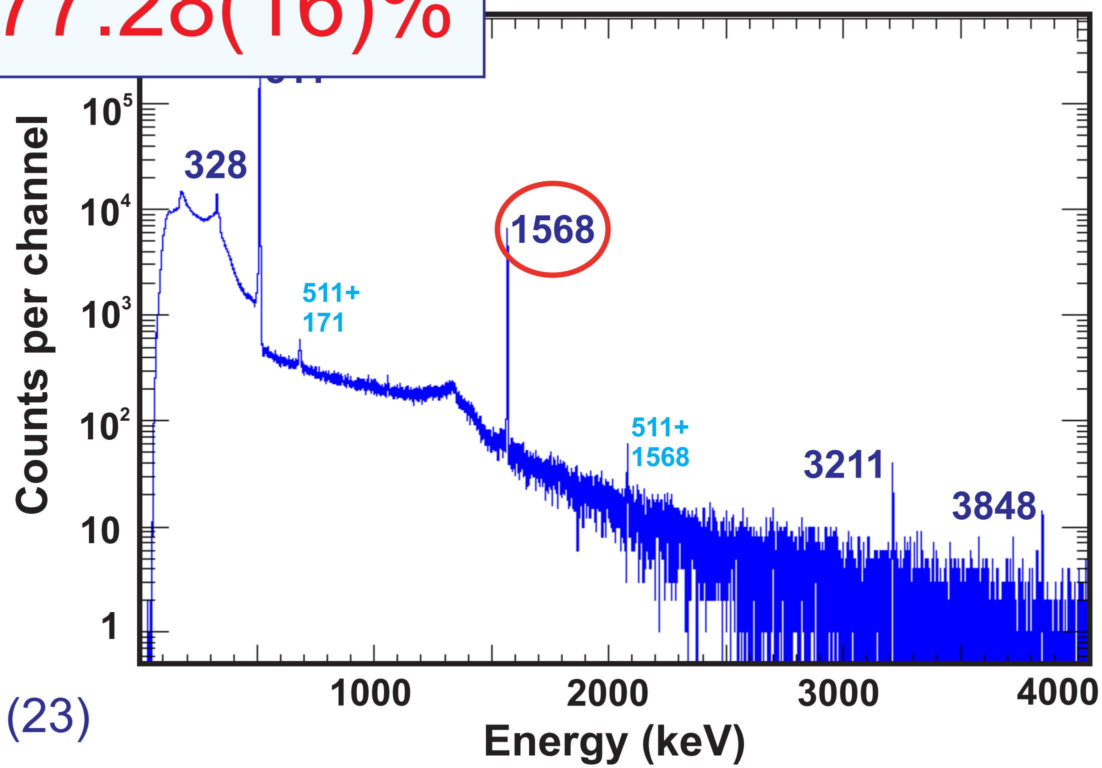


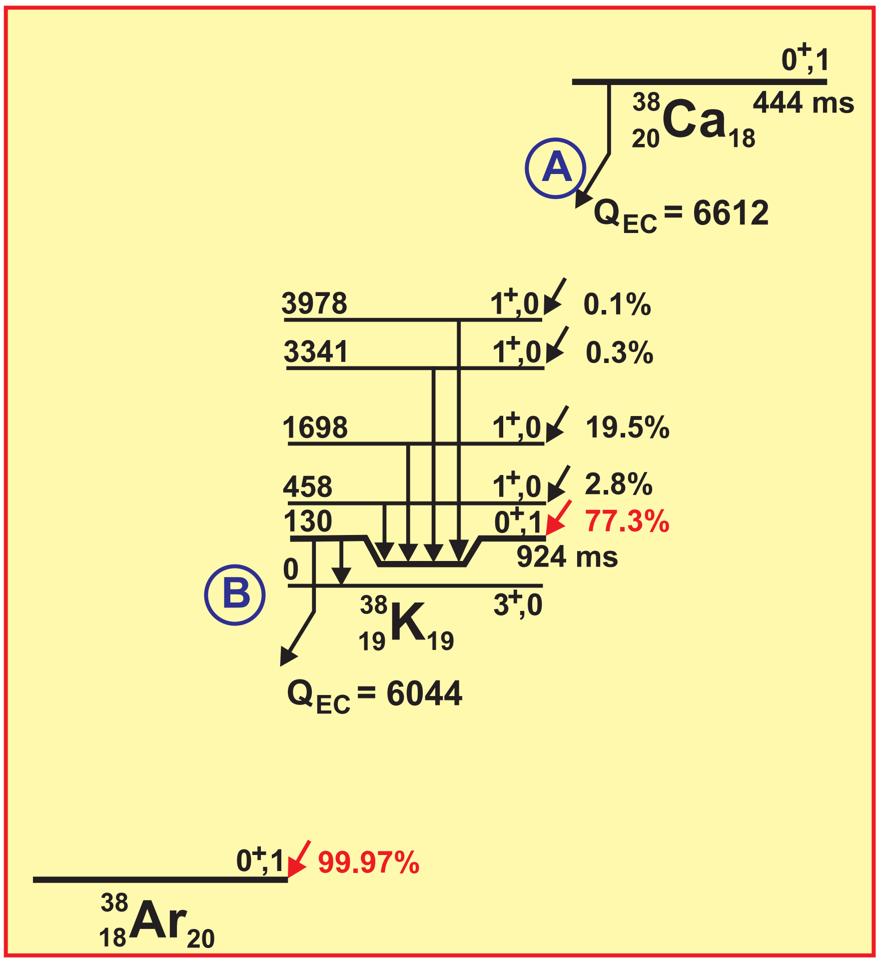
TESTS OF δ_C CALCULATIONS

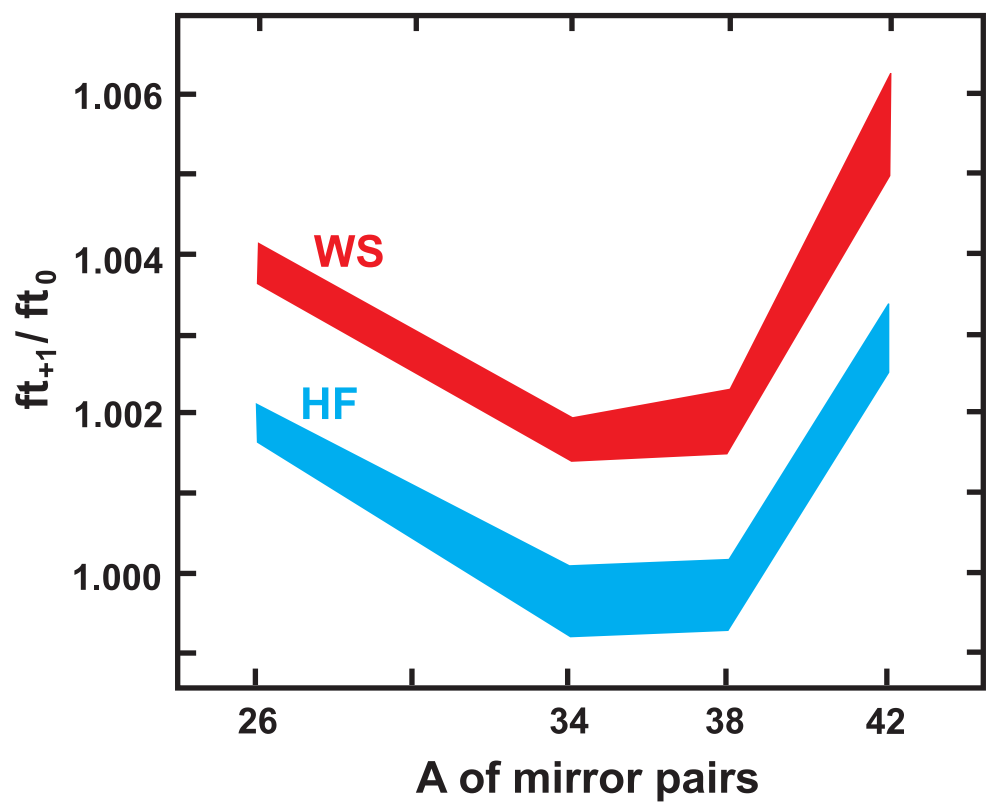
B. Measurements of mirror superallowed transitions:

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

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

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

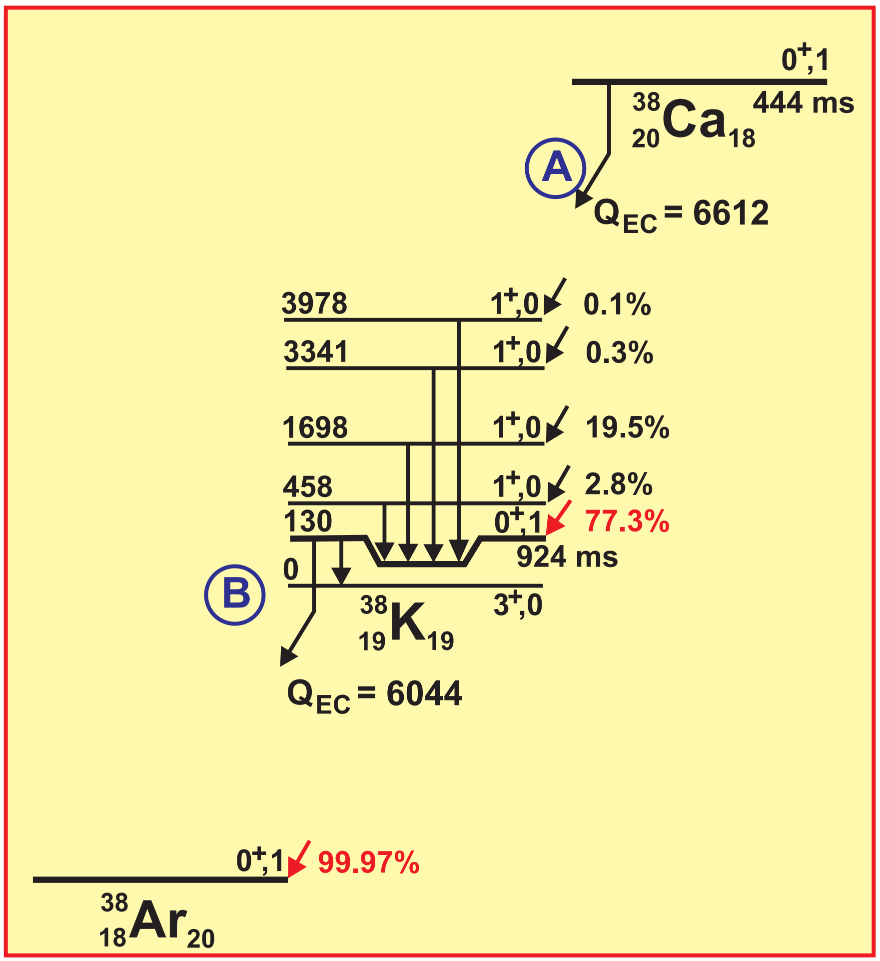




TESTS OF δ_C CALCULATIONS

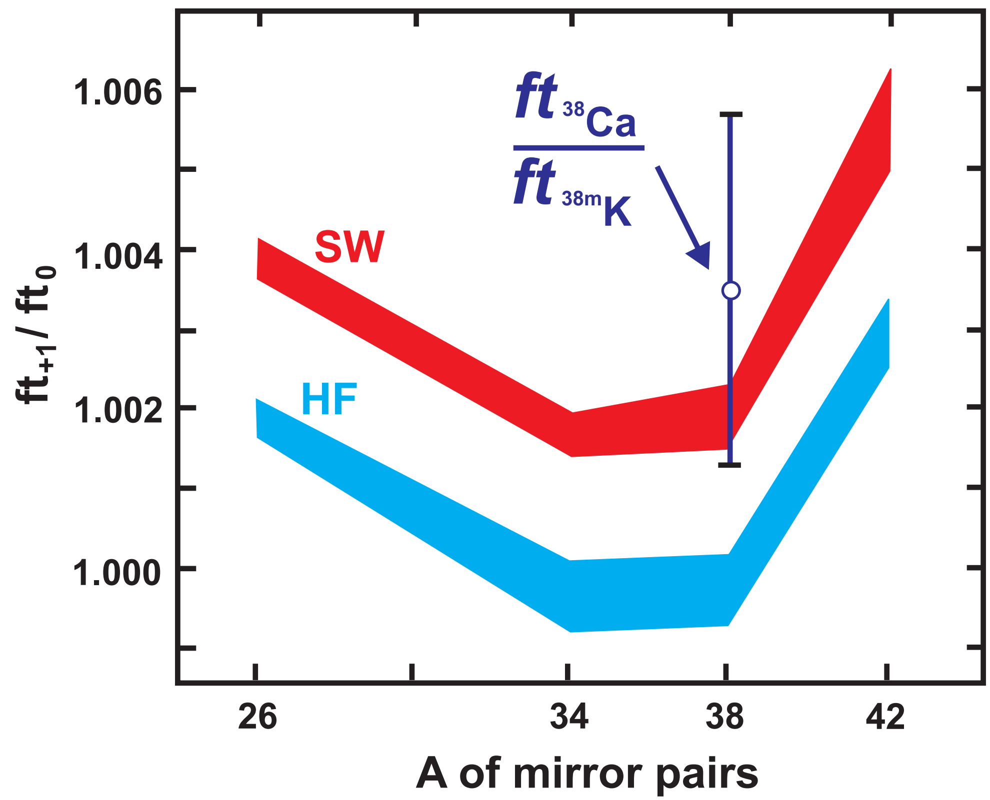
B. Measurements of mirror superallowed transitions:

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



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

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



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

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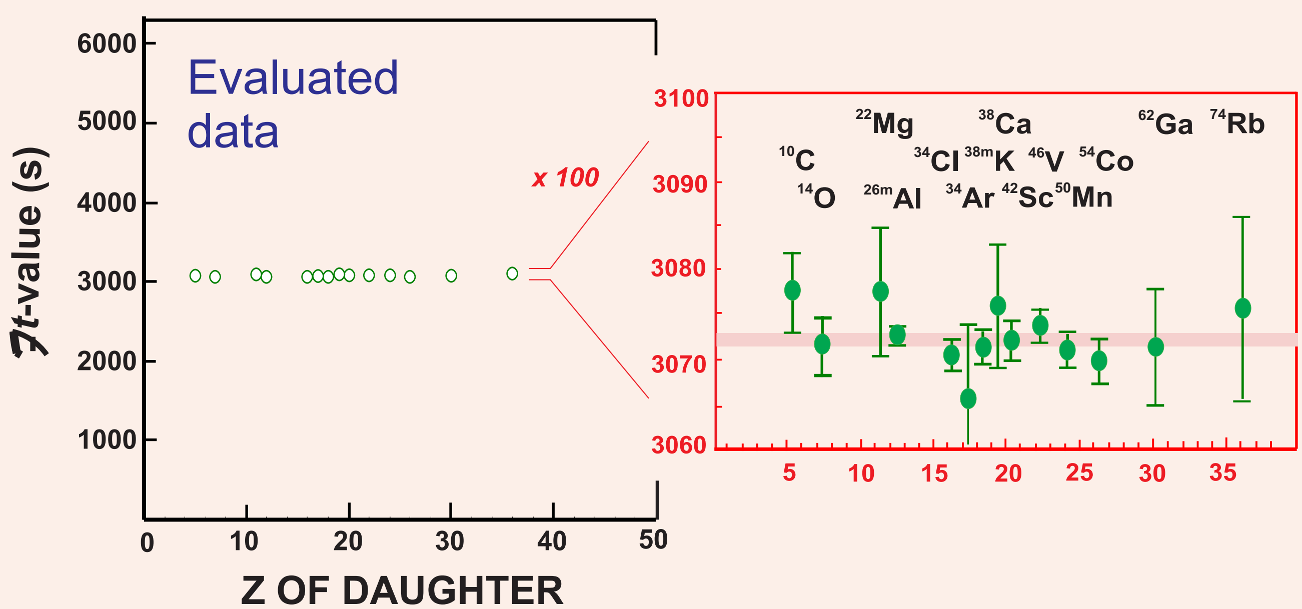
FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

G_V constant to ± 0.013%



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

$G_V(1+\Delta_R)^{1/2}/(\hbar c)^3 = 1.14958(15) \times 10^{-5}\ \mathrm{GeV}^{-2}$

$\chi^2/\nu = 0.6$

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

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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)

Validate correction terms

G_V constant to ± 0.013%

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

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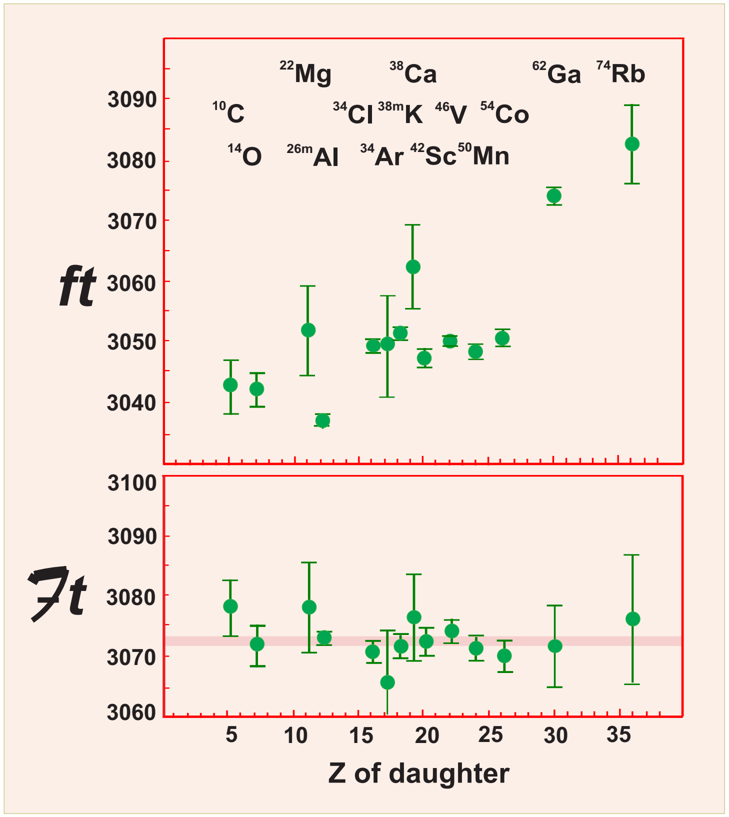

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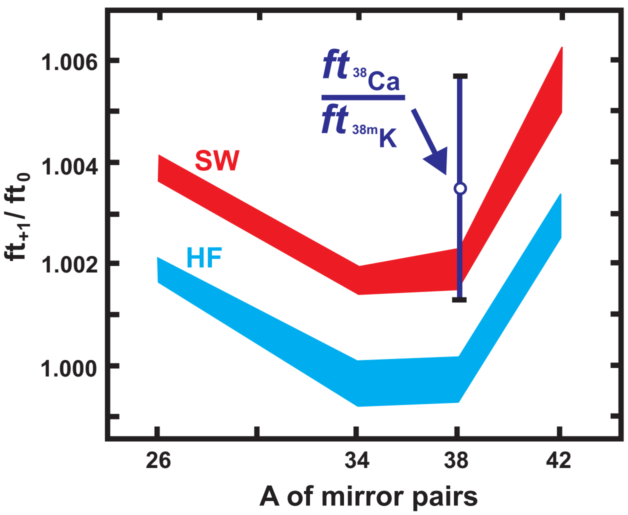
FROM MANY TRANSITIONS

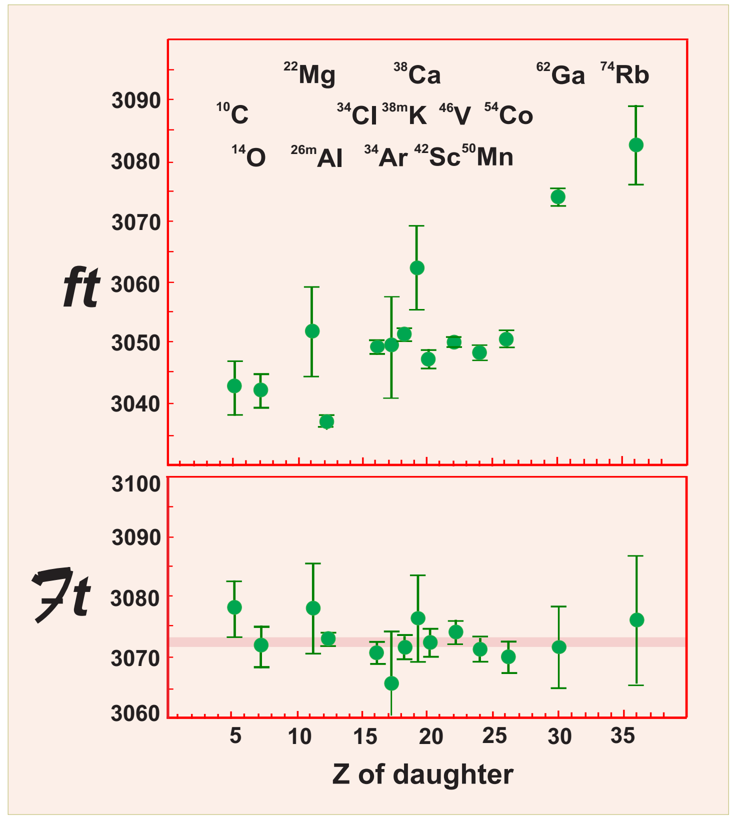
Test Conservation of the Vector current (CVC)

Validate correction terms ✔

G_V constant to ± 0.013%

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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Test Conservation of the Vector current (CVC)

Validate correction terms ✔

Test for Scalar current

G_V constant to ± 0.013%

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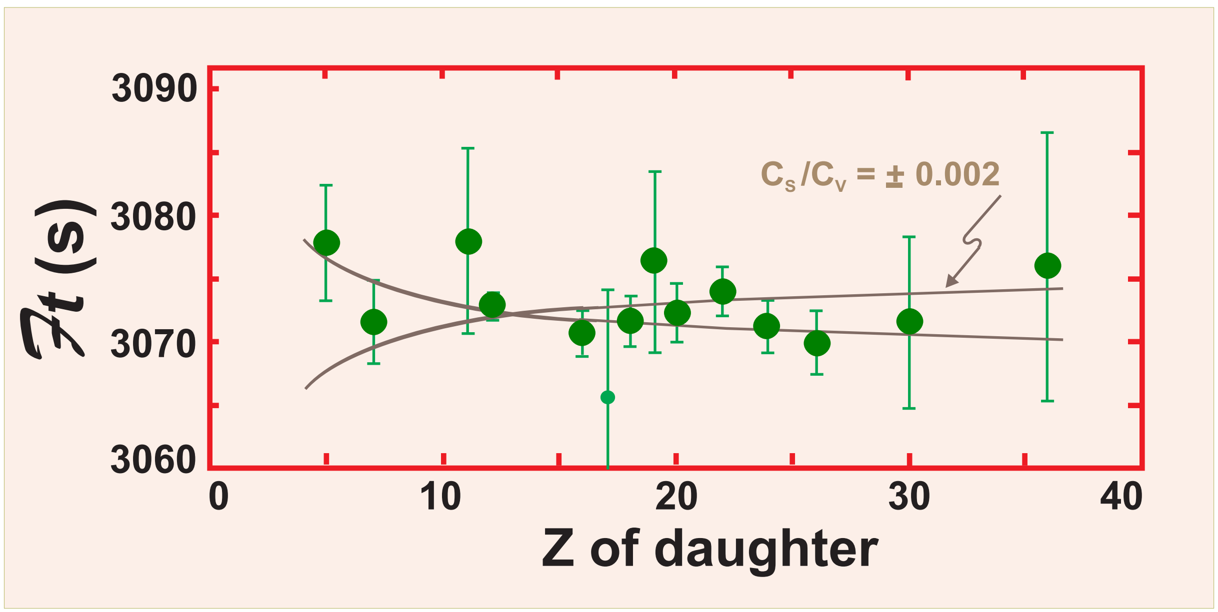
limit, C_S/C_V = 0.0014 (13)



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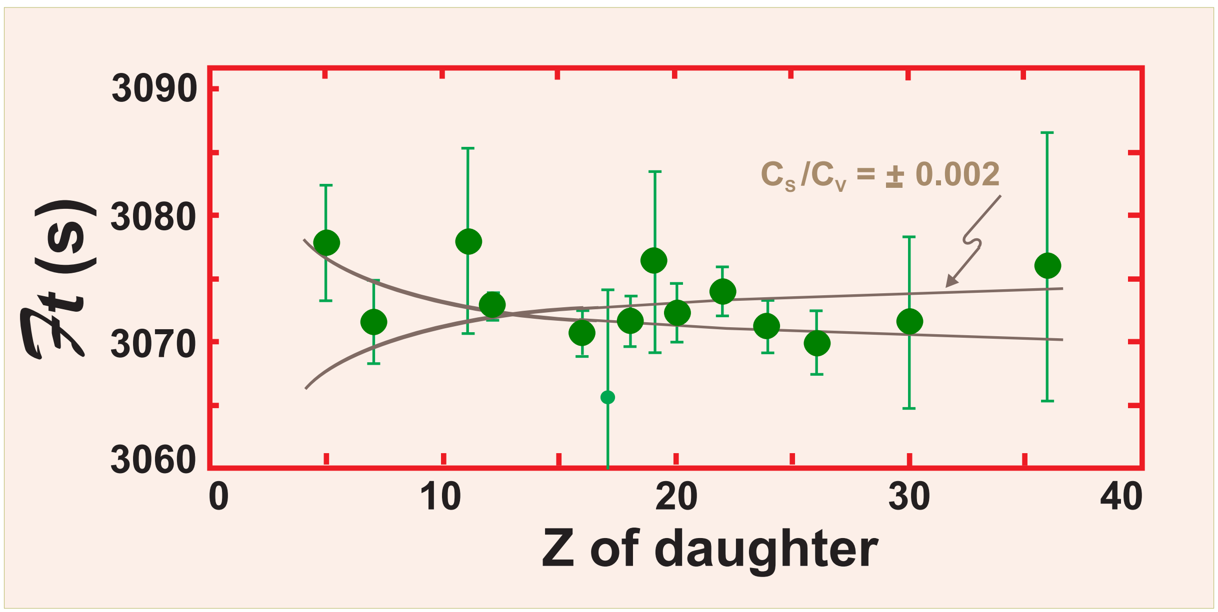

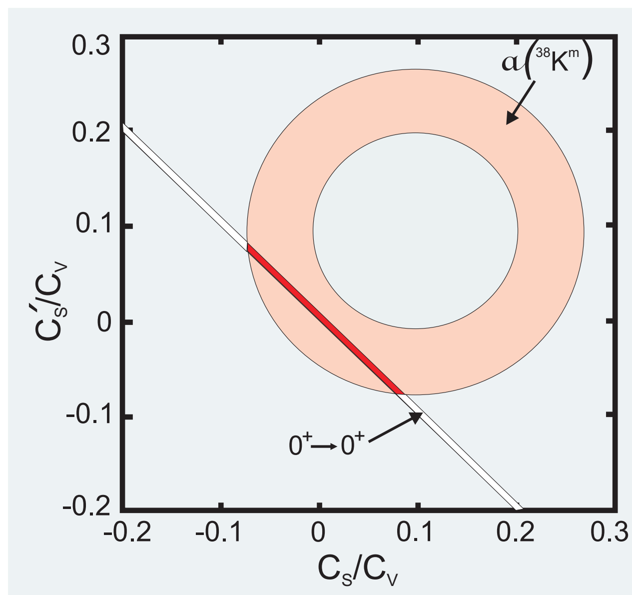

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FROM MANY TRANSITIONS

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Validate correction terms ✔

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Test for Scalar current

$\boxed{\text{limit, } C_S/C_V = 0.0014\ (13)}$

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

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

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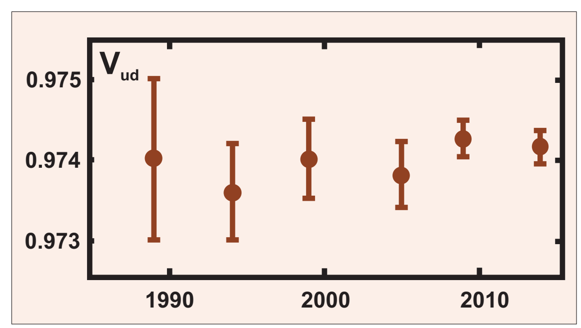

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$$V_{ud}^2 = G_V^2/G_\mu^2 = 0.94900 \pm 0.00042$$

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

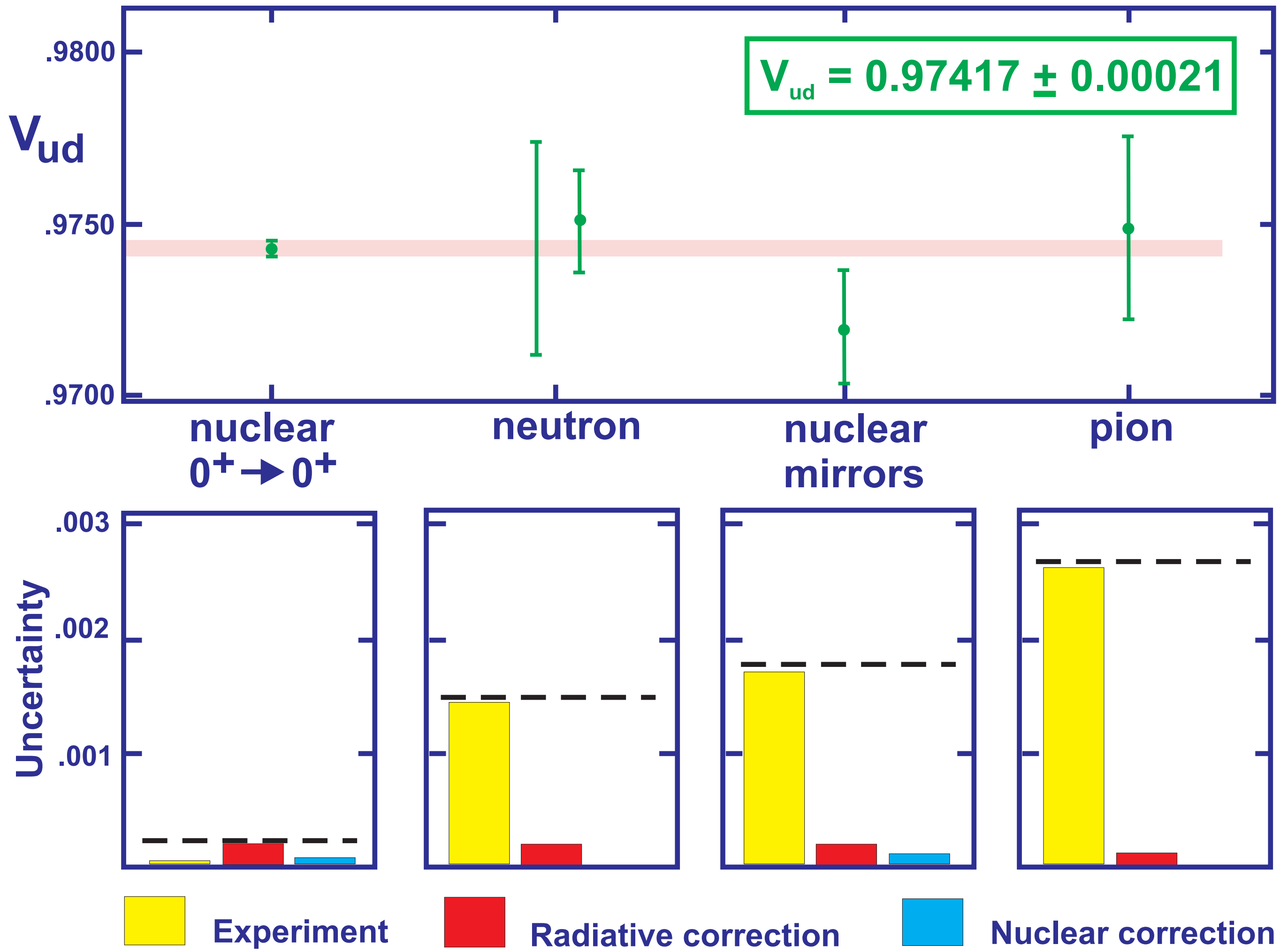
CURRENT STATUS OF CKM UNITARITY

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

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



FINAL REMARK ON V_{us}

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

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

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

Both require lattice calculations of form factors to obtain their result.

Until March 2014 these gave highly consistent results for $|V_{us}|$.

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Both require lattice calculations of form factors to obtain their result.

Until March 2014 these gave highly consistent results for $|V_{us}|$.

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 ...

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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1. Analysis of superallowed $0^+ \rightarrow 0^+$ nuclear β decay is shown to confirm CVC and thus yield V_{ud} = 0.97417(21).
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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. Isospin symmetry-breaking corrections in nuclei are the second largest.
5. These symmetry-breaking corrections have been tested by requiring consistency among 14 known transitions (CVC) and by comparing them with mirror transition pairs. One set of corrections passes both tests.
6. Further tests on mirror pairs are possible and are planned. This requires precise branching-ratio measurements of T_z = -1 parent decays.