SUPERALLOWED NUCLEAR BETA DECAY: RECENT RESULTS AND THEIR IMPACT ON V_{ud}

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Cyclotron Institute
Texas A&M University
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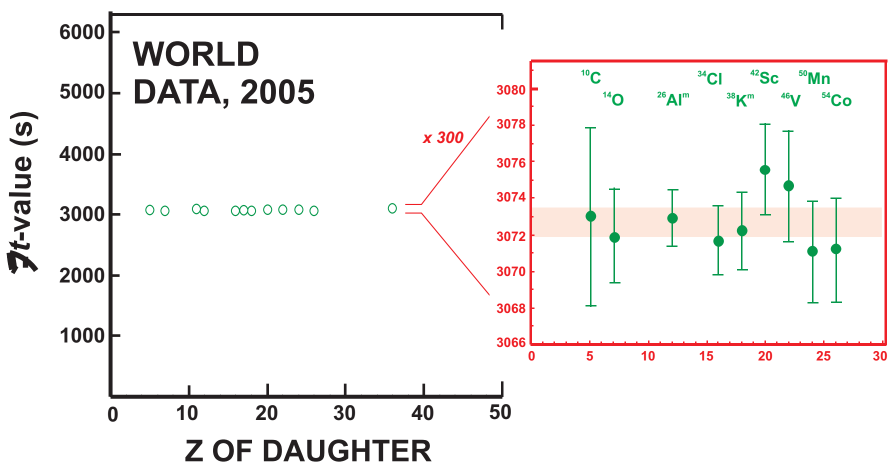
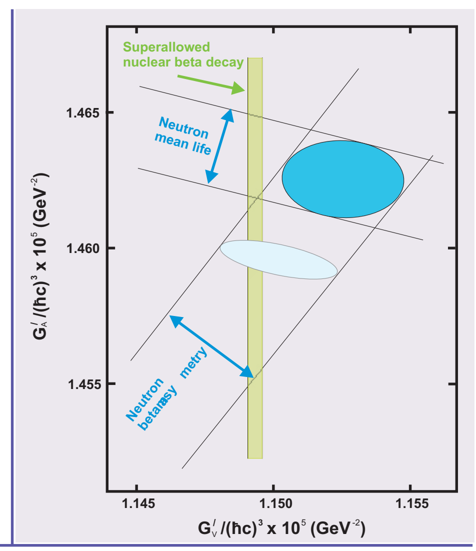
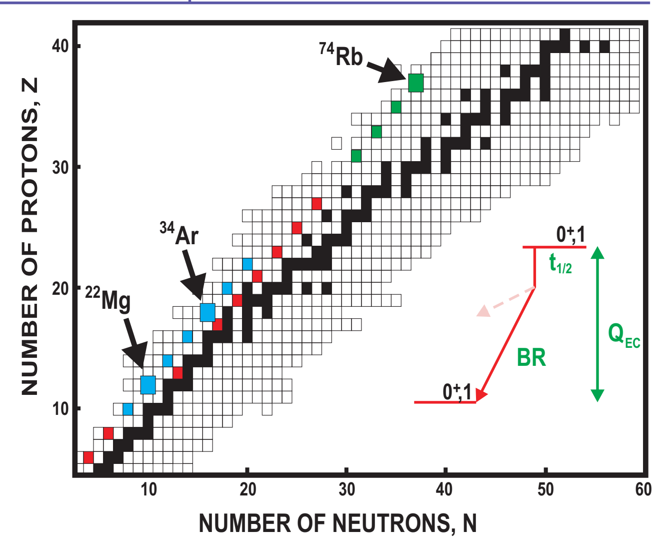
(with I.S. Towner)





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

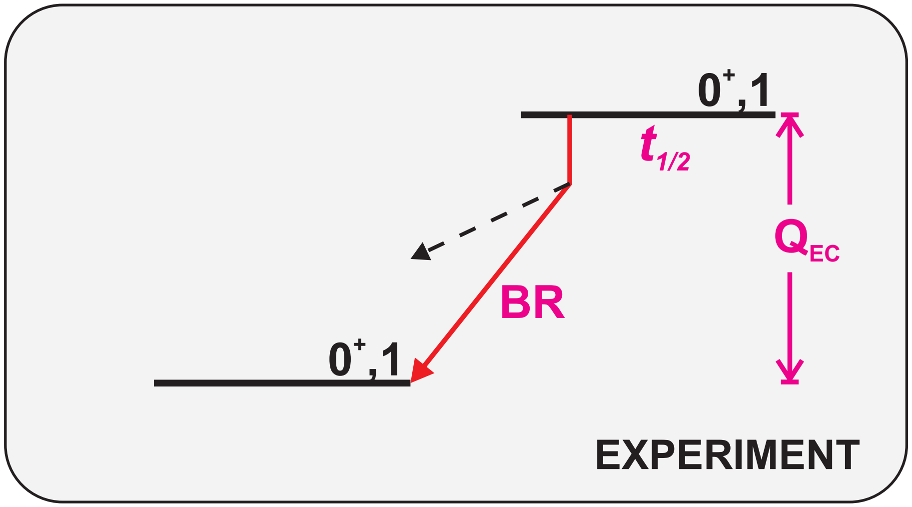


SUPERALLOWED $0^+ \rightarrow 0^+$ BETA DECAY

BASIC WEAK-DECAY EQUATION

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

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



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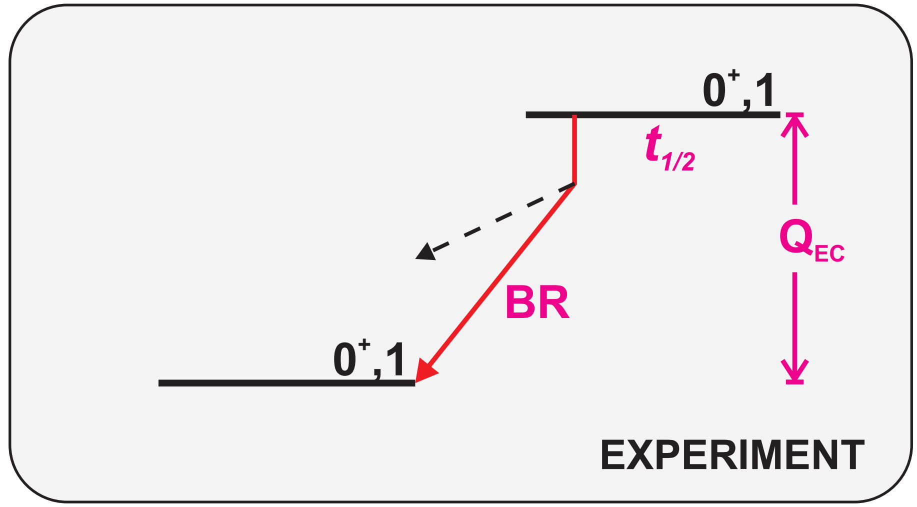

INCLUDING RADIATIVE CORRECTIONS

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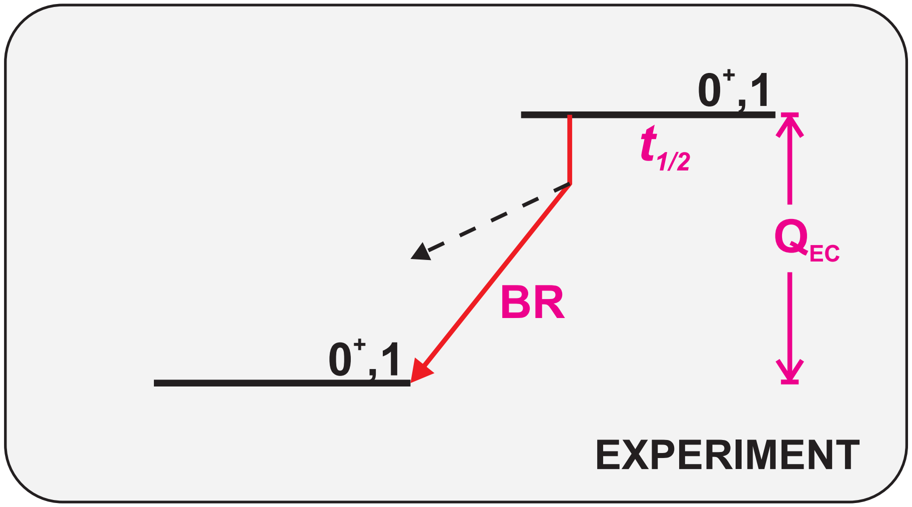

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$f(Z, Q_{EC})$ ~1.5%

f(nuclear structure) 0.3-0.7%

f(interaction) ~2.4%

WHAT CAN WE LEARN?

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FROM A SINGLE TRANSITION

Experimentally determine $G_V^2(1 + \;_R)$

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$\mathcal{F}t$ **values constant**

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WITH CVC VERIFIED

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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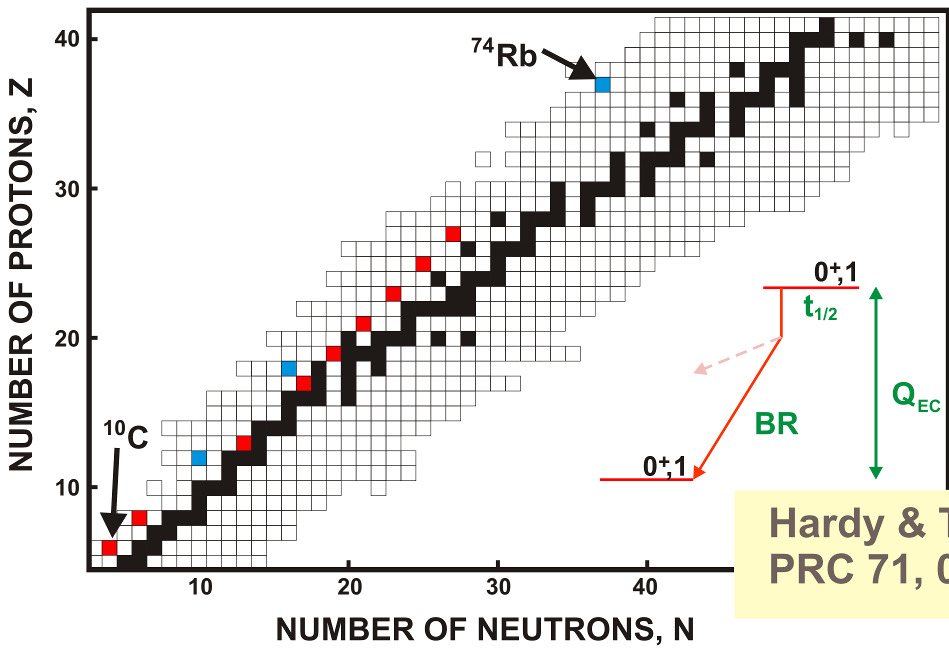
Test CKM unitarity

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

WORLD DATA FOR $0^+ \rightarrow 0^+$ DECAY, 2005



Hardy & Towner
PRC 71, 055501 (2005)

- 9 cases with *ft*-values measured to ~0.1% precision; 3 more cases with <0.4% precision.
- ~125 individual measurements with compatible precision

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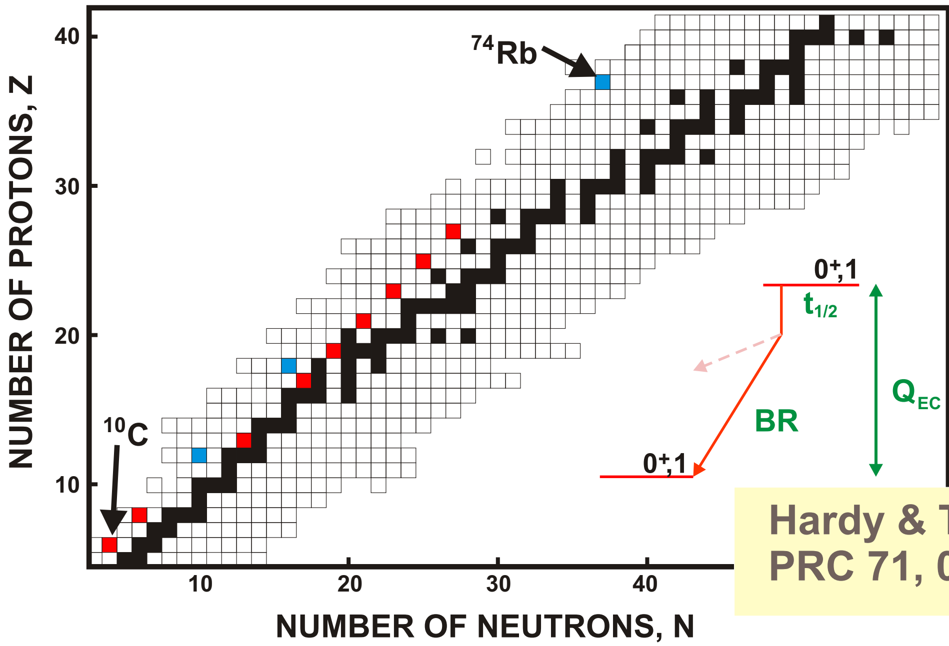

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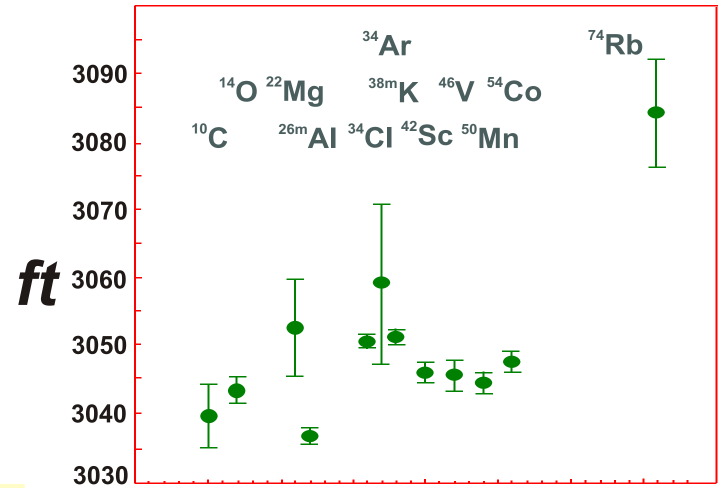

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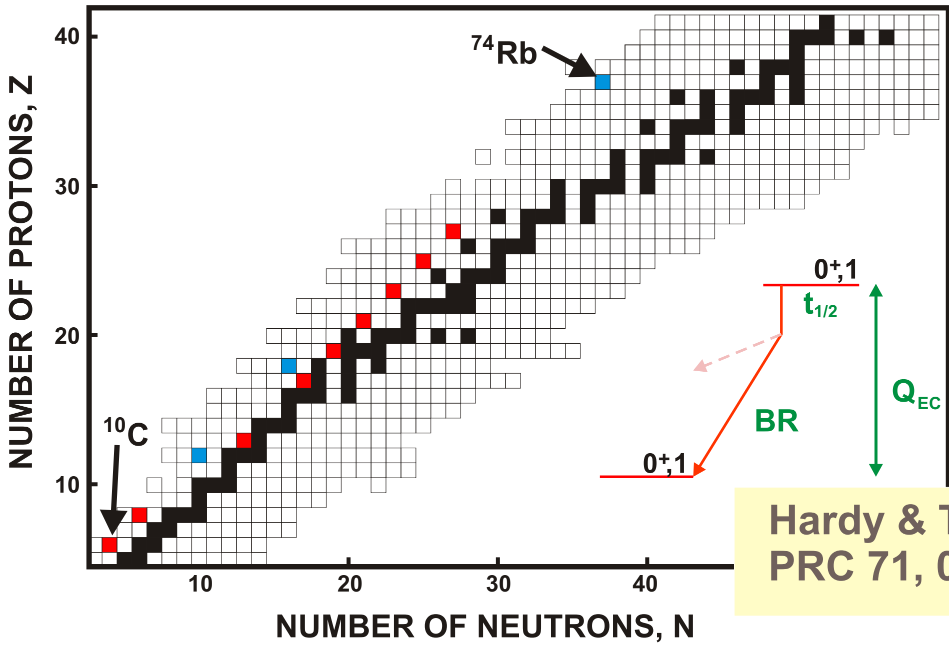

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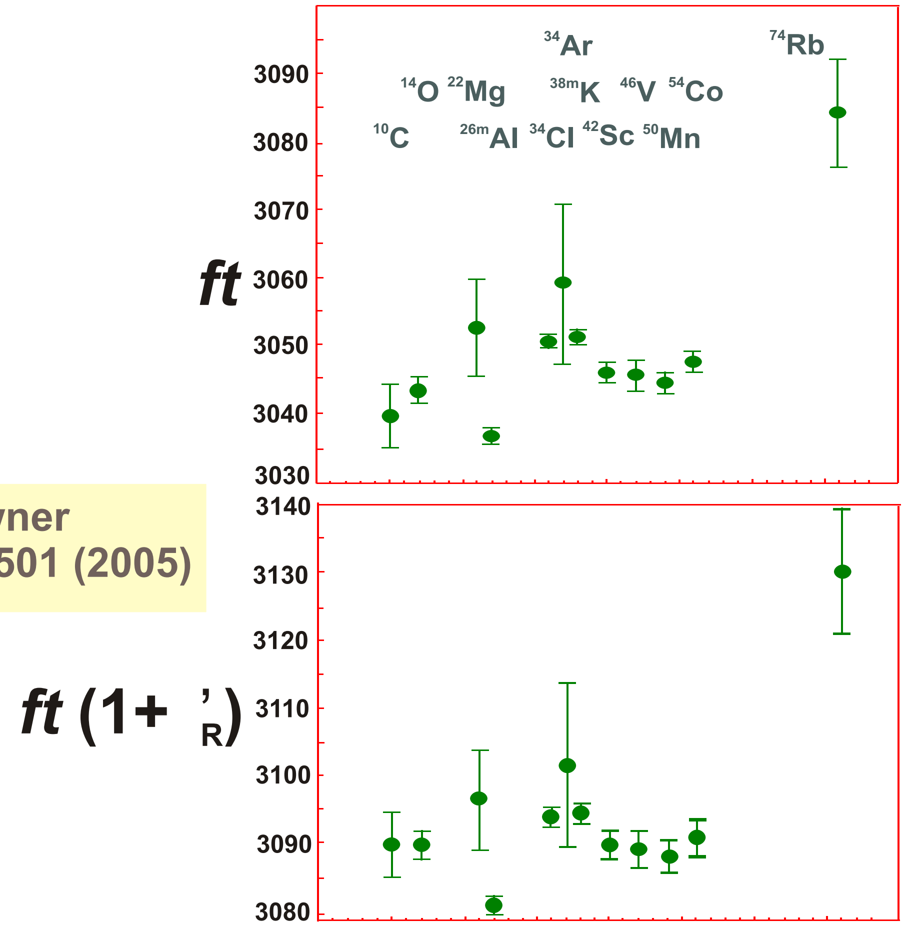

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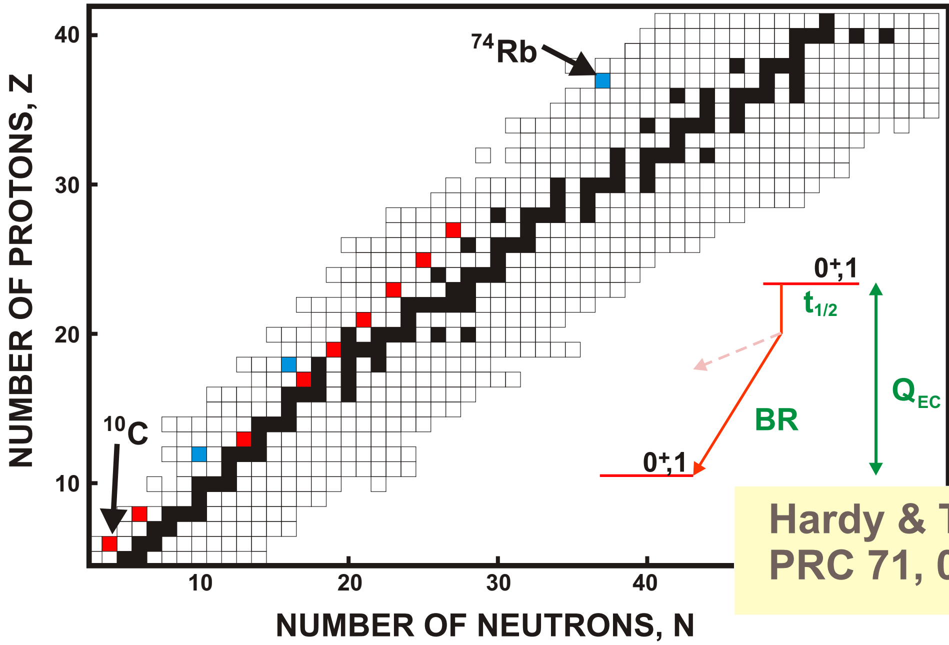

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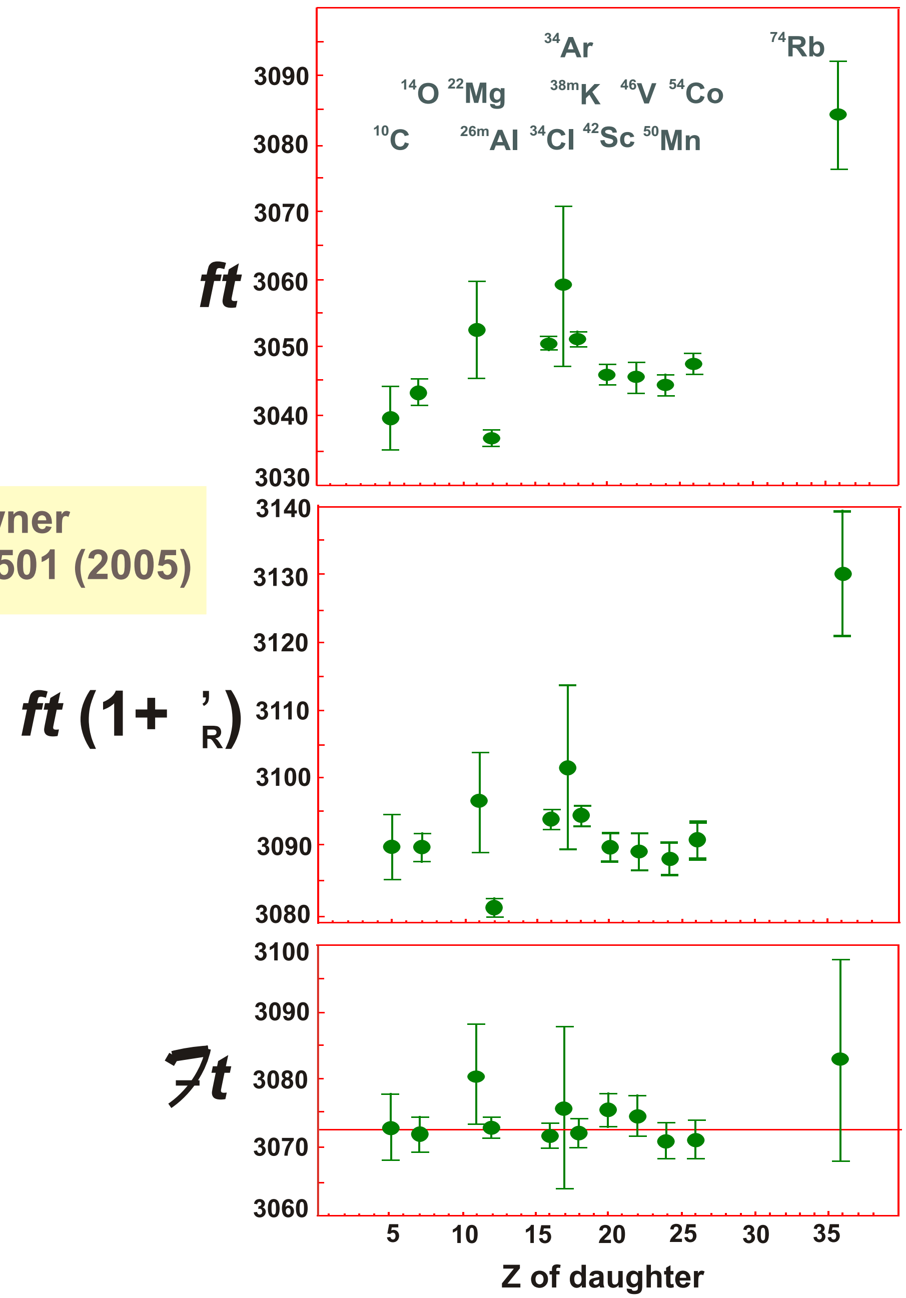

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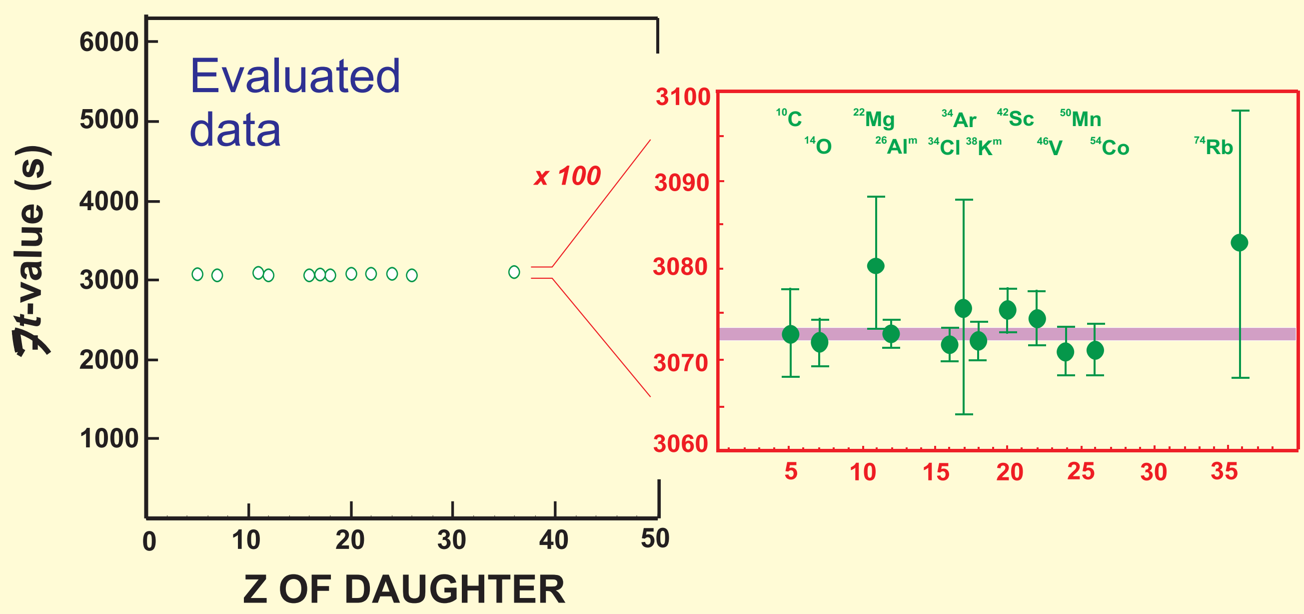

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$G_V'/(\hbar c)^3$
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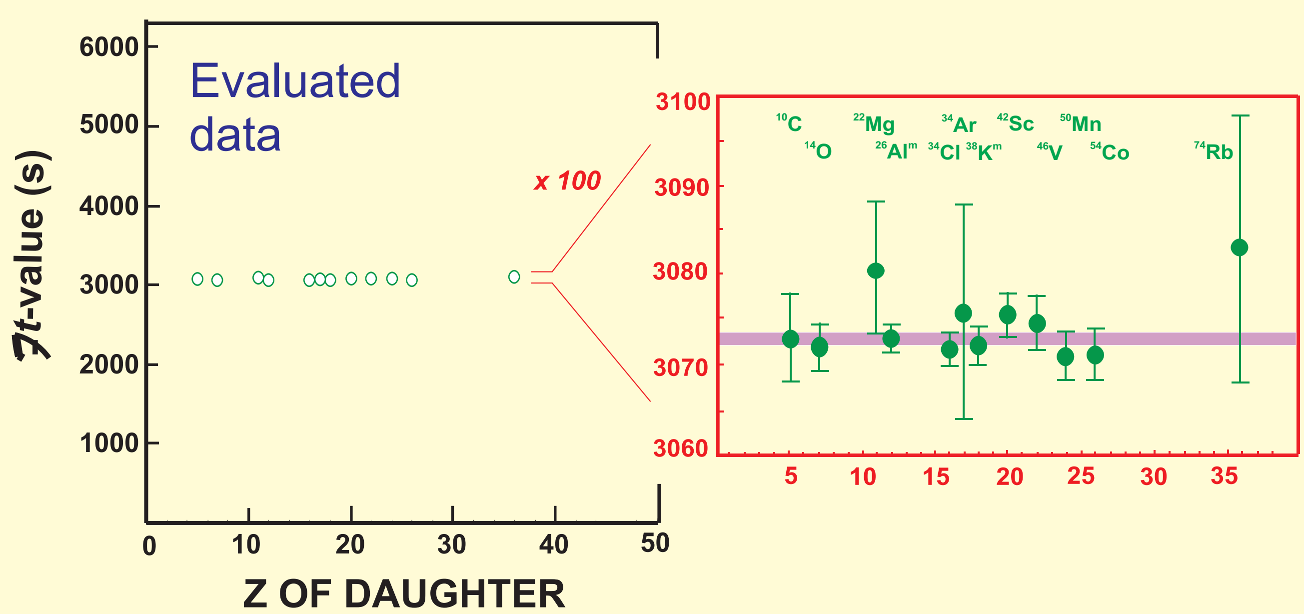

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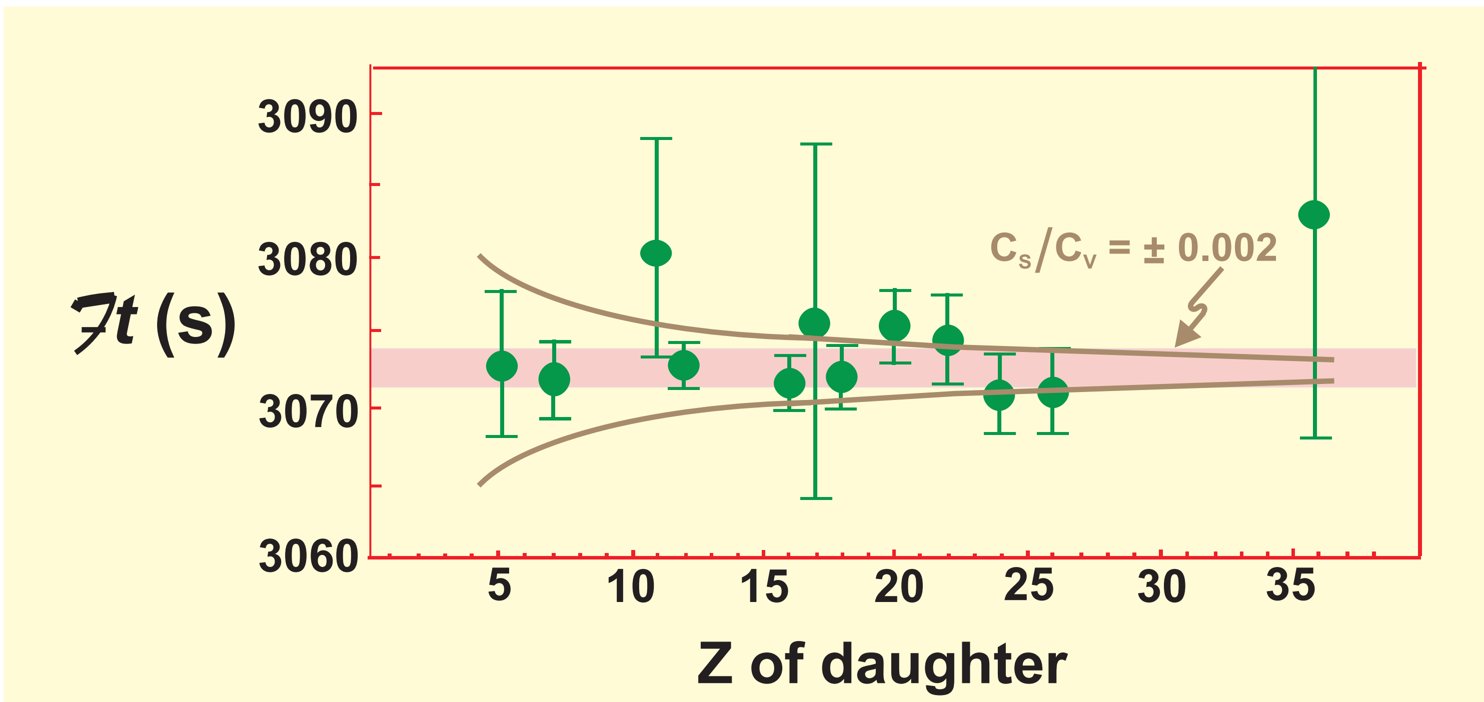

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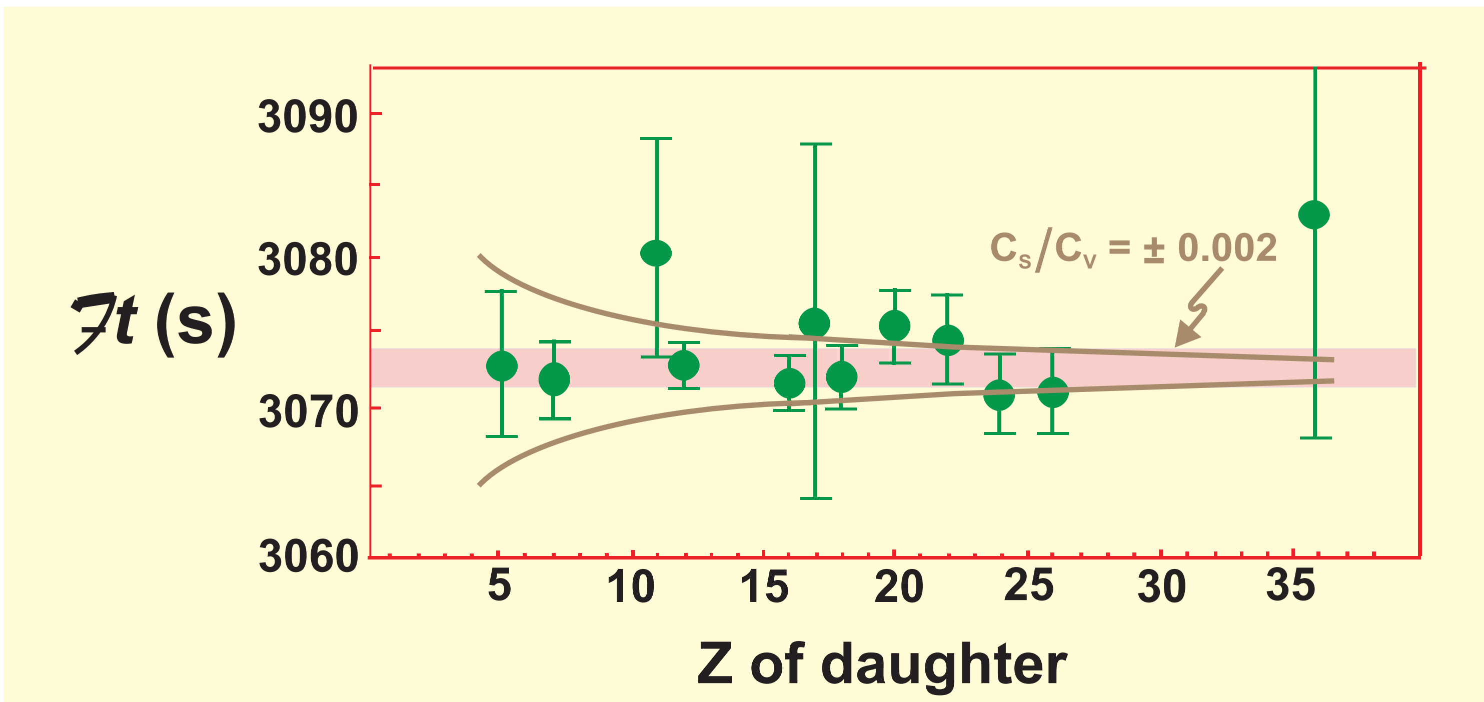

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Compare:

neutron	$V_{ud} = 0.9745 \pm 0.0018$
pion	$V_{ud} = 0.9751 \pm 0.0027$

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- **Goal is to tighten the window for new physics by reducing the uncertainty on V_{ud}.**

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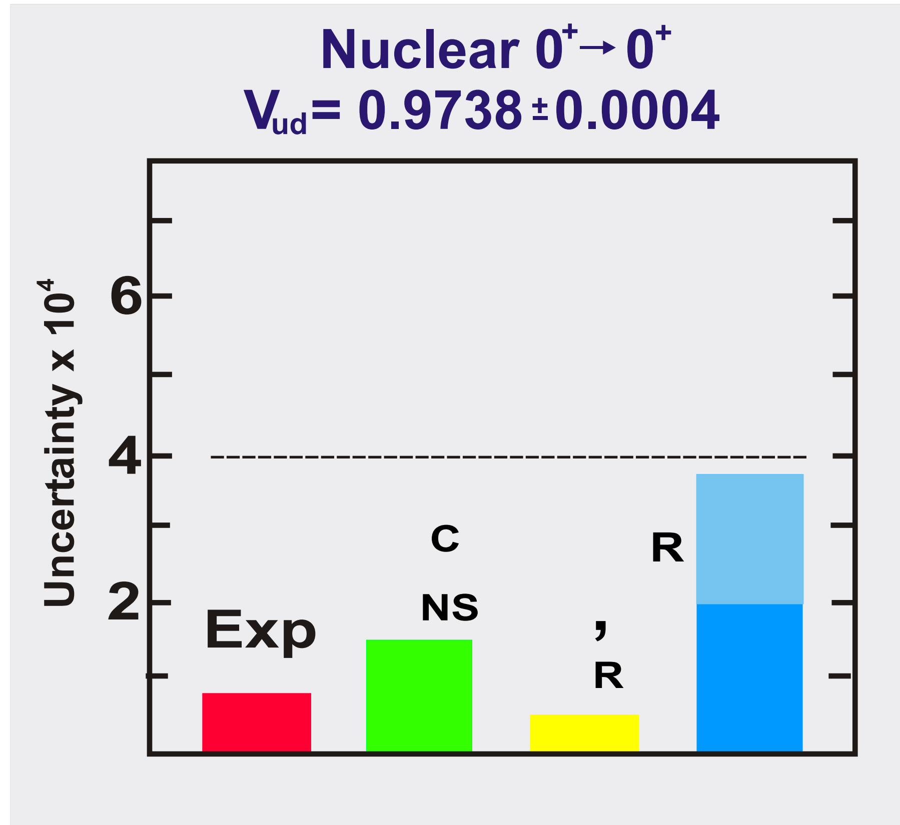

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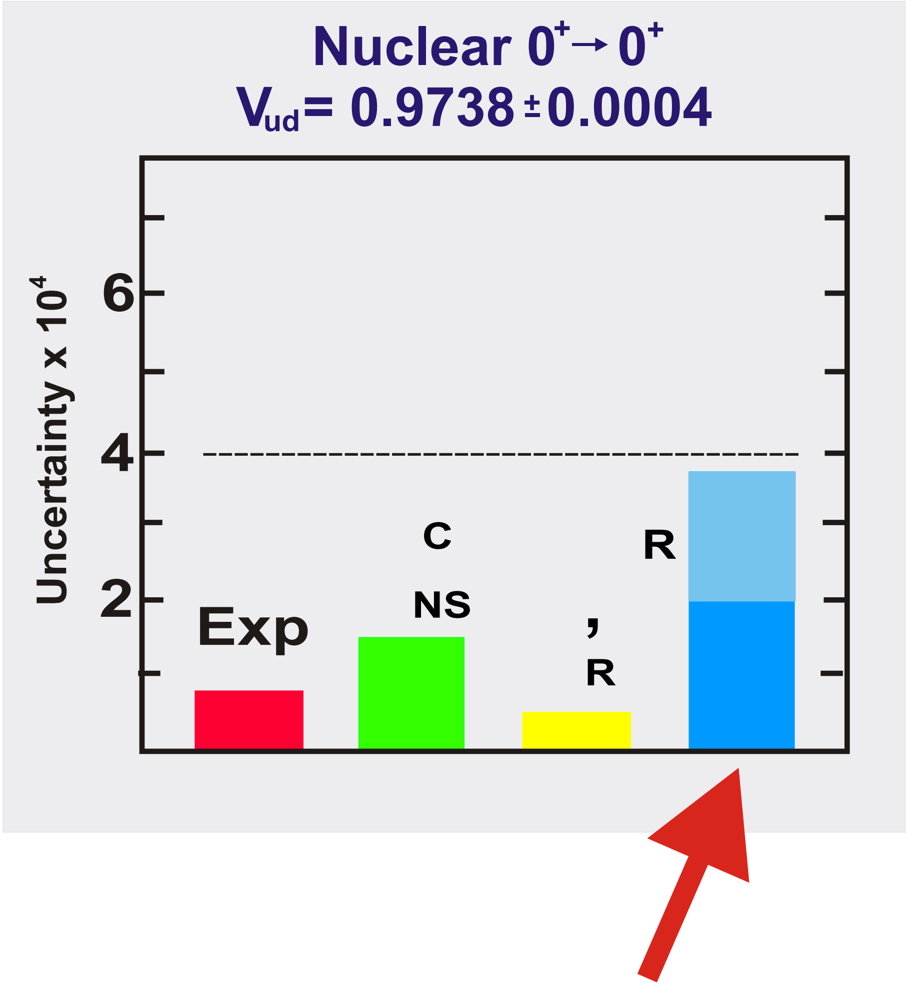
Marciano & Sirlin
PRL 96, 032002 (2006)



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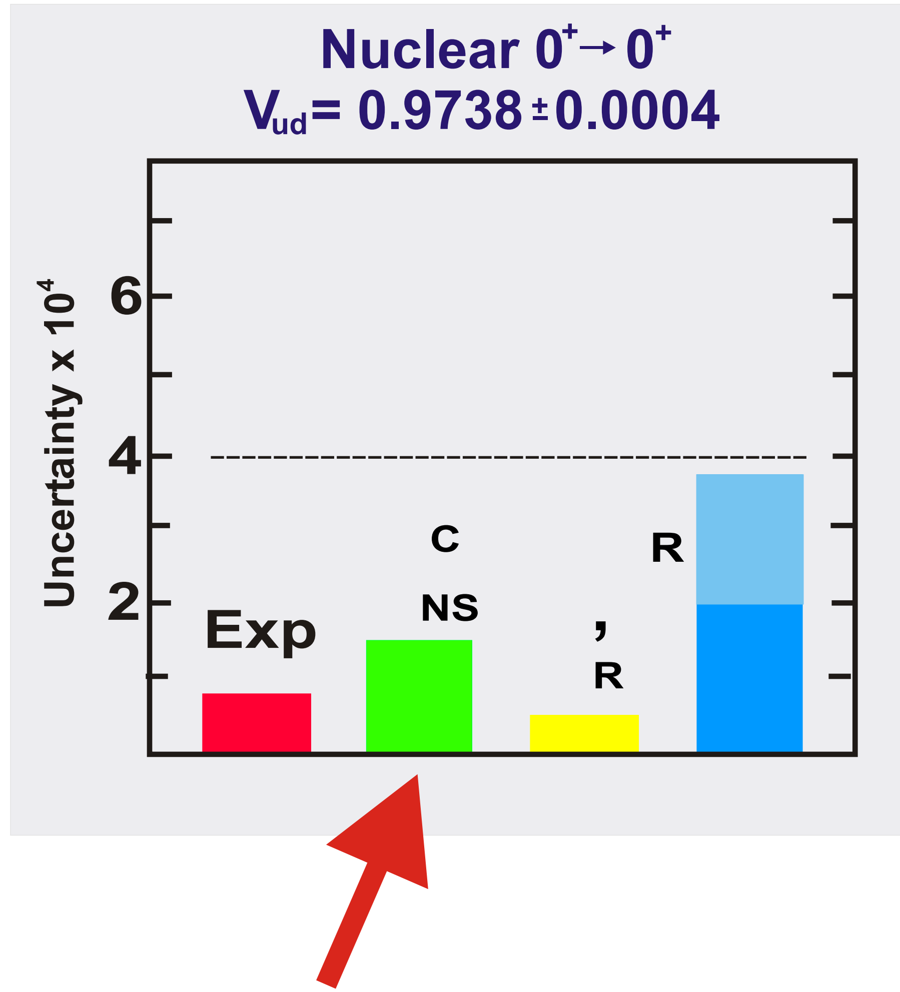

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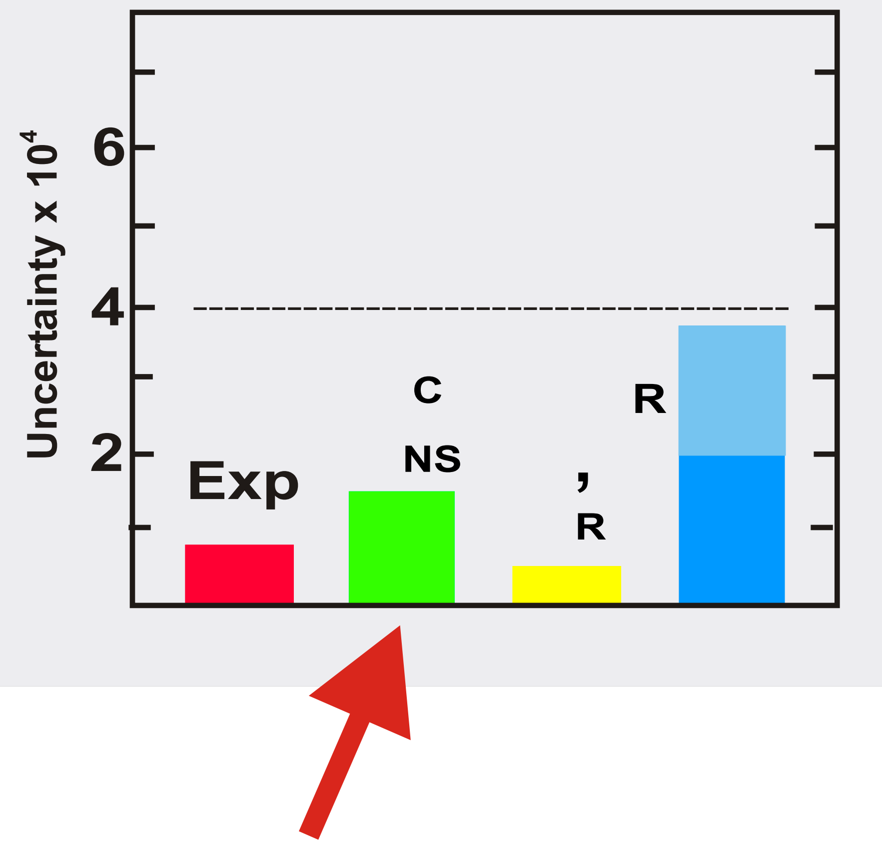
Well known cases being improved and new cases explored.

Nuclear $0^+ \rightarrow 0^+$
$V_{ud} = 0.9738 \pm 0.0004$



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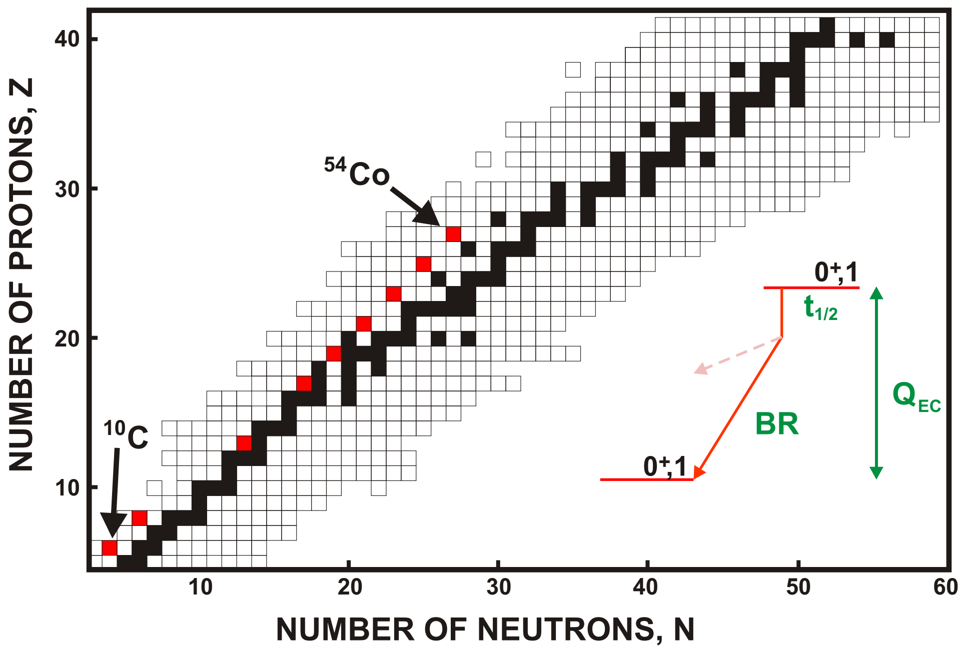

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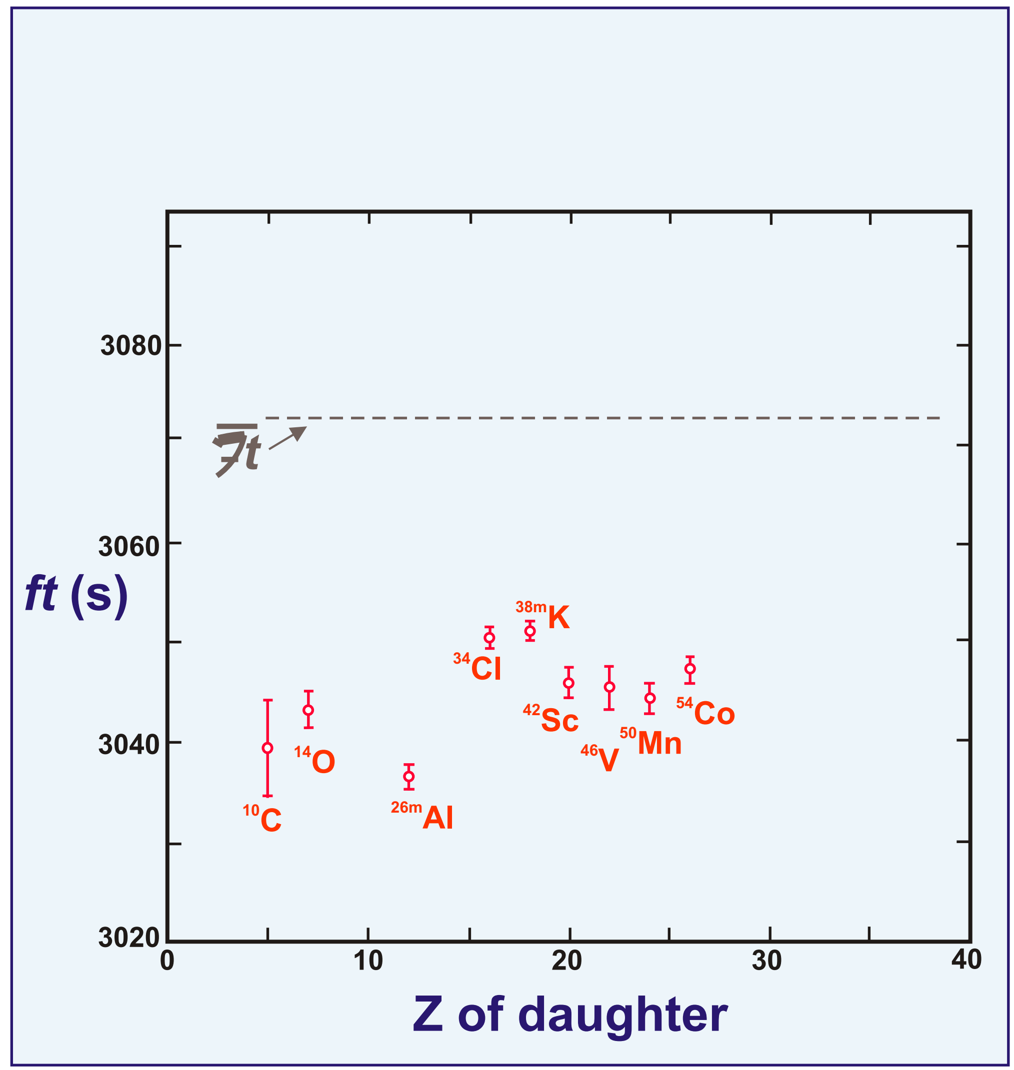
Strategy is to probe the nucleus-to-nucleus variation in $_{C}$ - $_{NS}$.



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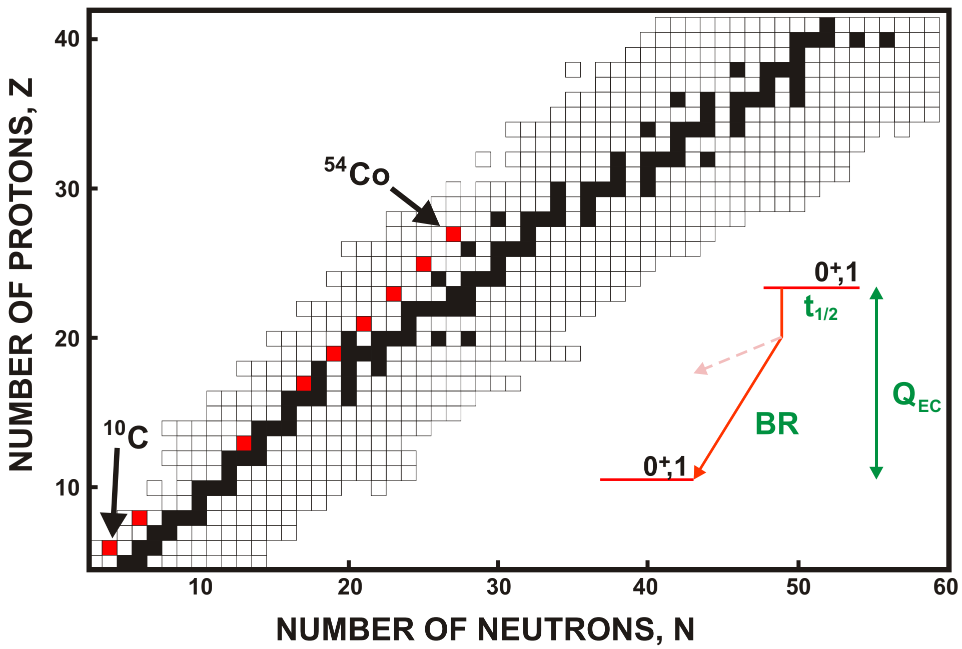

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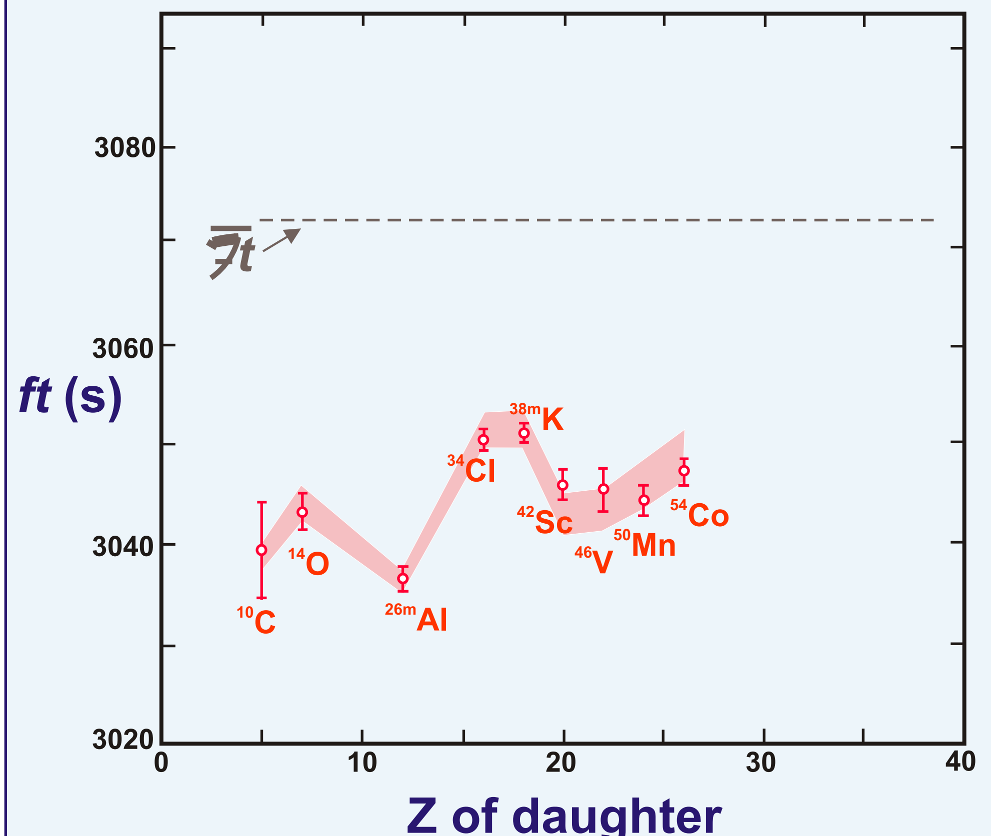

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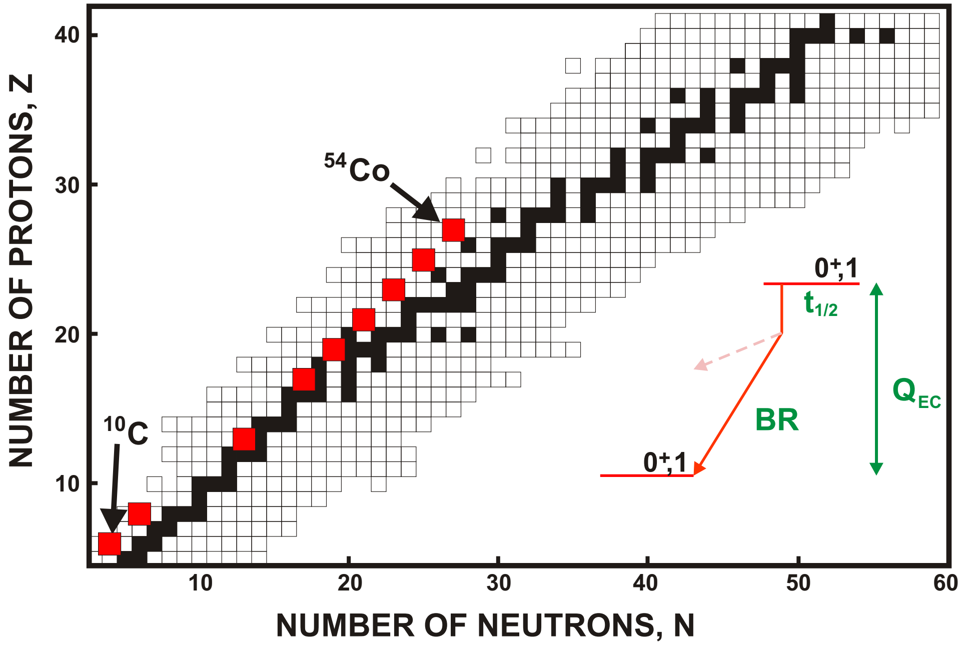

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Increase measured precision on nine best *ft*-values

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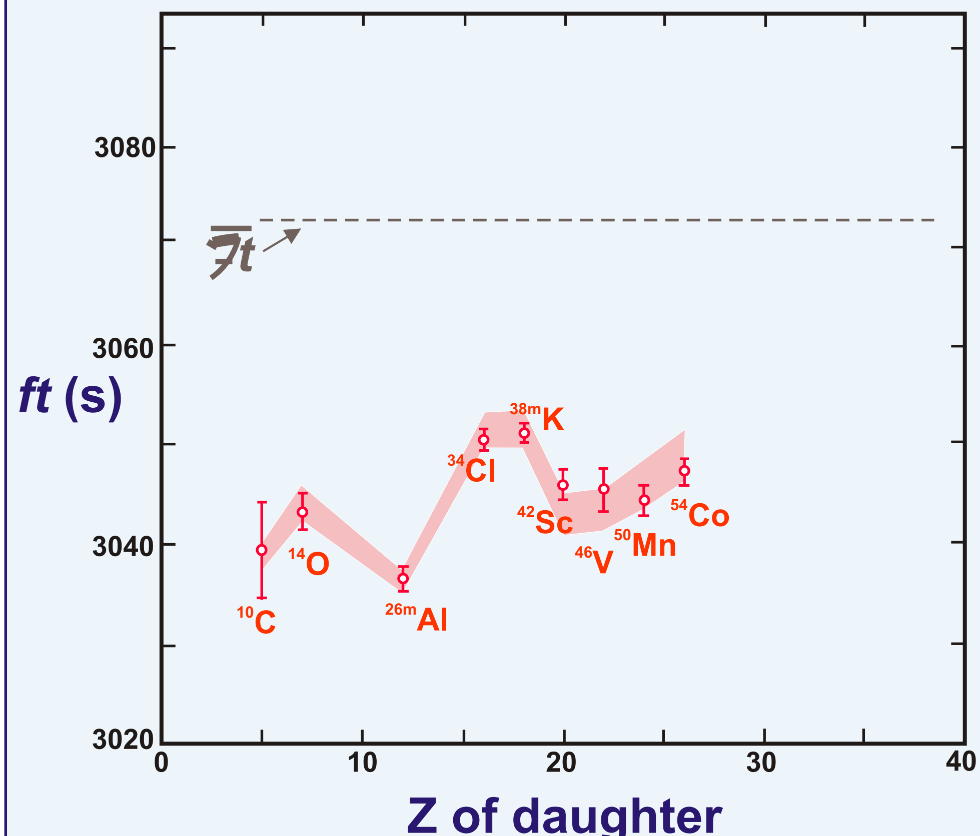

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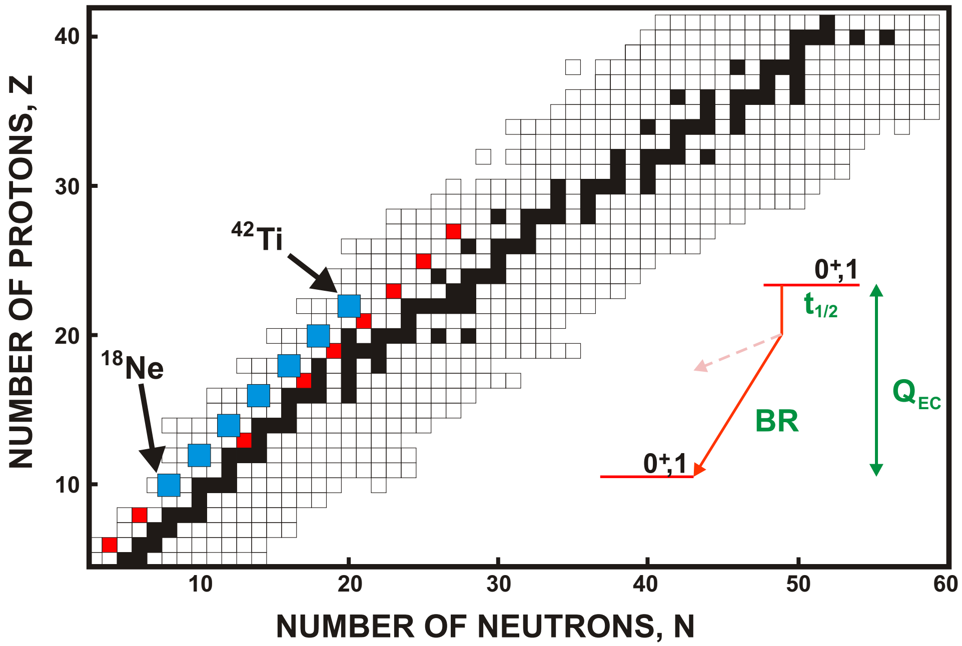

Increase measured precision on nine best *ft*-values

measure new $0^+ \rightarrow 0^+$ decays with $18 \leq A \leq 42$ ($T_Z = -1$)

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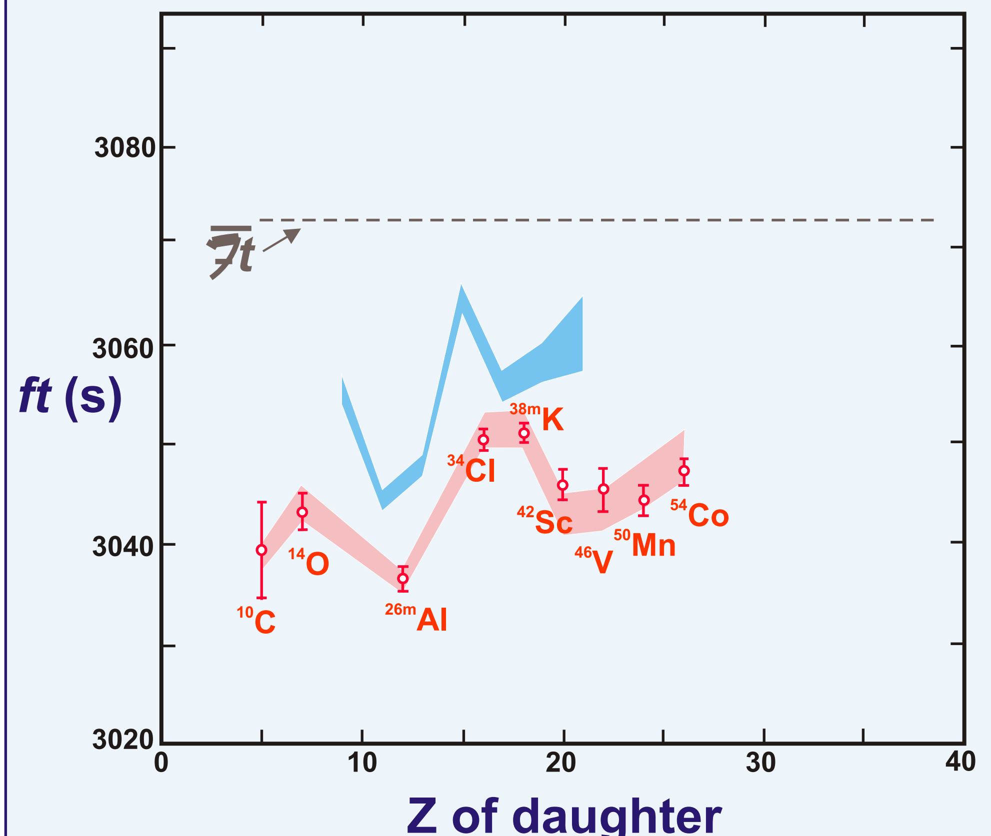

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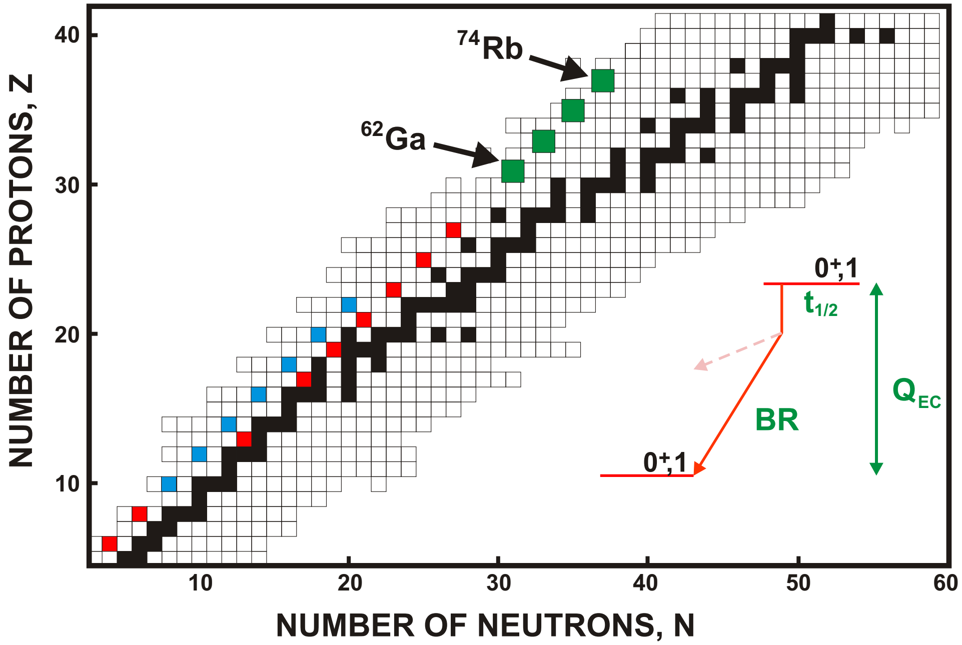

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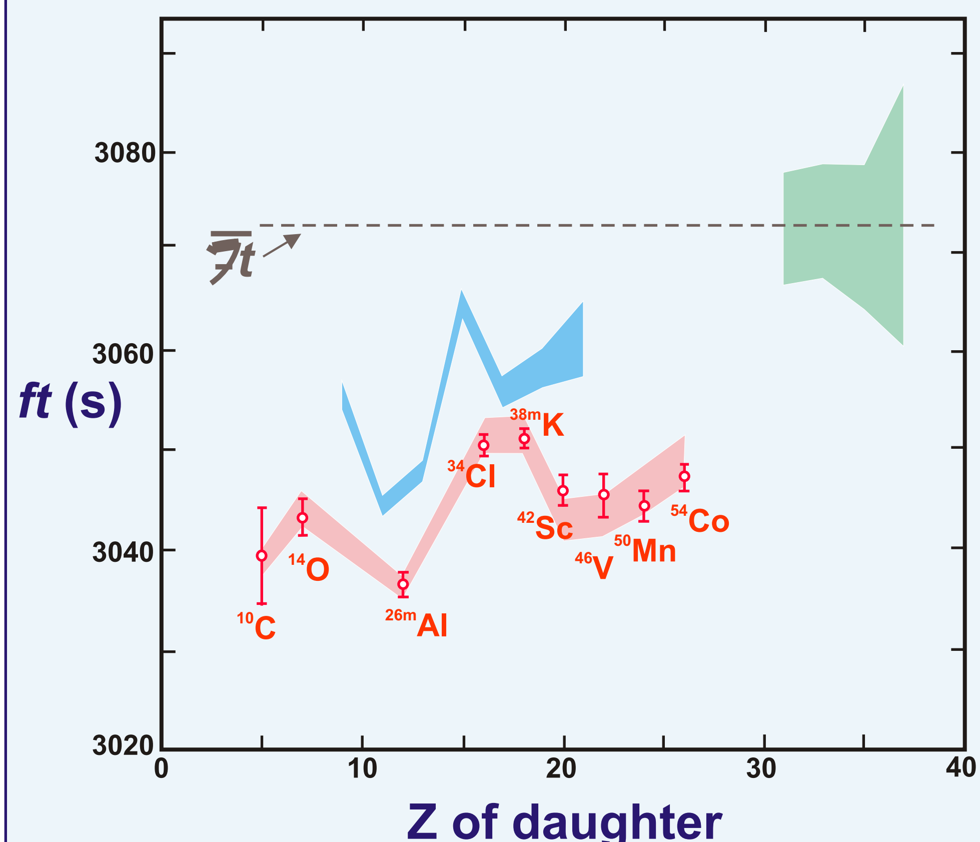

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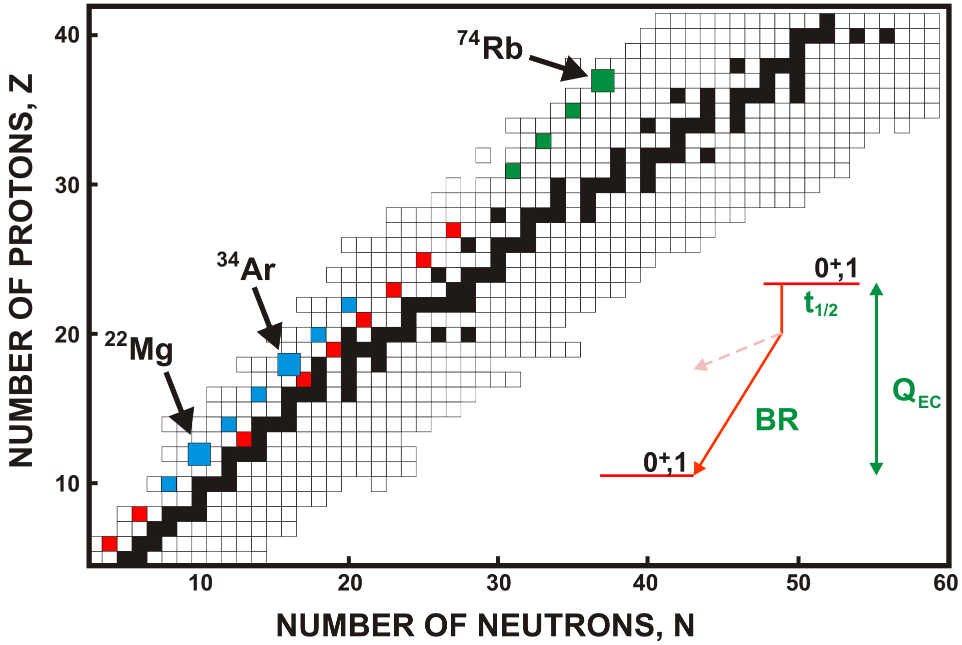

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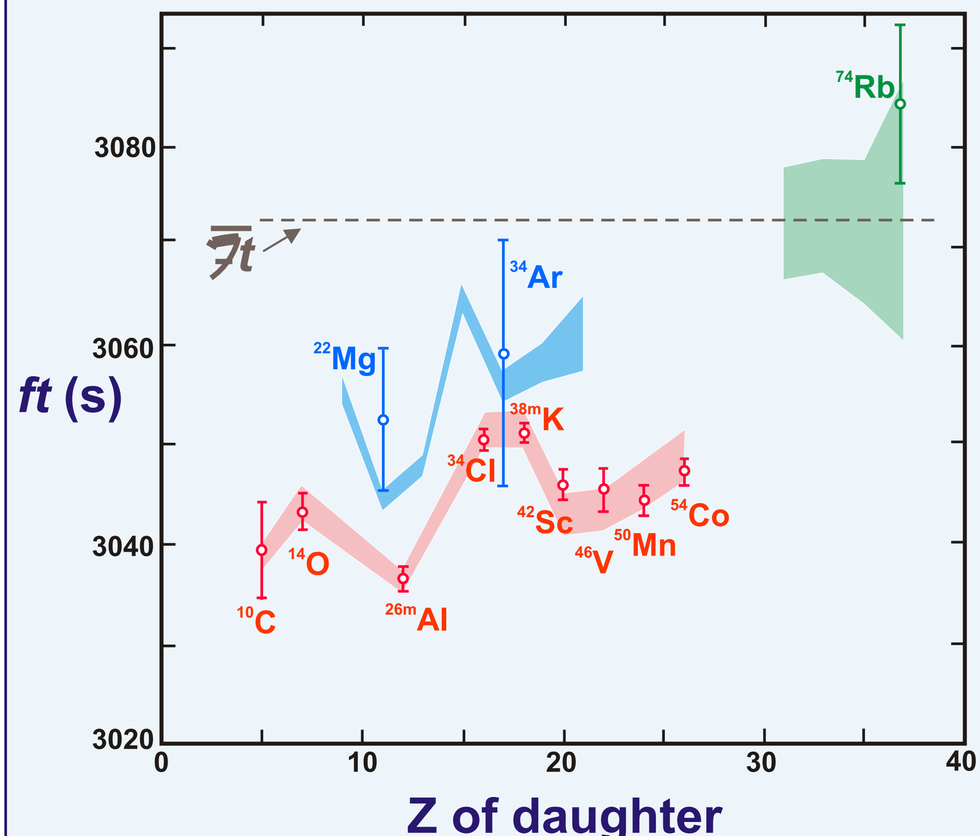

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measure new $0^+ \rightarrow 0^+$ decays with $A \geq 62$ (T_z = 0)

RECENT OR CURRENT EXPERIMENTS

Q_{EC} values:

Argonne (Canadian Penning trap)

^{46}V Savard *et al.*, PRL 95, 102501 (2005)

^{10}C, ^{14}O, ^{26}Al^{m}, ^{34}Cl, ^{42}Sc

Jyvaskyla (JYFLTRAP)

^{62}Ga Eronen *et al.* PLB 636, 191 (2006)

^{26}Al^{m}, ^{42}Sc, ^{46}V Eronen *et al.*, PRL 97, 232501 (2006)

^{50}Mn, ^{54}Co

NSCL (LEBIT)

^{38}Ca Bollen *et al.*, PRL 96, 152501 (2006)

Munich Tandem

^{46}V Faestermann *et al.*, Progress Report

ISOLTRAP

^{38}Ca George *et al.*, PRL 98, 162501 (2007)

Half-lives:

Auckland/Canberra

^{50}Mn Barker & Byrne, PRC 73, 064306 (2006)

LBNL

^{14}O Burke *et al.*, PRC 74, 025501 (2006)

Texas A&M

^{34}Cl, ^{34}Ar Iacob *et al.* PRC 74, 055502 (2006)

^{10}C, ^{38}Ca

Branching ratios:

TRIUMF

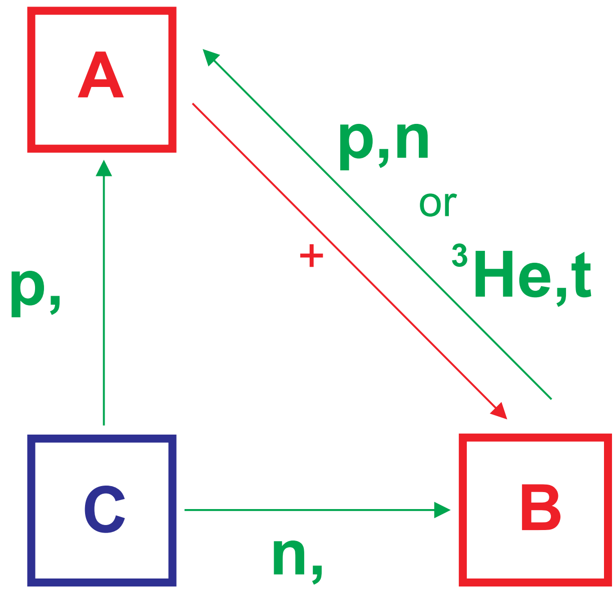
^{62}Ga Hyland *et al.*, PRL 97, 102501 (2006)

Texas A&M

^{14}O Towner & Hardy, PRC 72, 055501 (2005)

^{34}Ar, ^{38}Ca

METHODS USED FOR PRECISION MEASUREMENTS OF Q_{EC}



- **B(p,n)A threshold: p energy referred to standard volt.**

  ±120 eV

  Auckland:
  e.g. Phys. Rev. **C58** (1998) 821.

- **C(p,)A and C(n,), Q value difference: p energy calibrated to known (p,).**

  ±100-200 eV

  Oak Ridge/Utrecht:
  e.g. Nucl. Phys. **A529** (1991) 39.

- **B(^{3}He,t)A and B'(^{3}He,t)A', Q_{EC} doublet: difference measured with voltmeter.**

  ±130-200 eV

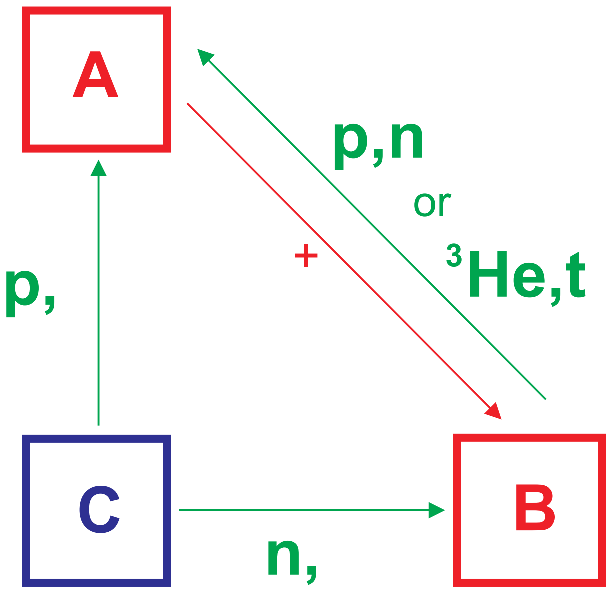
  Chalk River:
  e.g. Nucl. Phys. **A472** (1987) 419.

- **Separate mass measurements of A and B: measured with on-line Penning trap.**

  ±50-400 eV

  e.g. Argonne (CPT):
  Phys. Rev. Lett. **95** 102501 (2005).

METHODS USED FOR PRECISION MEASUREMENTS OF Q_{EC}



- **B(p,n)A threshold: p energy referred to standard volt.**

  ±120 eV

  Auckland:
  e.g. Phys. Rev. **C58** (1998) 821.

- **C(p,)A and C(n,), Q value difference: p energy calibrated to known (p,).**

  ±100-200 eV

  Oak Ridge/Utrecht:
  e.g. Nucl. Phys. **A529** (1991) 39.

- **B(^{3}He,t)A and B'(^{3}He,t)A', Q_{EC} doublet: difference measured with voltmeter.**

  ±130-200 eV

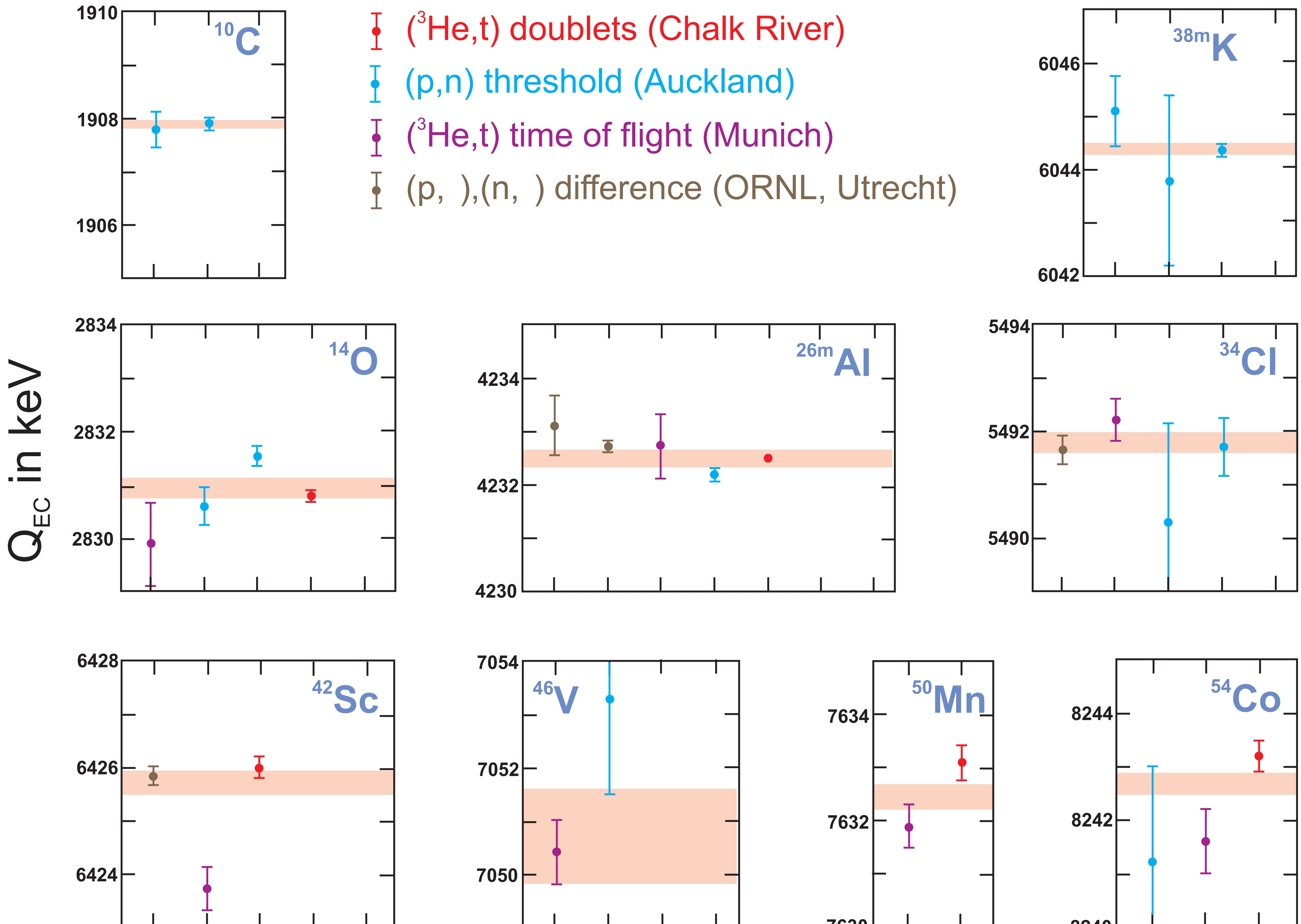
  Chalk River:
  e.g. Nucl. Phys. **A472** (1987) 419.

- **Separate mass measurements of A and B: measured with on-line Penning trap.**

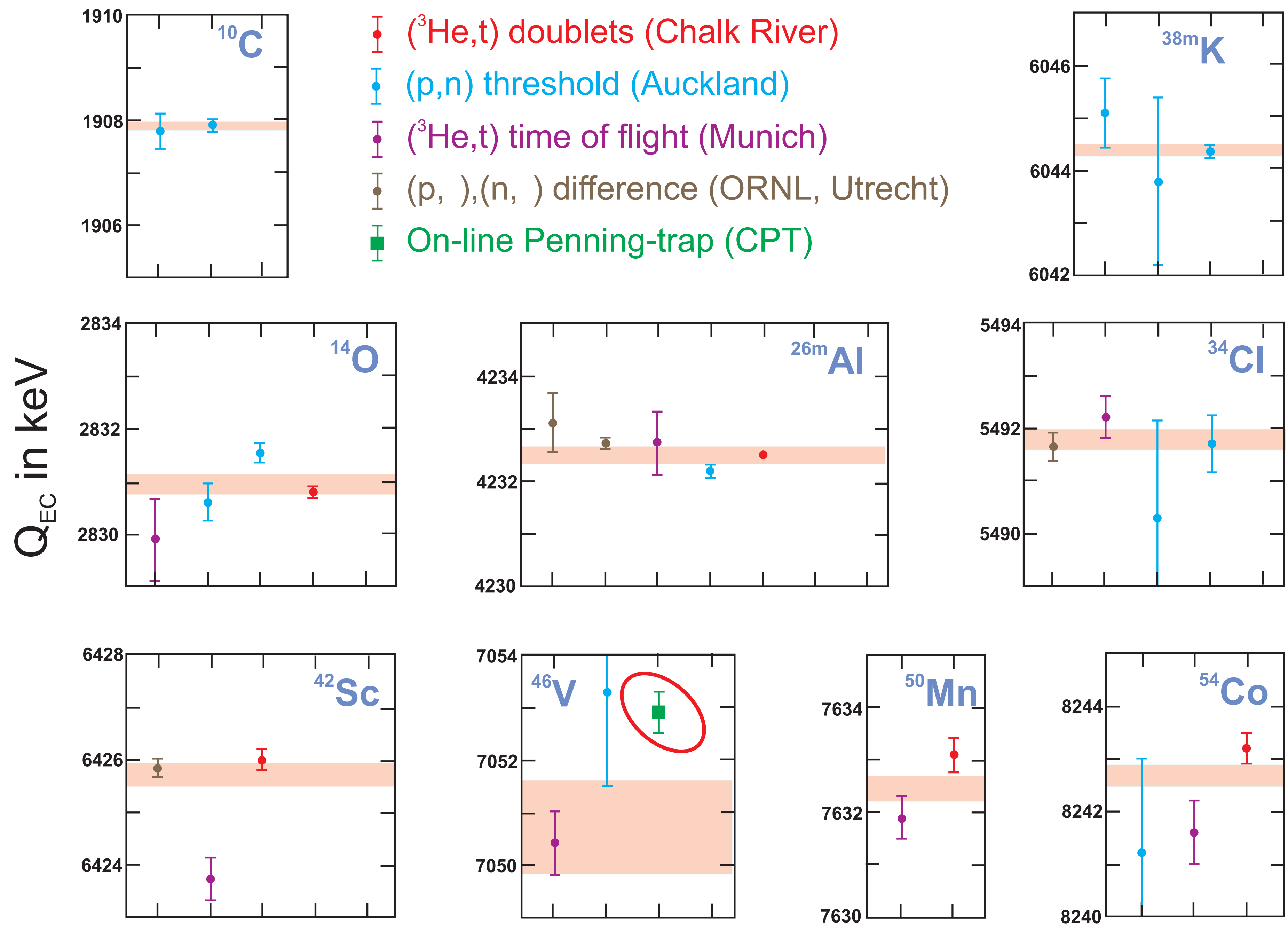
  ±50-400 eV

  e.g. Argonne (CPT):
  Phys. Rev. Lett. **95** 102501 (2005).

Q_{EC} FOR SUPERALLOWED TRANSITIONS (keV)



Q_{EC} FOR SUPERALLOWED TRANSITIONS (keV)



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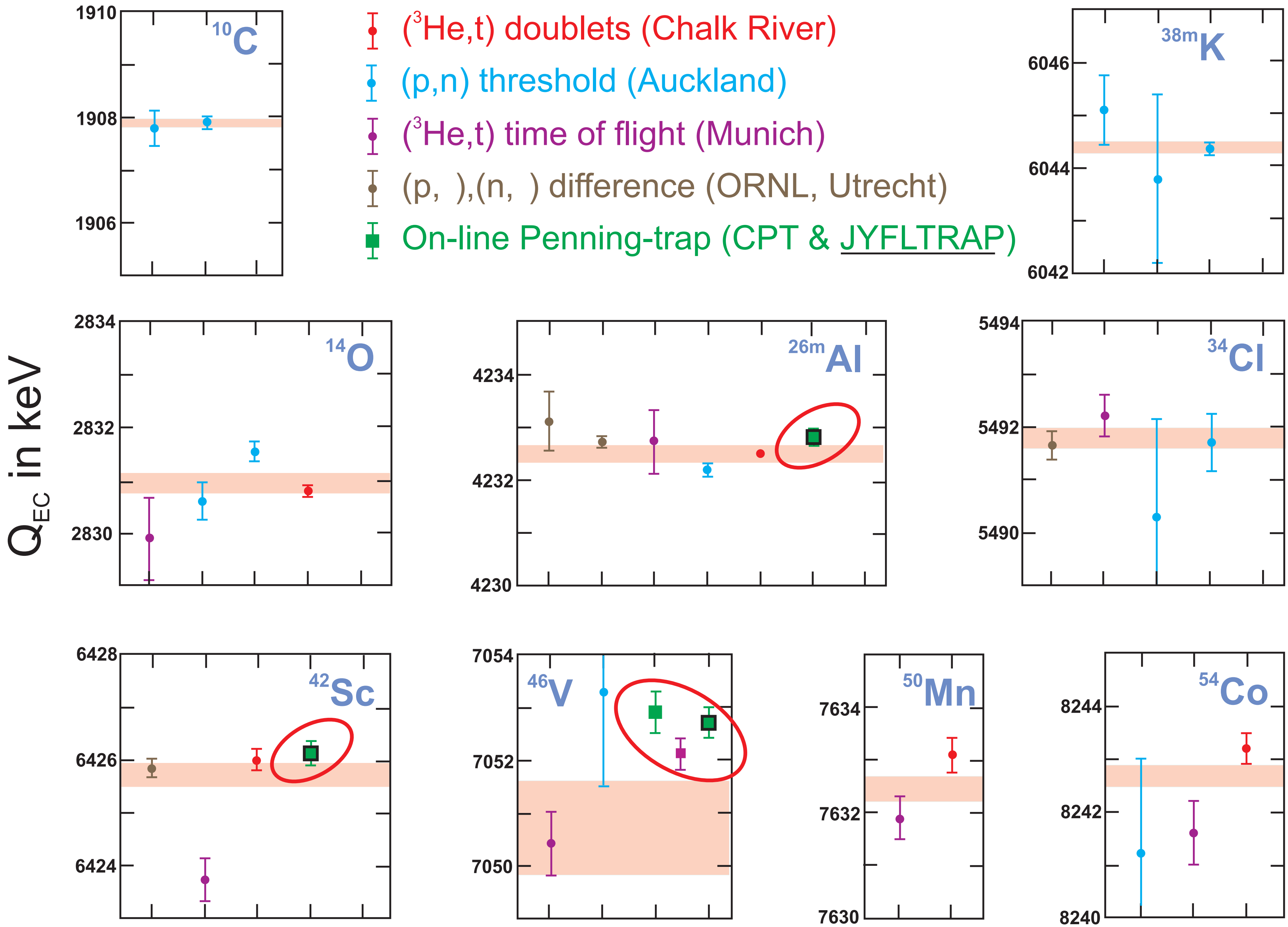
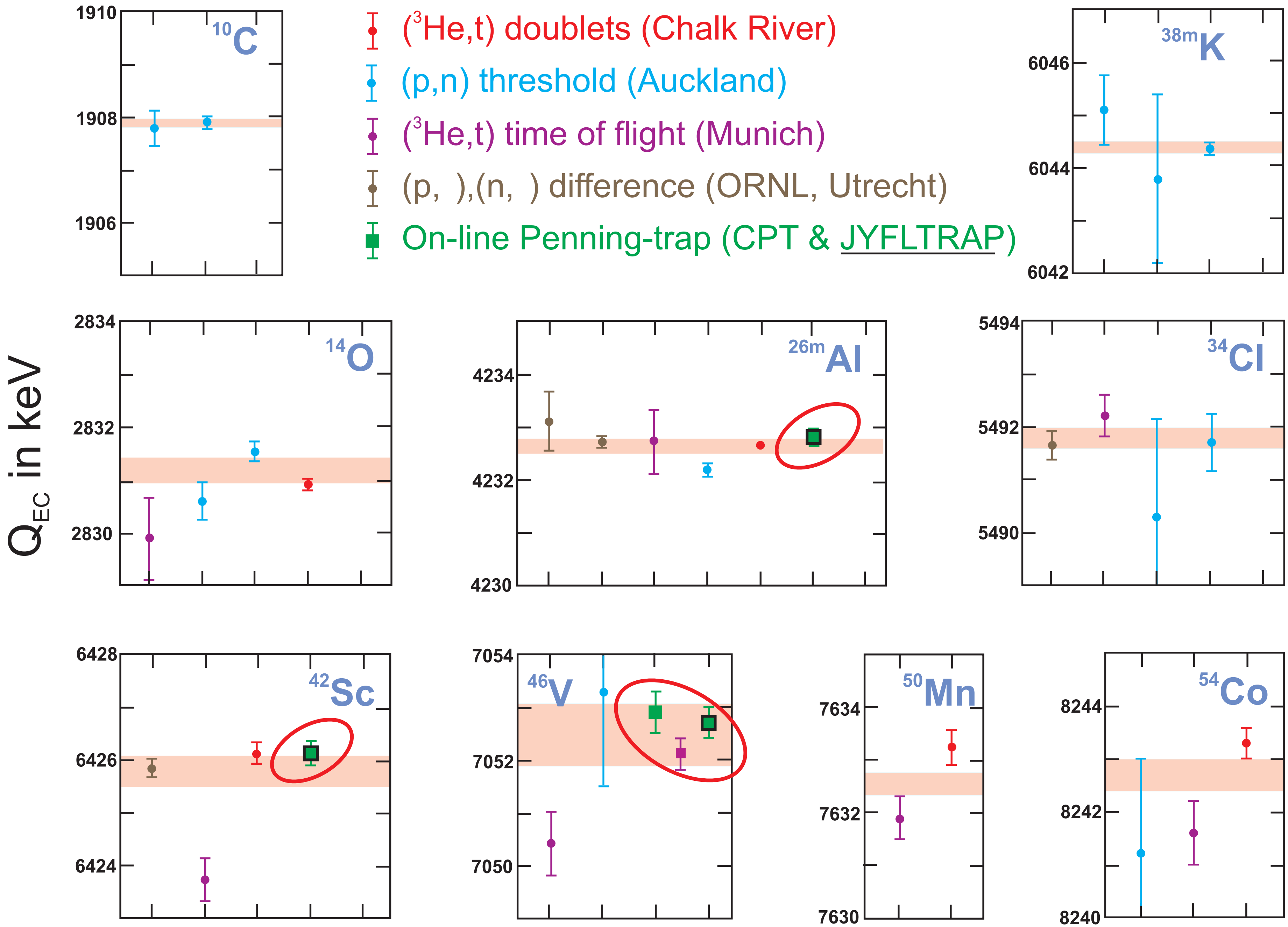
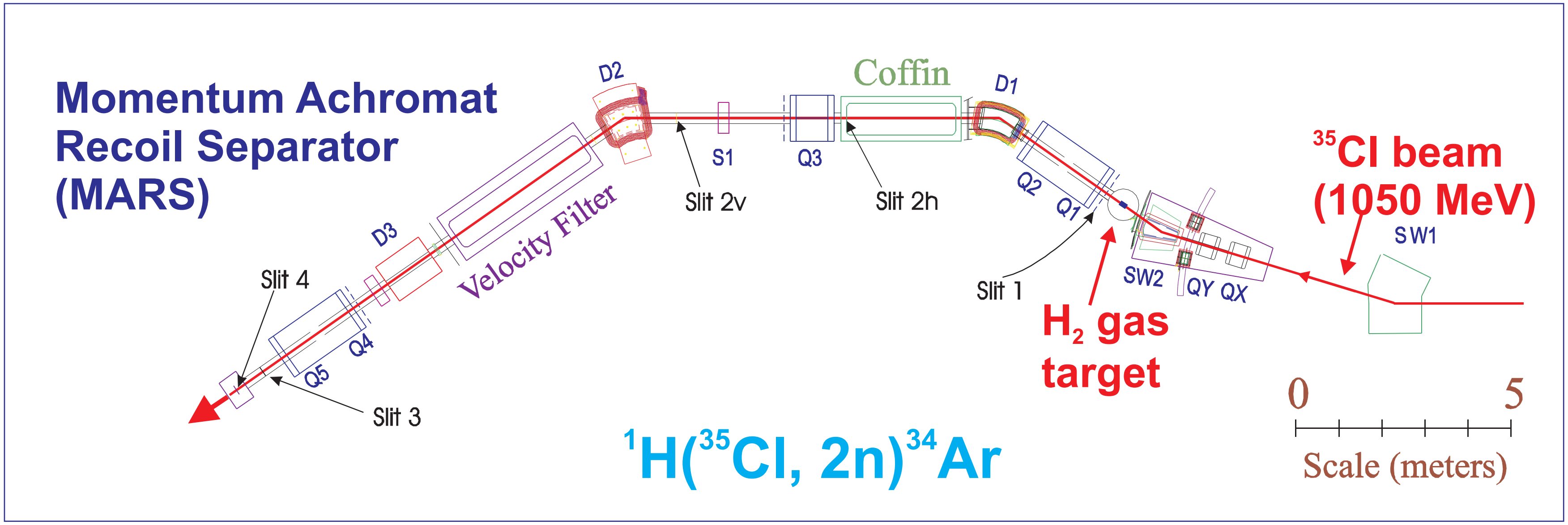


Q_{EC} FOR SUPERALLOWED TRANSITIONS (keV)



PRECISION DECAY MEASUREMENTS AT TAMU



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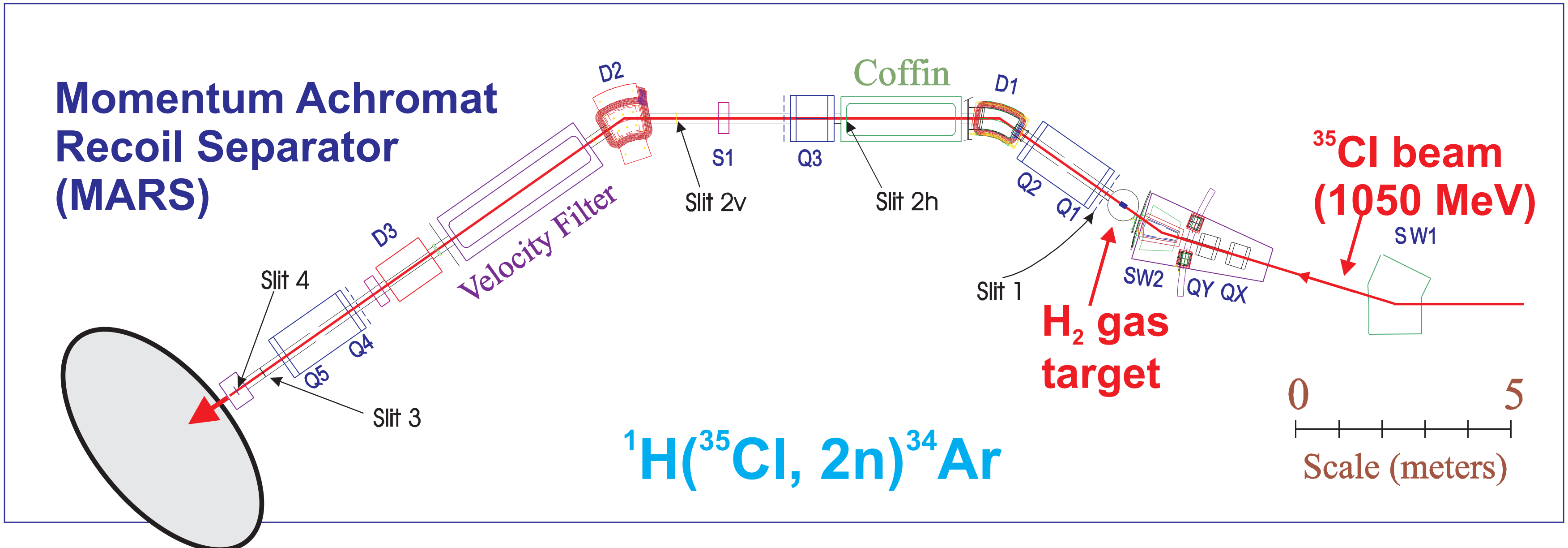

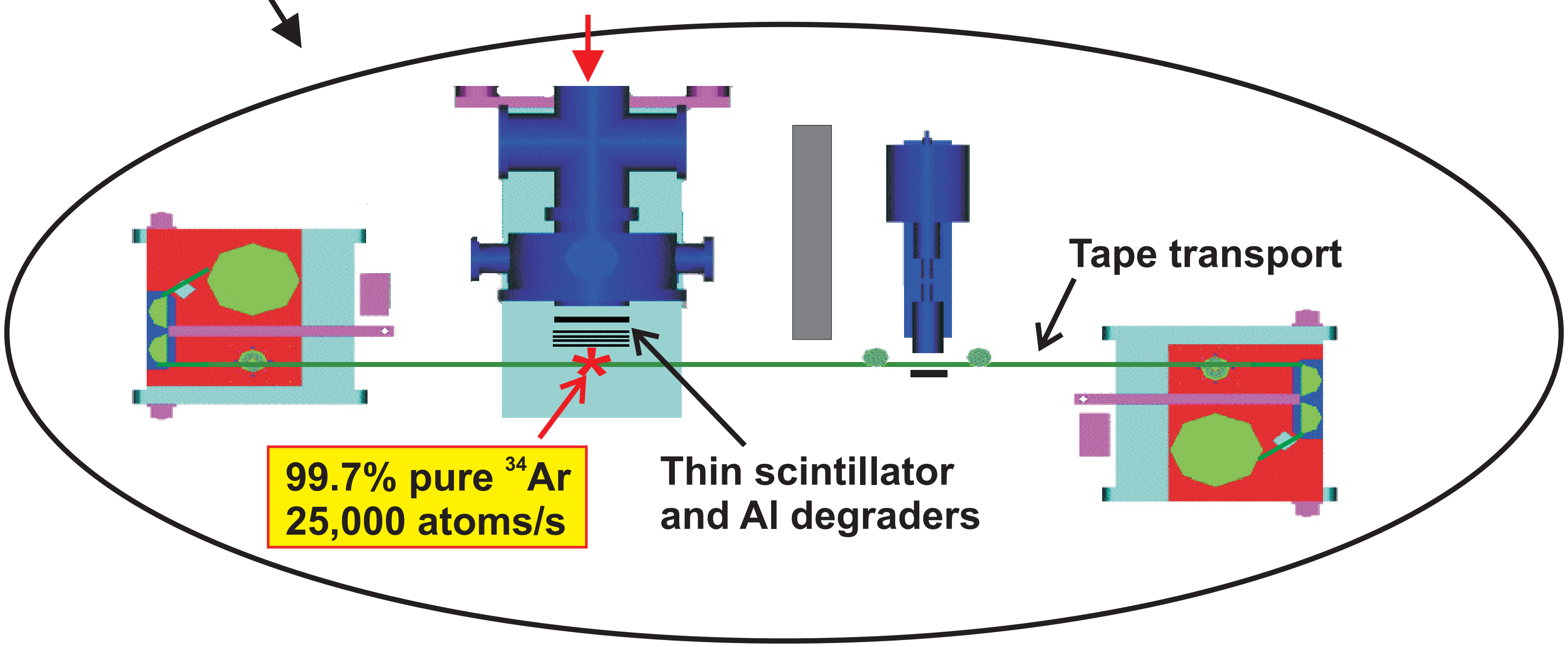

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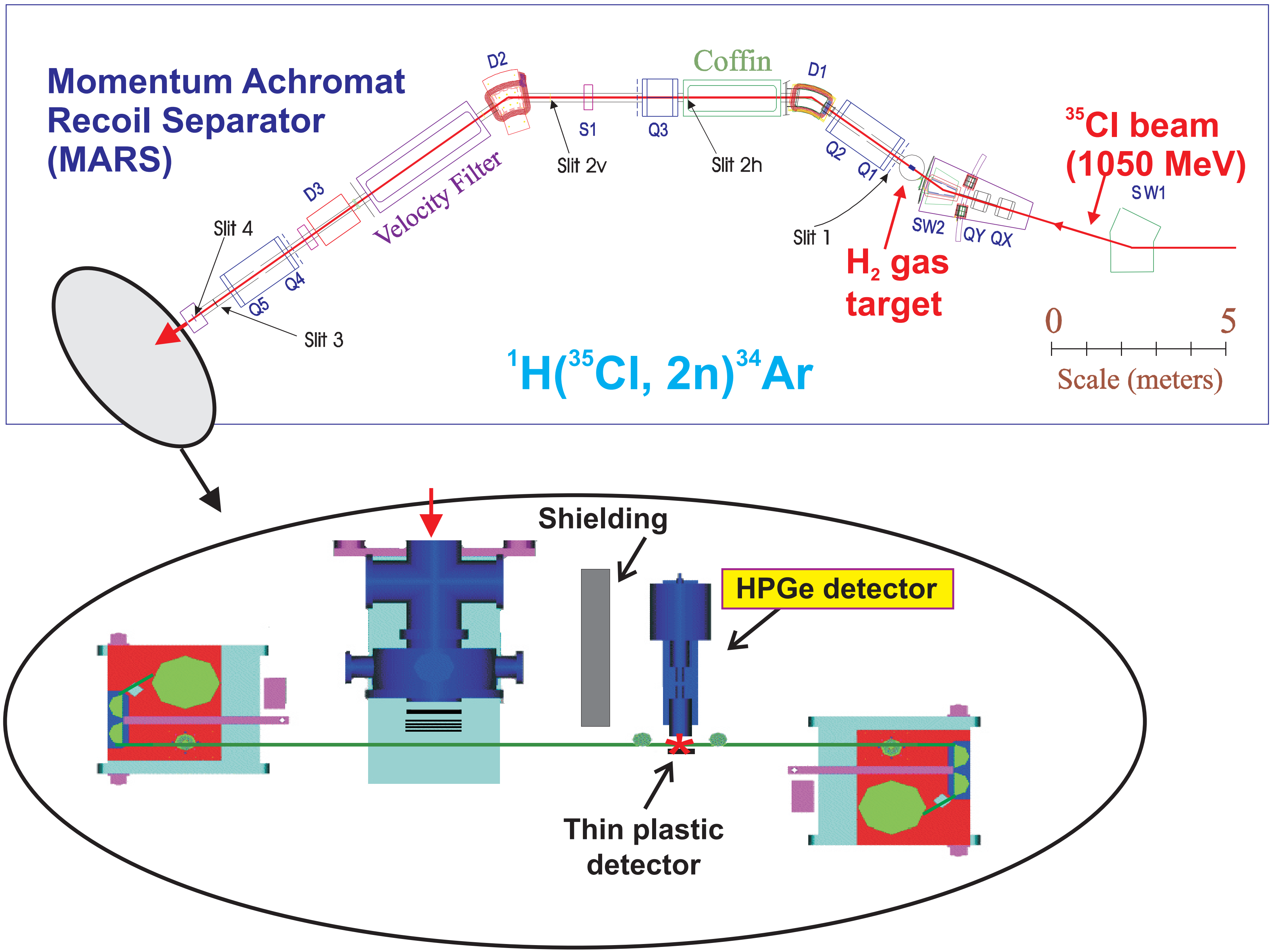
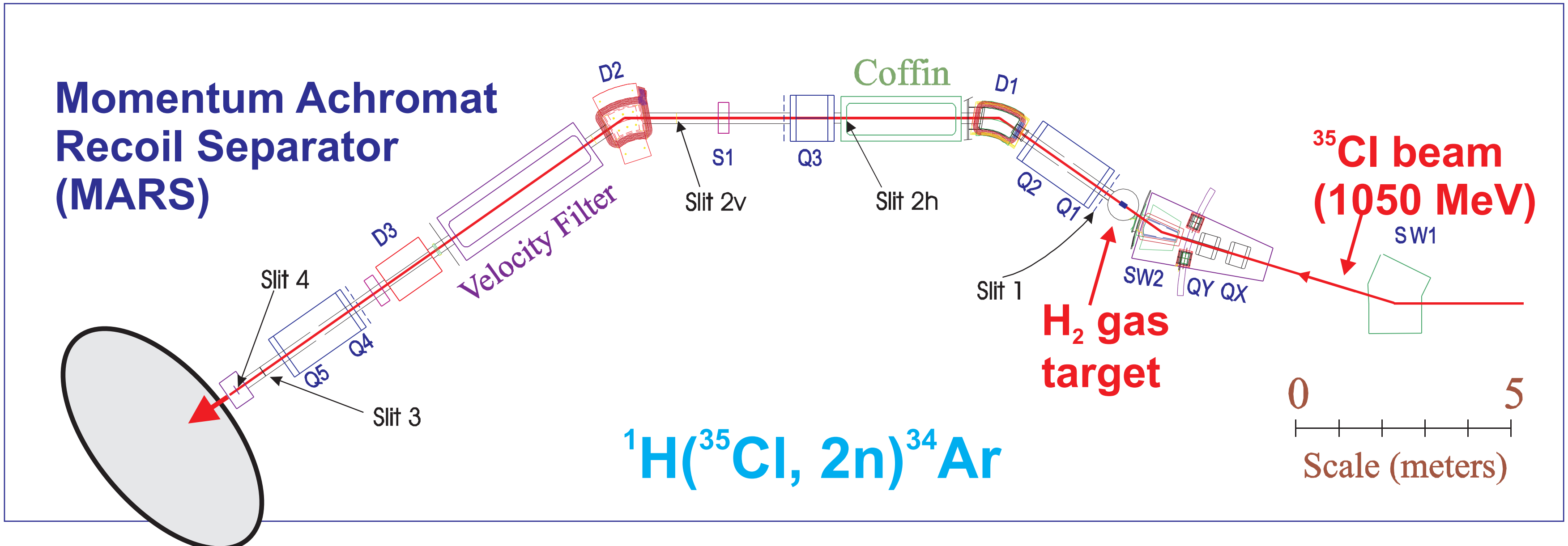
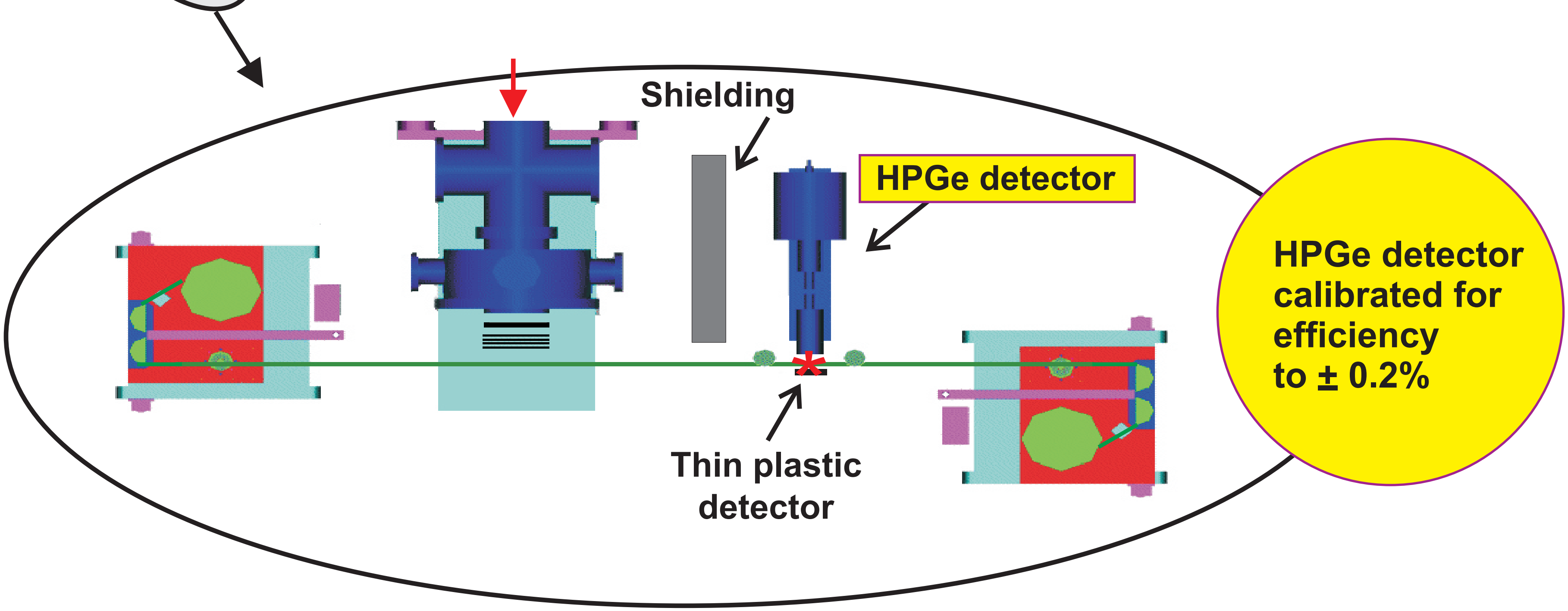


PRECISION DECAY MEASUREMENTS AT TAMU





DETECTOR EFFICIENCY
50 keV < E < 1.4 MeV

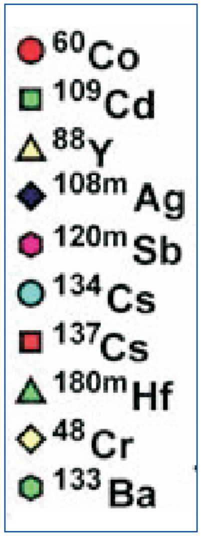
Source measurements
vs
unscaled Monte Carlo calculations (CYLTRAN)

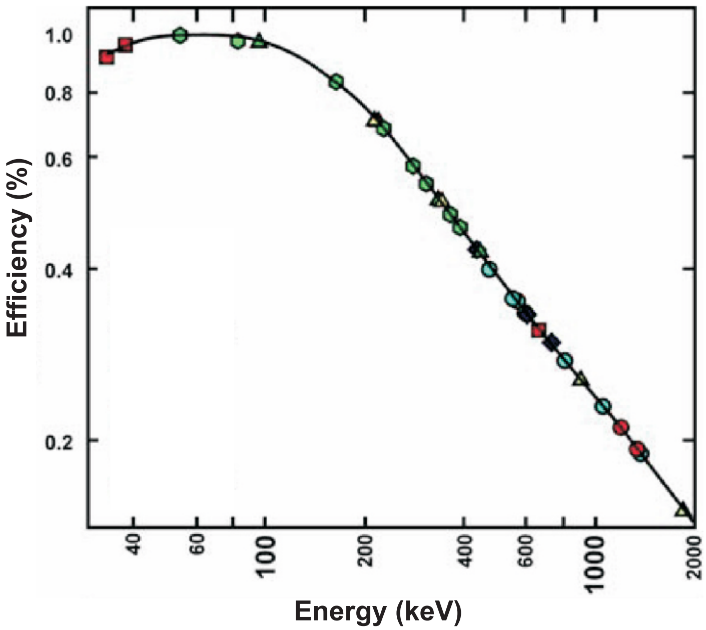
Physical properties and location of HPGe crystal measured precisely

10 sources recorded

4 key sources, 3 locally made, have pure cascades

^{60}Co source from PTB with activity known to + 0.1%





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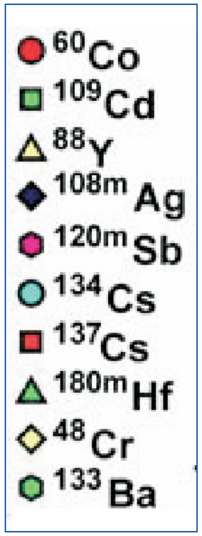

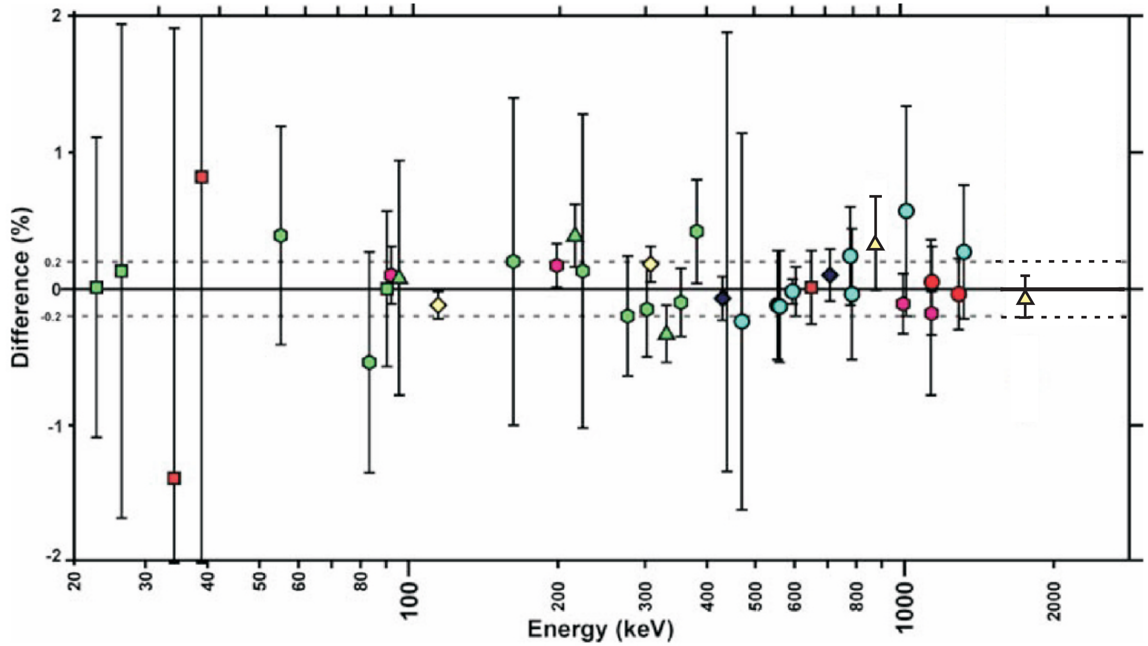

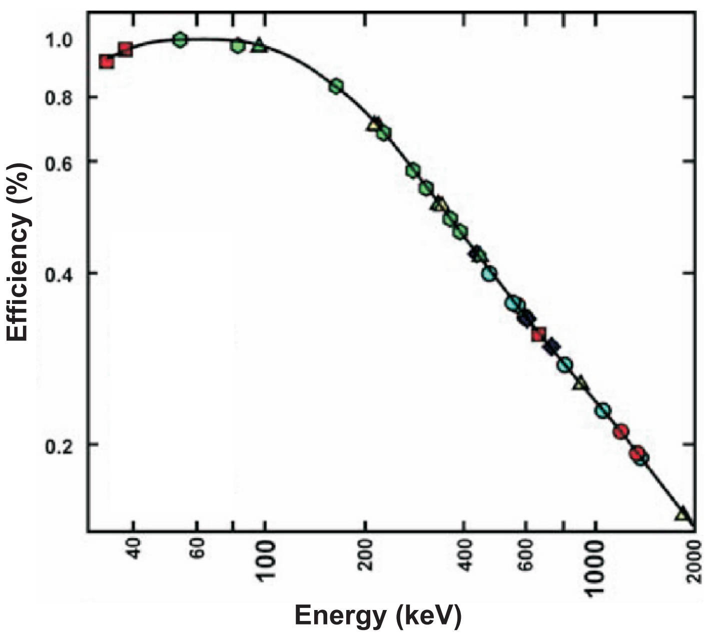

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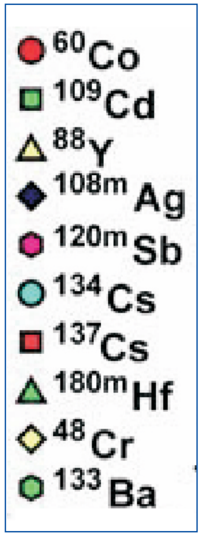
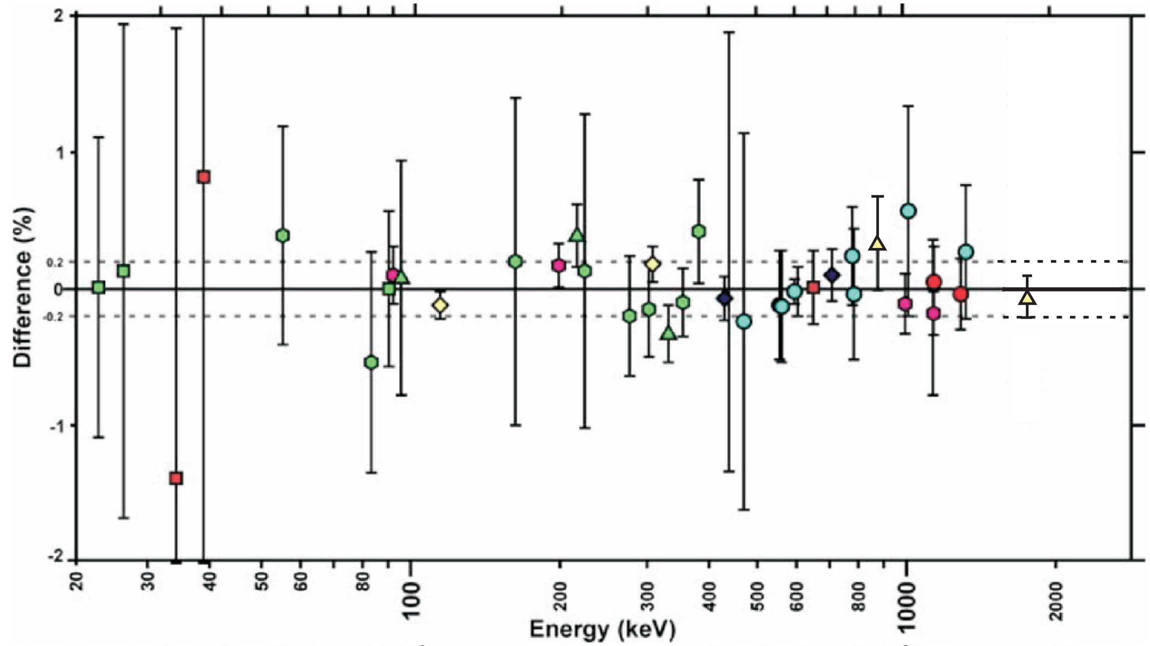
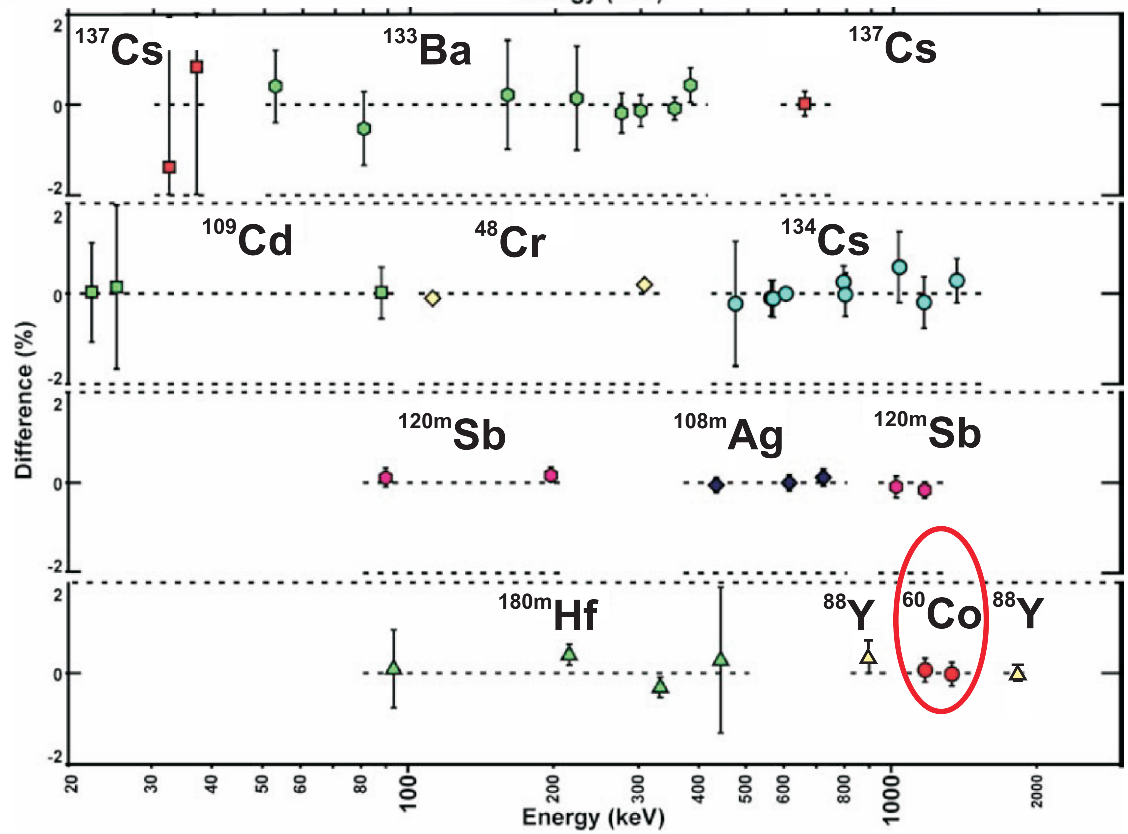
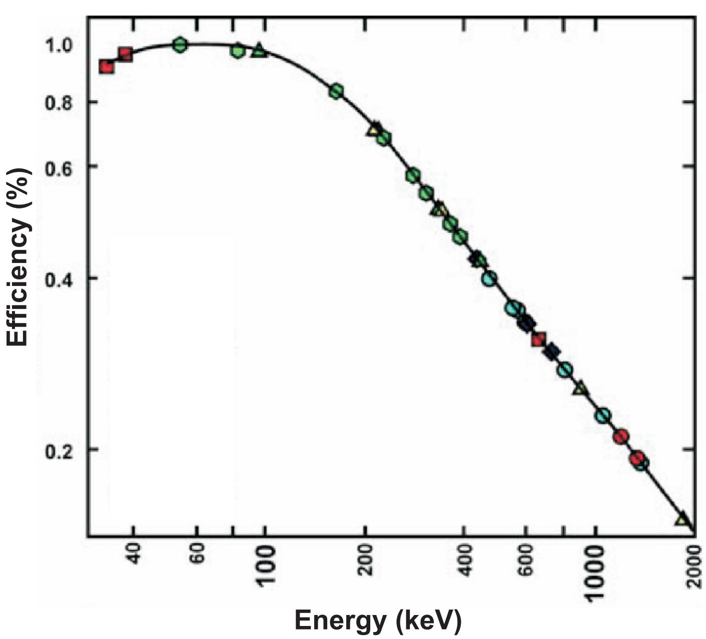
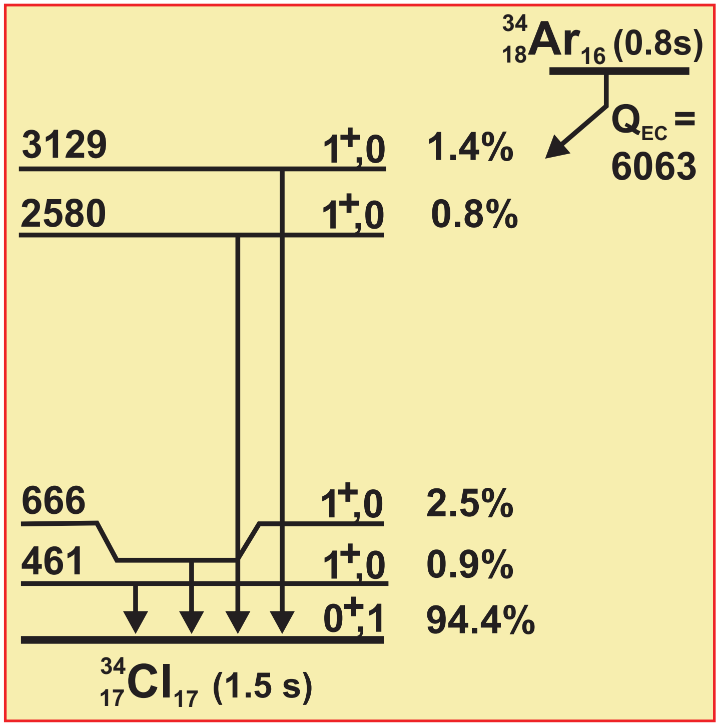


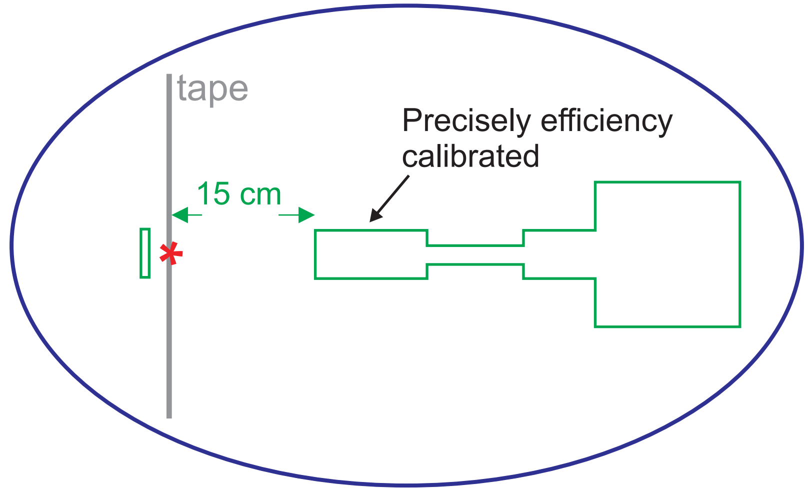






BETA-DECAY BRANCHING OF ^{34}Ar





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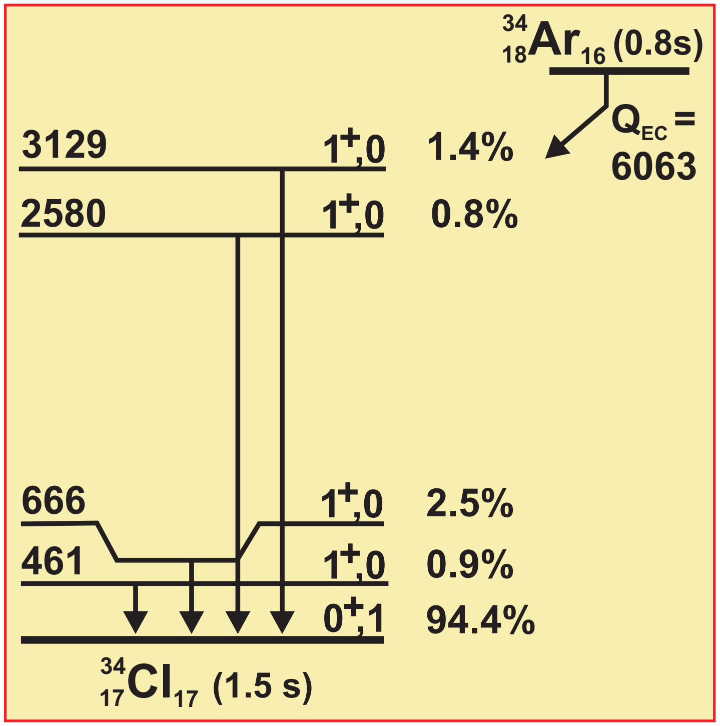
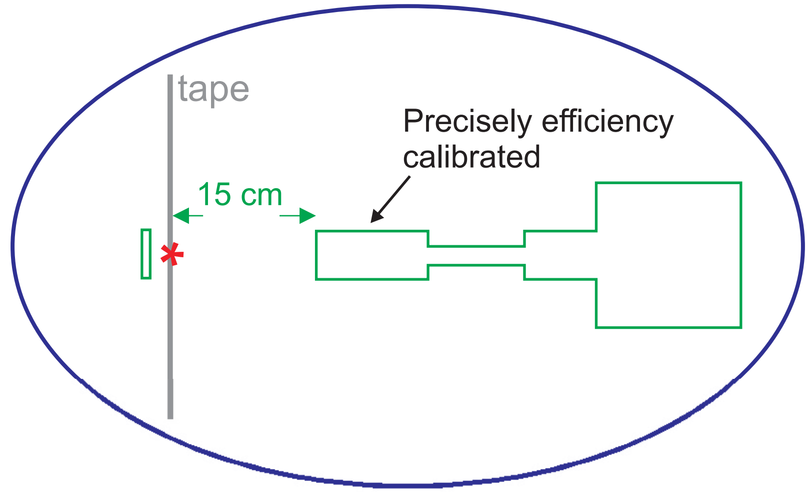
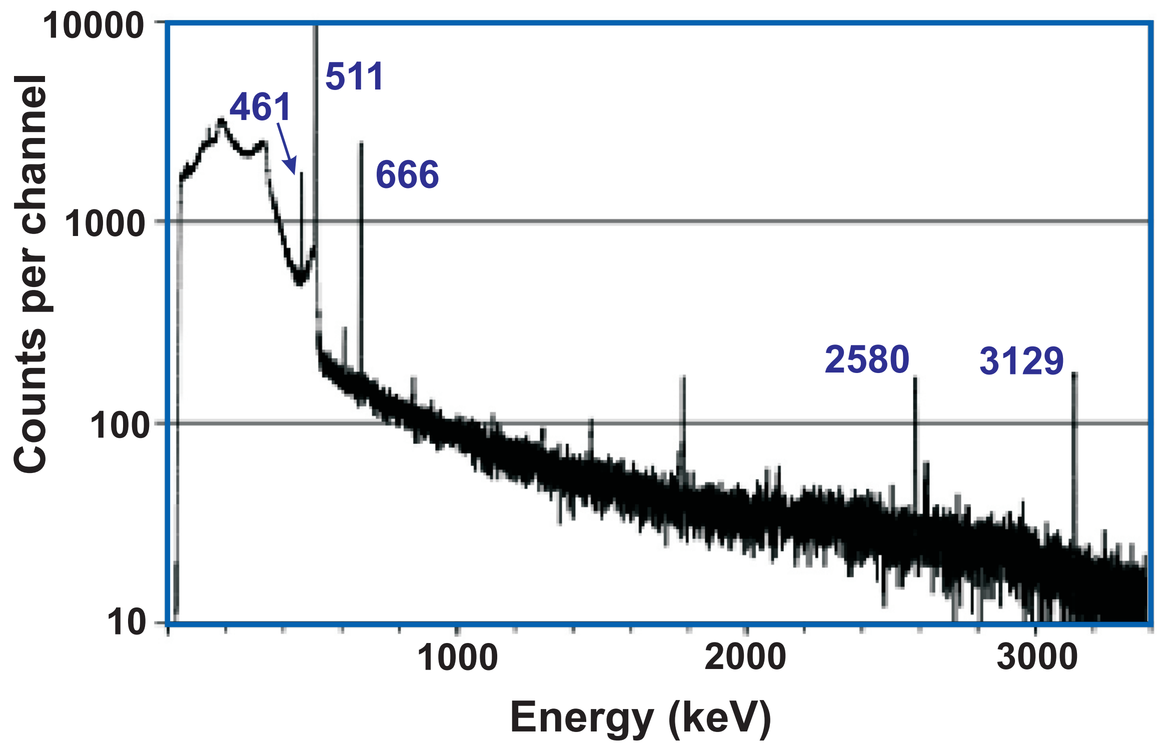
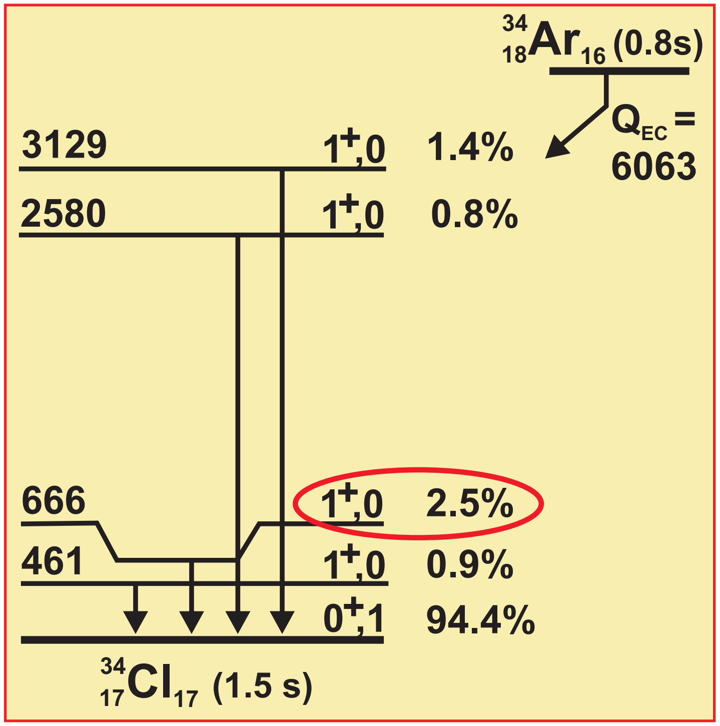
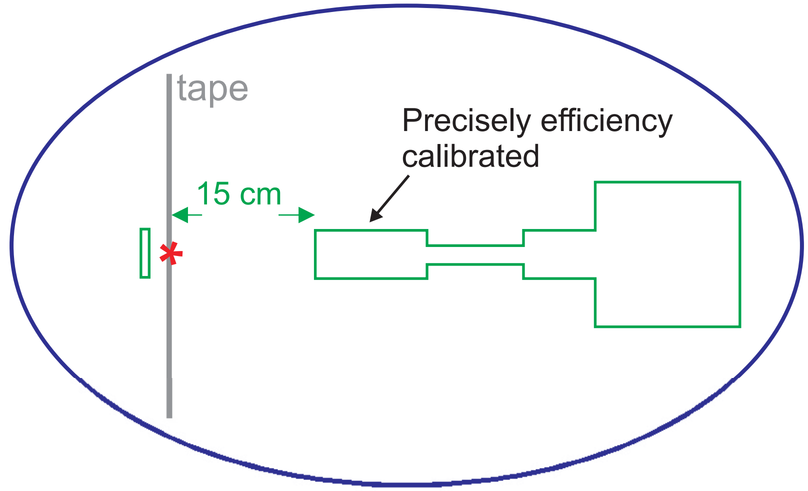




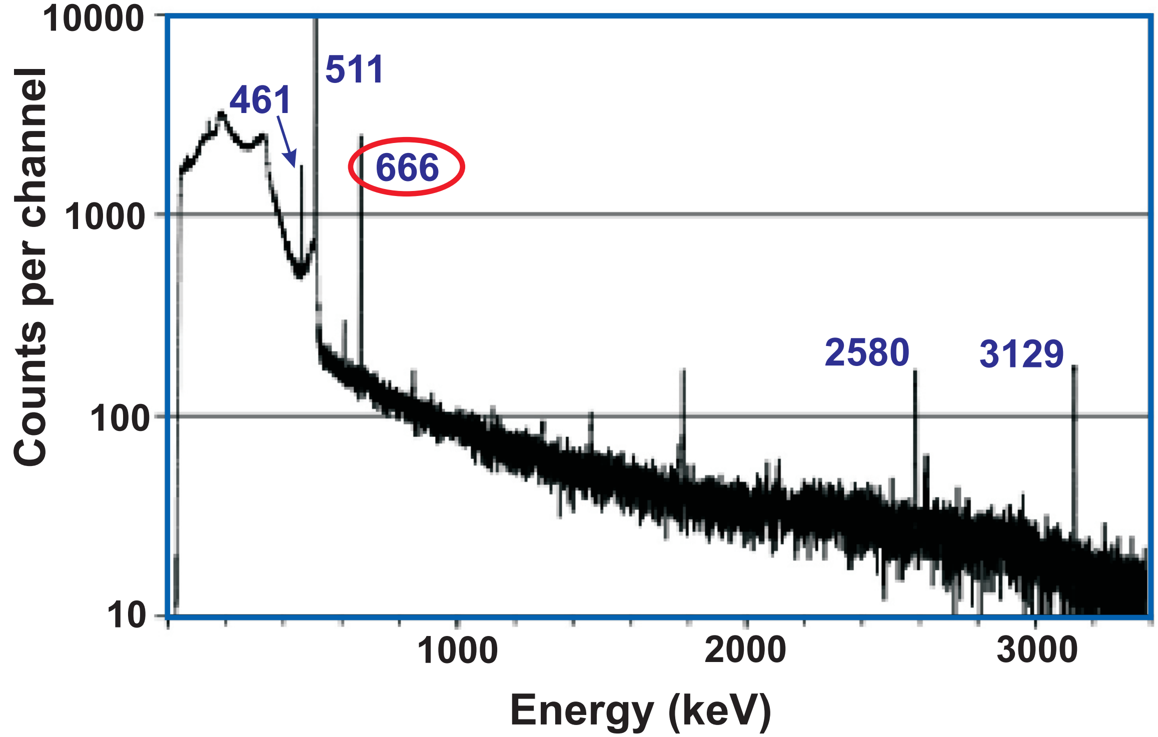


BETA-DECAY BRANCHING OF ^{34}Ar

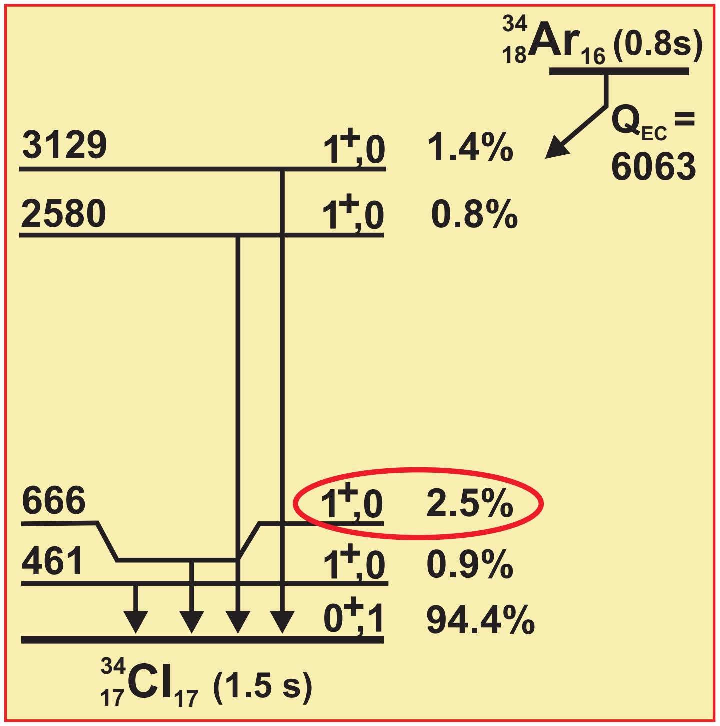


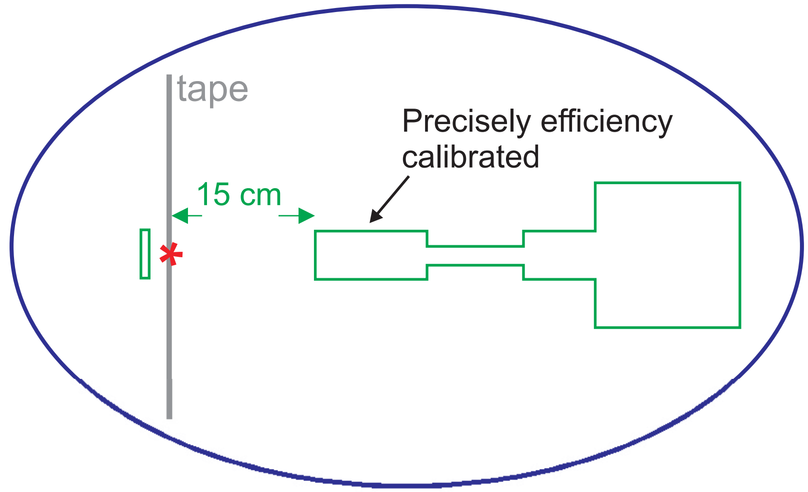


$$\frac{N_1}{N} = \frac{N_0\, R_1}{N_0} \quad 1$$

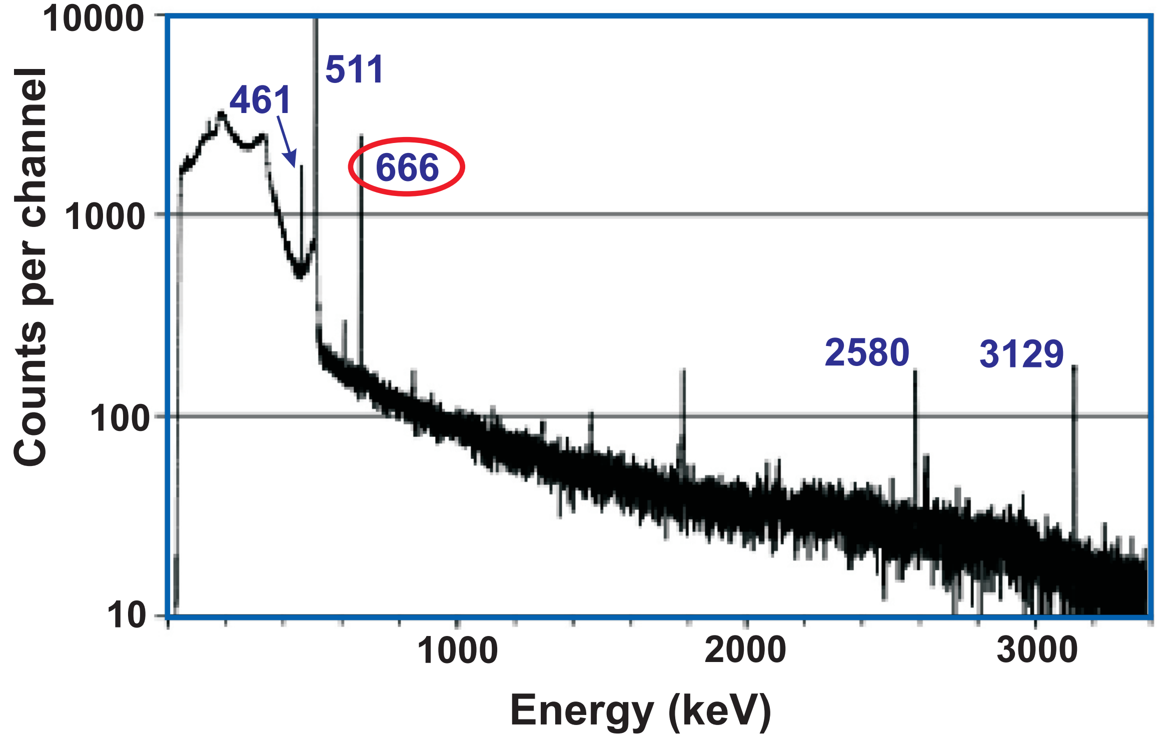


BETA-DECAY BRANCHING OF ^{34}Ar

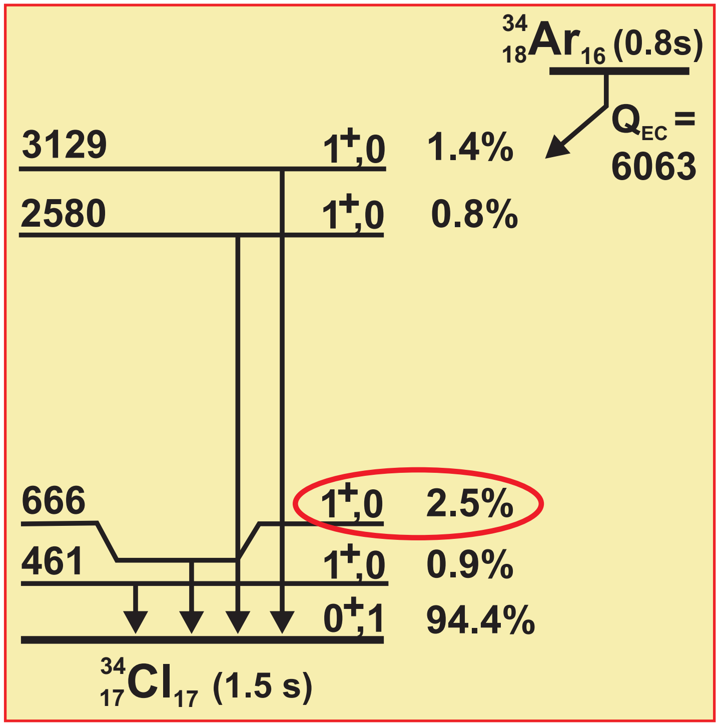


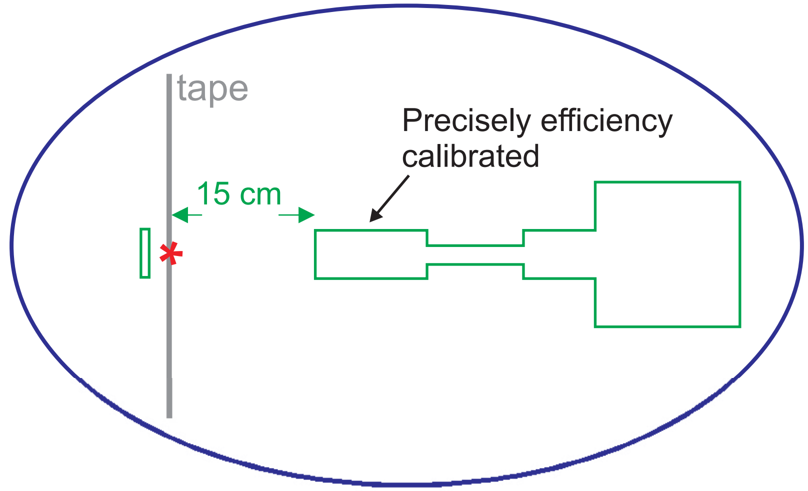


$$\frac{N_1}{N} = \frac{\cancel{N_0}\, R_1}{\cancel{N_0}}$$



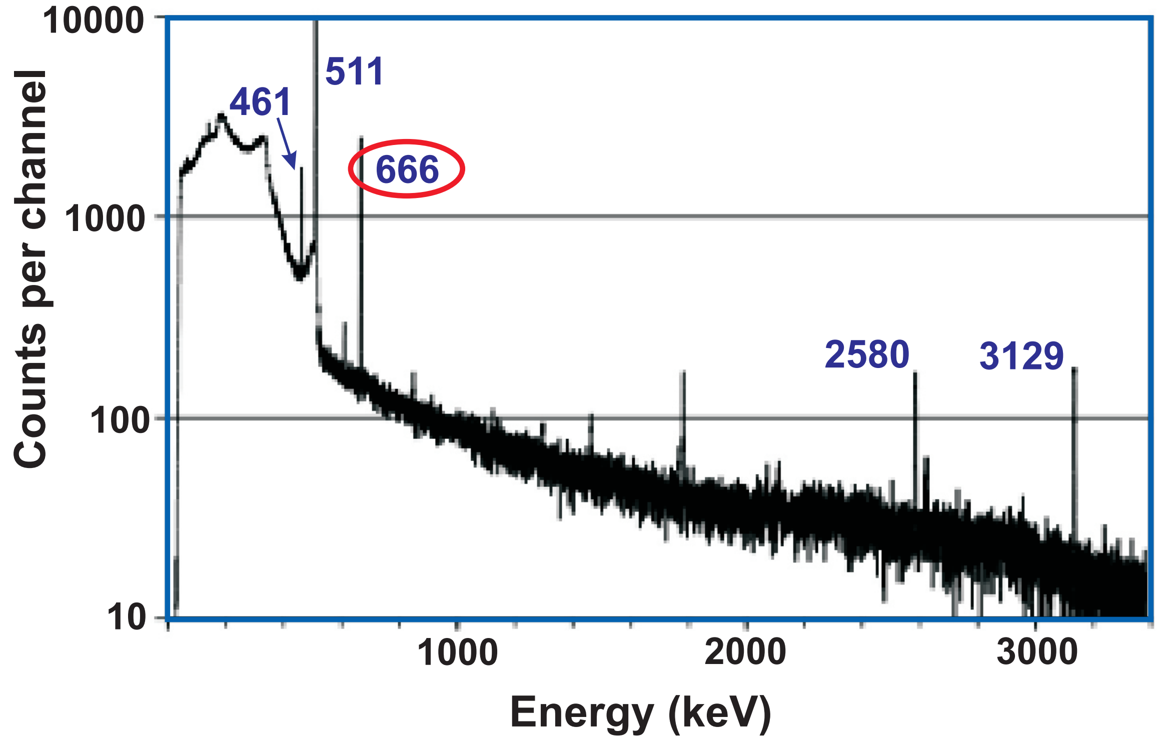
BETA-DECAY BRANCHING OF ^{34}Ar



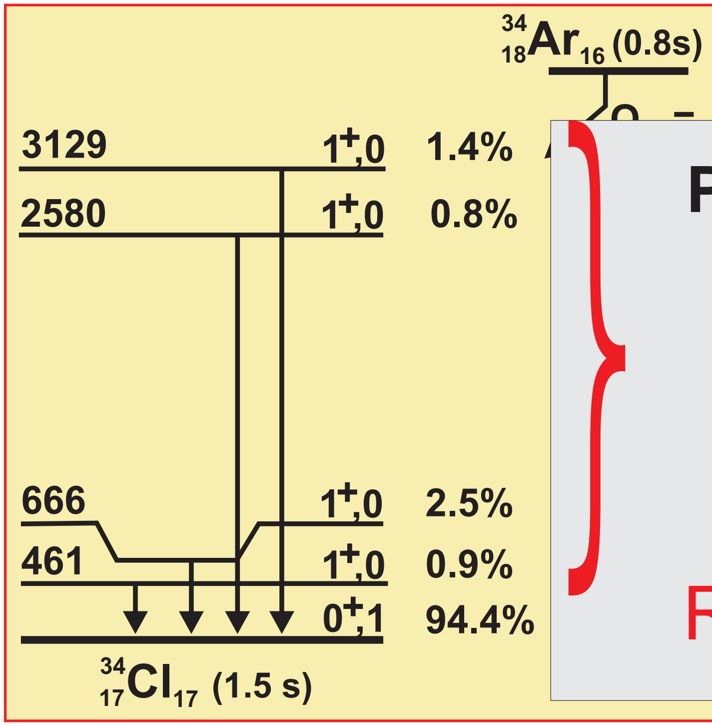


$$\frac{N_1}{N} = \frac{N_0 \, R_1 \; {}_1}{N_0}$$

$$R_1 = \frac{N_1}{N \; {}_1} \; k$$



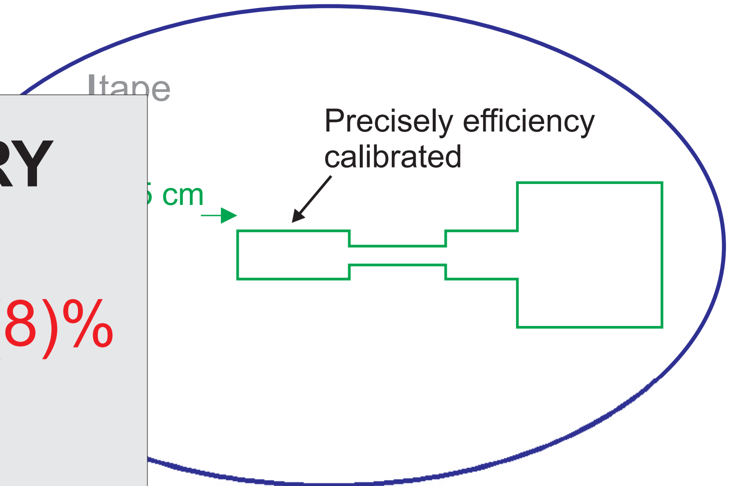
BETA-DECAY BRANCHING OF ^{34}Ar

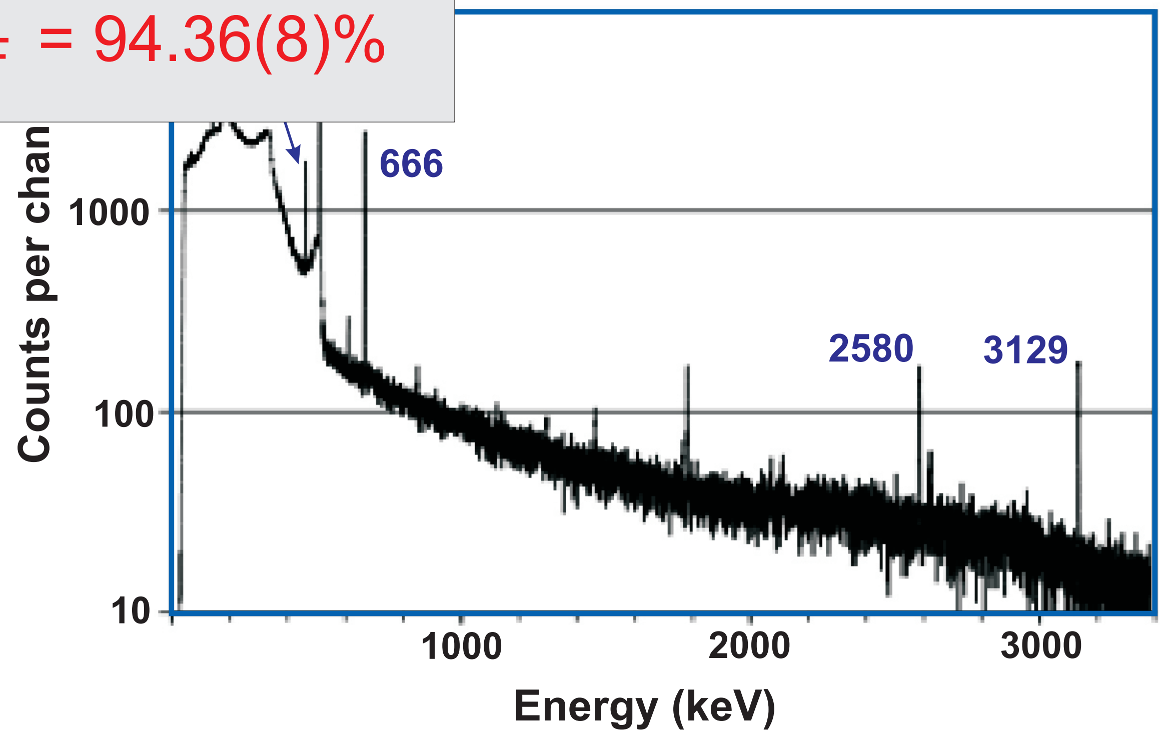


PRELIMINARY

R_{GT} = 5.64(8)%

R_F = 94.36(8)%

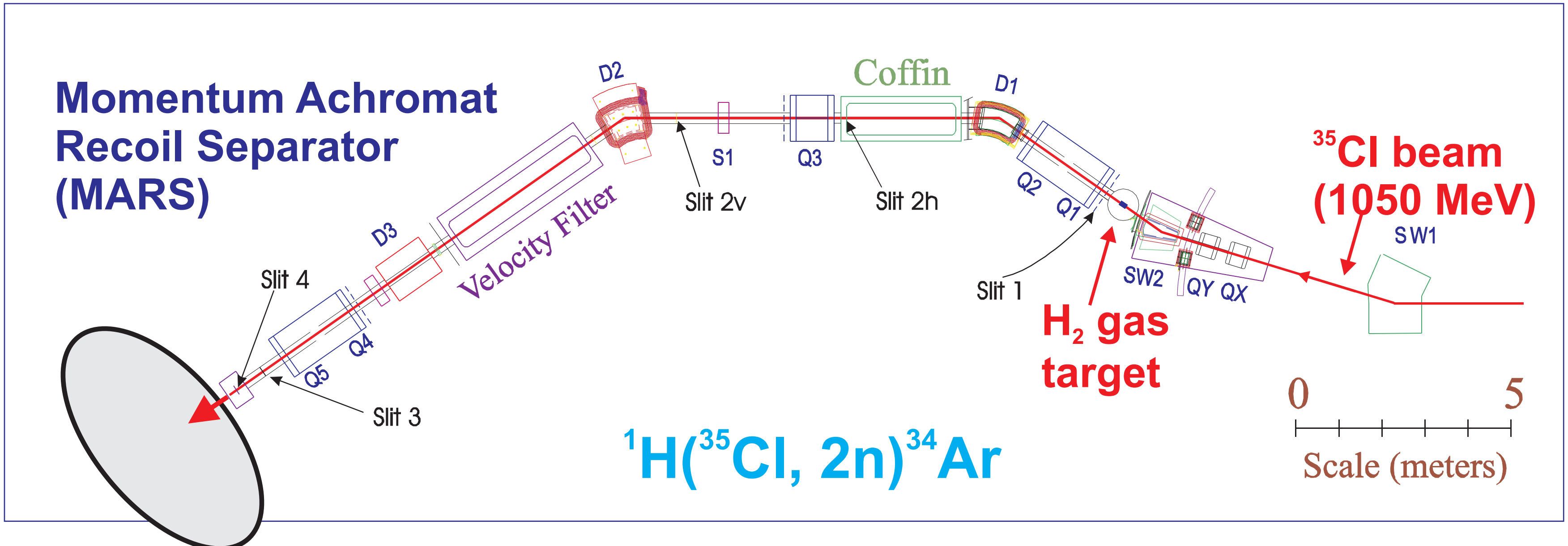


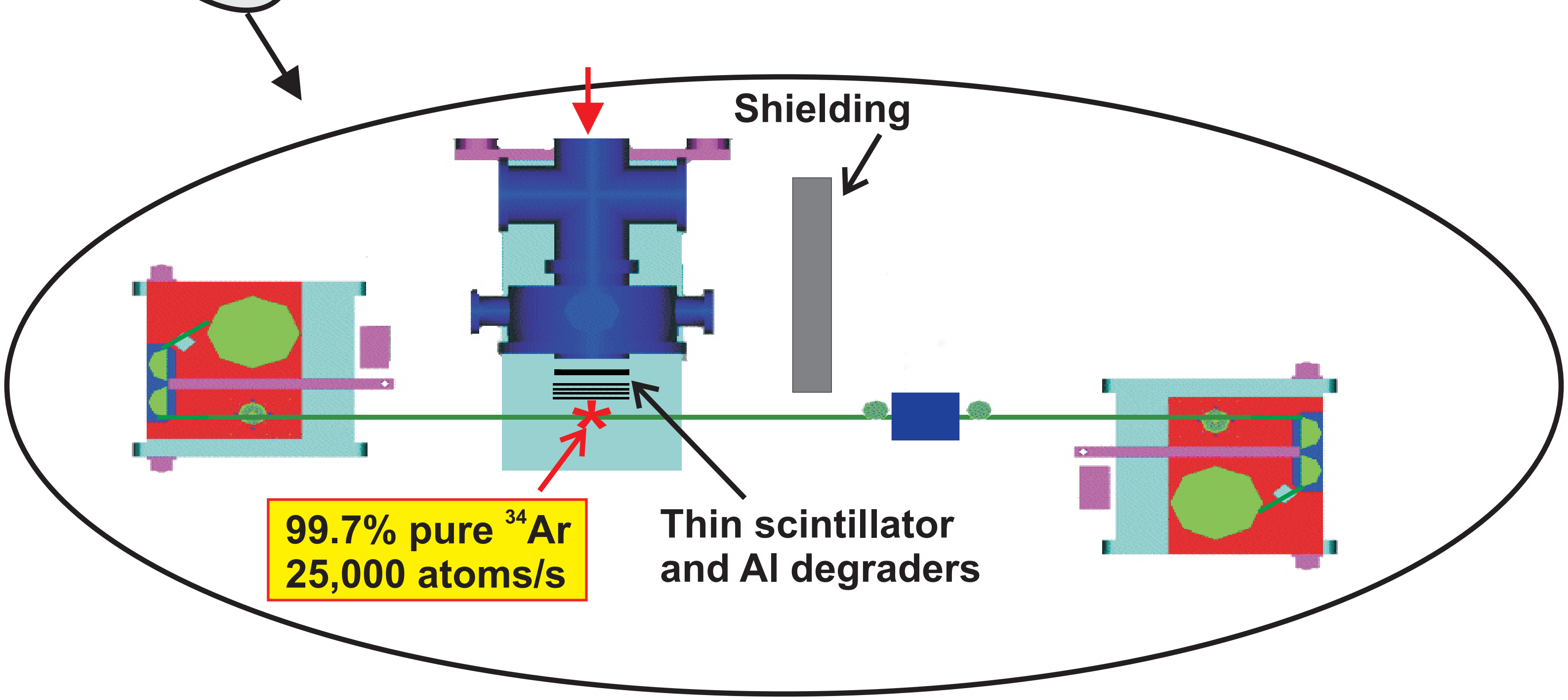


$$\frac{N_1}{N} = \frac{N_o R_1 {}_1}{N_o}$$

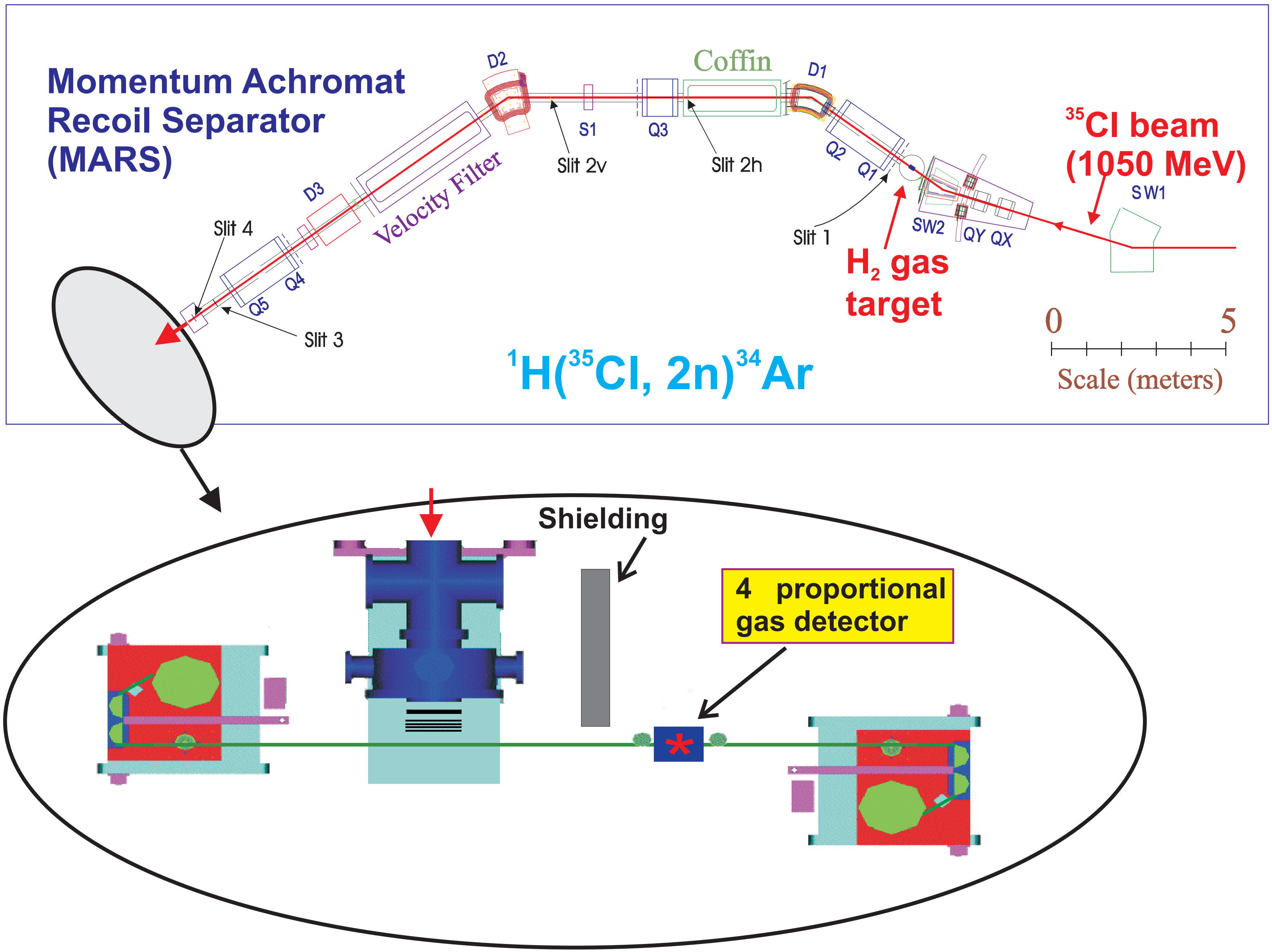
$$R_1 = \frac{N_1}{N_1} k$$

PRECISION DECAY MEASUREMENTS AT TAMU





PRECISION DECAY MEASUREMENTS AT TAMU



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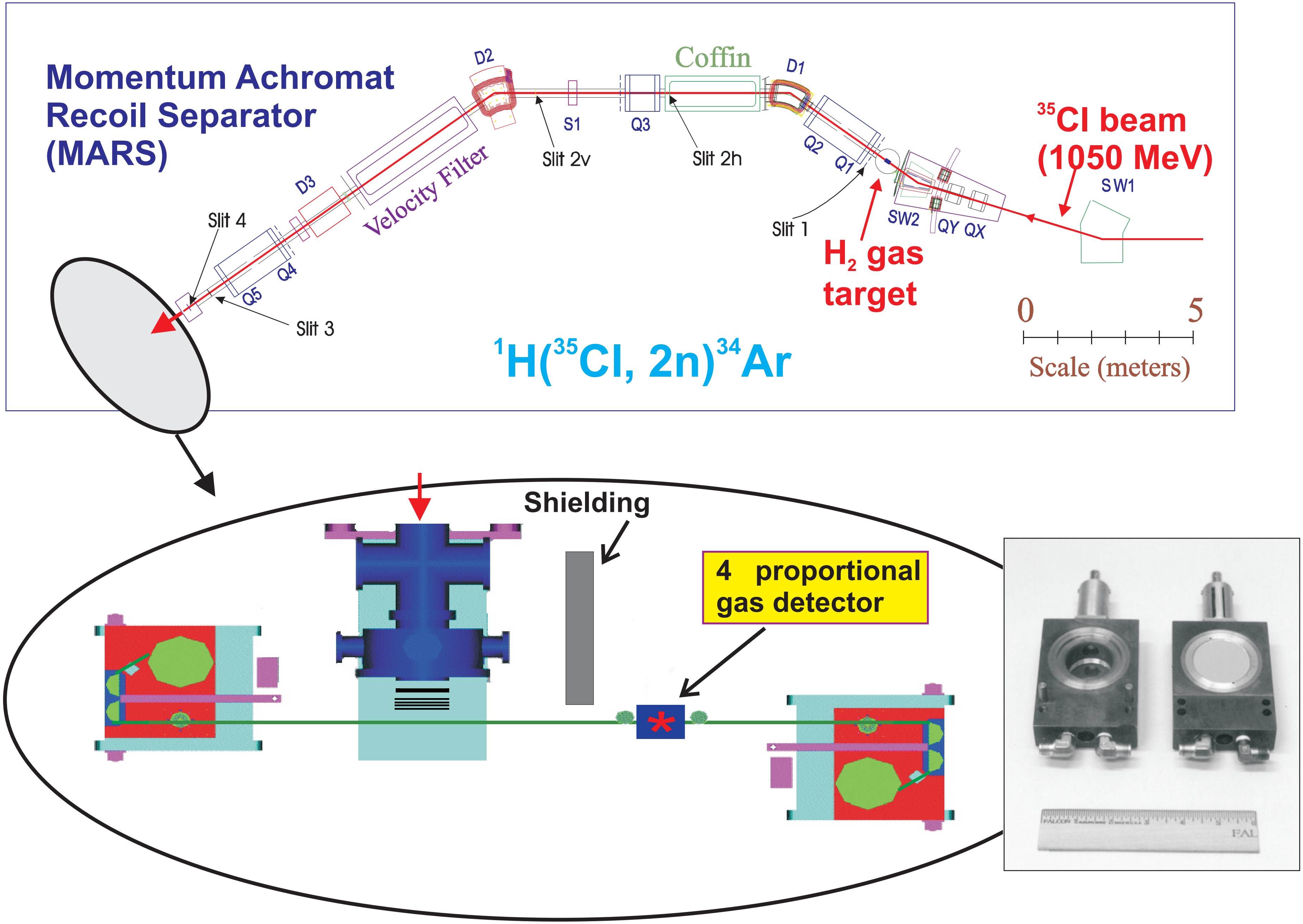
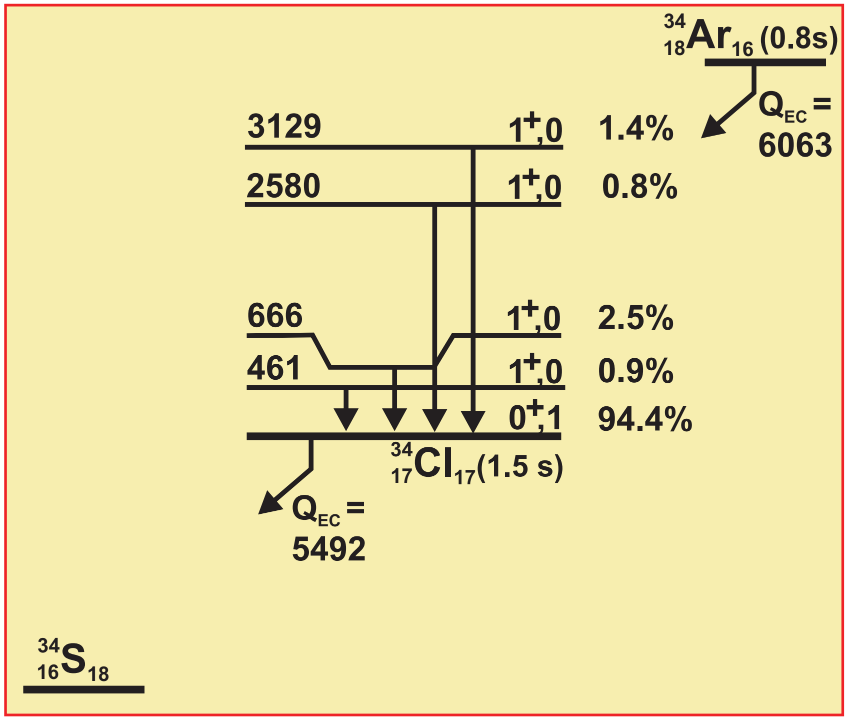


HALF LIFE OF ^{34}Ar



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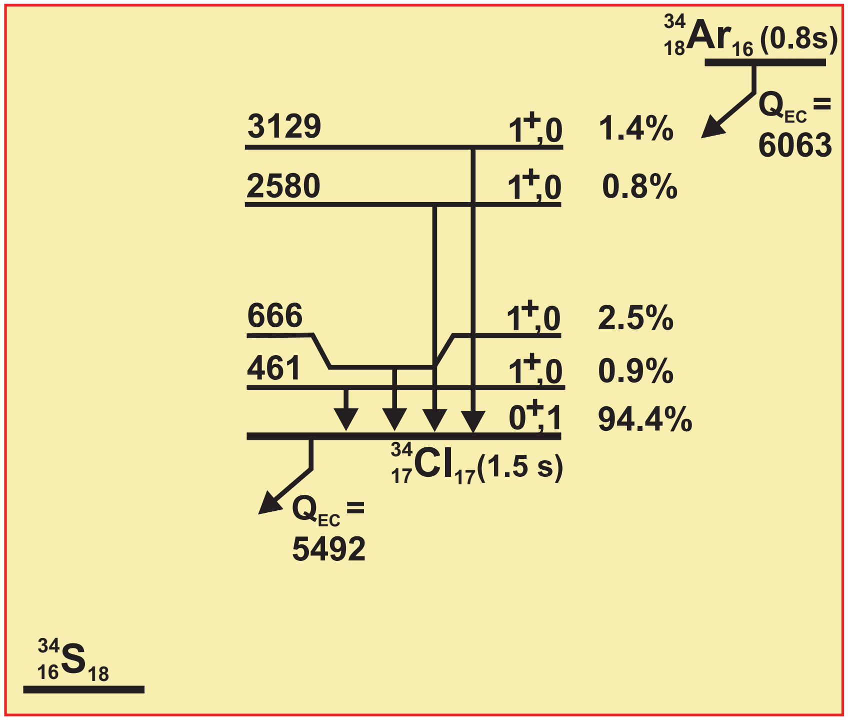

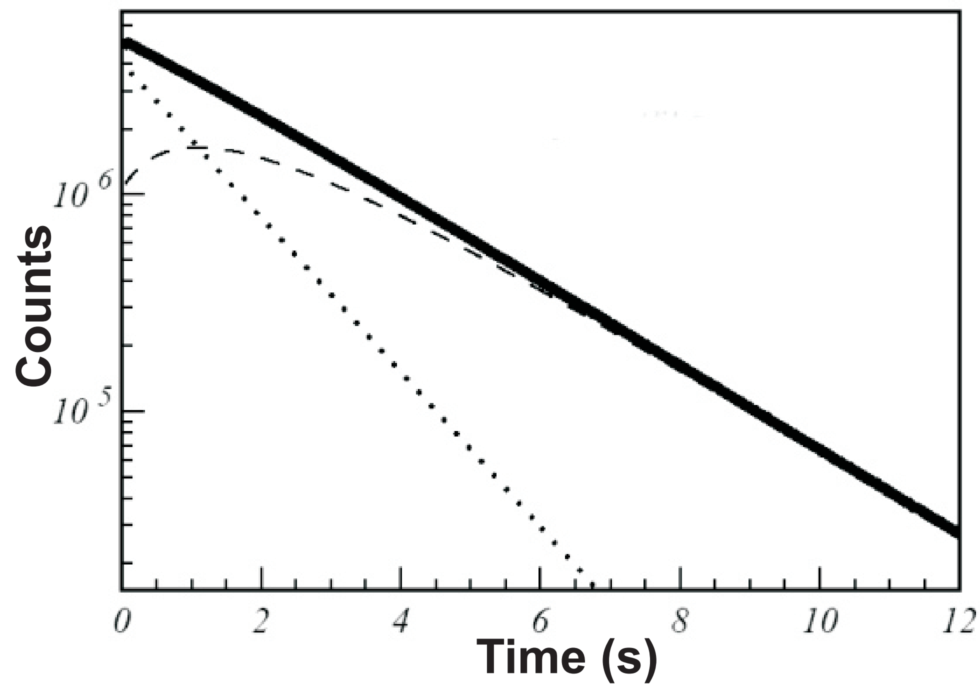

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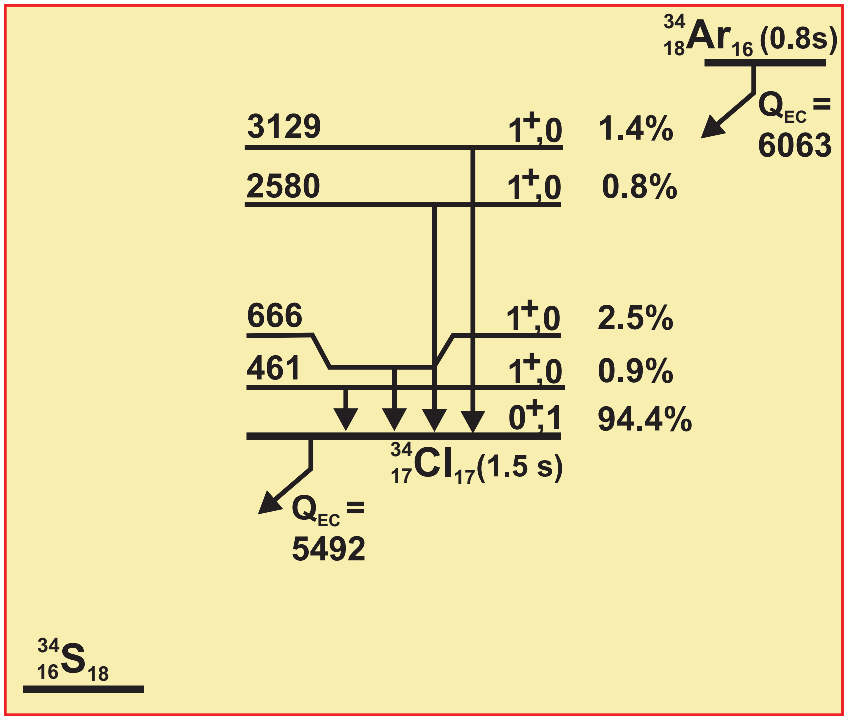
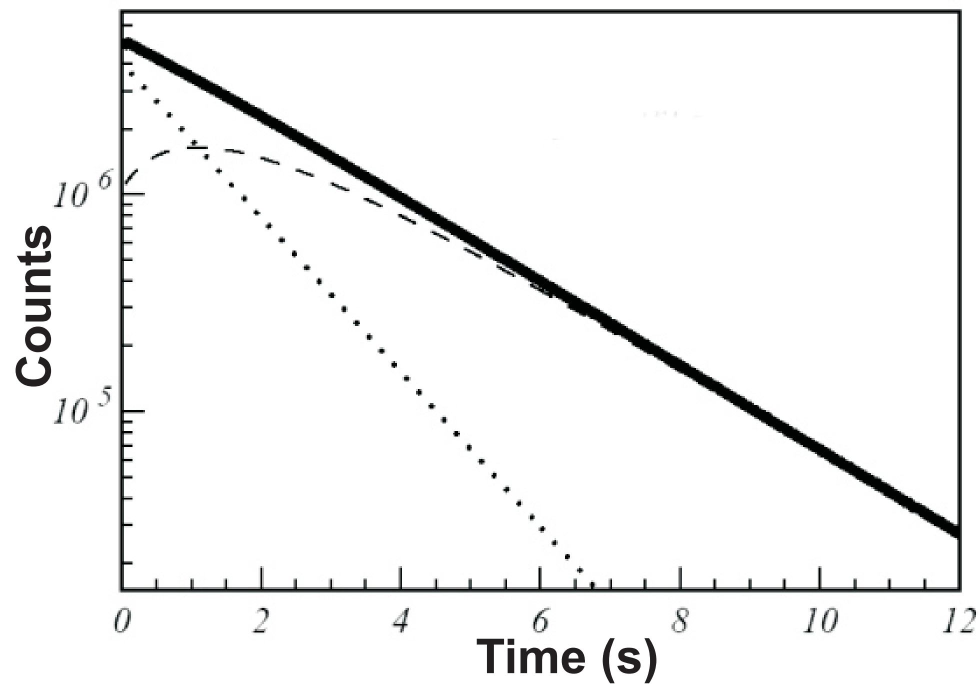


$$_{tot} = C_1 e^{\,_1 t} + C_2 e^{\,_2 t}$$

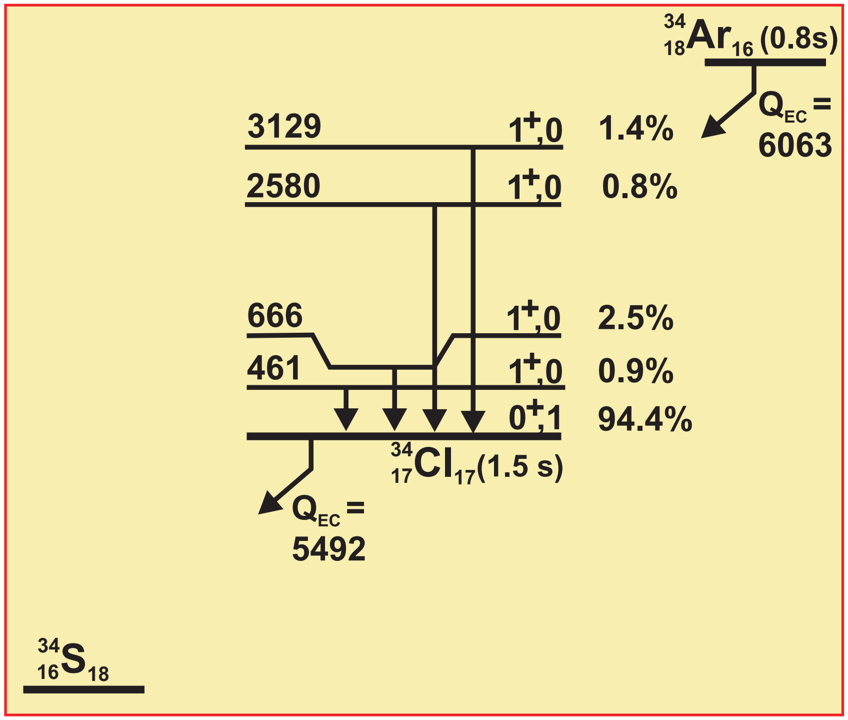


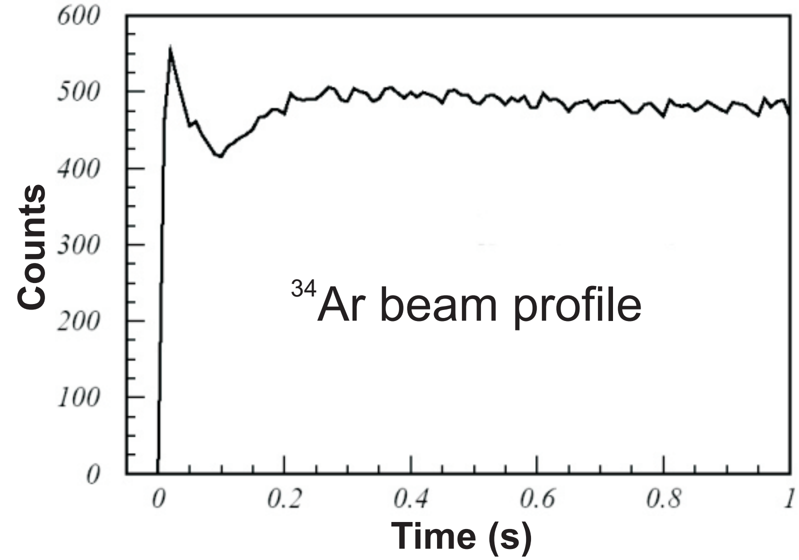
where

$$C_1 = N_1 \;_1 \frac{2\;_2 - \;_1}{_2 - \;_1}$$

$$C_2 = \left(N_2 - \frac{N_1\;_1}{_2 - \;_1}\right) \;_2$$

HALF LIFE OF ^{34}Ar





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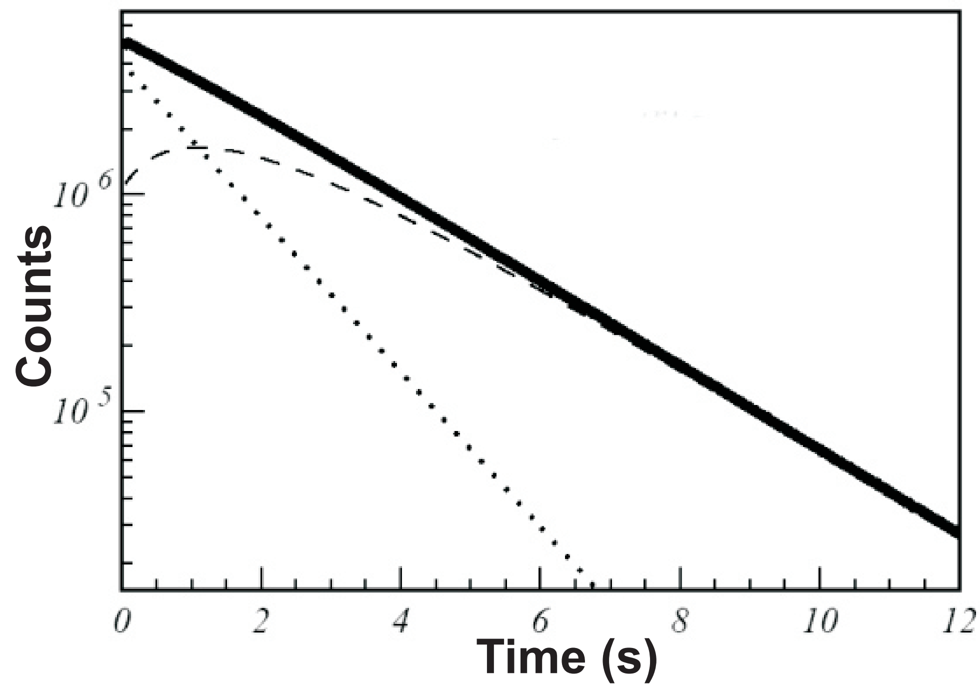

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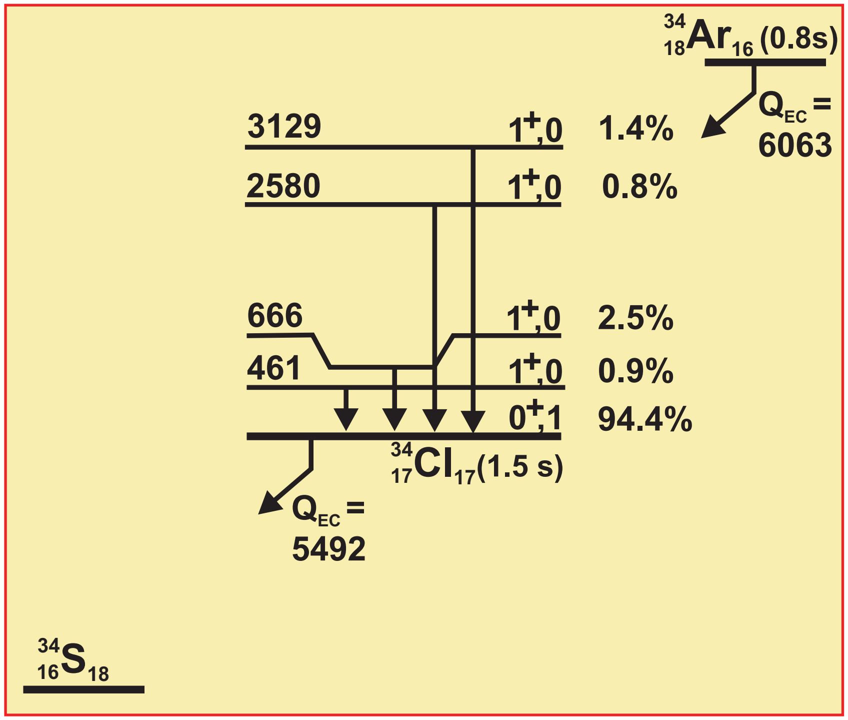
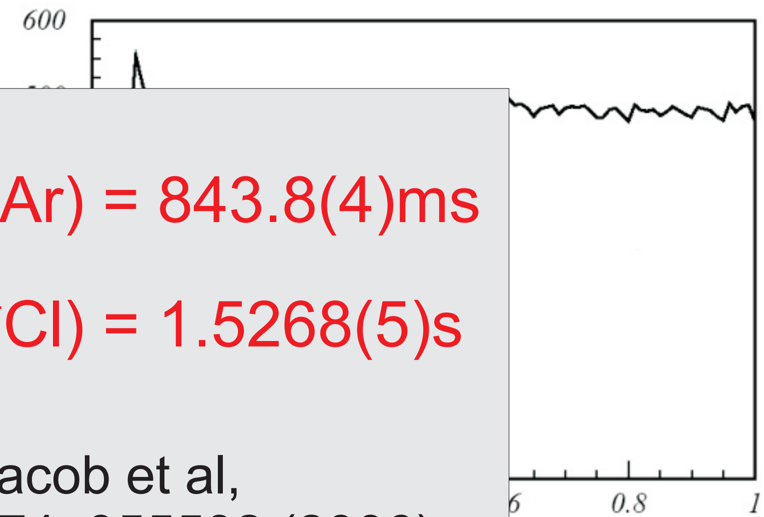


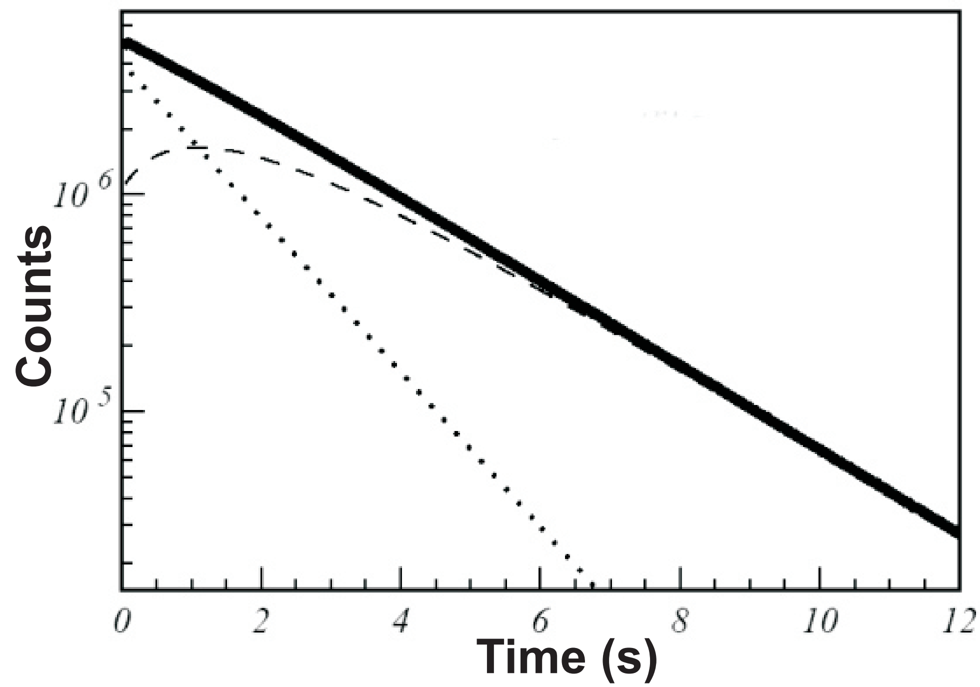


$t_{1/2}$ (^{34}Ar) = 843.8(4)ms

$t_{1/2}$ (^{34}Cl) = 1.5268(5)s

V.E. Iacob et al,
PRC 74, 055502 (2006)

$$_{tot} = C_1 e^{\,_1 t} + C_2 e^{\,_2 t}$$



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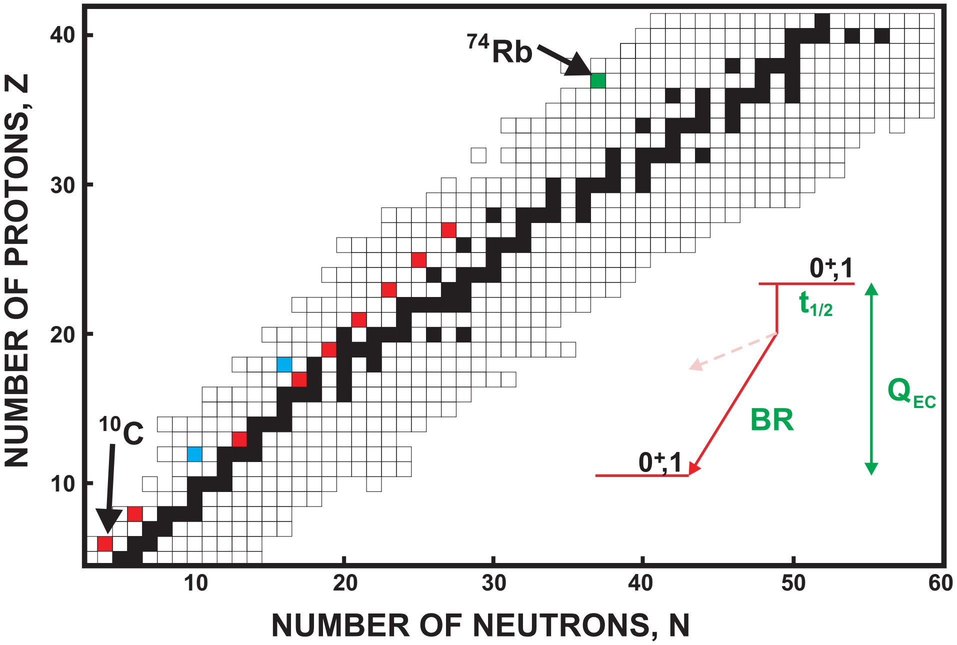
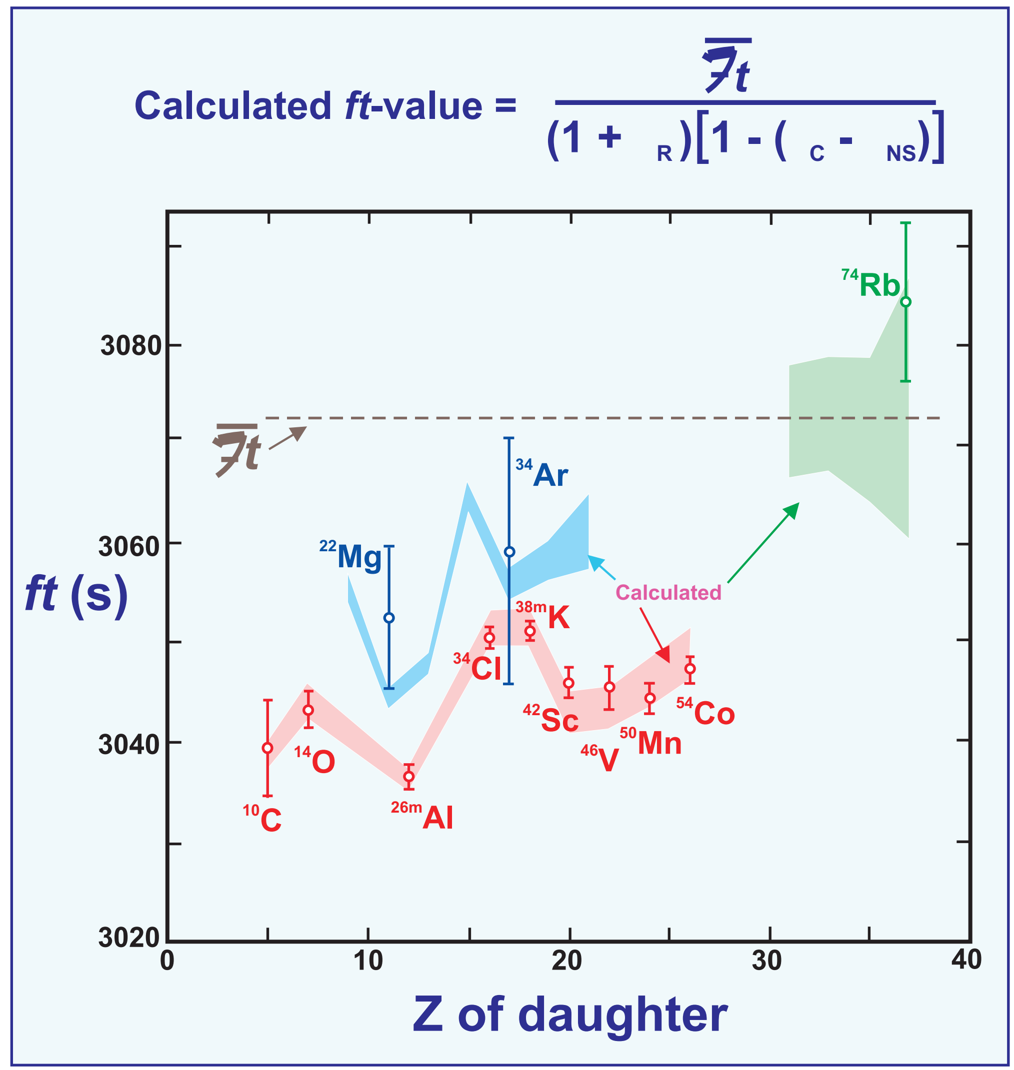
STATUS OF RESULTS AS OF MAY 2007



Results of 2005 survey



What's new?

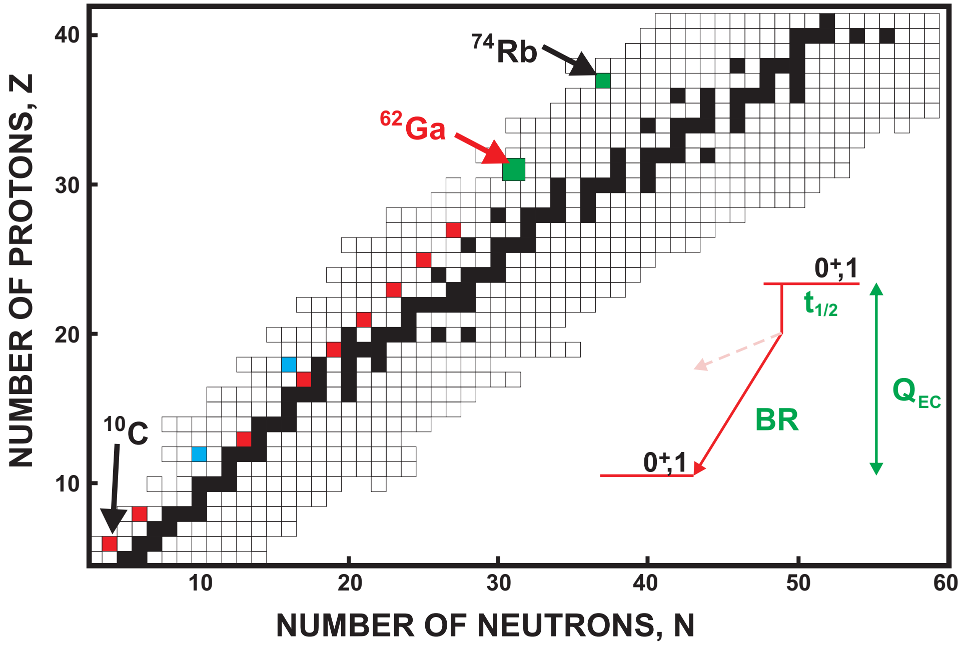
^{62}Ga: new case added

^{34}Ar: BR, $t_{1/2}$ results improved

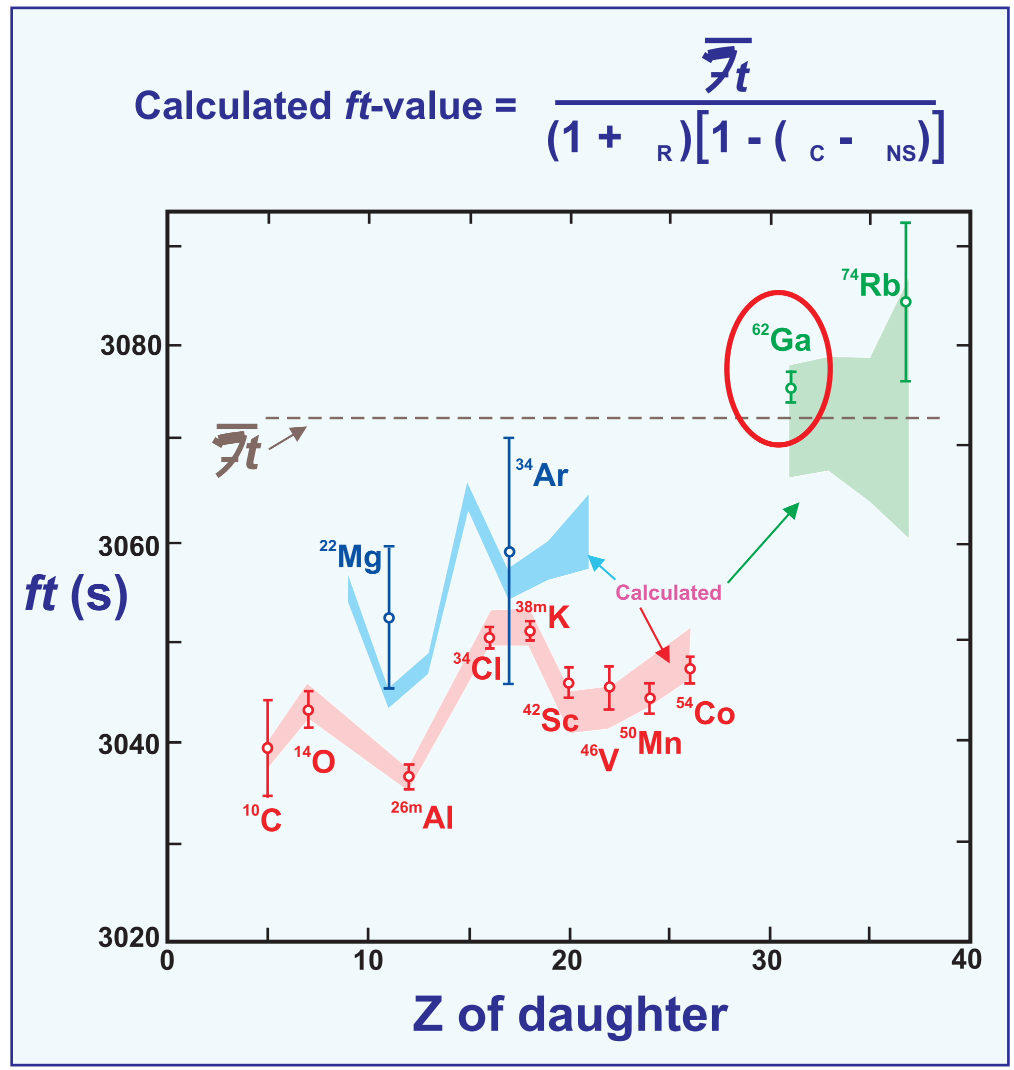
^{46}V: Q_{EC} value improved

^{10}C – ^{42}Sc: Q_{EC} values improved

STATUS OF RESULTS AS OF MAY 2007



Updated results



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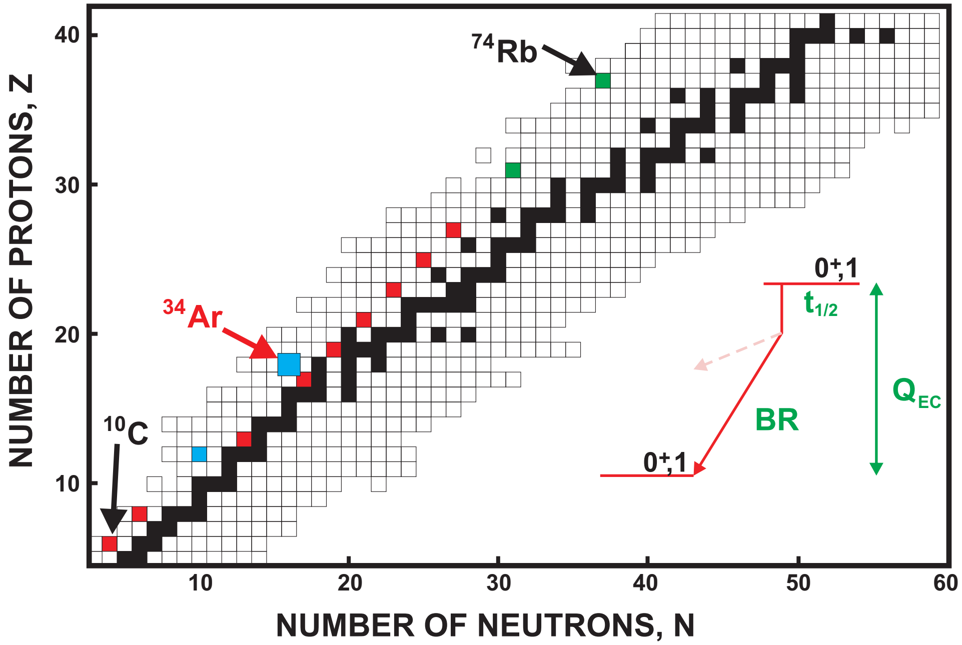

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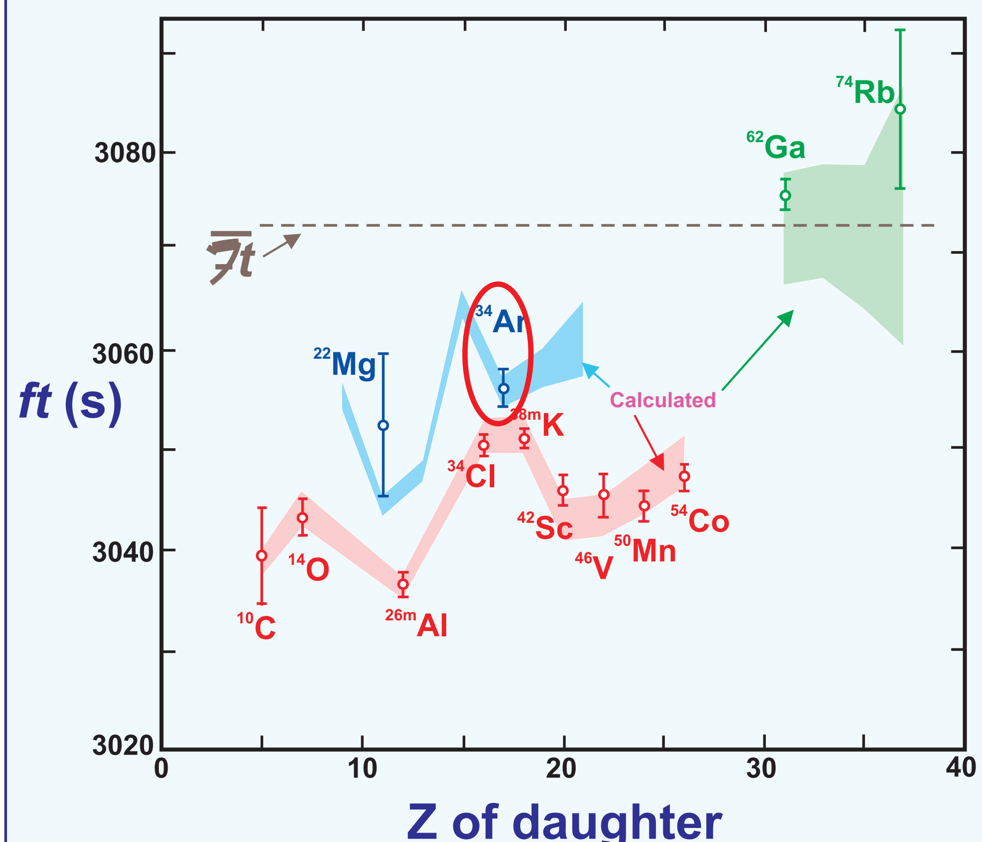
Updated results

Calculated *ft*-value = $\dfrac{\overline{\mathcal{F}t}}{(1 + {}_{R})[1 - ({}_{C} - {}_{NS})]}$



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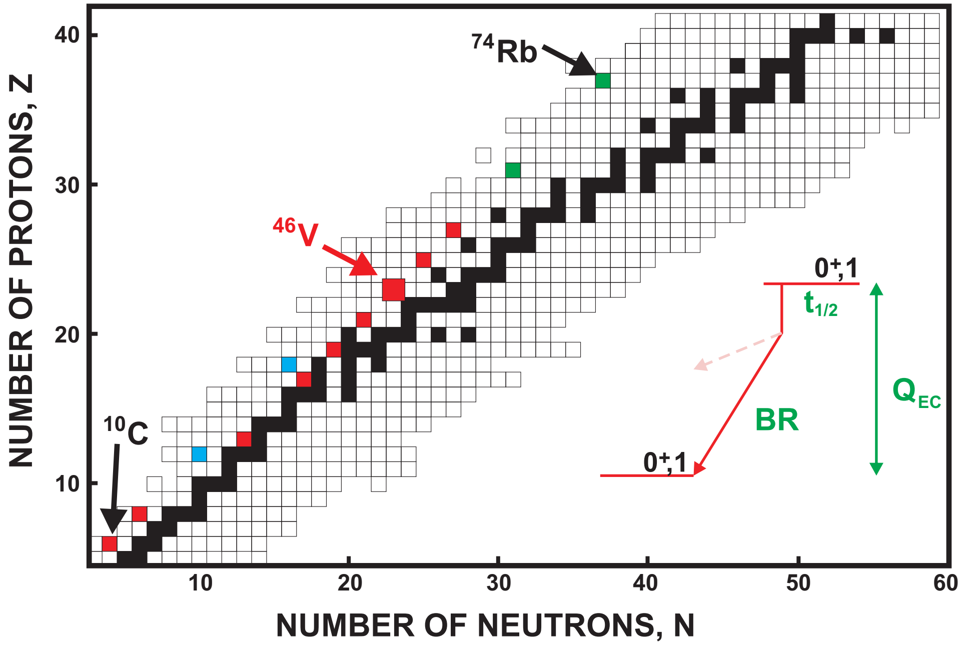
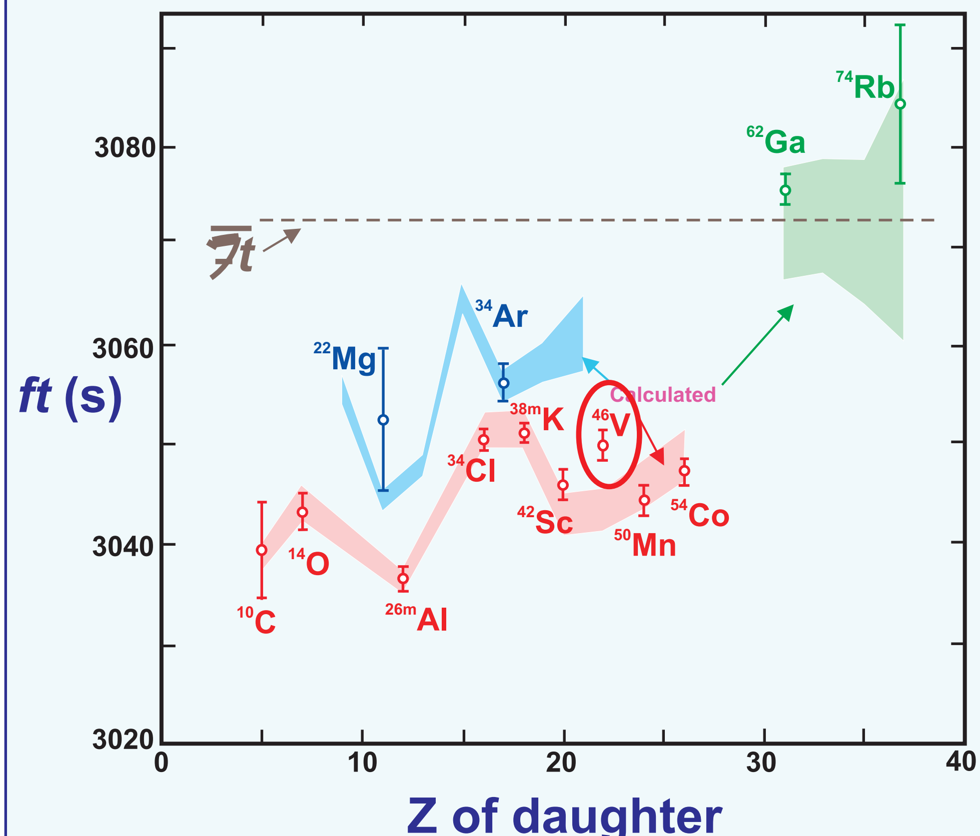


Updated results

Calculated *ft*-value = $\dfrac{\overline{\mathcal{F}t}}{(1 + {}_{R})[1 - ({}_{C} - {}_{NS})]}$



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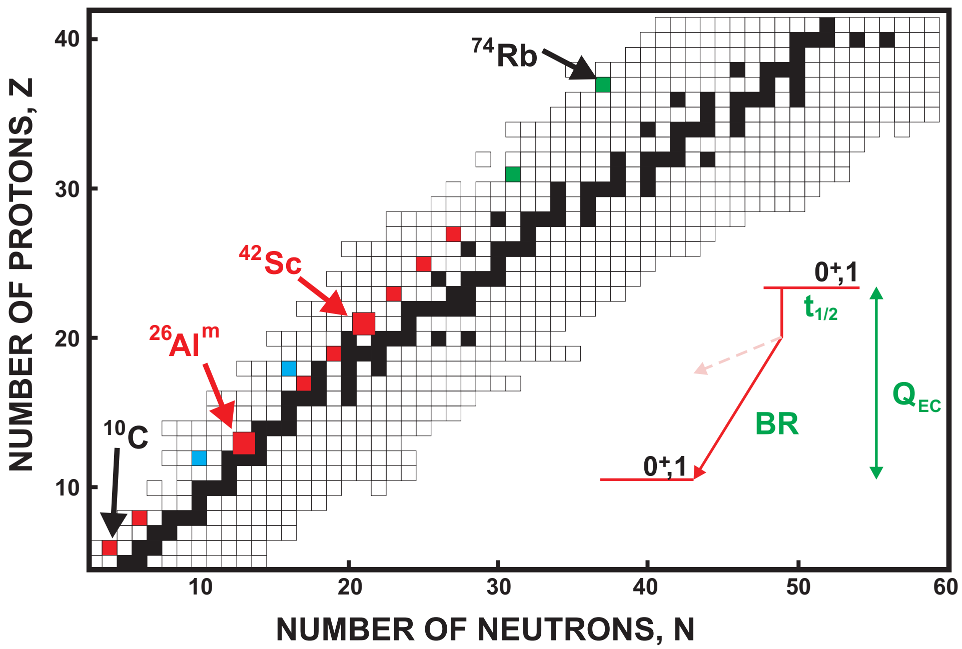
STATUS OF RESULTS AS OF MAY 2007

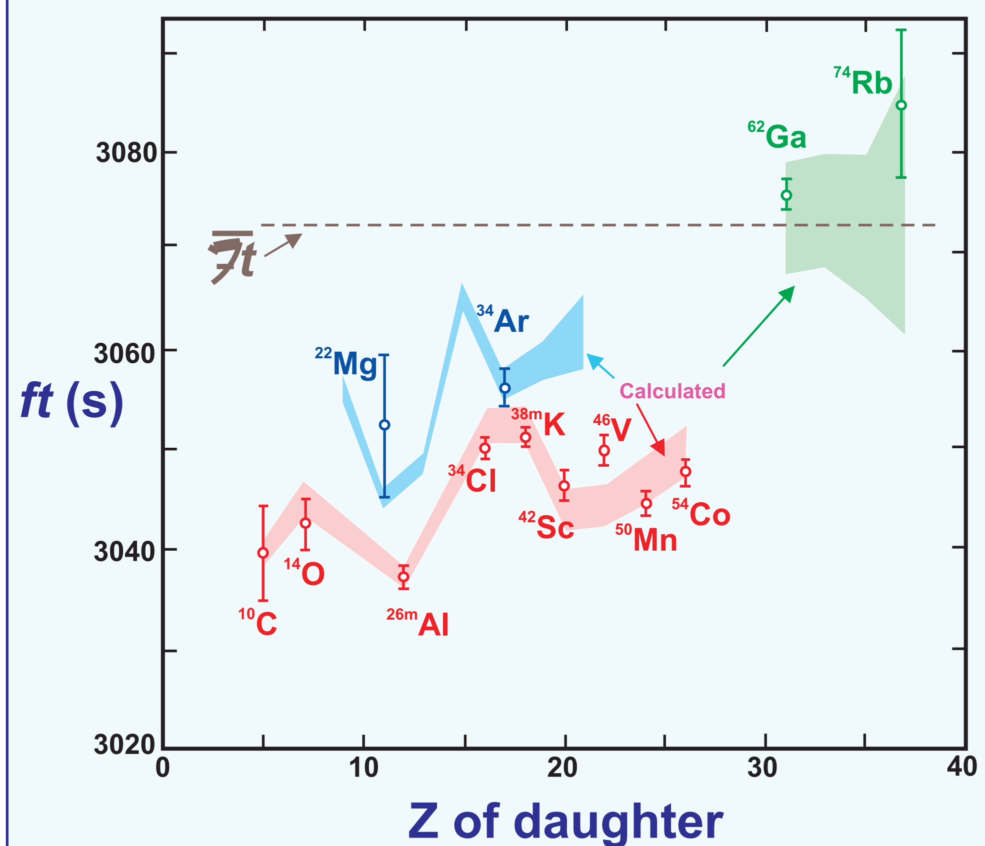


What's new?

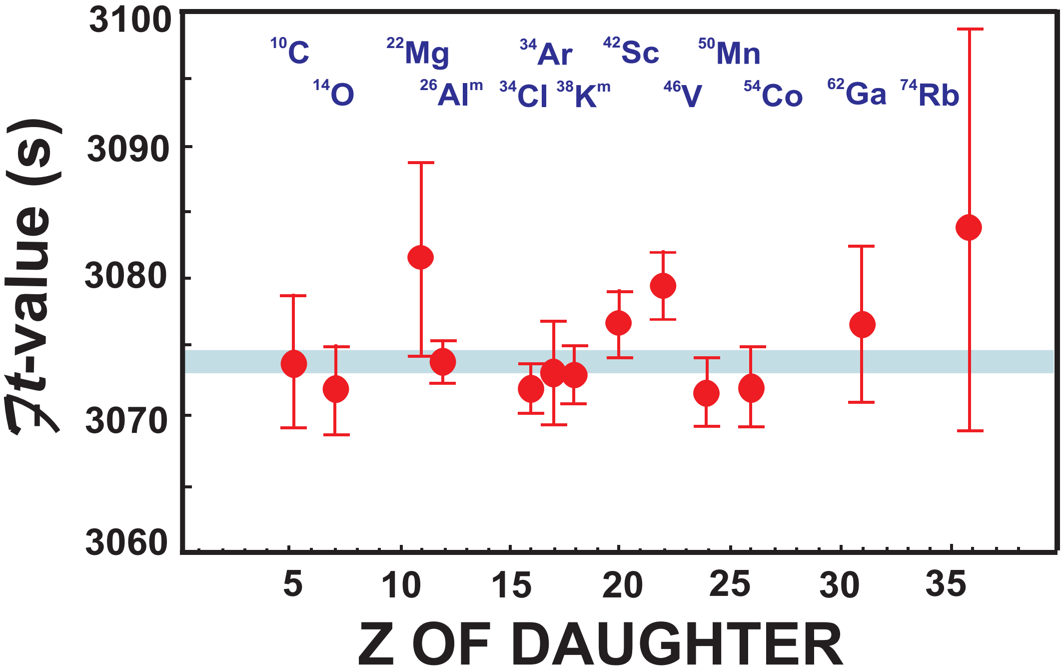
- ✔ ^{62}Ga: new case added
- ✔ ^{34}Ar: BR, $t_{1/2}$ results improved
- ✔ ^{46}V: Q_{EC} value improved
- ➡ ^{10}C – ^{42}Sc: Q_{EC} values improved

Updated results + re-fit

Calculated *ft*-value = $\dfrac{\overline{\mathcal{F}t}}{(1 + \ _{R})[1 - (\ _{C} - \ _{NS})]}$



THE BOTTOM LINE AS OF MAY 2007



$\overline{\mathcal{F}t}$ = 3073.9(8)

V_{ud} = 0.97378(27)

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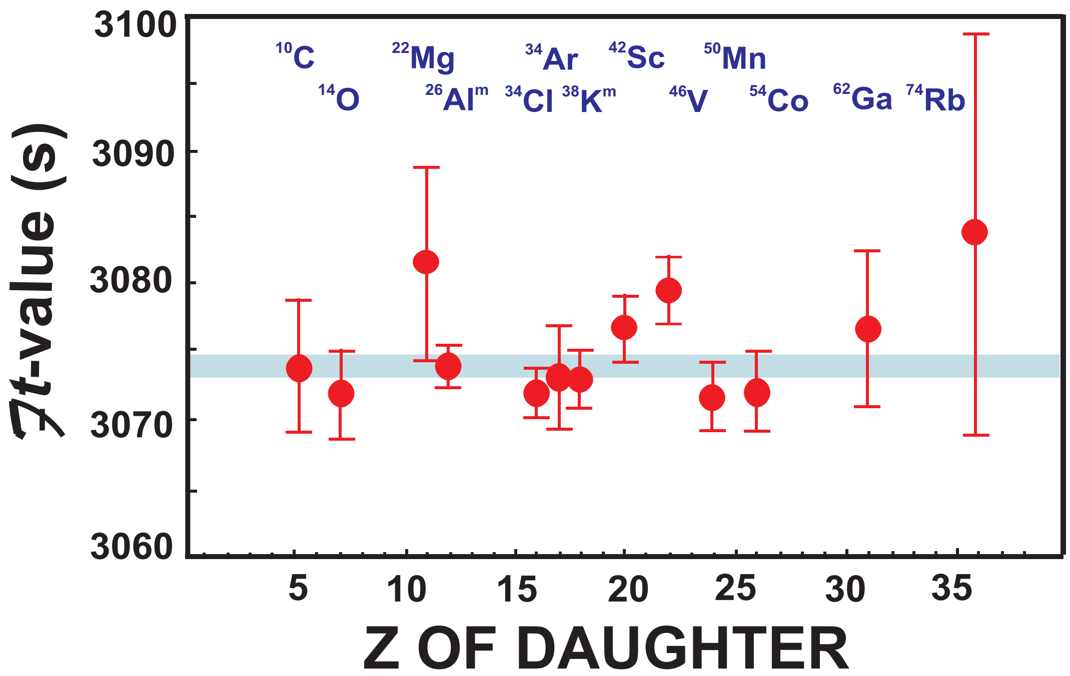

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2005 Review:
V_{ud} = 0.97380(40)

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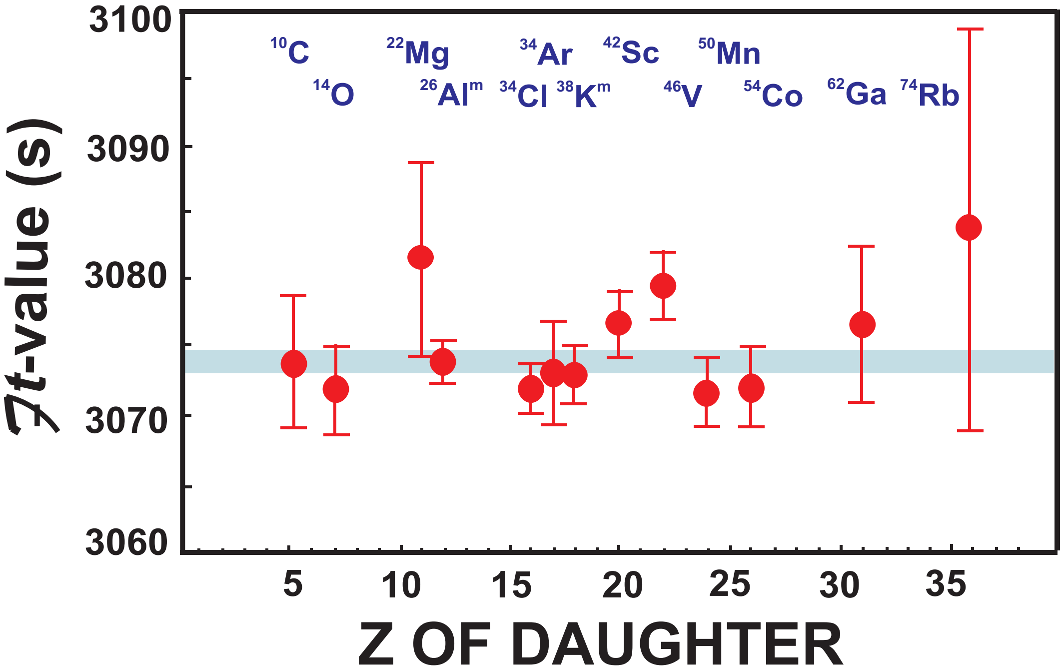

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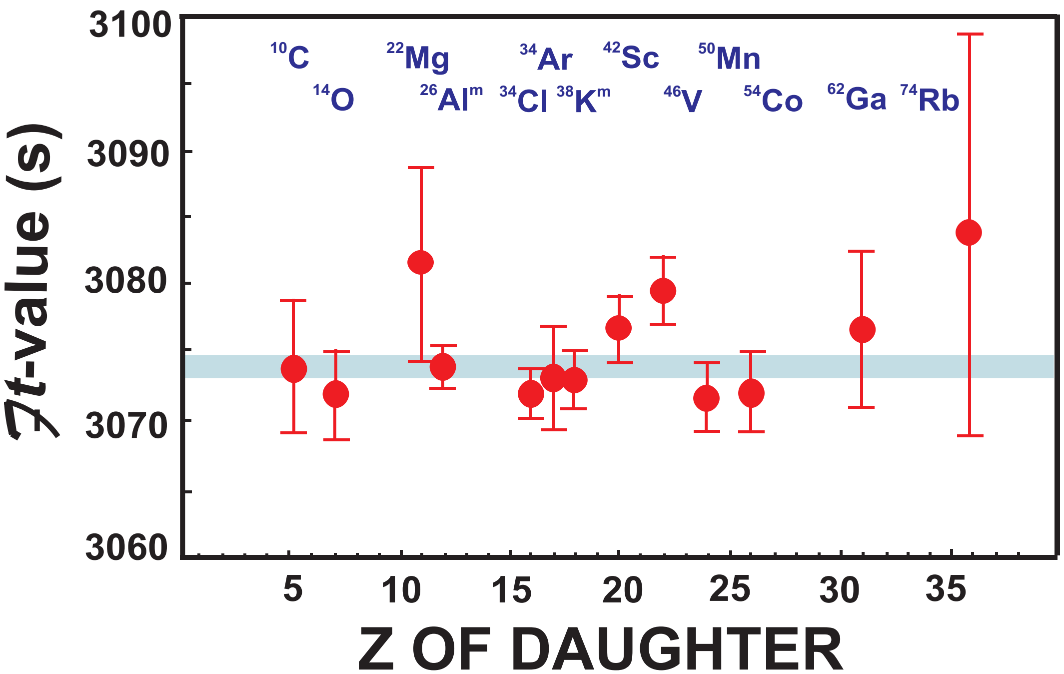


$\overline{\mathcal{F}t}$ = 3073.9(8)

V_{ud} = 0.97378(27)

2005 Review:
V_{ud} = 0.97380(40)

CKM UNITARITY:

$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9992(11)$

V_{ud}^2: 0.9483(5)

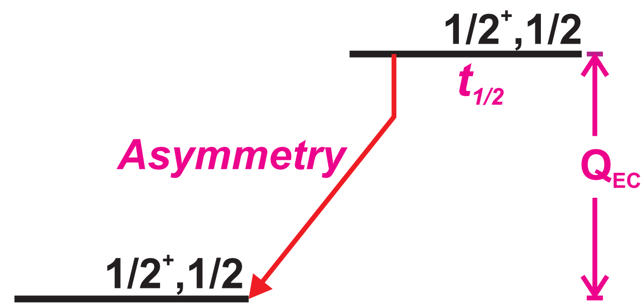
V_{us}^2: 0.0509(9)

V_{ub}^2: <0.0001

Most of the reduction in the uncertainty on V_{ud} since 2005 comes from the improvement in the calculated radiative correction $_{R}$.

NEUTRON BETA DECAY

EXPERIMENTS



WEAK DECAY EQUATION

$$ft = \frac{K}{G_V^2 < \ >^2 + G_A^2 < \quad >^2}$$

$f = f(Q \ )$

$t = f(t_{1/2})$

$G_{V,A}$ = coupling consts

< > = matrix elements

NEUTRON DECAY

$$ft = \frac{K}{G_V^2 \, (1 + 3 \ ^2)}$$

$= G_A/G_V$

RADIATIVE CORRECTIONS

$t \rightarrow t\,(1 + \ _R)$

$G_{V,A}^2 \rightarrow G_{V,A}^2\,(1 + \ _R) = G_{V,A}^{\prime\,2}$

$_R = f(Q \ )$

$_R = f(\text{interaction})$

TO DETERMINE G_V TWO EXPERIMENTS ARE REQUIRED:

Neutron lifetime $\longrightarrow G_V^{\prime\,2} + 3G_A^{\prime\,2}$

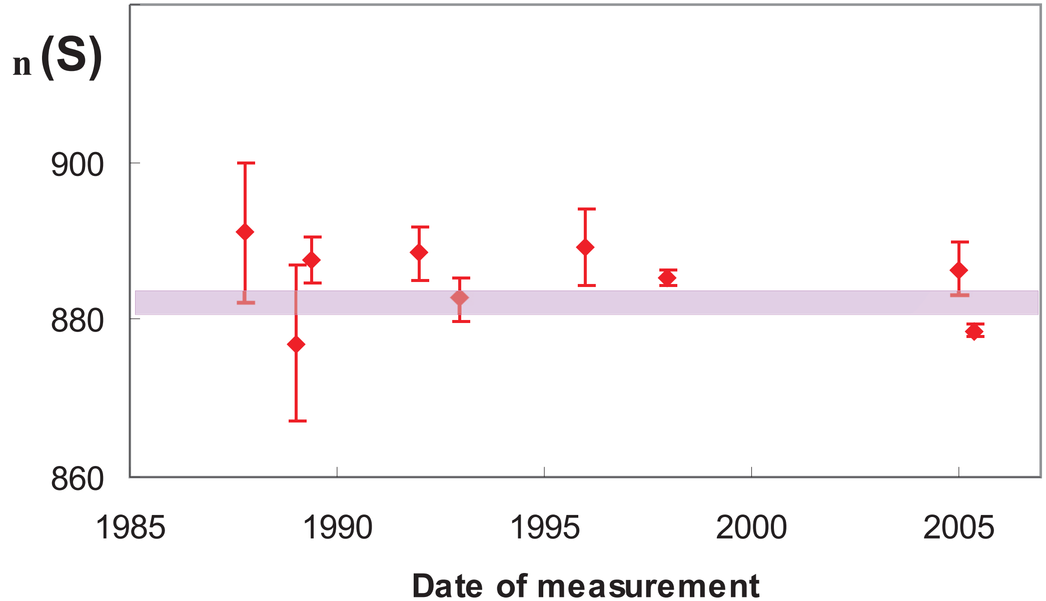
Beta-decay asymmetry $\longrightarrow G_A^{\prime}/G_V^{\prime}$

NEUTRON DECAY DATA, 2006

Mean life:

$_{n}$ = 882.0 ± 1.3 s

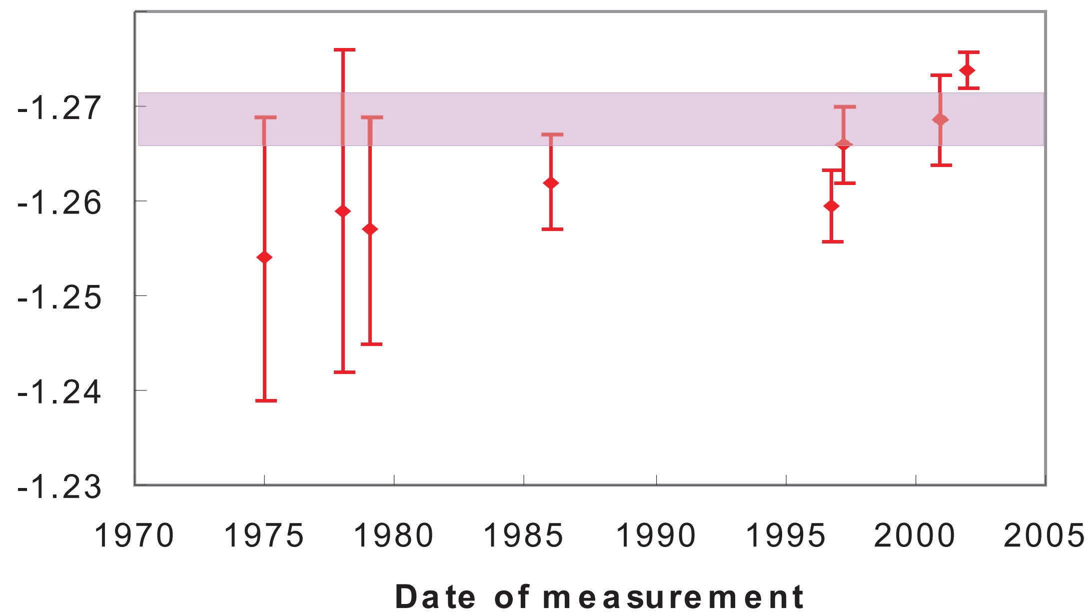
^{2}/N = 5.4



Beta asymmetry:

= -1.2690 ± 0.0028

^{2}/N = 2.6



NEUTRON DECAY DATA, 2006

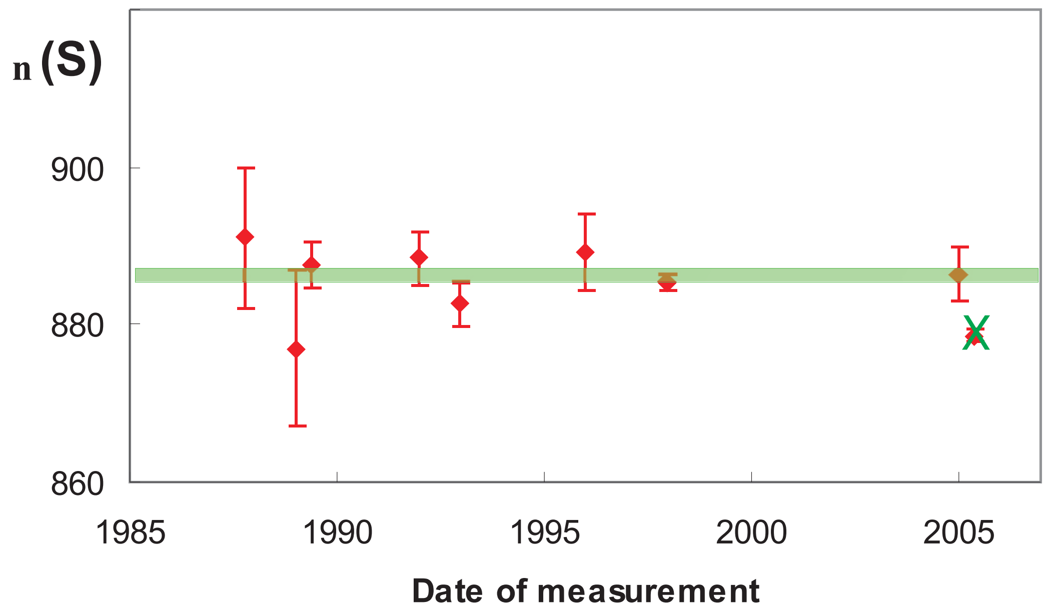
Mean life:

$_n$ = 882.0 ± 1.3 s

^{2}/N = 5.4

$_n$ = 885.6 ± 0.8 s

^{2}/N = 0.5



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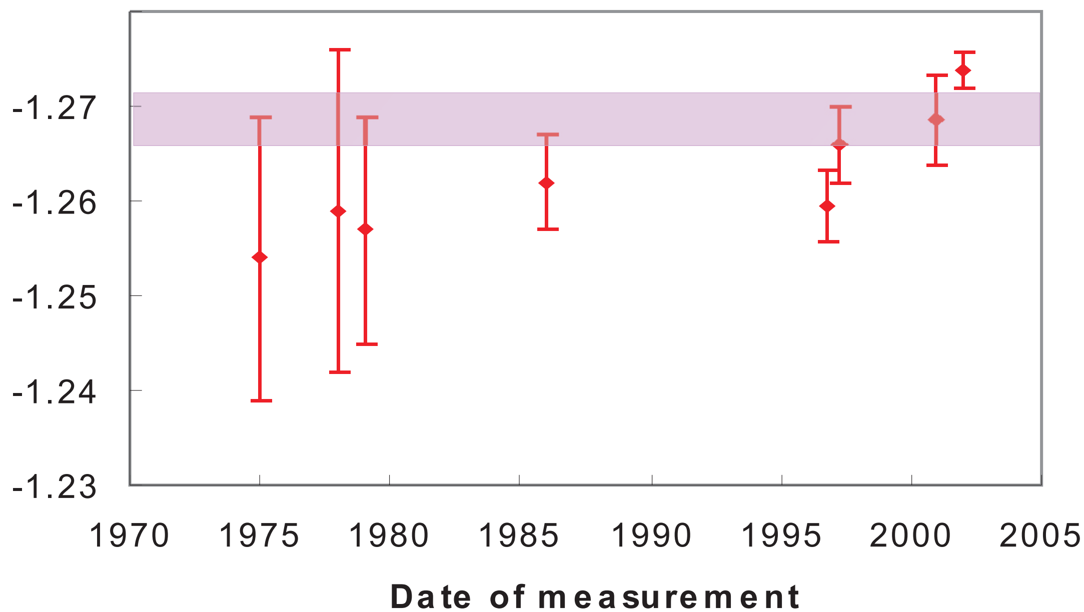
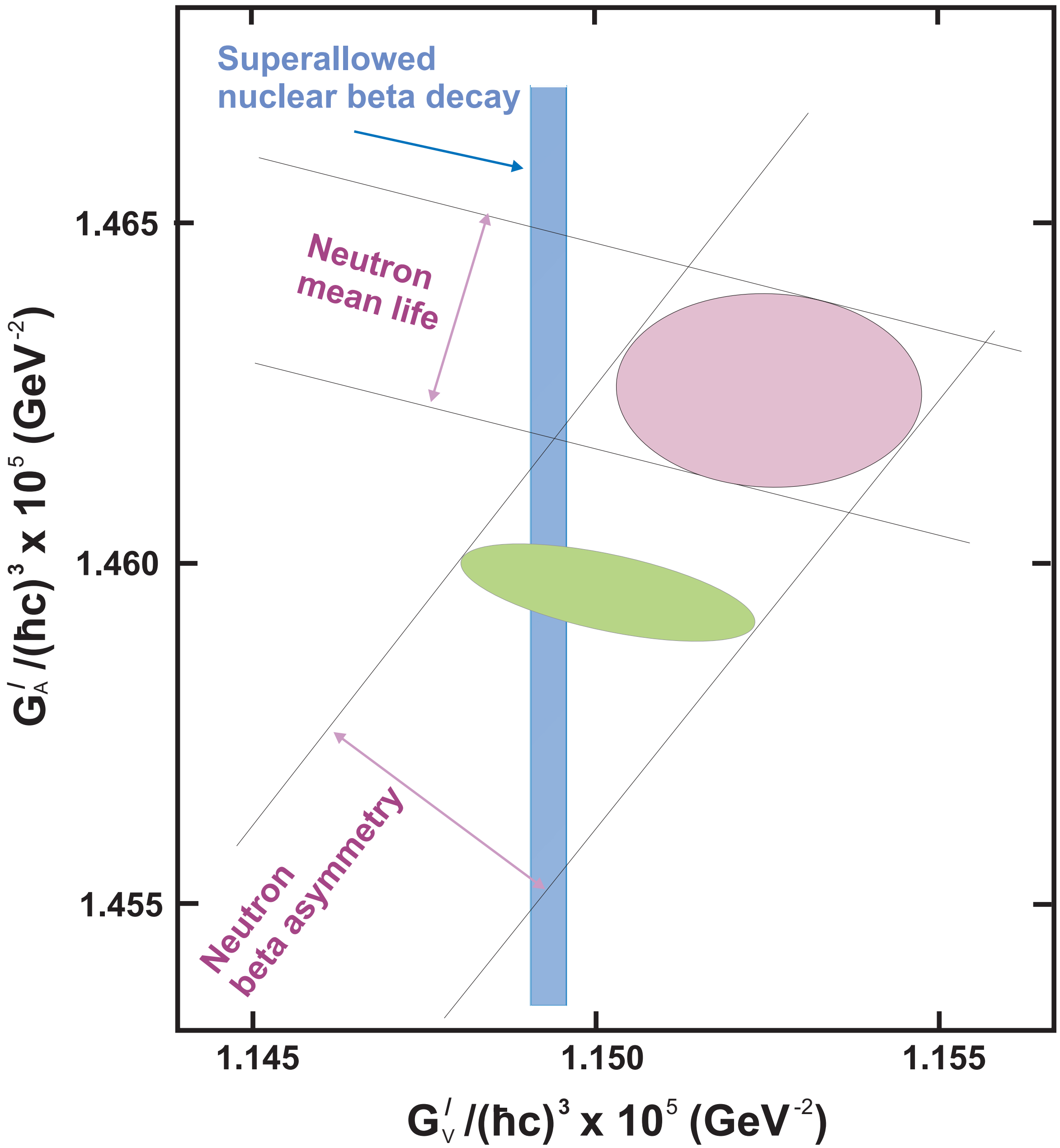


$G_A^{/}$, $G_V^{/}$ FROM NEUTRON & NUCLEAR DECAY DATA



PION BETA DECAY

$^{+} \rightarrow \ ^{0} e^{+}$ $\qquad 0^{-} \rightarrow 0^{-}$

$$V_{ud}^{2} = \frac{K}{2G_F^{2}(1+ \ _{R})(1+ \ _{R})\mathit{ft}}$$

$\mathit{t} = t_{1/2}/BR$ $\qquad$ BR ~ 10^{-8}

PION BETA DECAY

$^{+} \rightarrow \; ^{0} e^{+}$ $\qquad\qquad$ $0^{-} \rightarrow 0^{-}$

$$V_{ud}^{2} = \frac{K}{2G_F^{2}(1+ \; _R)(1+ \; _R) ft}$$

$t = t_{1/2}/BR$ $\qquad$ BR ~ 10^{-8}

PIBETA experiment

D. Pocanic *et al.*, PRL **93**, 181803

measured $\frac{BR(\; ^{+} \rightarrow \; ^{0} e^{+} \;)}{BR(\; ^{+} \rightarrow e^{+} \;)}$

result $V_{ud} = 0.9732 \pm 0.0032$ expt BR $_{e}$

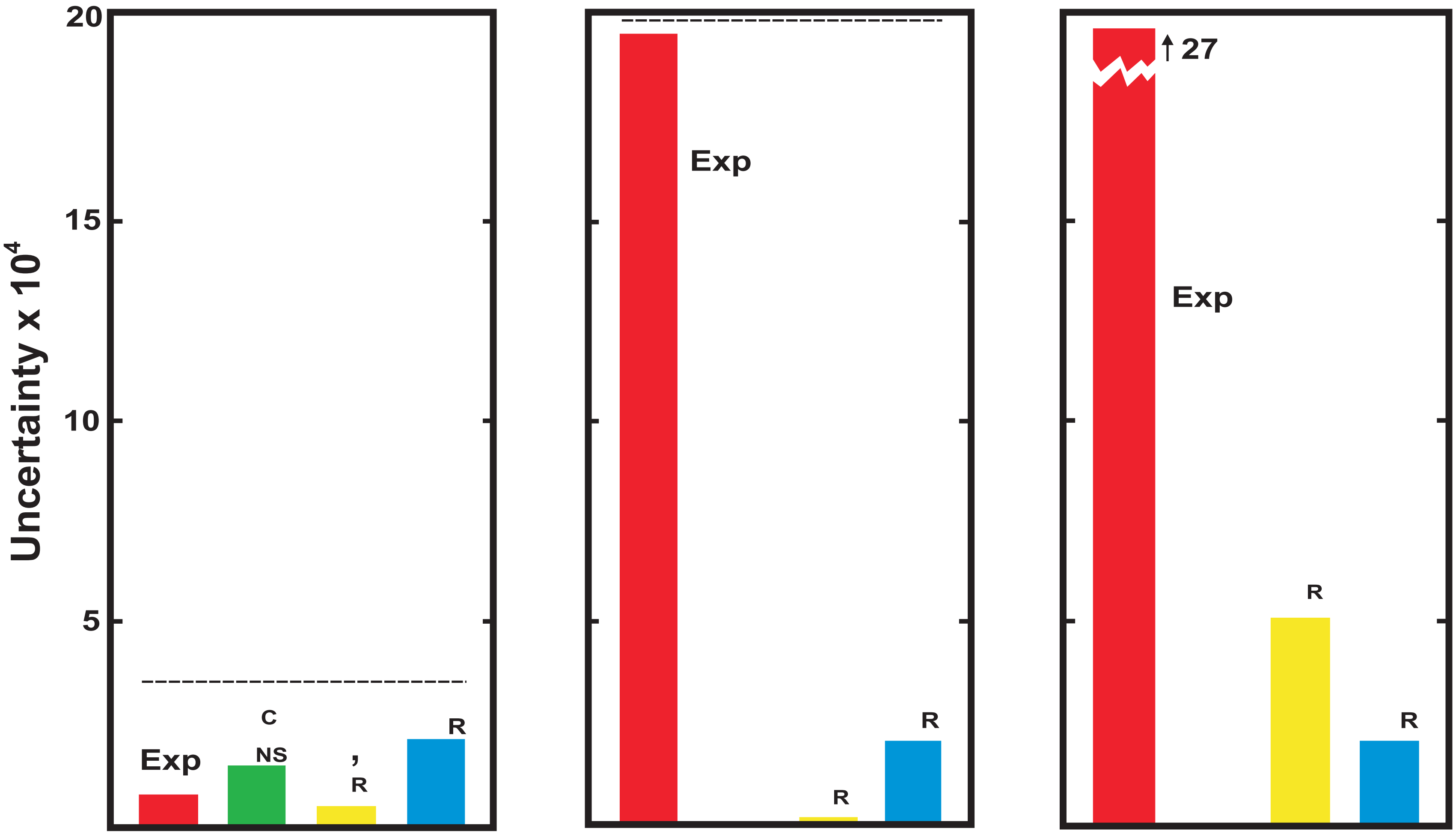
$= 0.9751 \pm 0.0027$ theo BR $_{e}$

CONTRIBUTIONS TO V_{ud} UNCERTAINTY

Nuclear $0^+ \rightarrow 0^+$
$V_{ud} = 0.9738 \pm 0.0003$

Neutron
$V_{ud} = 0.9745 \pm 0.0018$
(0.9765 ± 0.0020)

Pion beta decay
$V_{ud} = 0.9751 \pm 0.0027$
(0.9732 ± 0.0032)



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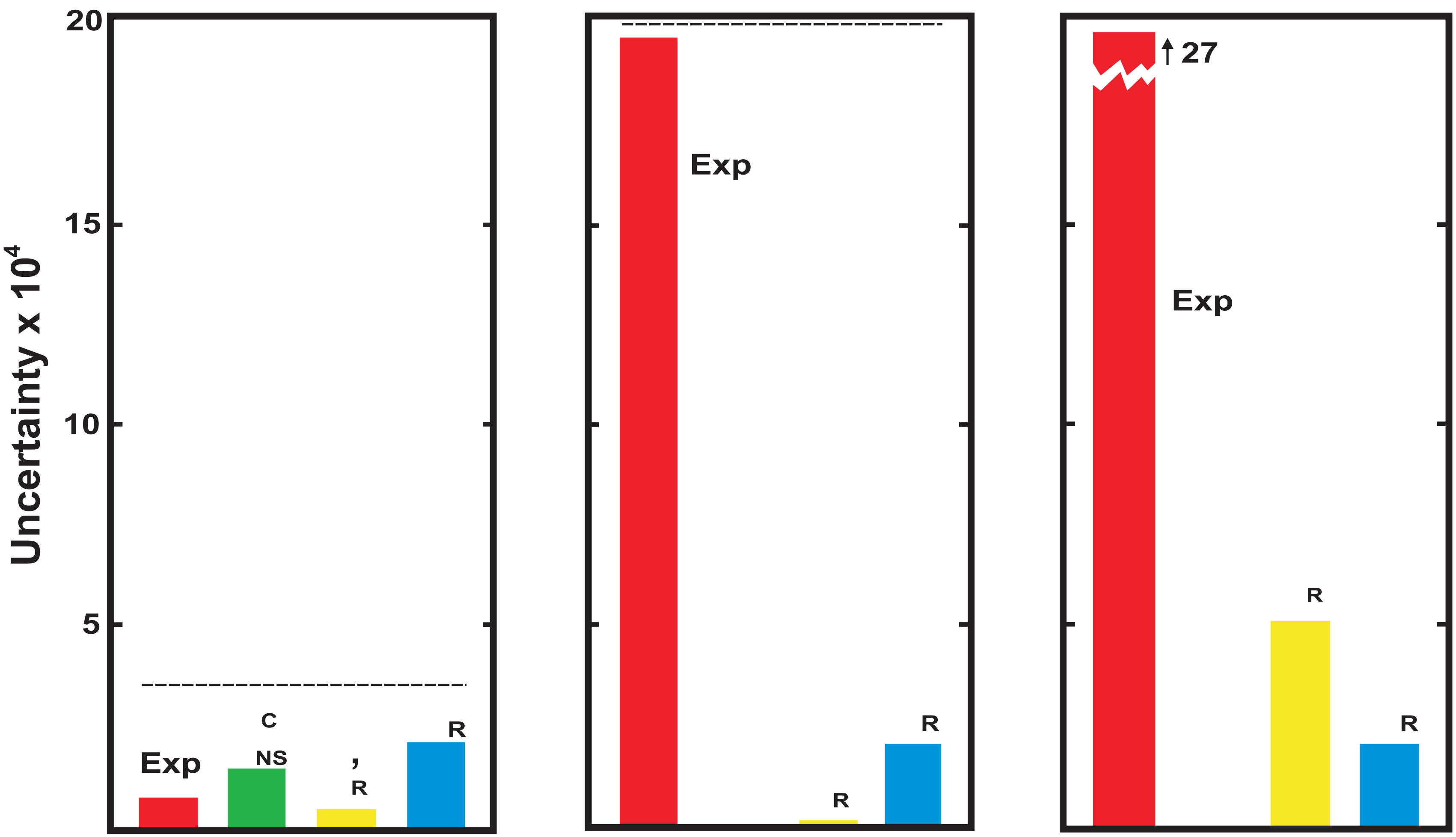

SUMMARY

1. The 2005 superallowed -decay survey yielded tight limits on new physics: CVC verified to 0.026%; $|C_S/C_V| < 0.0013$.
2. In the past two years, the nuclear result for V_{ud} has been considerably improved by both theory and experiment.
3. Neutron and pion decays still yield much less precise values for V_{ud}, limited by experimental uncertainties.
4. The superallowed decay result for V_{ud} has been stable (with decreasing uncertainties) for decades.
5. Much nuclear activity is now focused on reducing V_{ud} uncertainty *via* tests of structure-dependent correction terms.
6. With one possible exception, nuclear results continue to support calculated structure-dependent correction terms.
7. CKM unitarity now verified to 0.1%. Uncertainty dominated by V_{us}, but V_{ud} will no doubt become critical again.
8. The value of V_{ud} can be improved further.