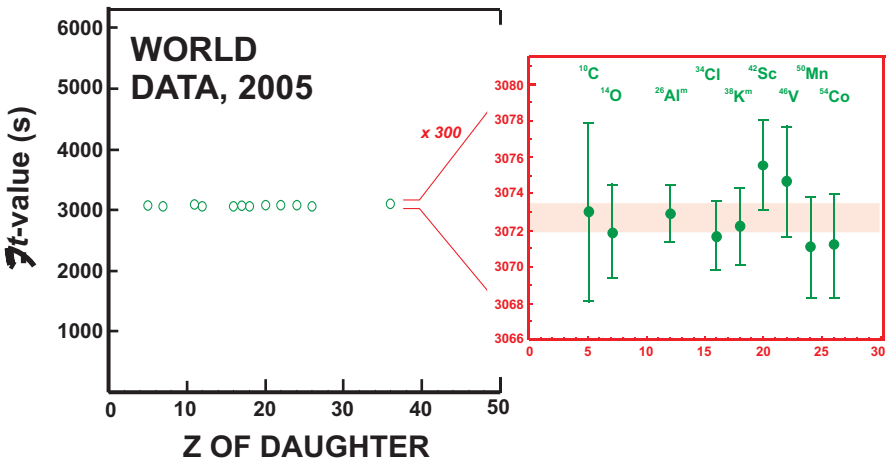
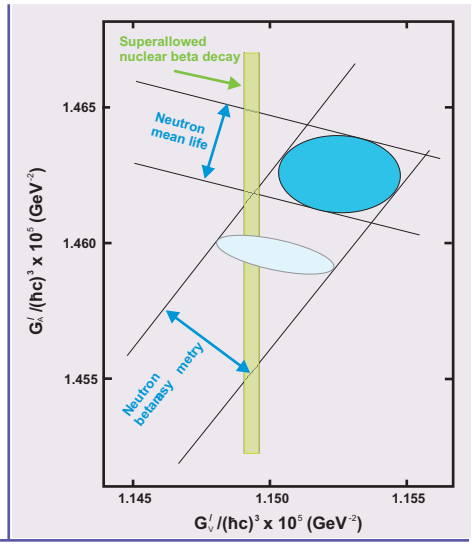
PRECISION MEASUREMENTS

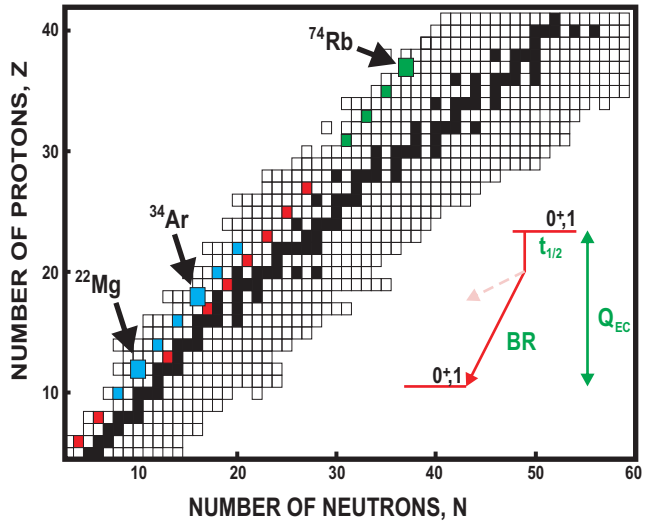
2. Results (Superallowed -decay and Internal Conversion)

J.C. Hardy
Cyclotron Institute
Texas A&M University
U.S.A.





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



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

BASIC WEAK-DECAY EQUATION

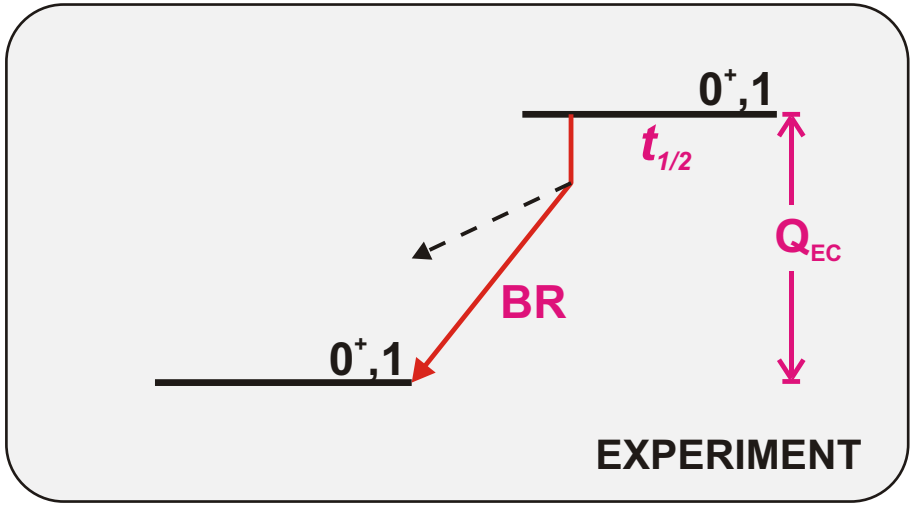
$$ft = \frac{K}{G_V^2 \langle \quad \rangle^2}$$

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

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

G_V = vector coupling constant

$\langle \quad \rangle$ = Fermi matrix element



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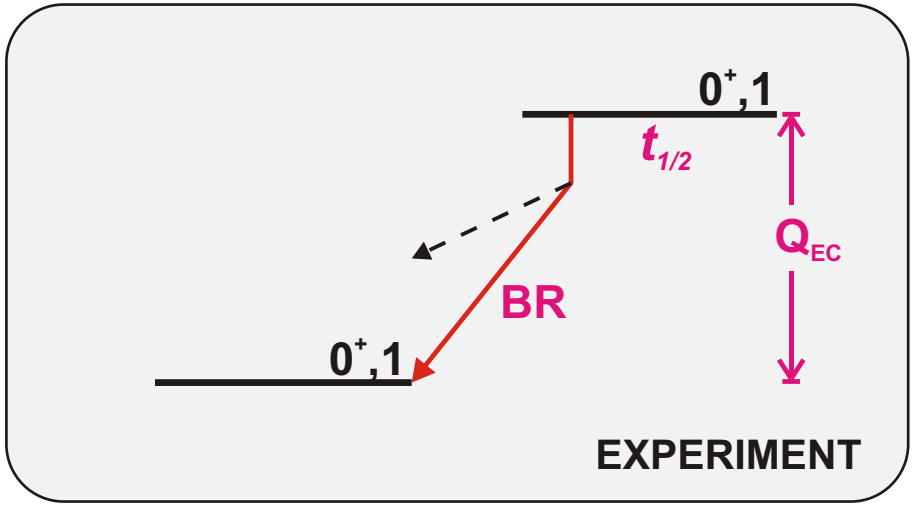

INCLUDING RADIATIVE CORRECTIONS

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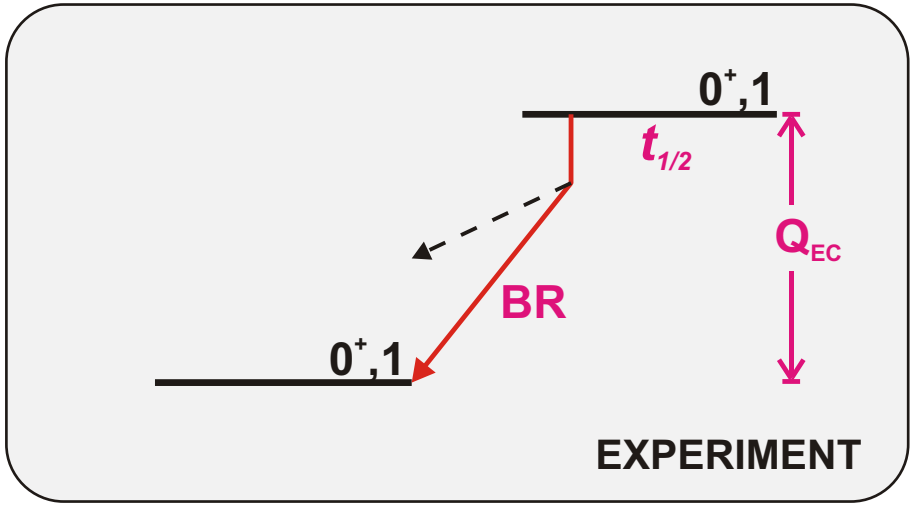

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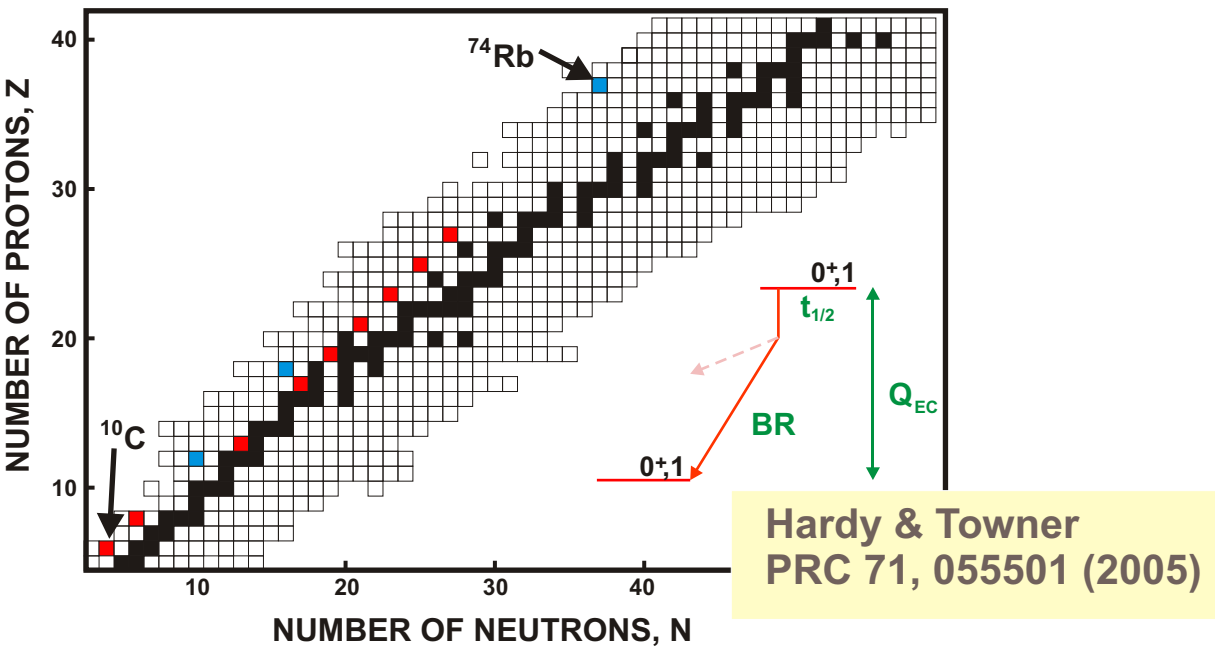
$f(Z, Q_{EC})$ ~1.5%

f(nuclear structure) 0.3-0.7%

f(interaction) ~2.4%

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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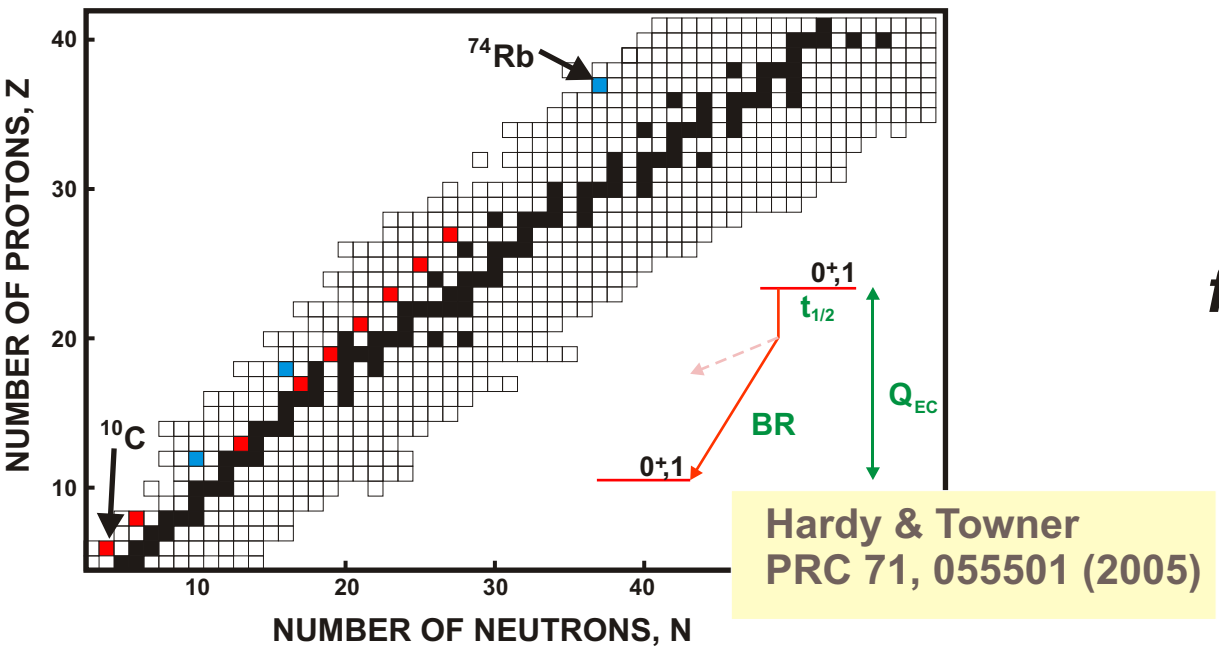

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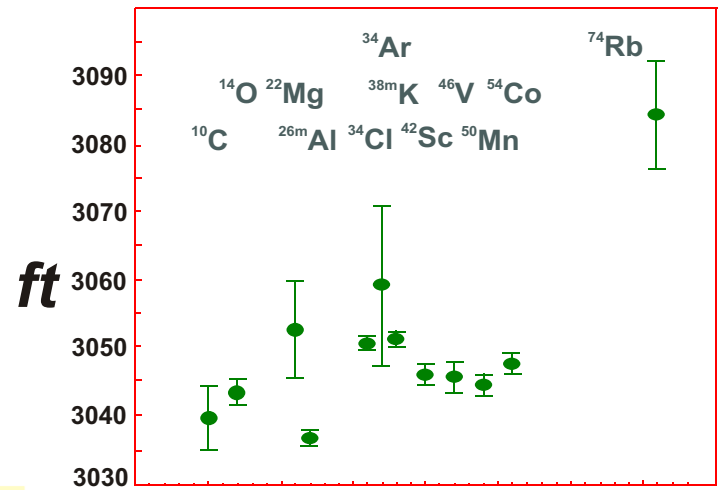

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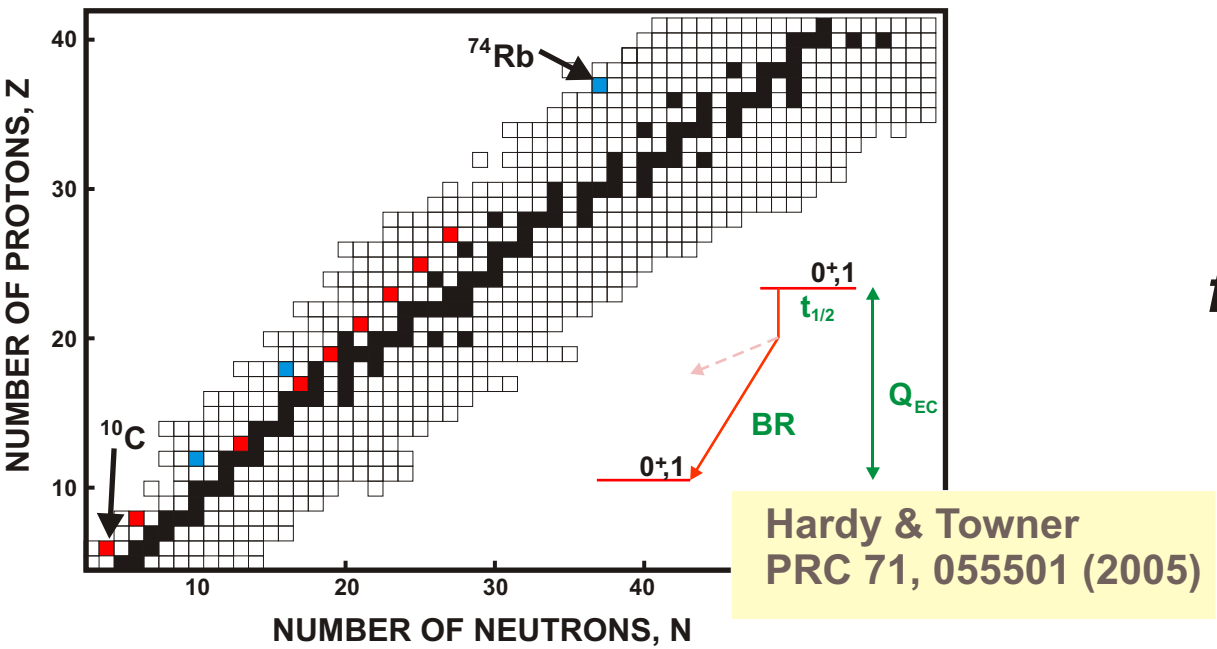

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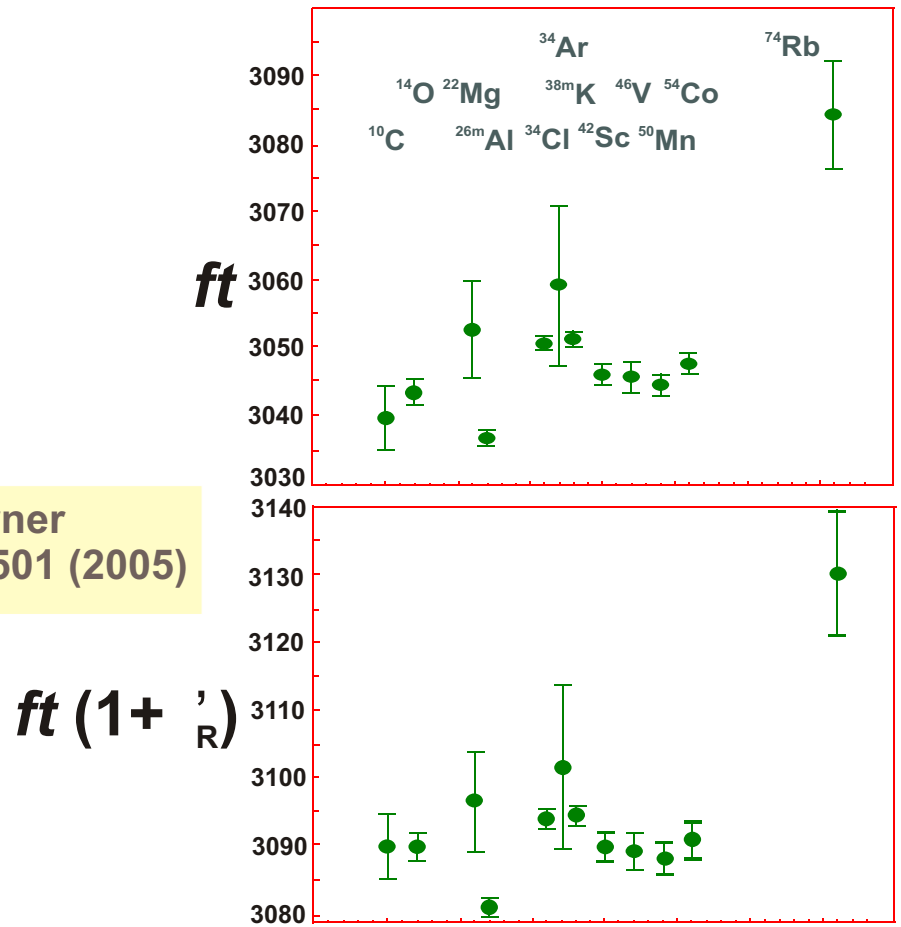

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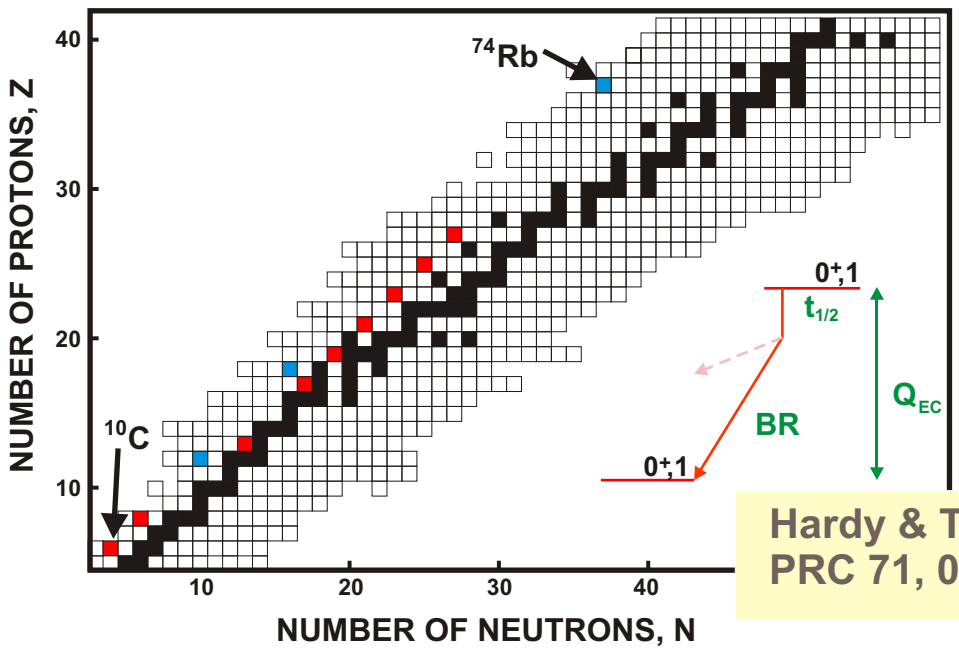

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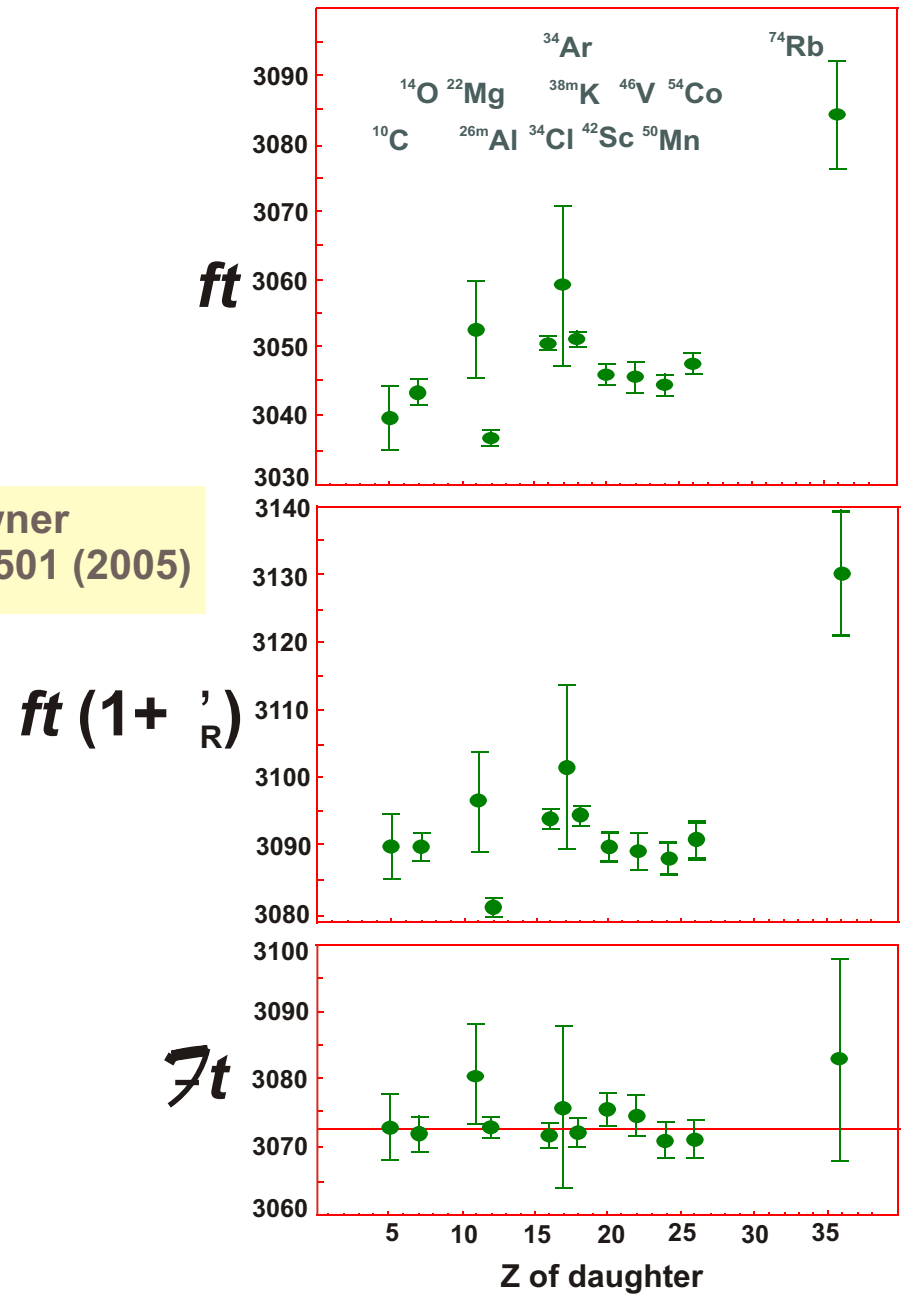

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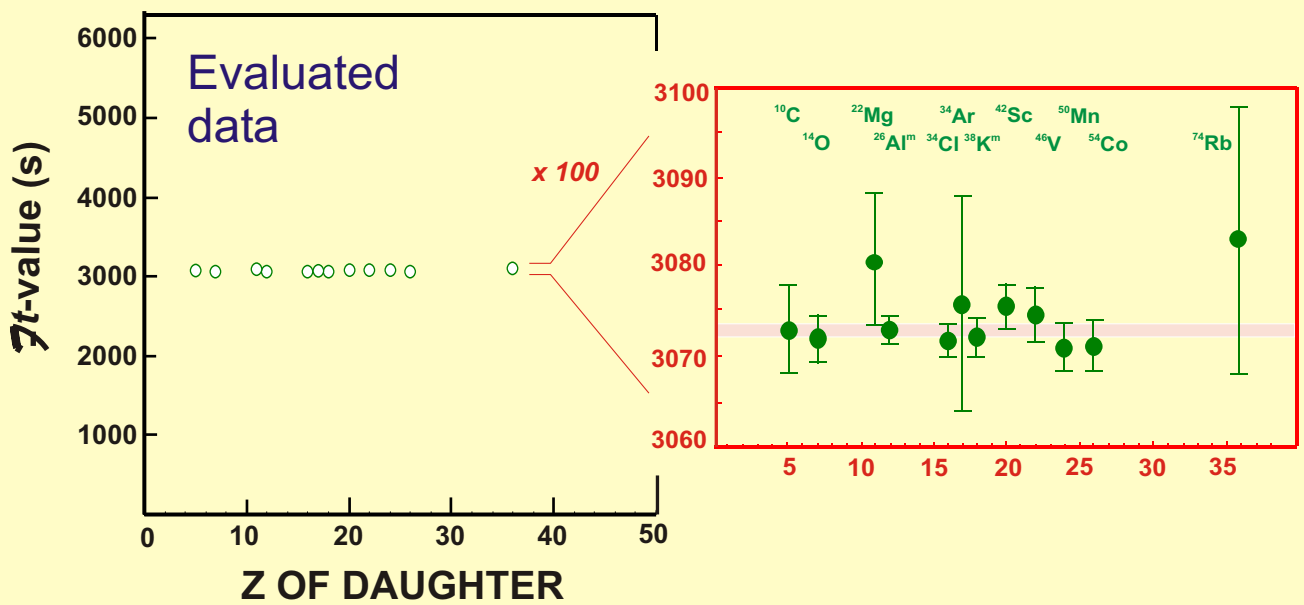

$\mathcal{F}t$ = 3072.7(8)

$G_V'/(hc)^3$
= 1.14950(15)
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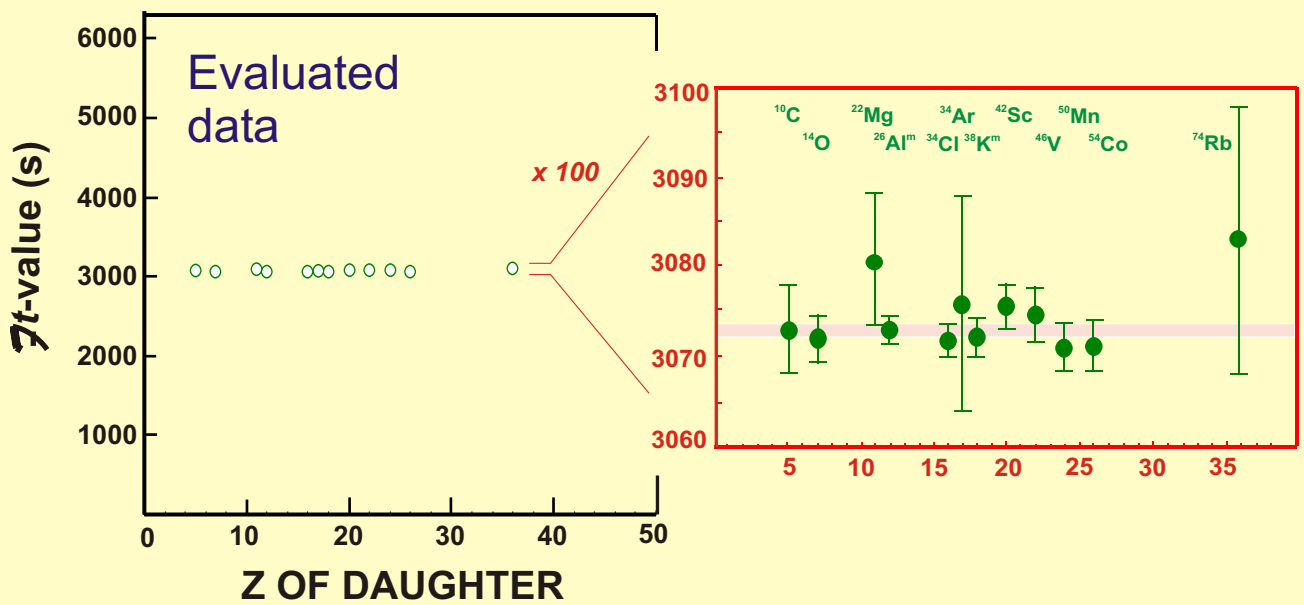

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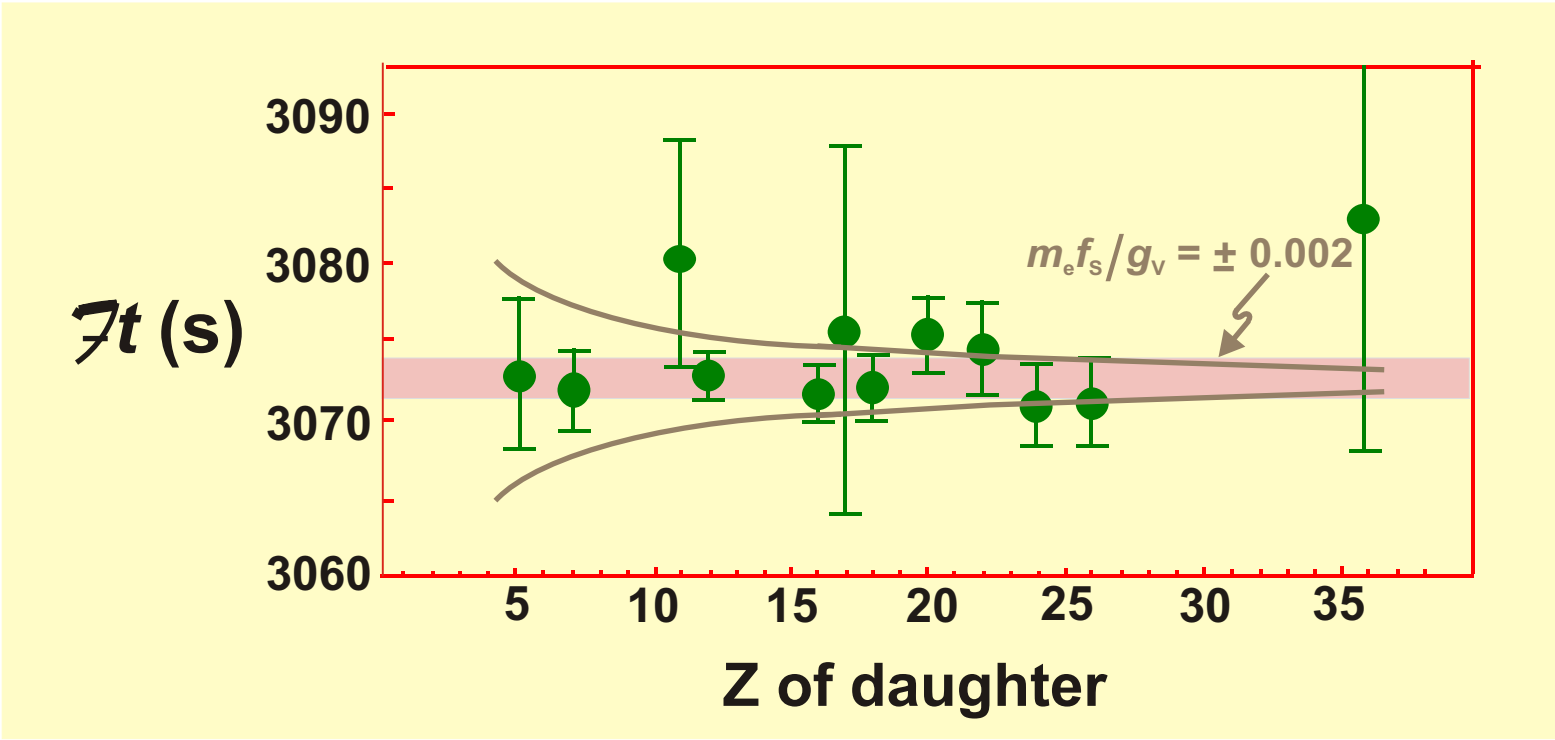

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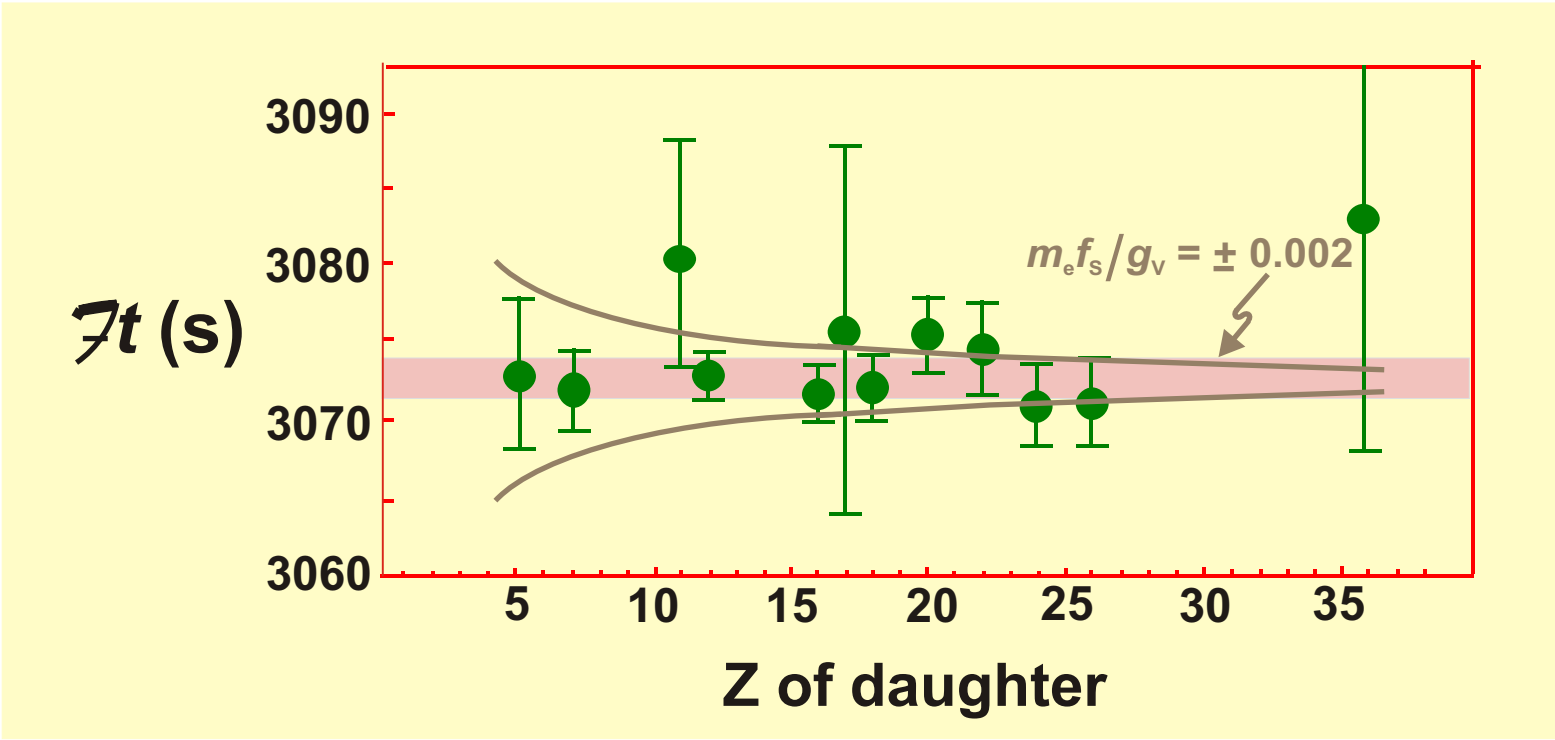

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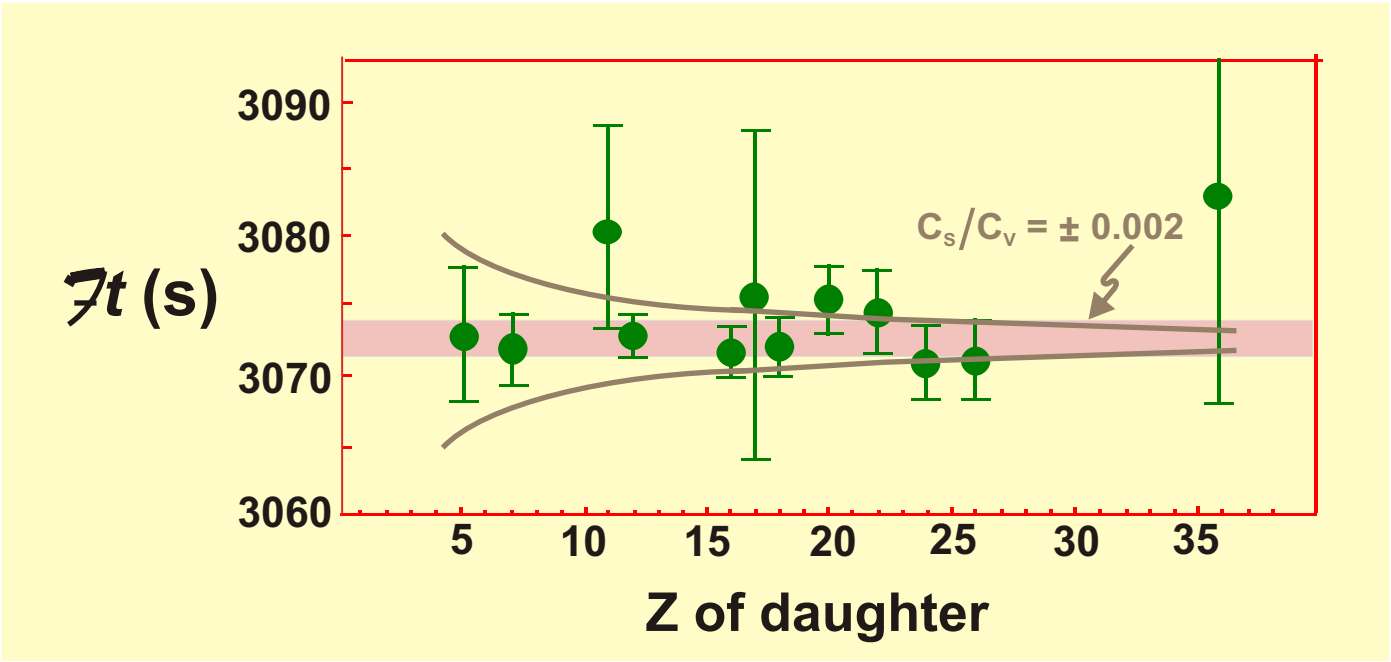

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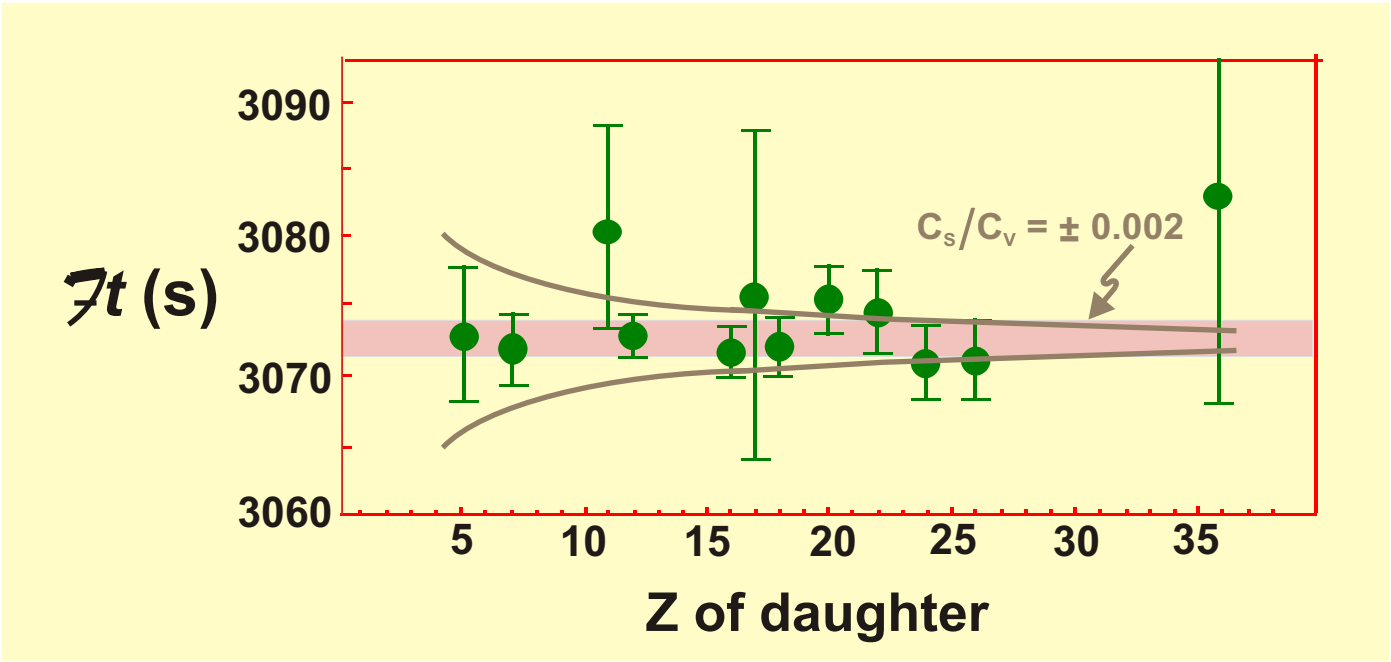

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weak eigenstates

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nuclear (n &) decays
muon decay
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± 0.0001 exp't

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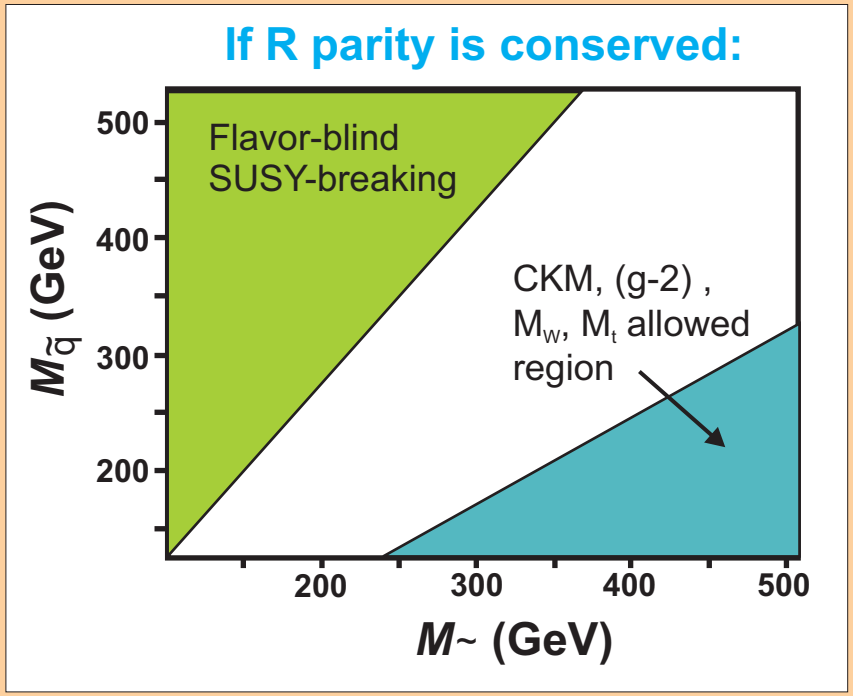

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6) Supersymmetry ✔ limits set Kurylov & Ramsey-Musolf PRL 88, 071804 (2002)

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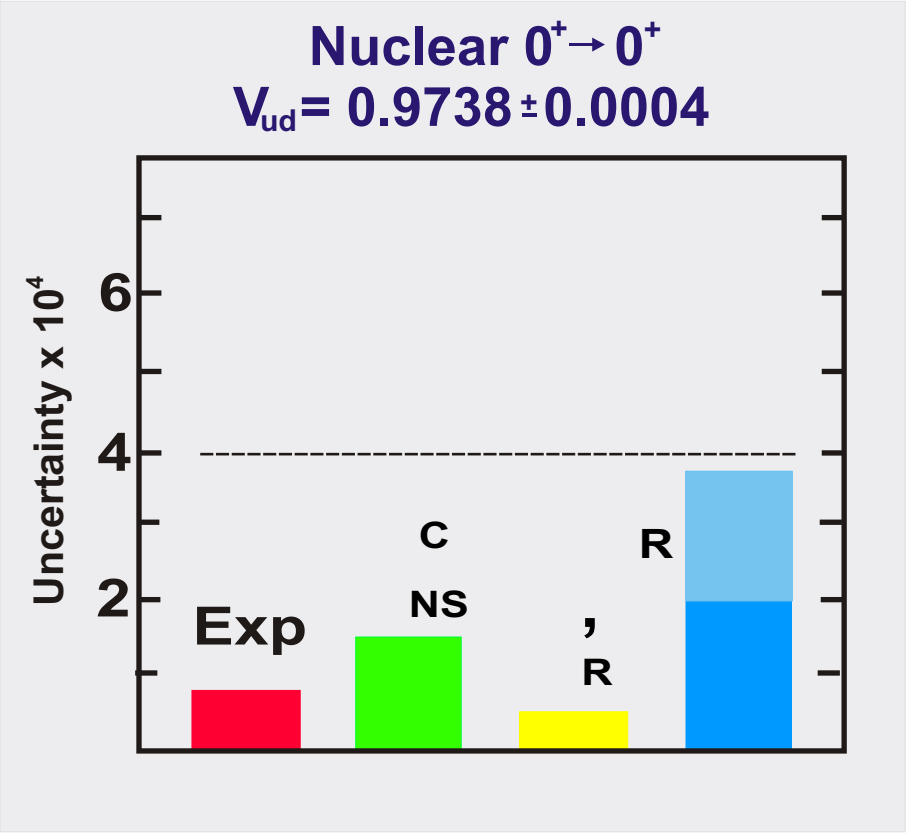

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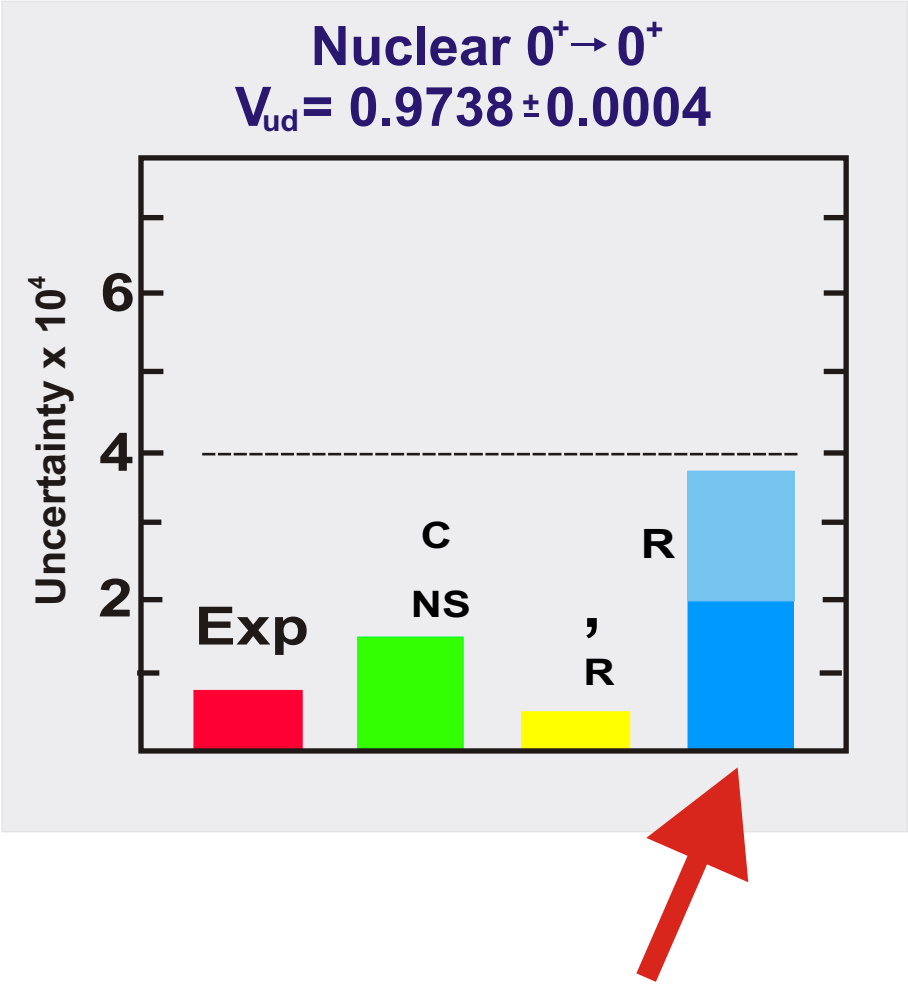
Marciano & Sirlin
PRL 96, 032002 (2006)



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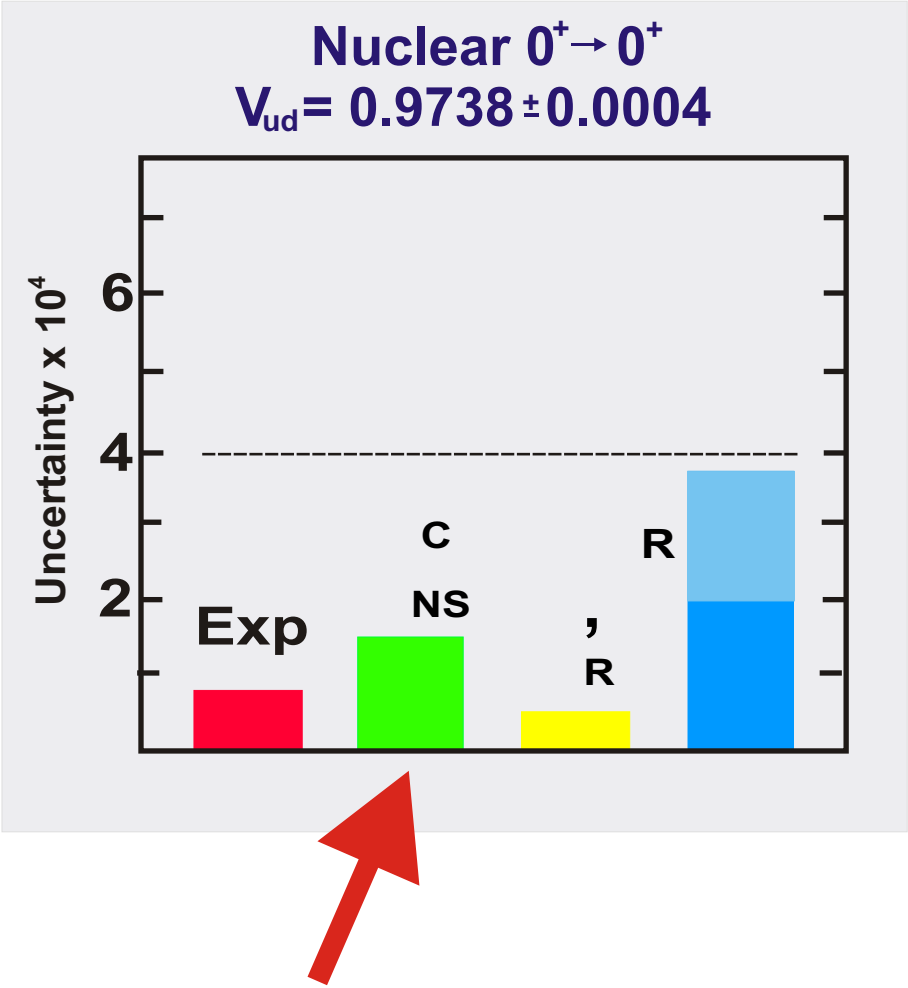

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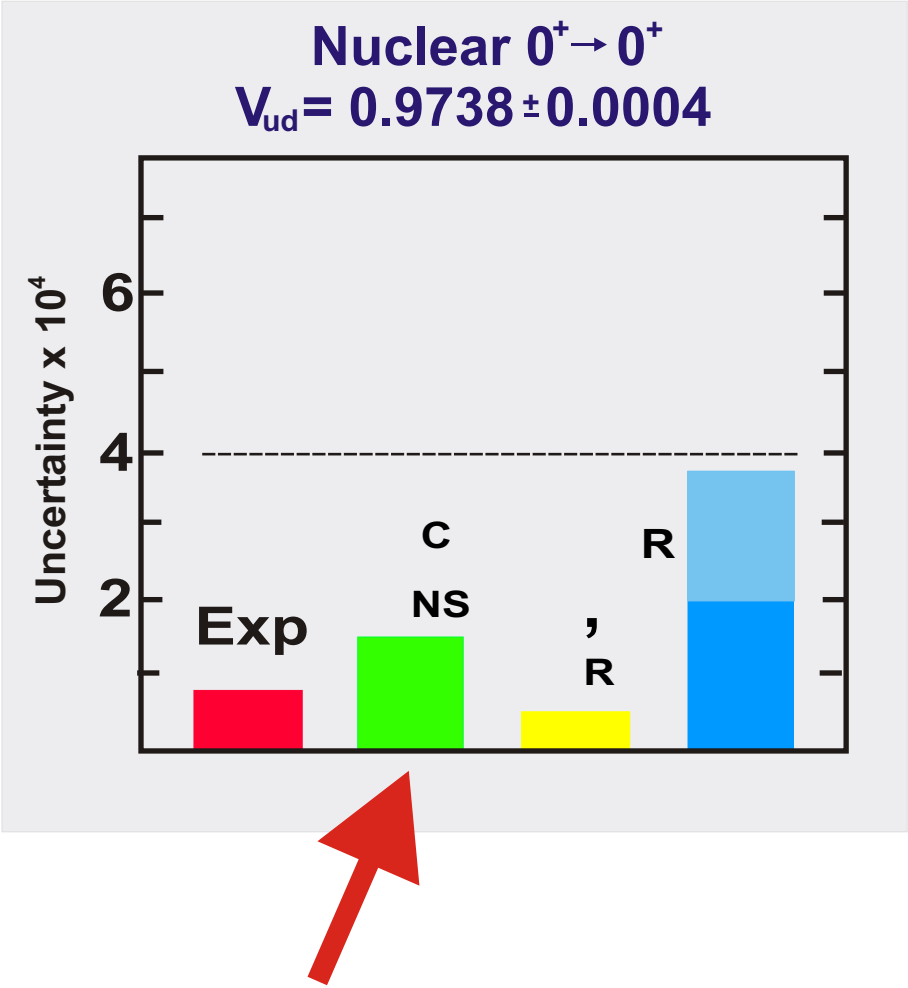
Well known cases being improved and new cases explored.



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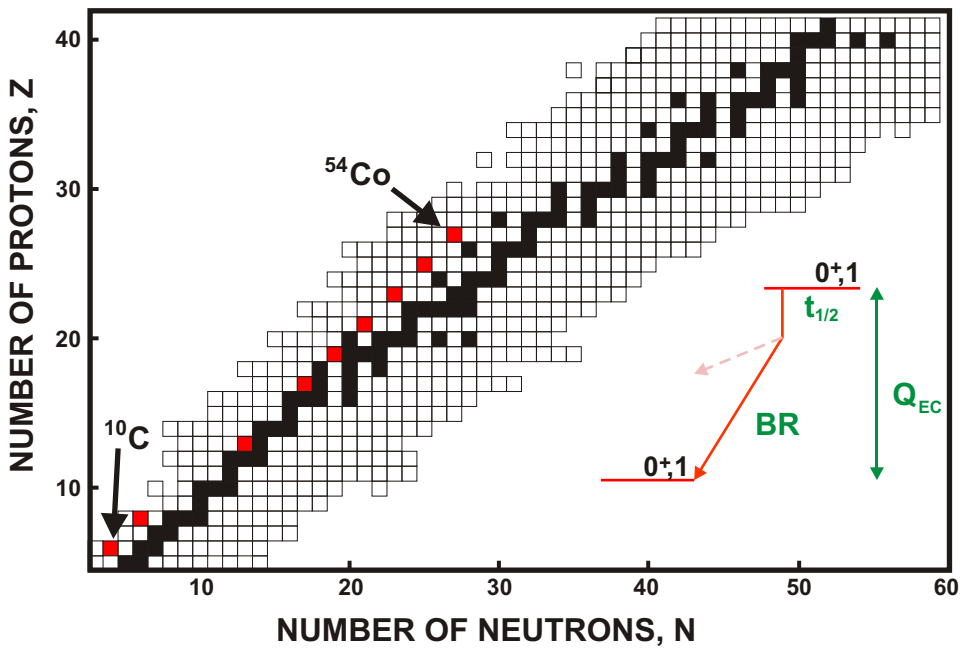

Strategy is to probe the nucleus-to-nucleus variation in $_C$ - $_{NS}$.

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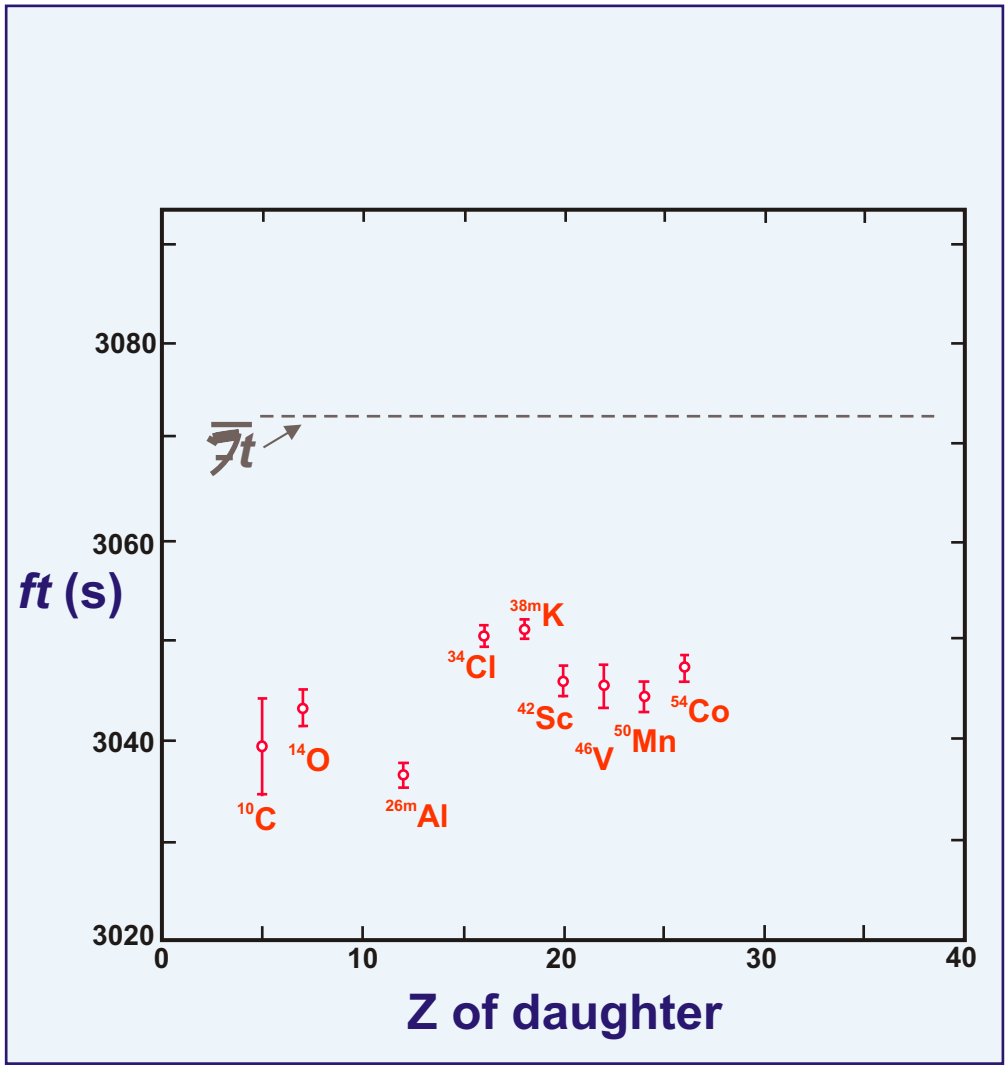

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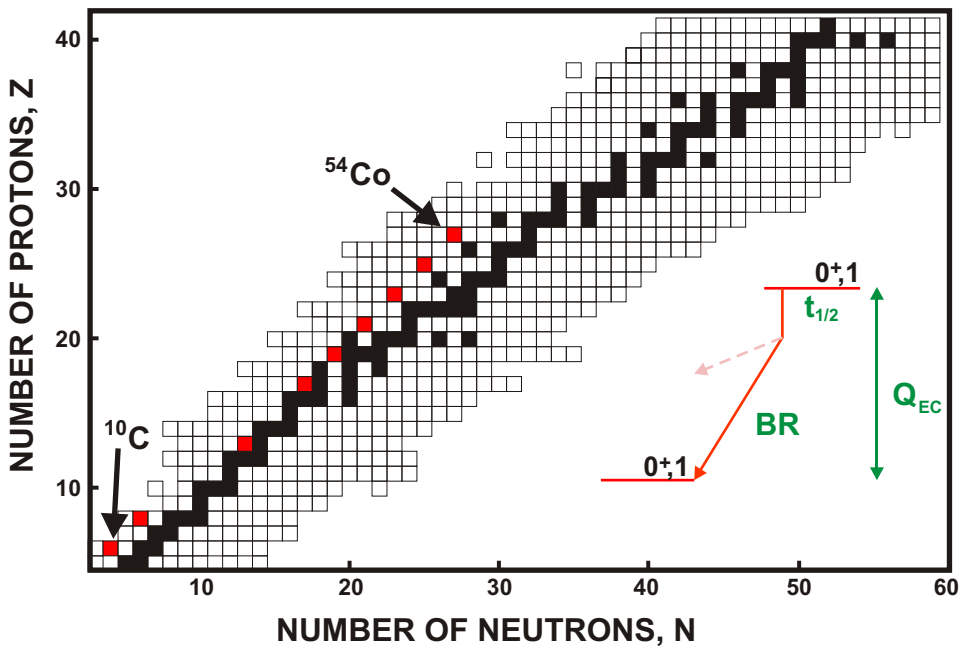
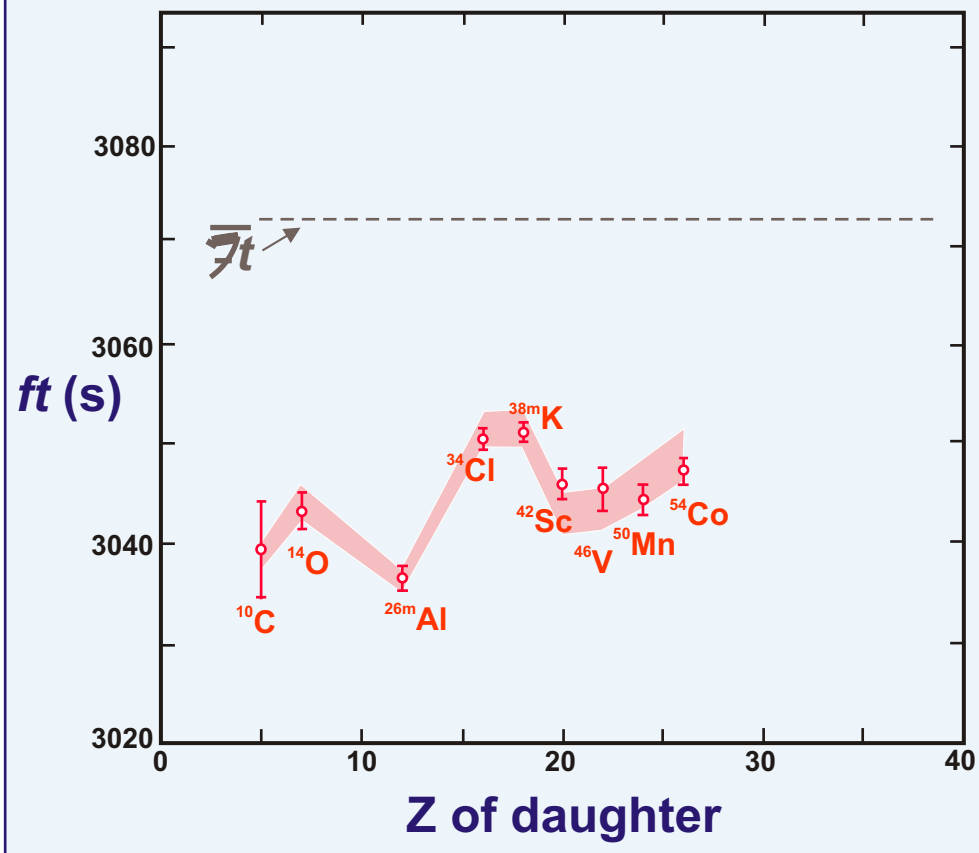


Strategy is to probe the nucleus-to-nucleus variation in $_C$ - $_{NS}$.

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

$$\text{Calculated } ft\text{-value} = \frac{\mathcal{F}t}{(1 + {}_R)\left[1 - ({}_C - {}_{NS})\right]}$$



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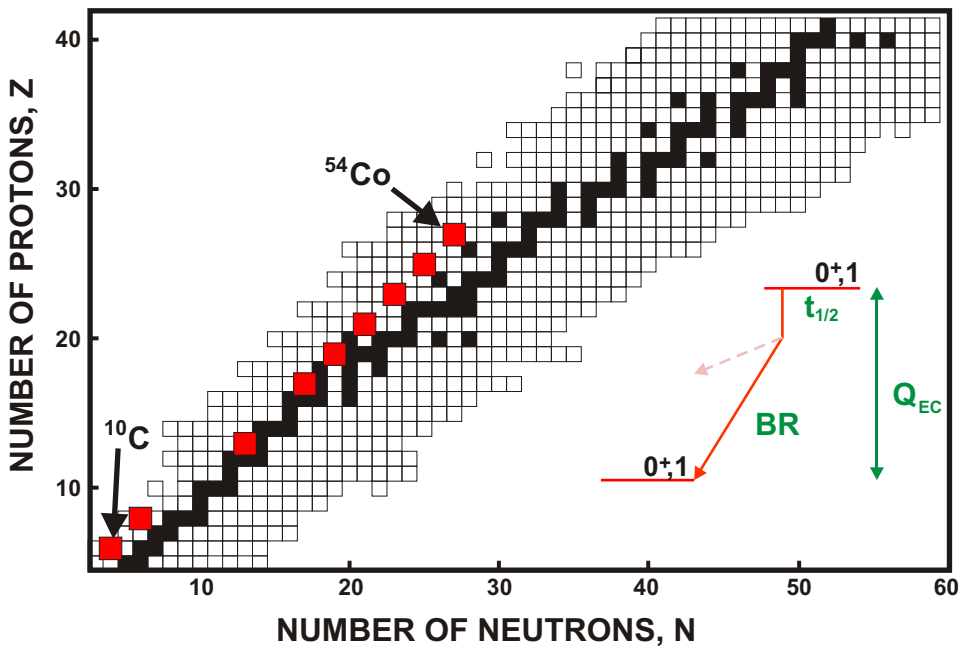

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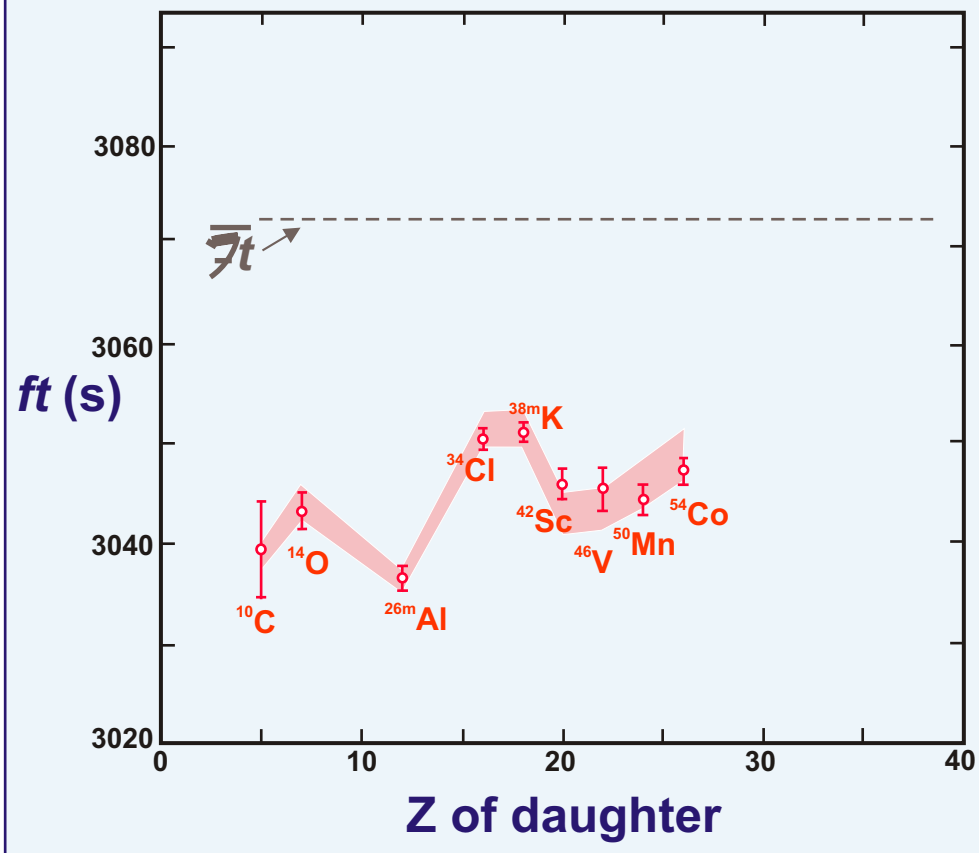
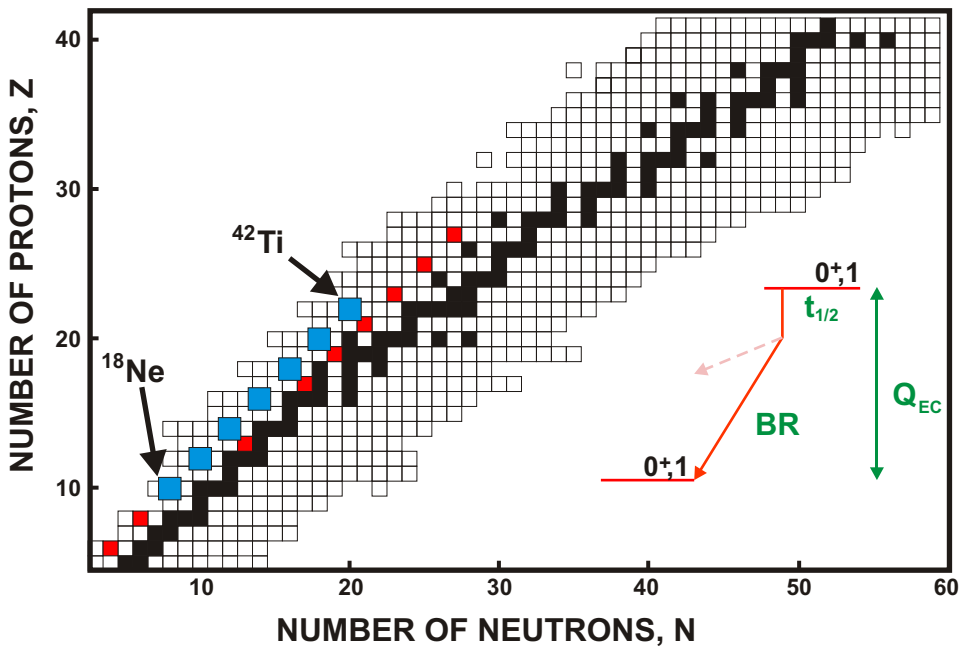


Increase measured precision on nine best *ft*-values

CURRENT DIRECTION OF NUCLEAR EXPERIMENTS



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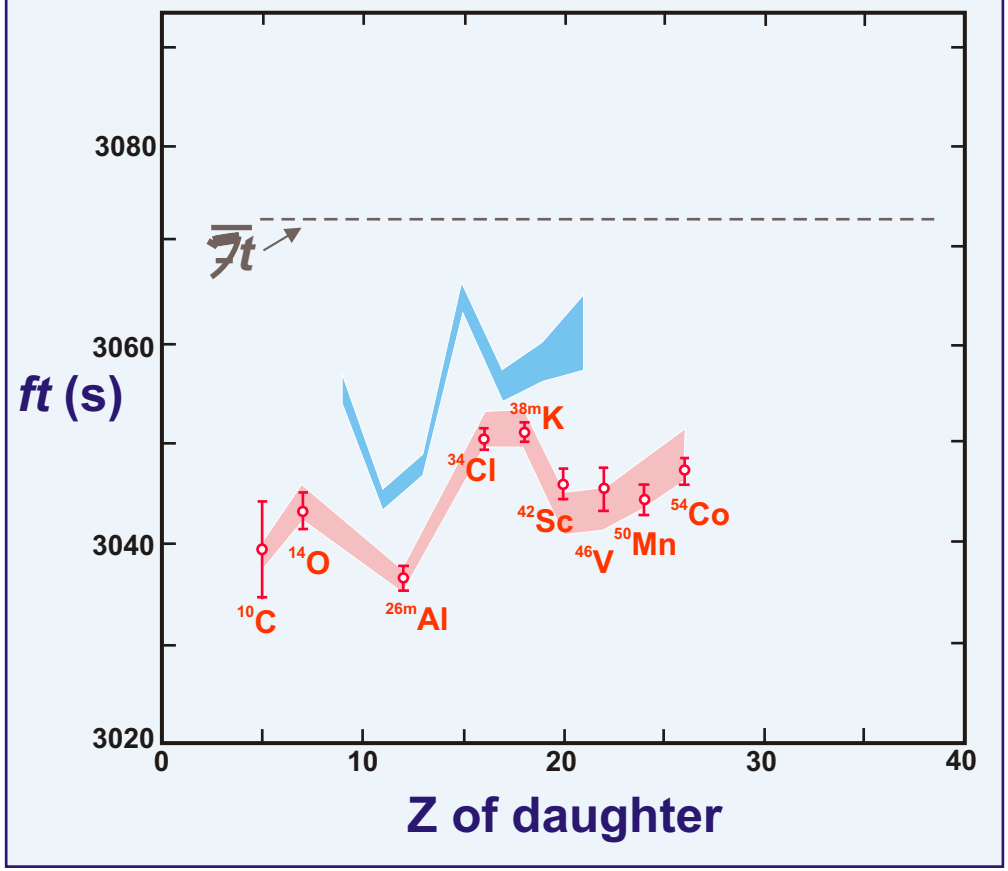
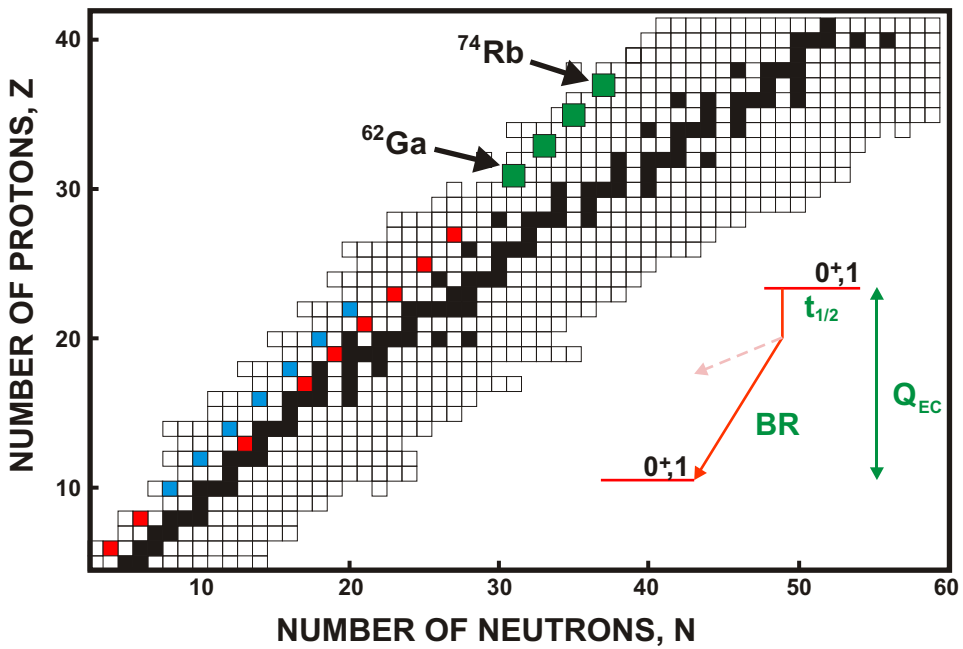


Increase measured precision on nine best *ft*-values

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

CURRENT DIRECTION OF NUCLEAR EXPERIMENTS



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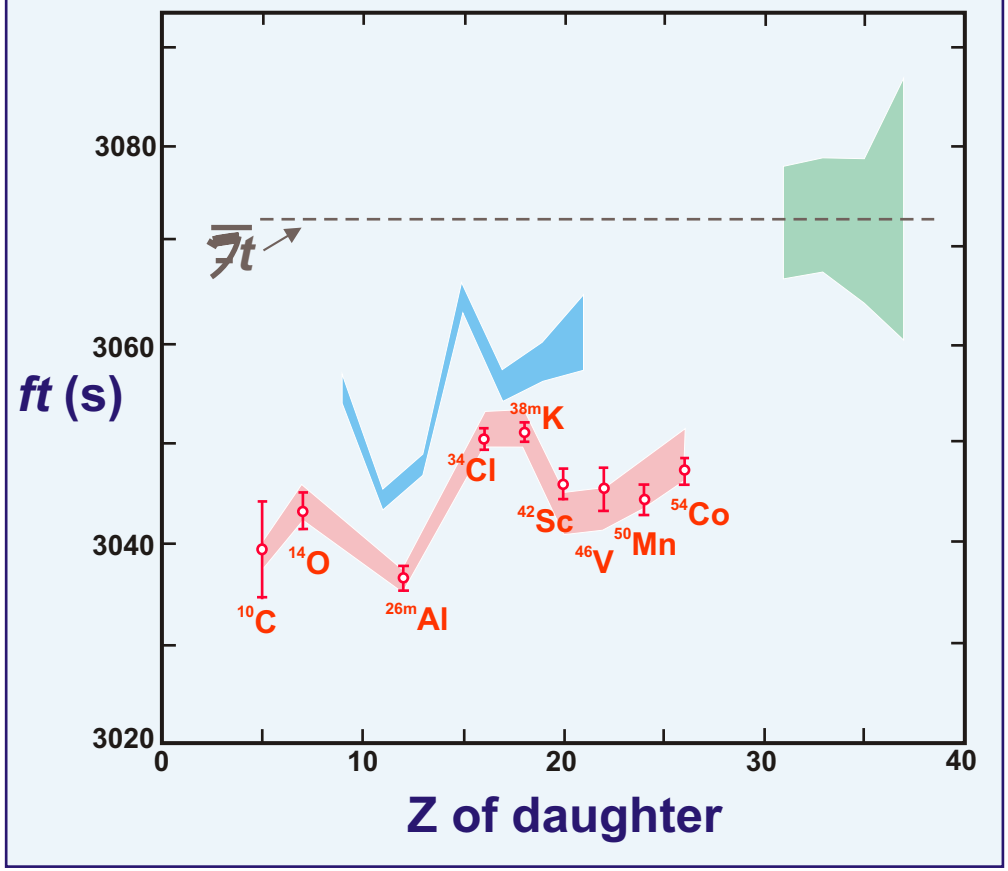
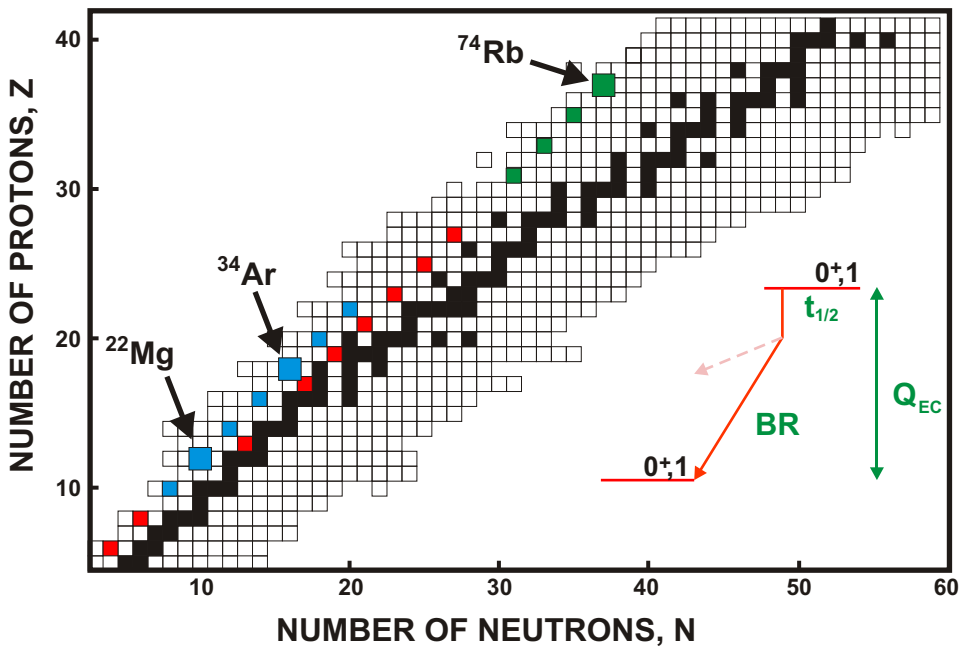


Increase measured precision on nine best *ft*-values

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

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

CURRENT DIRECTION OF NUCLEAR EXPERIMENTS



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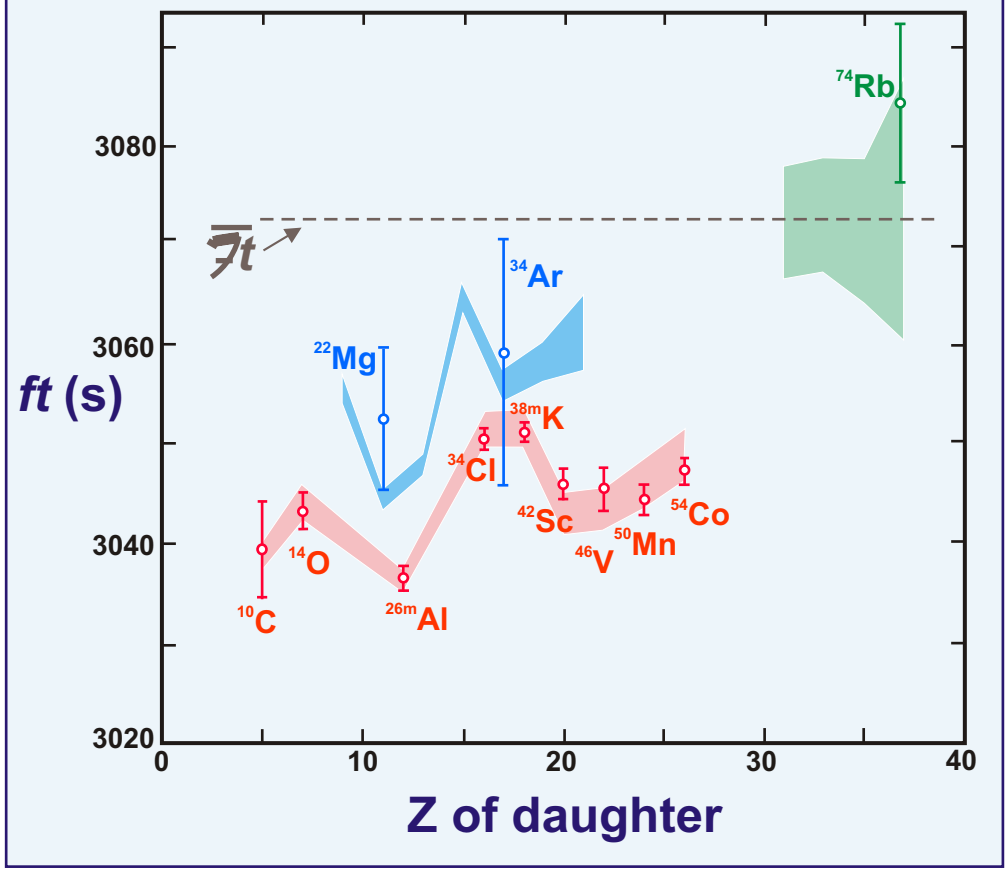

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measure new $0^+ \rightarrow 0^+$ decays with $18 \leq A \leq 42$ ($T_z = -1$)

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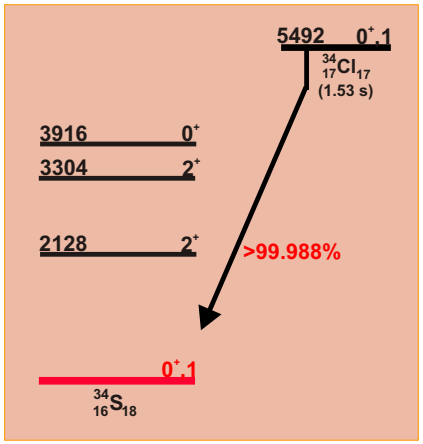
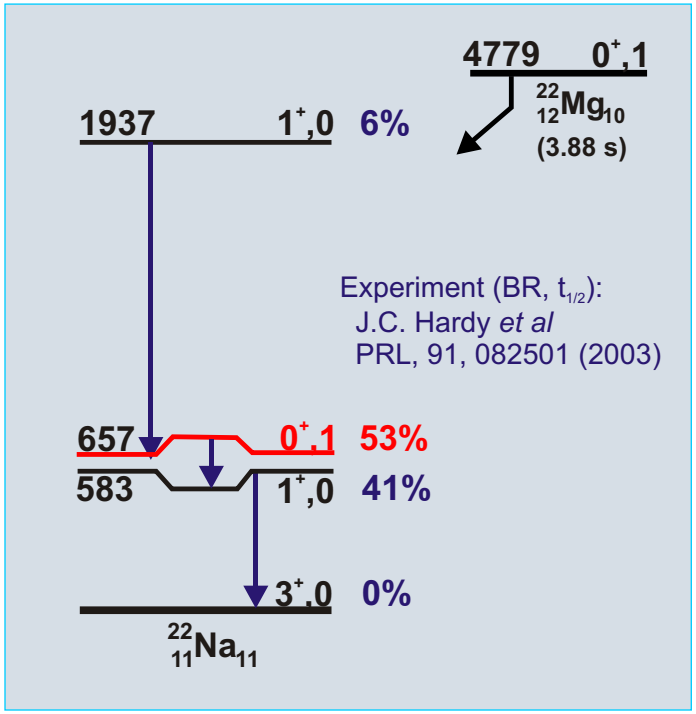
THE CHALLENGES OF NEW CASES

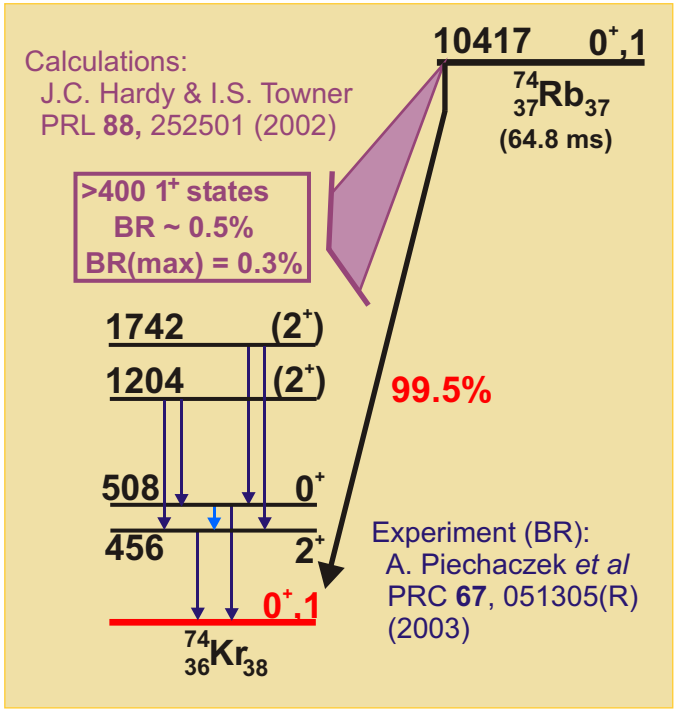


Typical standard case

- Low production rate
- Branching ratio < 100%
- "Pandemonium" excited states
- Similar parent/daughter half-lives
- Exotic mass measurement



T_z = -1 parent, $18 \leq A \leq 42$



T_z = 0 parent, $A \geq 62$

$t_{1/2}$: G.C. Ball *et al* PRL **86**, 1454 (2001)

Q_{EC}: A. Kellerbauer *et al*, PRL **93**, 072502 (2004)

RECENT OR CURRENT EXPERIMENTS

Q_{EC} values:

Argonne (Canadian Penning trap)

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

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

Jyvaskyla (JYFLTRAP)

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

^{26}Al^{m}, ^{42}Sc, ^{46}V

NSCL (LEBIT)

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

Munich Tandem

^{46}V

Half-lives:

Auckland/Canberra ^{50}Mn P.H. Barker *et al.* PRC 73, 064306 (2006)

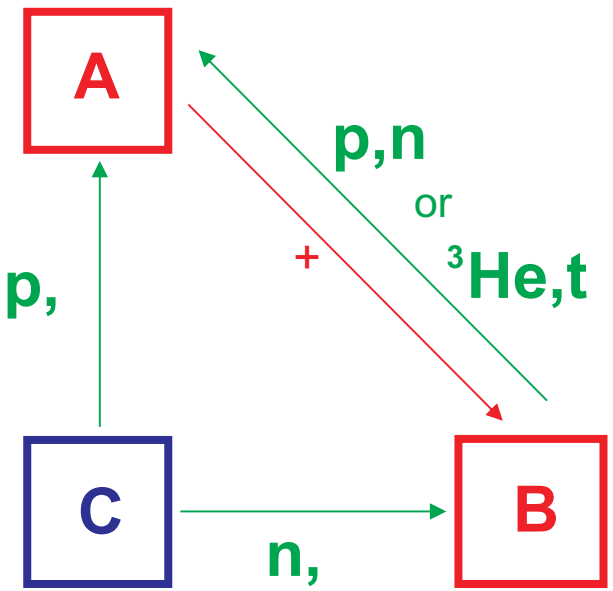
Texas A&M ^{10}C, ^{34}Cl, ^{34}Ar, ^{38}Ca

Branching ratios:

TRIUMF ^{62}Ga

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

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  Chalk River:
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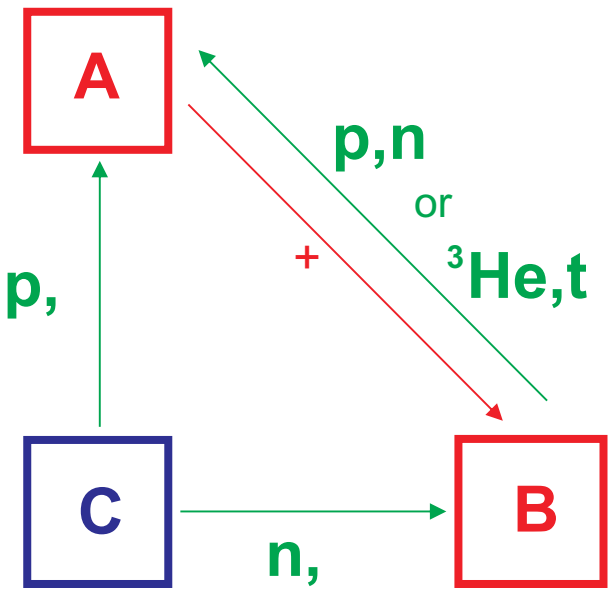

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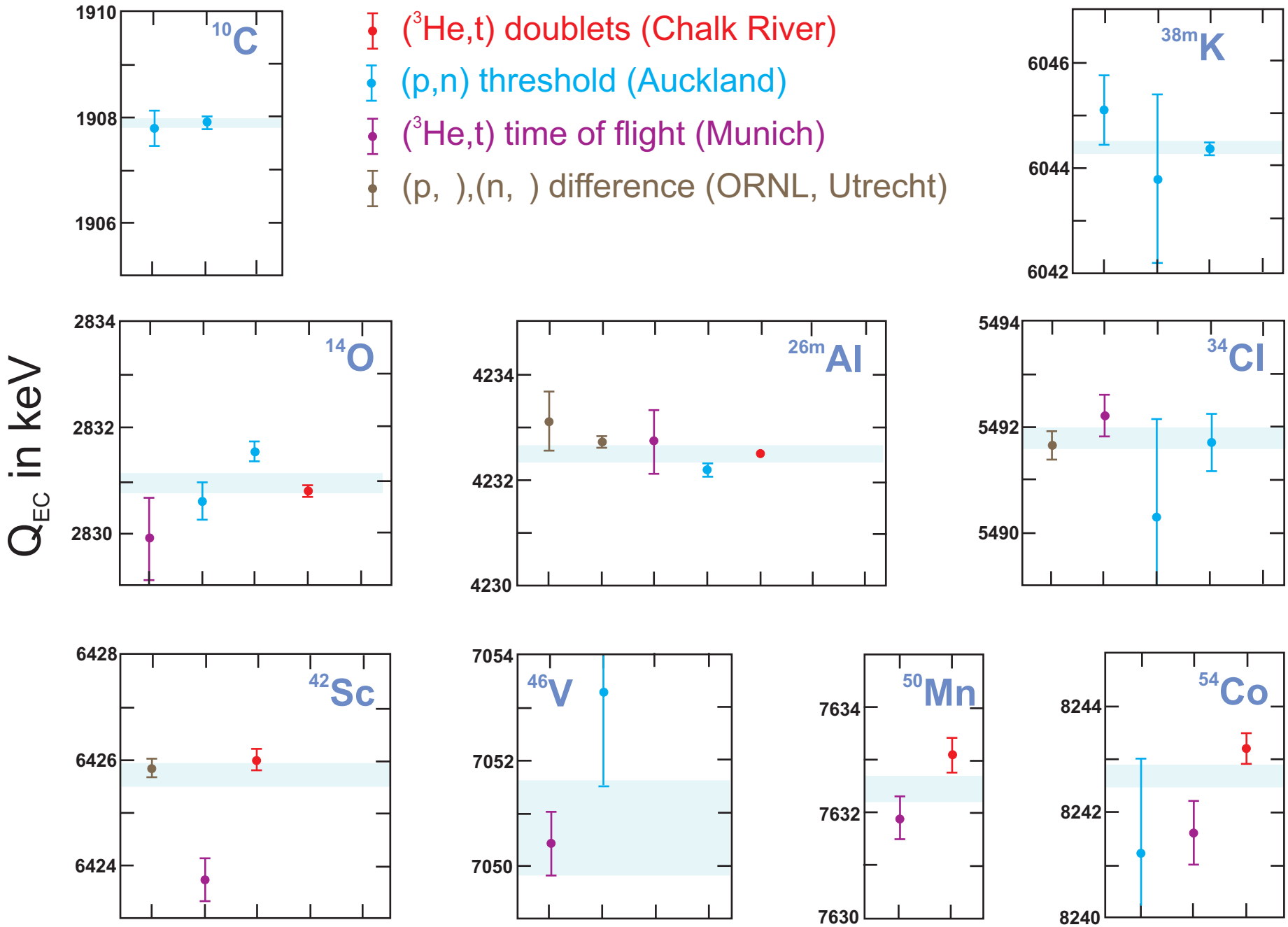
Q_{EC} FOR SUPERALLOWED TRANSITIONS (keV)



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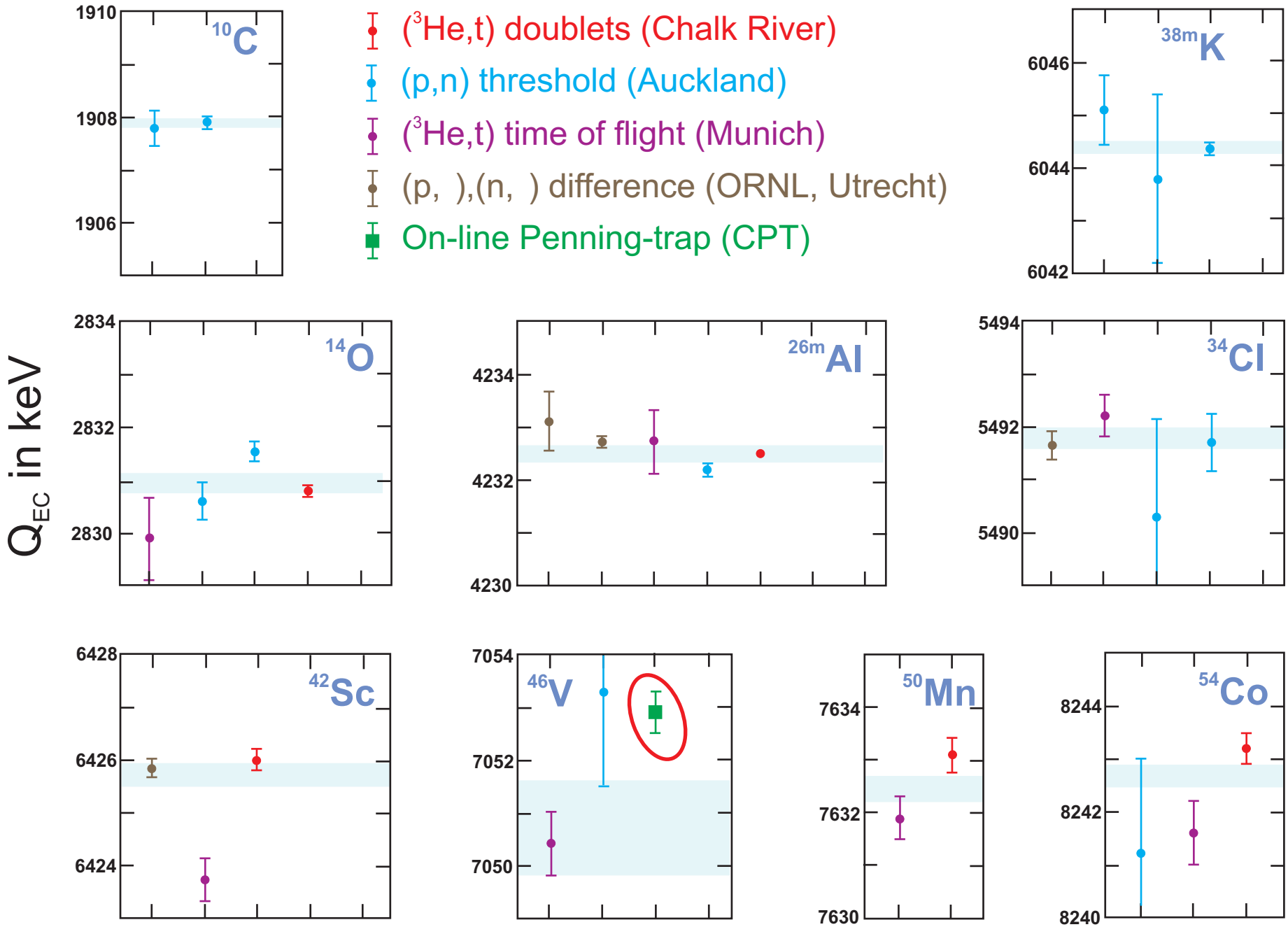

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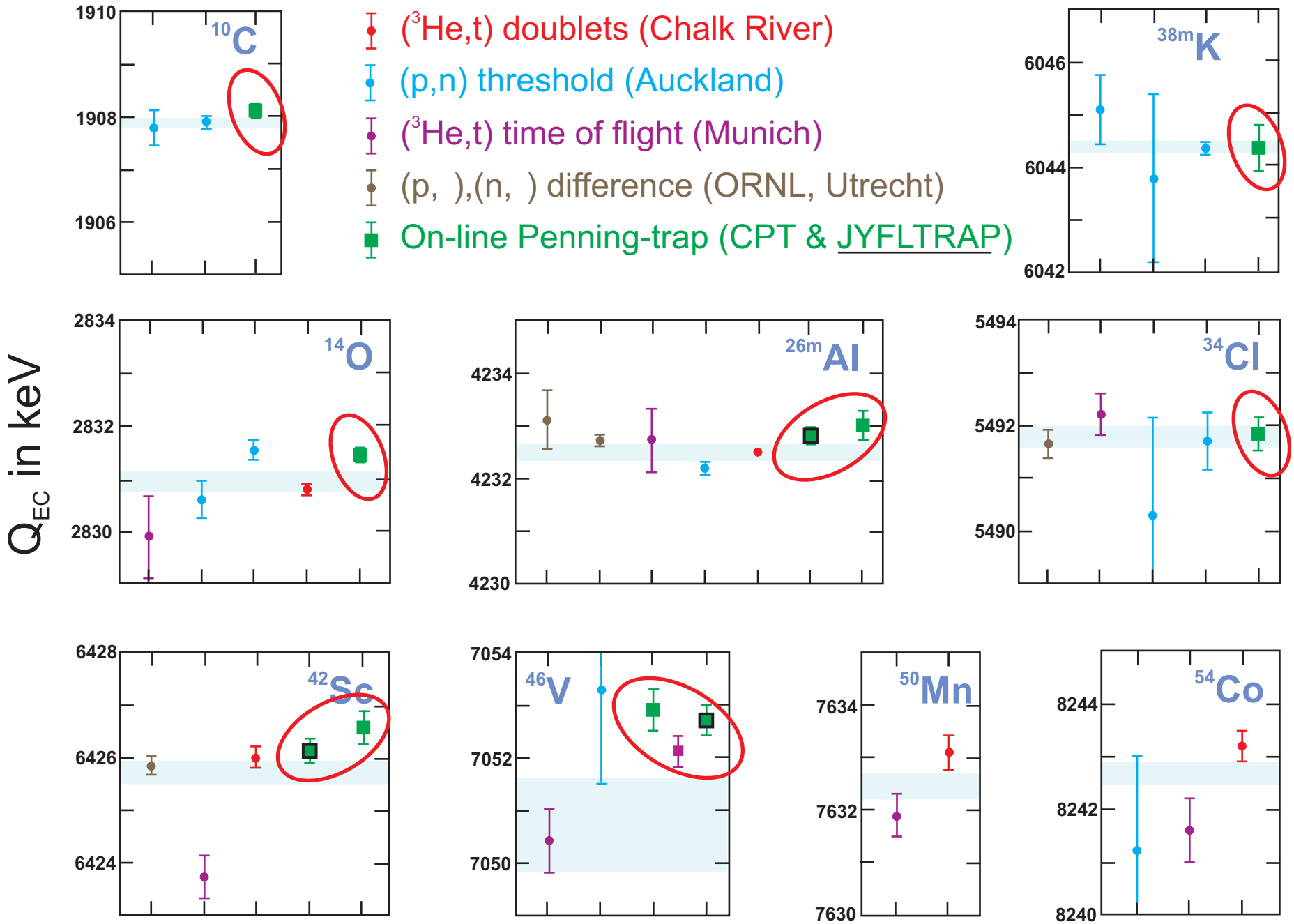

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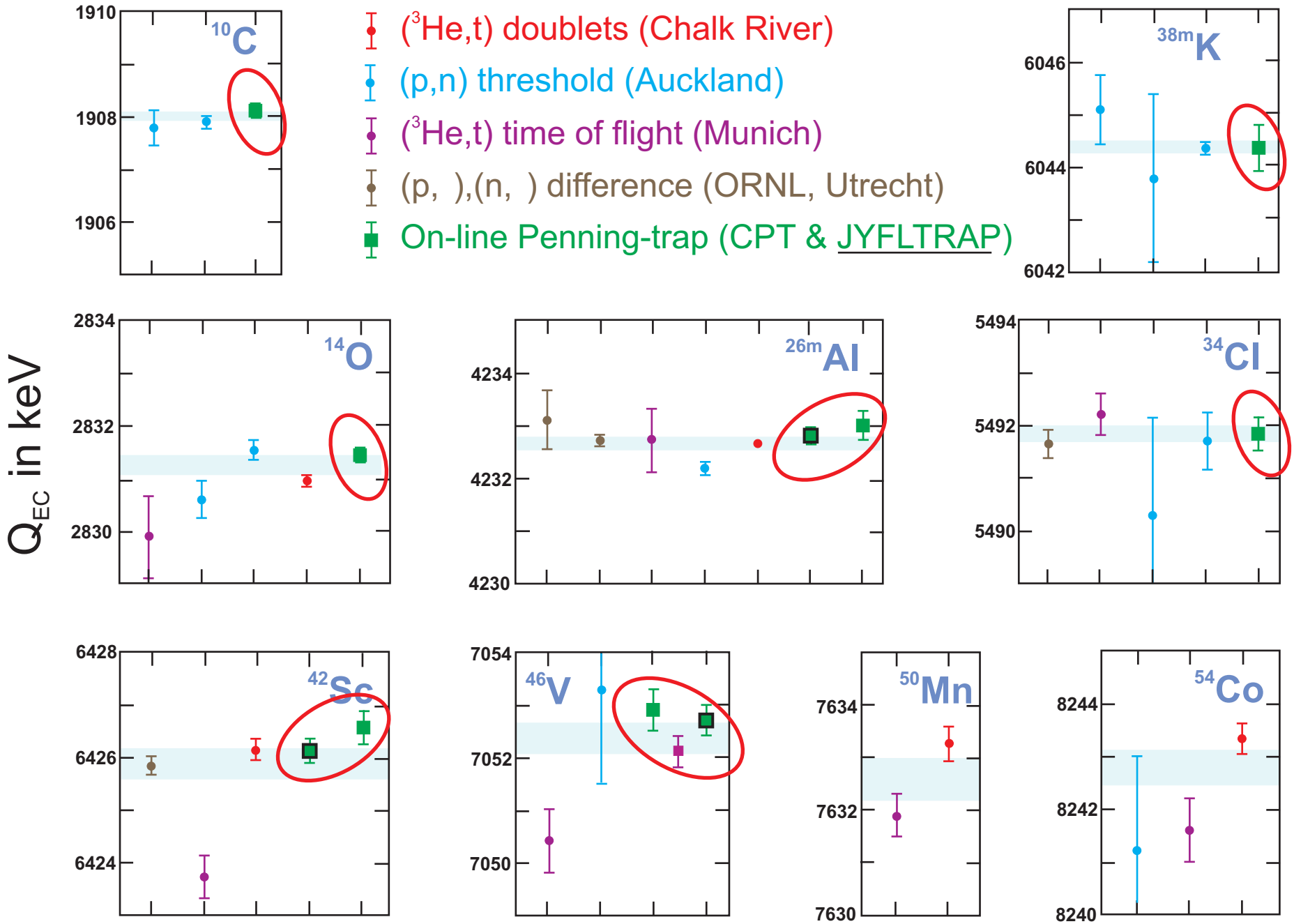
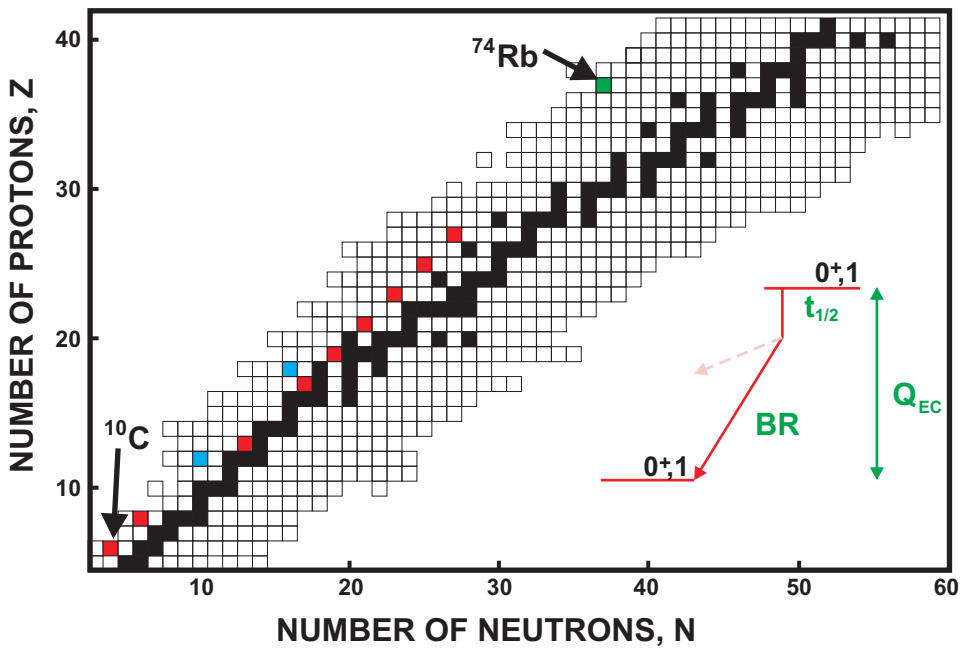
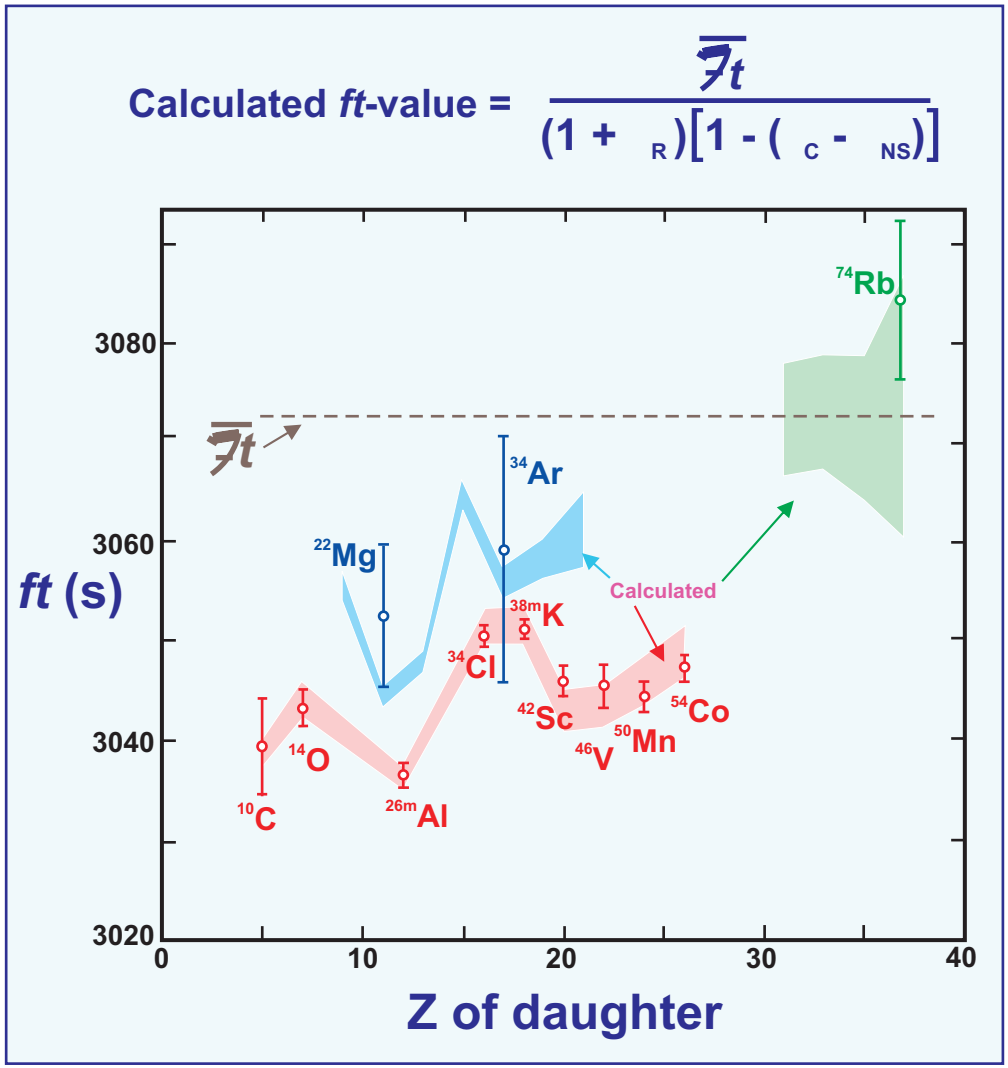


STATUS OF RESULTS AS OF APRIL 2006



Results of 2005 survey



What's new?

- ^{62}Ga: new case added
- ^{34}Ar: $t_{1/2}$ results improved
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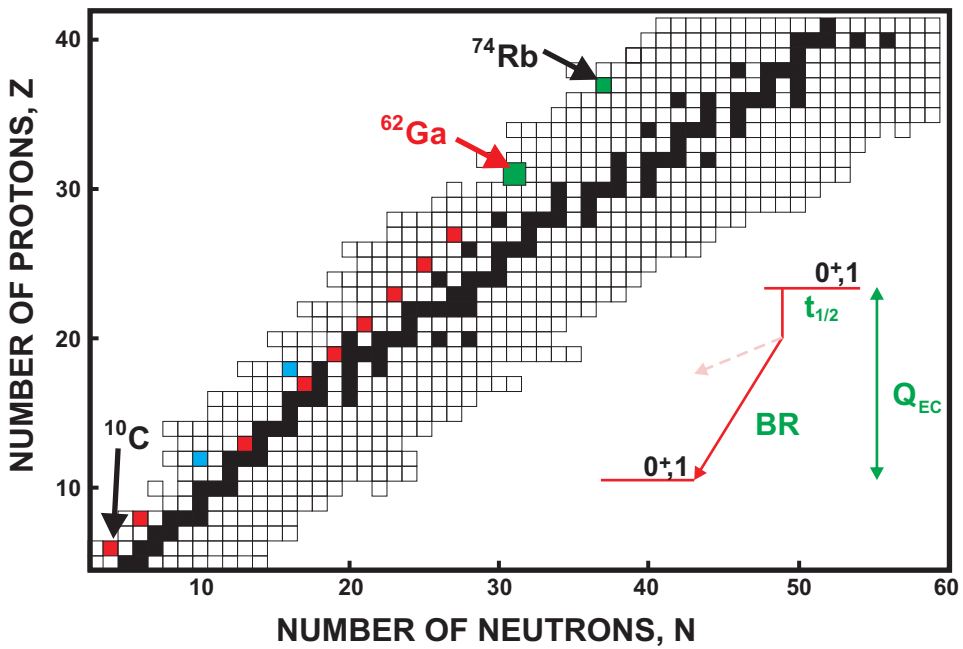
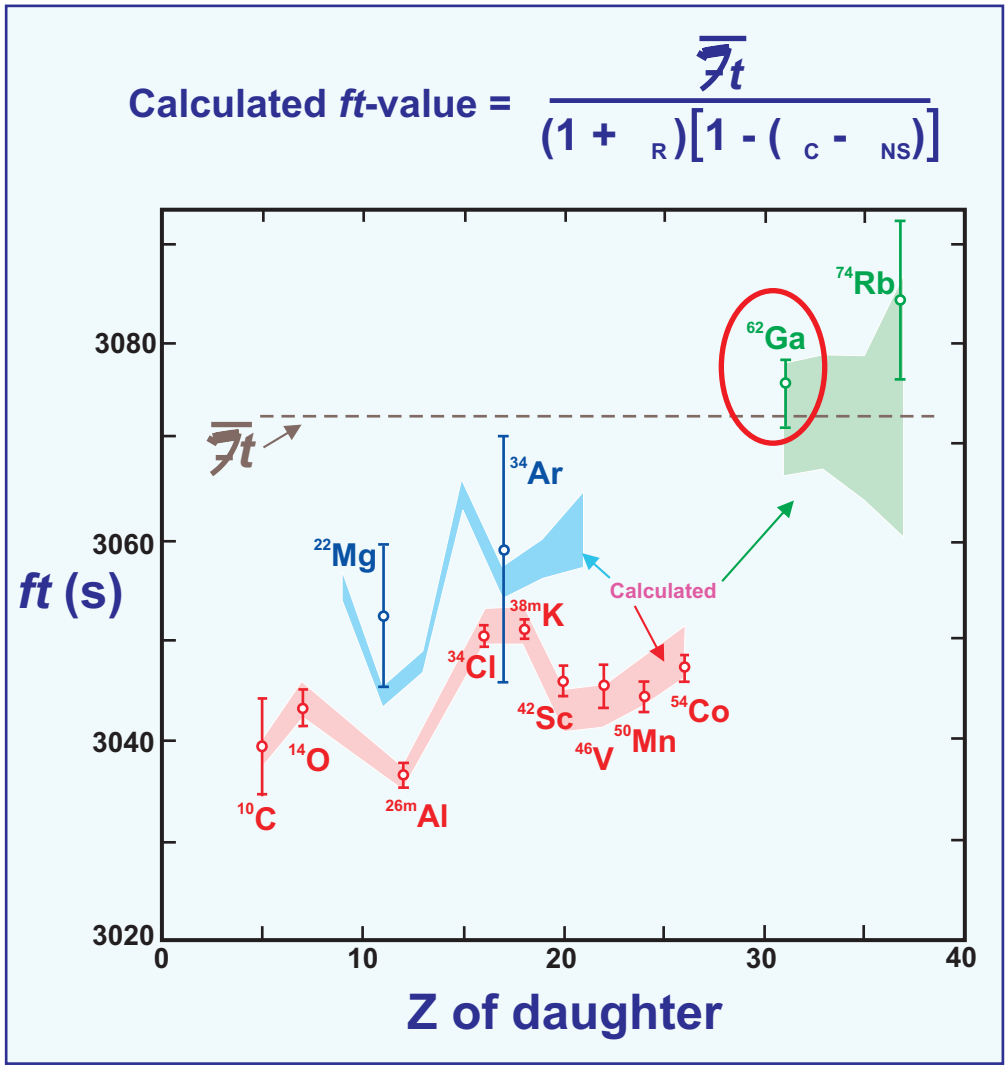


Updated results



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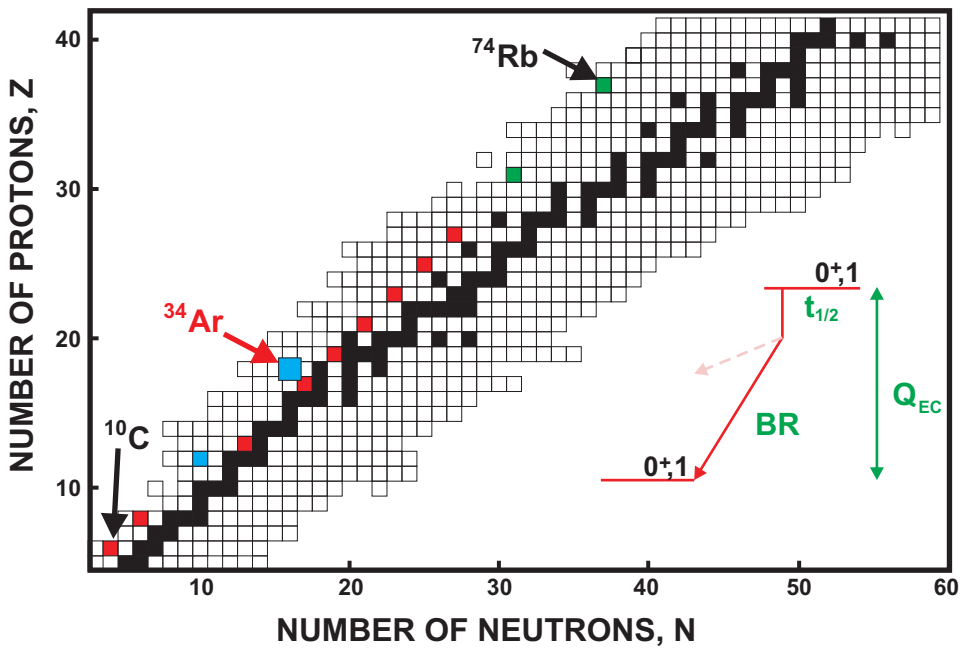

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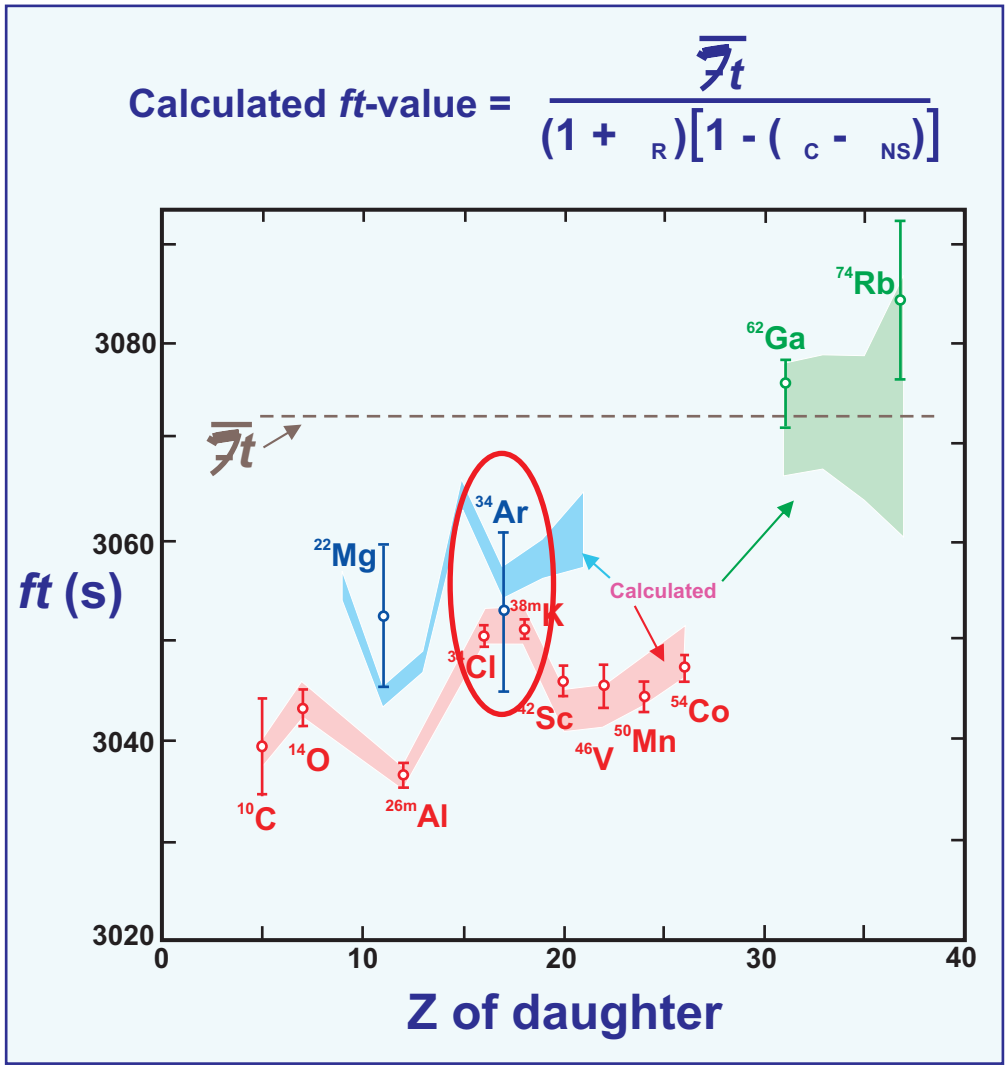

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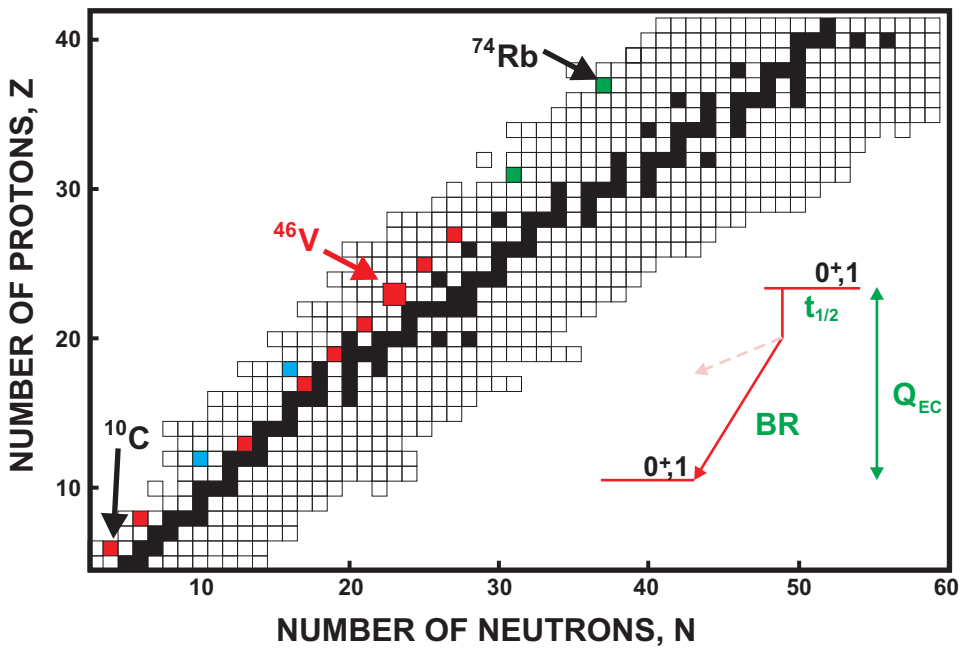

Updated results

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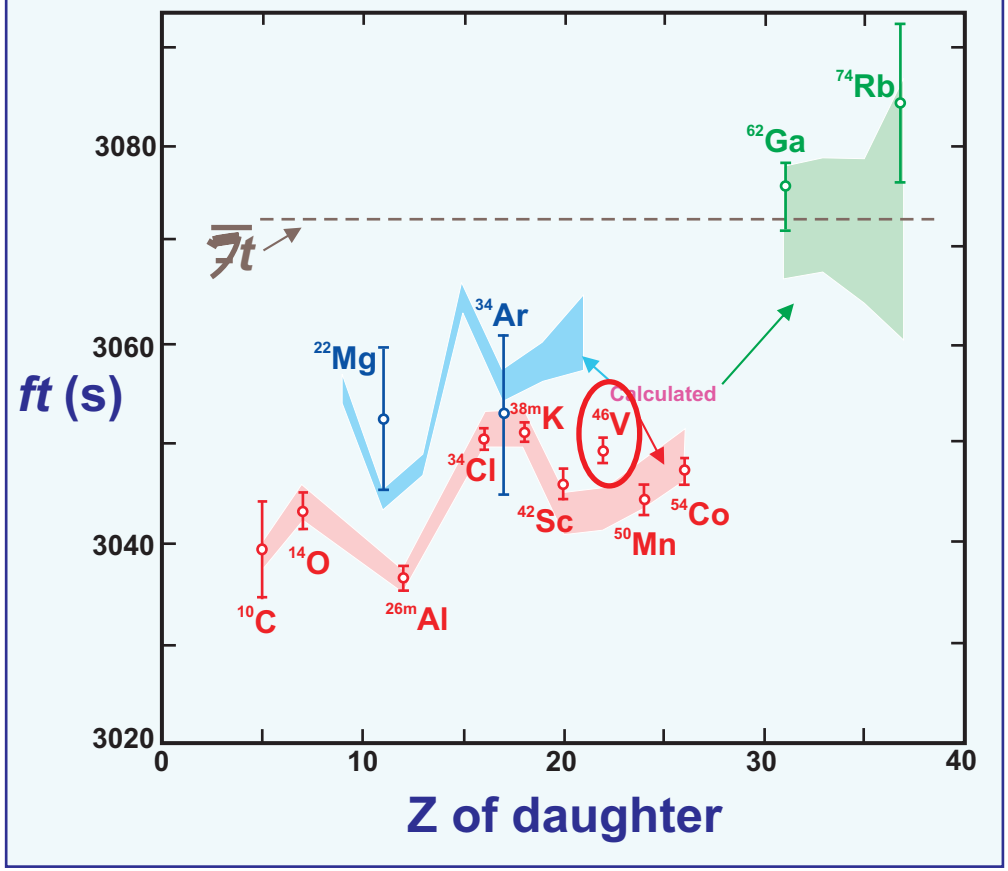

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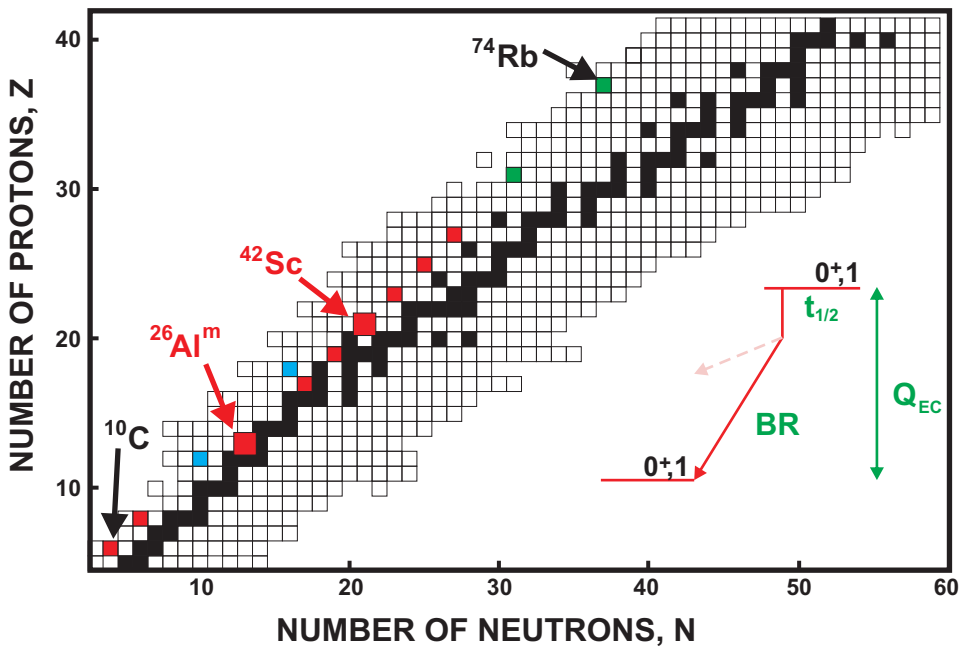
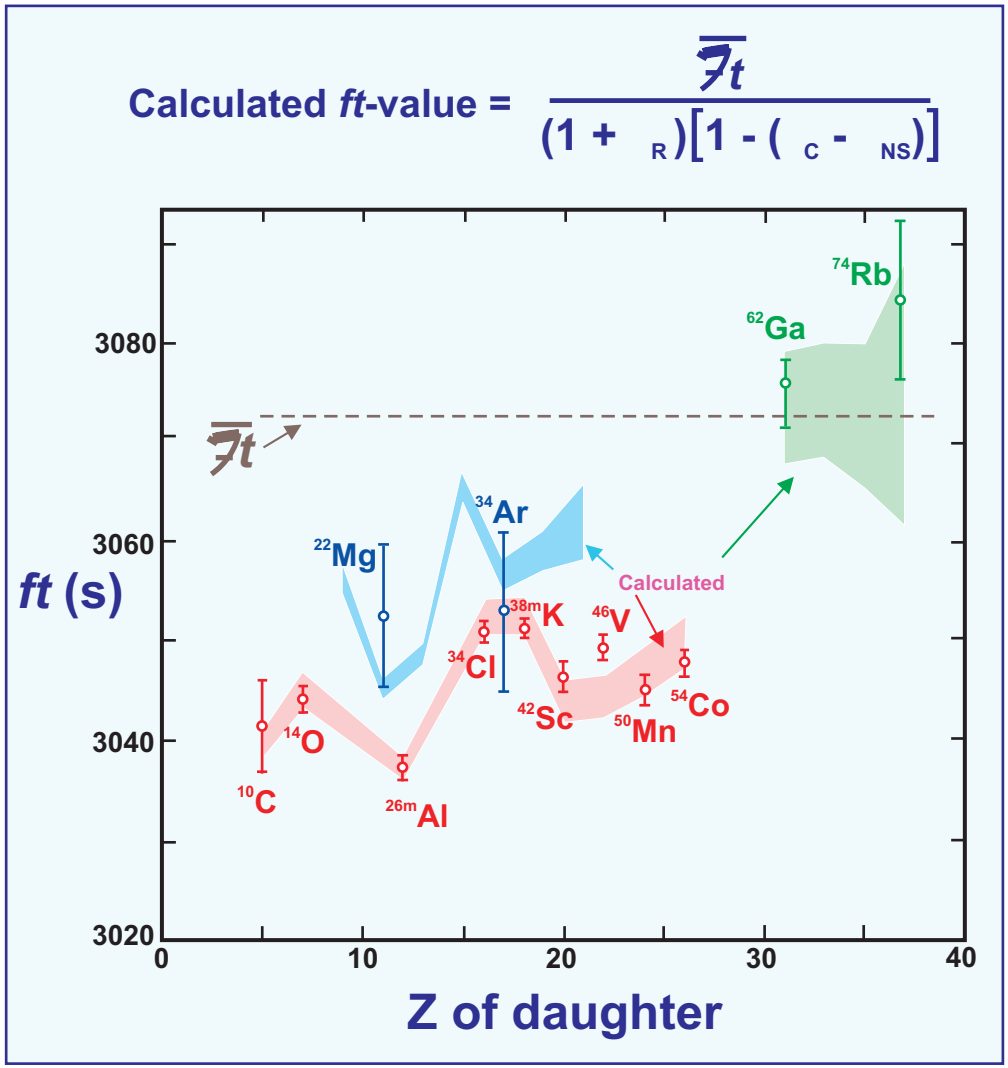


Updated results + re-fit



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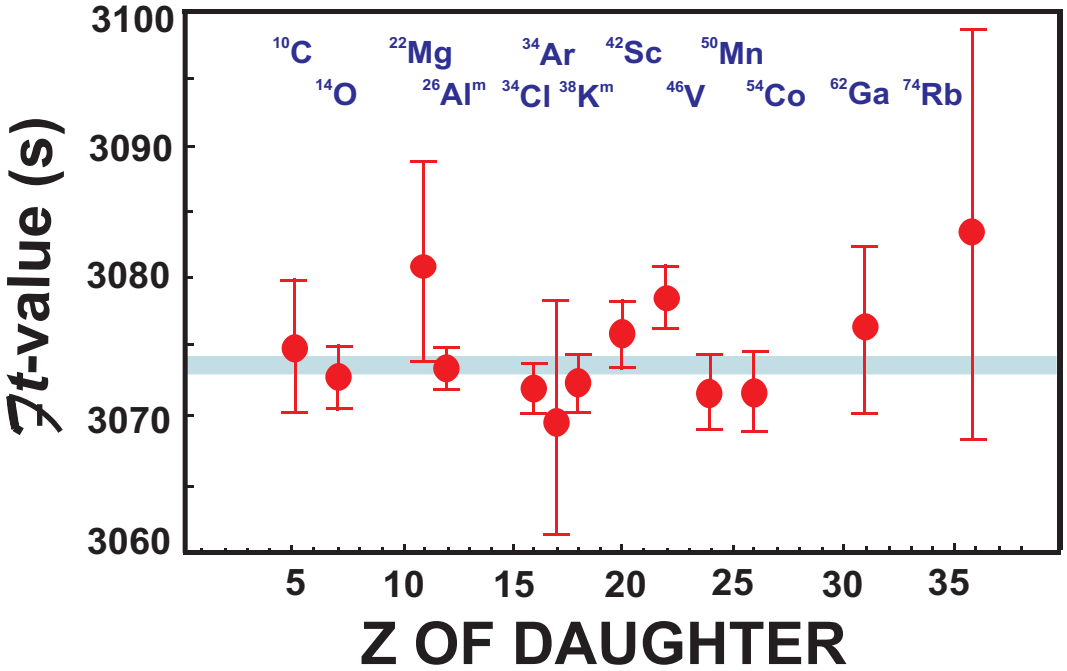
THE BOTTOM LINE AS OF APRIL 2006



$\overline{\mathcal{F}t}$ = 3073.5(7)

V_{ud} = 0.97363(26)

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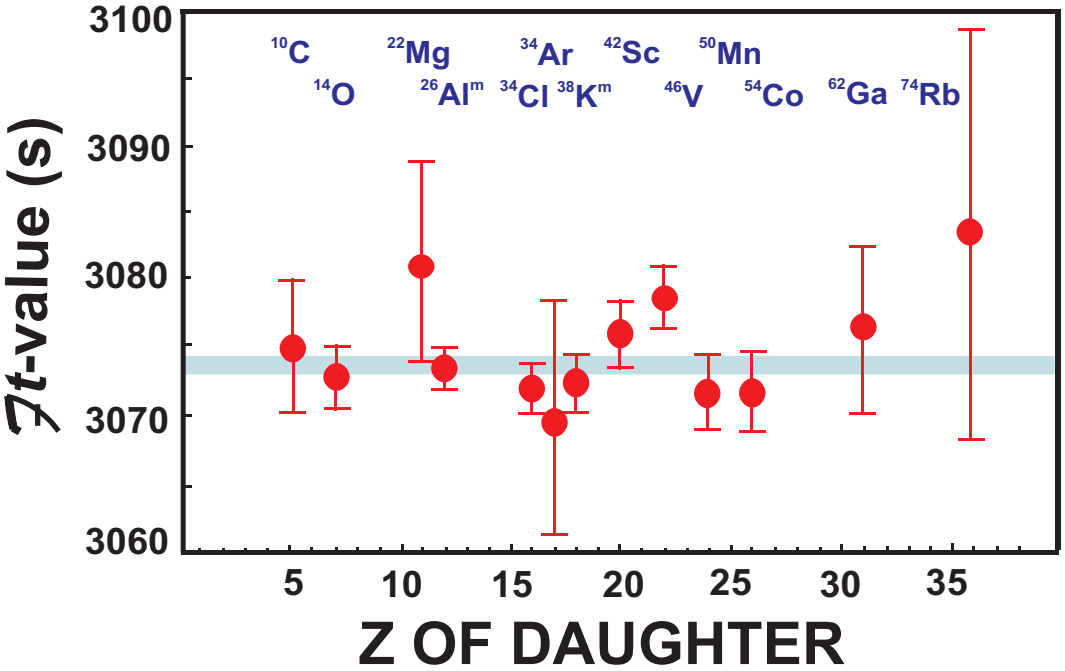

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2005 Review:

$\overline{\mathcal{F}t}$ = 3072.7(8)

V_{ud} = 0.9738(4)

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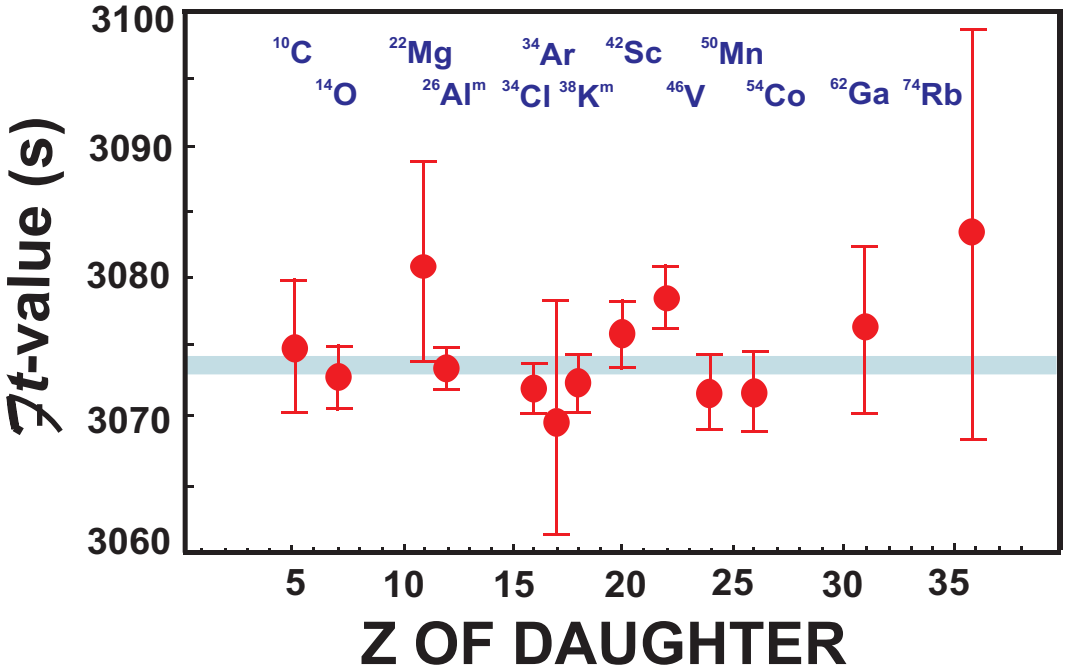


$\overline{\mathcal{F}t}$ = 3073.5(7)

V_{ud} = 0.97363(26)

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

2005 Review:

$\overline{\mathcal{F}t}$ = 3072.7(8)

V_{ud} = 0.9738(4)

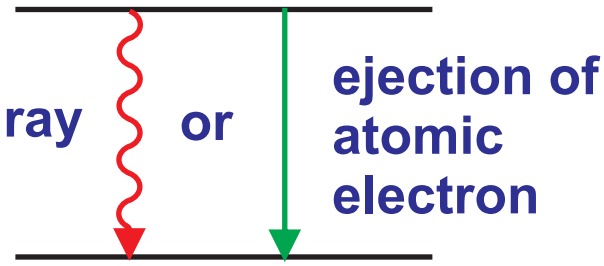
OUTCOME OF SUPERALLOWED MEASUREMENTS

1. Last year's superallowed -decay survey yielded tight limits on new physics: CVC verified to 0.026%; $|C_S/C_V| < 0.0013$.
2. CKM unitarity confirmed to 0.1%. Currently V_{us} uncertainty contributes more than that of V_{ud}.
3. Superallowed decay yields most precise value for V_{ud}. This value is proving to be very robust!
4. Much activity is now focused on reducing V_{ud} uncertainty *via* tests of structure-dependent correction terms.
5. So far, new measurements confirm the validity of the calculated correction terms, although there may be an unexpected structural anomaly at A=46.
6. In the past year, the nuclear result for V_{ud} has been considerably improved by both theory and experiment.
7. The value of V_{ud} can be improved further.

INTERNAL CONVERSION

Internal conversion coefficient (ICC)

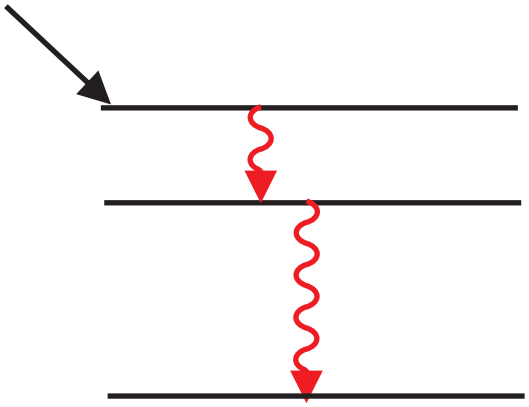
$$\frac{e}{K} \qquad K$$



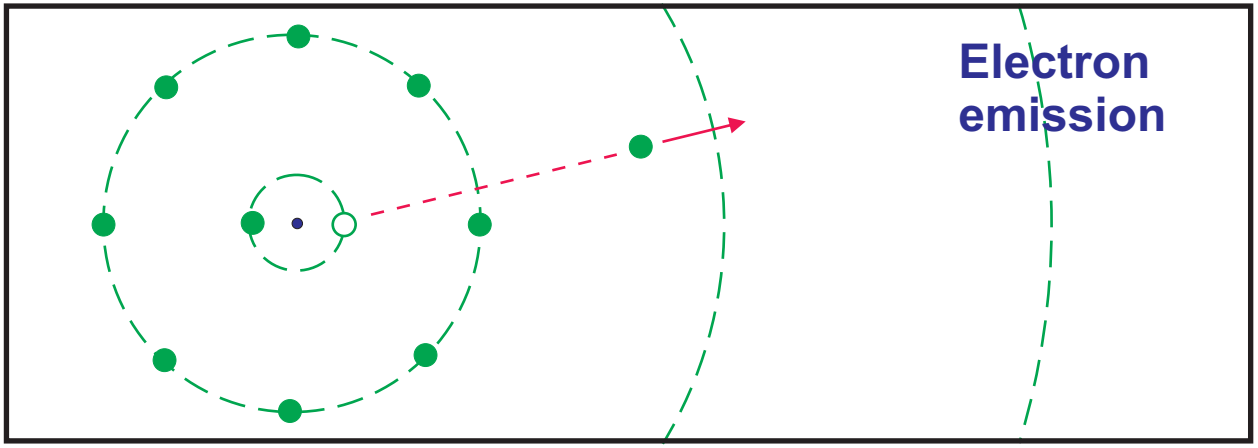
Why are accurate calculations important?

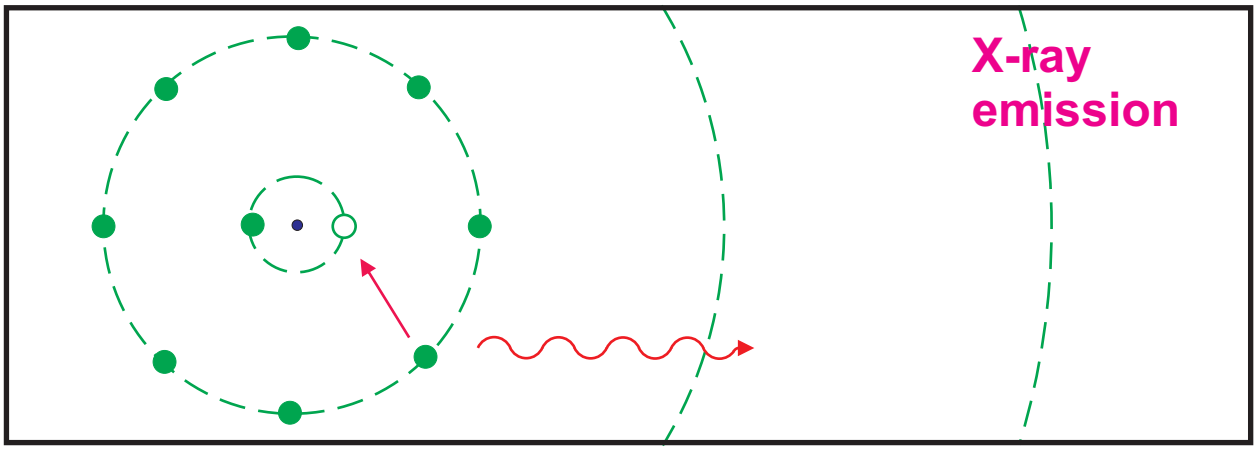
Usually only rays are measured, so to determine total transition probabilities ICCs must be used. Most decay schemes are produced this way.

Essential for precise efficiency calibration of Ge detectors.



K-SHELL INTERNAL CONVERSION





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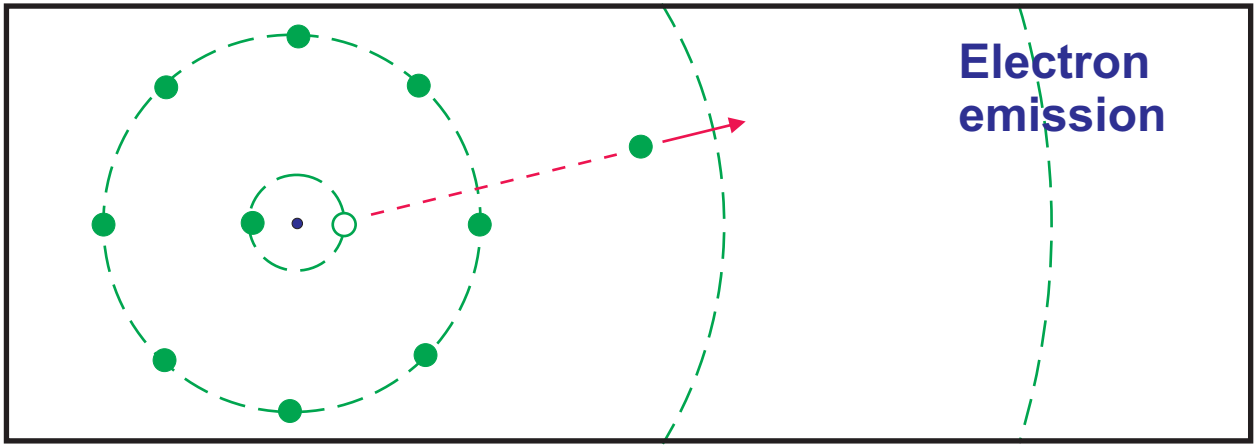

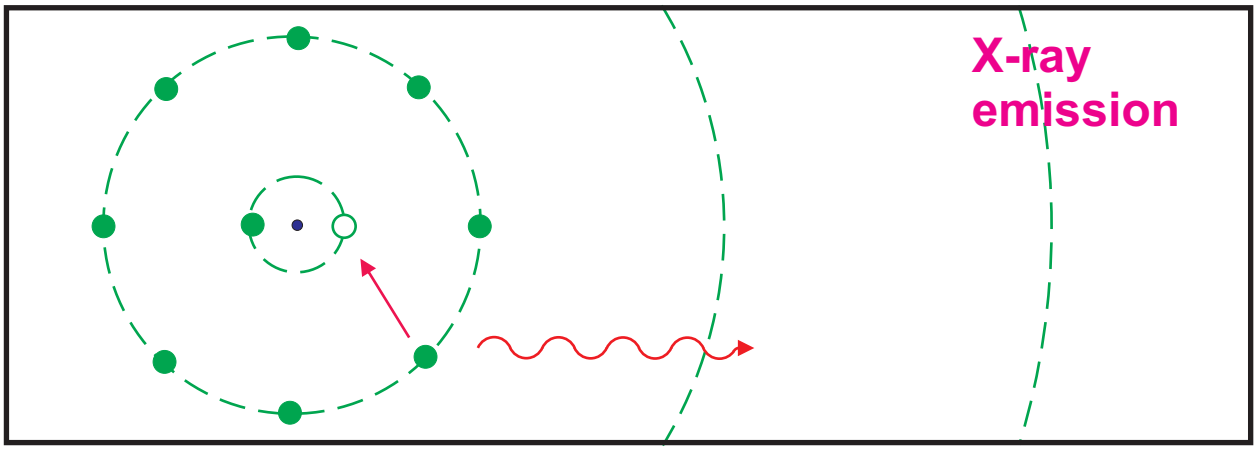

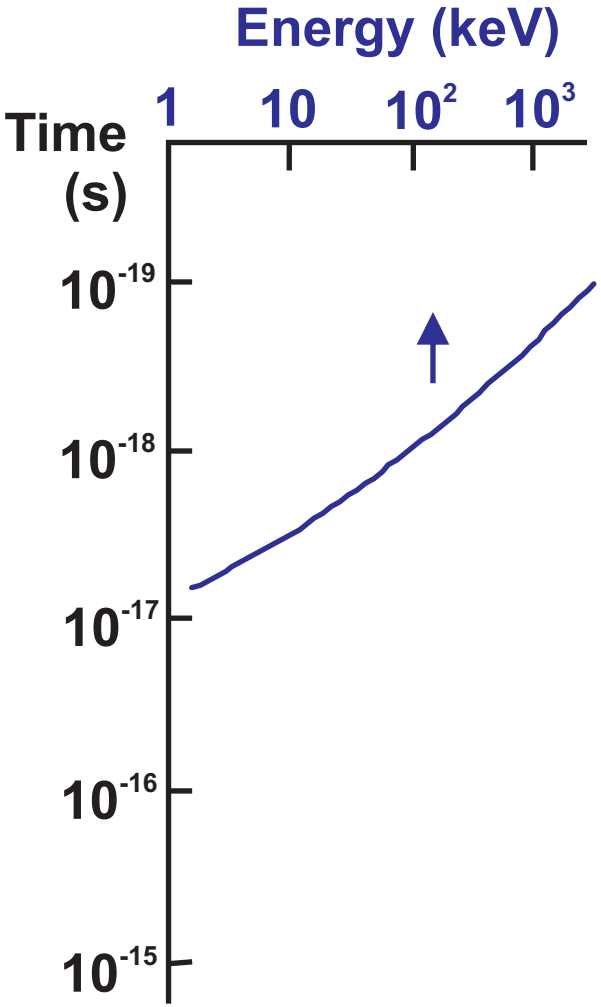

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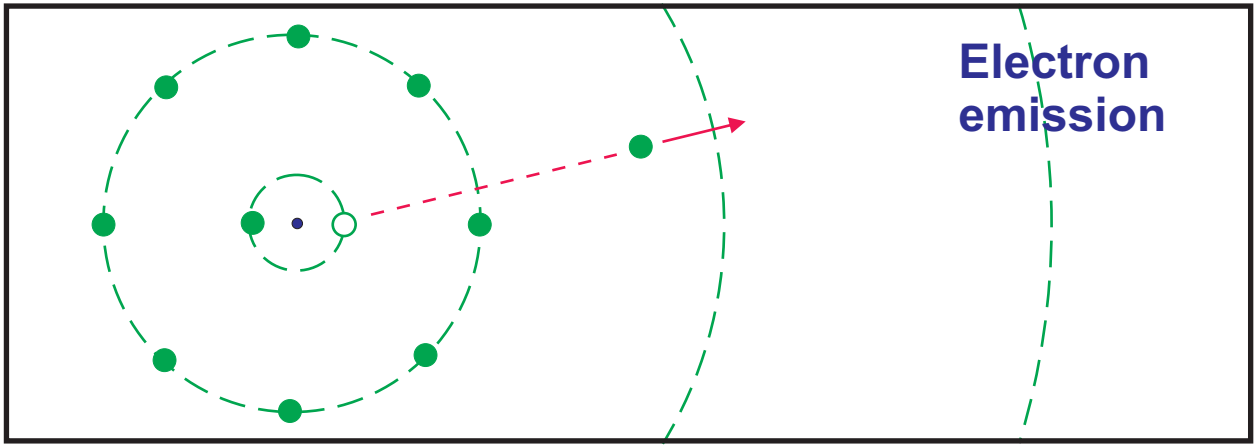

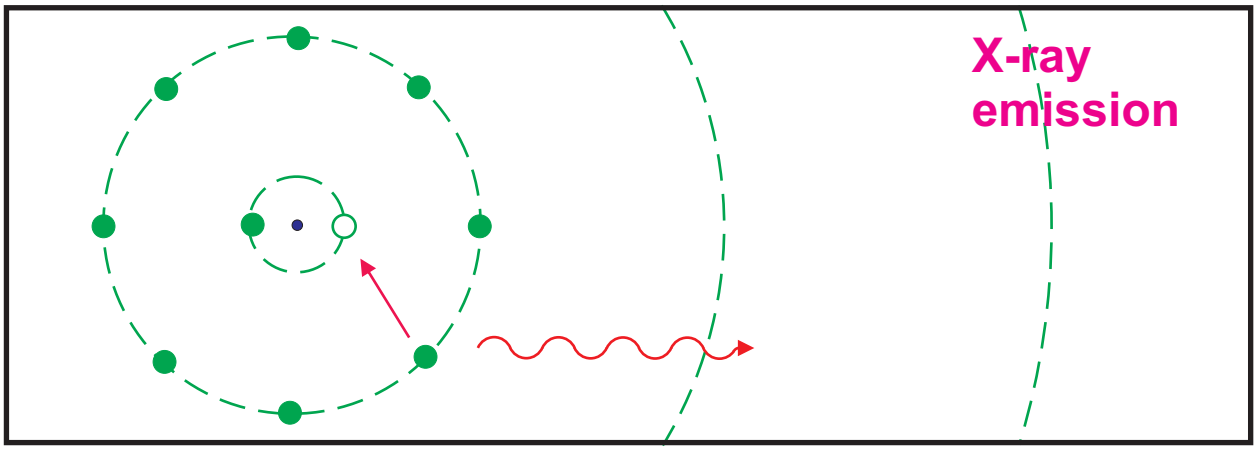

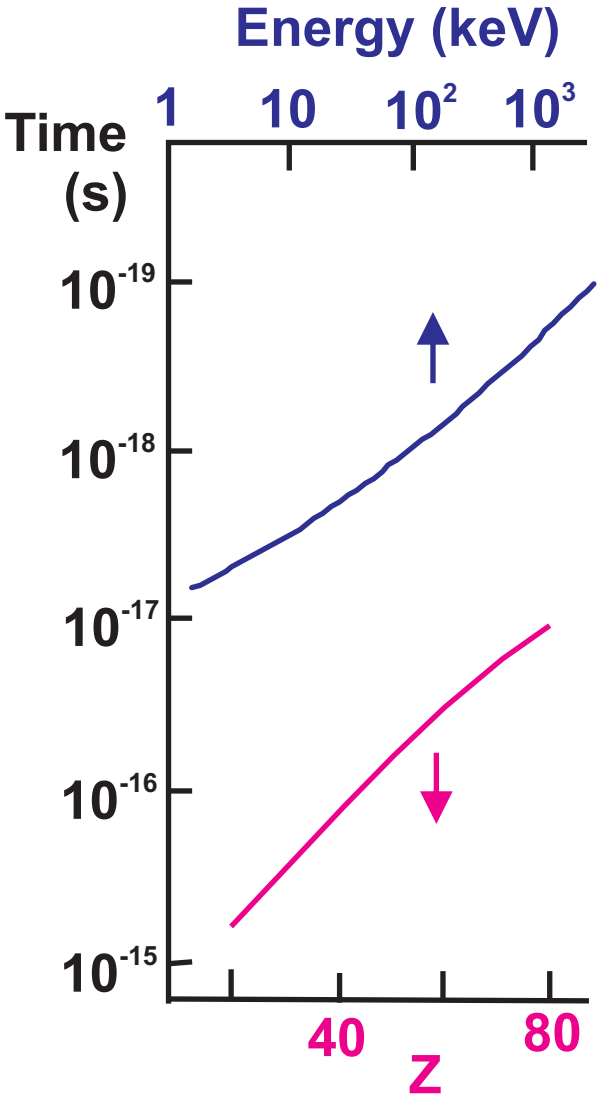

THE PROBLEM

- Simple considerations indicate that the electron has reached the continuum before the K-shell hole has filled.
- Internal-conversion coefficients (ICCs) have been calculated both ways – with and without the atomic hole.
- A survey of 100 measured ICCs [Raman *et al.* PRC 66 (2002) 044312] indicates slight preference for ICCs calculated without the hole.

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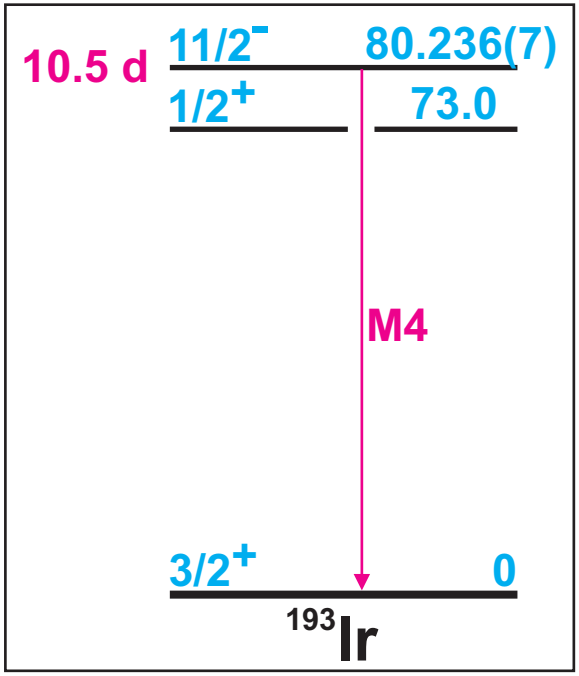
What's going on?

A DEFINITIVE TEST

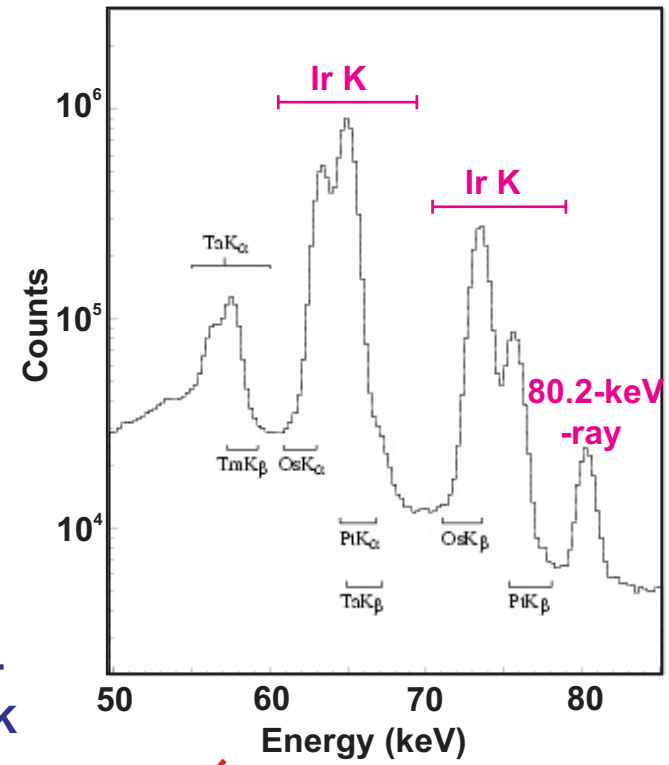
- The 80-keV *M4* transition from $^{193}Ir^{m}$ is extremely sensitive to the treatment of the hole – 10% difference.
- With Z=77 and E_e = 4.1 keV, this case should have the maximum probability of the hole filling before the electron reaches the continuum.

MEASUREMENT OF ICC FOR DECAY OF $^{193}Ir^{m}$



K binding energy
= 76.112(1) keV

Spectrum from HPGe detector efficiency calibrated to ±0.15%



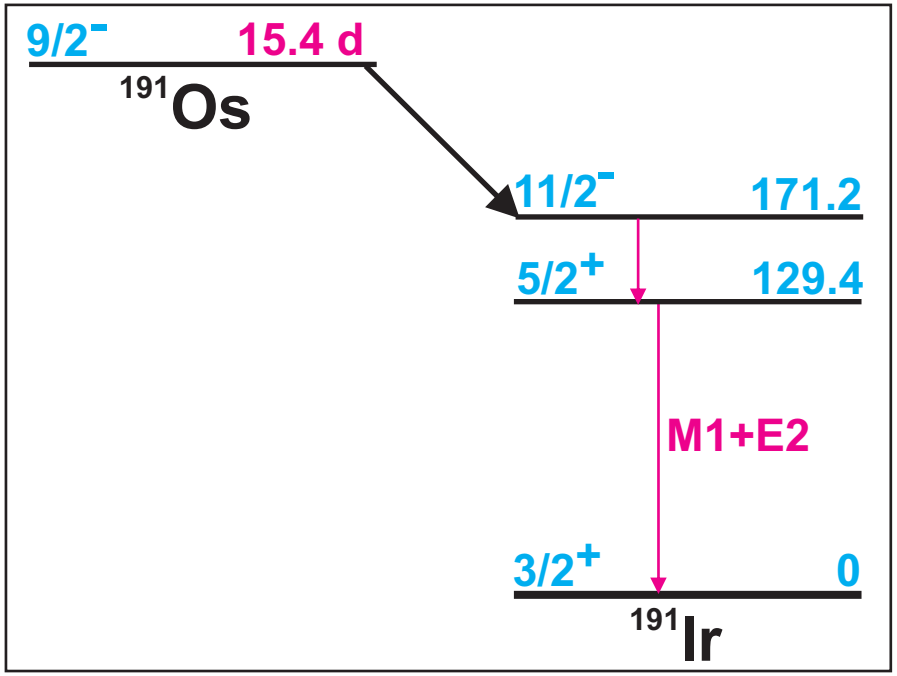
$$_{K} \quad _{K} = \frac{(N_K + N_K)}{N} \quad \frac{}{_{K}}$$

Model	K
No hole	92.3(1)
Hole, frozen orbitals	103.5(1) ✔
Hole, self-con. field	99.7(1)

$_{K}$ = 0.958(4)
from systematics

$_{K}$ = 103.0(8)

CONFIRMATION OF FLUORESCENCE YIELD FOR IRIDIUM



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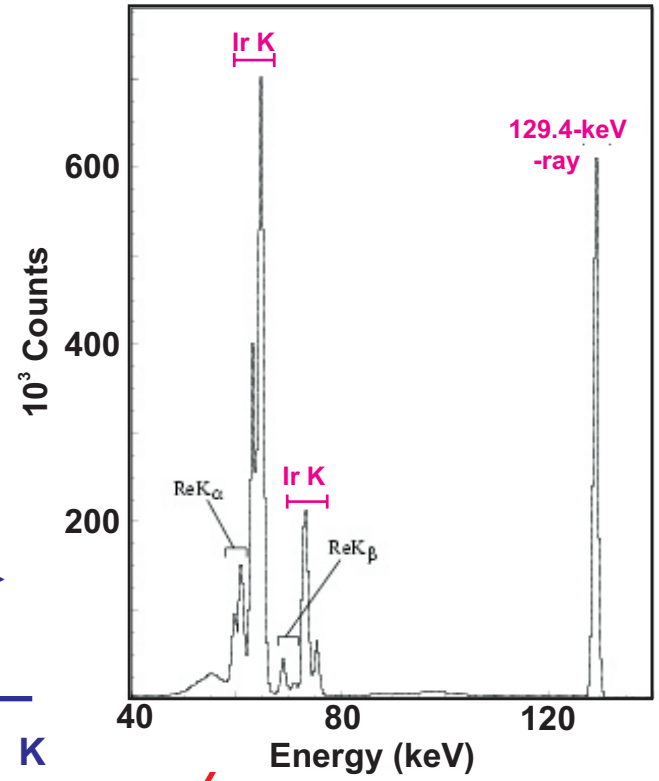


$$_K \quad _K = \frac{(N_K + N_K)}{N} \quad _K$$

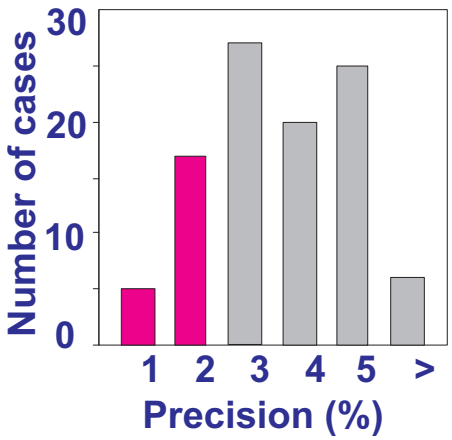
Model	$_K$
No hole	2.137(8)
Hole, frozen orbitals	2.147(8)
Hole, self-con. field	2.147(8)

$$_K = 0.954(9)$$

$_K = 0.958(4)$
from systematics

EXPERIMENT VS THEORY FOR MOST PRECISE ICCs

Survey of 100 cases by Raman *et al (PRC 66, 044312 (2002)*



The 20 cases with precision of <2% statistically dominate any comparison with theory. We select these cases.

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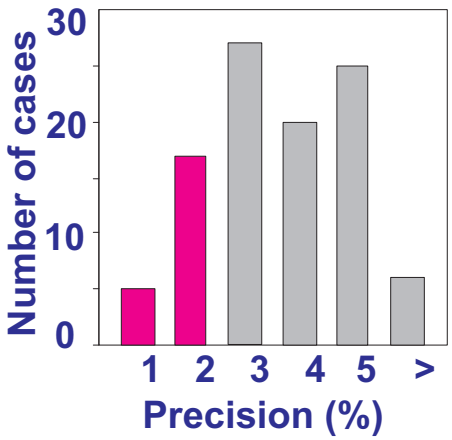

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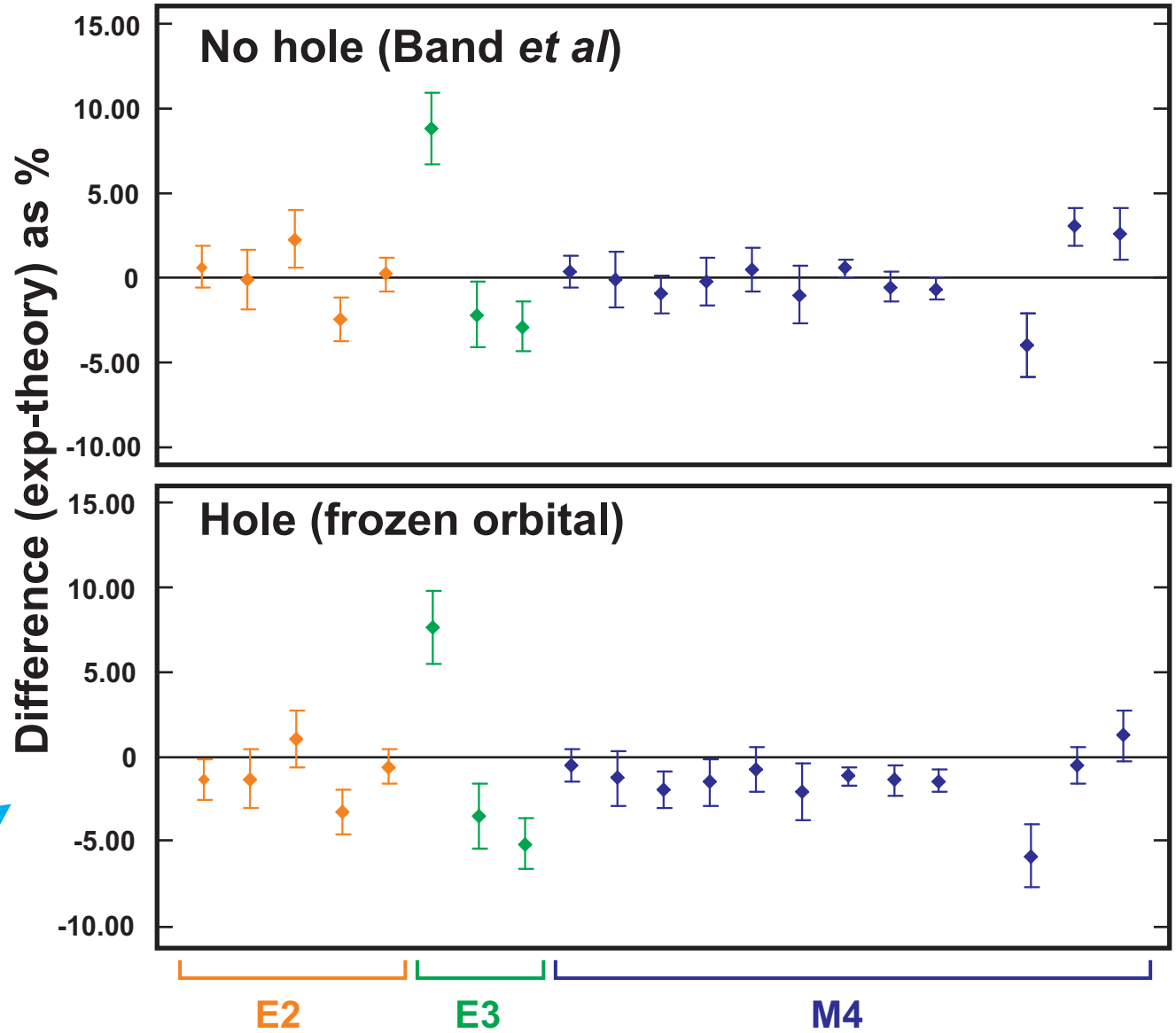
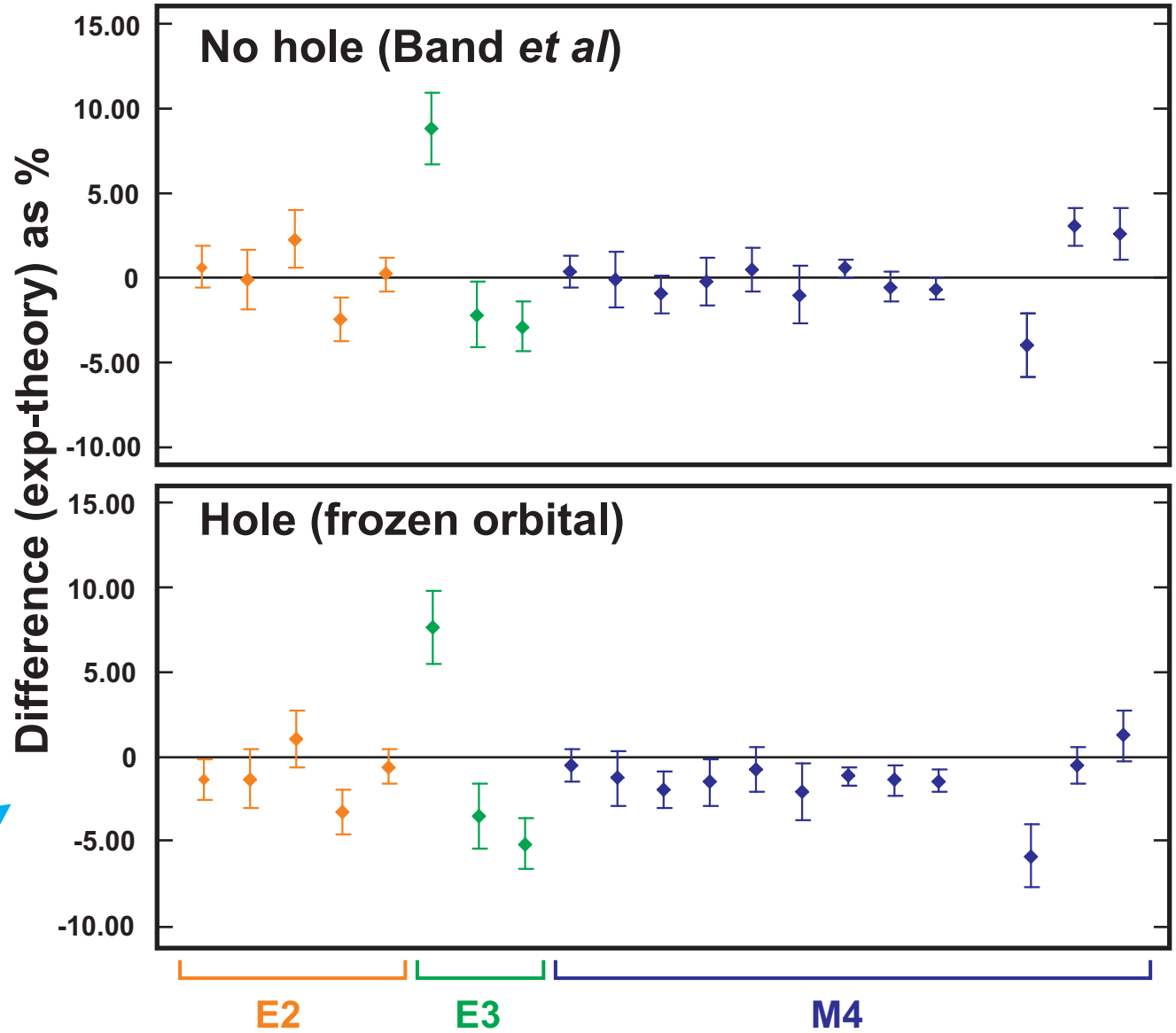


EXPERIMENT VS THEORY FOR MOST PRECISE ICCs

20 cases from Raman *et al.*

	Average differences	$^2/N$
No hole	+0.46(39)%	2.4
Hole	-1.25(36)%	2.2



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With $^{193}Ir^m$ included

	Average differences	$^2/N$
No hole	+0.99(79)%	11.1
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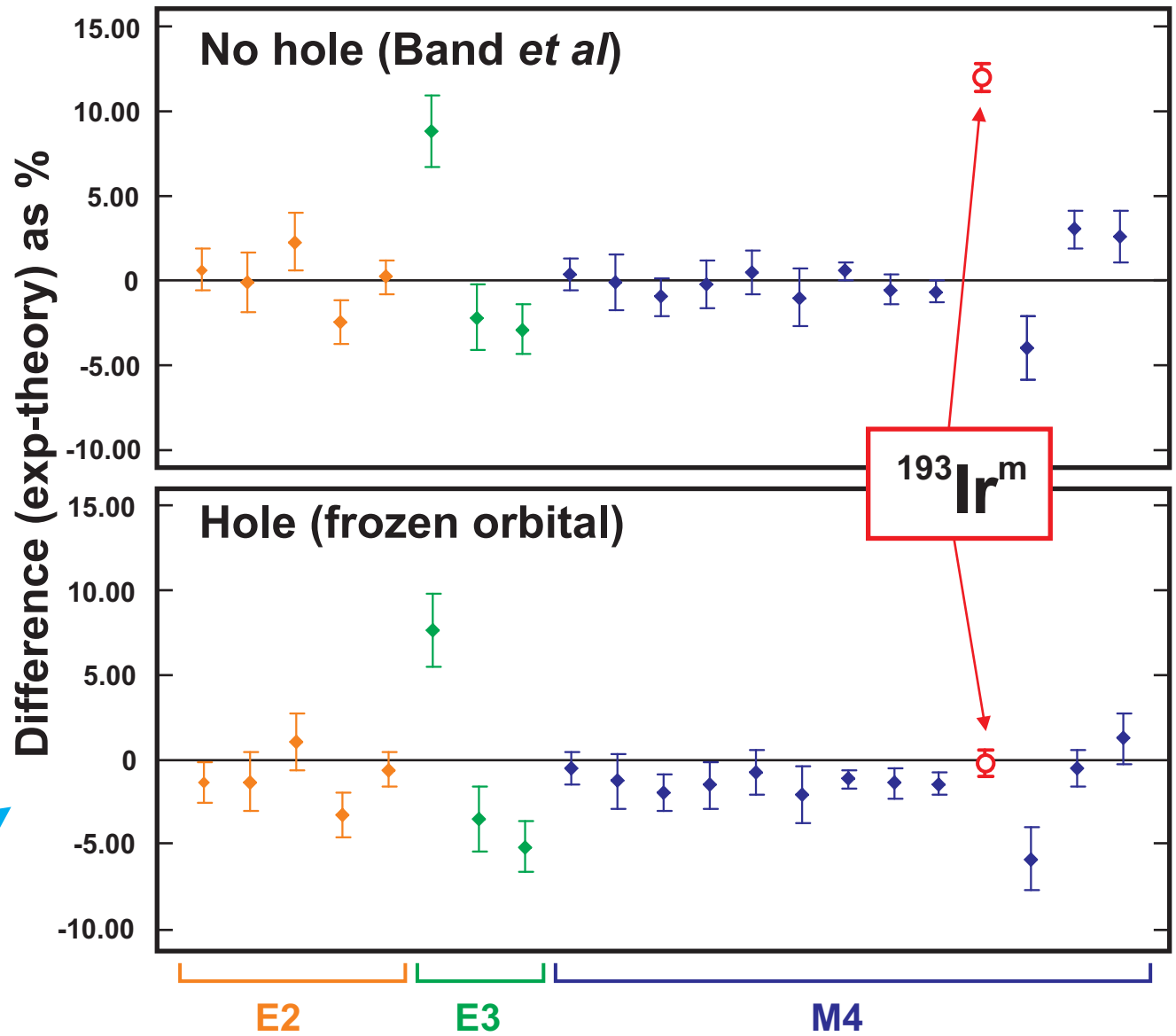

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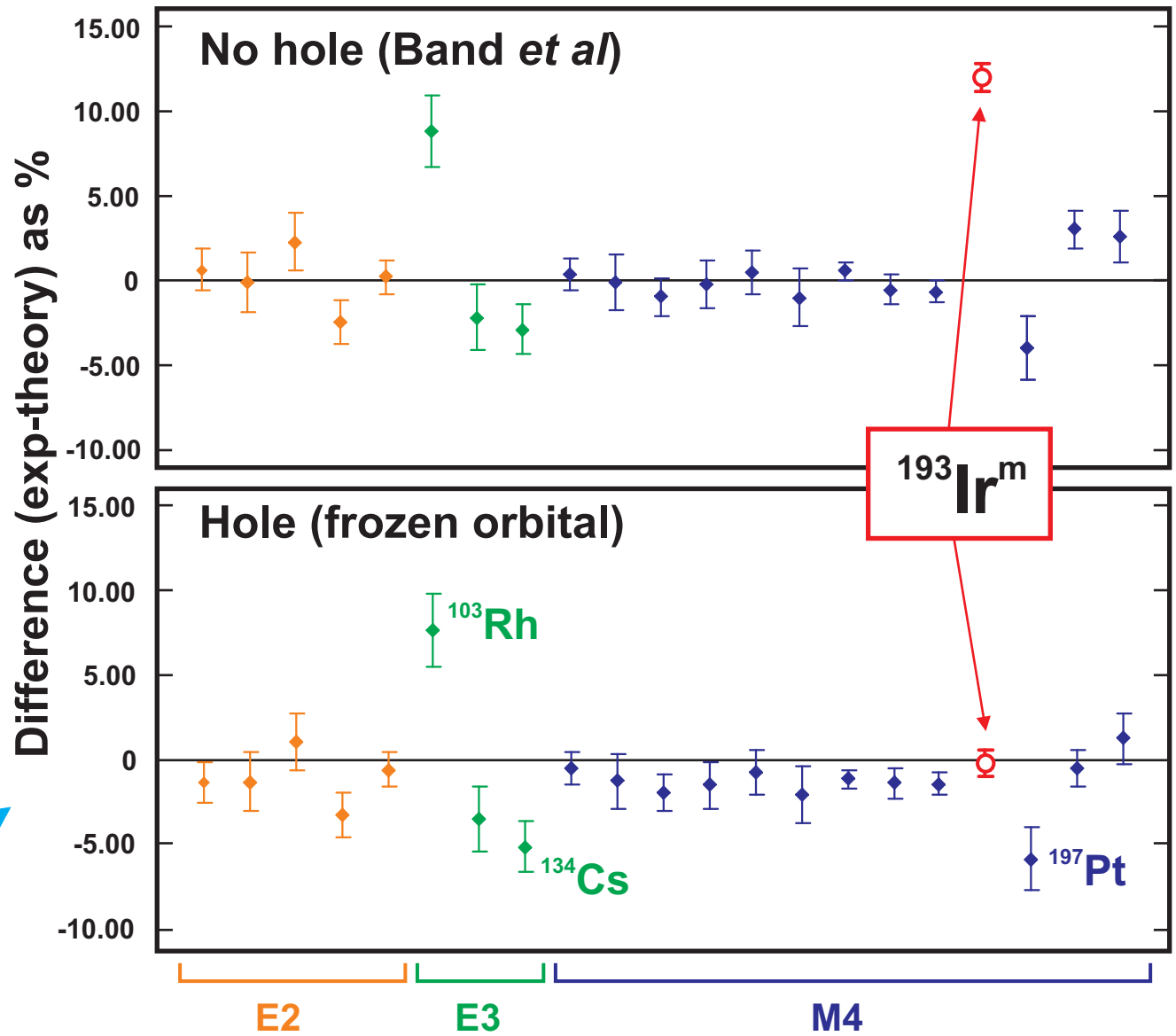

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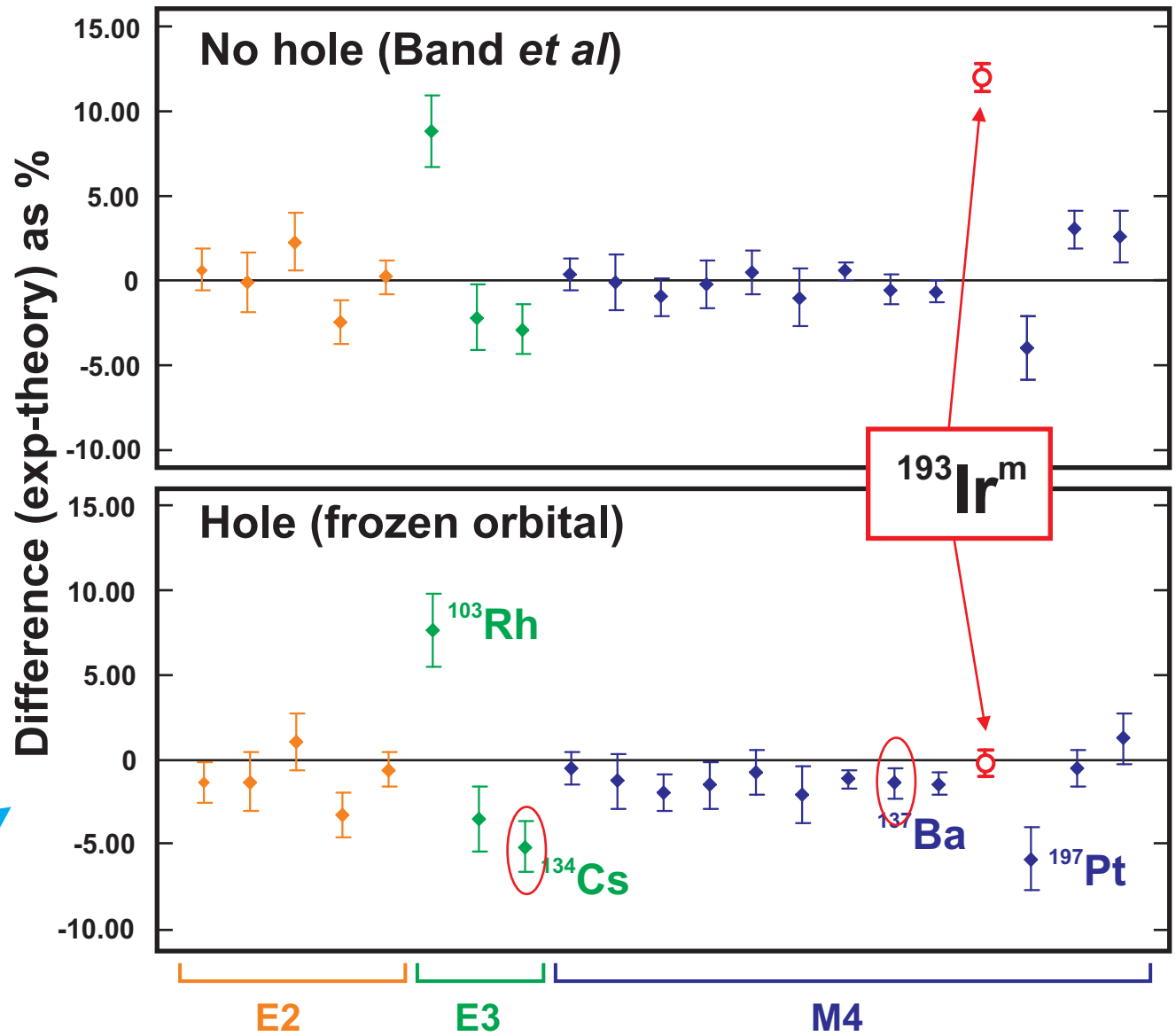
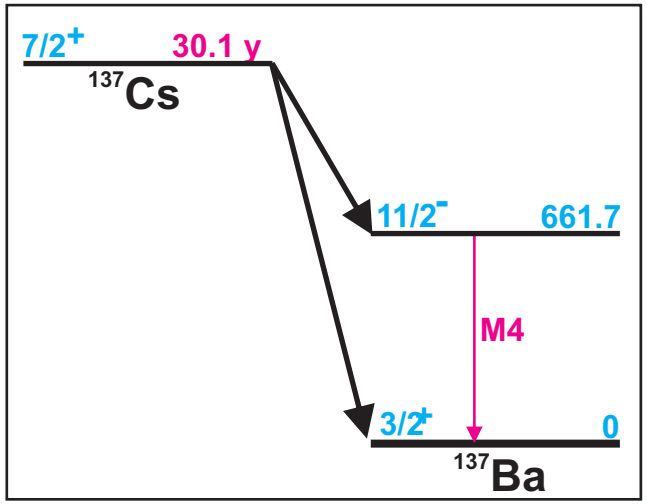
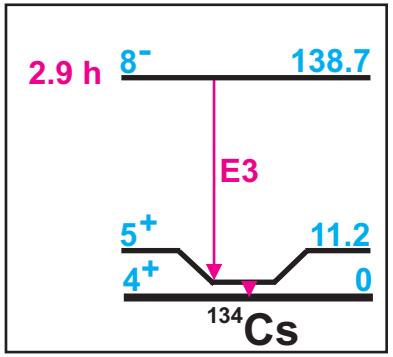


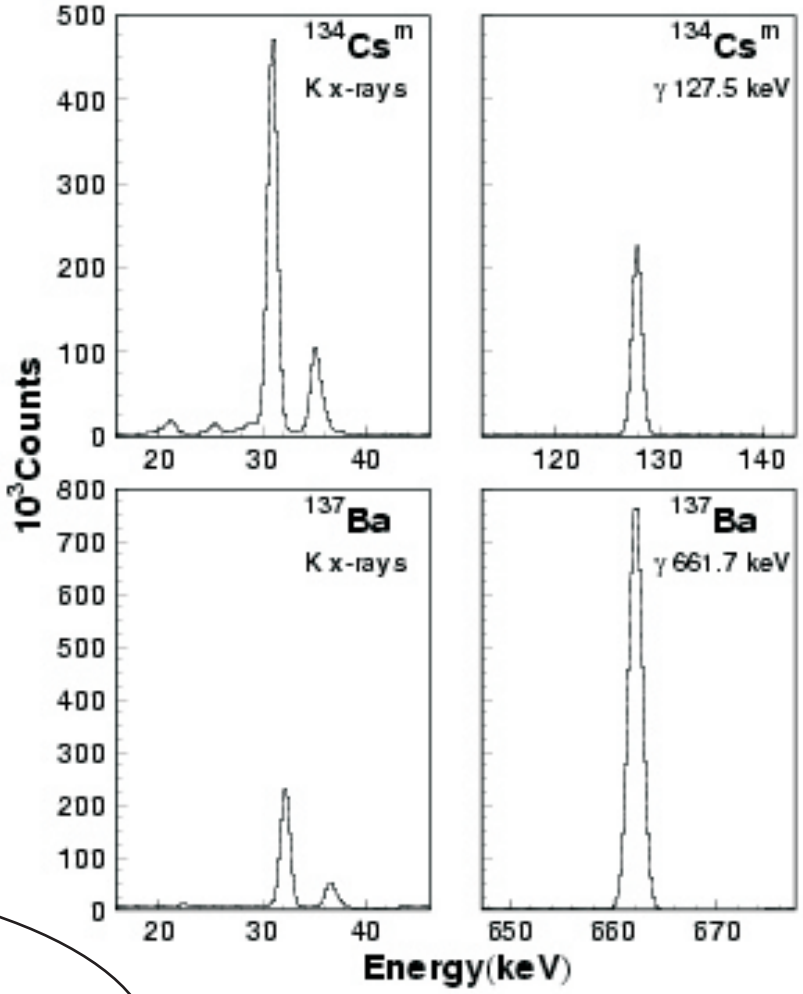
K-SHELL ICC RATIOS – ^{134}CS / ^{137}BA





$$\left(\frac{K(^{134}Cs)}{K(^{137}Ba)}\right)$$

is essentially independent of efficiency at 30 keV.



No hole	29.5
Hole, frozen orbitals	30.0
Previous experiment	28.8(5)
This experiment	**29.8(3)**

OUTCOME OF ICC MEASUREMENTS

1. Measurement of ICC for M4 transition from $^{193}Ir^{m}$ shows that calculations must take account of atomic vacancy.

2. Measurement of ICC ratio for transitions in ^{134}Cs and ^{137}Ba suggests that apparent discrepancies between previous experiments and theory may not be correct.

3. Future measurements will focus on verifying calculations in lighter nuclei and on re-examining cases with significant discrepancies from theory.

COLLABORATORS

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N. Nica
L. Trache
M. Sanchez-Vega
J. Goodwin
R.E. Tribble
+ numerous undergraduates

Experiments elsewhere:

G. Savard (ANL and U Chicago)
J. Aysto (U. Jyvaskyla)

Precision calibration:

R.G. Helmer (Idaho State U)