SUPERALLOWED NUCLEAR DECAY:

Precision measurements for basic physics

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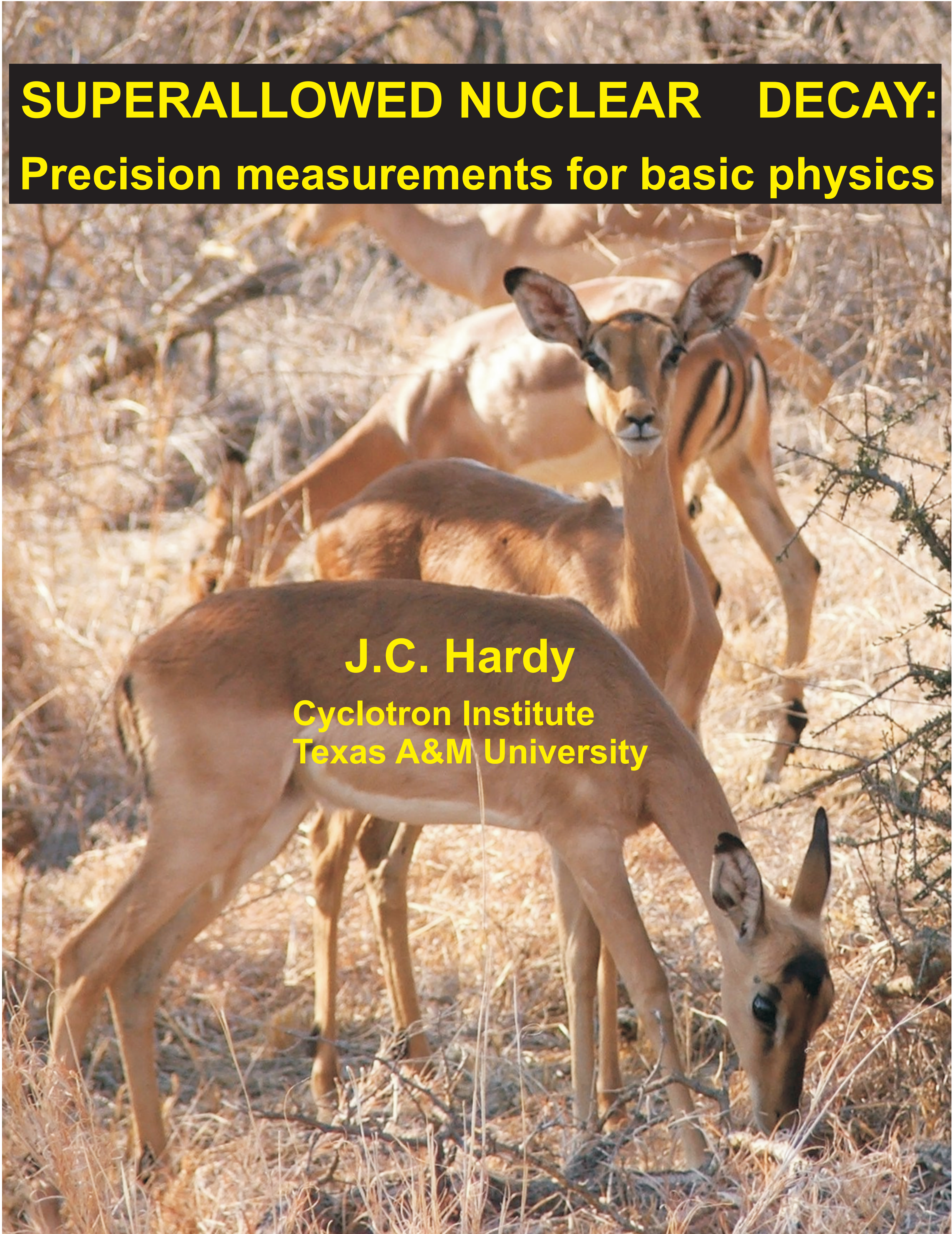


SUPERALLOWED $0^+ \rightarrow 0^+$ BETA DECAY

BASIC WEAK-DECAY EQUATION

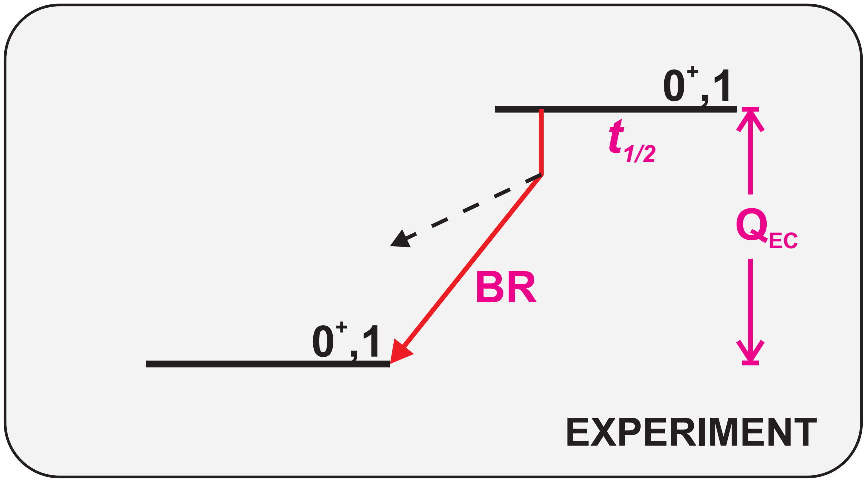
$$ft = \frac{K}{G_V^{\,2} < \quad >^2}$$

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

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

G_V = vector coupling constant

<   > = Fermi matrix element



Reference: Hardy & Towner, Phys. Rev. C79, 055502 (2009)

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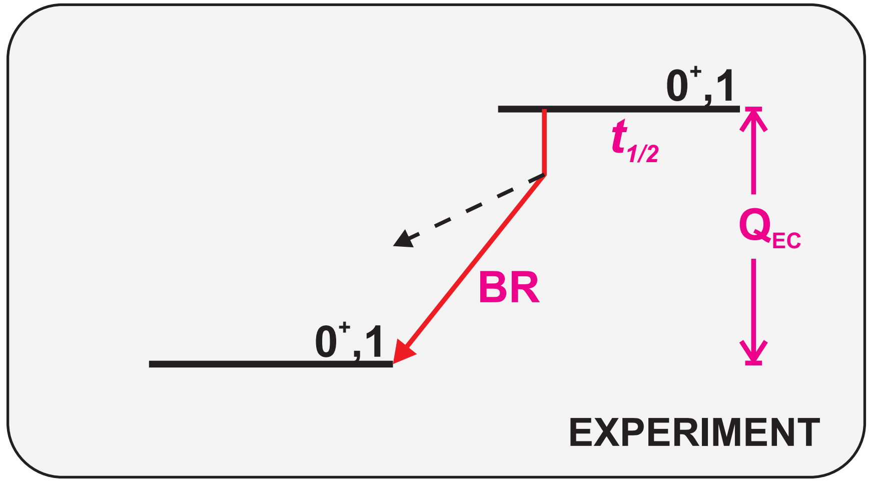


INCLUDING RADIATIVE CORRECTIONS

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

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

f(nuclear structure)
0.3-0.7%

f(interaction)
~2.4%

THEORETICAL UNCERTAINTIES
0.05 – 0.10%

WHAT CAN WE LEARN?

FROM A SINGLE TRANSITION

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

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

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

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

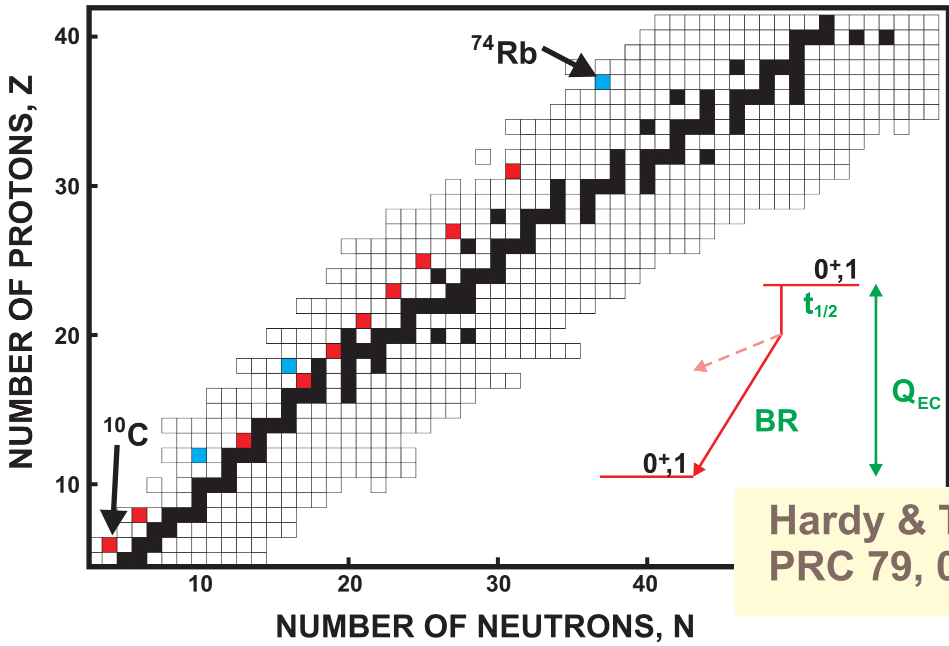
Determine V_{ud}^2

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

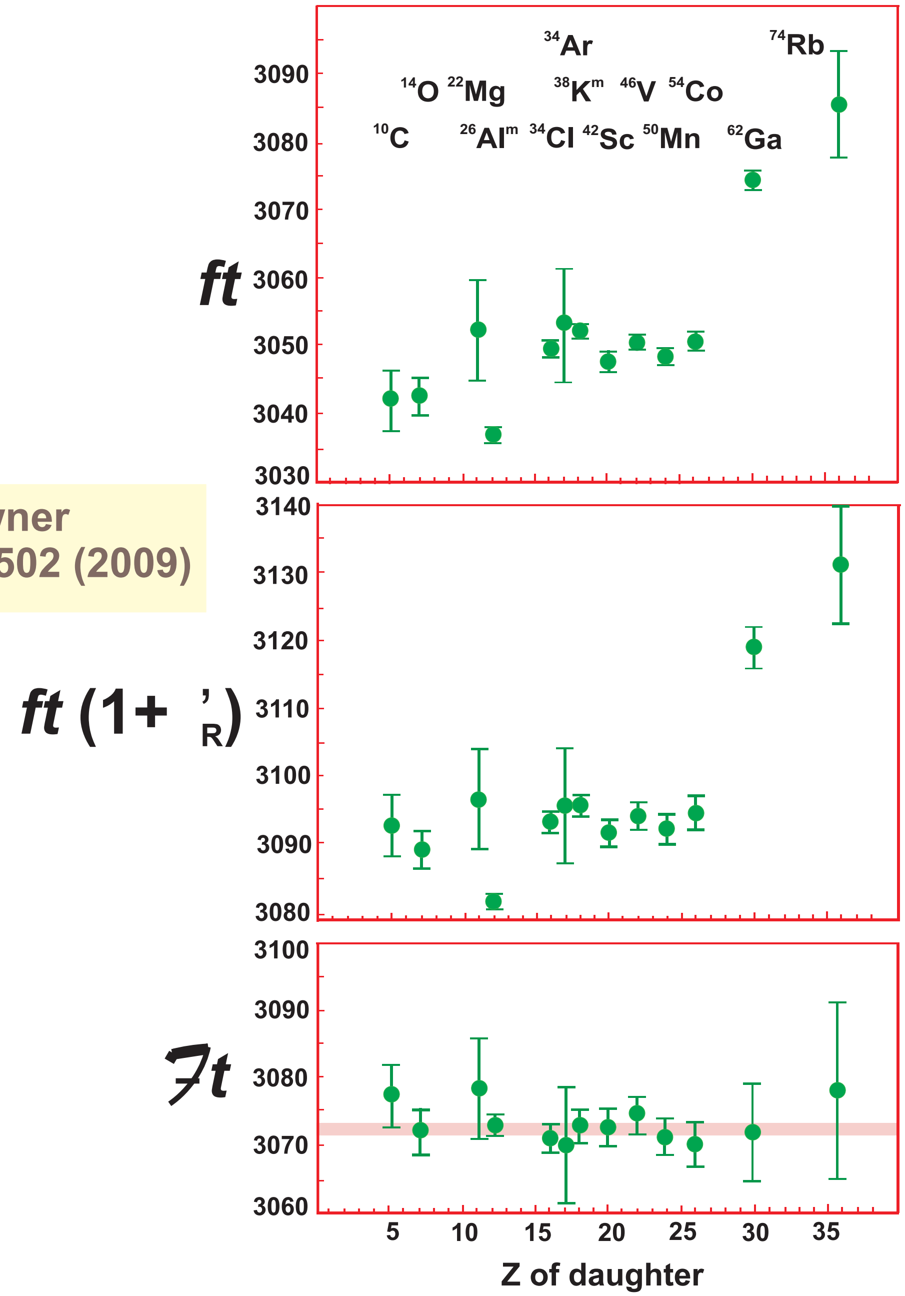
Test CKM unitarity

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

WORLD DATA FOR $0^+ \rightarrow 0^+$ DECAY, 2008



Hardy & Towner
PRC 79, 055502 (2009)



- 10 cases with *ft*-values measured to ~0.1% precision; 3 more cases with <0.3% precision.
- ~150 individual measurements with compatible precision

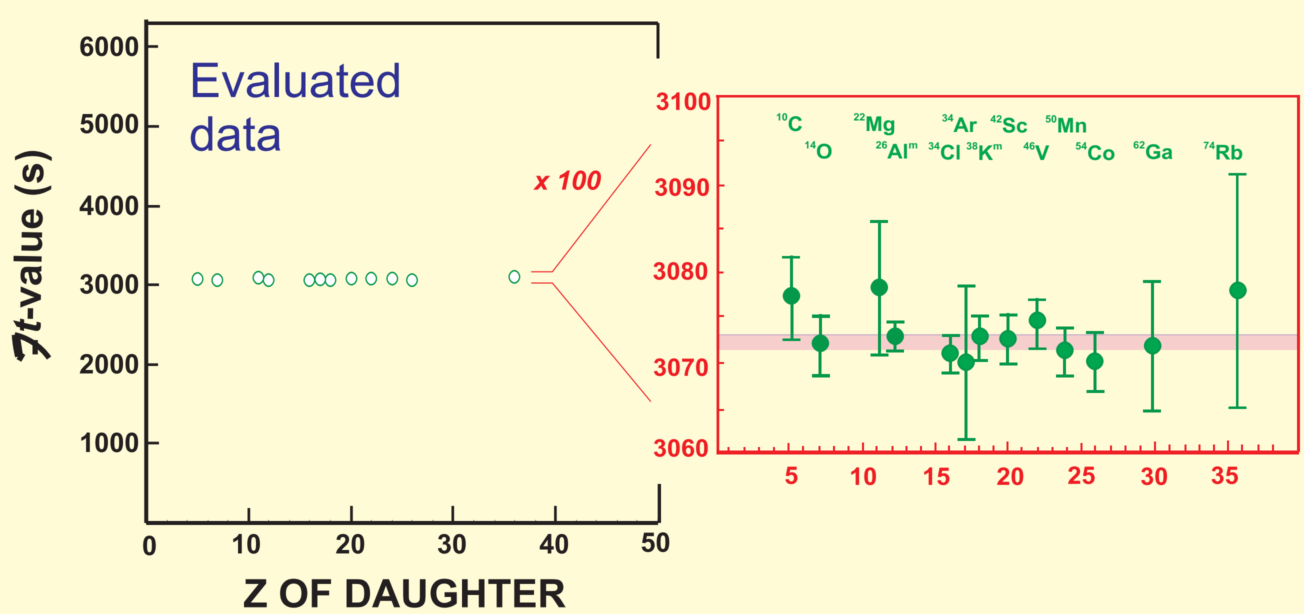
$$\mathcal{F}t = ft\,(1 + \;'_{R})[1 - (\;_{C} - \;_{NS})] = \frac{K}{2G_V^{\,2}\,(1 + \;_{R})}$$

RESULTS FROM $0^+ \rightarrow 0^+$ DECAY IN 2008

1) G_V constant

$$\mathcal{F}t = \frac{K}{2G_V^2\,(1 + \;_R)}$$

✔ verified to ± 0.013%



$\overline{\mathcal{F}t}$ = 3072.2(8)

$G_V(1+\;_R)^{1/2}/(\hbar c)^3$
= 1.14961(15)
x10^{-5} GeV^{-2}

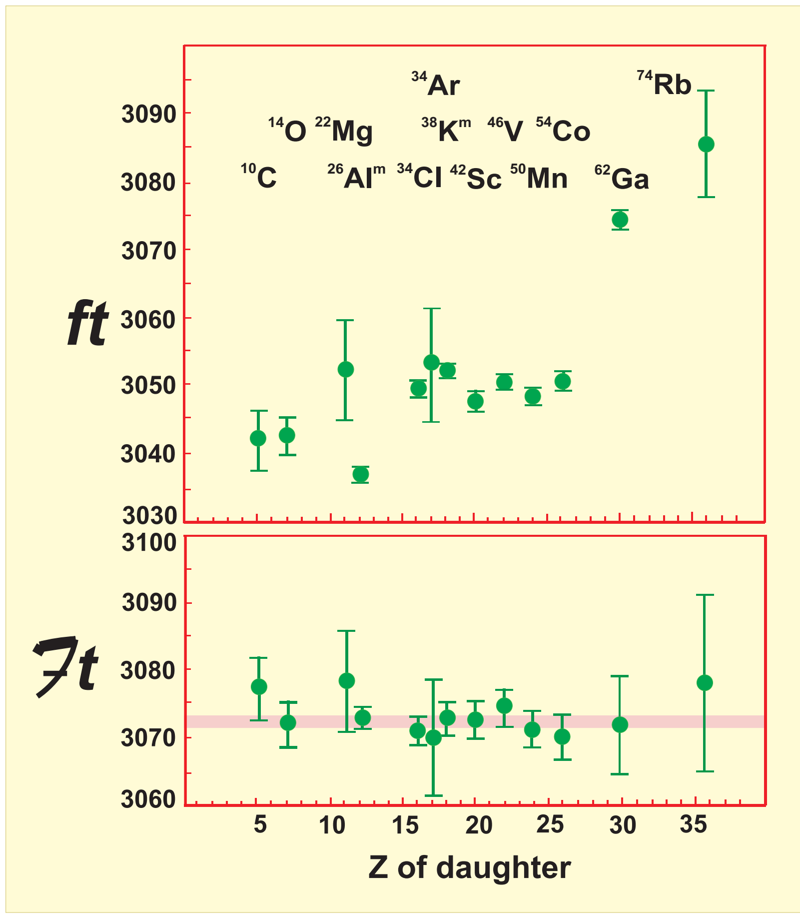
RESULTS FROM $0^+ \rightarrow 0^+$ DECAY IN 2008

1) G_V constant

$$\mathcal{F}t = \frac{K}{2G_V^2\,(1 + \quad _R)}$$

✔ verified to ± 0.013%

2) Correction terms validated ✔

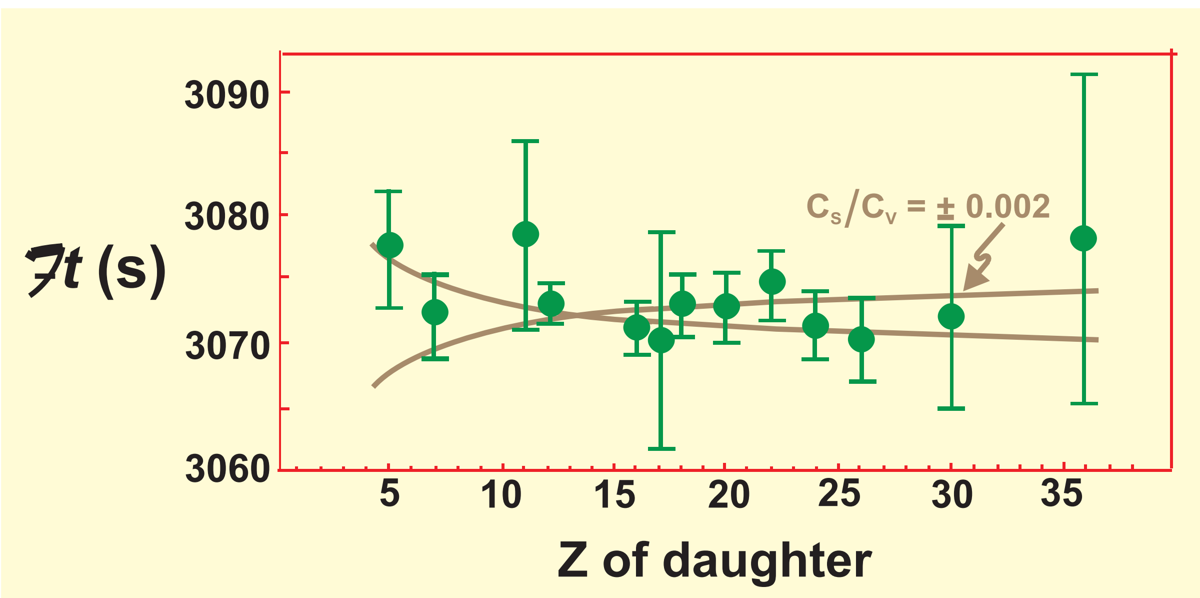


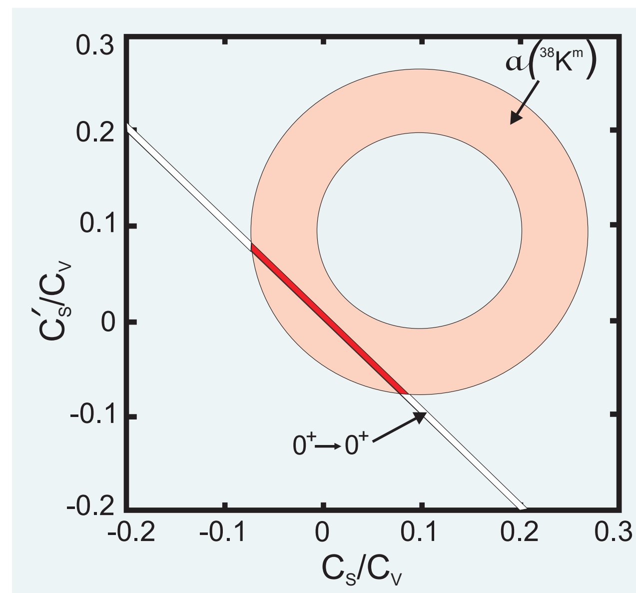
RESULTS FROM $0^+ \rightarrow 0^+$ DECAY IN 2008

1) G_V constant $\quad \mathcal{F}t = \dfrac{K}{2G_V^{\,2}\,(1 + {}_R)}$ ✔ verified to ± 0.013%

2) Correction terms validated ✔

3) Scalar current zero ✔ limit, $C_S/C_V = 0.0011\ (14)$





RESULTS FROM $0^+ \rightarrow 0^+$ DECAY IN 2008

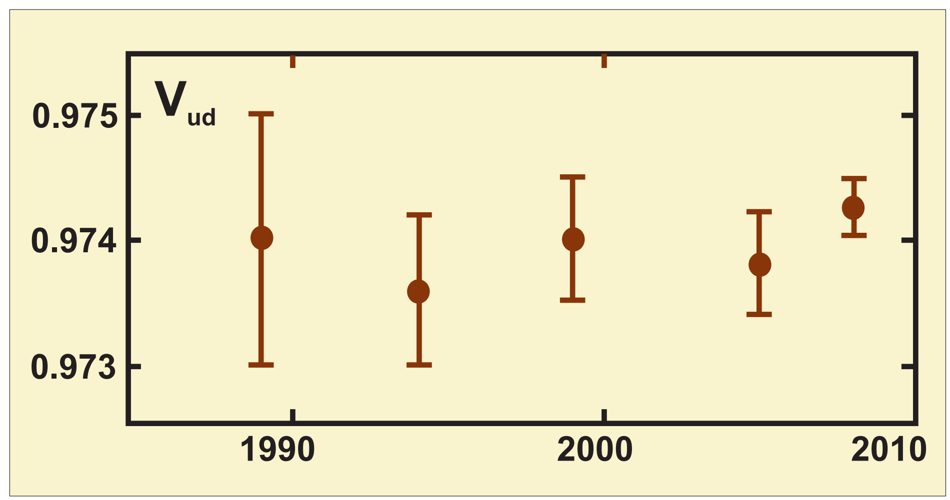
1) G_V constant $\quad \mathcal{F}t = \frac{K}{2G_V^2\,(1 + {}_R)}$ ✔ verified to ± 0.013%

2) Correction terms validated ✔

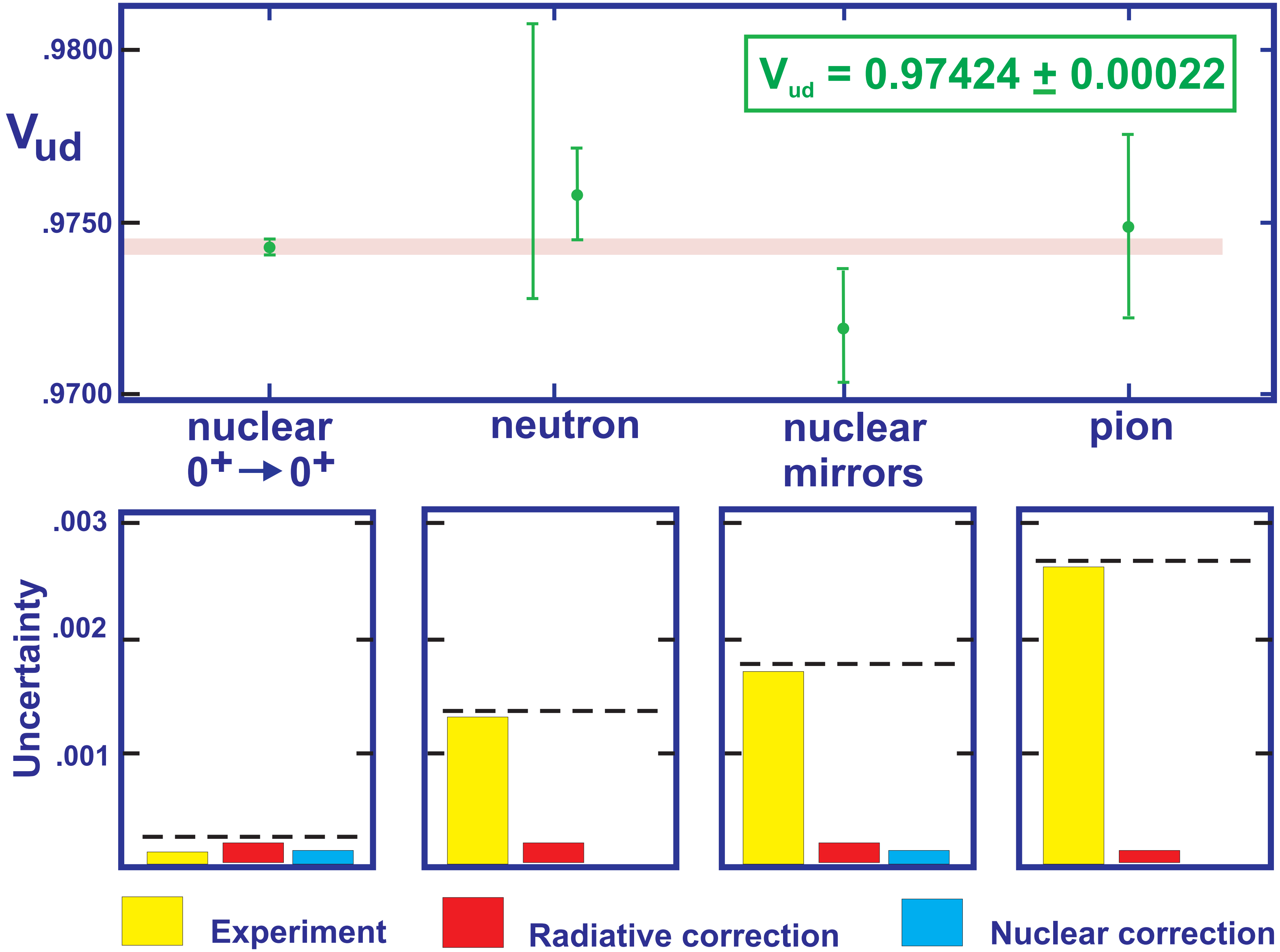
3) Scalar current zero ✔ limit, C_S/C_V = 0.0011 (14)

4) Precise value determined for V_{ud} $\quad V_{ud} = G_V/G$

V_{ud} = 0.97424 ± 0.00022



CURRENT STATUS OF V_{ud} – 2009



CURRENT STATUS, 2009

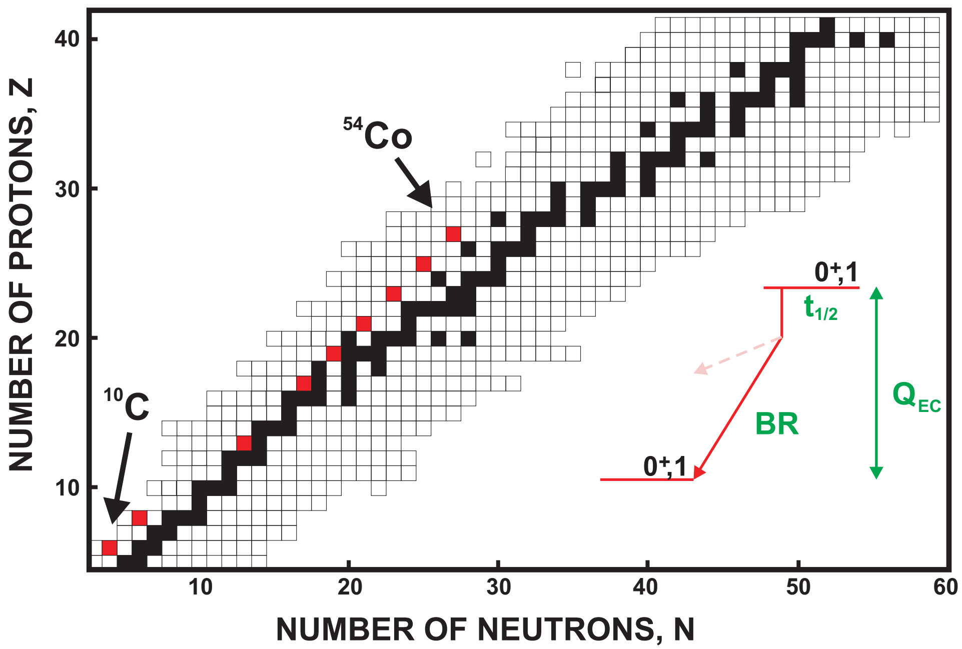
1. The best value for V_{ud} is obtained from superallowed $0^+ \rightarrow 0^+$ nuclear beta decays; it is more precise than the values from neutron and nuclear mirror decays by nearly a factor of ten.
2. The predominant contribution to the nuclear uncertainty is from the radiative correction. The symmetry-breaking corrections contribute less, and experiment contributes least of all.
3. The isospin-symmetry-breaking corrections are confirmed by consistent results from thirteen separate transitions.
4. The nuclear results confirm CVC, limit scalar currents and yield the current best value for V_{ud}, which satisfies CKM unitarity:

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99995(61)$$

0.9491(4)   0.0508(4)   <0.0001

5. Improvements are still possible if uncertainties can be reduced on the radiative corrections and on the symmetry-breaking corrections.

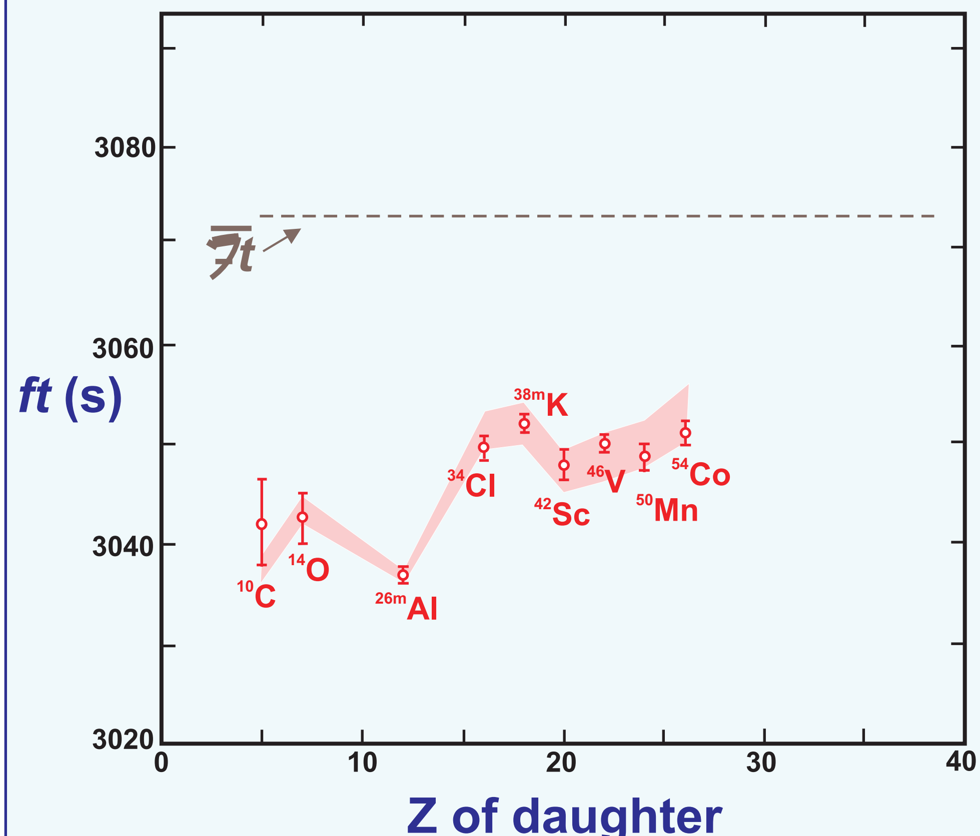
CURRENT DIRECTION OF NUCLEAR EXPERIMENTS



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

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

Calculated *ft*-value = $\dfrac{\overline{\mathcal{F}t}}{(1 + {}'_{R})[1 - ({}_{C} - {}_{NS})]}$



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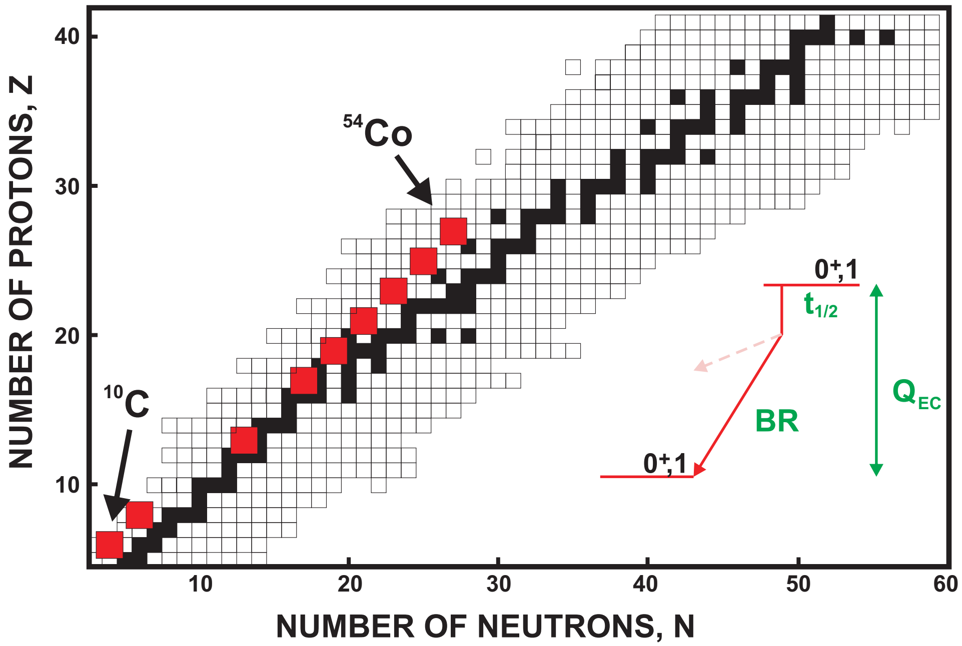

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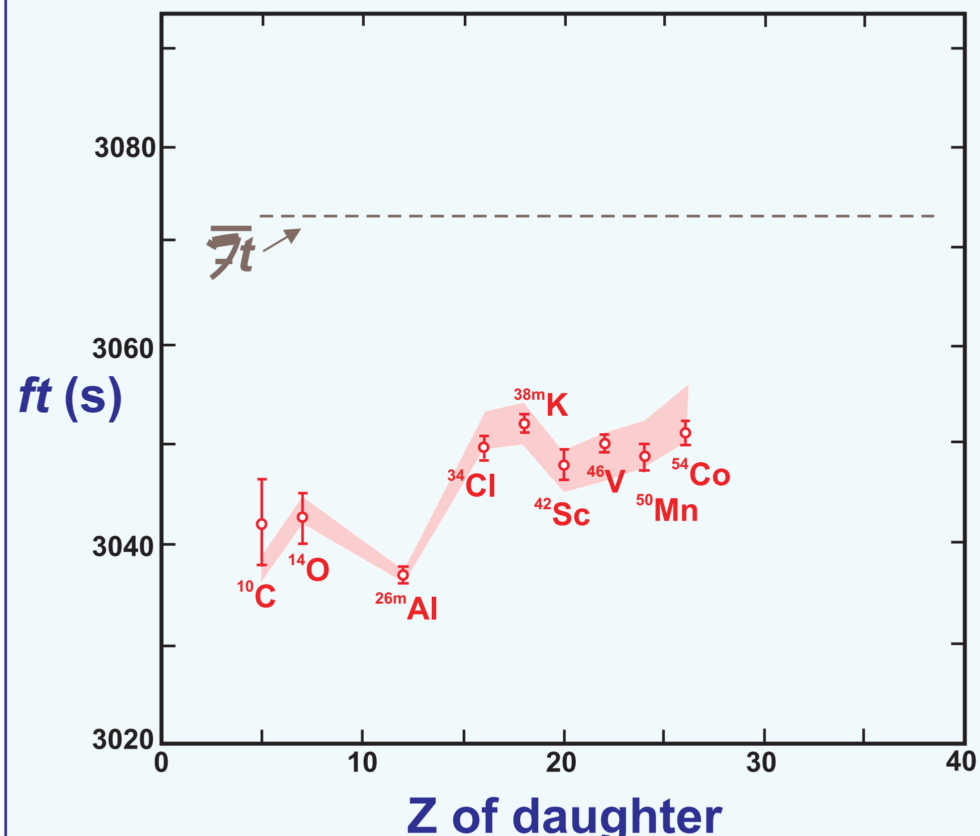
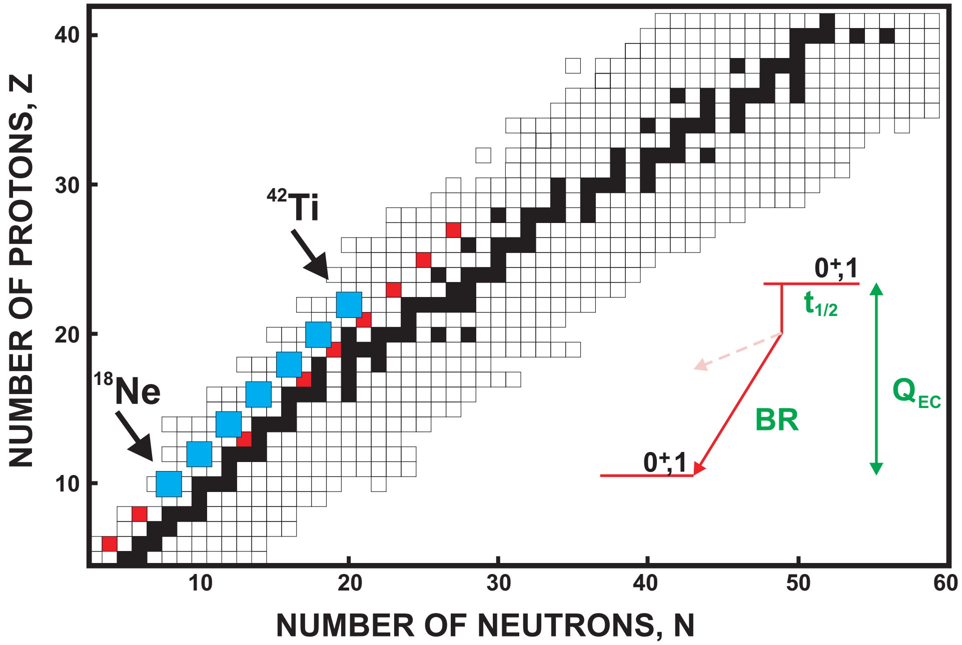


* **Increase measured precision on nine best *ft*-values**

CURRENT DIRECTION OF NUCLEAR EXPERIMENTS



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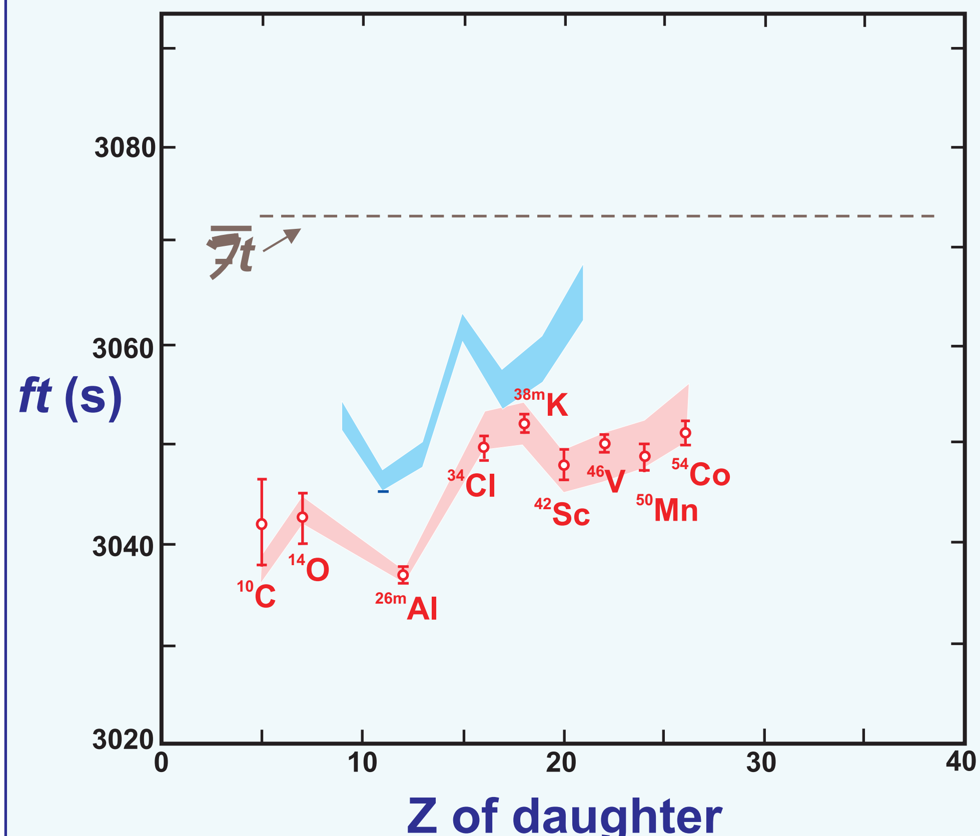
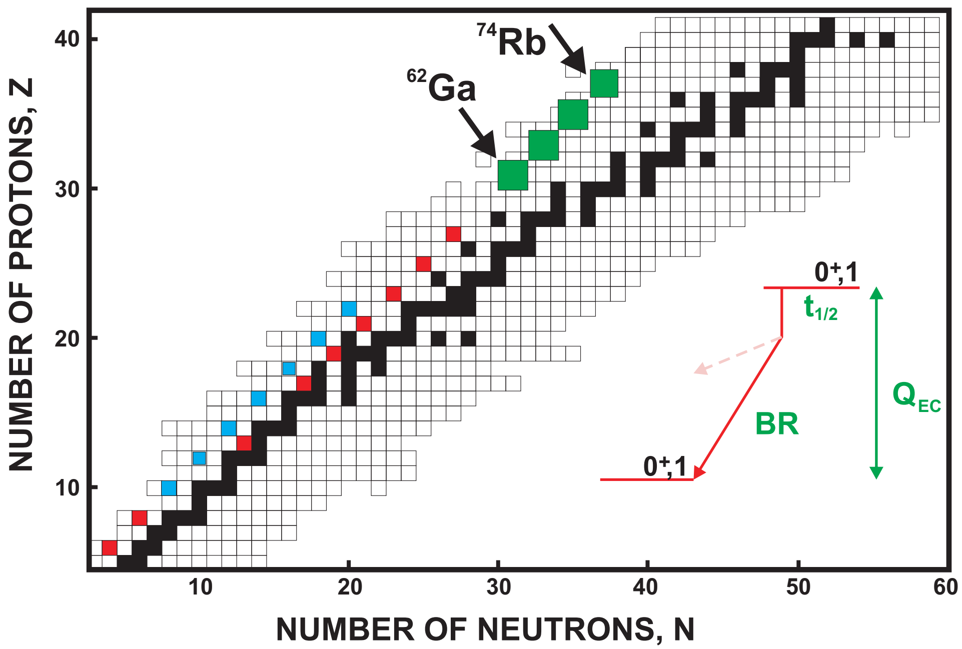


* **Increase measured precision on nine best *ft*-values**

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

CURRENT DIRECTION OF NUCLEAR EXPERIMENTS



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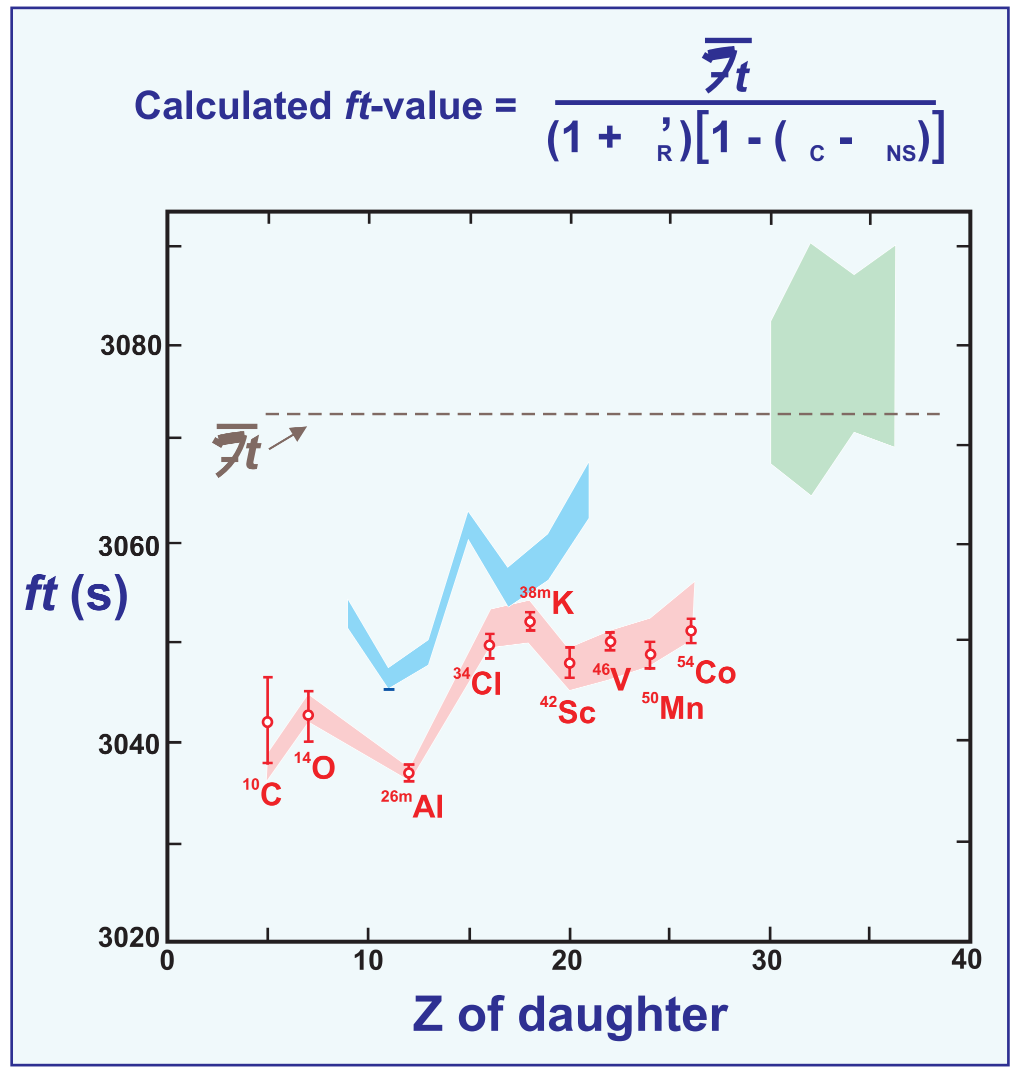

* **Increase measured precision on nine best *ft*-values**

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

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

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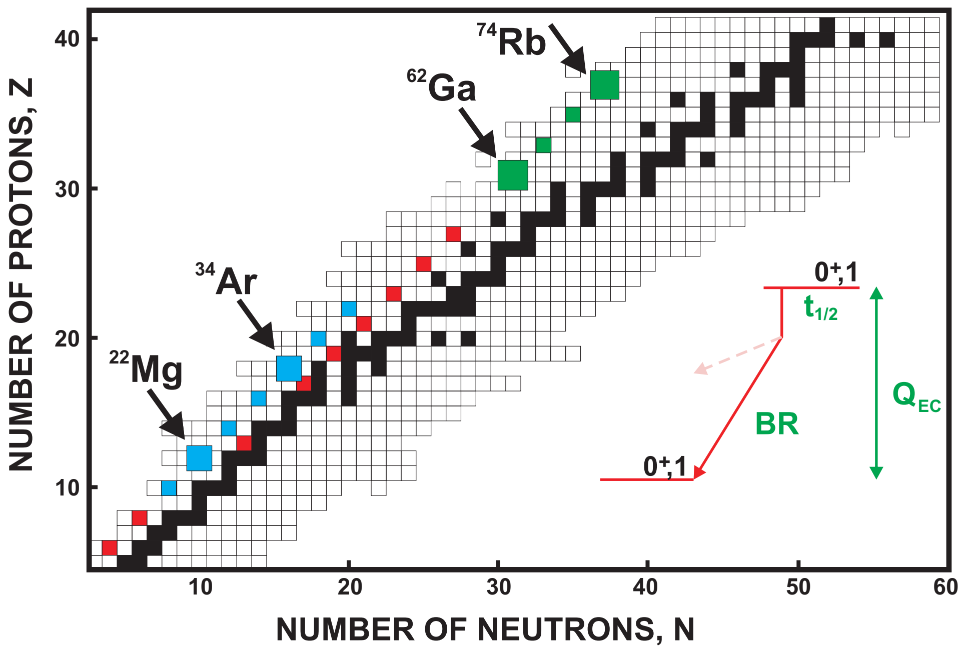

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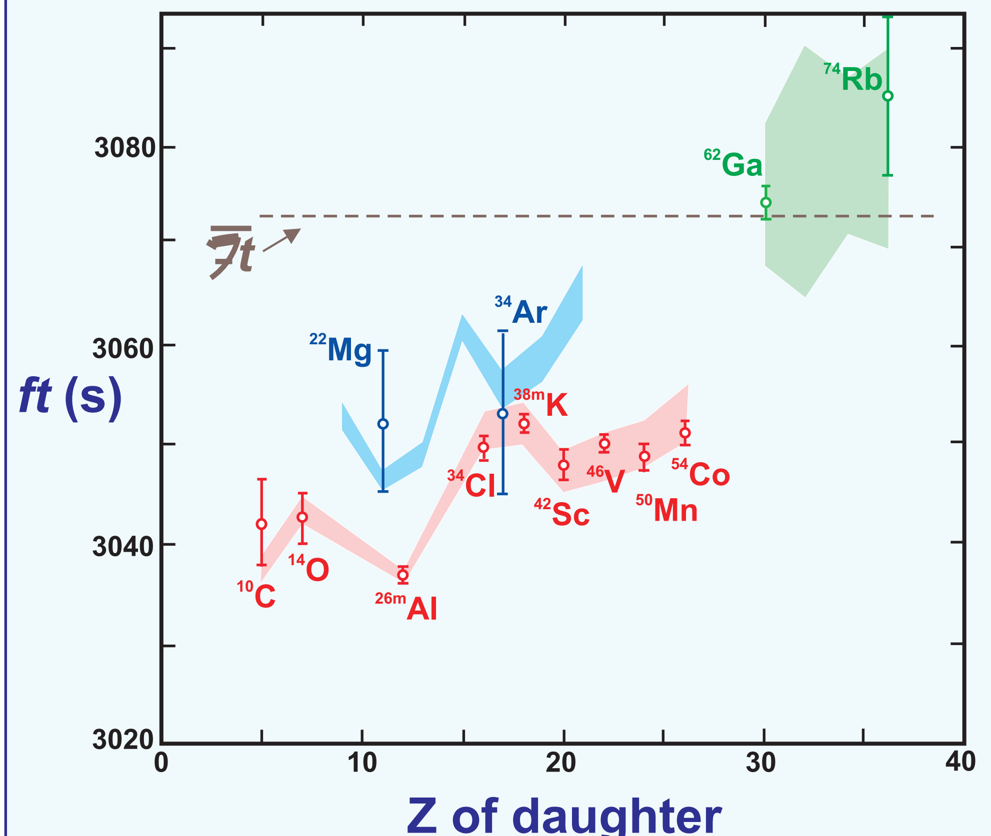


* **Increase measured precision on nine best *ft*-values**

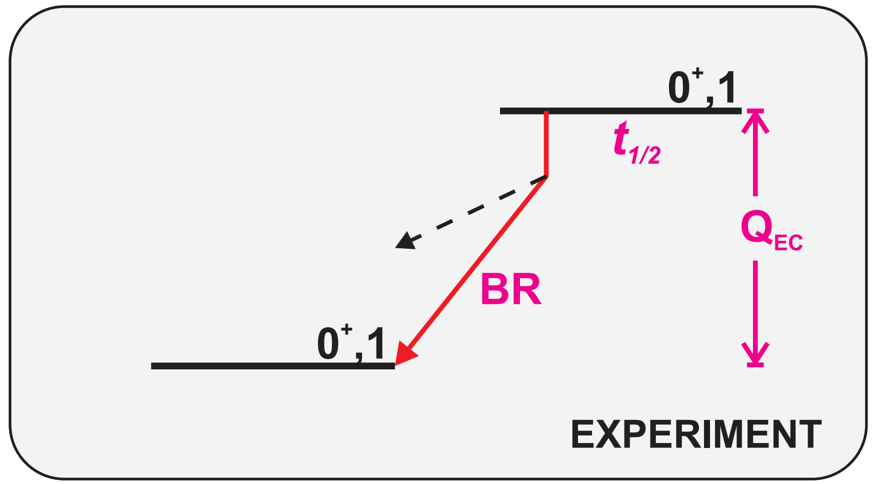
* **measure new $0^+ \rightarrow 0^+$ decays with $18 \leq A \leq 42$ (T_z = -1)**

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

PRECISION REQUIRED FROM EXPERIMENT

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

Precision required for CKM unitarity test: **< 0.1%**

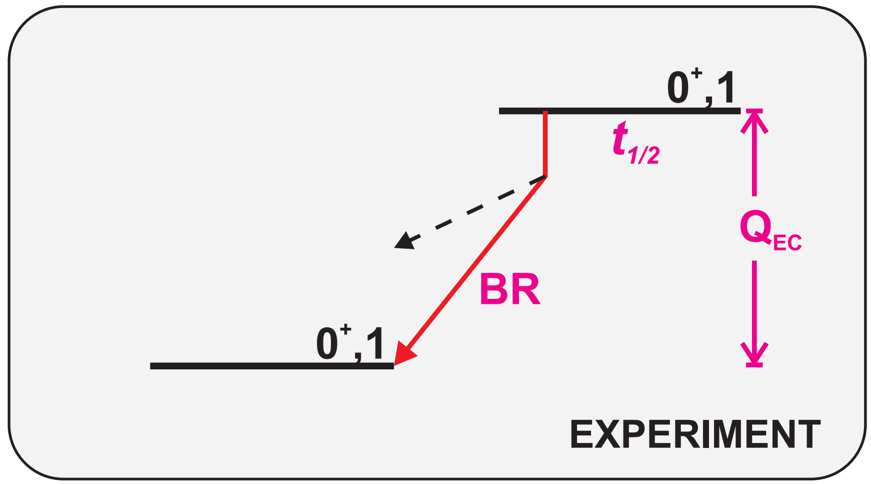


PRECISION REQUIRED FROM EXPERIMENT

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

Precision required for CKM unitarity test: **< 0.1%**

Precision achievable for calculated corrections: **0.05-0.10%**



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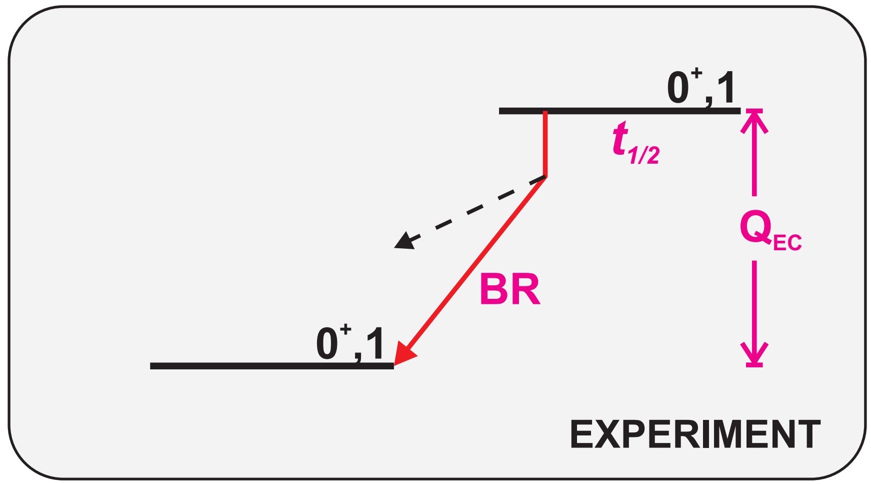


Required from experiment:

$f = f(Z, Q_{EC}) \propto Q^5$

Precision for Q **0.01%**

200eV – 1keV

$t = t_{1/2}$ /BR

Precision for t **0.05%**

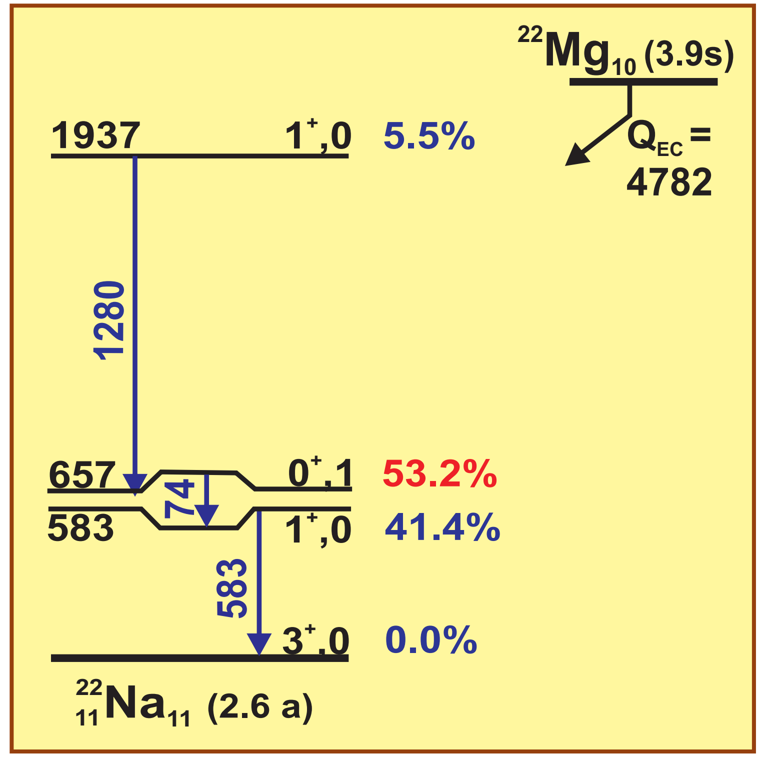
By the usual nuclear physics standards, these are very challenging requirements!

GUIDELINES FOR PRECISION MEASUREMENTS

- Experimental apparatus should be as simple as possible.
- All experimental parameters must be under control and testable.
- Experimental equipment should be dedicated only to this measurement.
- Calibration is often the most important part of the measurement.
- Tests for sources of systematic error must dominate data acquisition.
- Redundancy is desirable in both measurement and analysis.
- No inconsistencies can be overlooked.
- A complete error budget is the most important part of the result.

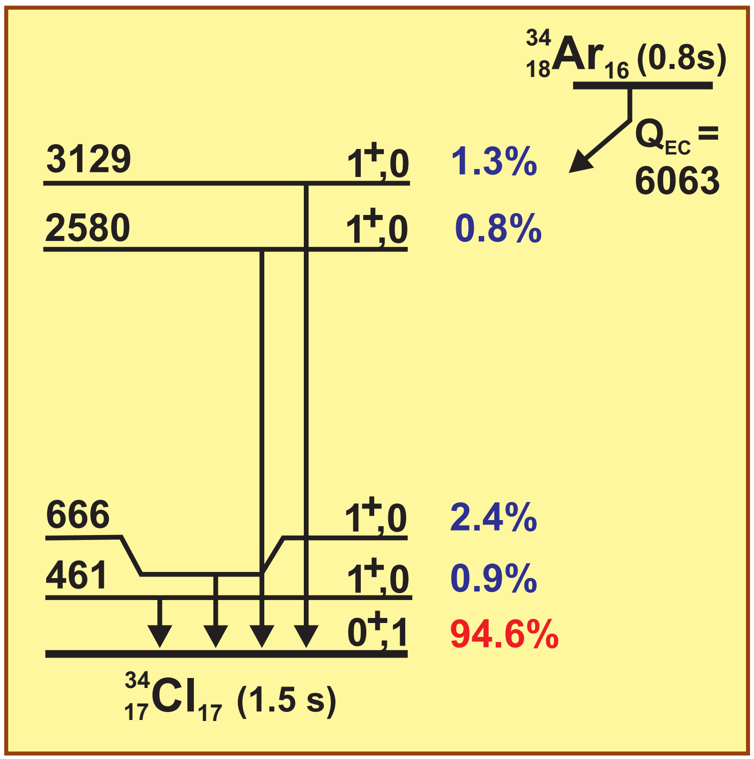
BRANCHING-RATIO MEASUREMENTS

In all cases we measure the intensities of -delayed rays.

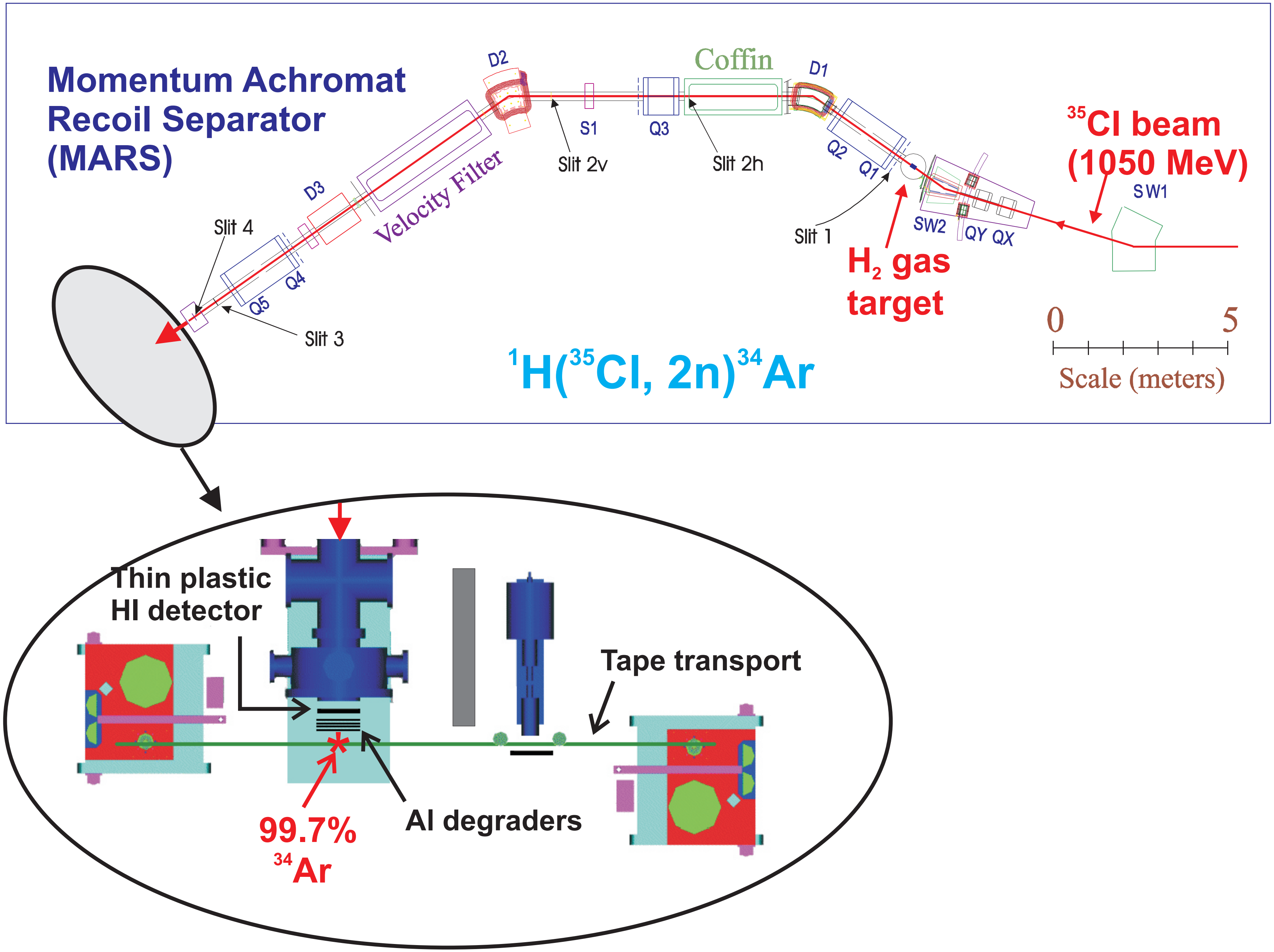


Relative intensities

Absolute intensities



PRECISION DECAY MEASUREMENTS AT TAMU



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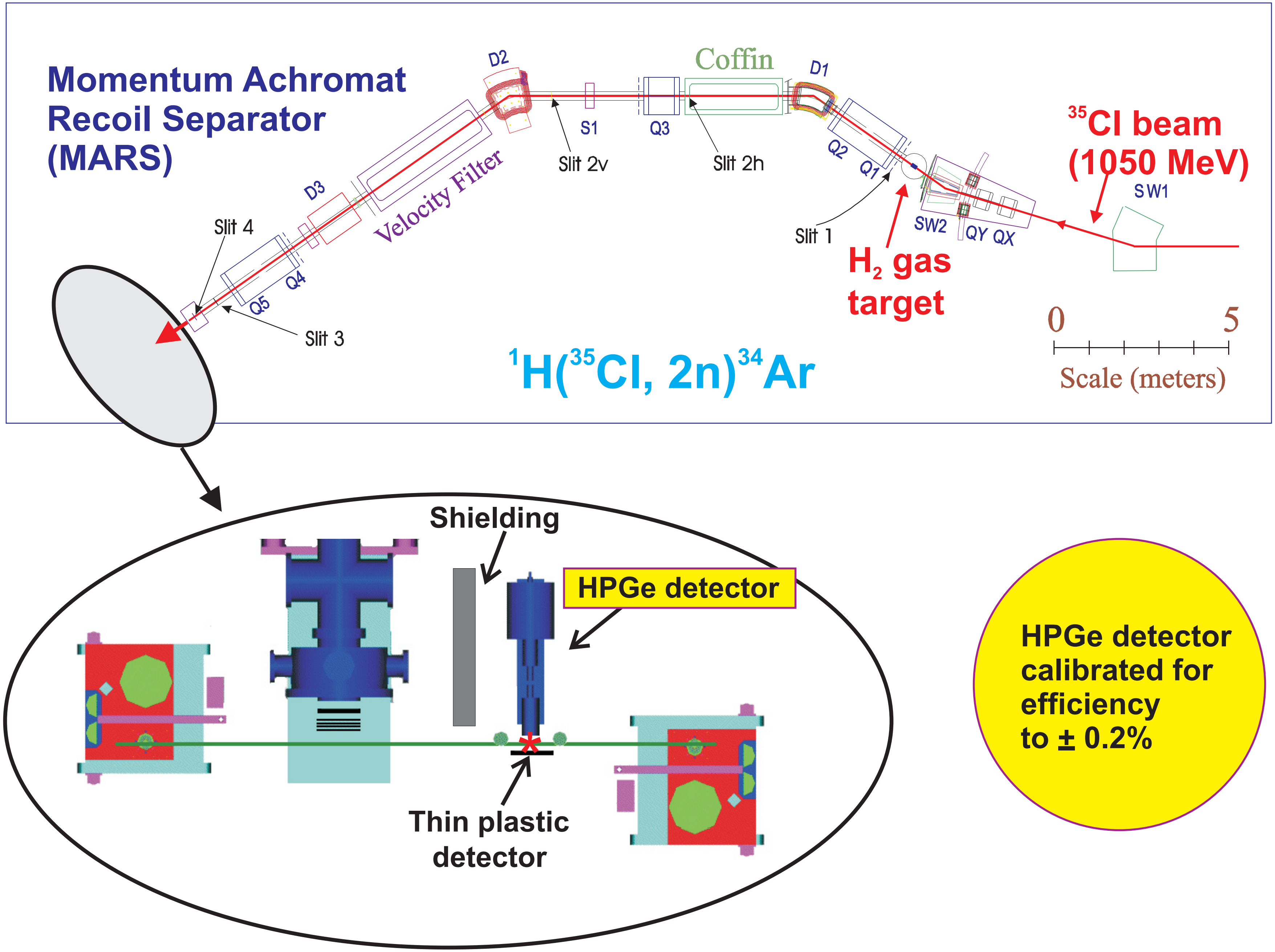


HPGe detector calibrated for efficiency to ± 0.2%

HPGe DETECTOR CALIBRATION

Commercial standard sources:

Relative intensities not known in any case to better than 0.4%.

Source activity (absolute intensity) can be specified to 2-5%; rarely to 1%.

For higher precision:

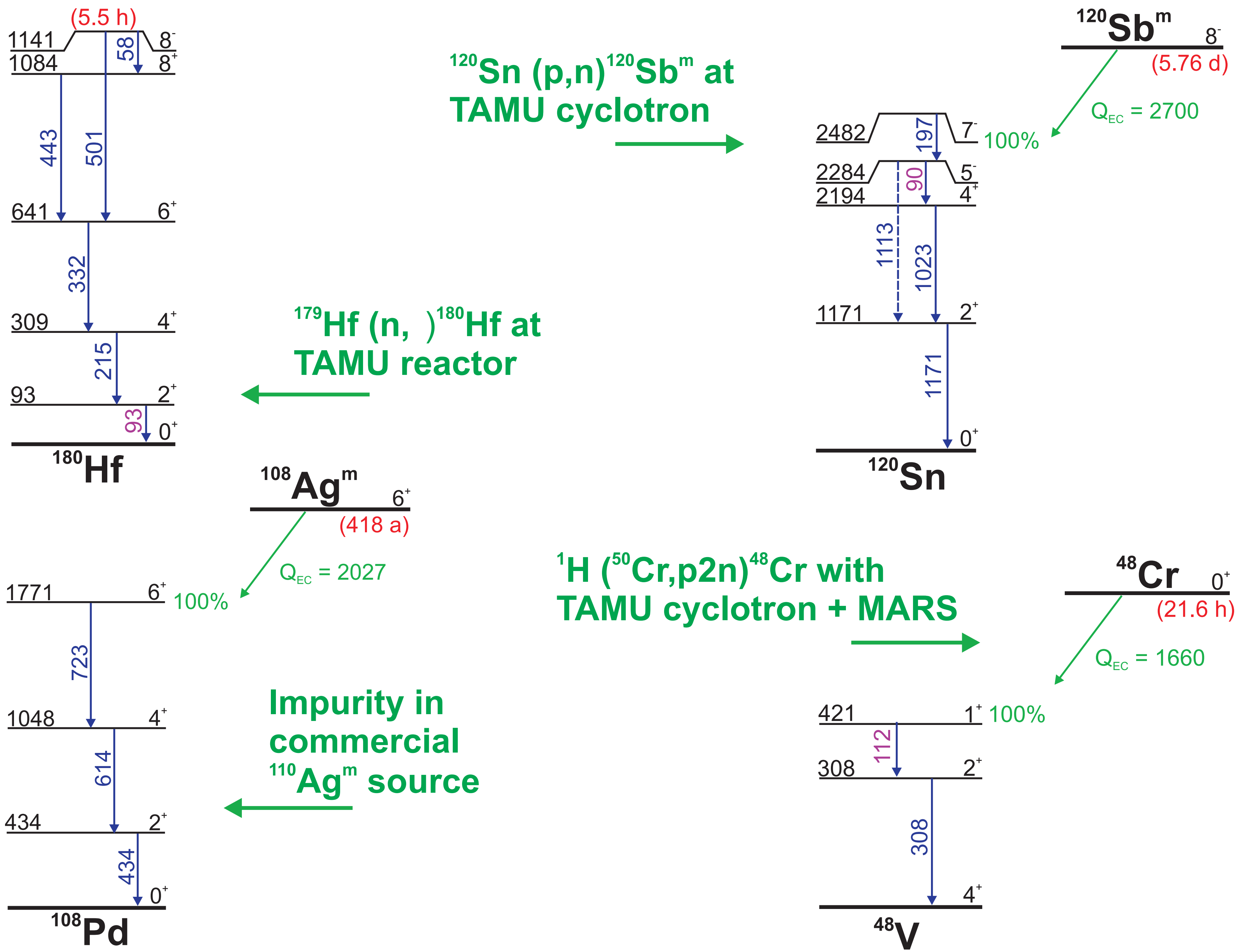
Source activity for certain cases can be measured to 0.1% by 4 coincidence counting; in our case ^{60}Co at PTB Lab.

Schoenfeld *et al.*, Appl. Rad & Isot. 56 (2002) 215.

Use clean -ray cascades; home-made sources.

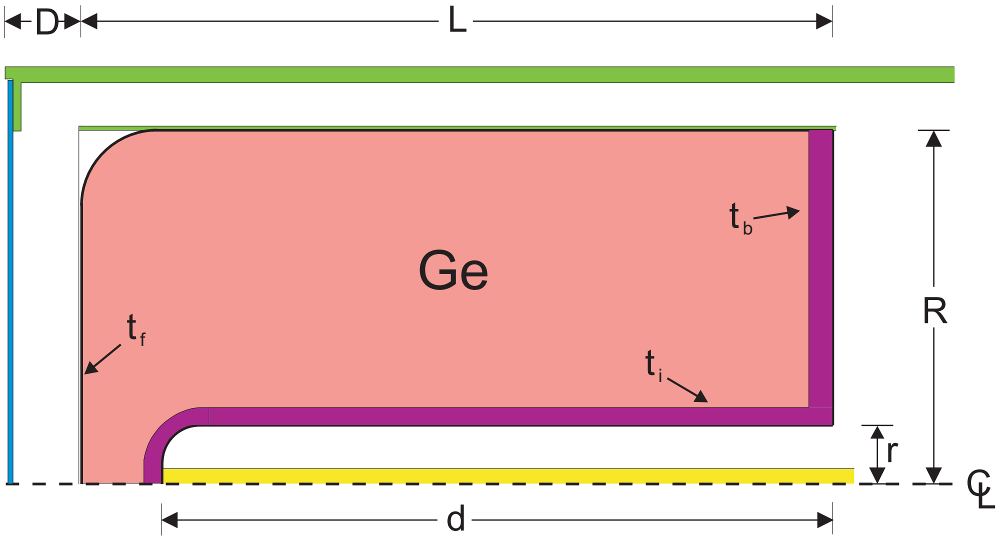
Combine Monte Carlo calculations with measured points.

KEY RADIOACTIVE SOURCES



MONTE CARLO CALCULATIONS

EG&G ORTEC Gamma-X HPGe

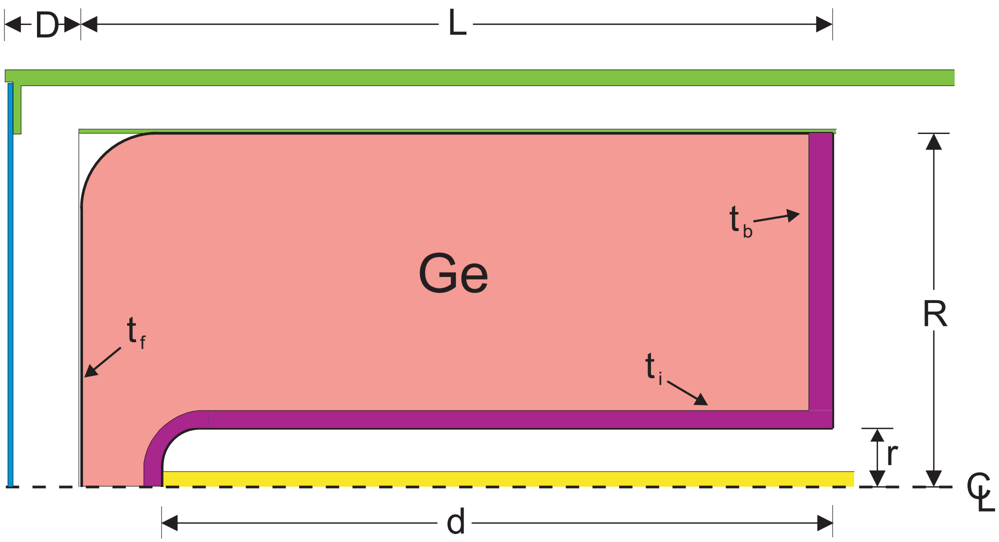


DIMENSION	NOMINAL
Crystal radius, R	34.95 mm
Crystal active length, $L - t_f - t_b$	77.7 mm
Cap face to crystal distance, D	5.6 mm
Hole radius, r	5.8 mm
Hole depth, d	69.7 mm
Depth internal (Li) dead layer, t_i	>1 mm
Depth front dead layer, t_f	>0.3 m

X-ray picture of crystal

MONTE CARLO CALCULATIONS

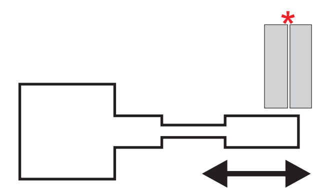
EG&G ORTEC Gamma-X HPGe

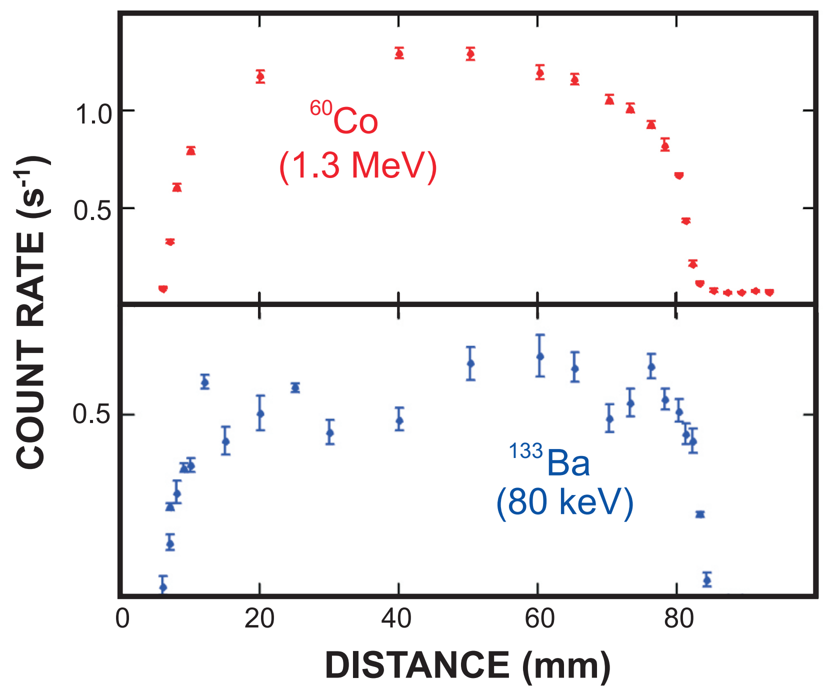


DIMENSION	NOMINAL	MEASURED or FITTED
Crystal radius, R	34.95 mm	
Crystal active length, $L - t_f - t_b$	77.7 mm	75.4 mm
Cap face to crystal distance, D	5.6 mm	
Hole radius, r	5.8 mm	
Hole depth, d	69.7 mm	
Depth internal (Li) dead layer, t_i	>1 mm	
Depth front dead layer, t_f	>0.3 m	

X-ray picture of crystal

Crystal side-scan





MONTE CARLO CALCULATIONS

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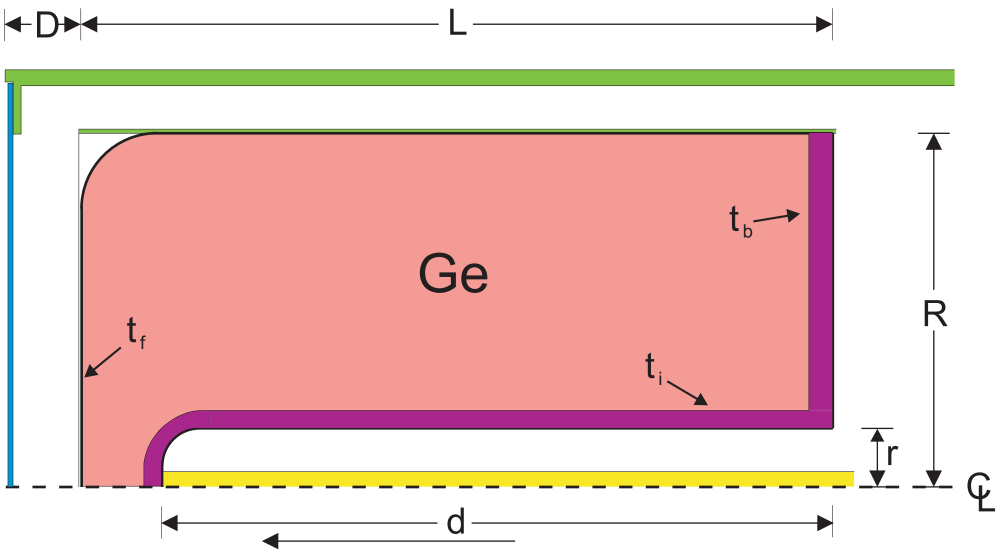

DIMENSION	NOMINAL	MEASURED or FITTED
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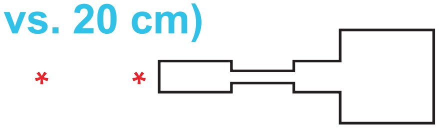
Crystal active length, $L - t_f - t_b$	77.7 mm	75.4 mm
Cap face to crystal distance, D	5.6 mm	7.2 mm
Hole radius, r	5.8 mm	
Hole depth, d	69.7 mm	
Depth internal (Li) dead layer, t_i	>1 mm	
Depth front dead layer, t_f	>0.3 m	

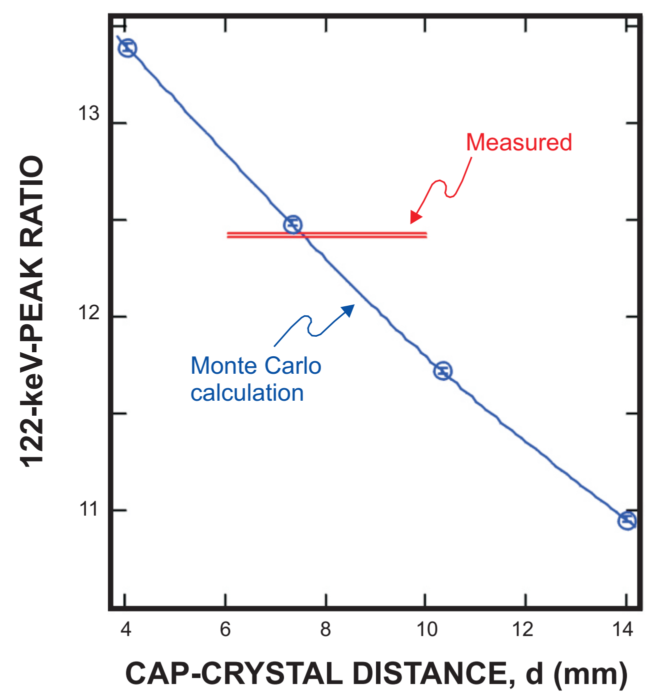
X-ray picture of crystal

Crystal side-scan

Distance ratio for ^{57}Co

(4 cm vs. 20 cm)





MONTE CARLO CALCULATIONS

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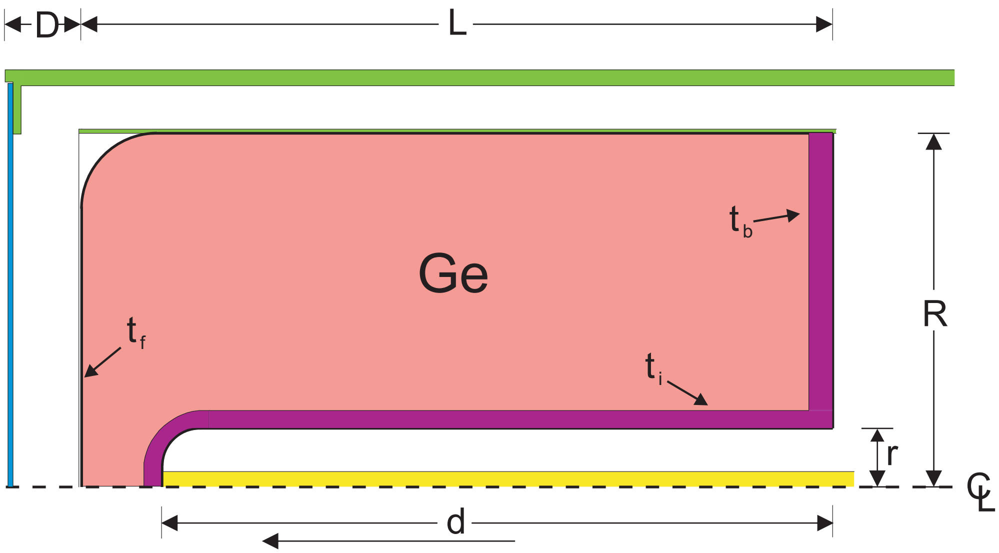

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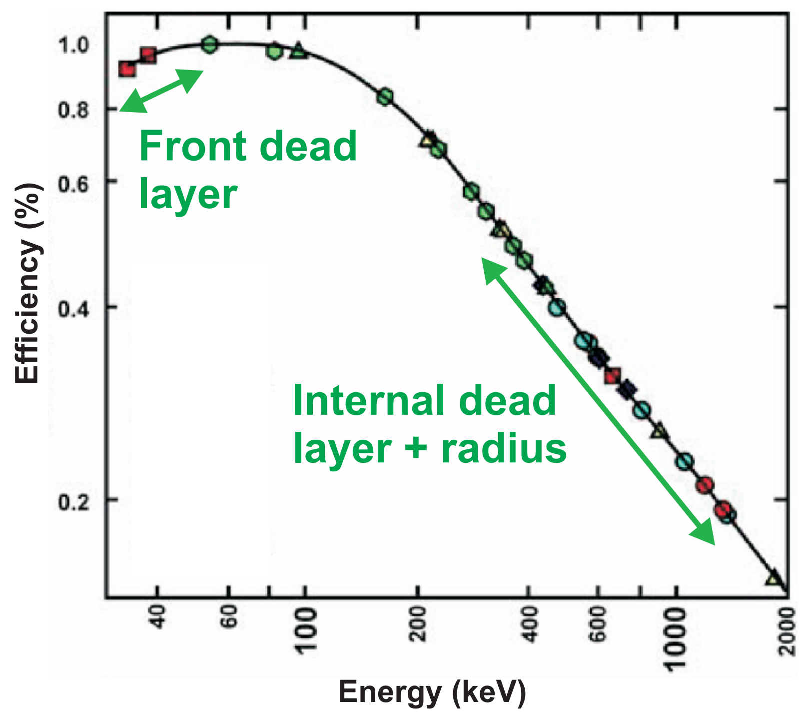
Hole radius, r	5.8 mm	
Hole depth, d	69.7 mm	
Depth internal (Li) dead layer, t_i	>1 mm	1.34 mm
Depth front dead layer, t_f	>0.3 m	2.5 m

X-ray picture of crystal

Crystal side-scan

Distance ratio for ^{57}Co

Fitted for energy dependence



DETECTOR EFFICIENCY
50 keV < E < 1.4 MeV

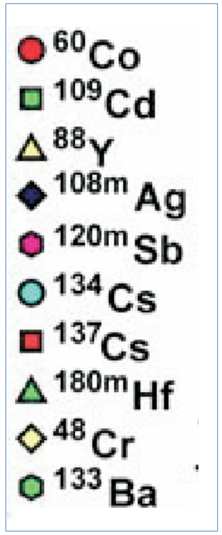
Source measurements
vs
unscaled Monte Carlo calculations

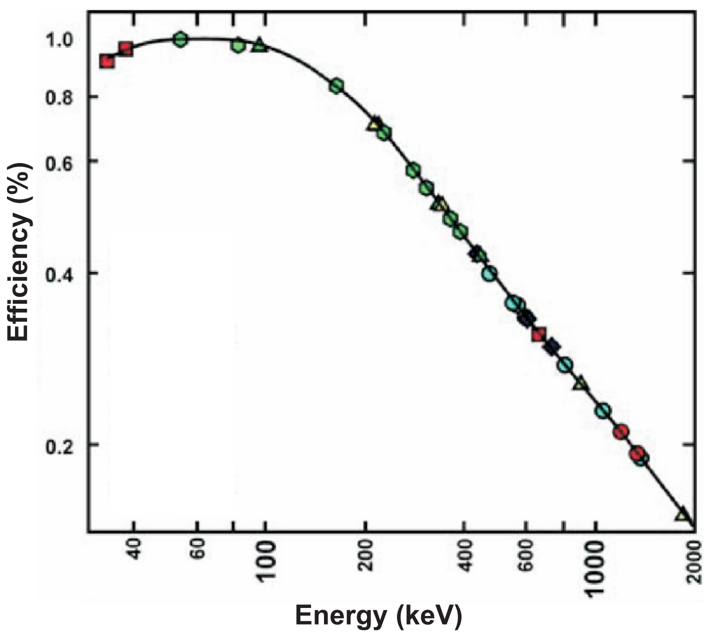
Physical properties and location of HPGe crystal measured precisely

10 sources recorded

4 key sources, 3 locally made, have pure cascades

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





Helmer *et al.*,
NIM A511, 360 (2003)

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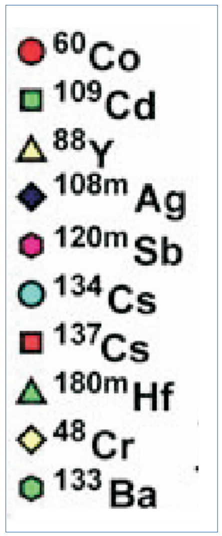
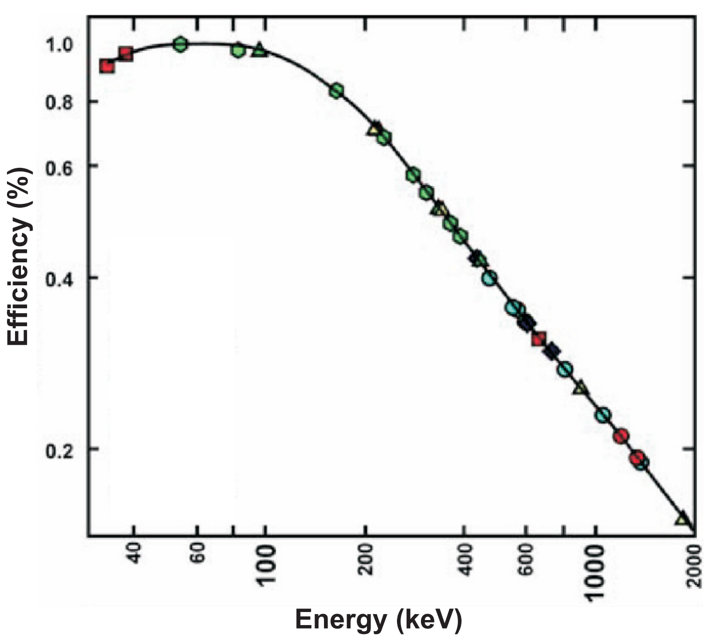
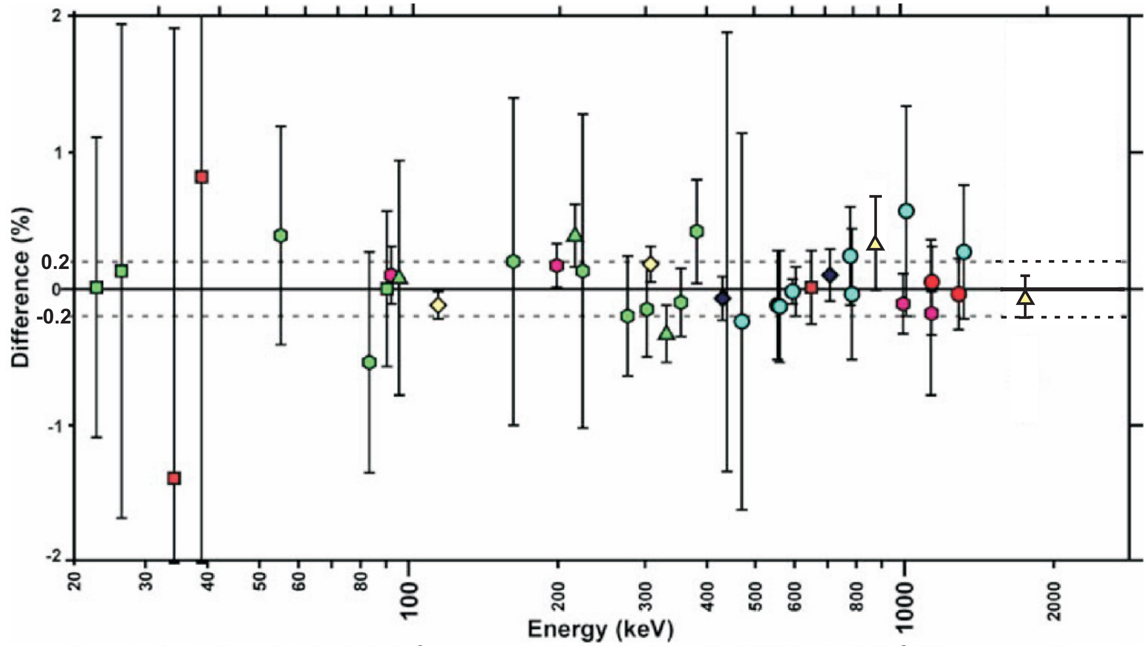
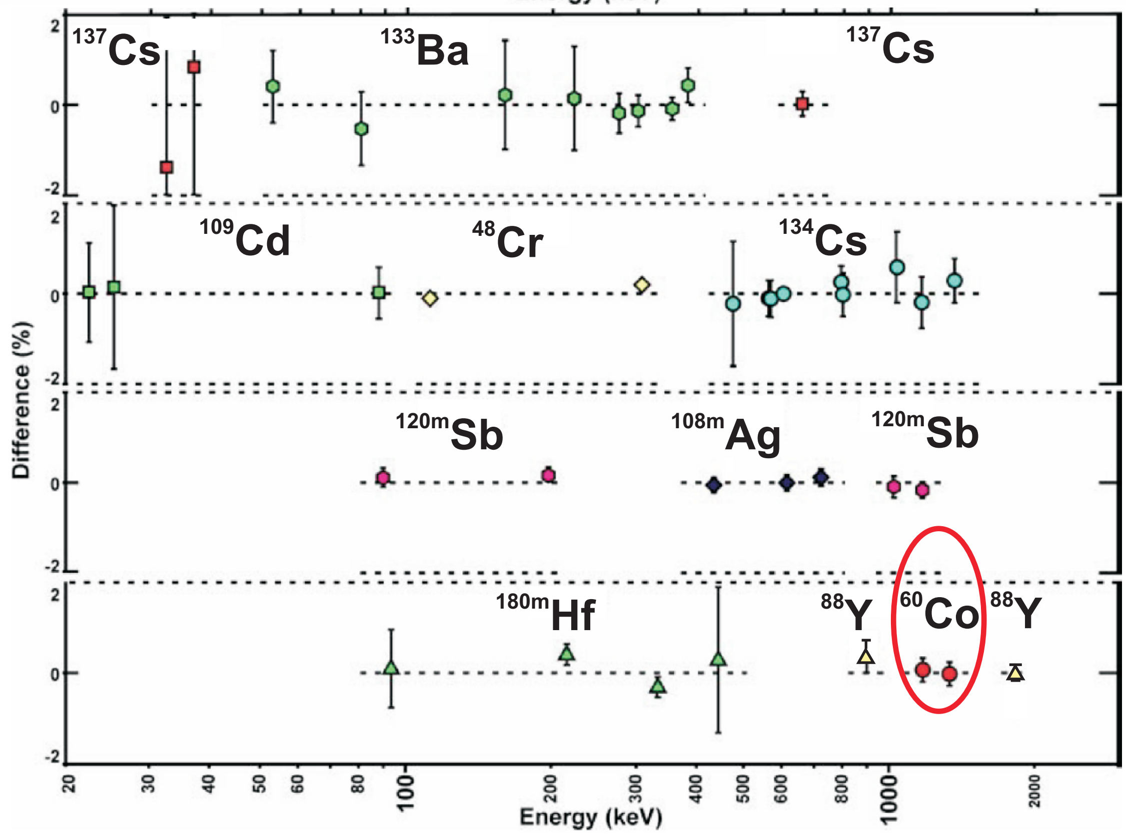
^{60}Co source from PTB with activity known to ± 0.1%



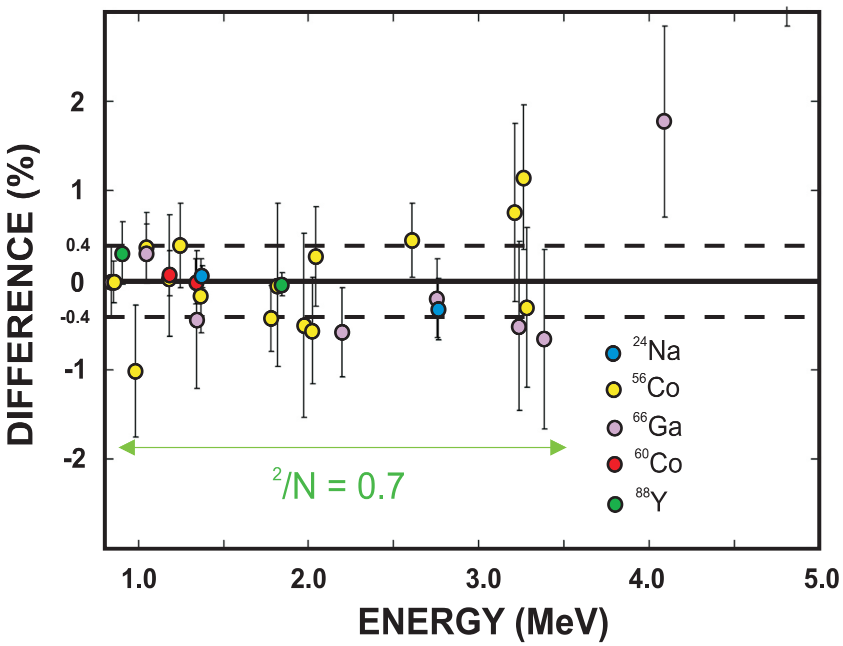






DETECTOR CHARACTERIZATION - DETAILS

Efficiency extended up to 3.5 MeV



Helmer *et al.*, Appl. Rad. Isot. 60, 173 (2004)

DETECTOR CHARACTERIZATION - DETAILS

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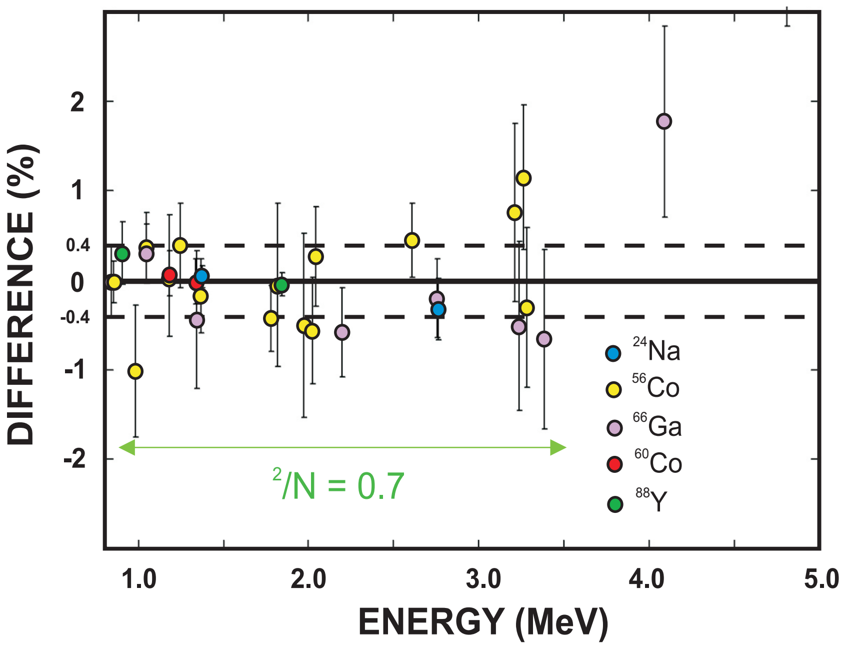
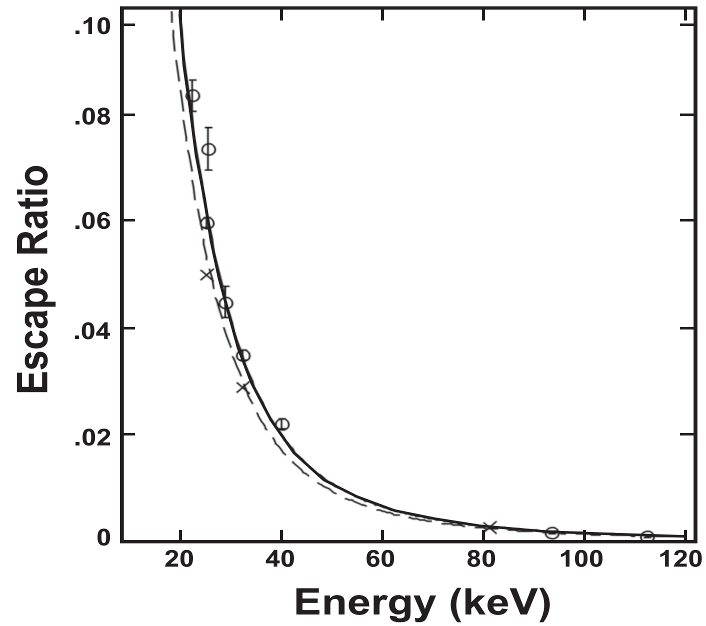
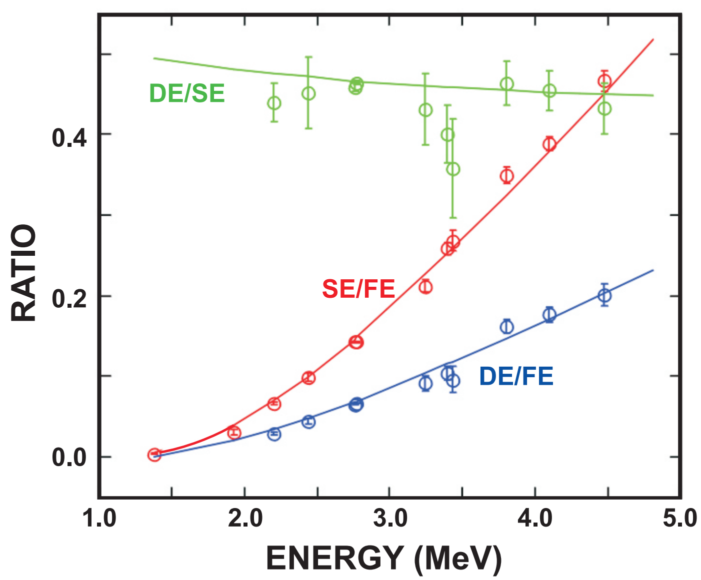


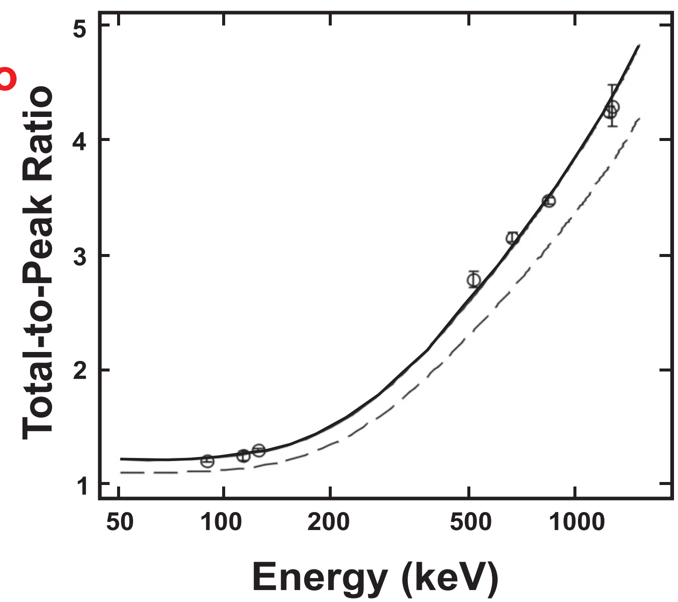
Ge x-ray excape





Total-to-peak ratio (for summing corrections)

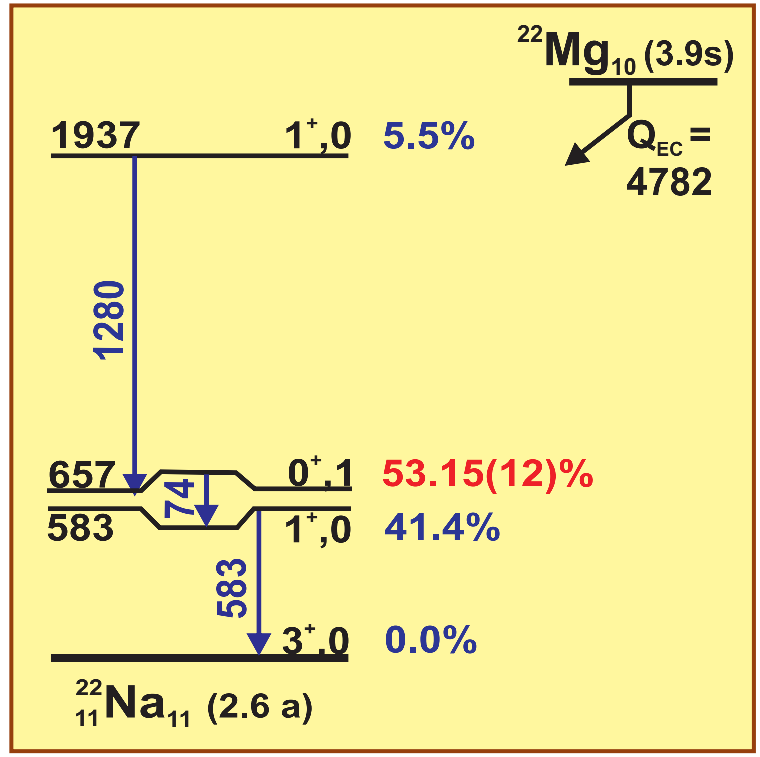
511-keV escape ratios

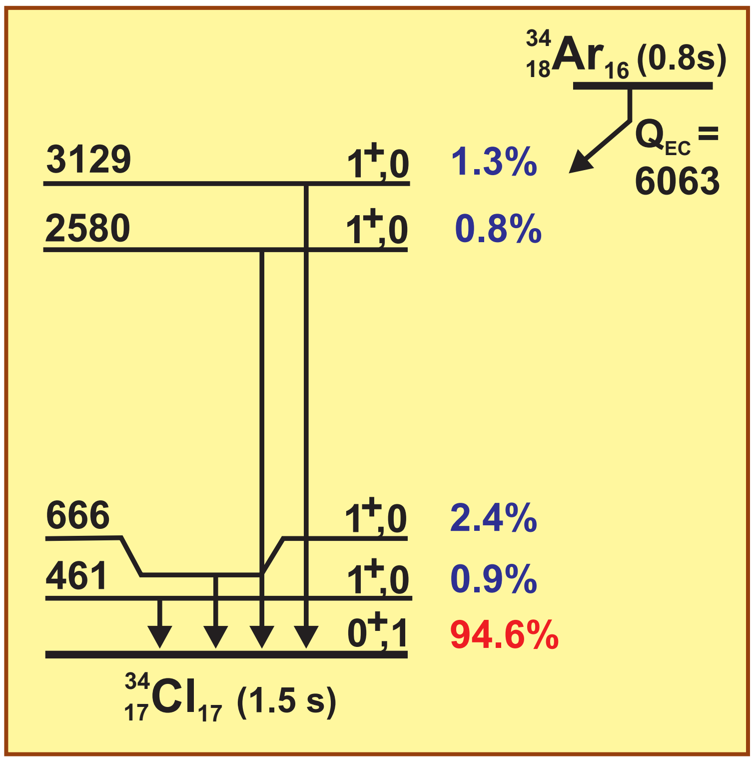


BRANCHING-RATIO RESULTS

Where no ground-state decay occurs, a -ray spectrum and relative efficiencies are enough to obtain branching ratios.

Hardy *et al.*, PRL 91, 082501 (2003).



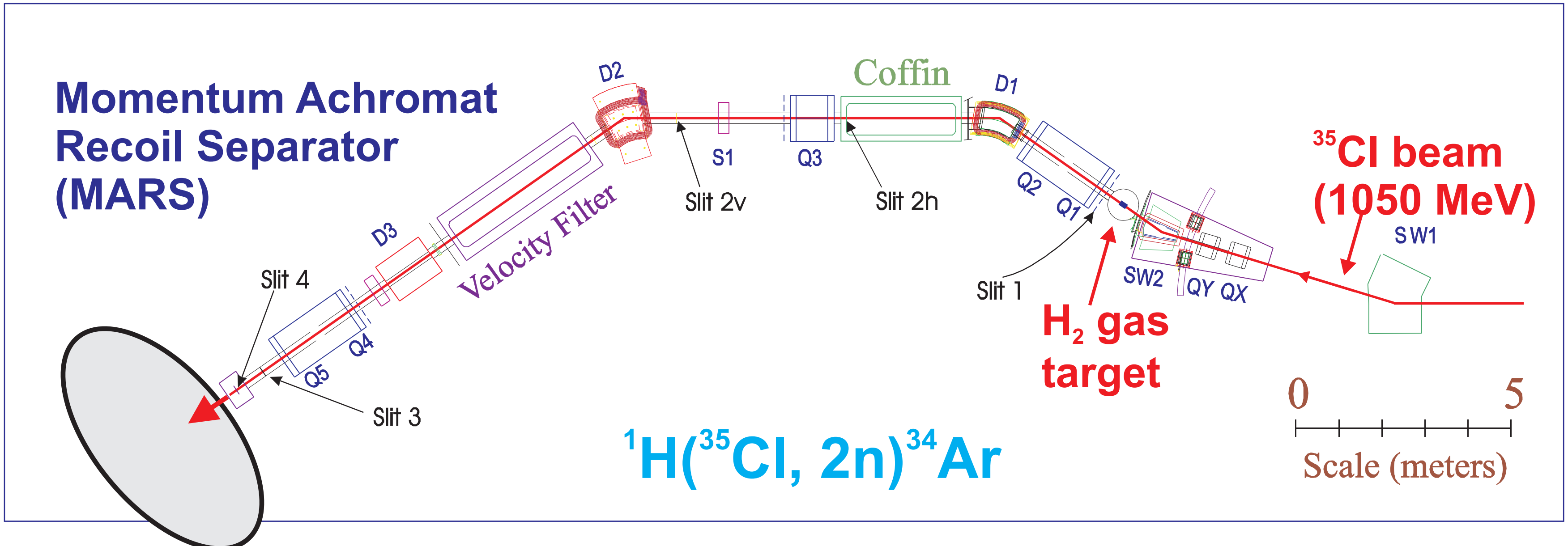


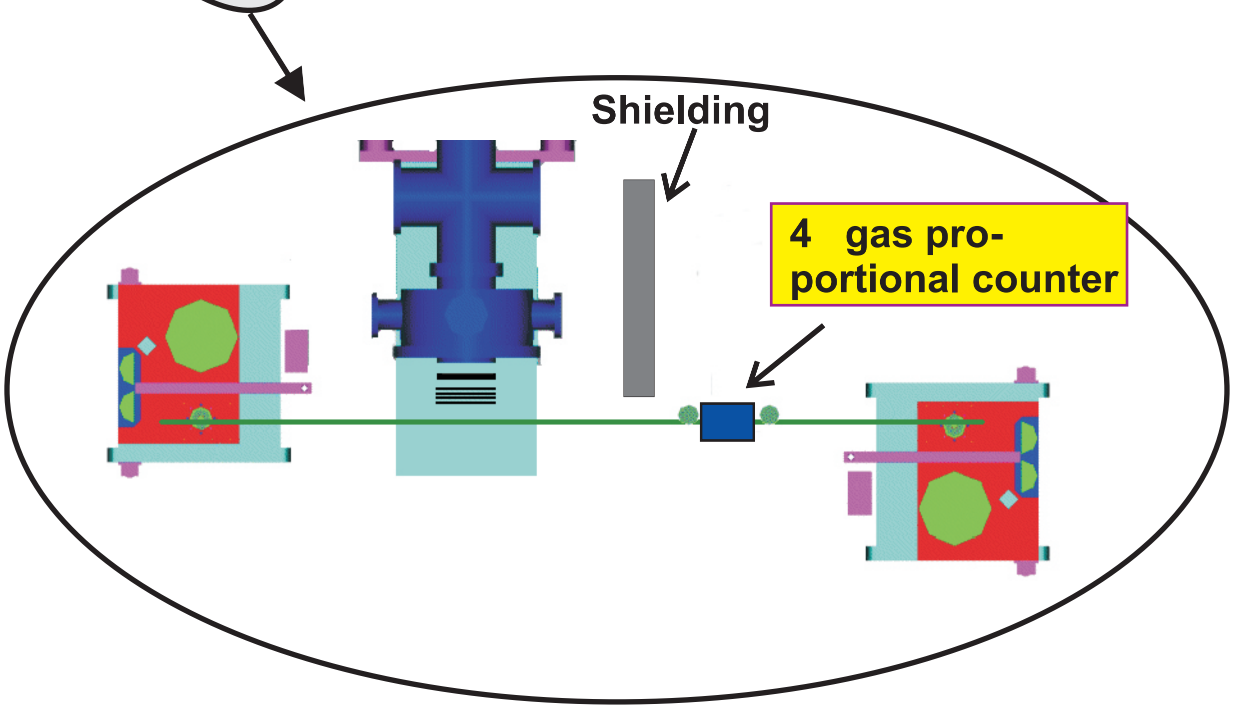
Where ground state decay occurs, we use the relation:

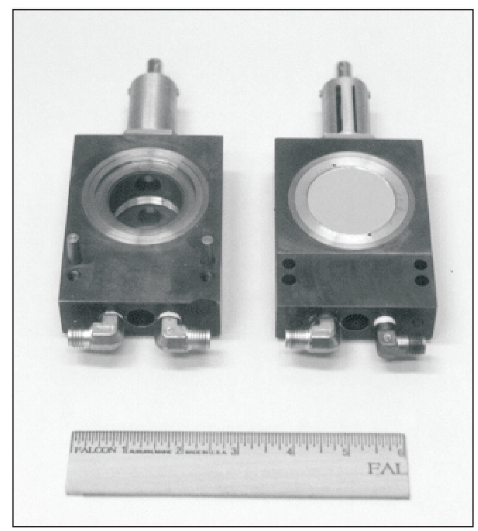
$$\frac{n}{n} = \frac{N_0 \quad\quad BR]}{N_0}$$

$$BR] = \frac{n}{n}$$

PRECISION HALF-LIFE MEASUREMENTS AT TAMU



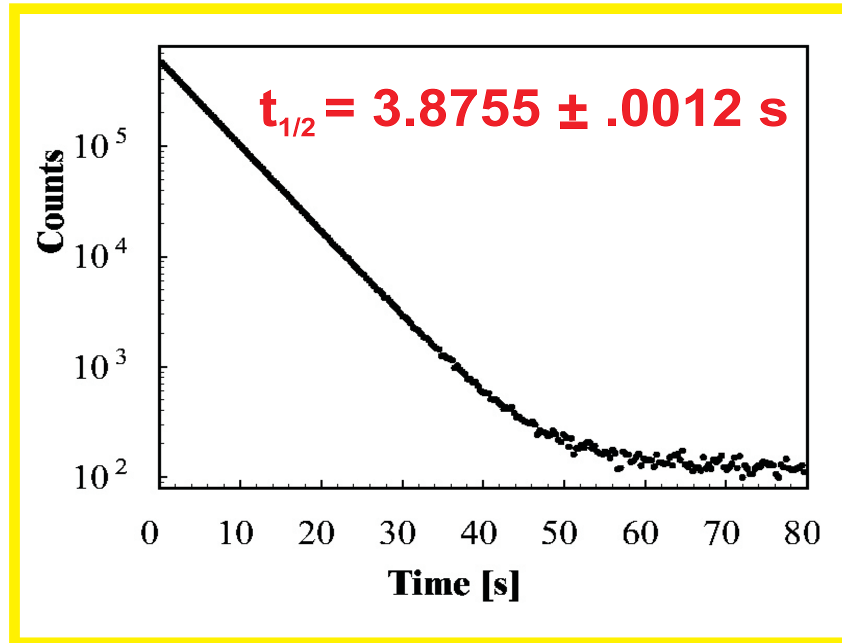


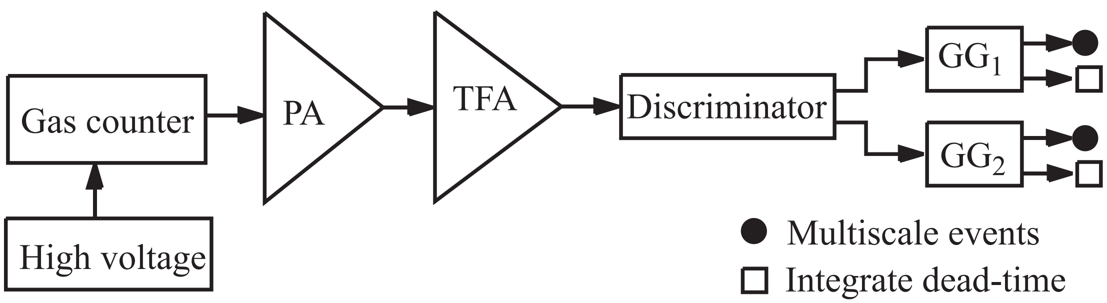


HALF-LIFE RESULTS

IMPORTANT FEATURES

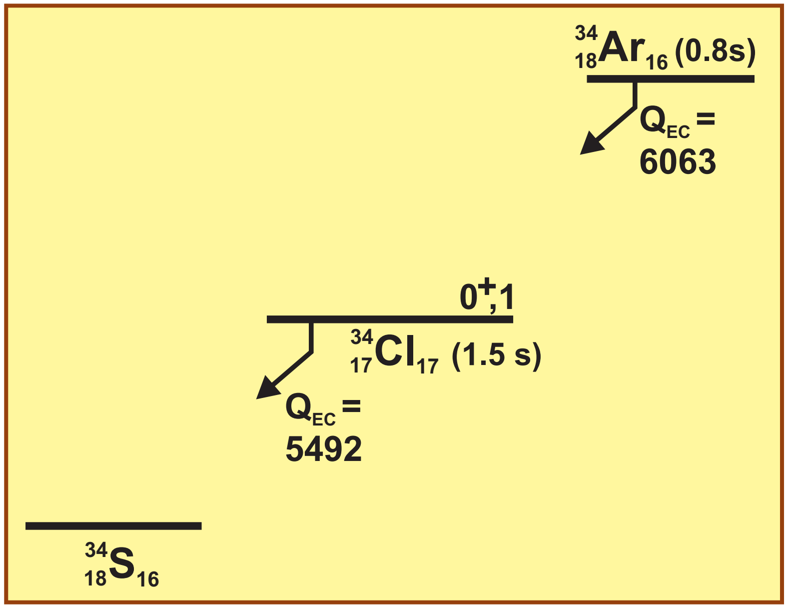
- Extremely high source purity -- separation by Z/A and range.
- Very low background
- Rapid transport (130 ms) to shielded counting position.
- Dominant dead-time, fixed and measured.





- Decay data stored cycle-by-cycle so actual instantaneous rate can be used in analysis.
- Precise statistical procedures used, all tested with Monte Carlo simulated data matched to actual experimental conditions.

HALF-LIFE RESULTS – A MORE DIFFICULT CASE



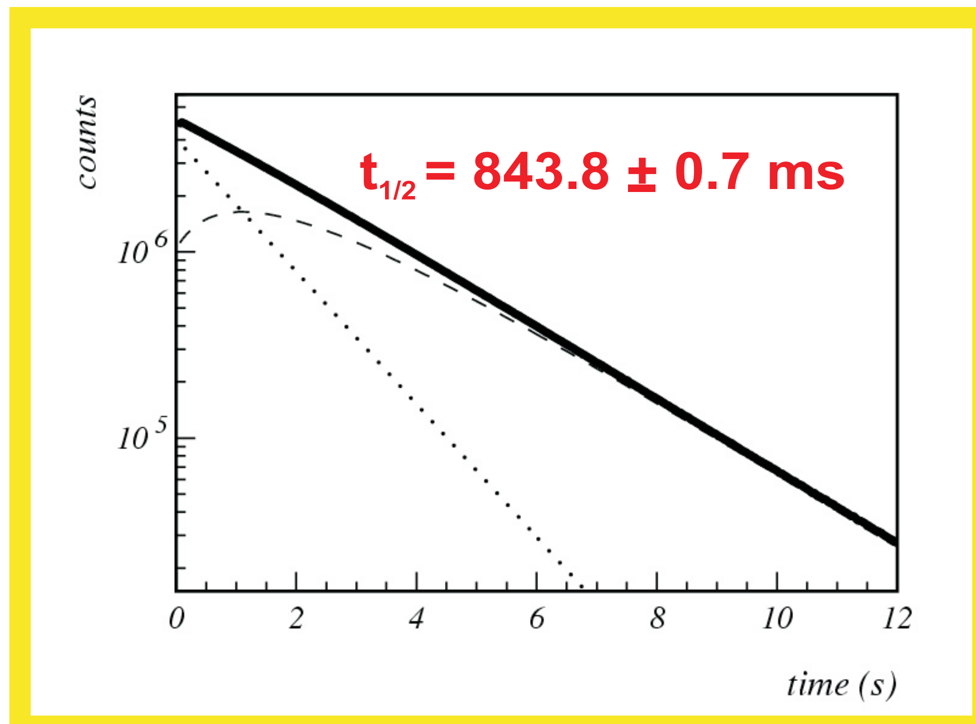
Parent and daughter have comparable half-lives and are indistinguishable with detector.

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

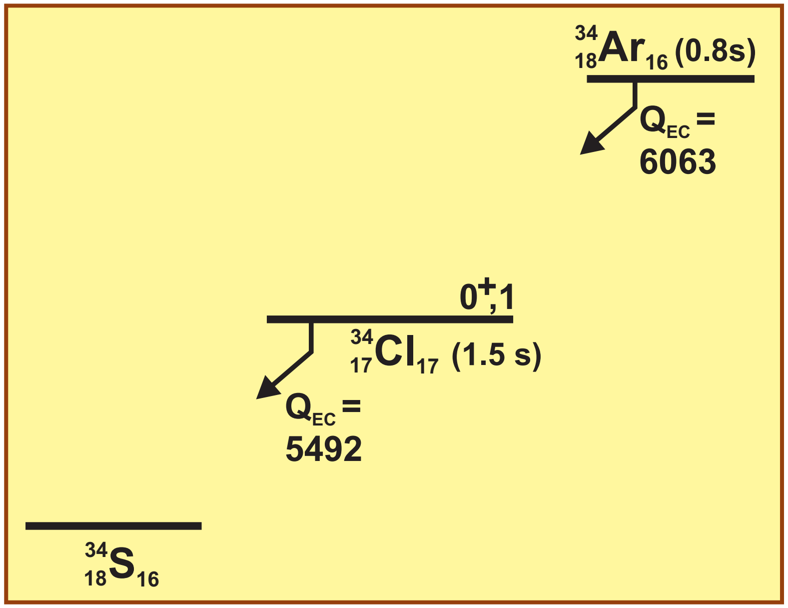
where

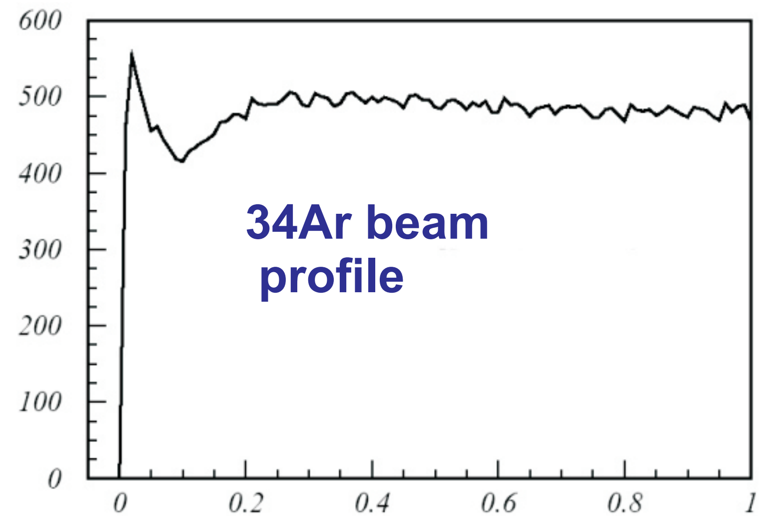
$$C_1 = N_1 \ _1 \frac{2 \ _2 - \ _1}{_2 - \ _1}$$

$$C_2 = N_2 \frac{N_1 \ _1}{_2 - \ _1}$$



HALF-LIFE RESULTS – A MORE DIFFICULT CASE



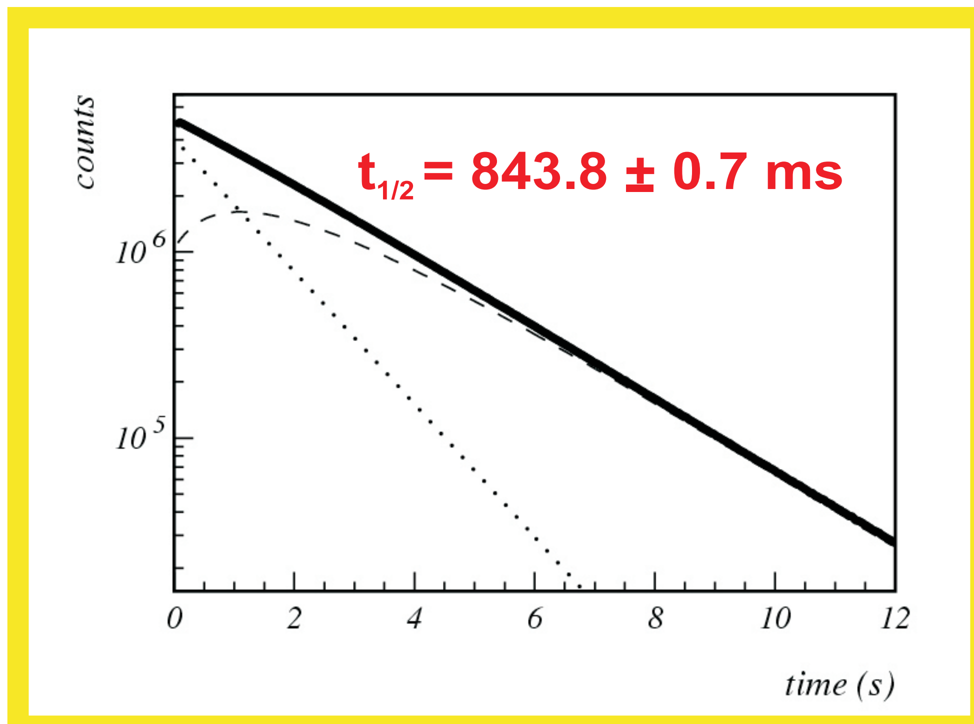


$$_{tot} = C_1 e^{-\,_1 t} + C_2 e^{-\,_2 t}$$

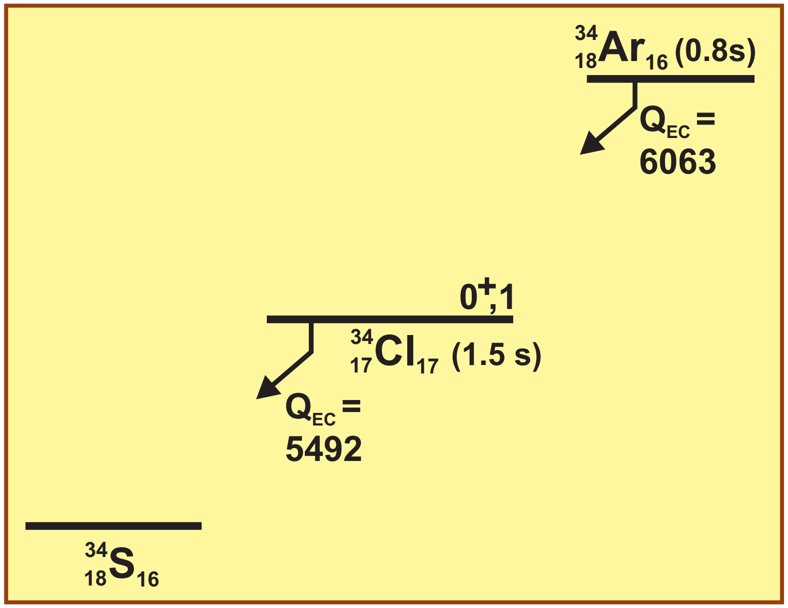
where

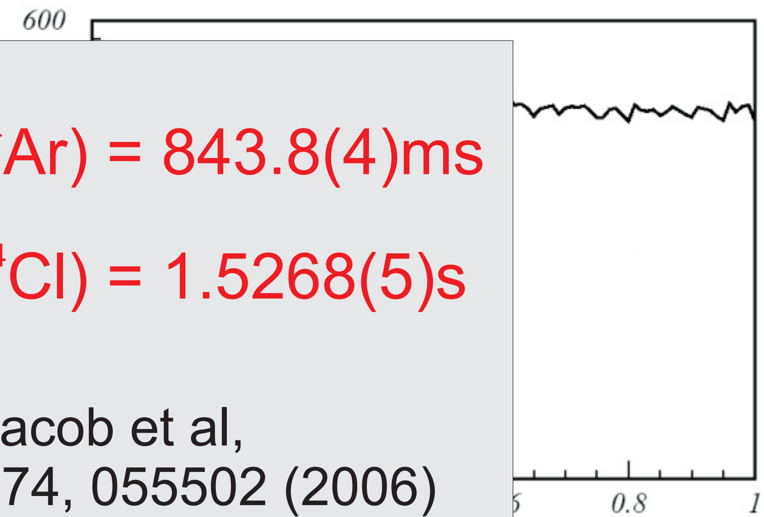
$$C_1 = N_1 \;_1 \frac{2 \;_2 - \;_1}{_2 - \;_1}$$

$$C_2 = N_2 \frac{N_1 \;_1}{_2 - \;_1}$$



HALF-LIFE RESULTS – A MORE DIFFICULT CASE





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

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

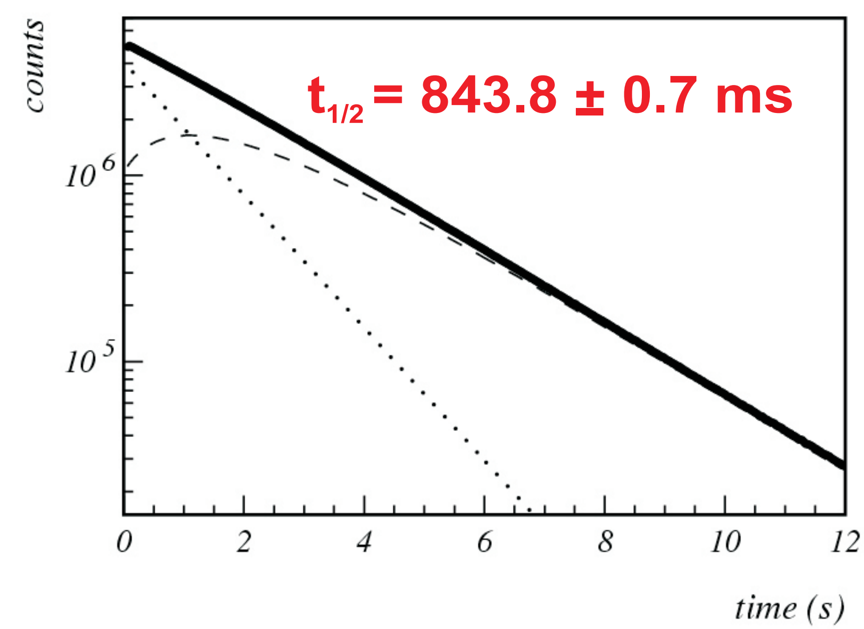
V.E. Iacob et al,
PRC 74, 055502 (2006)

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

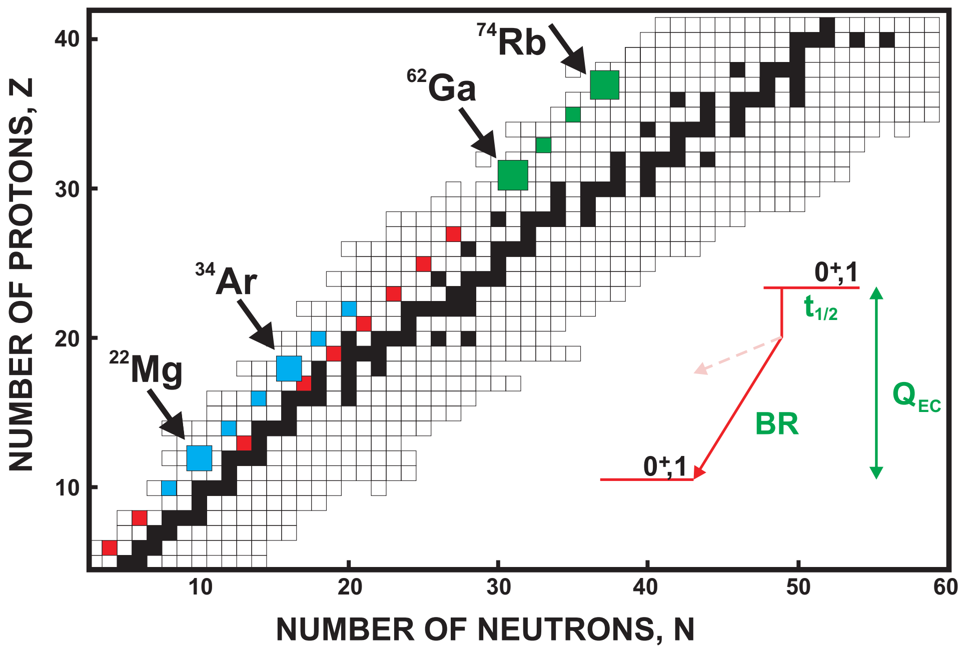
where

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

$$C_2 = N_2 \frac{N_1 \ _1}{_2 - \ _1}$$

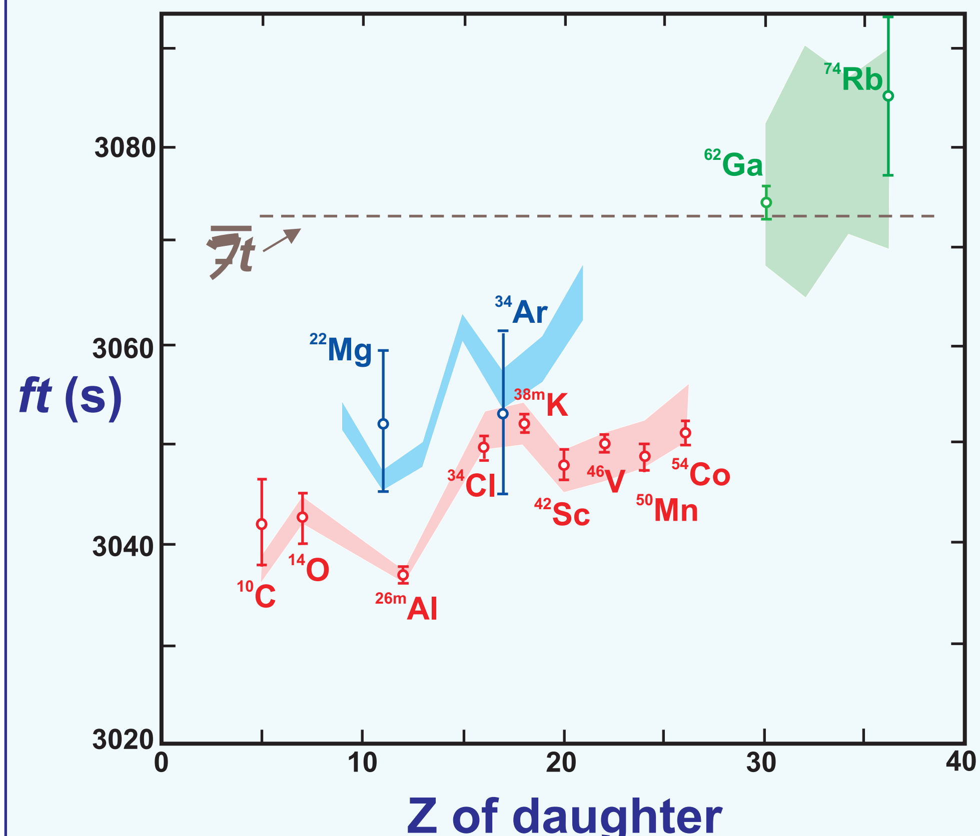


CURRENT DIRECTION OF NUCLEAR EXPERIMENTS



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

Calculated *ft*-value = $\frac{\overline{\mathcal{F}t}}{(1 + {}'_{R})[1 - ({}_{C} - {}_{NS})]}$



* **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)**

SUMMARY

1. CKM unitarity is currently satisfied to within 0.06%.

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99995(61)$$

0.9491(4)   0.0508(4) <0.0001

2. This result already sets tight limits on "new physics" beyond the standard model: for example right-hand currents and extra Z bosons.
3. Since superallowed beta decay sets the current value for V_{ud}, any improvements of those limits in the near term will likely come from that source.
4. Experimental progress is still being made towards tighter uncertainties and even more stringent tests of the weak interaction.