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

BASIC WEAK-DECAY EQUATION

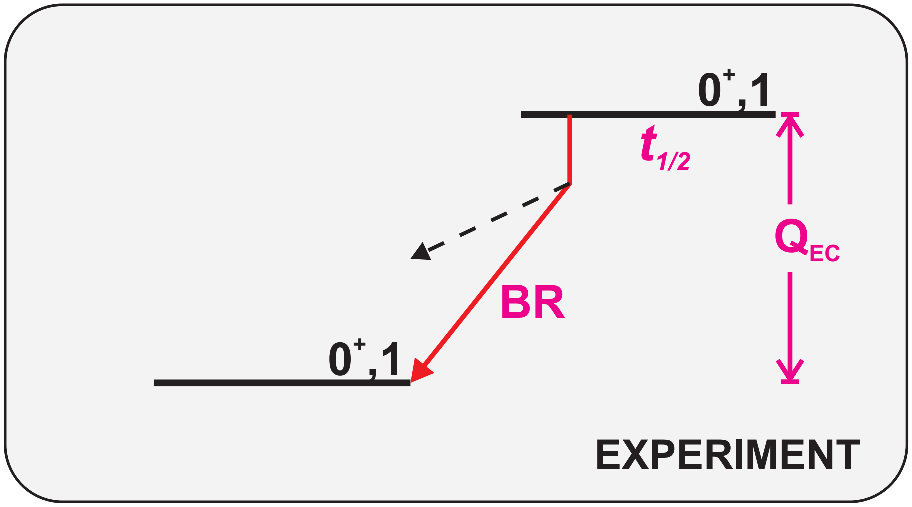
$$ft = \frac{K}{G_V^2 \langle \quad \rangle^2}$$

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



Reference: Hardy & Towner,
PRC 79, 055502 (2009)

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)
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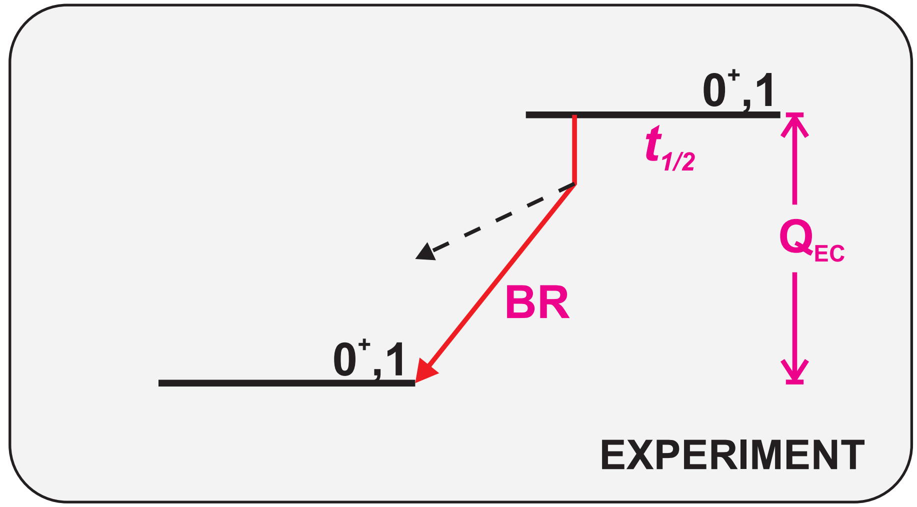


INCLUDING RADIATIVE AND ISOSPIN-SYMMETRY-BREAKING CORRECTIONS

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

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

f(nuclear structure) 0.3-1.5%

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

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

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 precis... (1 + $_R$)

Determi...

...unitarity

ONLY POSSIBLE IF PRIOR CONDITIONS SATISFIED

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

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

CKM MATRIX AND UNITARITY

CABIBBO-KOBAYASHI-MASKAWA QUARK-MIXING MATRIX

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

weak eigenstates (left vector); mass eigenstates (right vector)

THREE-GENERATION UNITARITY

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

Reference: Berennger *et al*. [PDG], PRD **86**, 010001 (2012)

CKM MATRIX AND UNITARITY

CABIBBO-KOBAYASHI-MASKAWA QUARK-MIXING MATRIX

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

weak eigenstates

mass eigenstates

This is the most demanding test available!

THREE-GENERATION UNITARITY

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

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

nuclear (n &) decays

muon decay

$K^+ \longrightarrow {}^0 e^+ {}_e$

$K_L^0 \longrightarrow {}^{\pm} e^{\mp} {}_e$

0.0507(4)

B decays

0.000015

WHAT PRECISION IS NEEDED?

$$1 - V_{us}^2 - V_{ub}^2 = 0.9493(4)$$

< 0.05%

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: **< 0.05%**

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

Required from experiment:

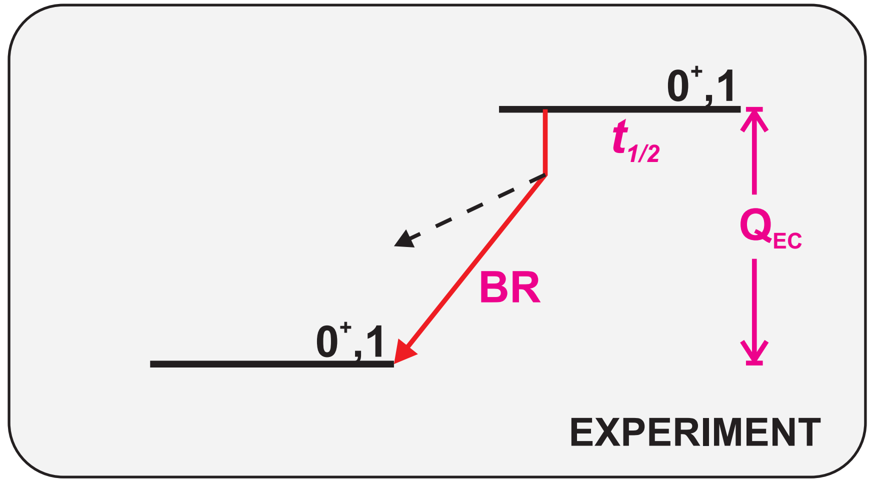
$t = t_{1/2}\,/BR$

Precision for t **0.05%**

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

Precision for Q **0.01%**

200eV – 1keV

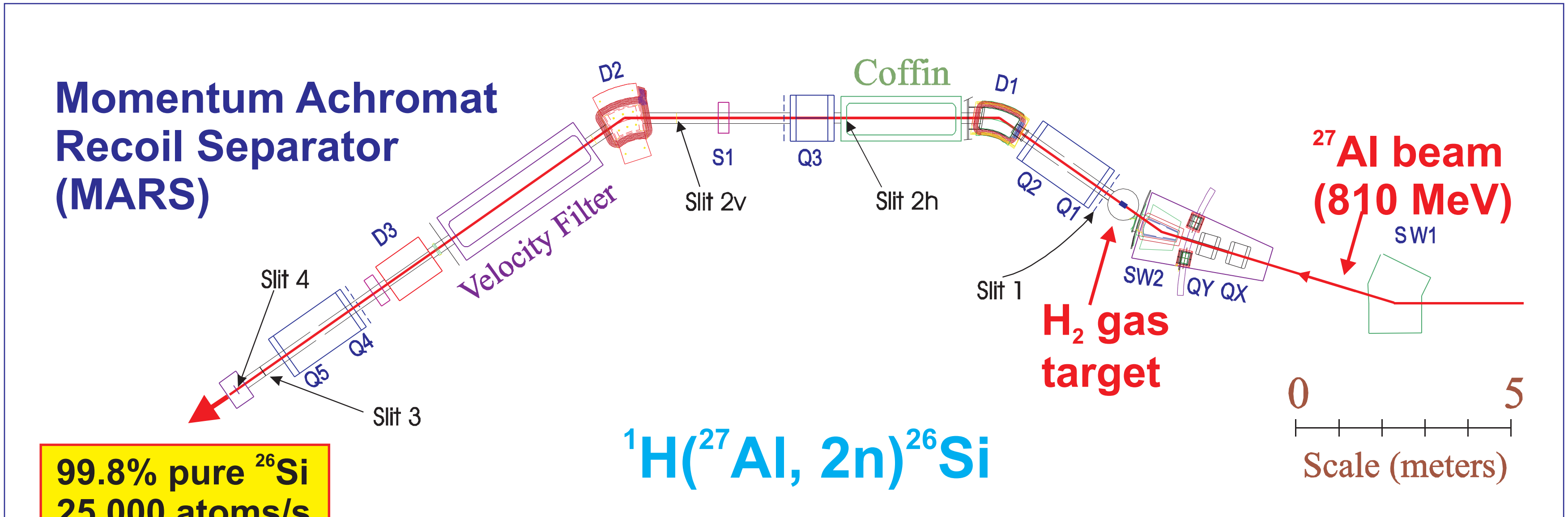


By the usual nuclear physics standards, these are very challenging requirements!

GUIDELINES FOR PRECISION MEASUREMENTS

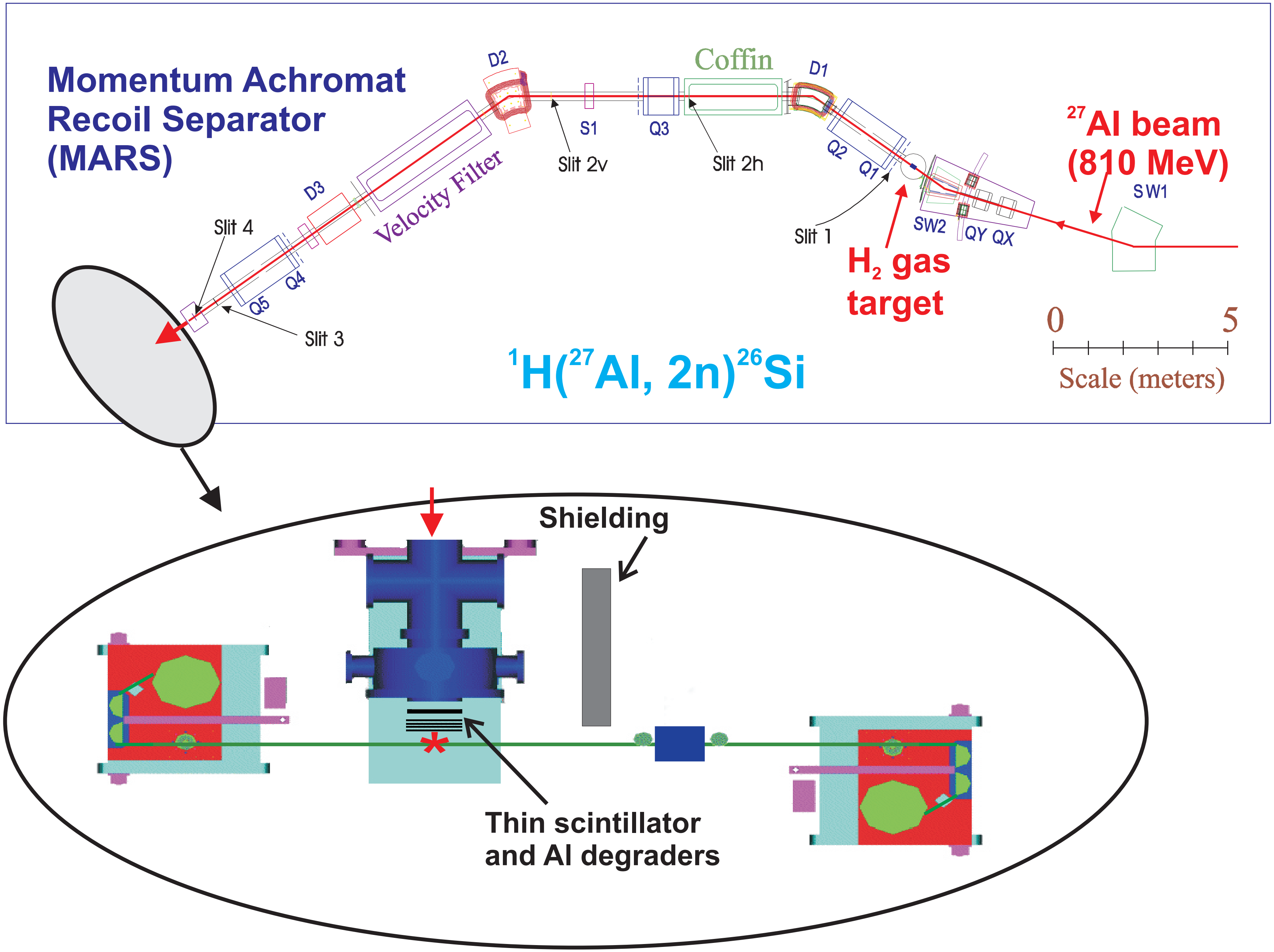
- Experimental apparatus should be as simple as possible.
- All experimental parameters must be under control and testable.
- Experimental equipment should be dedicated only to this measurement.
- Calibration is often the most important part of the measurement.
- Tests for sources of systematic error 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.

PRECISION DECAY MEASUREMENTS AT TAMU

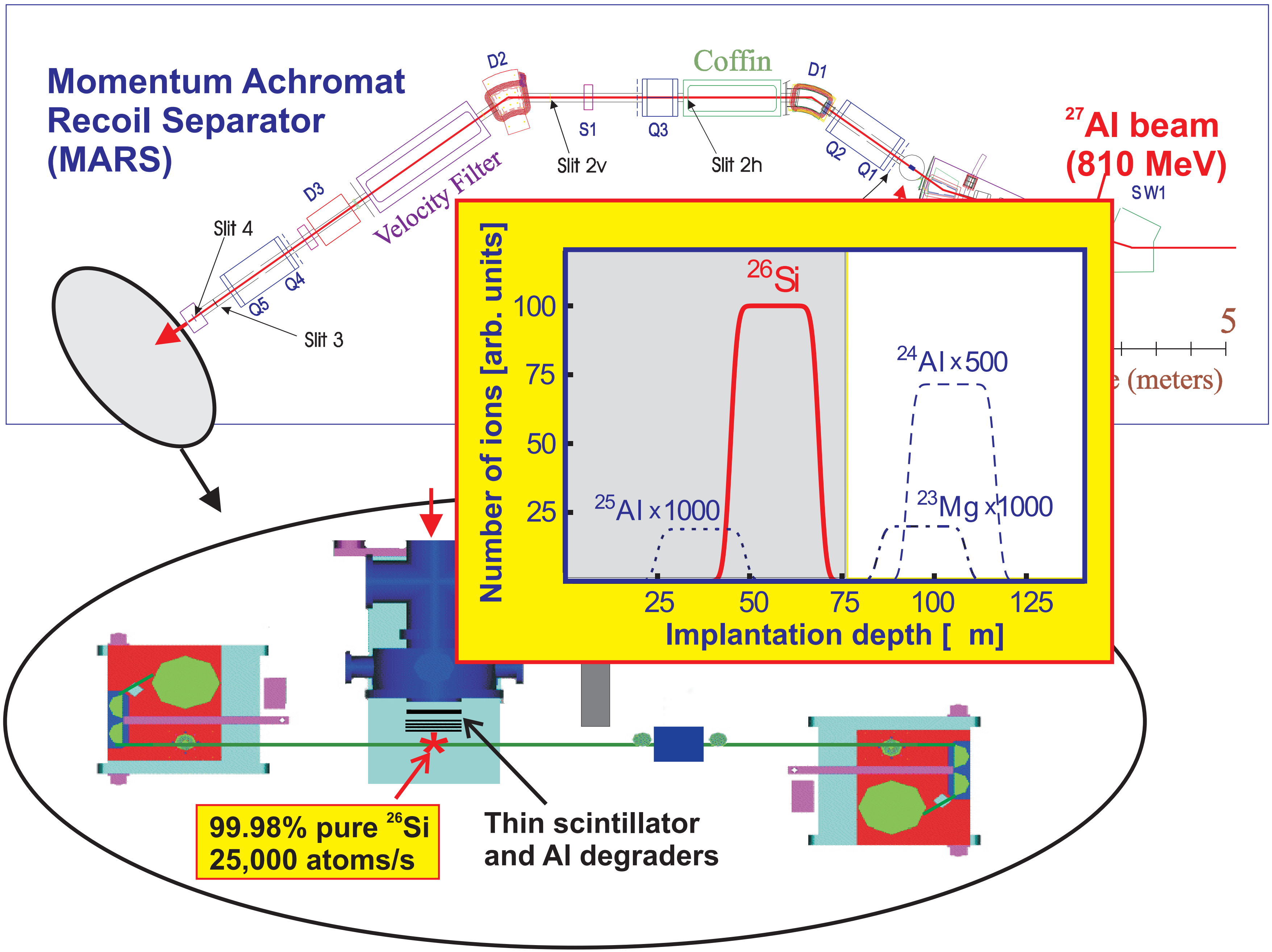


99.8% pure ^{26}Si
25,000 atoms/s

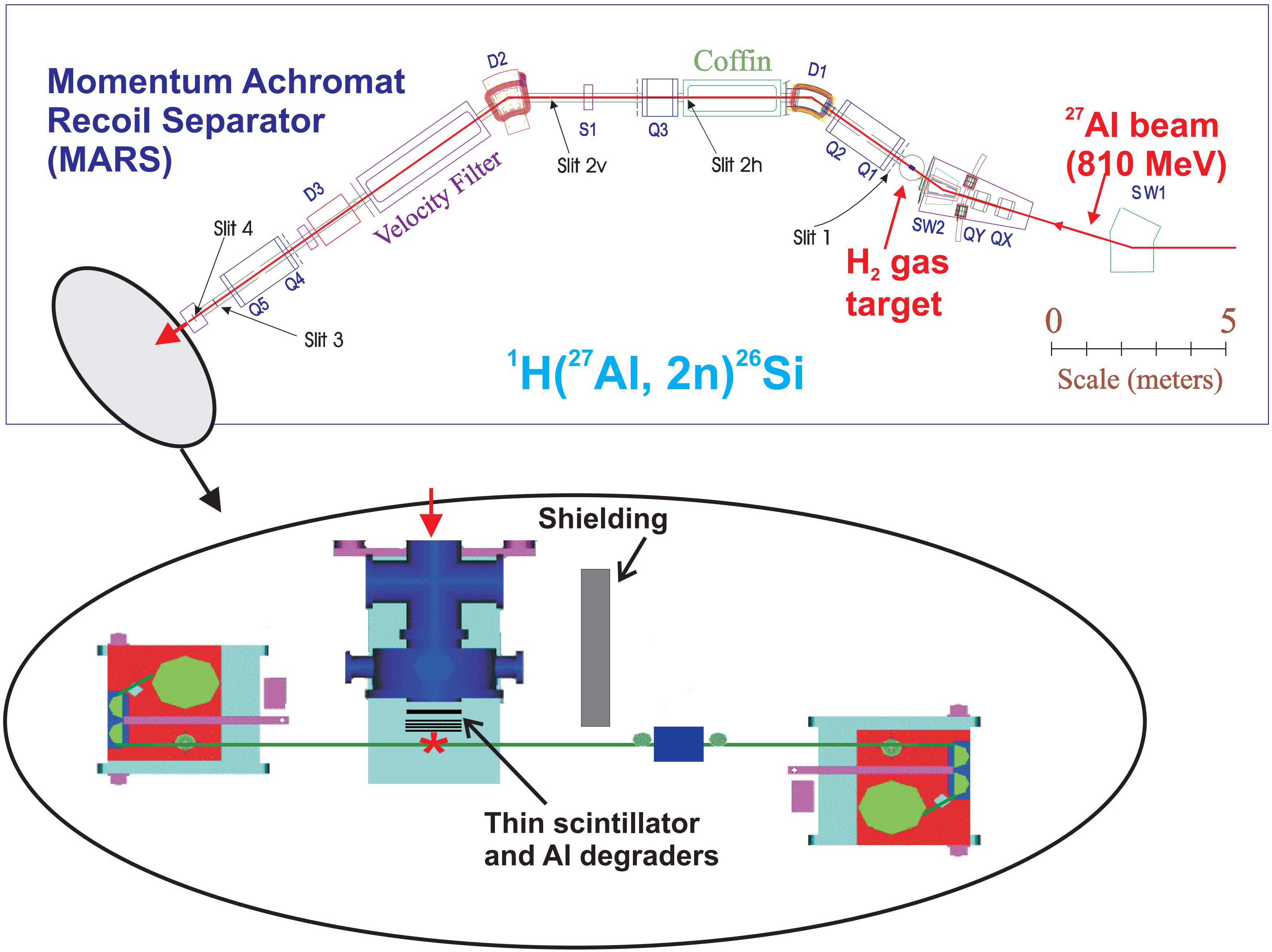
PRECISION DECAY MEASUREMENTS AT TAMU



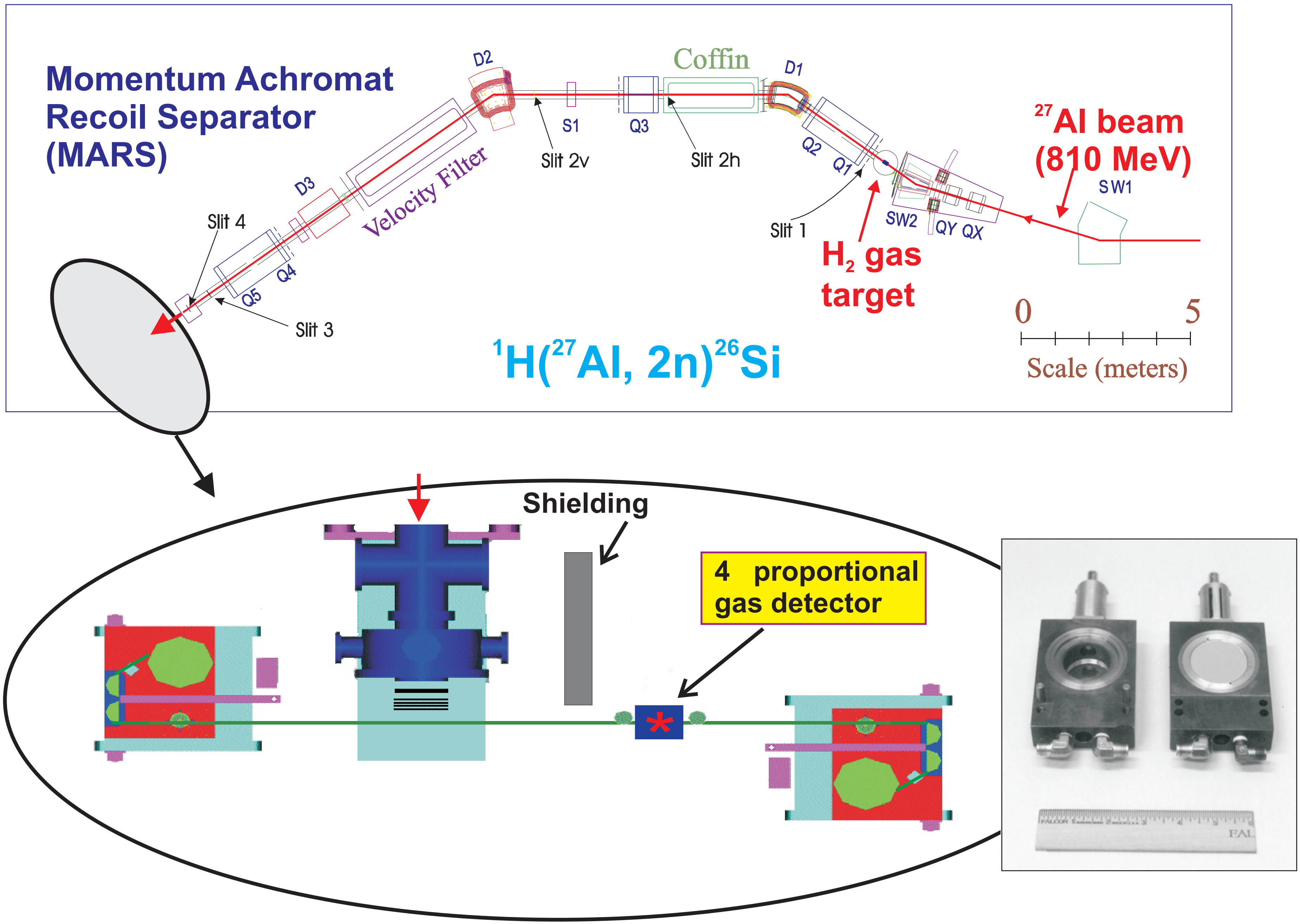
PRECISION DECAY MEASUREMENTS AT TAMU



PRECISION DECAY MEASUREMENTS AT TAMU



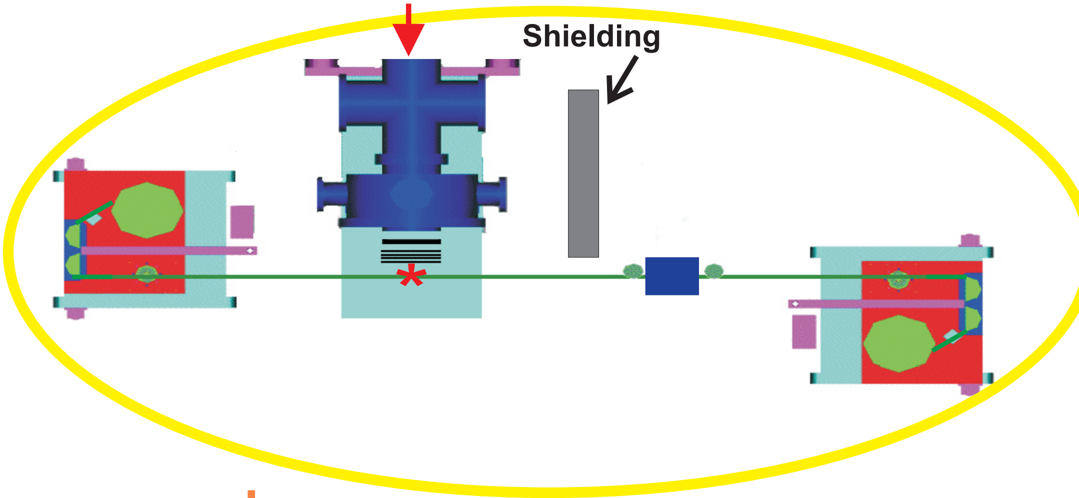
PRECISION DECAY MEASUREMENTS AT TAMU



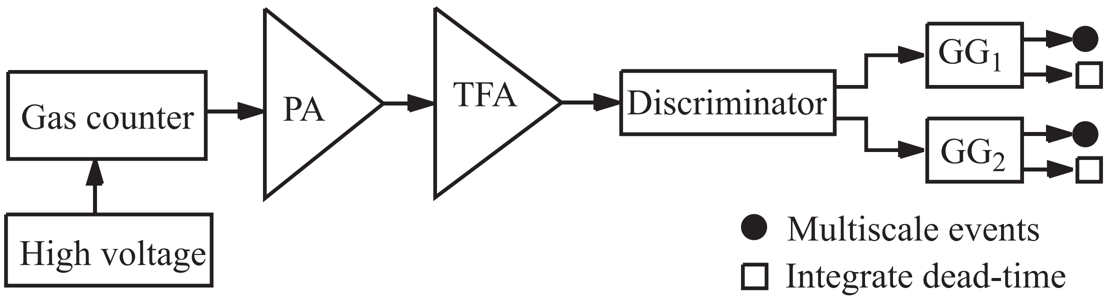
REQUIREMENTS FOR PRECISE HALF-LIFE MEASUREMENT

IMPORTANT FEATURES

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

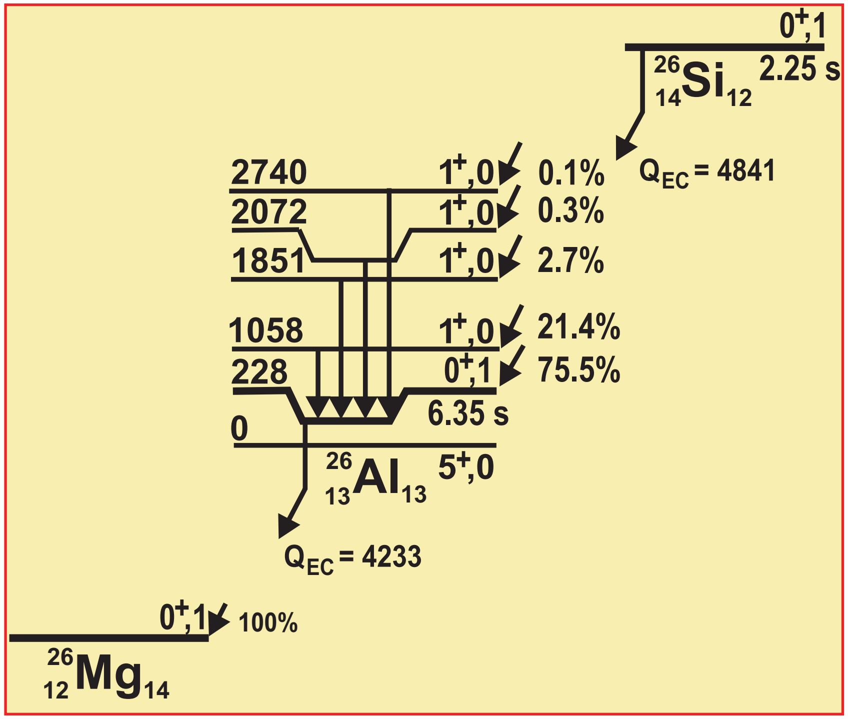


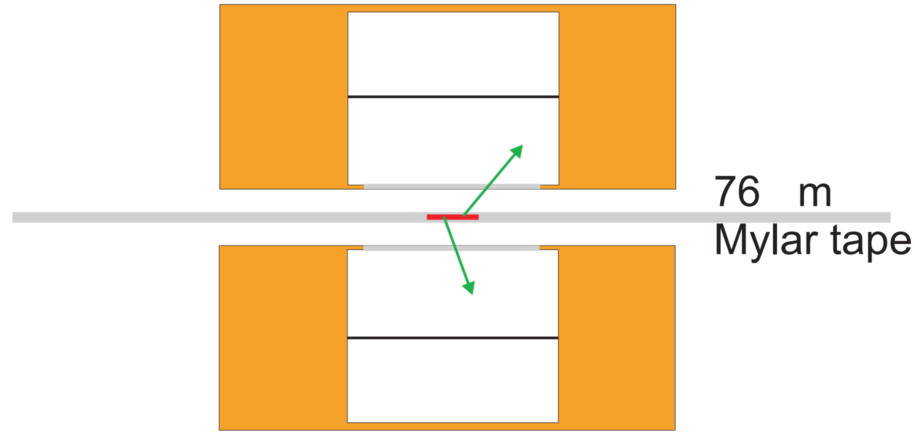
- Dominant dead-time, fixed and measured.

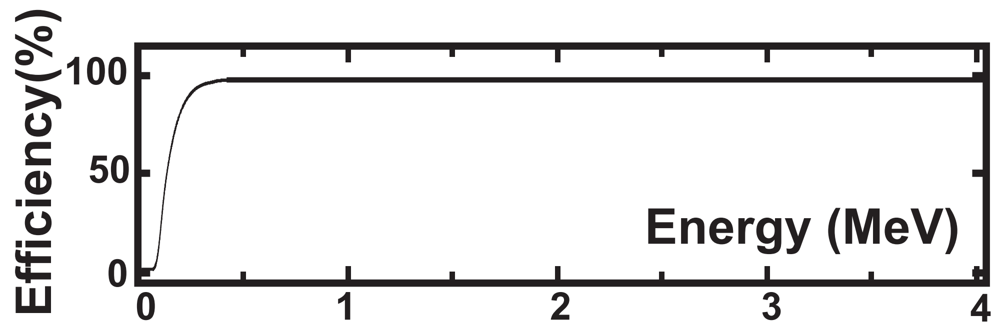


- Repeated measurements under different experimental conditions.
- Decay data stored cycle-by-cycle so actual instantaneous rate can be used in analysis.
- Precise statistical procedures used, including simultaneous fit to many cycles with single half-life.

HALF LIFE OF ^{26}Si





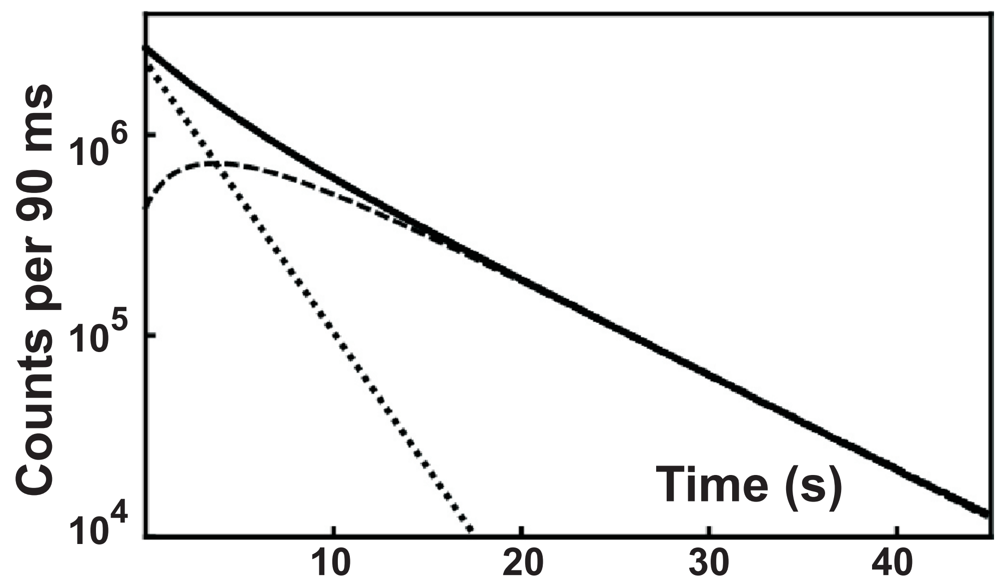


$$_{tot} = C_1 e^{\ _1 t} + C_2 e^{\ _2 t}$$

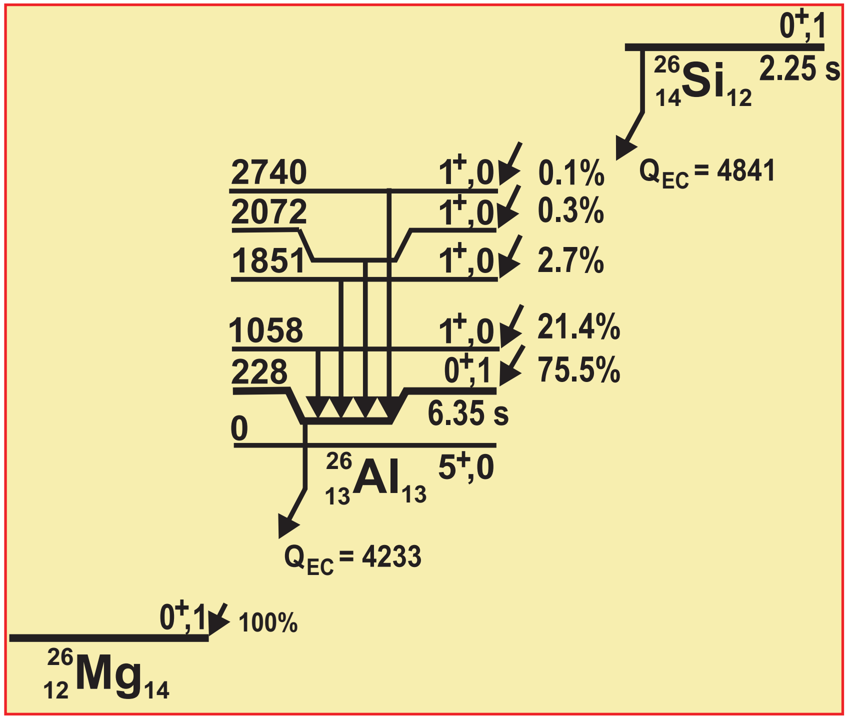
where

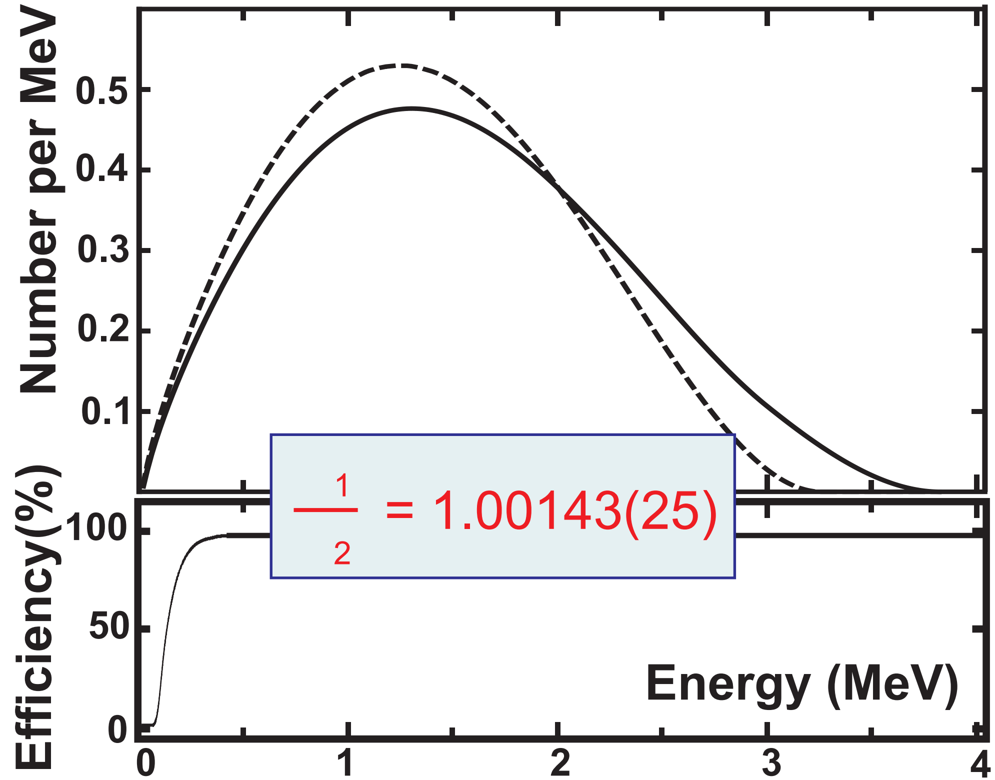
$$C_1 = N_1 \ _1 \left(\frac{1}{2} - \frac{2}{1 - 2} \right)$$

$$C_2 = N_1 \ _2 \ _2 \left(\frac{N_2}{N_1} + \frac{1}{1 - 2} \right)$$



HALF LIFE OF ^{26}Si





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

where

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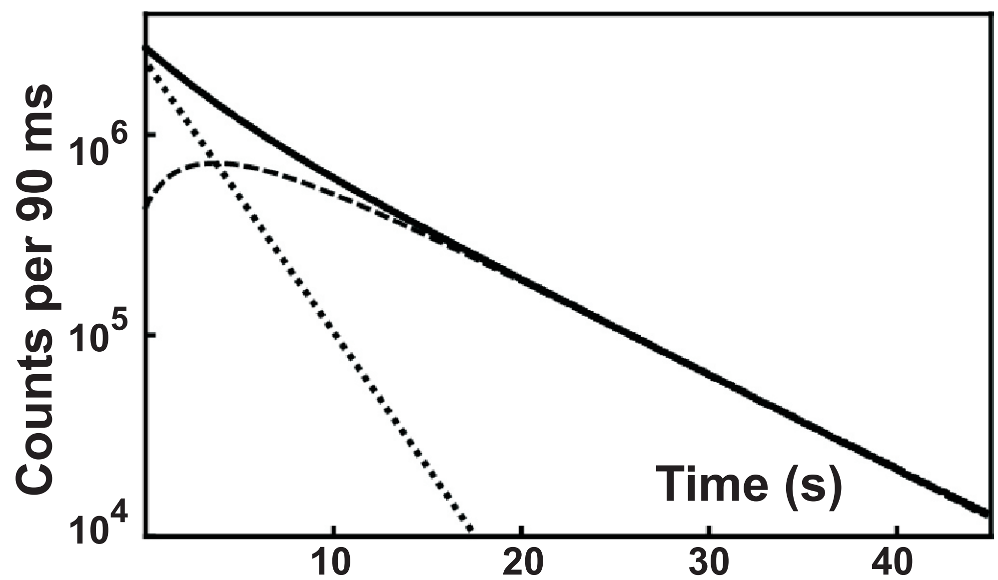
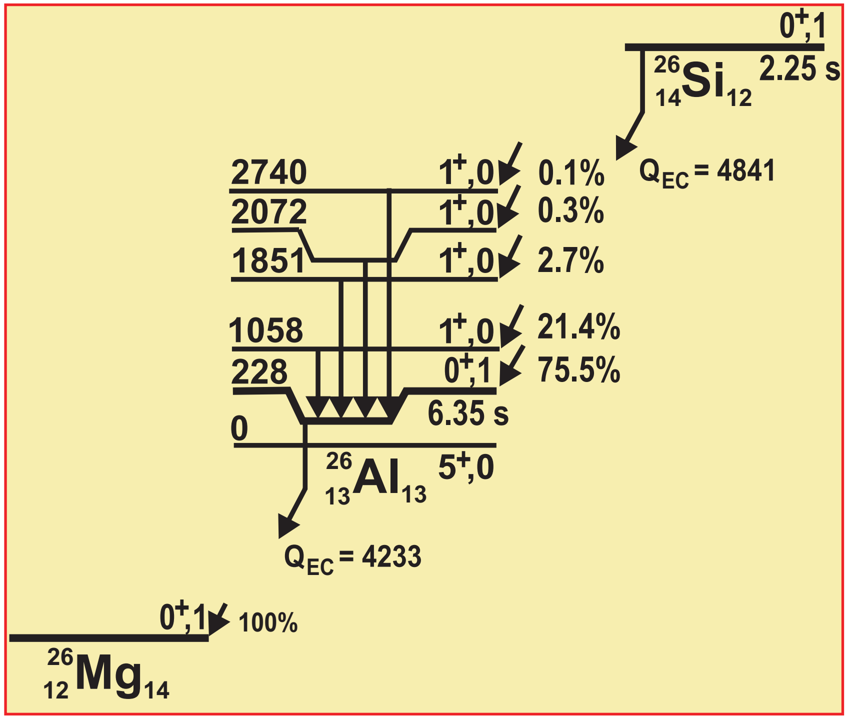
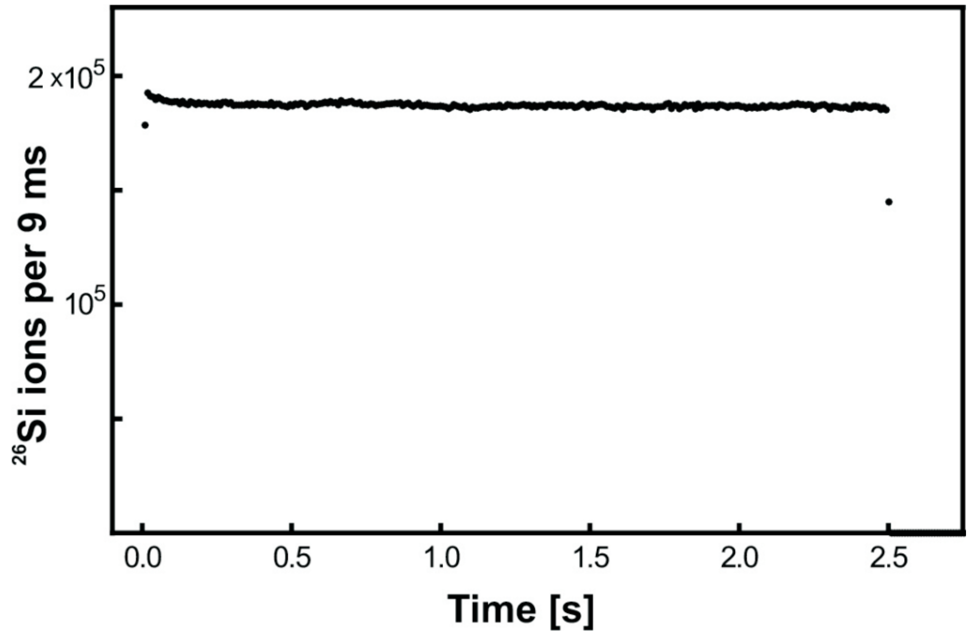
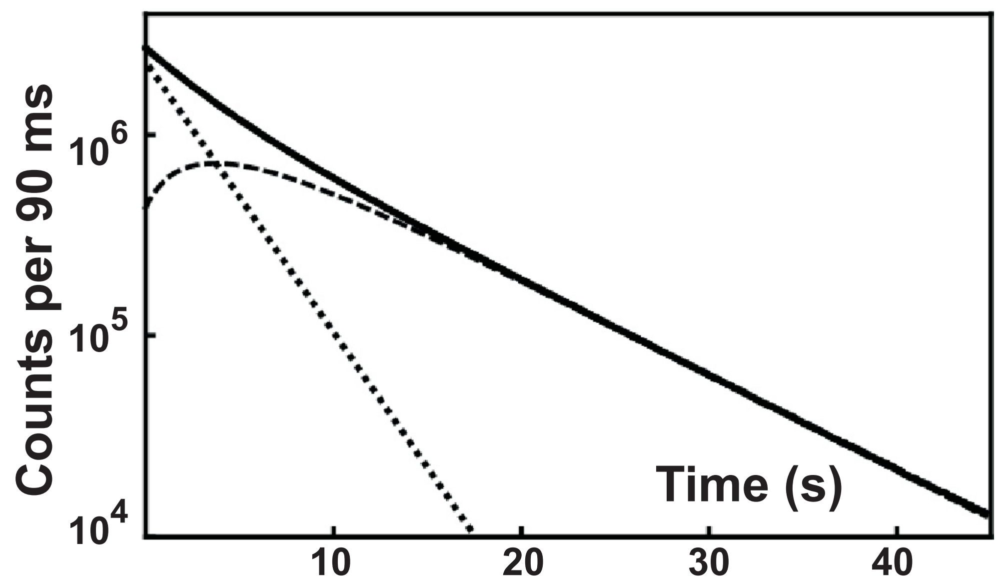


HALF LIFE OF ^{26}Si





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



where

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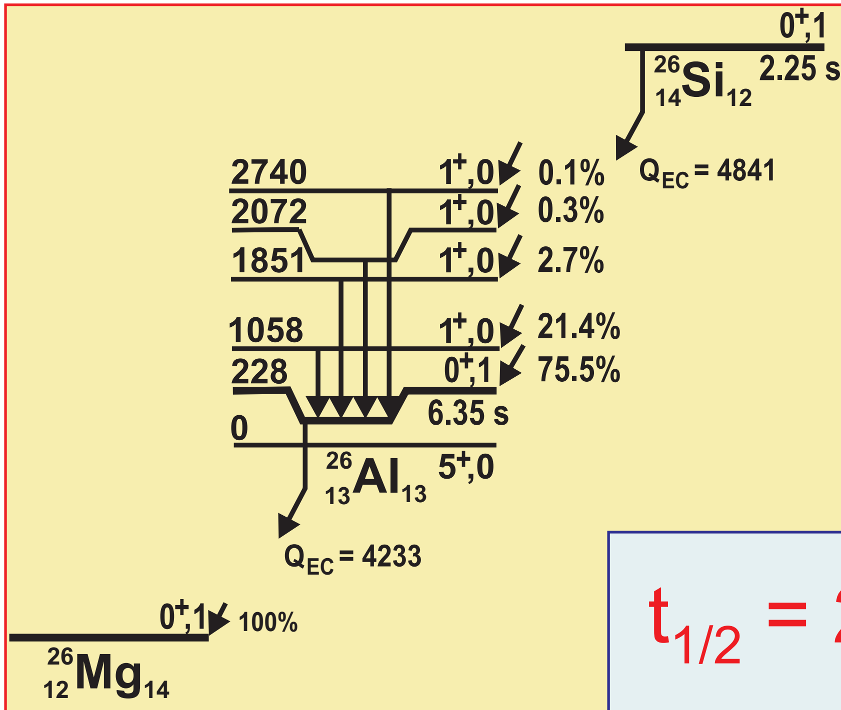
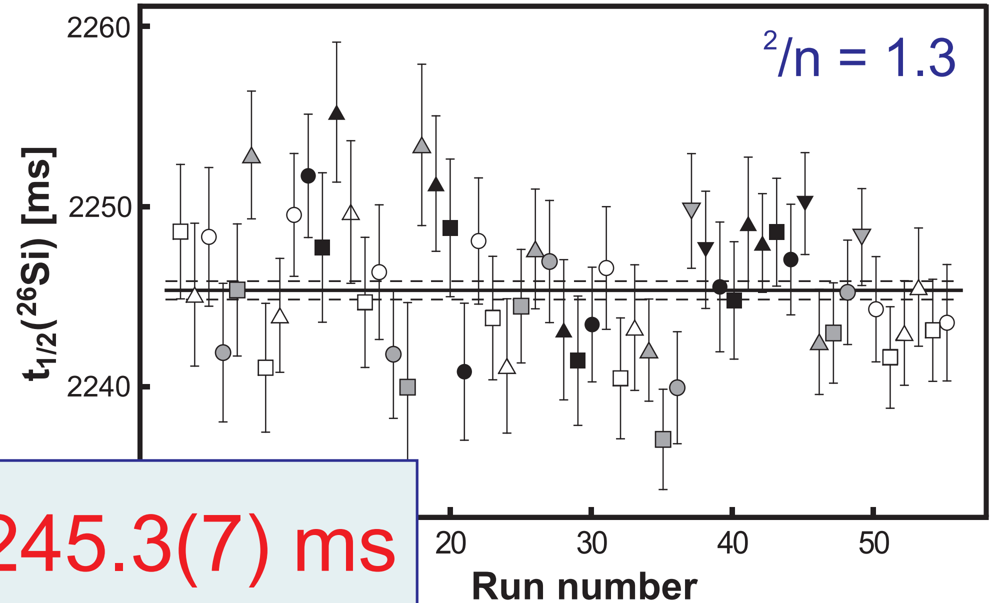
HALF LIFE OF ^{26}Si





$t_{1/2}$ = 2245.3(7) ms

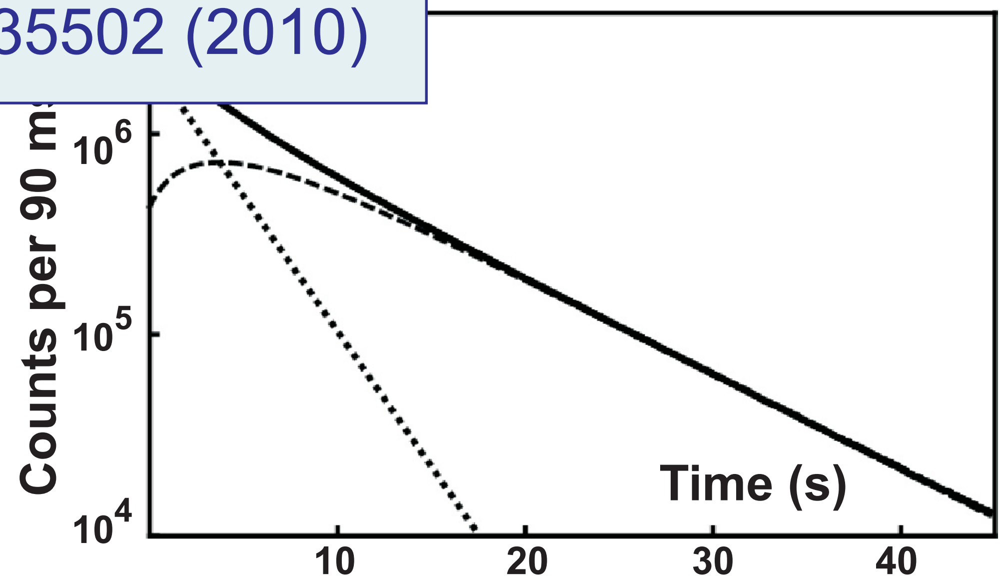
Iacob *et al.*, PRC **82**, 035502 (2010)

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

where

$$C_1 = N_1 \quad {}_1 \left(\frac{1}{2} - \frac{2}{1 - \quad 2} \right)$$

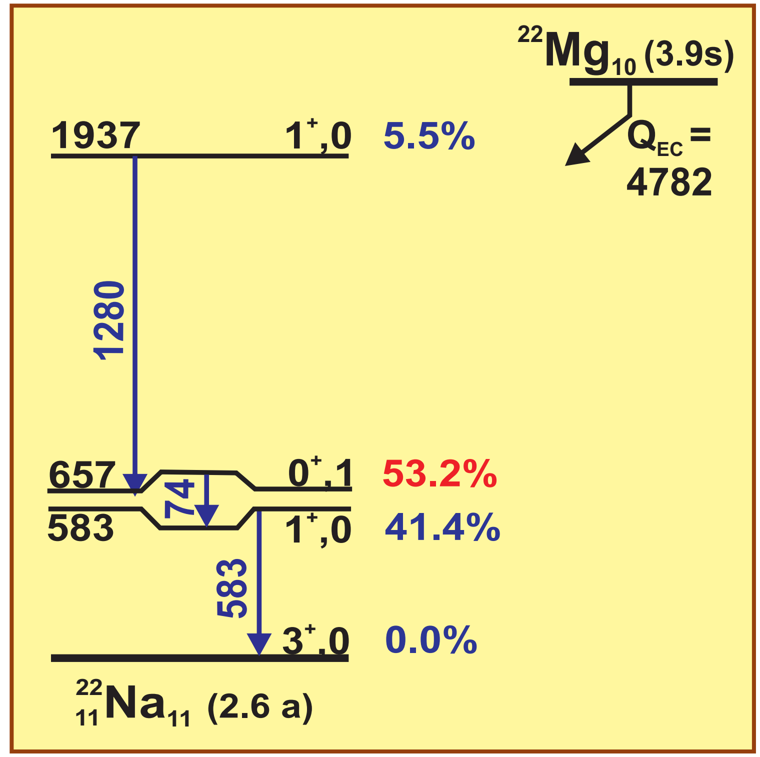
$$C_2 = N_1 \ {}_2 \ {}_2 \left(\frac{N_2}{N_1} + \frac{1}{1 - \quad 2} \right)$$



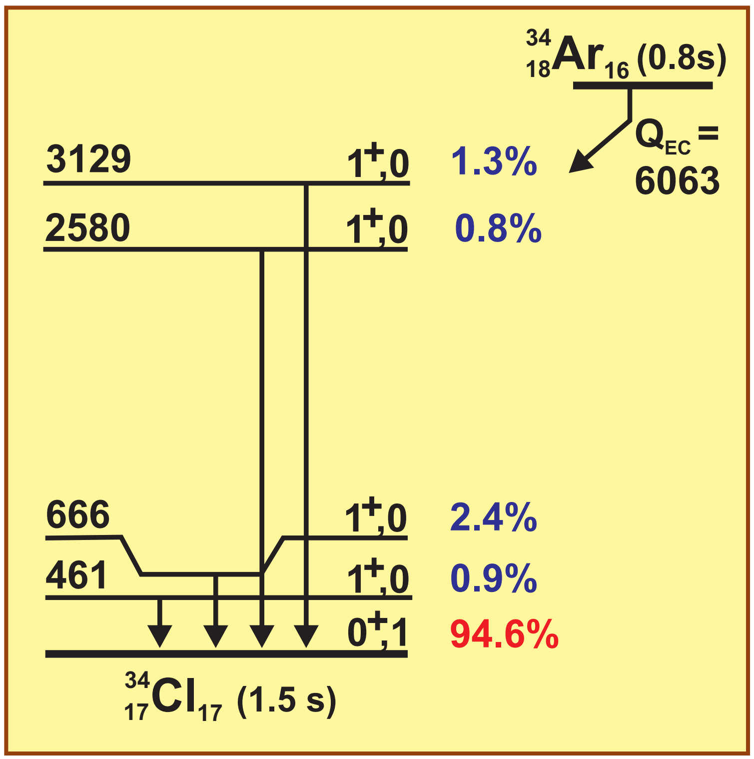
BRANCHING-RATIO MEASUREMENTS

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

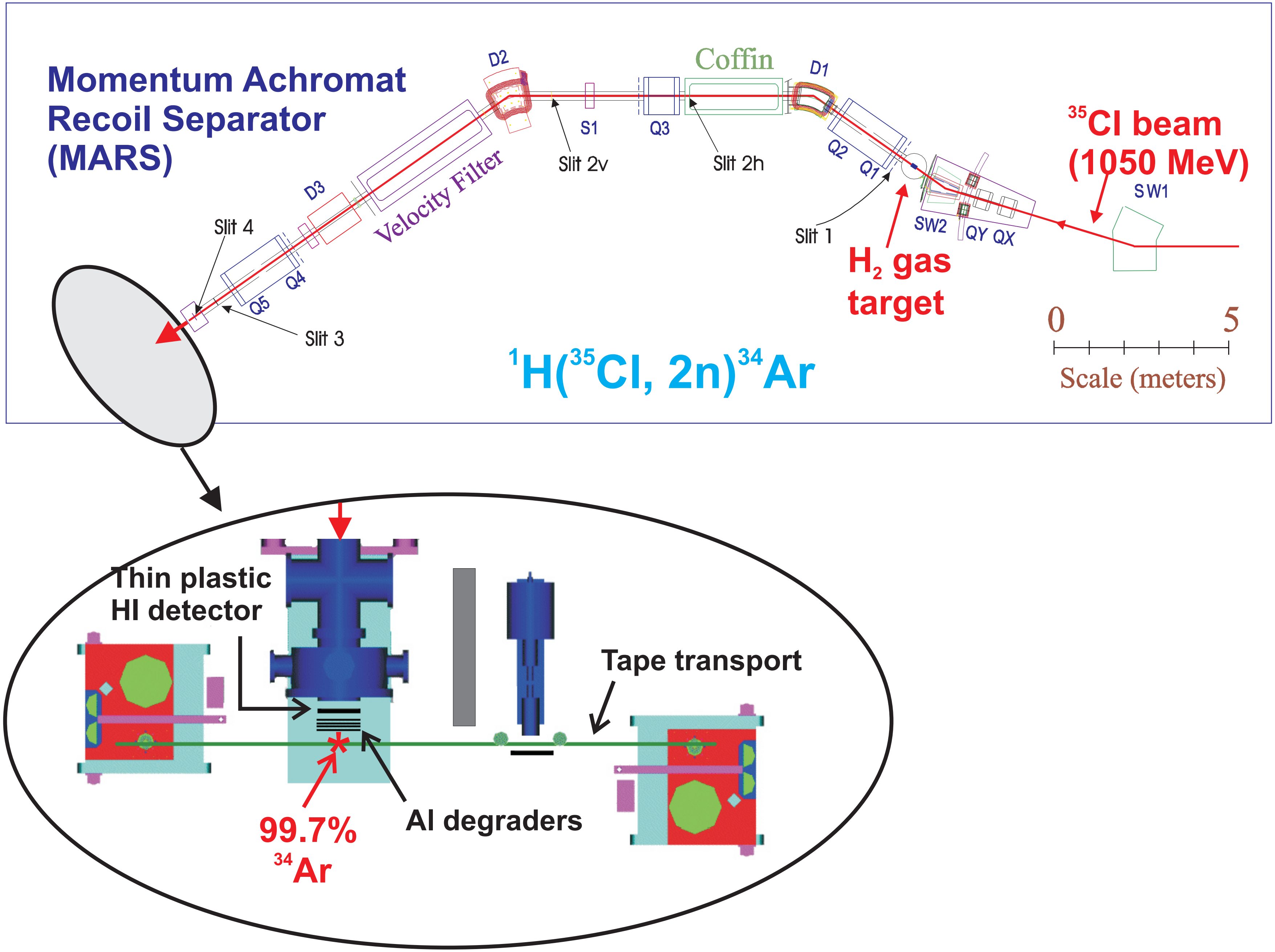
Relative intensities



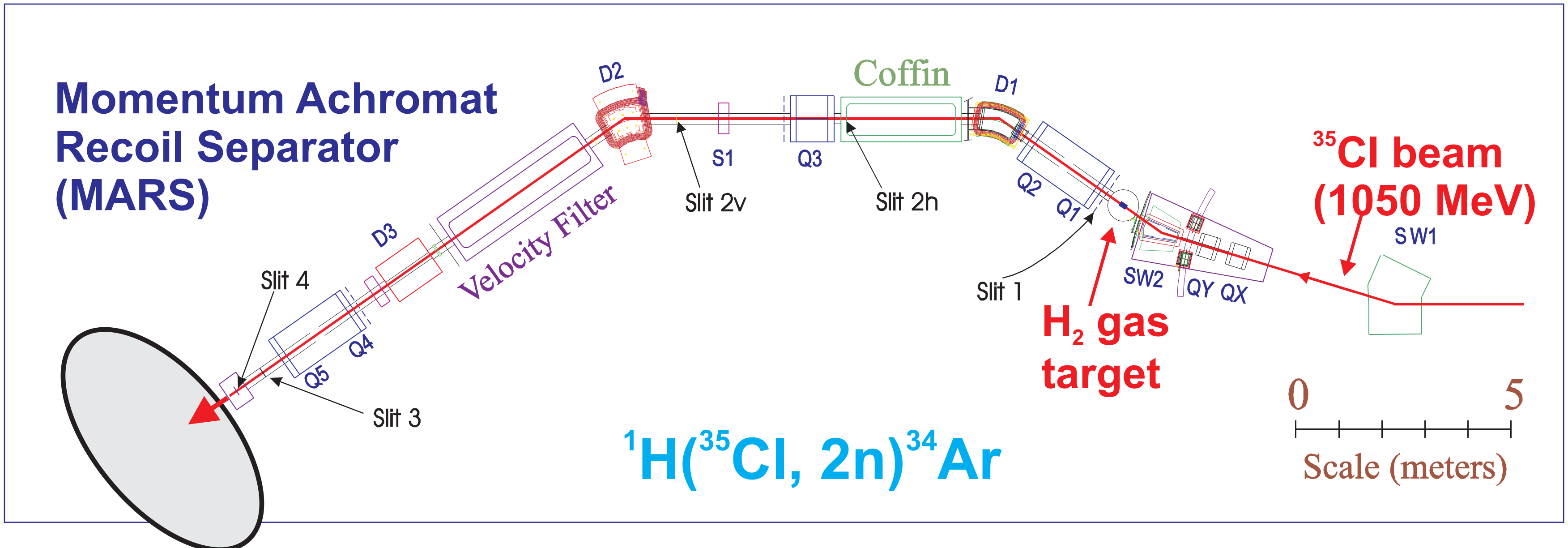
Absolute intensities

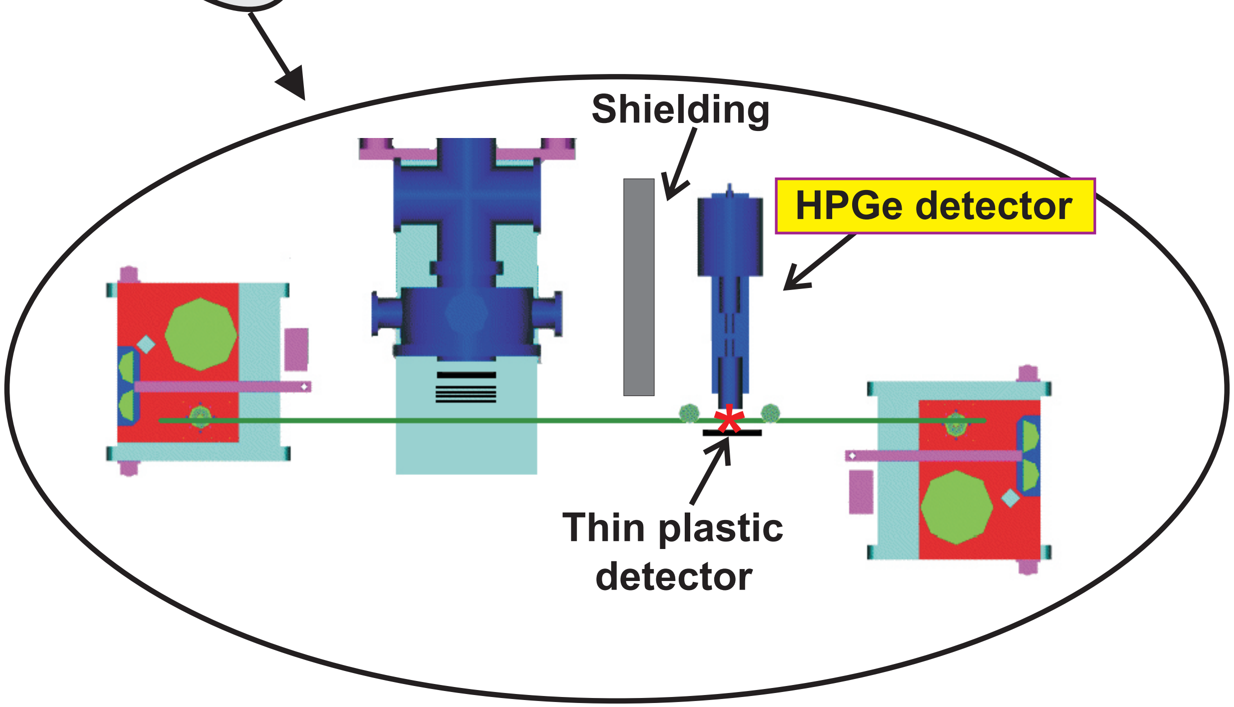


PRECISION DECAY MEASUREMENTS AT TAMU



PRECISION DECAY MEASUREMENTS AT TAMU





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:

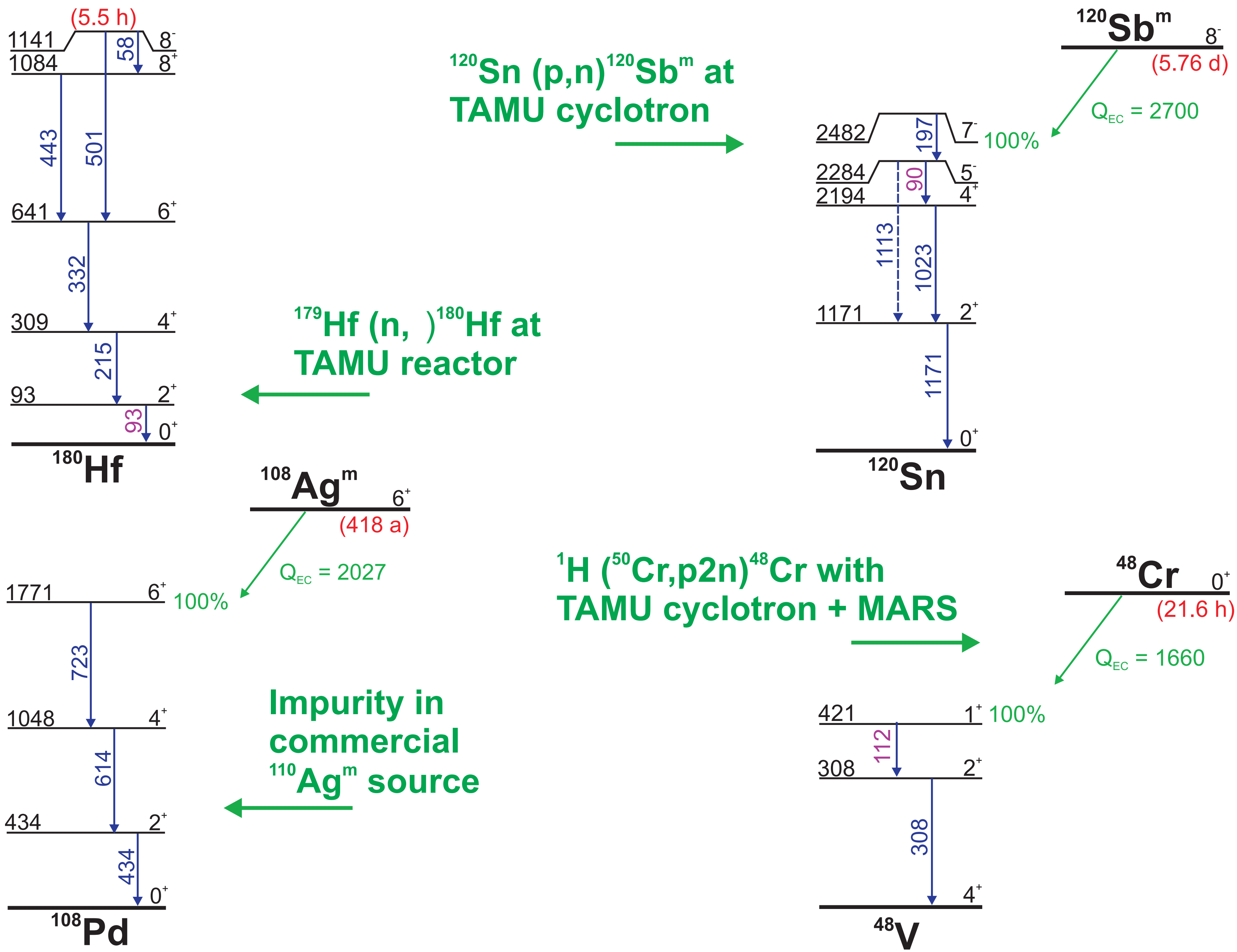
Source activity for certain cases can be measured to 0.1% by 4 coincidence counting; in our case ^{60}Co at PTB Lab.

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

Use clean -ray cascades; home-made sources.

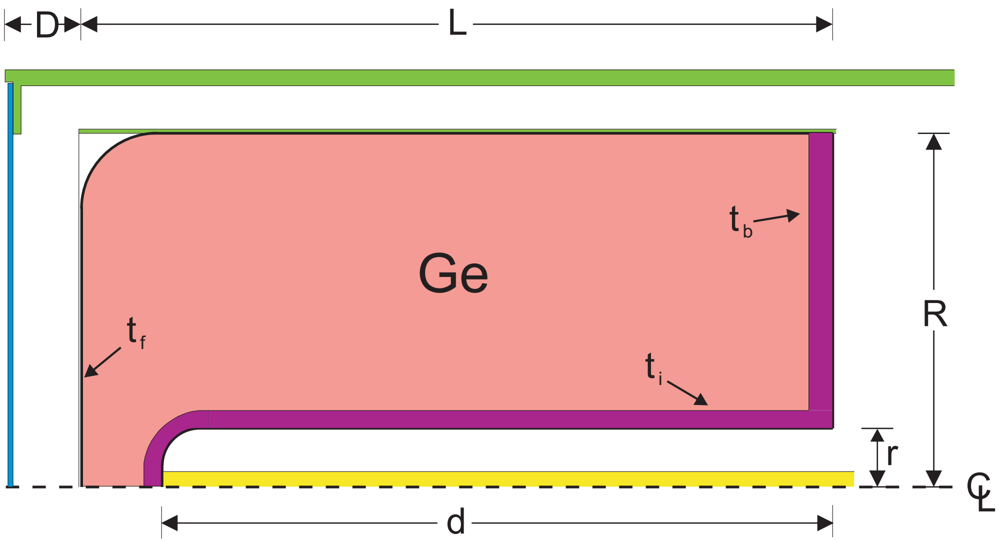
Combine Monte Carlo calculations with measured points.

KEY RADIOACTIVE SOURCES



MONTE CARLO CALCULATIONS

EG&G ORTEC Gamma-X HPGe

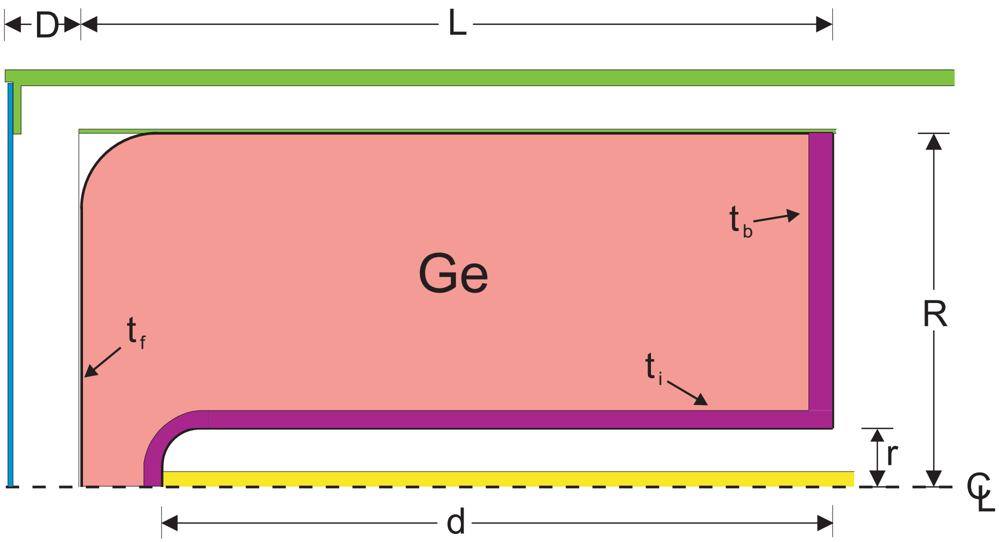


DIMENSION	NOMINAL
Crystal radius, R	34.95 mm
Crystal active length, $L - t_f - t_b$	77.7 mm
Cap face to crystal distance, D	5.6 mm
Hole radius, r	5.8 mm
Hole depth, d	69.7 mm
Depth internal (Li) dead layer, t_i	>1 mm
Depth front dead layer, t_f	>0.3 m

X-ray picture of crystal

MONTE CARLO CALCULATIONS

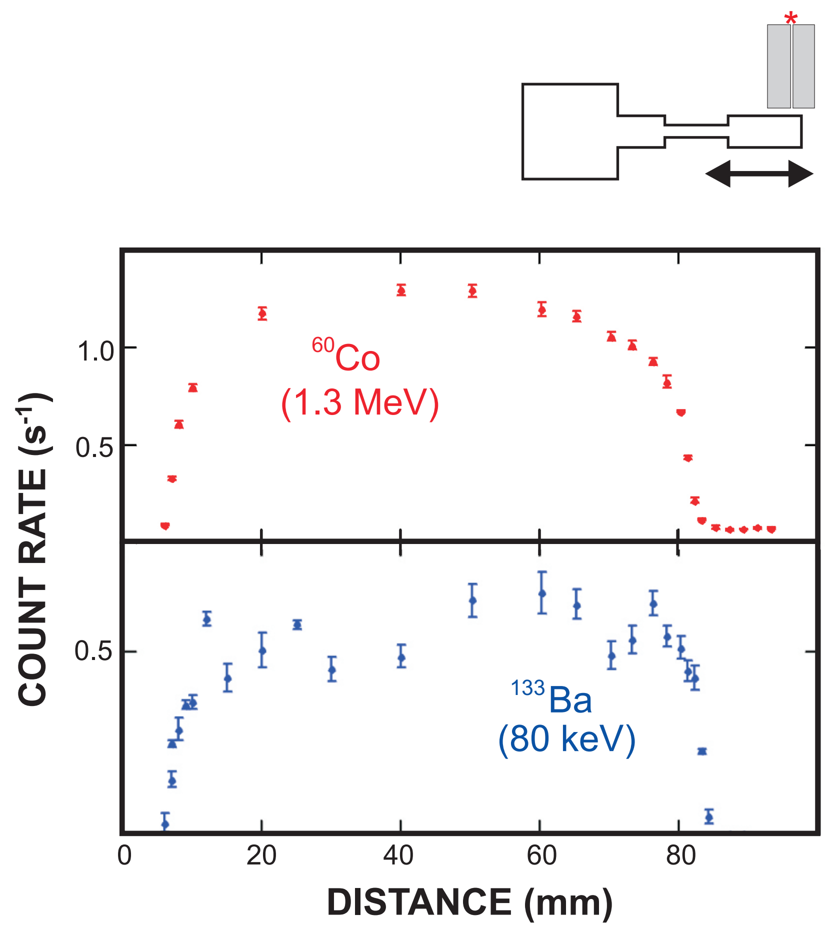
EG&G ORTEC Gamma-X HPGe



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	

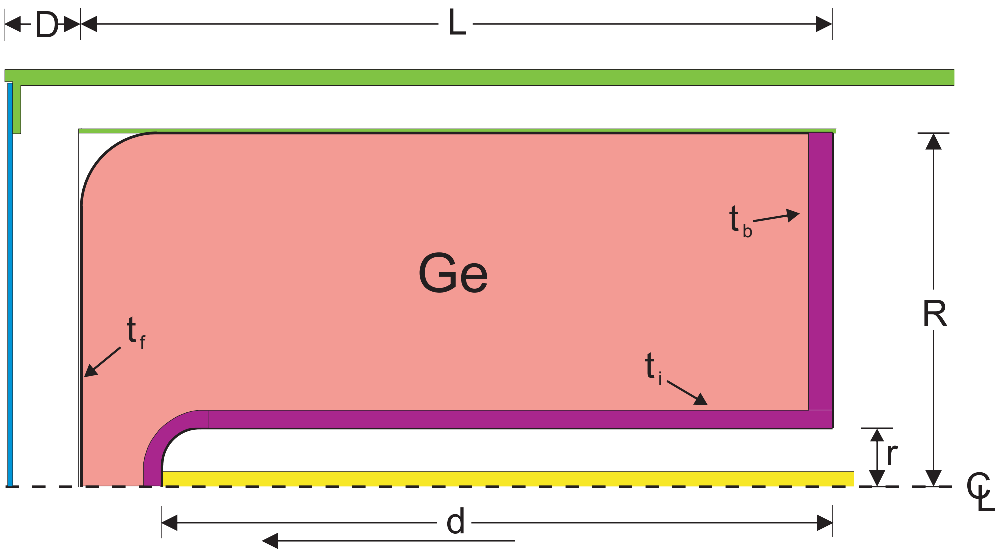
X-ray picture of crystal

Crystal side-scan



MONTE CARLO CALCULATIONS

EG&G ORTEC Gamma-X HPGe



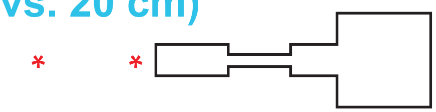
DIMENSION	NOMINAL	MEASURED or FITTED
Crystal radius, R	34.95 mm	
Crystal active length, $L - t_f - t_b$	77.7 mm	75.4 mm
Cap face to crystal distance, D	5.6 mm	7.2 mm
Hole radius, r	5.8 mm	
Hole depth, d	69.7 mm	
Depth internal (Li) dead layer, t_i	>1 mm	
Depth front dead layer, t_f	>0.3 m	

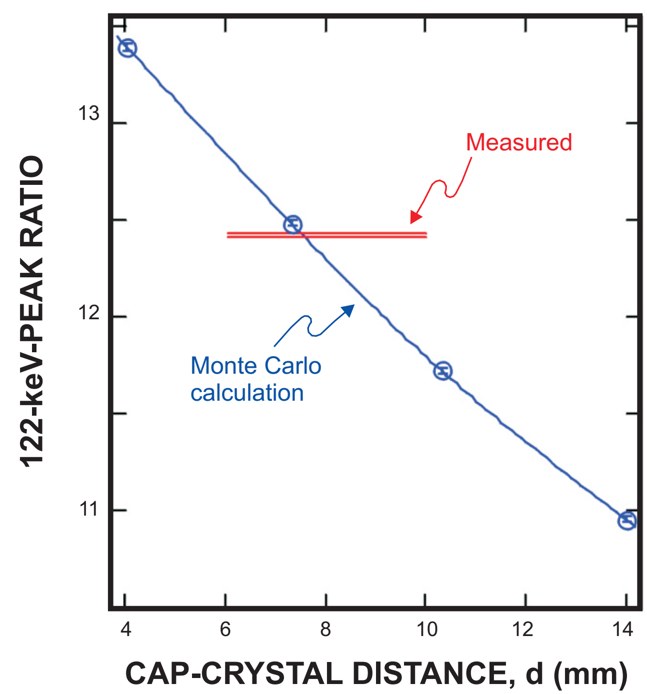
X-ray picture of crystal

Crystal side-scan

Distance ratio for ^{57}Co

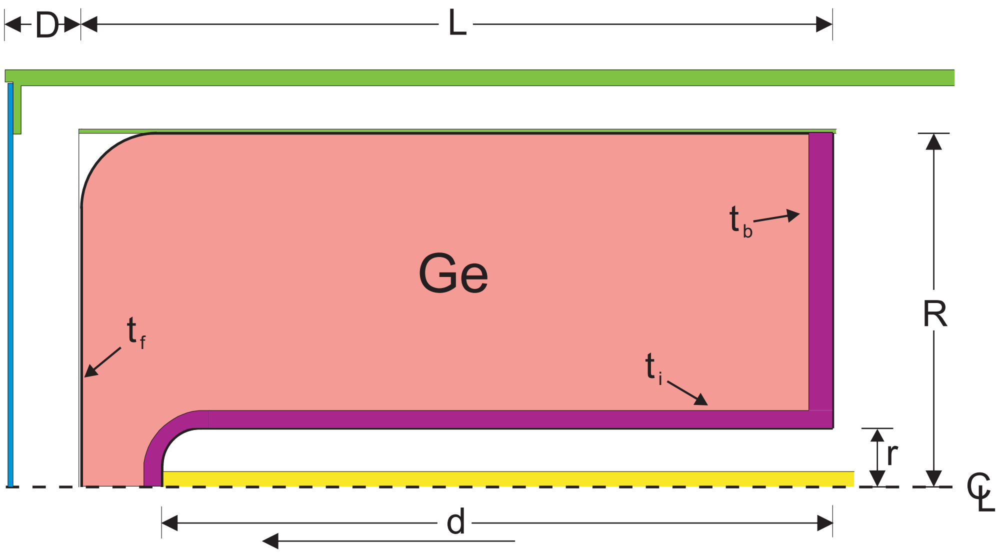
(4 cm vs. 20 cm)





MONTE CARLO CALCULATIONS

EG&G ORTEC Gamma-X HPGe



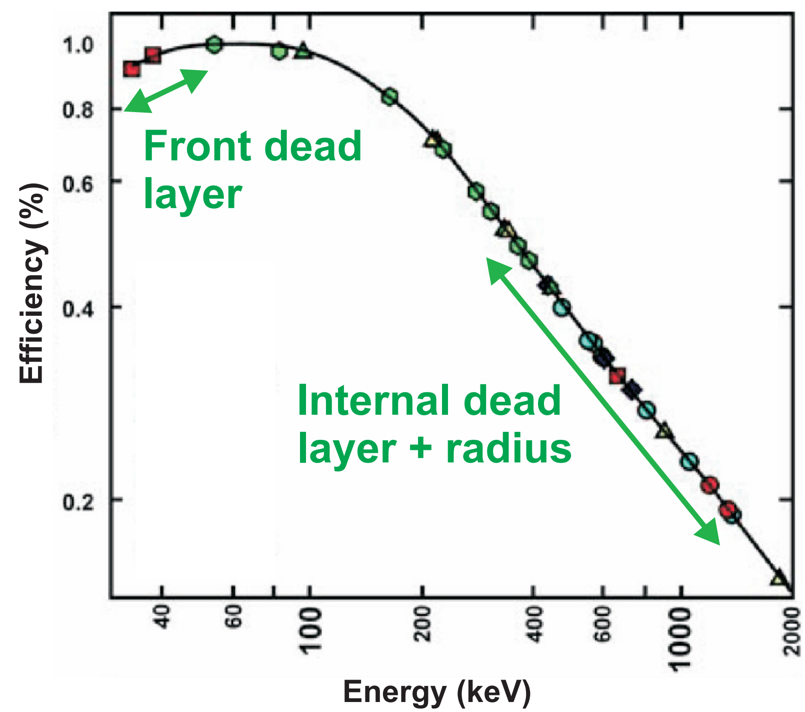
DIMENSION	NOMINAL	MEASURED or FITTED
Crystal radius, R	34.95 mm	34.49 mm
Crystal active length, $L - t_f - t_b$	77.7 mm	75.4 mm
Cap face to crystal distance, D	5.6 mm	7.2 mm
Hole radius, r	5.8 mm	
Hole depth, d	69.7 mm	
Depth internal (Li) dead layer, t_i	>1 mm	1.34 mm
Depth front dead layer, t_f	>0.3 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

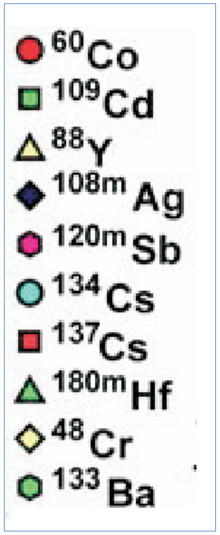
Source measurements
vs
unscaled Monte Carlo calculations (CYLTRAN)

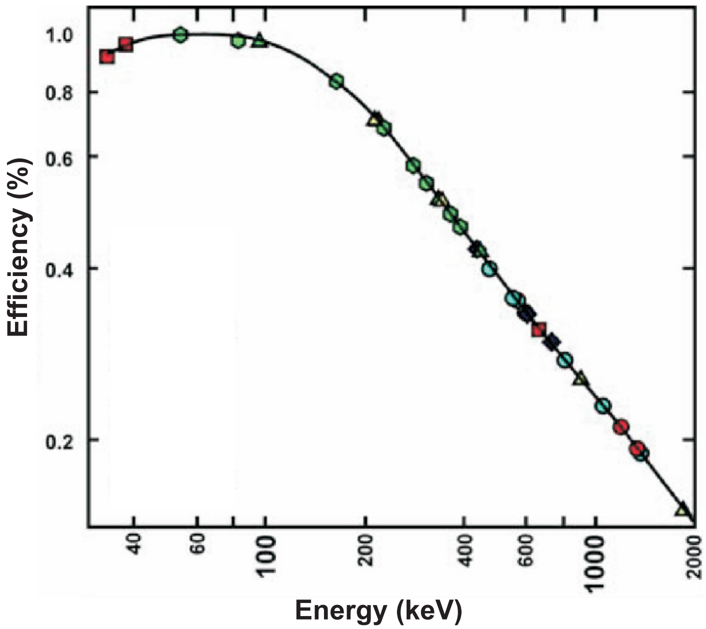
Physical properties and location of HPGe crystal measured precisely

10 sources recorded

4 key sources, 3 locally made, have pure cascades

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





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

DETECTOR EFFICIENCY
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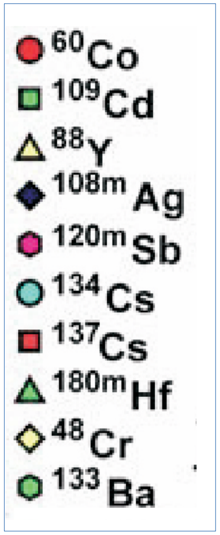
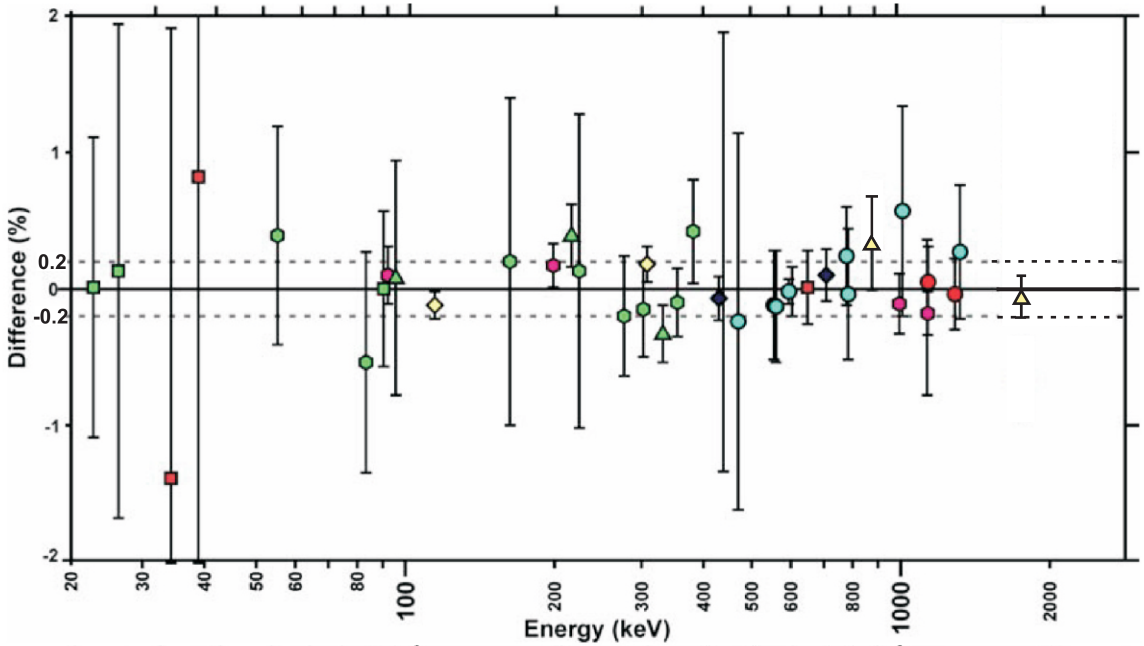
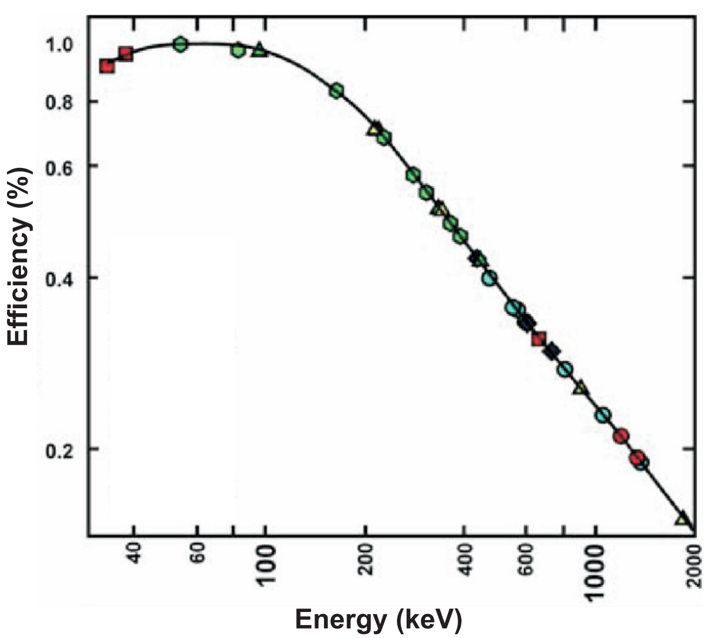
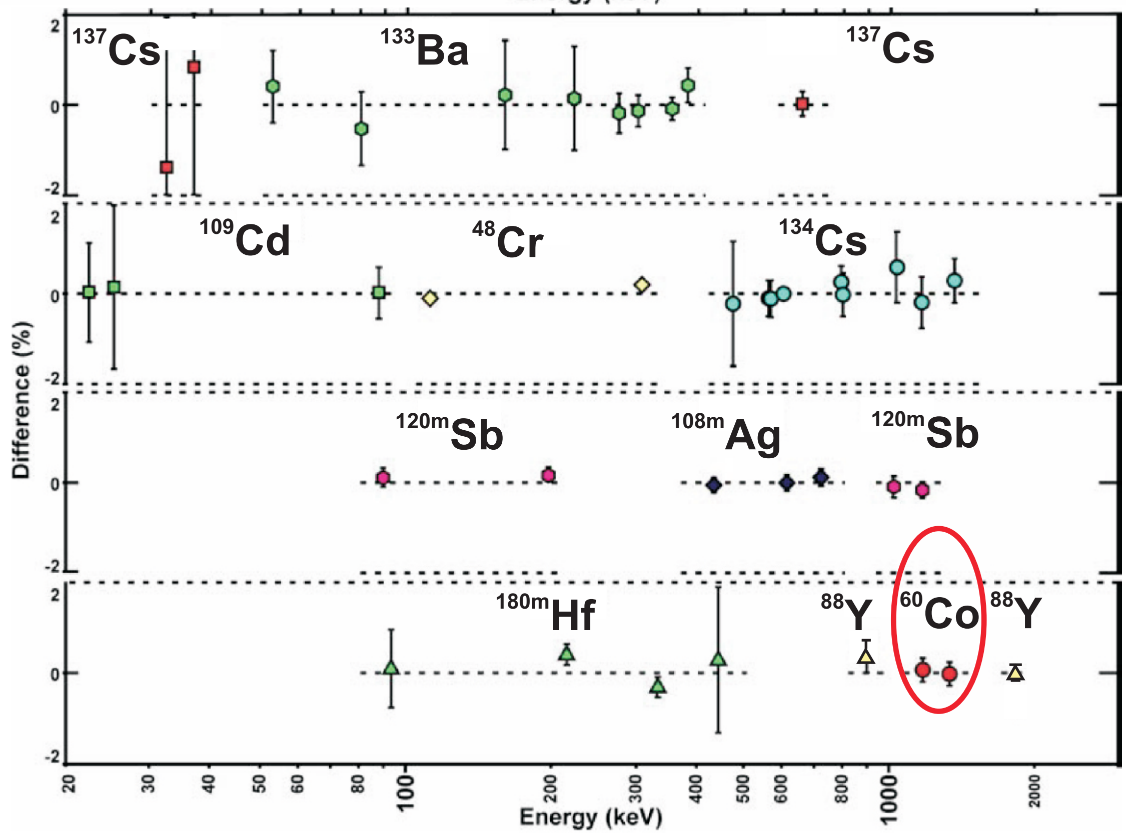


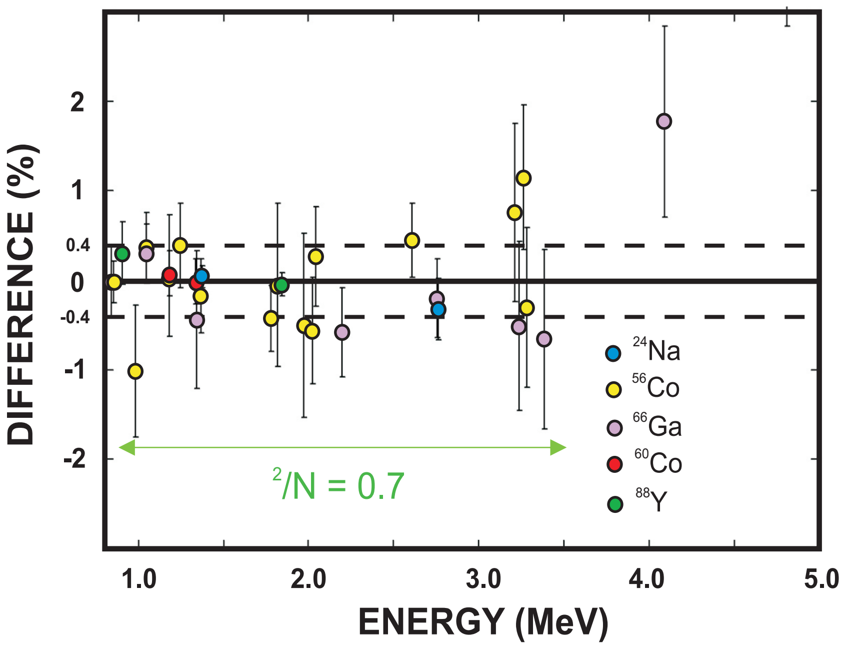






DETECTOR CHARACTERIZATION - DETAILS

Efficiency extended up to 3.5 MeV



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

DETECTOR CHARACTERIZATION - DETAILS

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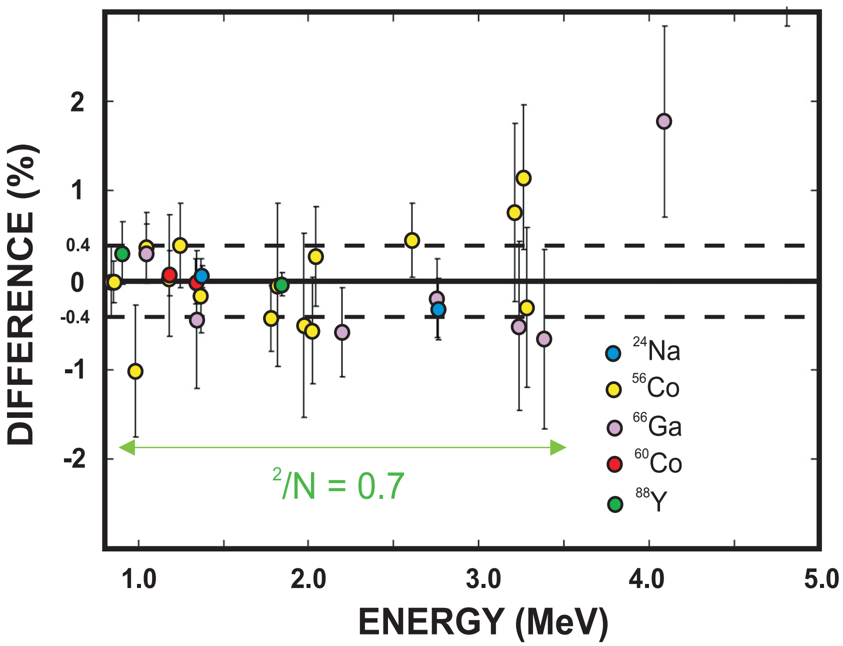
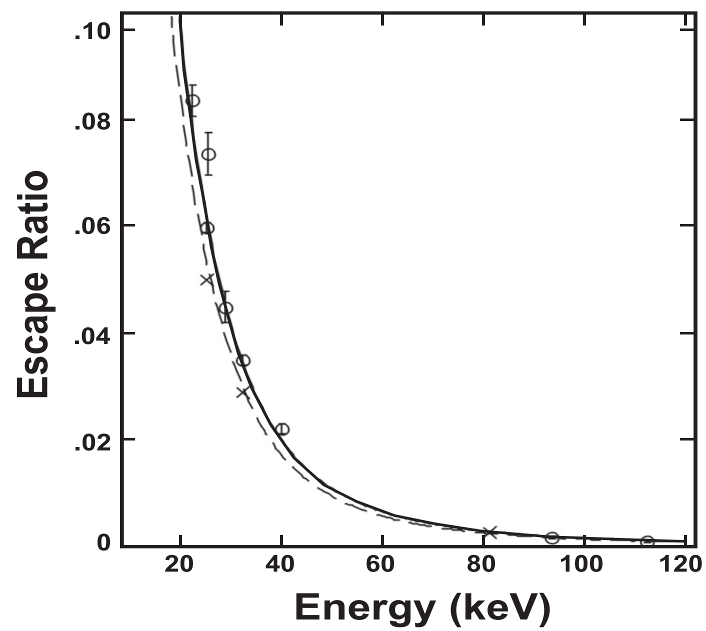
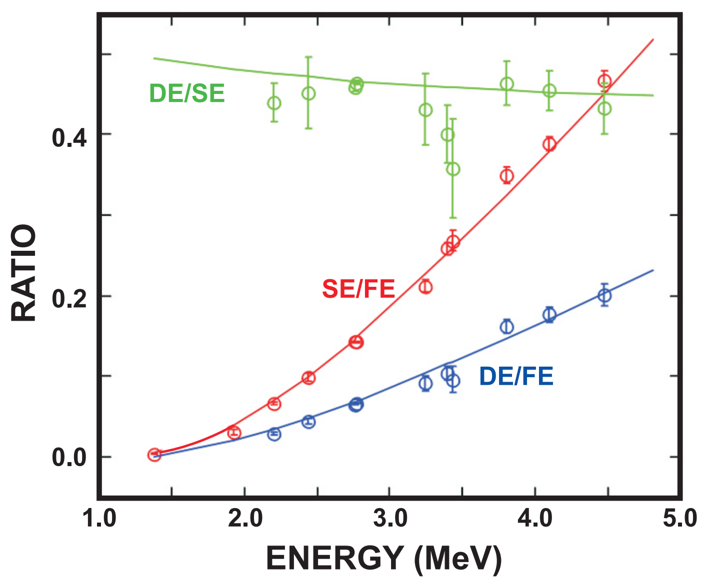


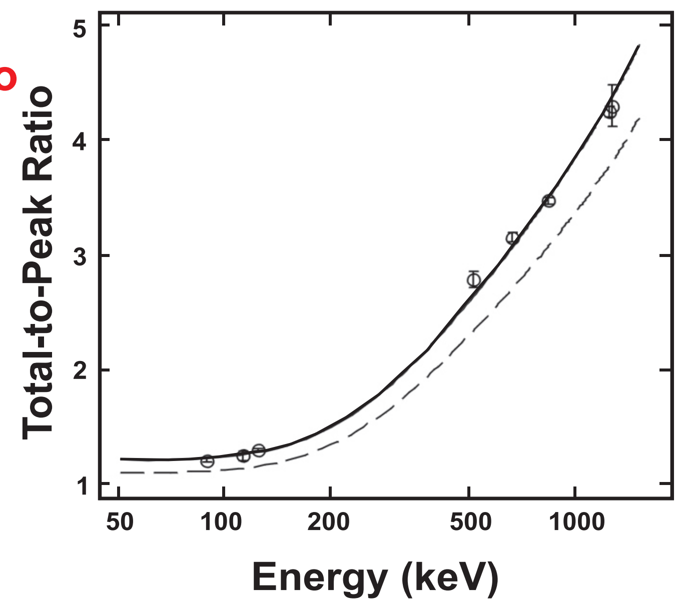
Ge x-ray escape



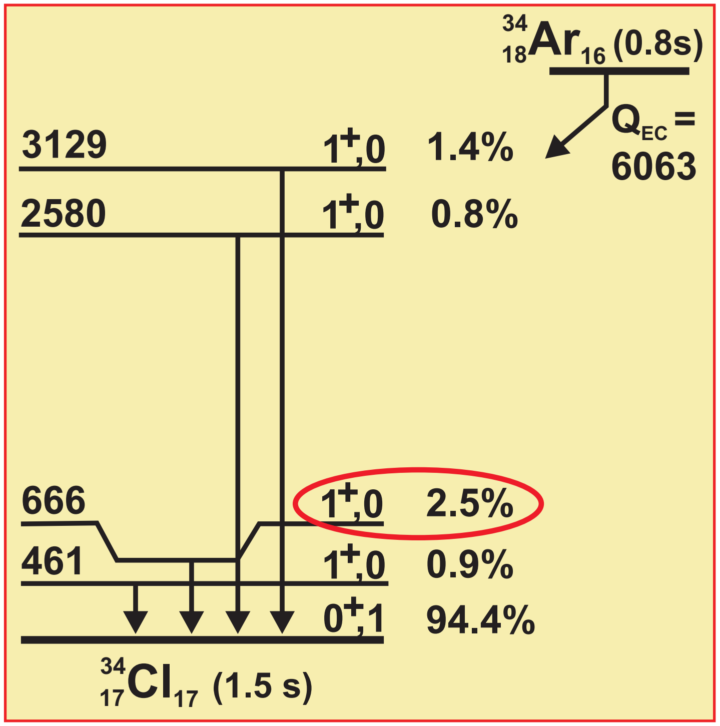


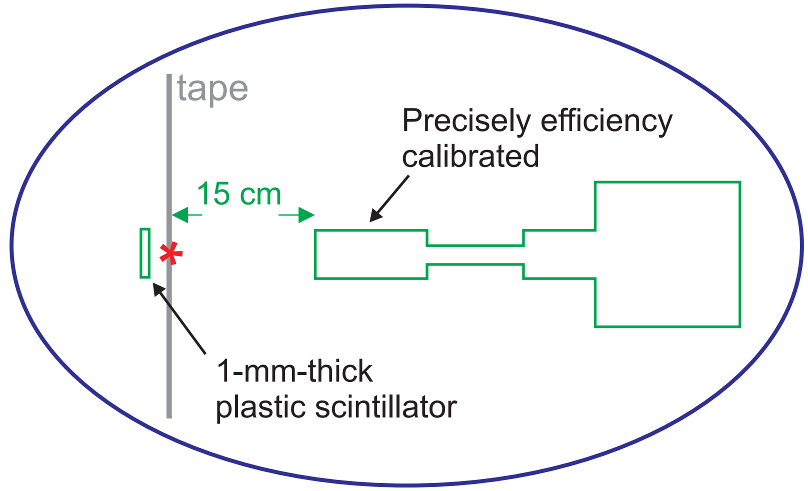
Total-to-peak ratio (for summing corrections) →

← **511-keV escape ratios**



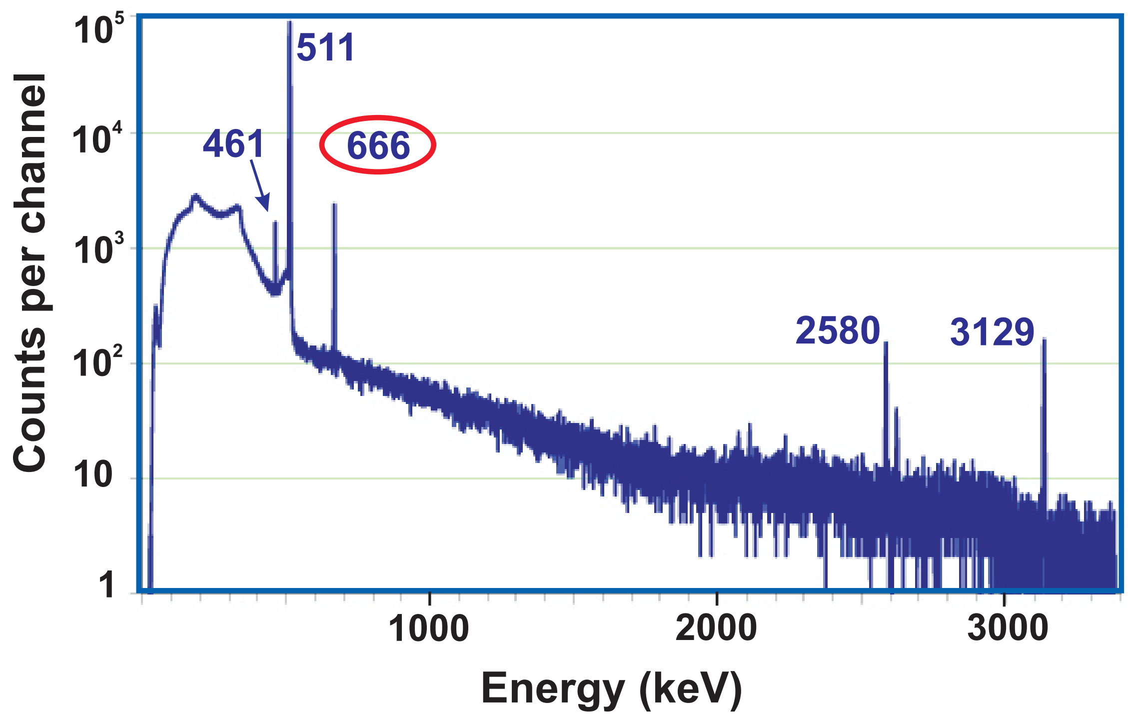
BETA-DECAY BRANCHING OF ^{34}Ar



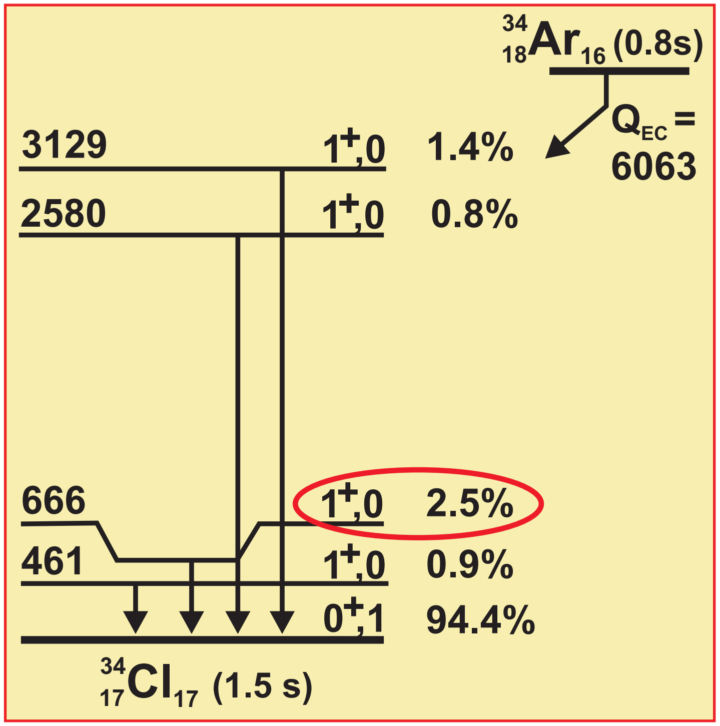


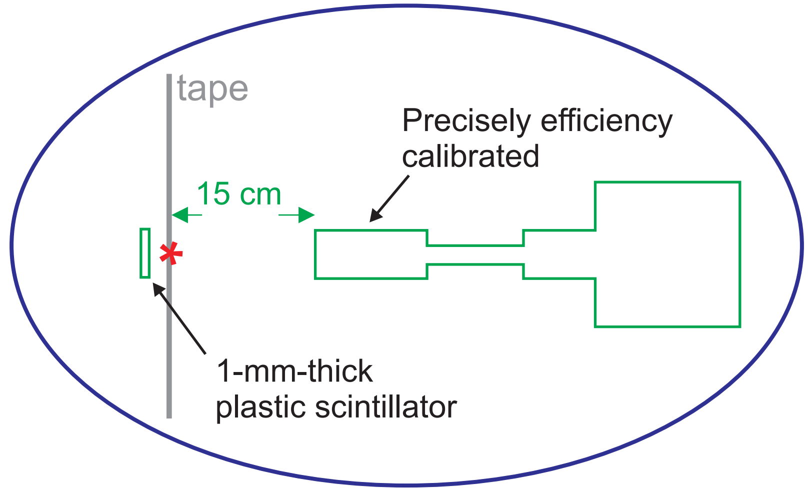
$$\frac{N_{1}}{N} = \frac{\not{N_o} R_1 \quad 1 \quad 1}{\not{N_o} \quad tot}$$

$$R_1 = \frac{N_1}{N \;\; 1} \frac{tot}{1} k$$



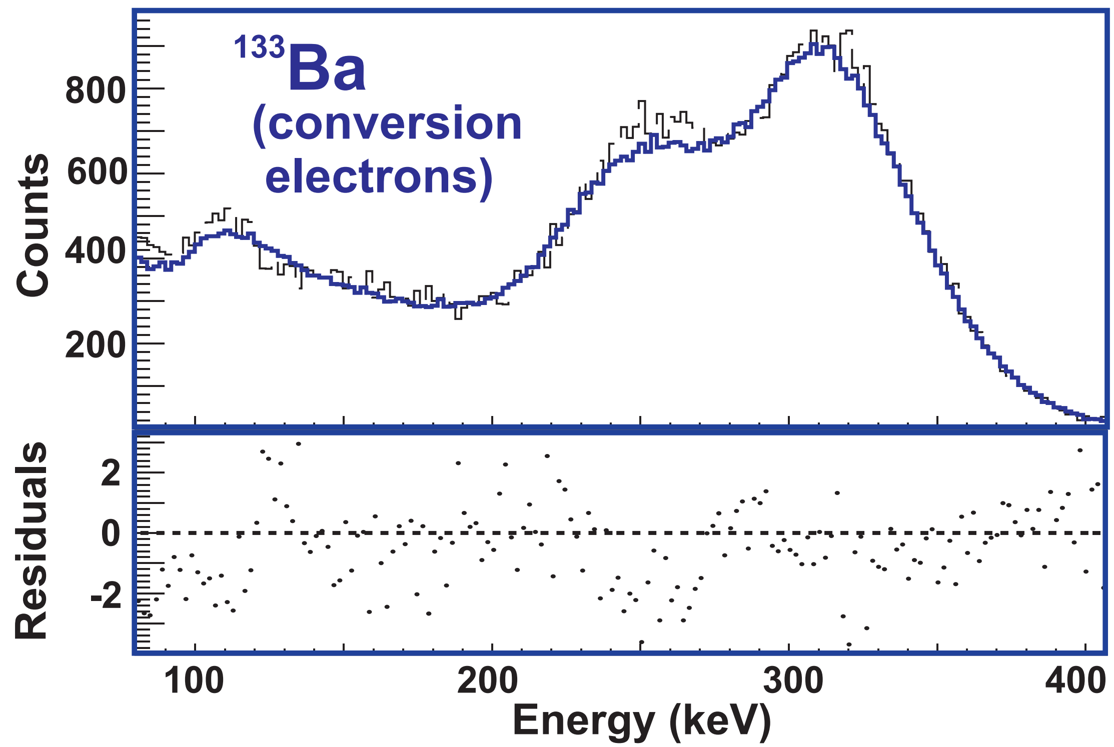
BETA-DECAY BRANCHING OF ^{34}Ar



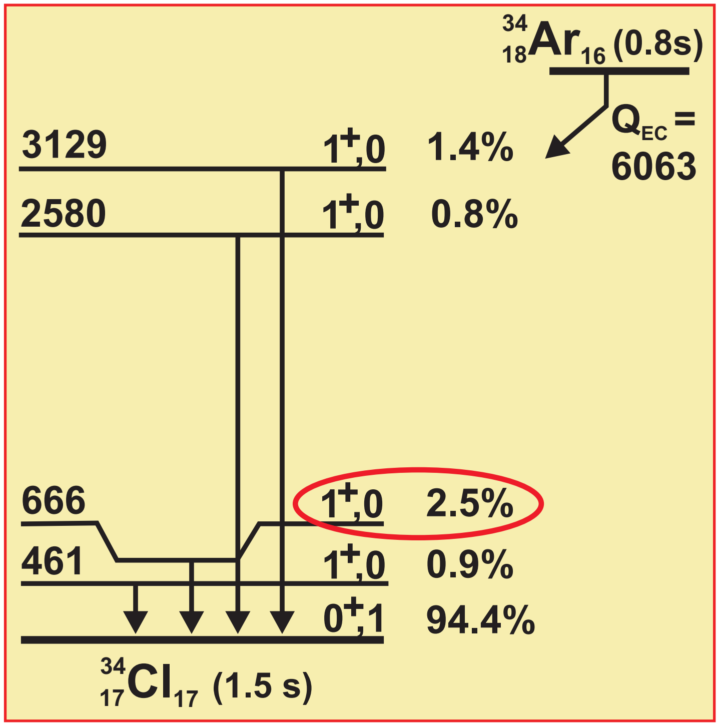


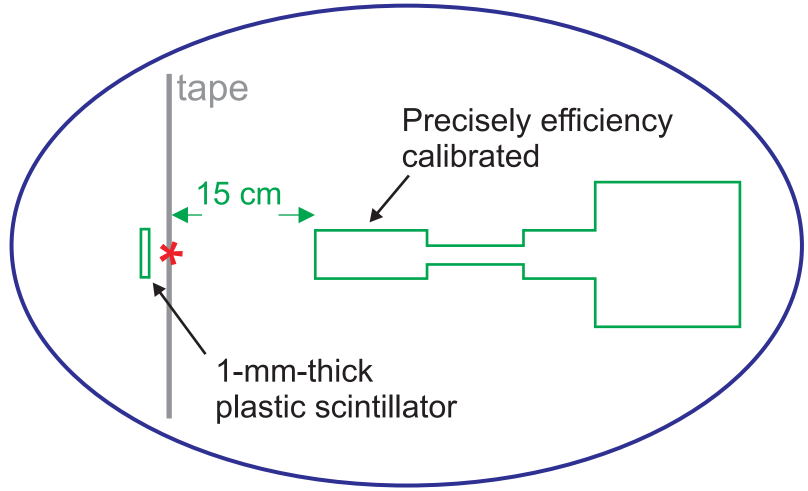
$$\frac{N_1}{N} = \frac{N_0 R_1 \;{}_1 \;{}_1}{N_0 \;{}_{tot}}$$

$$R_1 = \frac{N_1}{N_{\;1}} \frac{{}_{tot}}{{}_1} k$$



BETA-DECAY BRANCHING OF ^{34}Ar





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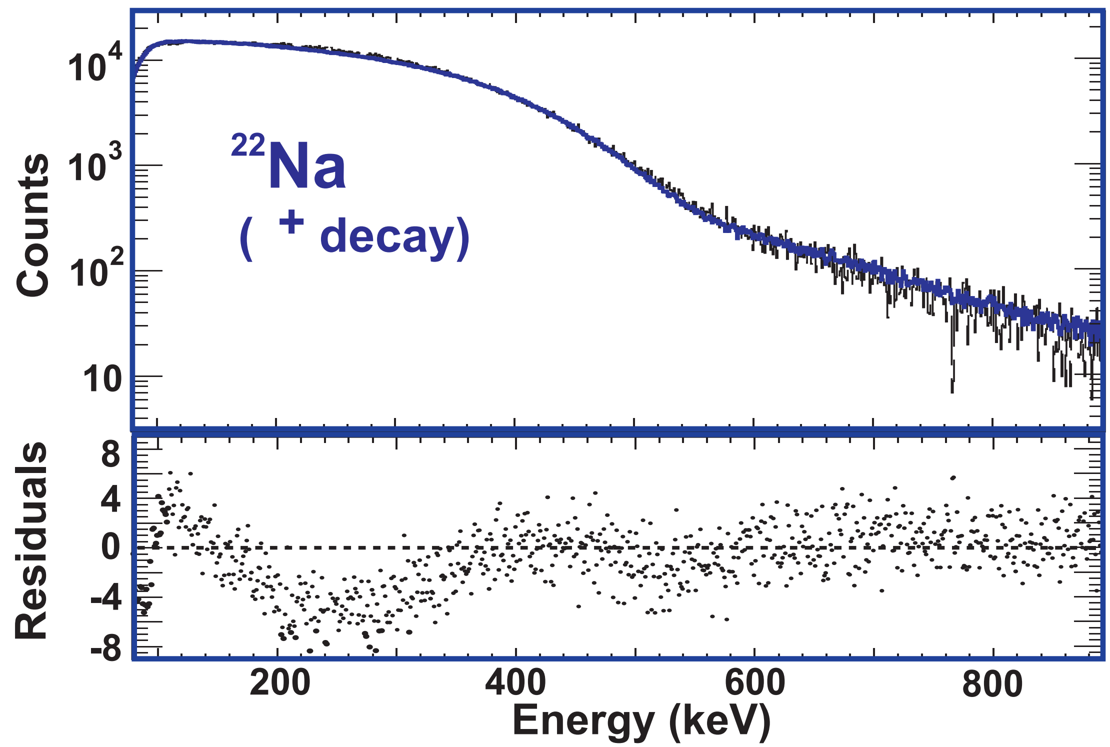
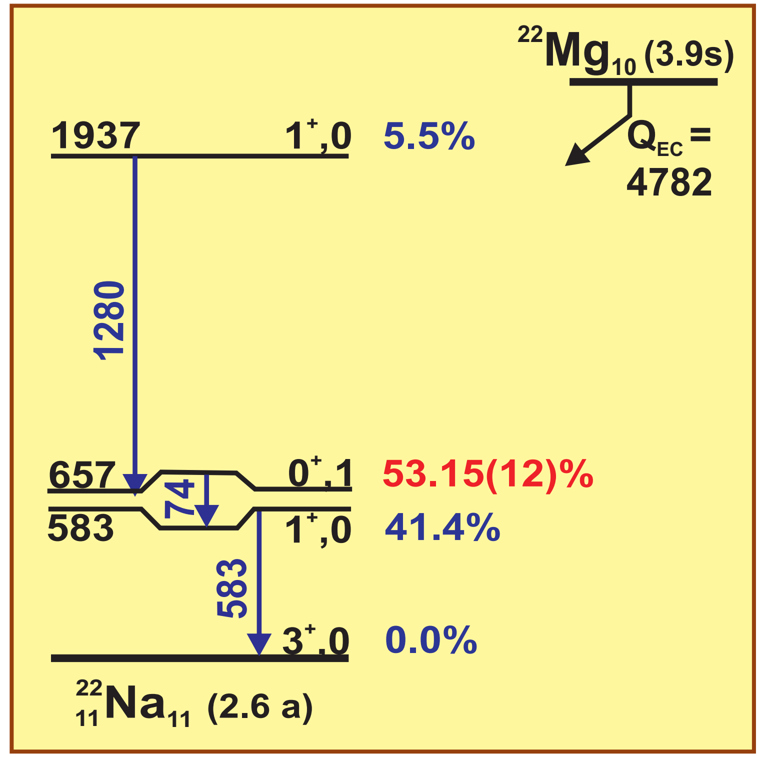
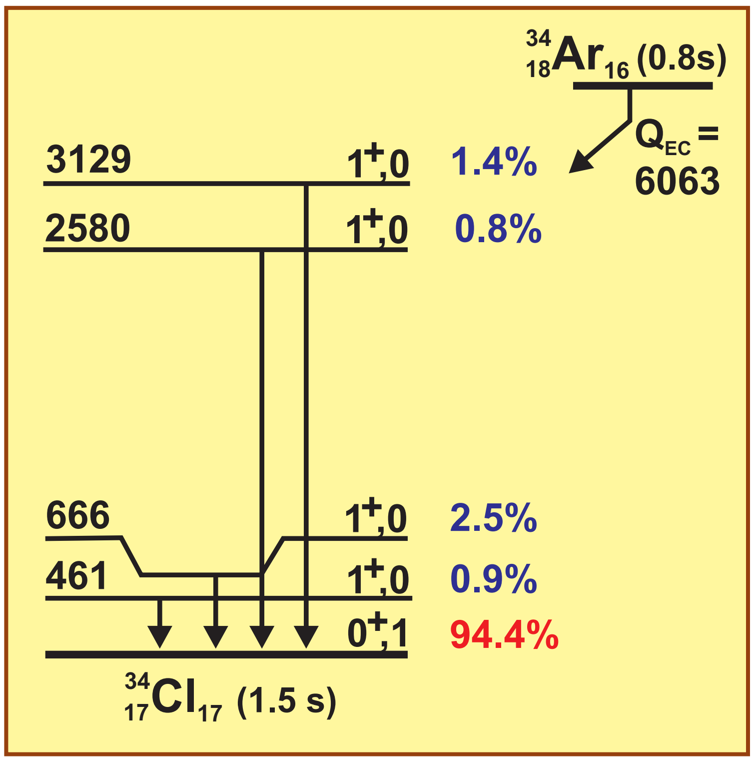


BRANCHING-RATIO RESULTS

Where no ground-state decay occurs, a -ray spectrum and relative efficiencies are enough to obtain branching ratios to ±0.2%.

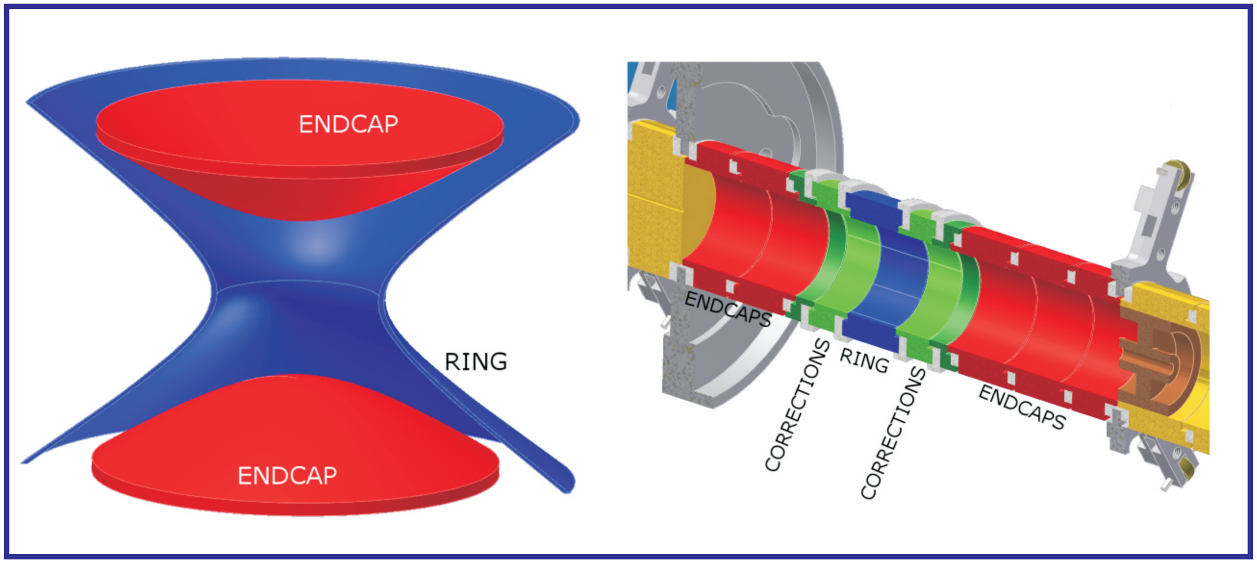
Hardy *et al.*, PRL 91, 082501 (2003).

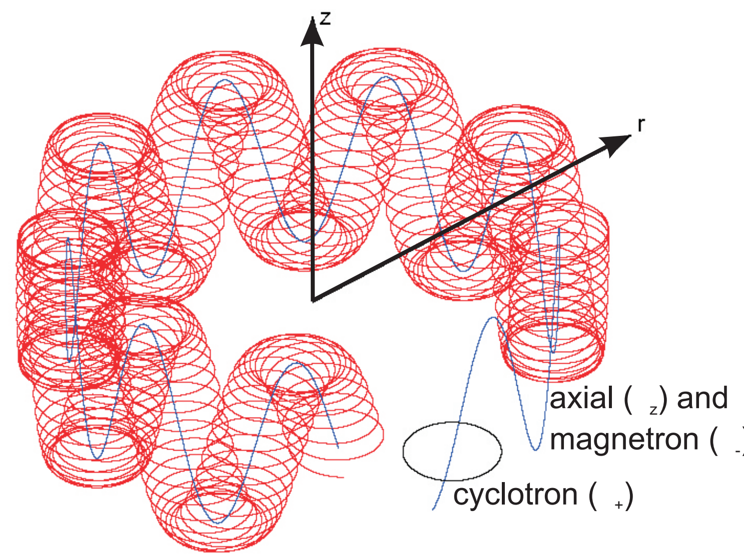




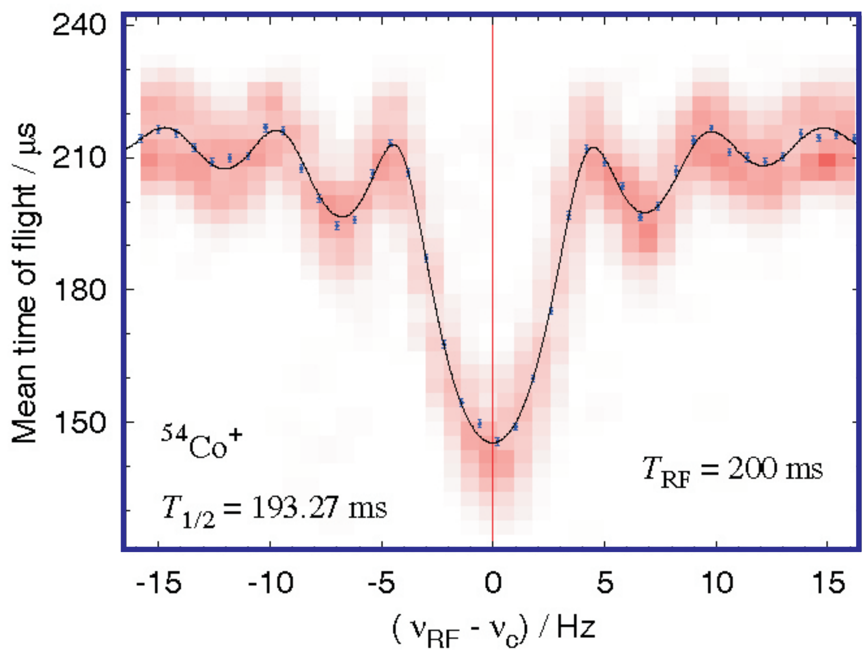
Where superallowed branch feeds the ground state, we measure the other branching ratios to ±0.2% and subtract them from 100%. In favorable cases (like ^{34}Ar) the result can be good to ±0.01%.

PENNING TRAP Q_{EC}-VALUE MEASUREMENTS





Time of flight of extracted ions as function of quadrupole rf excitation



$$_{+} \quad _{-} = \; _{c} = \frac{1}{2}\,\frac{q}{m}B$$

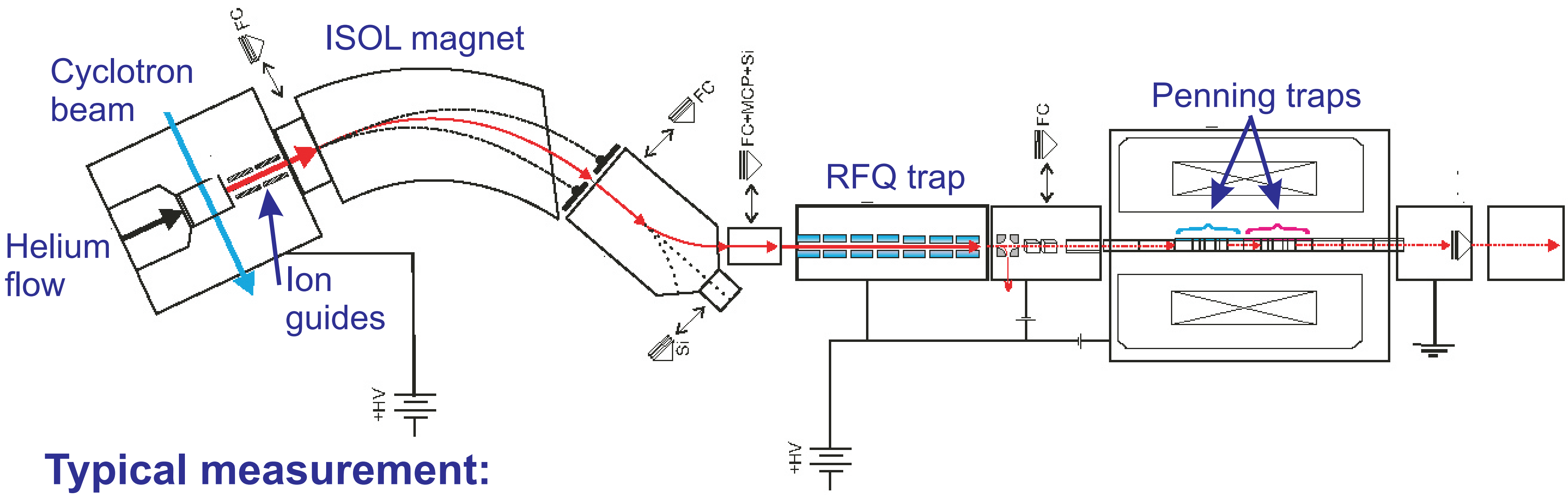
$$Q_{EC} = M_p - M_d$$

$$= \left(\frac{_{c,d}}{_{c,p}} - 1\right)\left(M_d - m_e\right)$$

Precision, $Q/Q = 0.001\%$

PENNING TRAP Q_{EC}-VALUE MEASUREMENTS

IGISOL System



Typical measurement:

Target	E(proton)	Reaction	Products
KCl	15 MeV	^{35}Cl(p, 2n)	^{34}Ar
		^{35}Cl(p, pn)	^{34}Cl + ^{34}Cl^{m}
		^{35}Cl(p, 2p)	^{34}S

^{34}Ar Q_{EC} value: 6061.83(8) keV

Eronen *et al.*, Phys. Rev. 83, 055501 (2011)

Or for the full Penning trap Q-value story:
Tommi Eronen, Jyvaskyla Research Report No. 12/2008 (Thesis)