HOW IDIOSYNCRATIC IS THE WEAK FORCE?

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Cyclotron Institute
Texas A&M University
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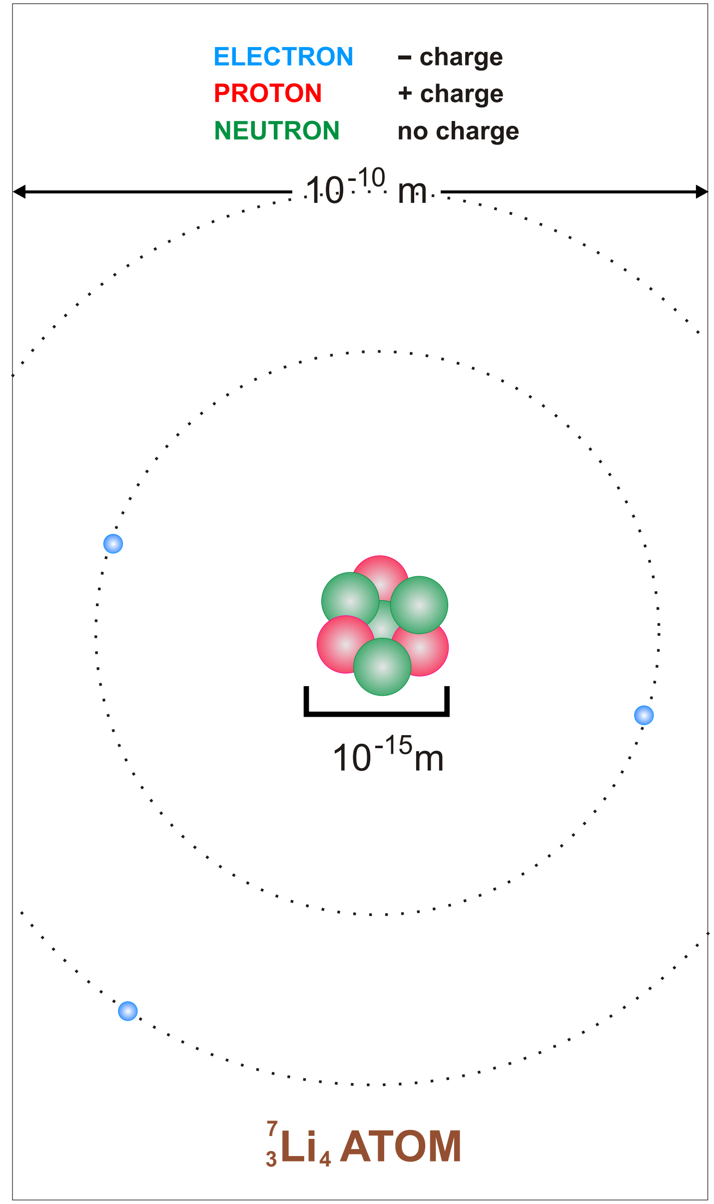
1. What is the weak force?
2. Is it universal?
3. The nucleus as laboratory
4. Current status of data
5. Measurements in progress
6. Summary and outlook

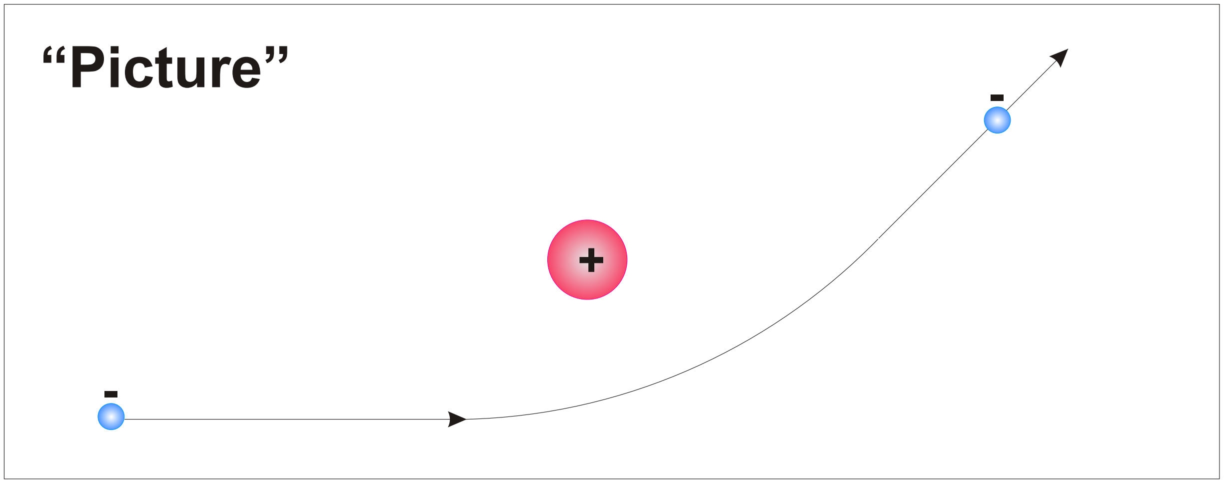
THE FORCES IN NATURE

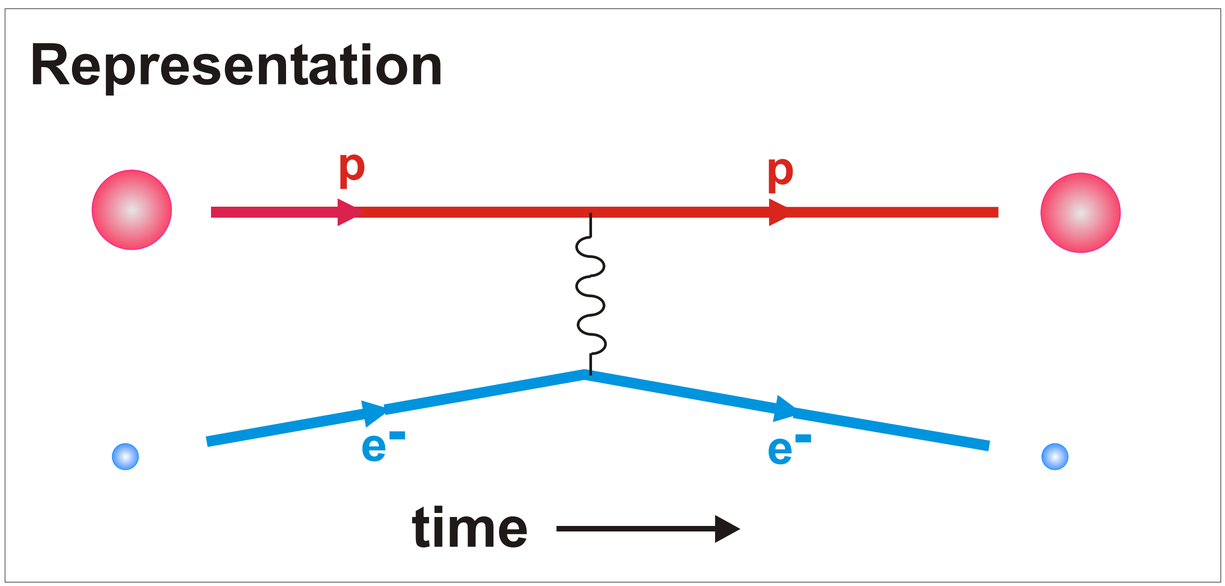
Name	Relative Strength	Range	Acts on
Strong	1	10^{-15}m	neutrons protons ...
Electromagnetic	10^{-2}	long ($1/r^2$)	charged particles
Weak	10^{-5}	10^{-18}m	all
Gravity	10^{-41}	long ($1/r^2$)	masses



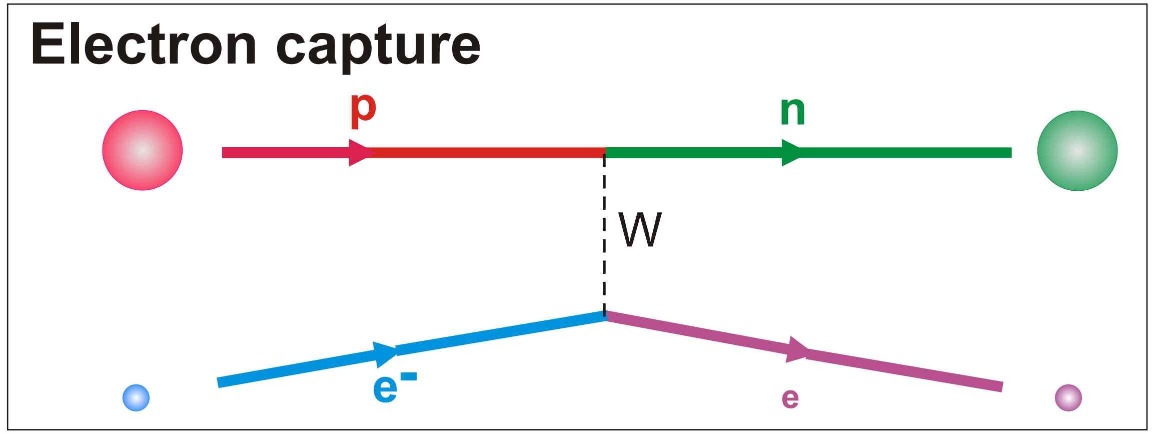
ELECTROMAGNET FORCE

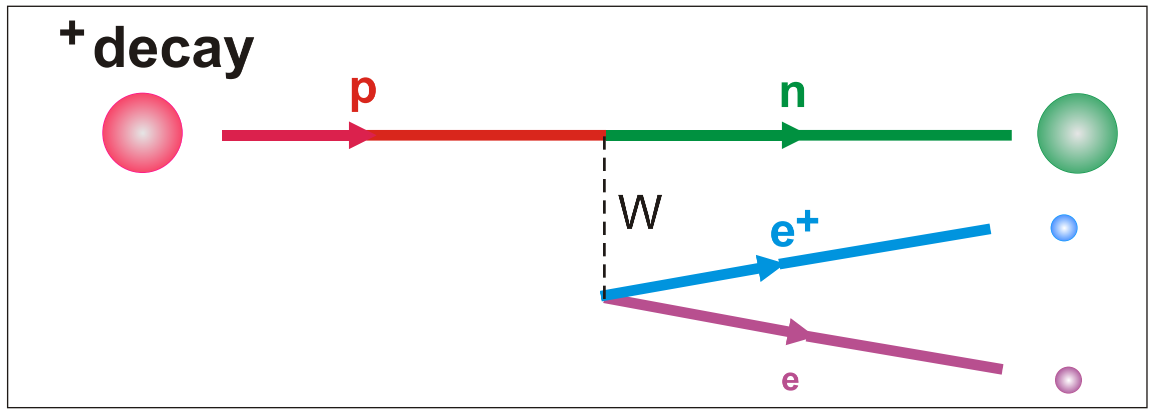
Electron scattering:

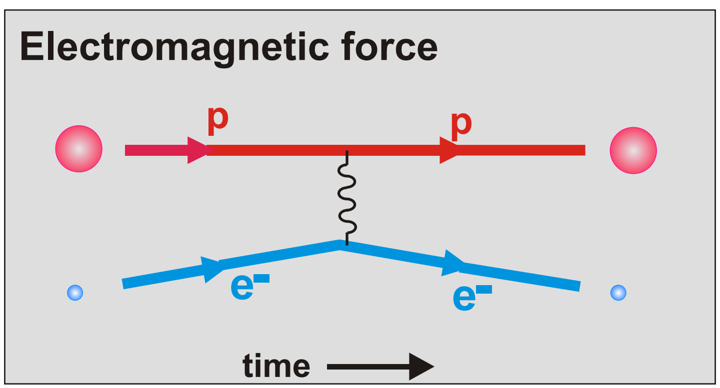


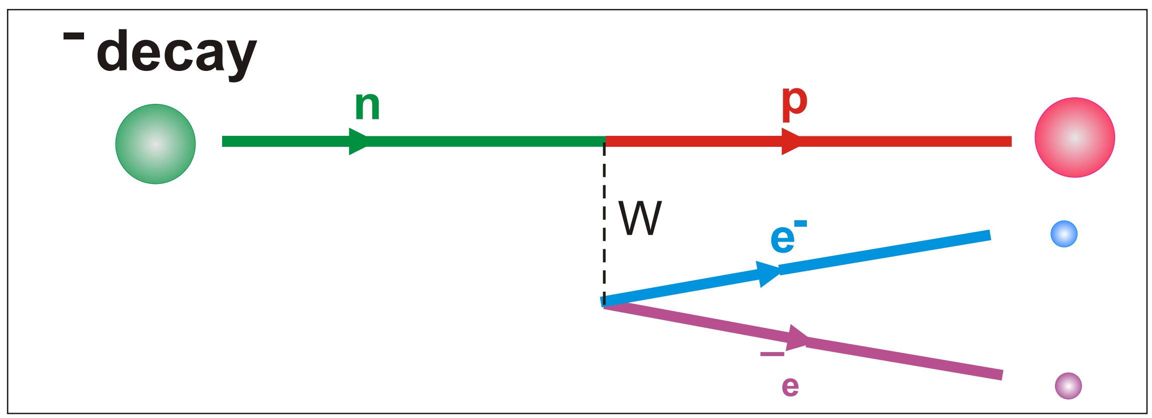


WEAK FORCE


Electron capture
p
n
W
e⁻
e

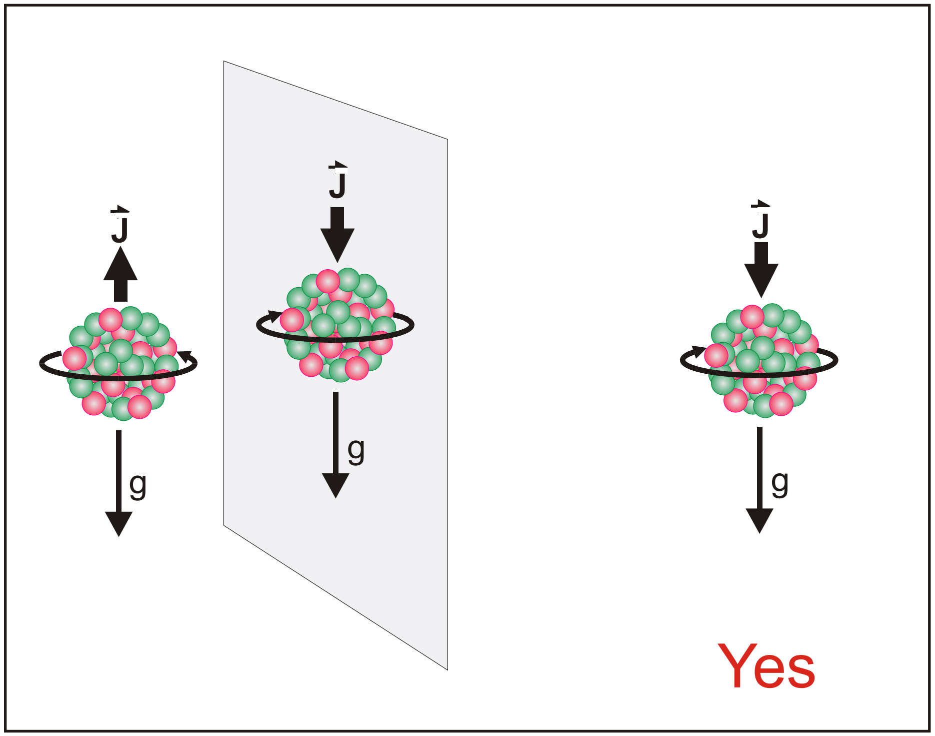

+ decay
p
n
W
e+
e


Electromagnetic force
p
p
e⁻
e⁻
time


- decay
n
p
W
e⁻
e

IS PARITY CONSERVED?

Gravity



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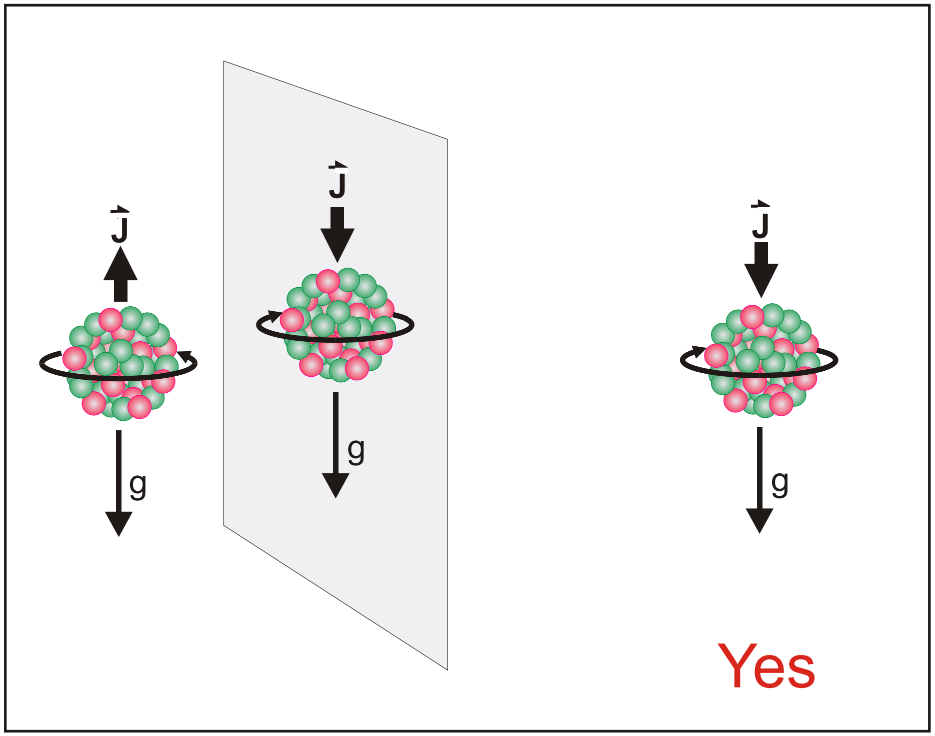
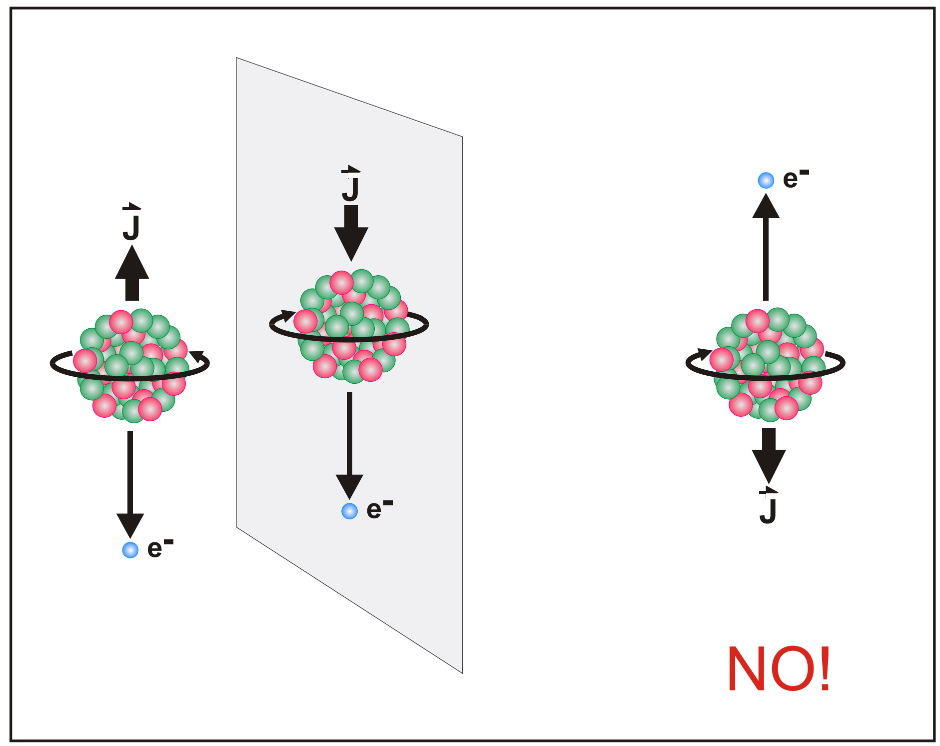
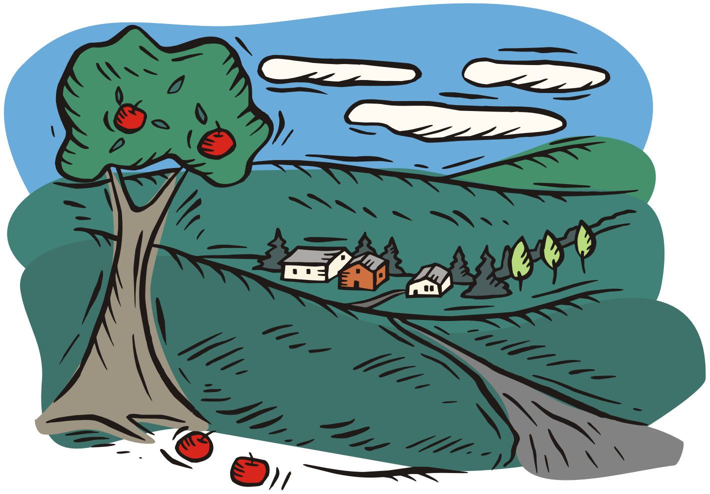


Weak interaction



WHAT ABOUT UNIVERSALITY?



Newton's Insight
~1700

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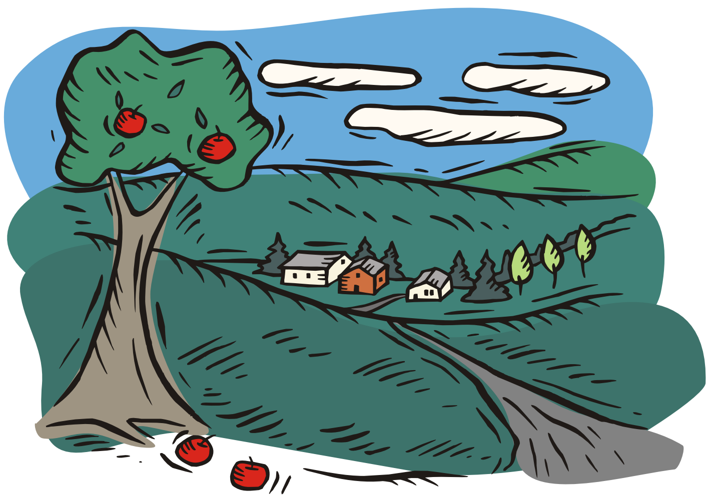

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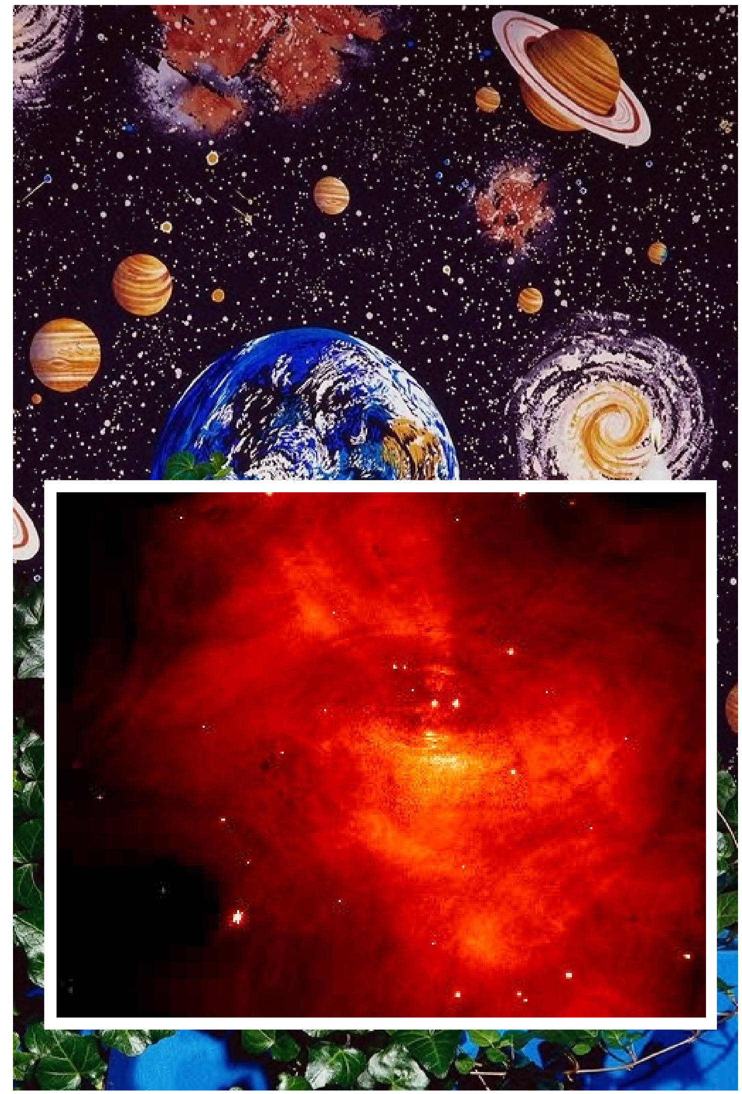
Universality
of
Gravitational force



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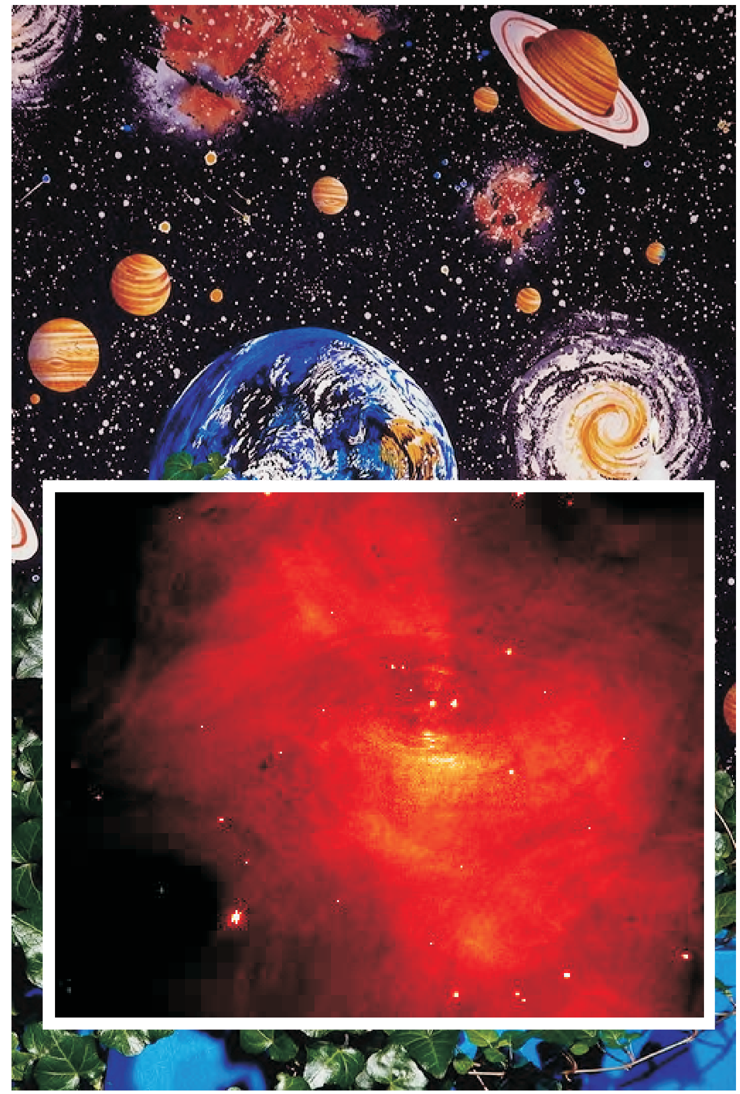
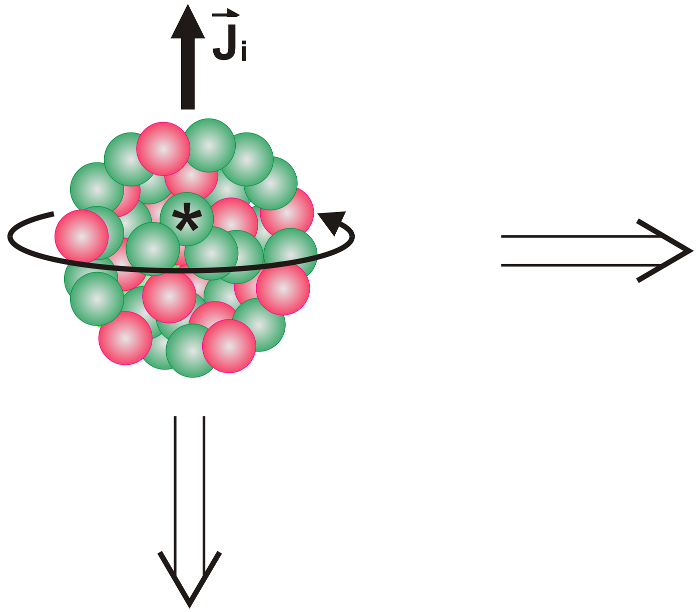
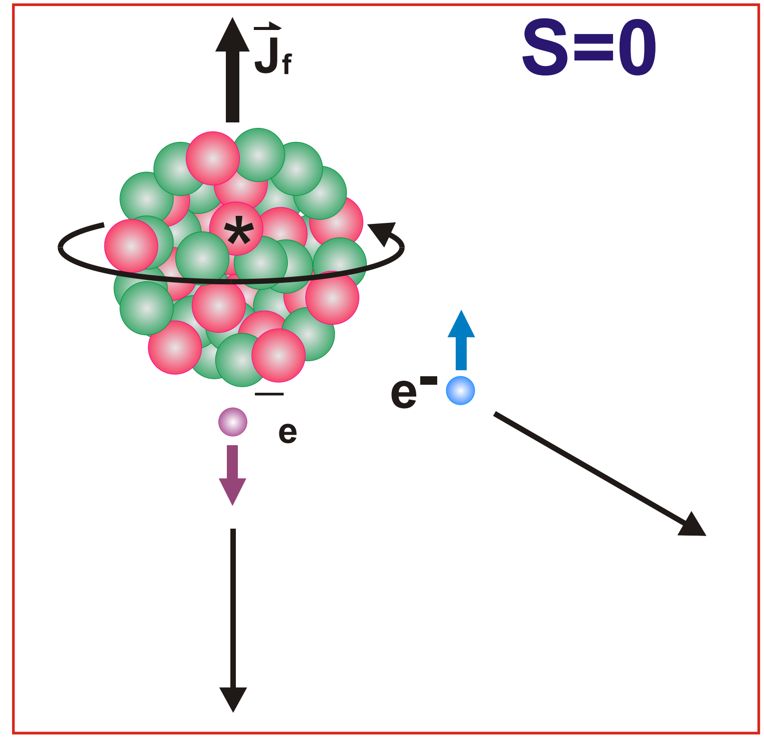
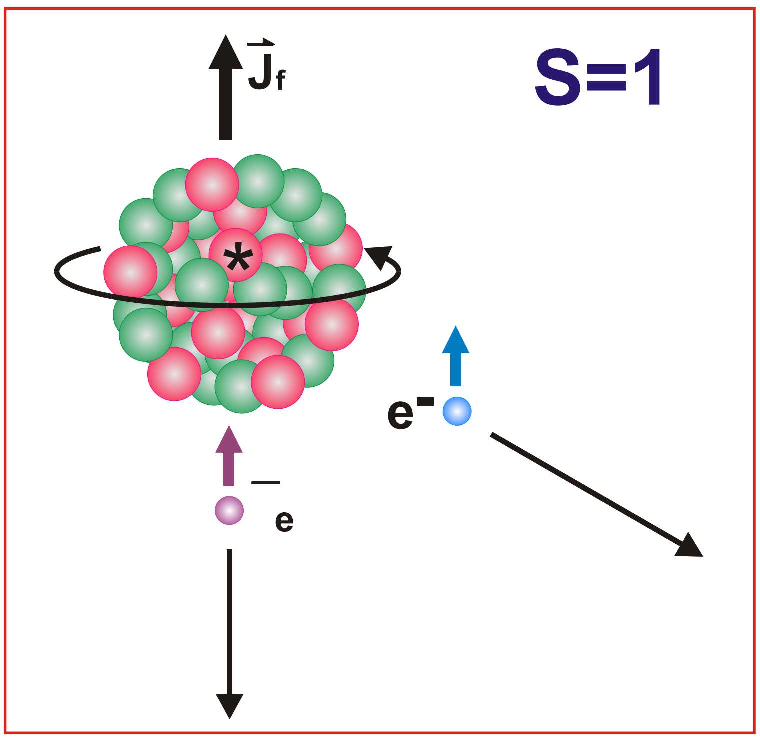


Now in 2007 .... Is this idiosyncratic weak force universal too?

NUCLEAR BETA DECAY

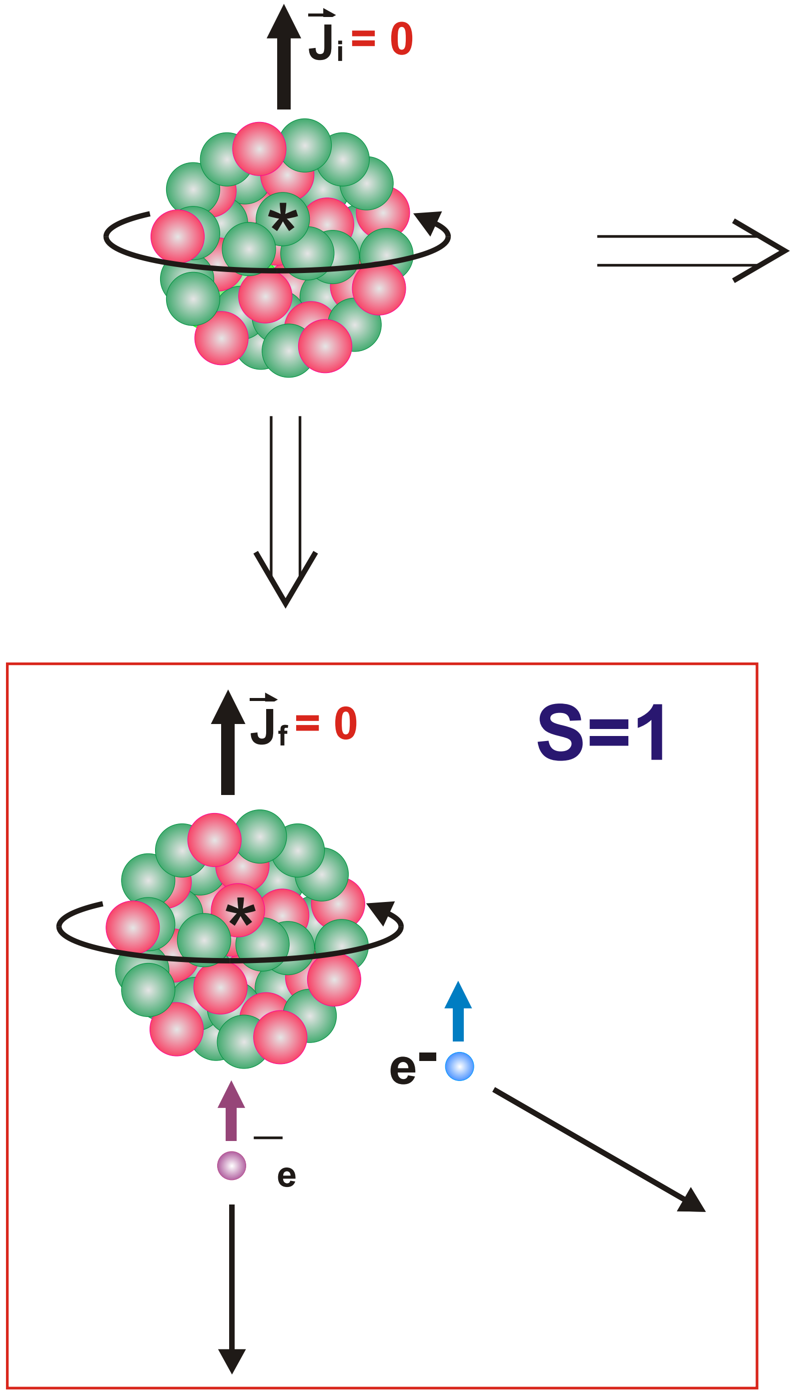


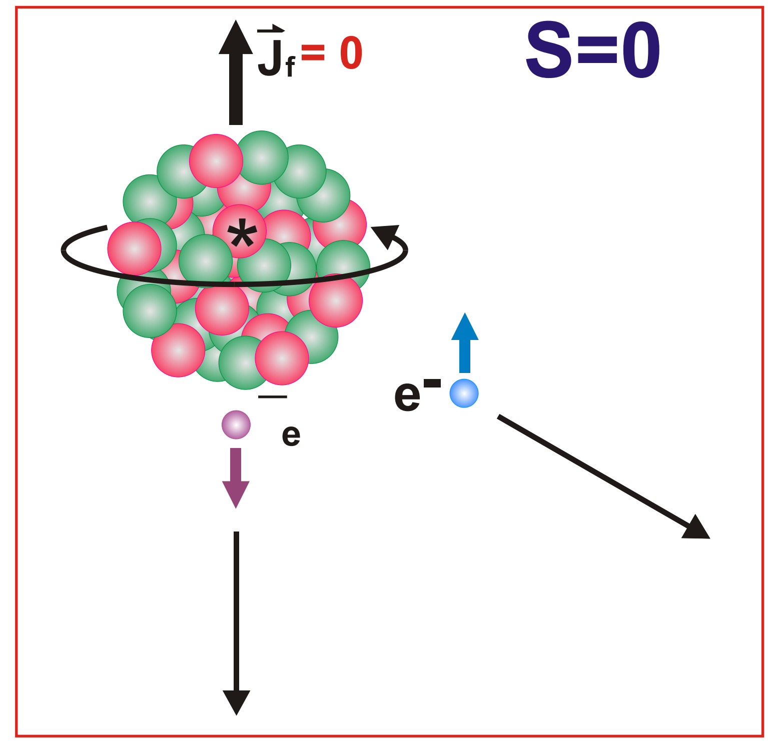




Both S=0 and S=1 transfers are allowed in general.

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





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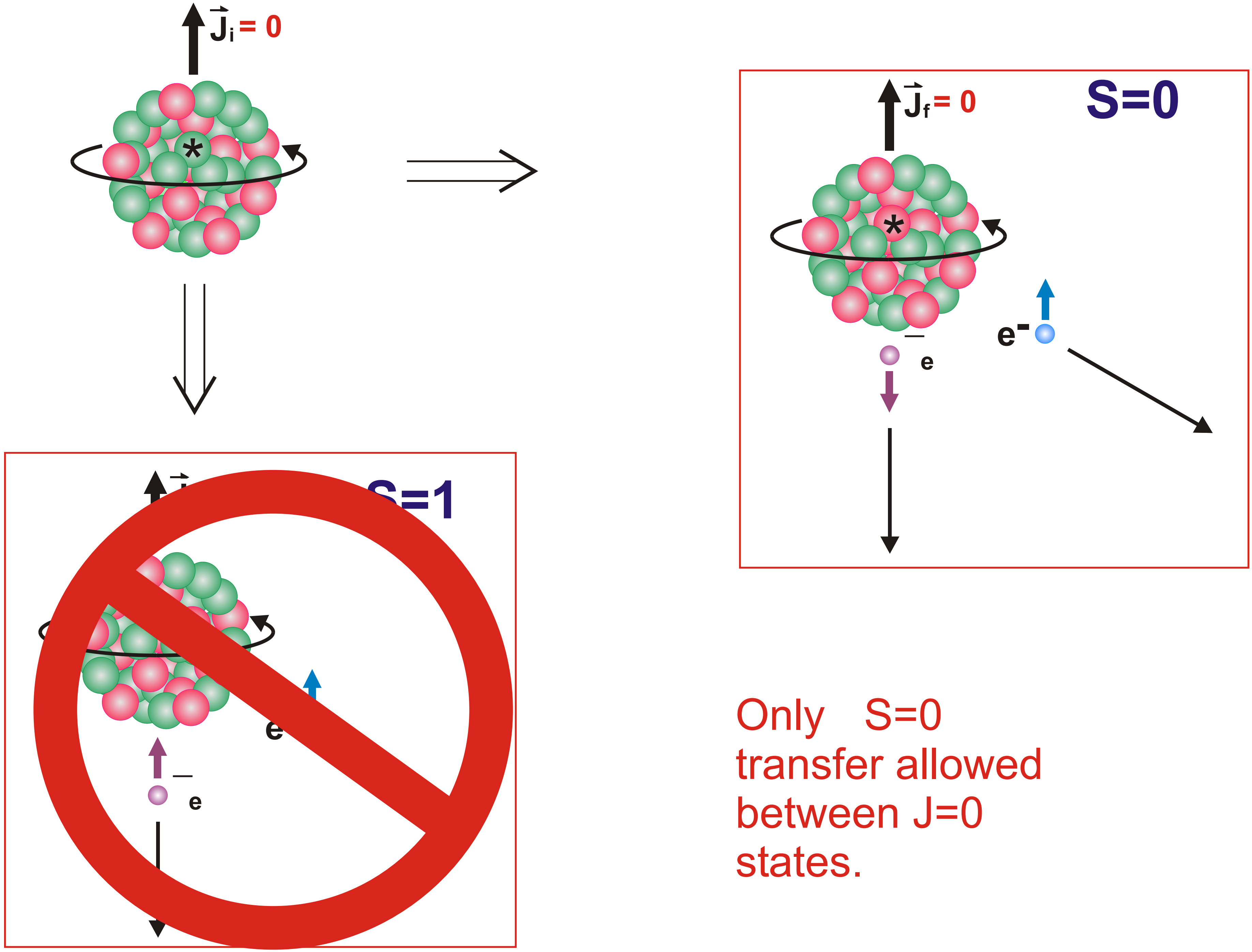
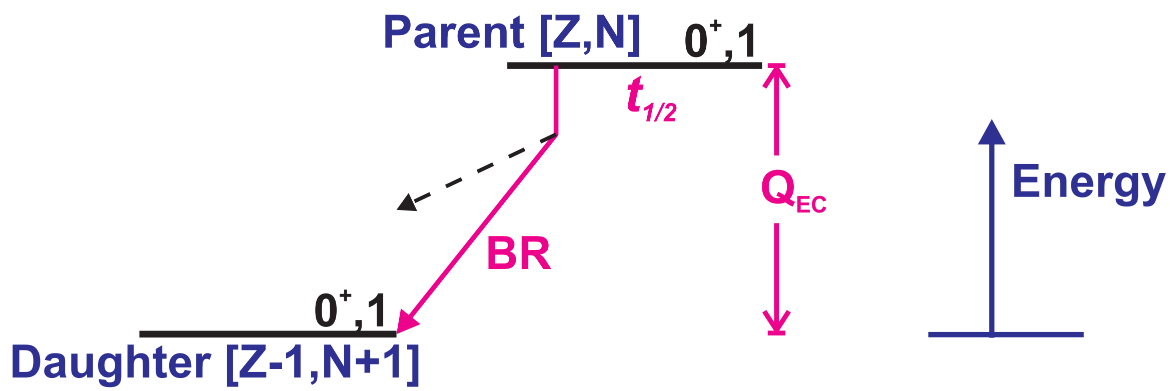


Only S=0 transfer allowed between J=0 states.

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

EXPERIMENT



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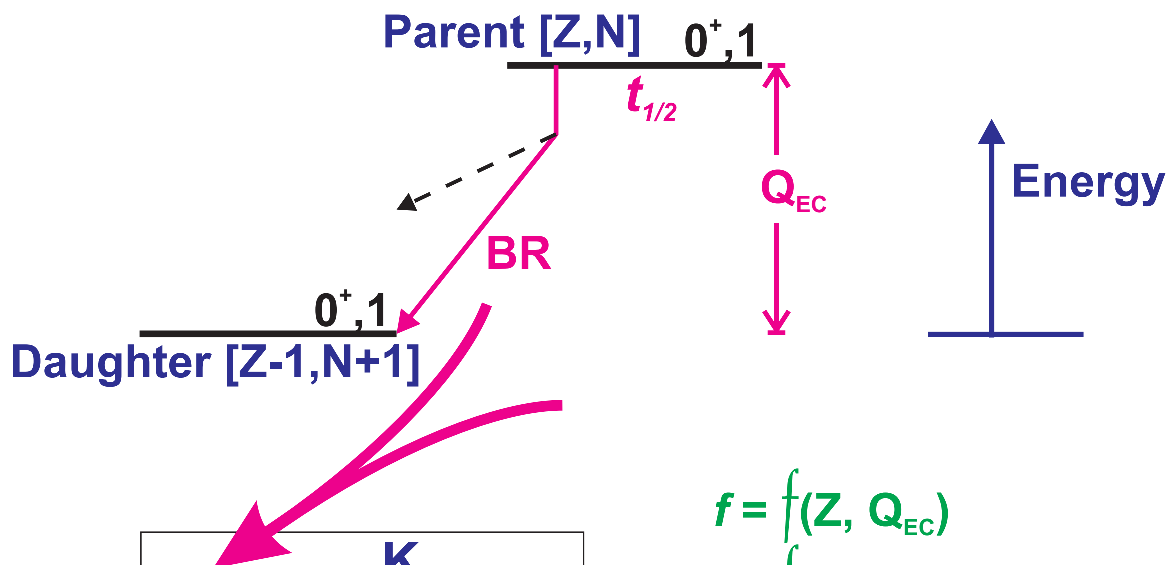


WEAK DECAY EQUATION

$$ft = \frac{K}{G_V^2 \langle 1 \rangle^2}$$

$f = f(Z, Q_{EC})$

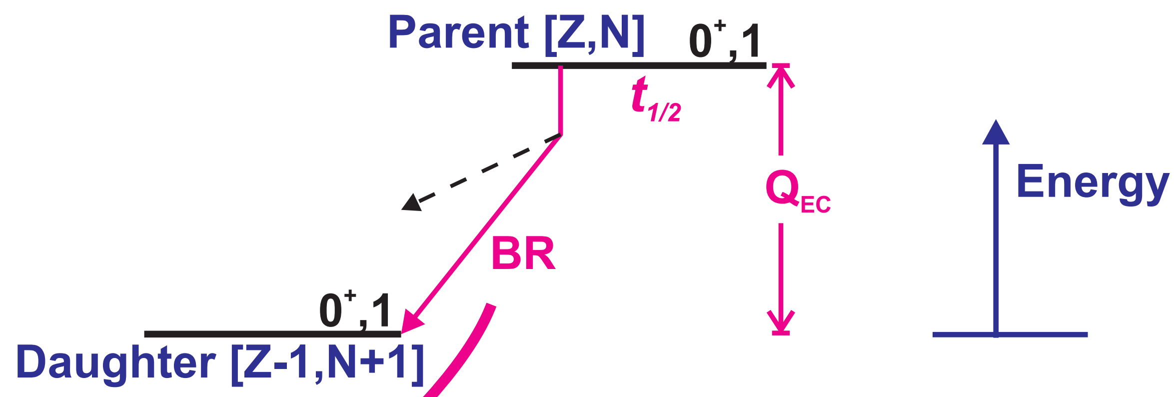
$t = f(t_{1/2}, BR)$

$\langle 1 \rangle$ = structure overlap

G_V = weak force strength

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

EXPERIMENT



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RADIATIVE CORRECTIONS

R R' NS C

all ~ 1%

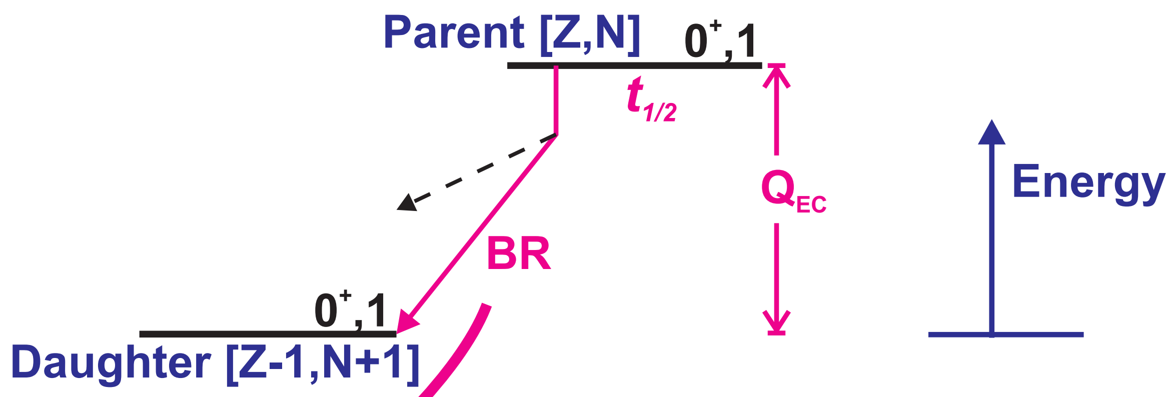
$_R = f(Z, Q_{EC})$

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

$_{NS}$, $_C = f(\text{nuclear structure})$

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

EXPERIMENT



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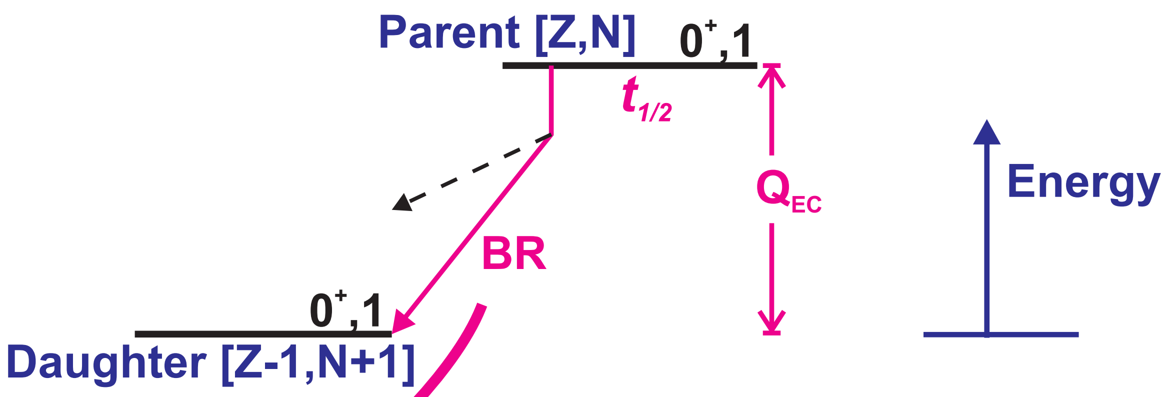
CORRECTED EQUATION

$$\mathcal{F}t = ft\,(1 + {}_R + {}_{NS} - {}_C) = \frac{K}{2G_V^2\,(1 + {}_R)}$$

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

EXPERIMENT



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RADIATIVE CORRECTIONS

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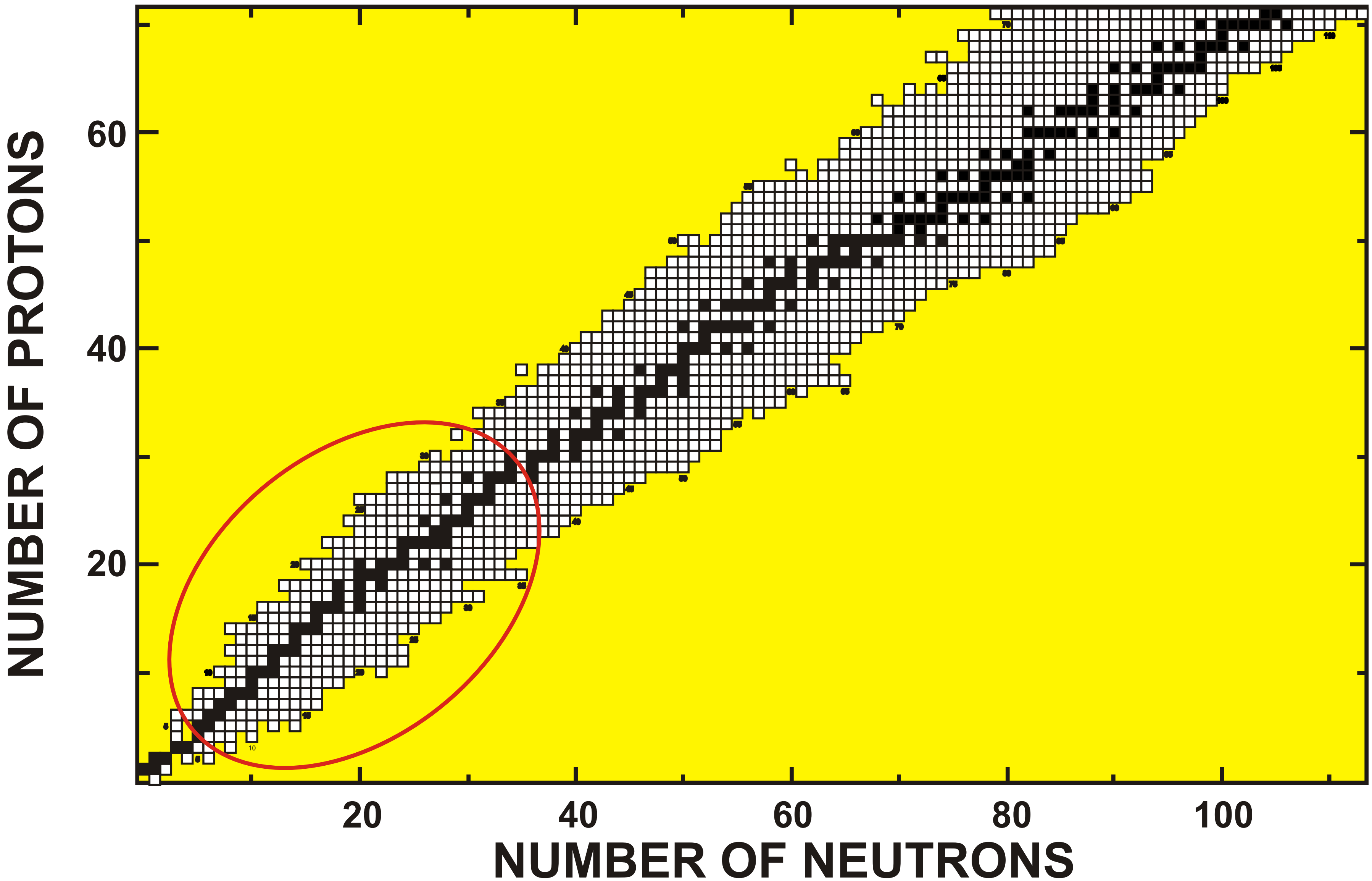
$$\mathcal{F}t = ft\,(1 + {}_{R} + {}_{NS} - {}_{C}) = \frac{K}{2G_V^{2}\,(1 + {}_{R})}$$

Do measured $\mathcal{F}t$ values yield a constant G_V?

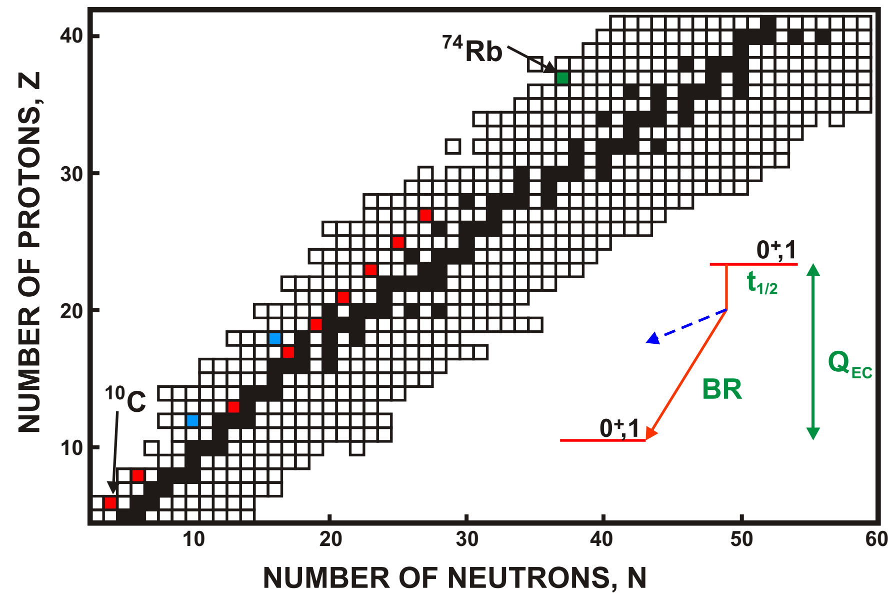
NUCLEAR CHART



WORLD DATA FOR $0^+ \rightarrow 0^+$ DECAYS

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

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



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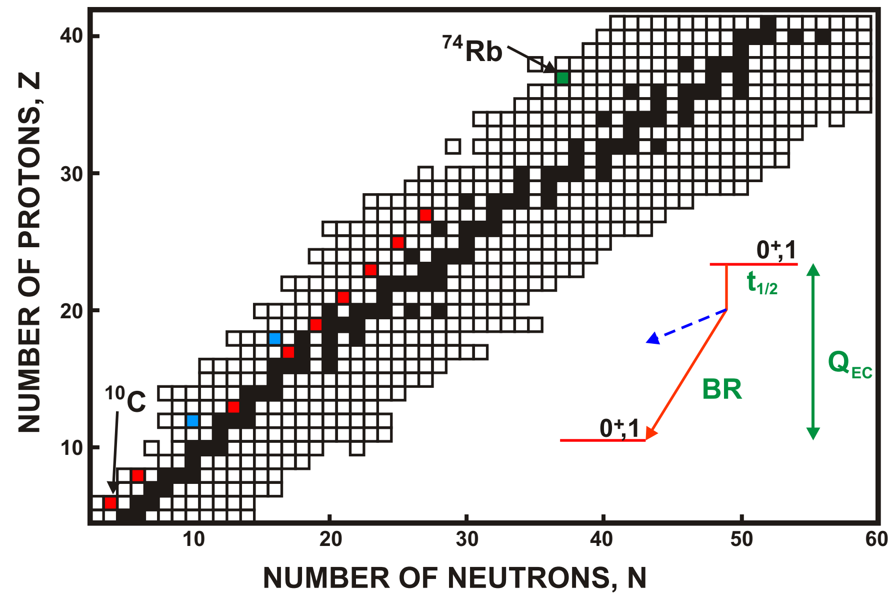
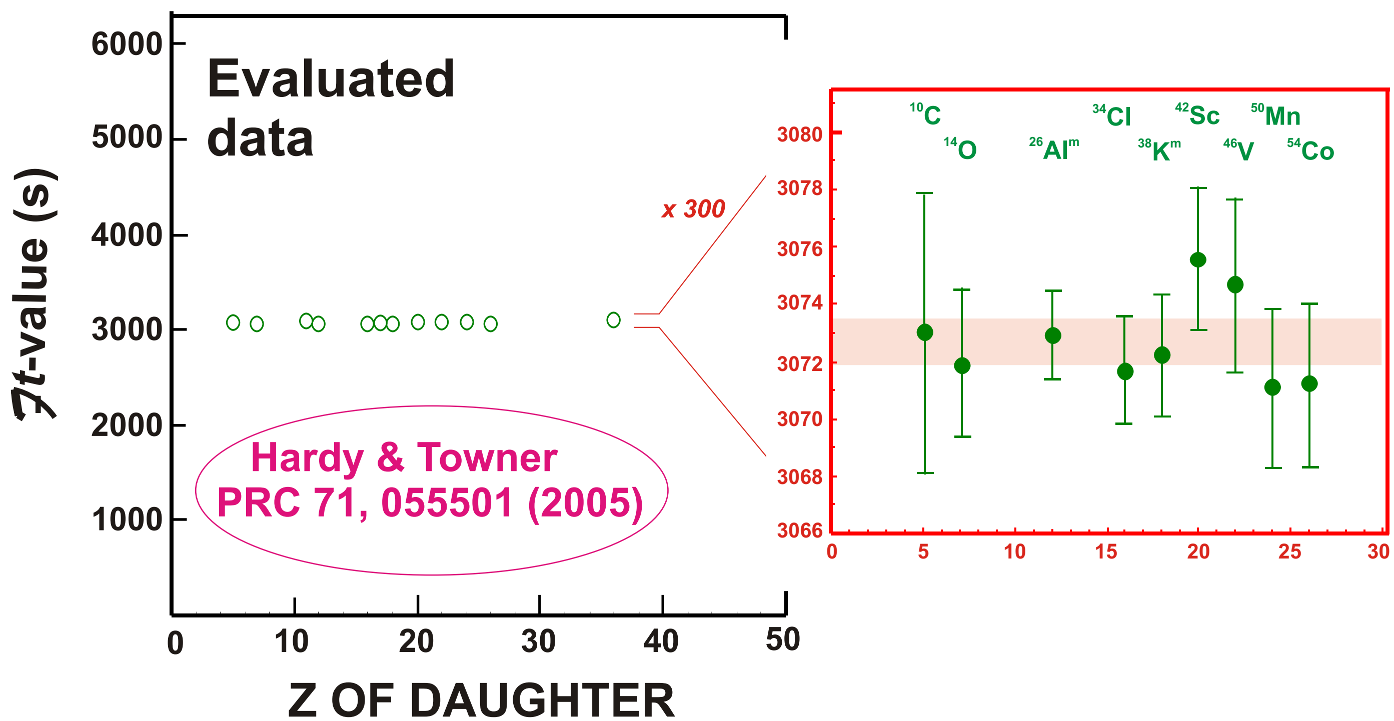
$$\mathcal{F}t = ft\,(1 + \delta'_R + \delta_{NS})(1 - \delta_C) = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$





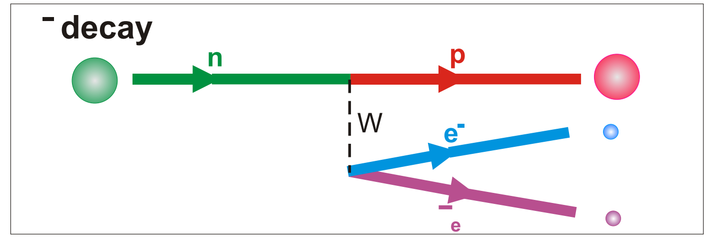
$\overline{\mathcal{F}t} = 3072.7(8)$

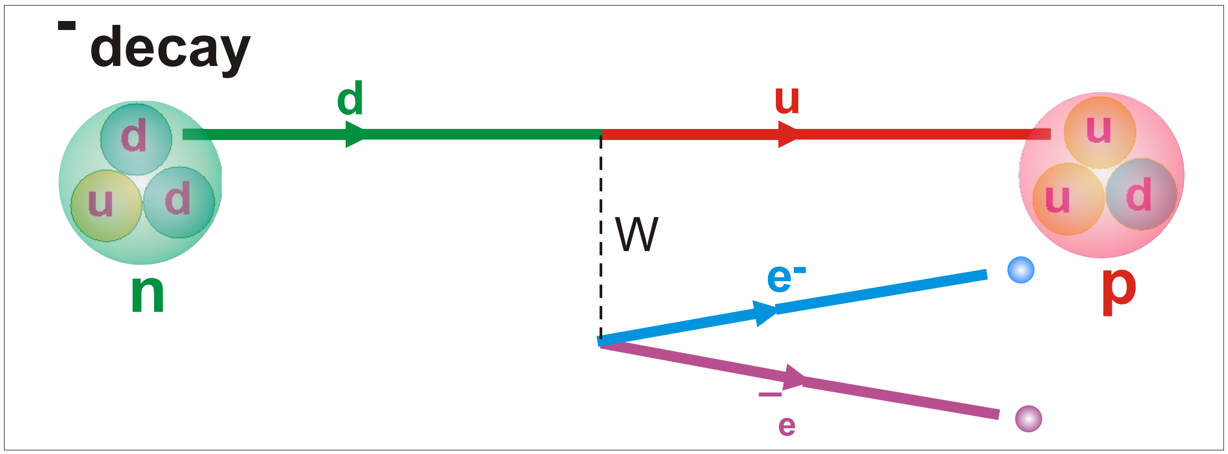
$G'_V/(\hbar c)^3 = 1.14950(15) \times 10^{-5}$ GeV^{-2}

$\chi^2/\nu = 0.4$

A WIDER VIEW

When a neutron (or proton) decays, it is really one of its constituent quarks that is decaying.





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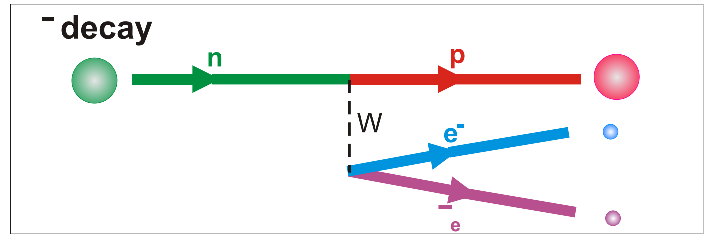
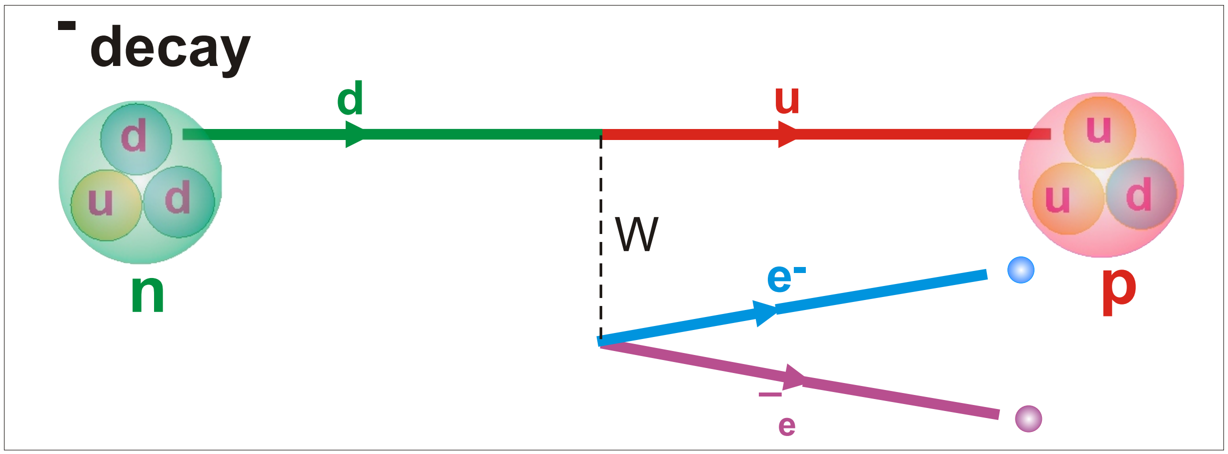
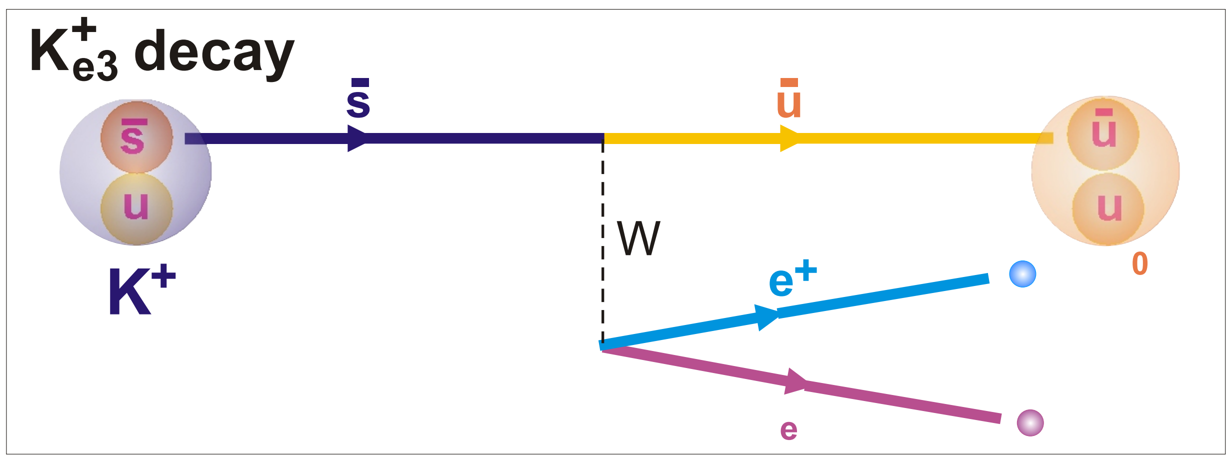




The weak decays of mesons involve different quark decays:



CKM MATRIX AND UNITARITY, 2007

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

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

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$|V_{ud}| = G_V / G$

nuclear (n &) decays

muon decay

0.9738 ± 0.0003

± 0.0001 exp't

$|V_{us}|$

$K^+ \longrightarrow \; ^0 e^+ \; _e$

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

0.2257 ± 0.0020

$|V_{ub}|$

B decays

0.0037 ± 0.0005

CKM MATRIX AND UNITARITY, 2007

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B decays

0.0037 ± 0.0005

WORLD DATA, 2005

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9992 \pm 0.0011$$

Where to from here?

Status today:

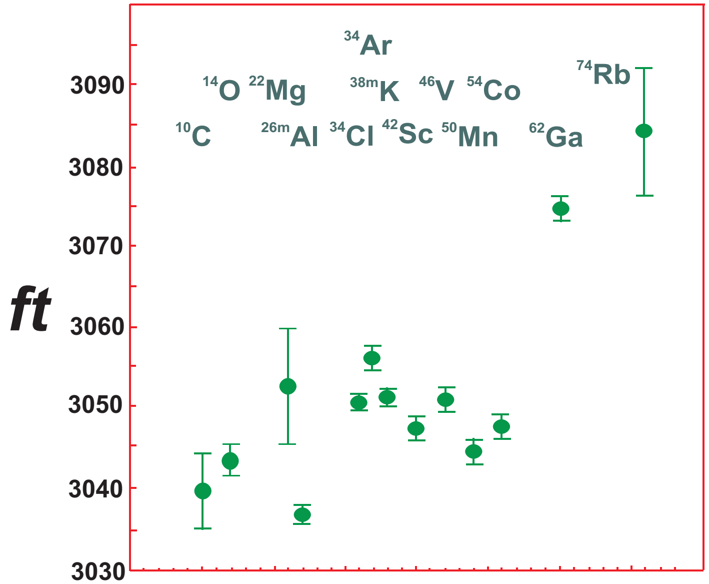
- Nuclei present a consistent picture: G_V constant
- Nuclear and kaon decays consistent: limits "new physics"
- Uncertainties dominated by theory

Active programs:

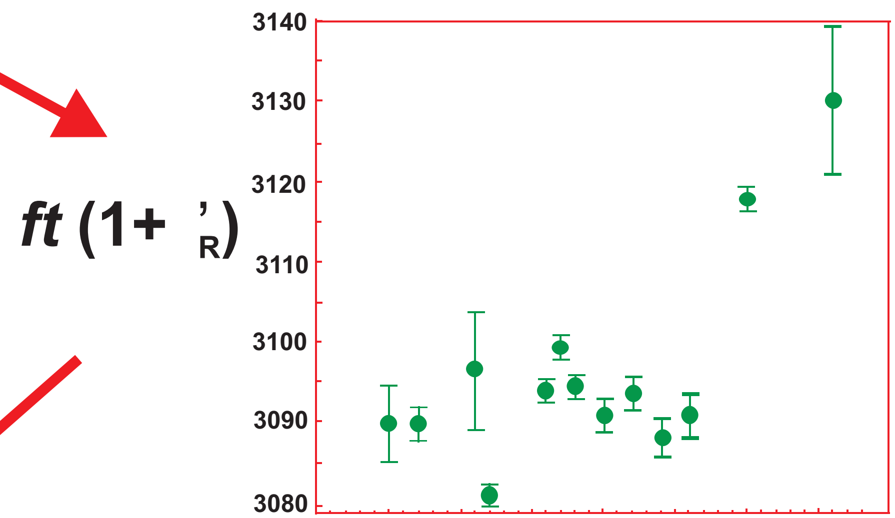
- Refine theoretical correction terms
- Measure new nuclear cases with larger calculated correction terms: independent test of corrections

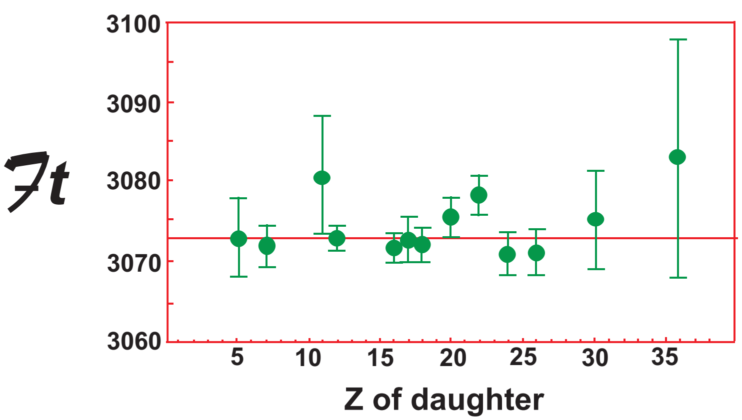
VALIDATION OF CORRECTION TERMS, $_C$ - $_{NS}$

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



Uncorrected *ft*-values for superallowed transitions scatter over a relatively wide range of values.

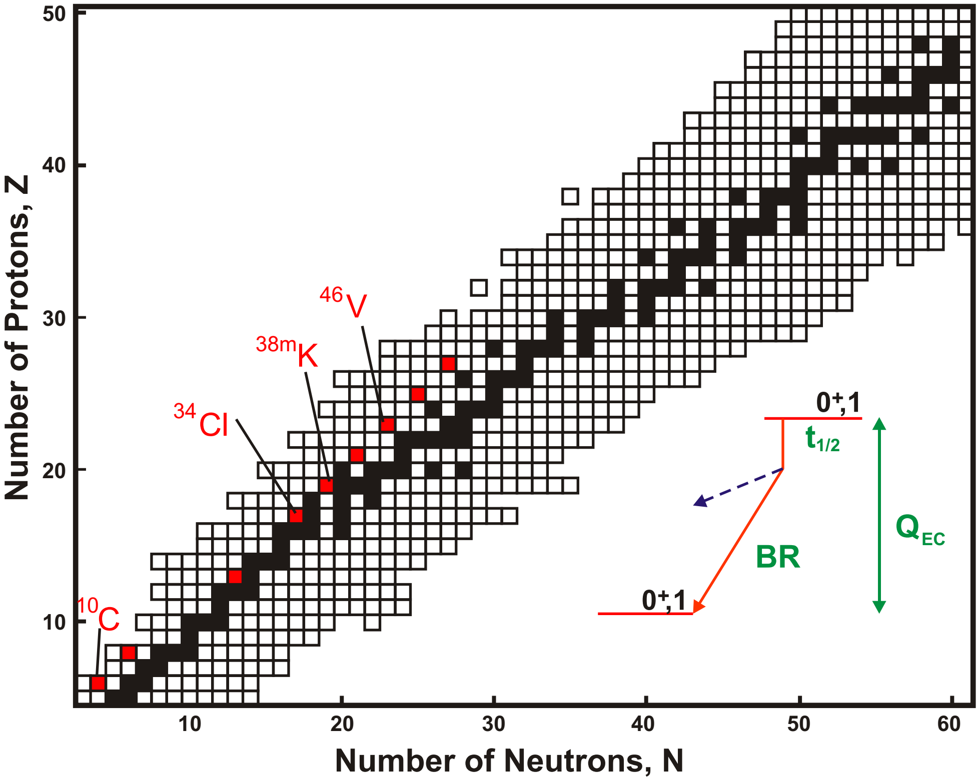




Corrected $\mathcal{F}t$-values have statistically identical values in agreement with CVC.

Extend test to other cases covering wider range of ($_C$ - $_{NS}$) values.

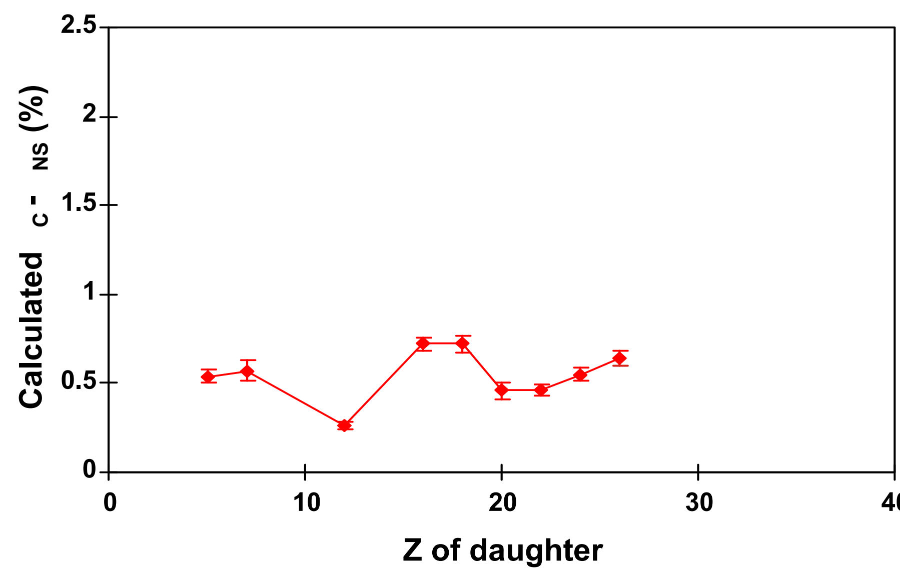
NEW MEASUREMENTS



Test $_{C}$ - $_{NS}$ to refine calculations and increase their credibility:

Increase measured precision on nine best *ft*-values

Calculations by Towner & Hardy, PRC 66, 035501 (2002)



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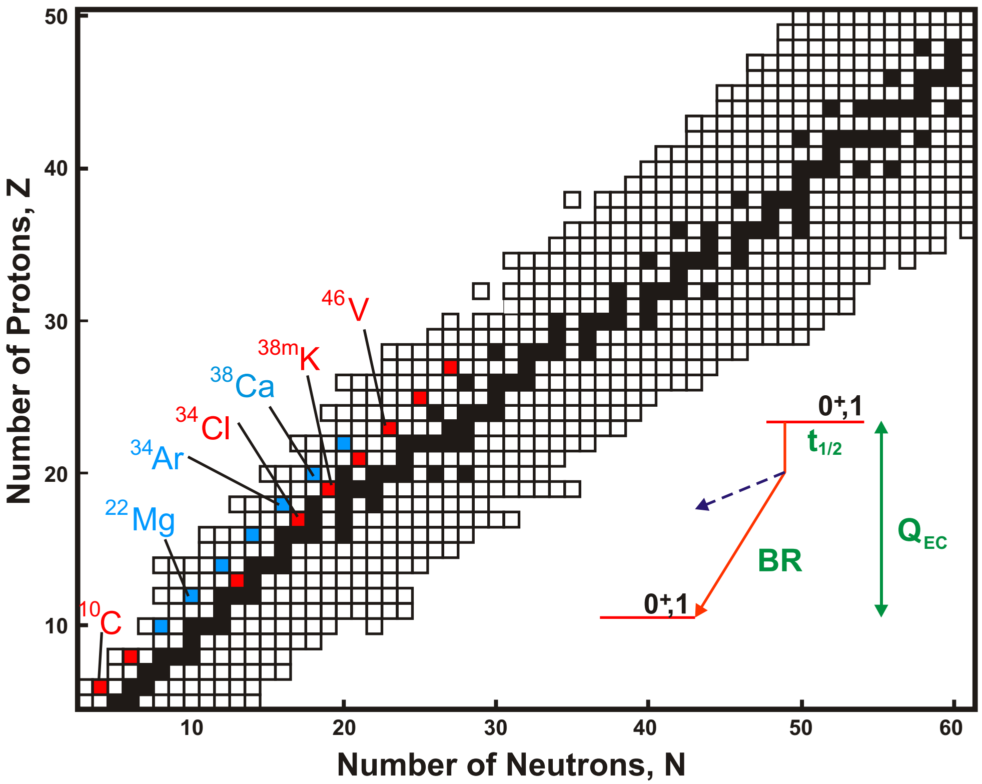

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measure new 0$^+$ → 0$^+$ decays with 18 ≤ A ≤ 42 (T$_Z$ = -1)

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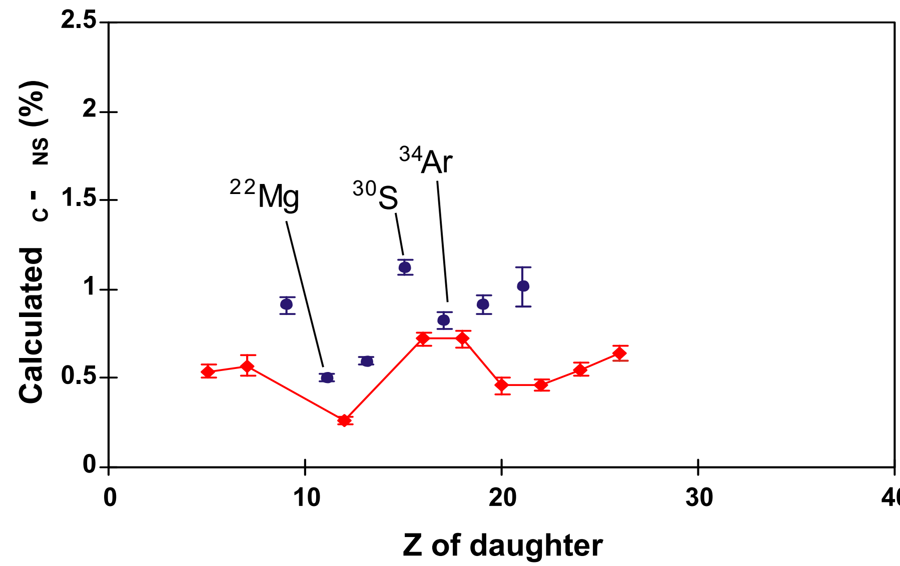

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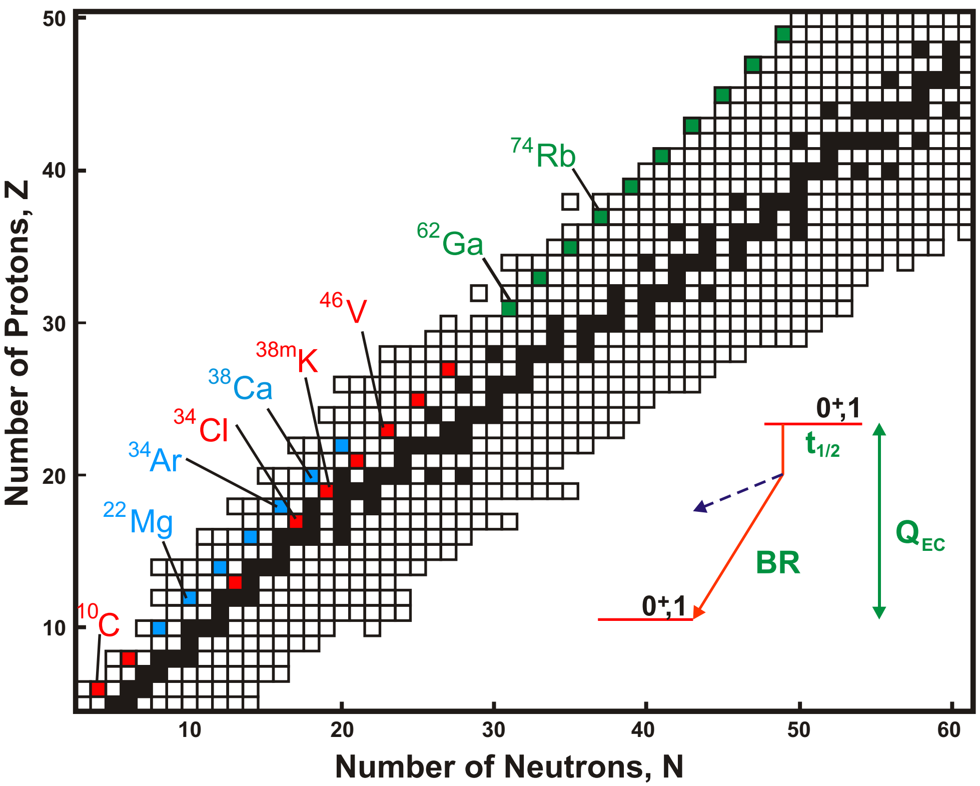

Test $_C$ - $_{NS}$ to refine calculations and increase their credibility:

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

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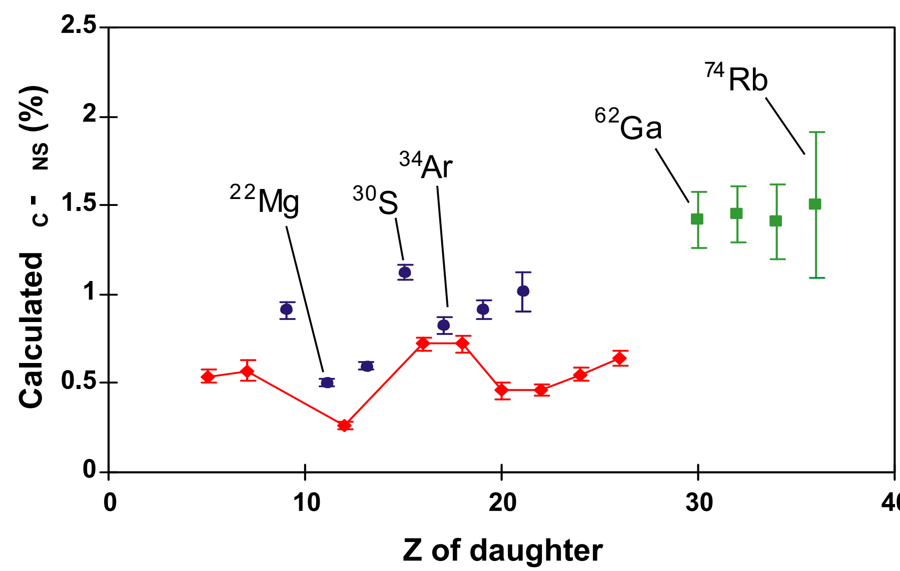

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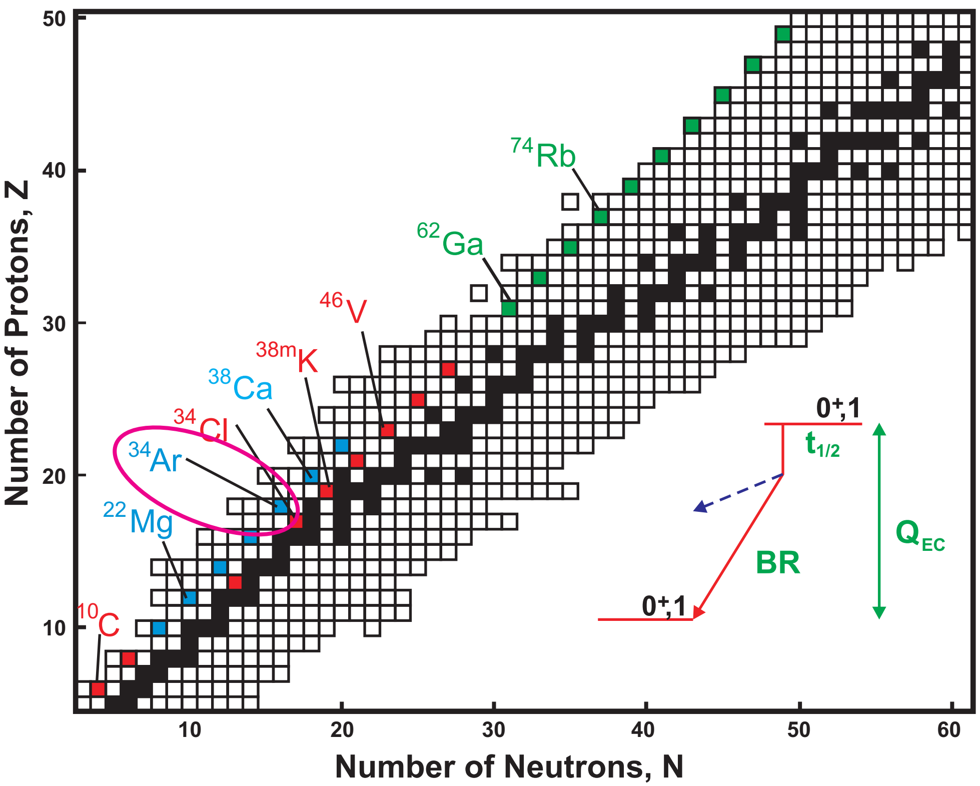

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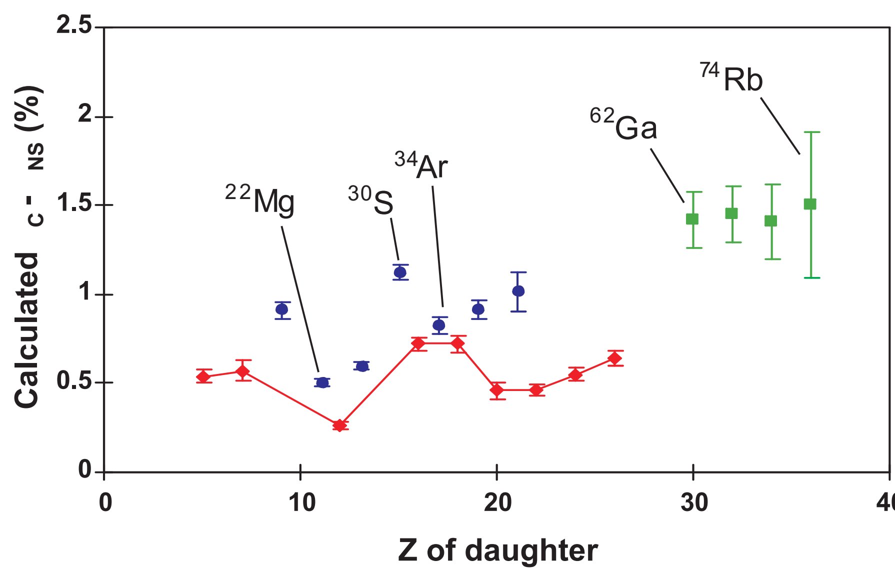

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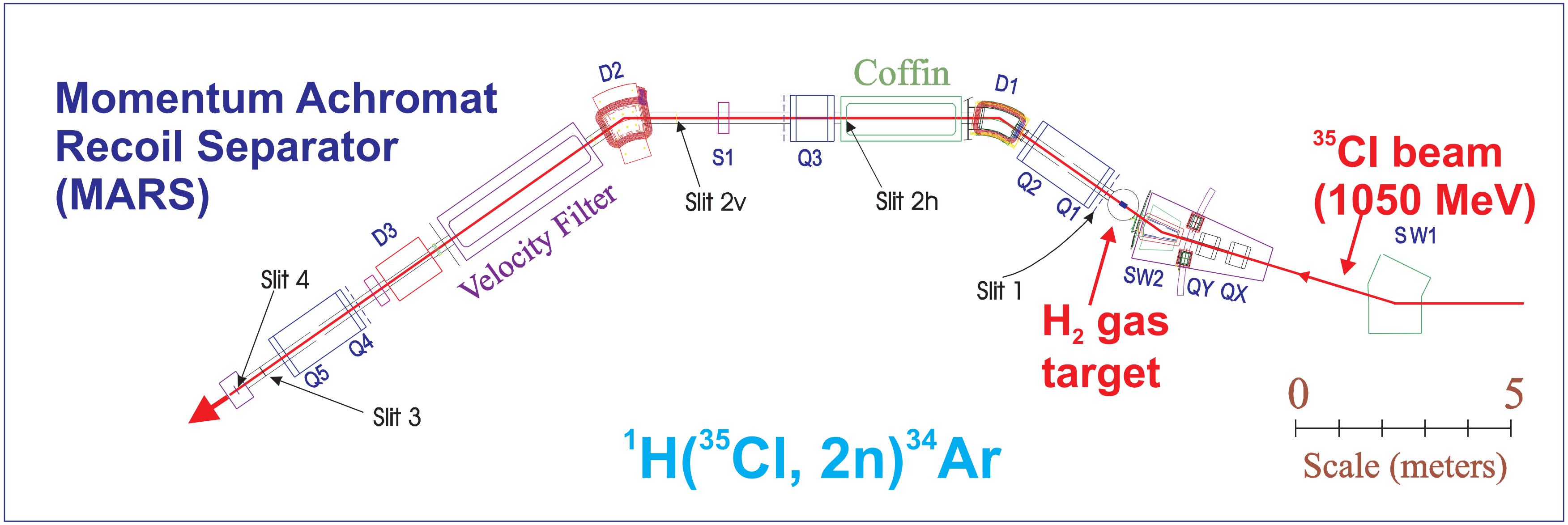
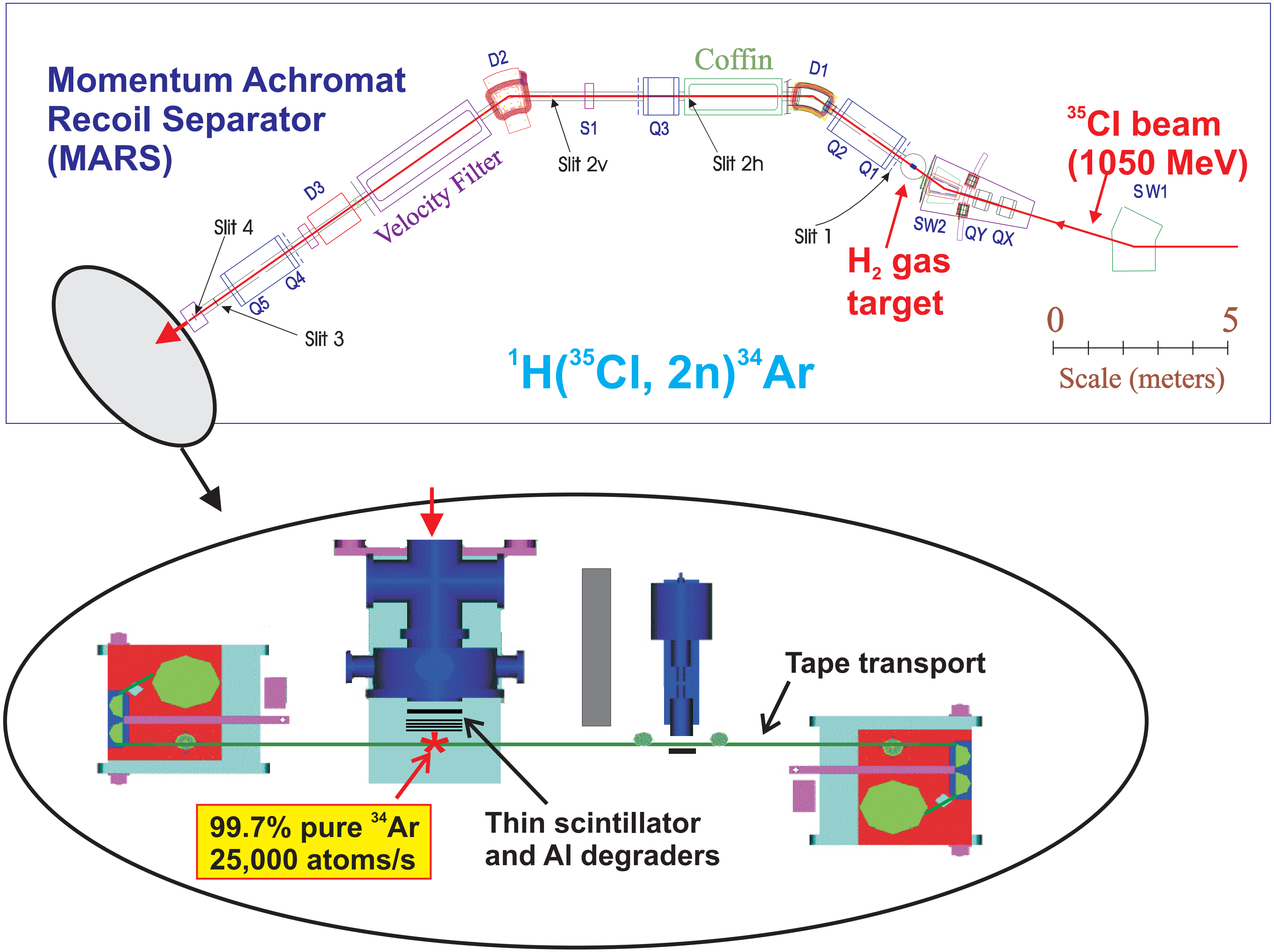
PRECISION DECAY MEASUREMENTS AT TAMU

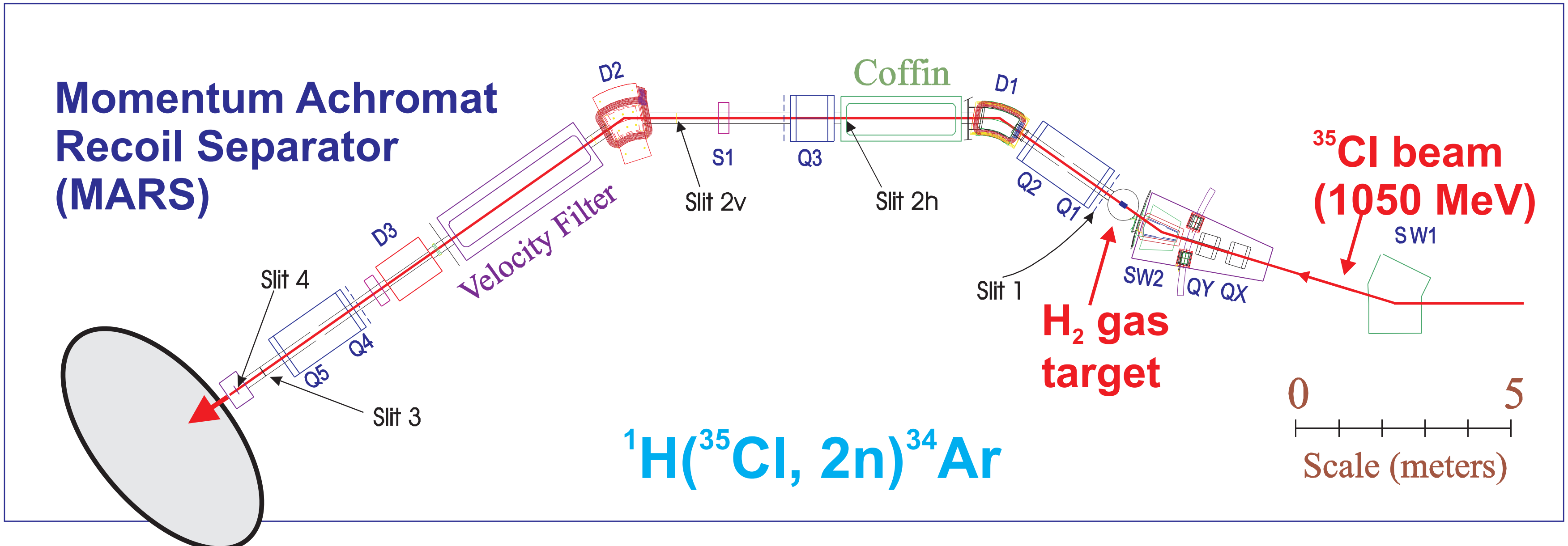


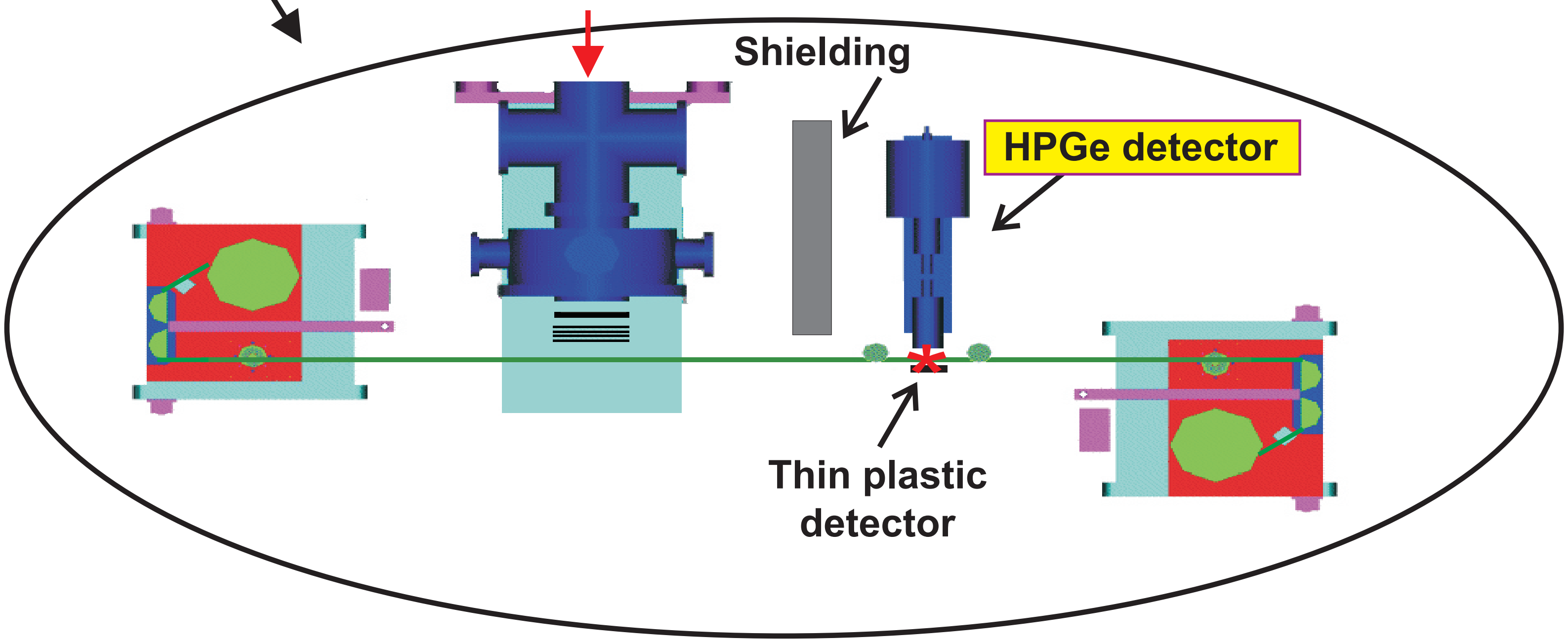
$^{1}H(^{35}Cl, 2n)^{34}Ar$

PRECISION DECAY MEASUREMENTS AT TAMU

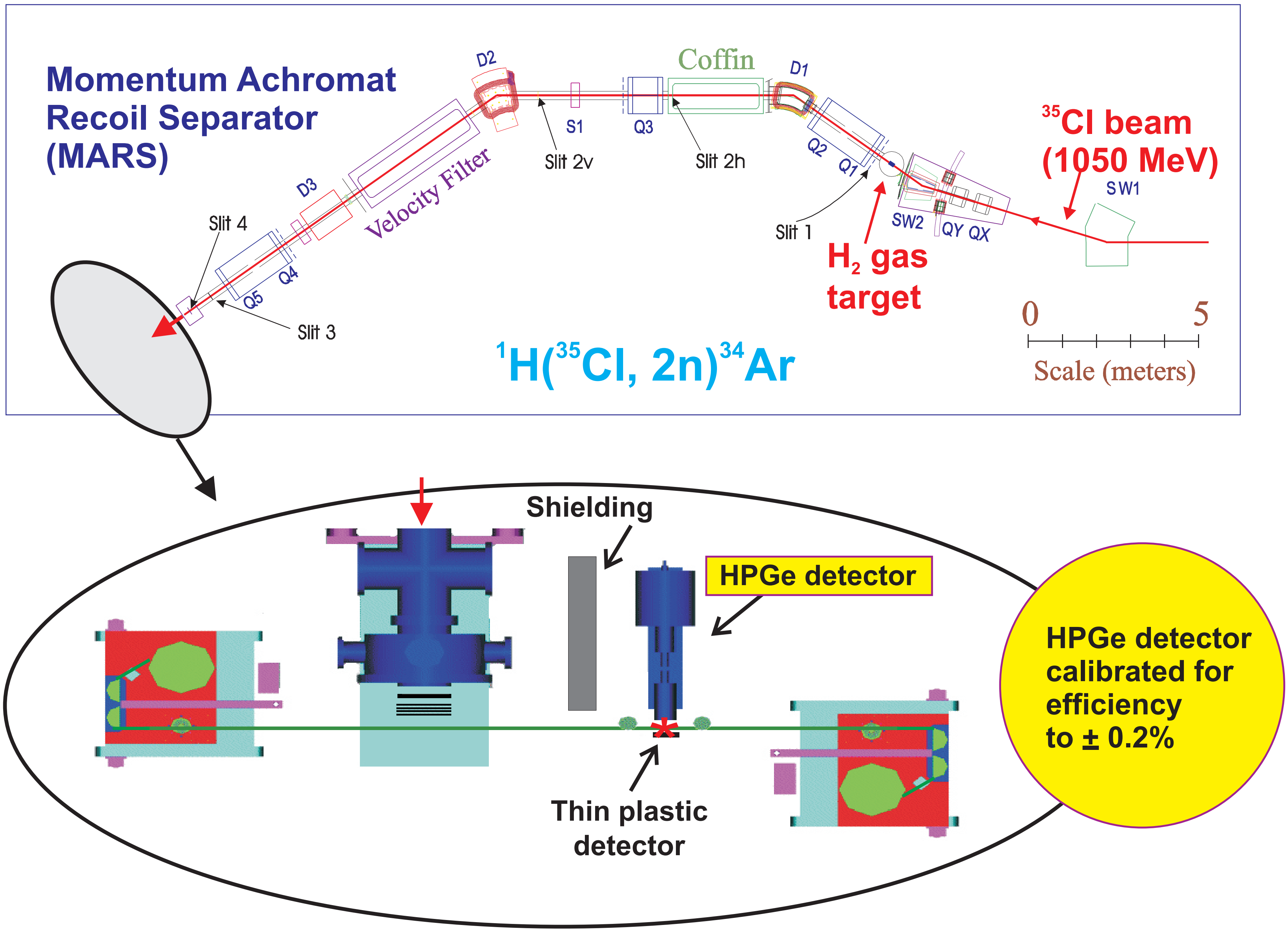


PRECISION DECAY MEASUREMENTS AT TAMU

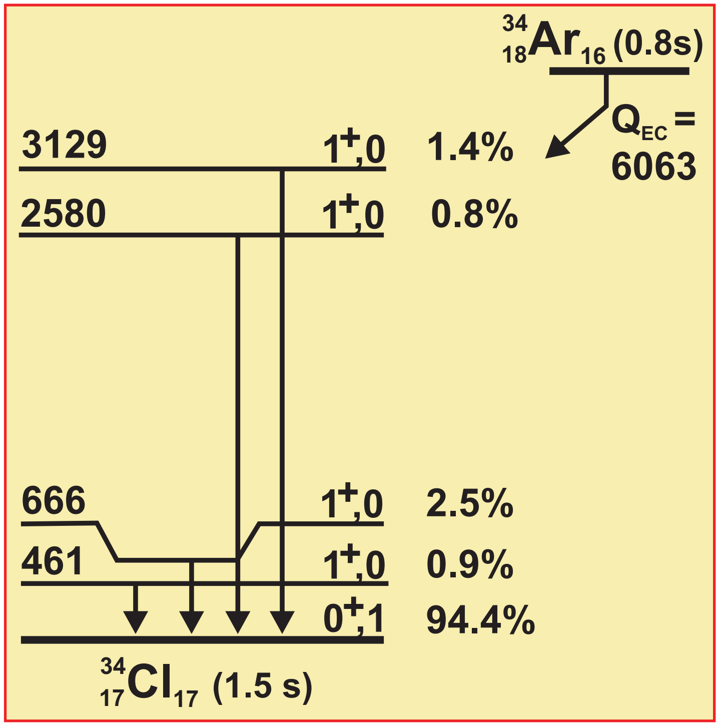


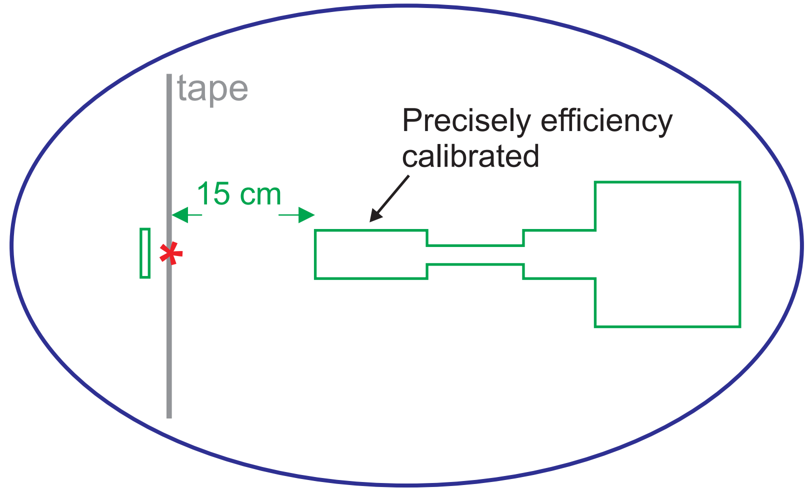


PRECISION DECAY MEASUREMENTS AT TAMU

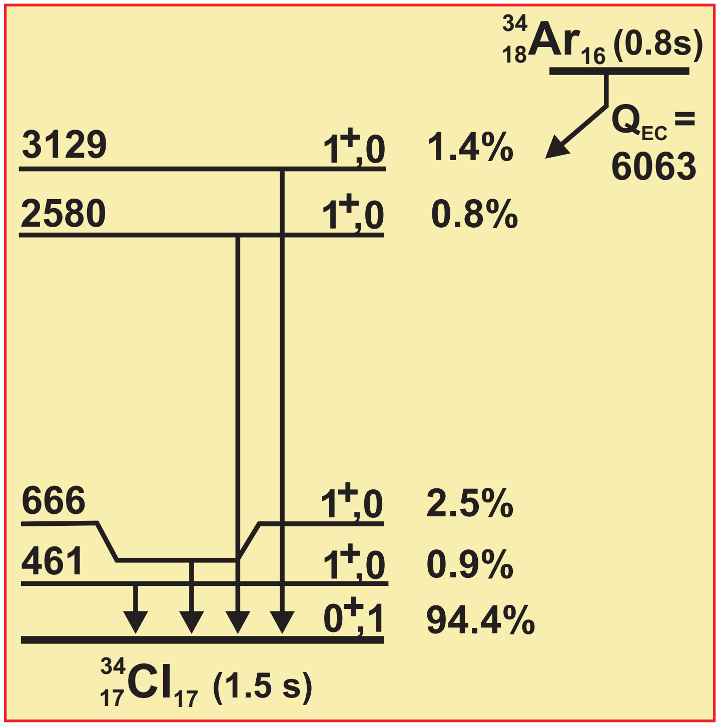


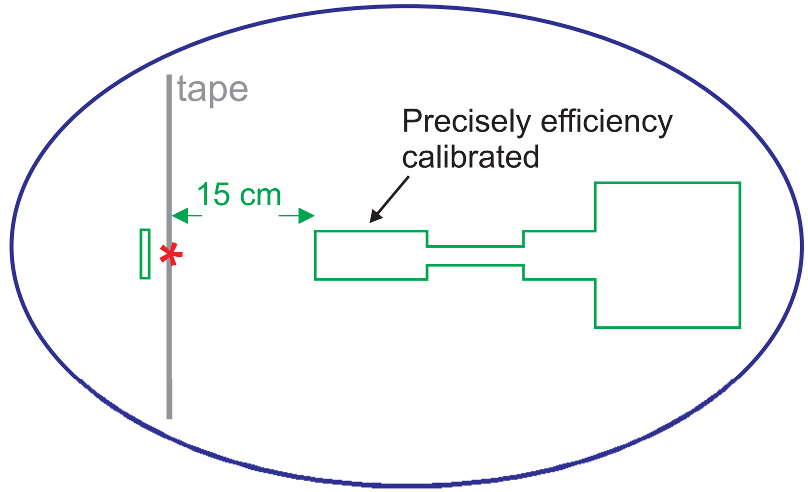
BETA-DECAY BRANCHING OF ^{34}Ar

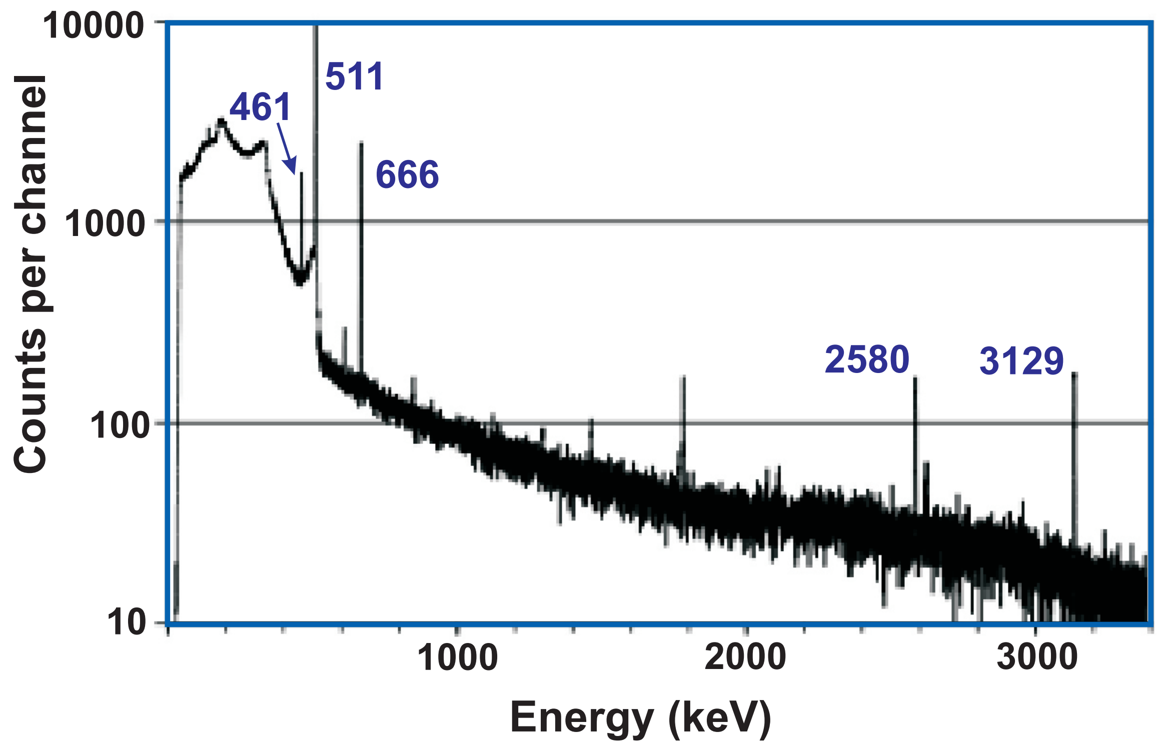




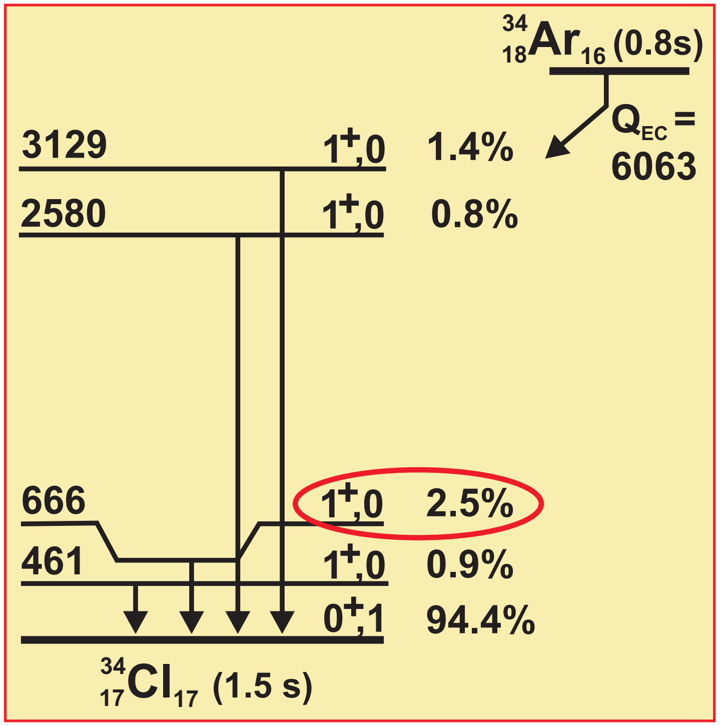
BETA-DECAY BRANCHING OF ^{34}Ar



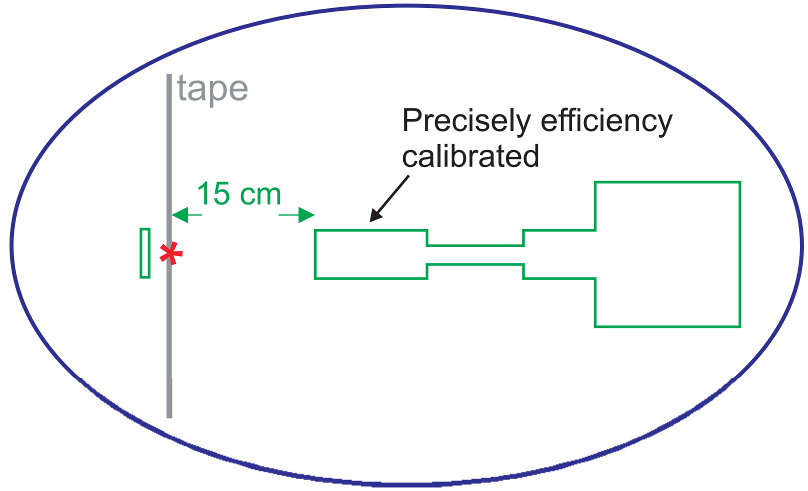


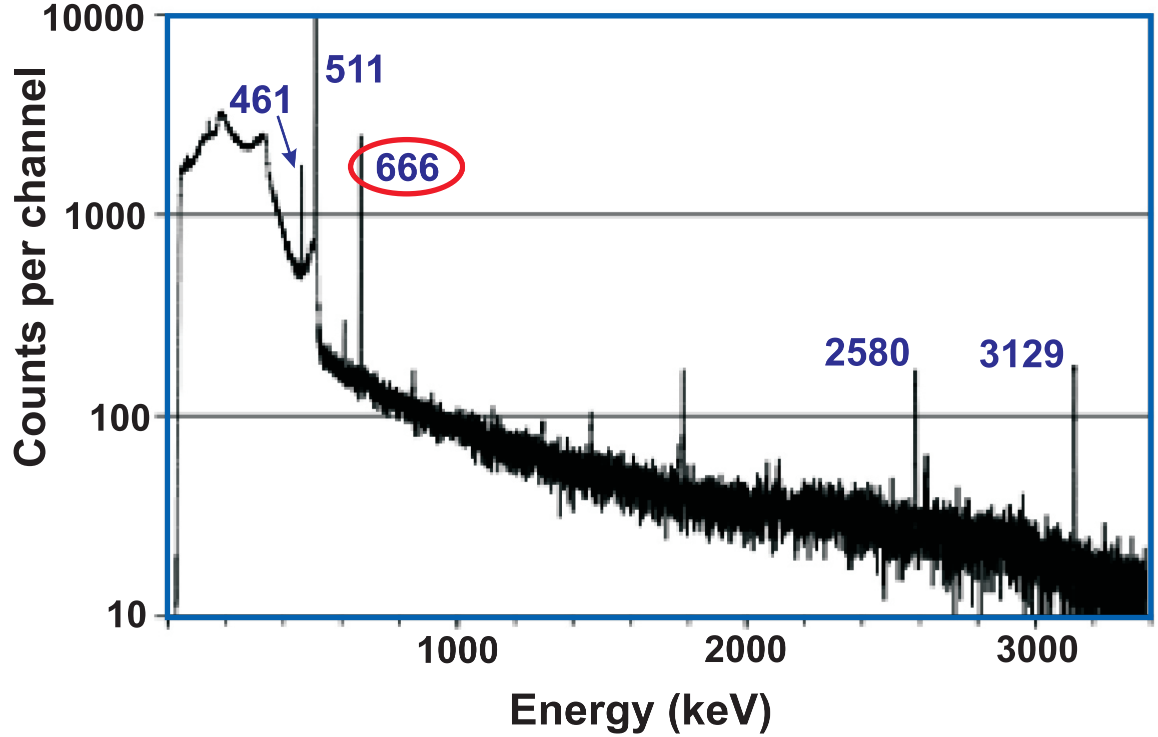


BETA-DECAY BRANCHING OF ^{34}Ar

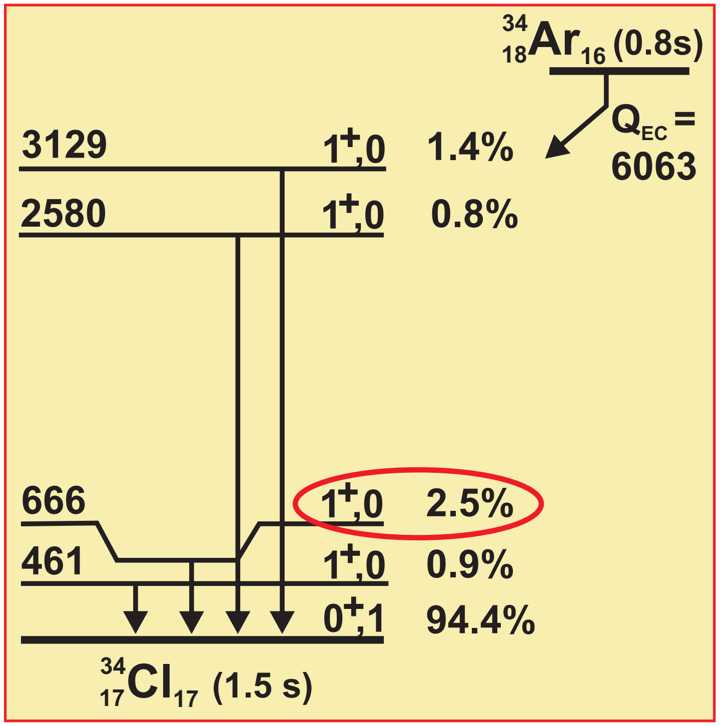


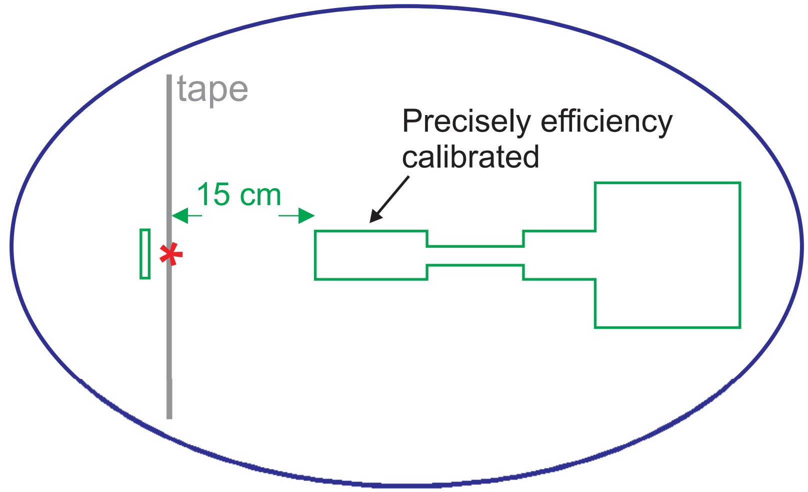
$$\frac{N_1}{N} = \frac{N_0 R_1}{N_0}\ ^{1}$$



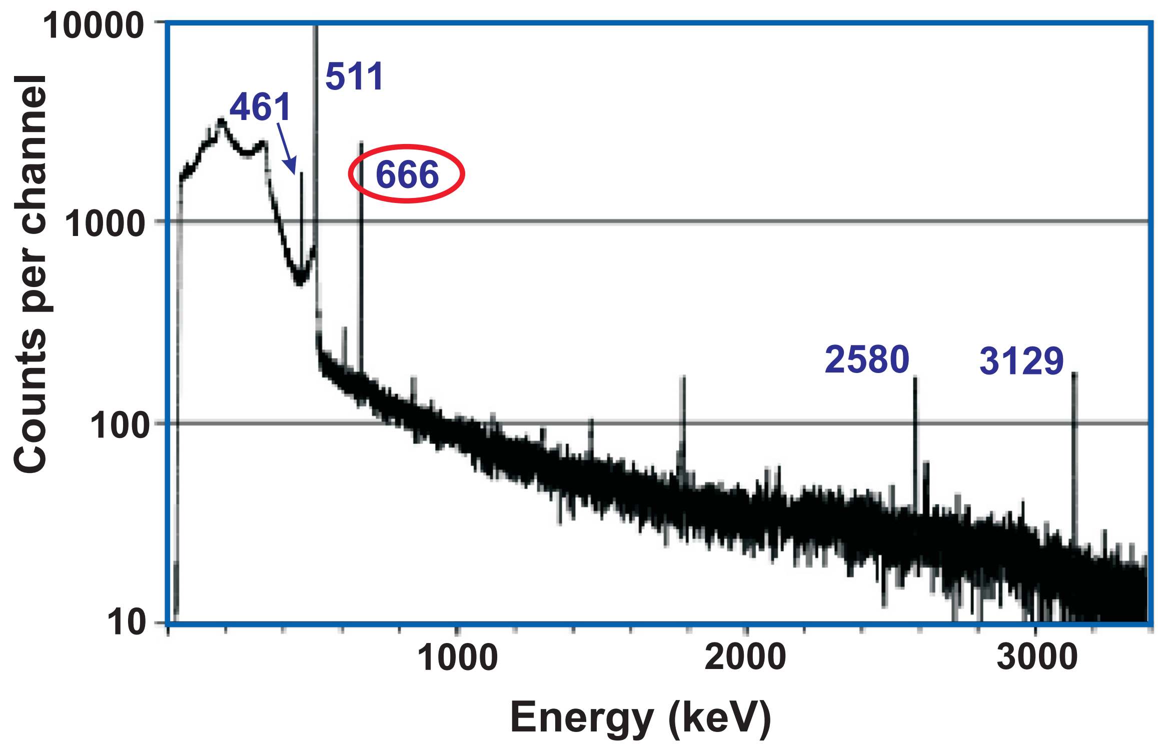


BETA-DECAY BRANCHING OF ^{34}Ar

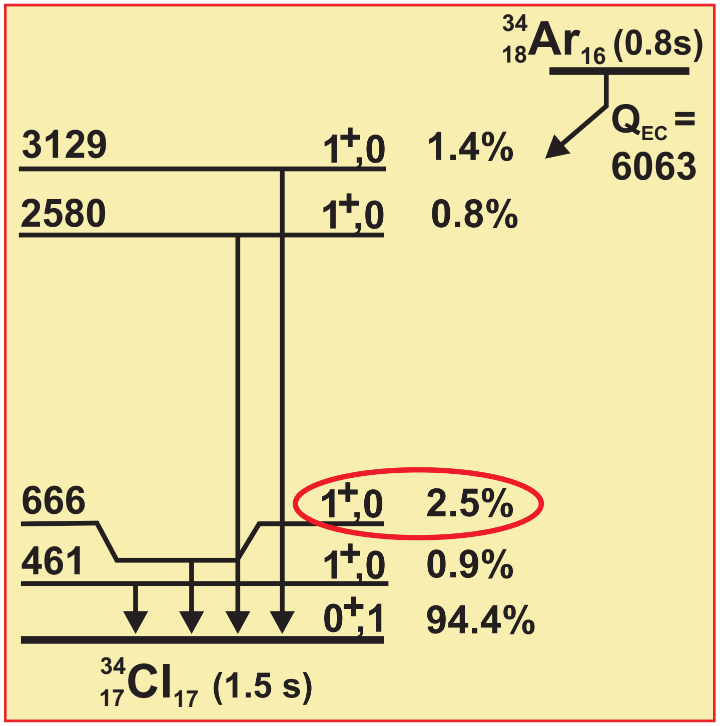


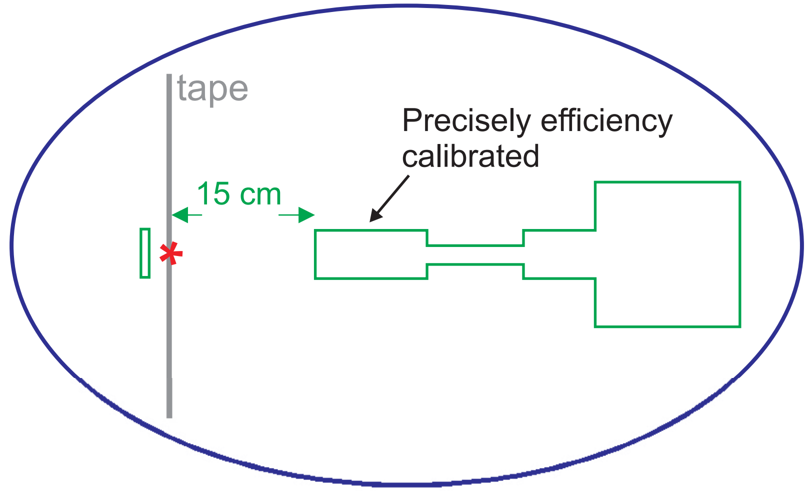


$$\frac{N_1}{N} = \frac{\cancel{N_0}\, R_1}{\cancel{N_0}} \quad 1$$



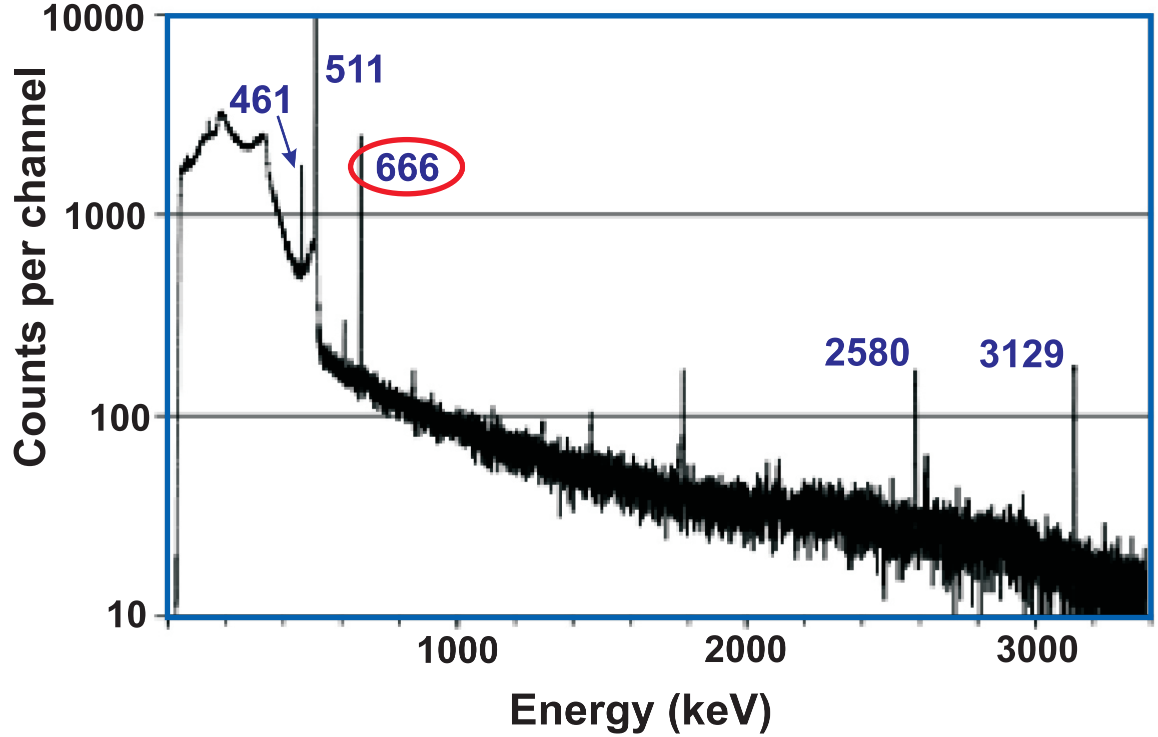
BETA-DECAY BRANCHING OF ^{34}Ar



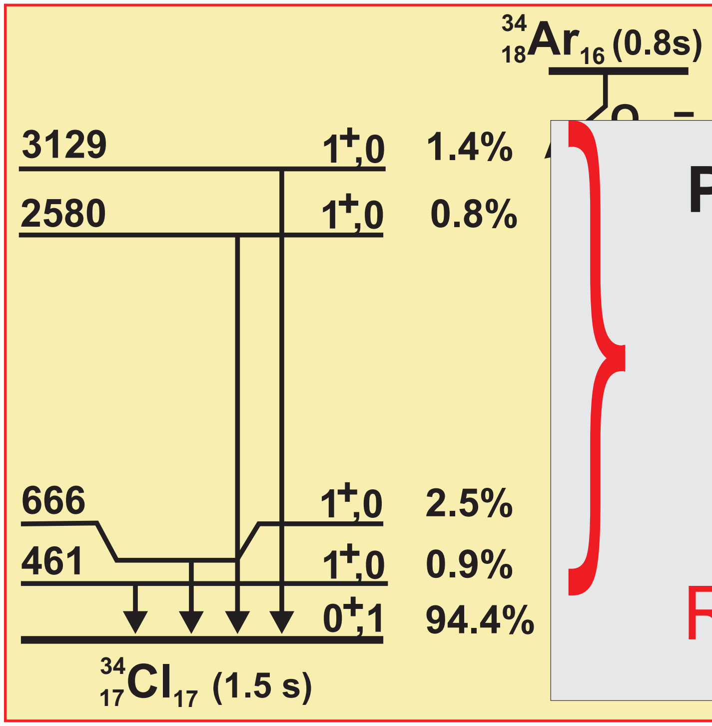


$$\frac{N_1}{N} = \frac{N_o R_1 \;{}_1}{N_o}$$

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



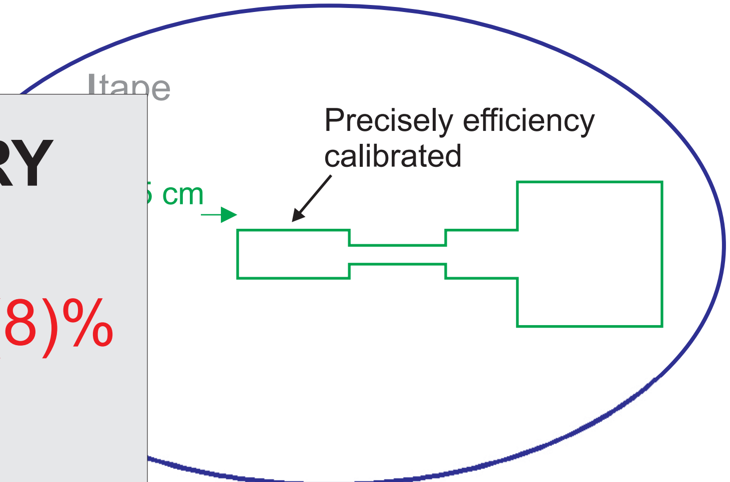
BETA-DECAY BRANCHING OF ^{34}Ar

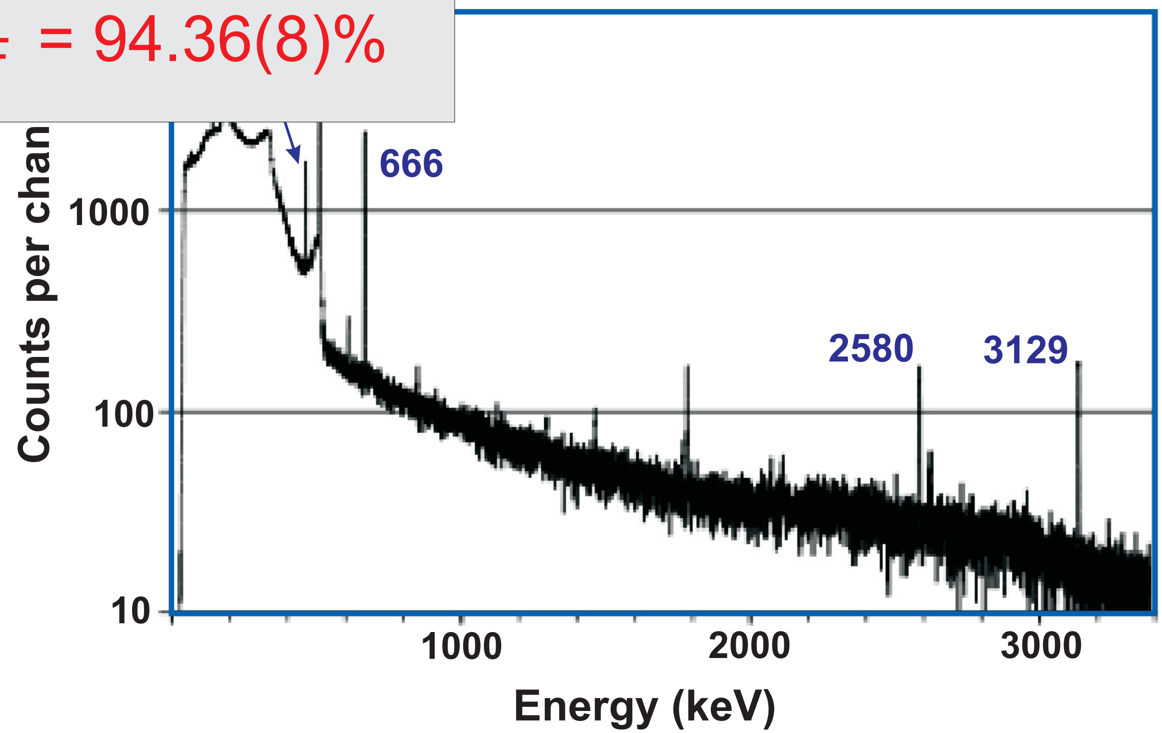


PRELIMINARY

$R_{GT} = 5.64(8)\%$

$R_F = 94.36(8)\%$

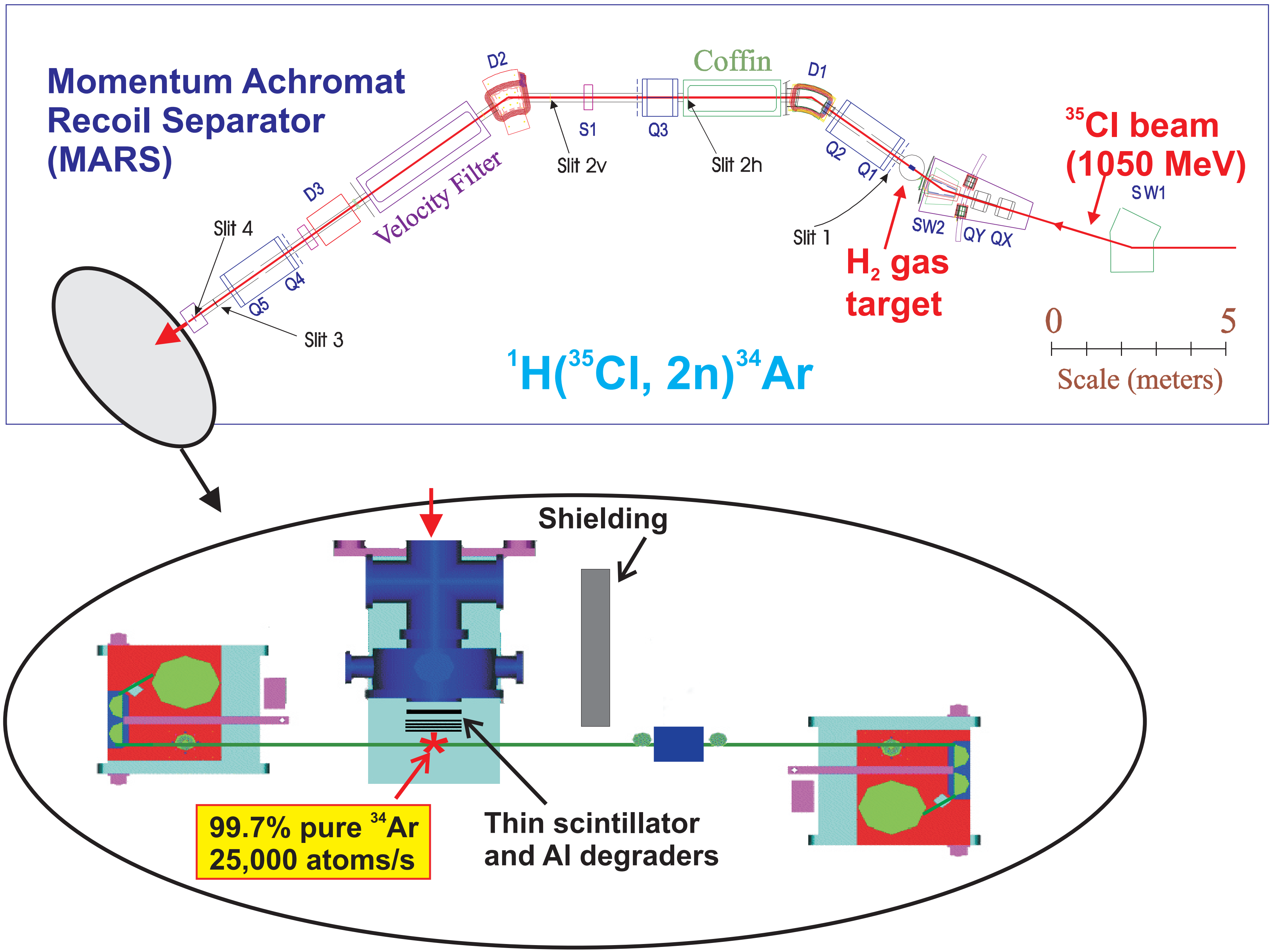




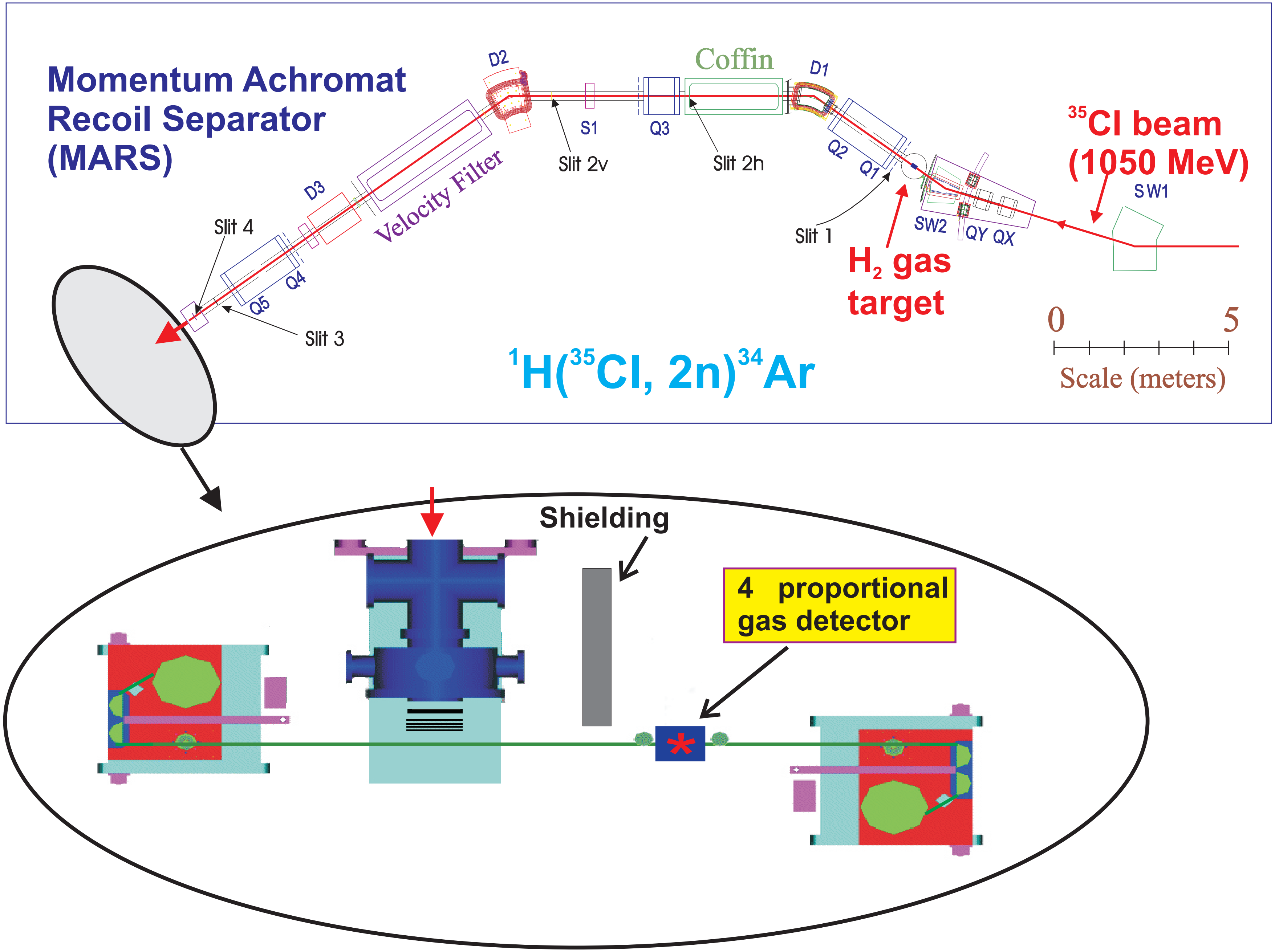
$$\frac{N_1}{N} = \frac{\not{N_0}\, R_1}{\not{N_0}}$$

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

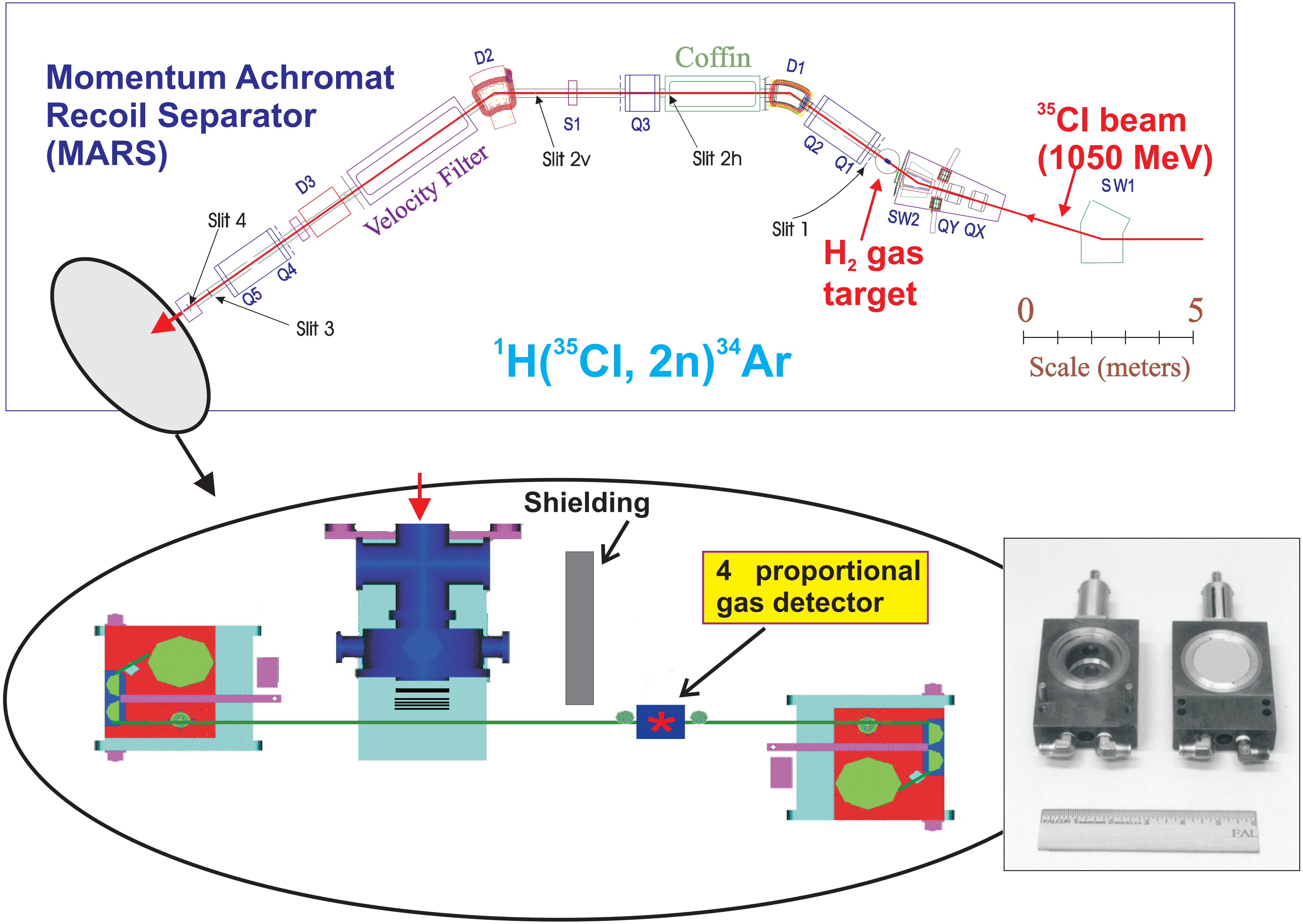
PRECISION DECAY MEASUREMENTS AT TAMU



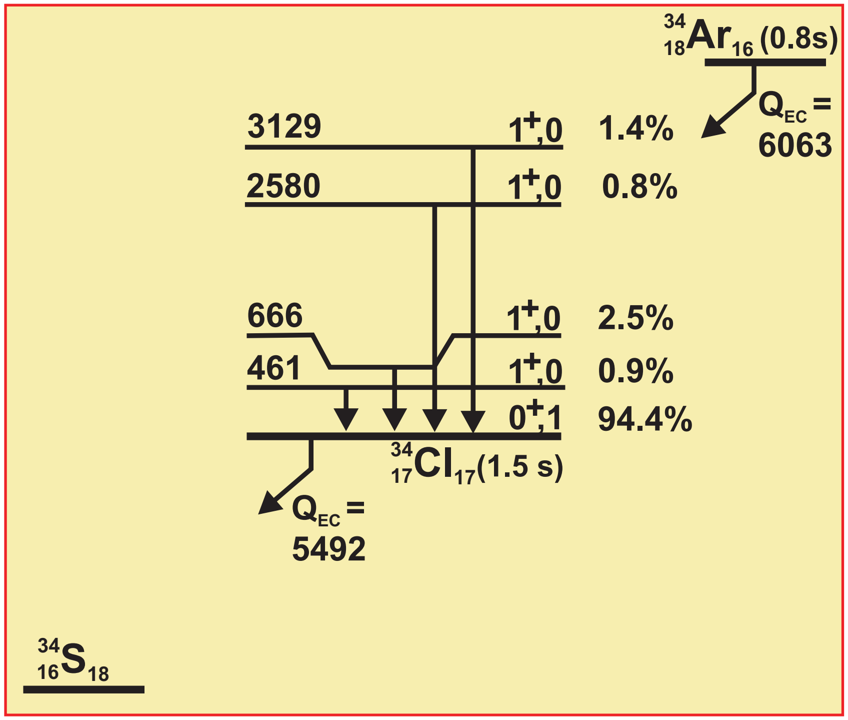
PRECISION DECAY MEASUREMENTS AT TAMU



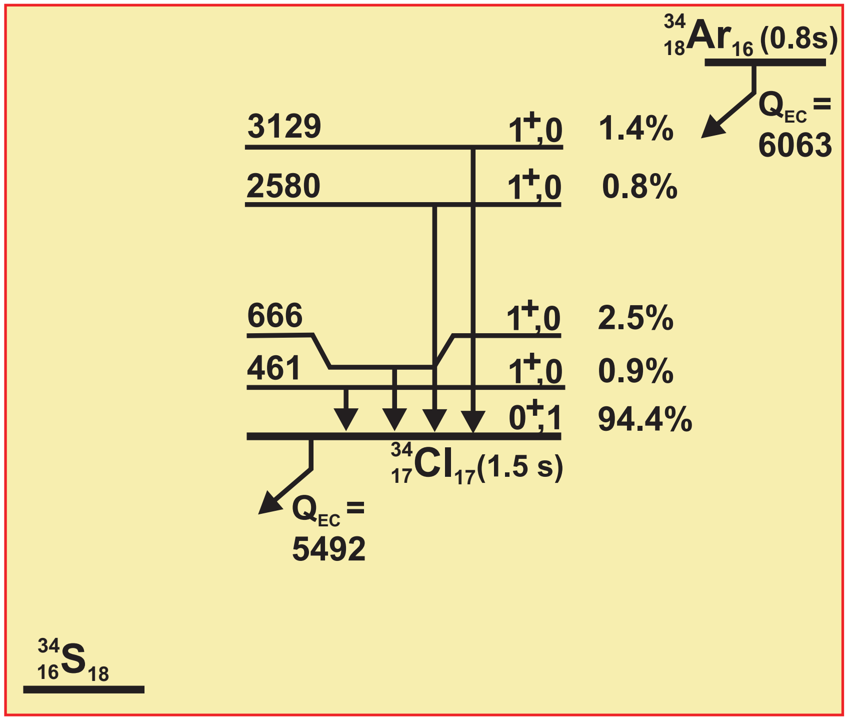
PRECISION DECAY MEASUREMENTS AT TAMU

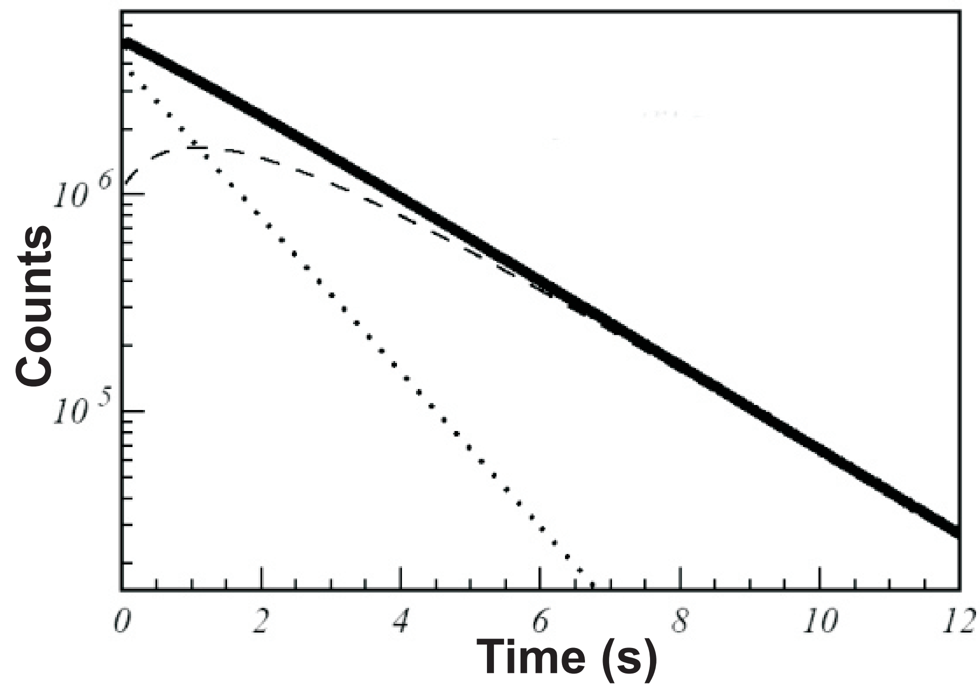


HALF LIFE OF ^{34}Ar

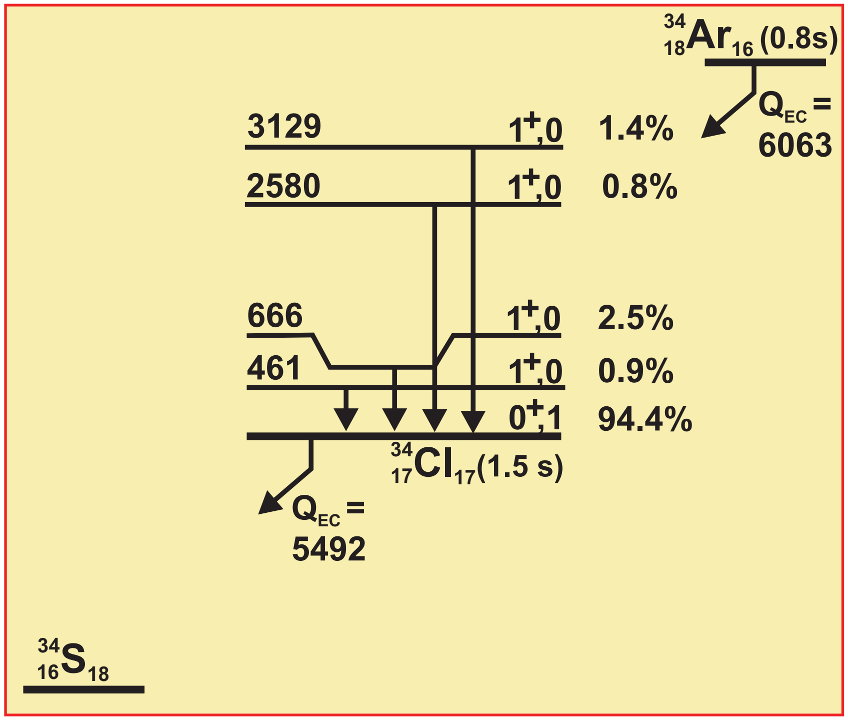


HALF LIFE OF ^{34}Ar

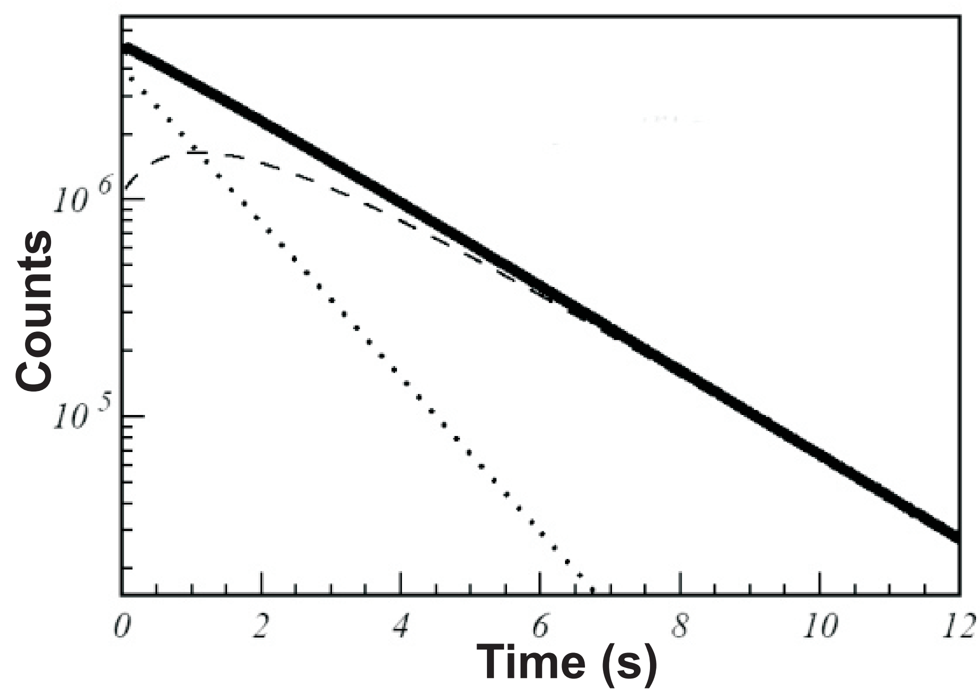




HALF LIFE OF ^{34}Ar



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

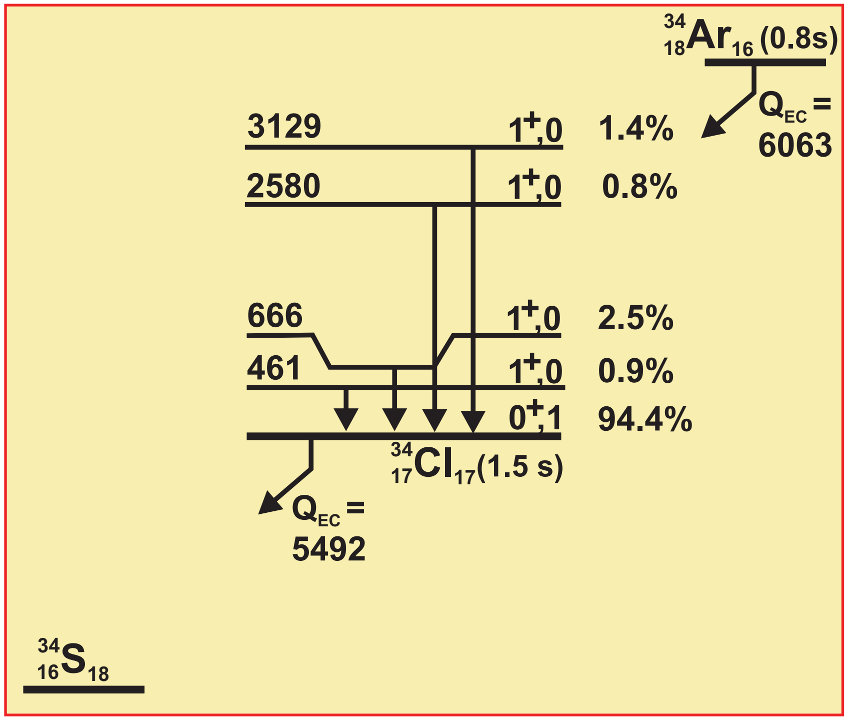


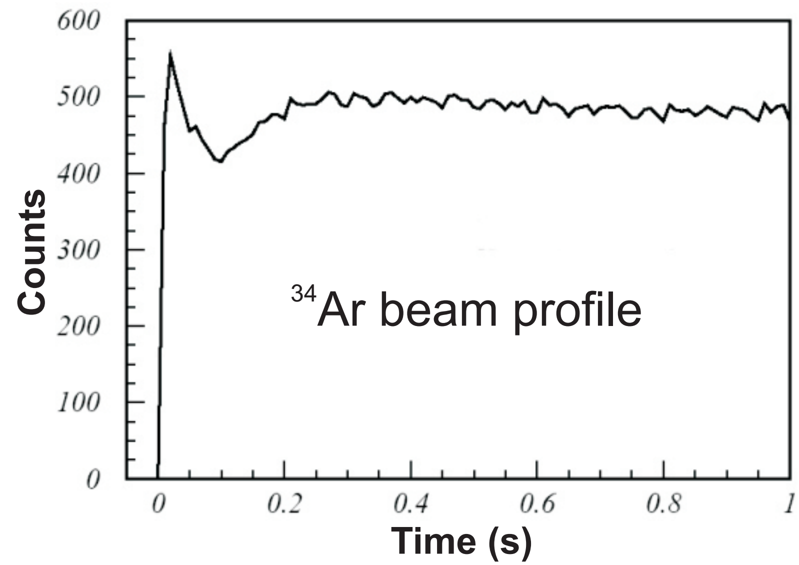
where

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

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

HALF LIFE OF ^{34}Ar



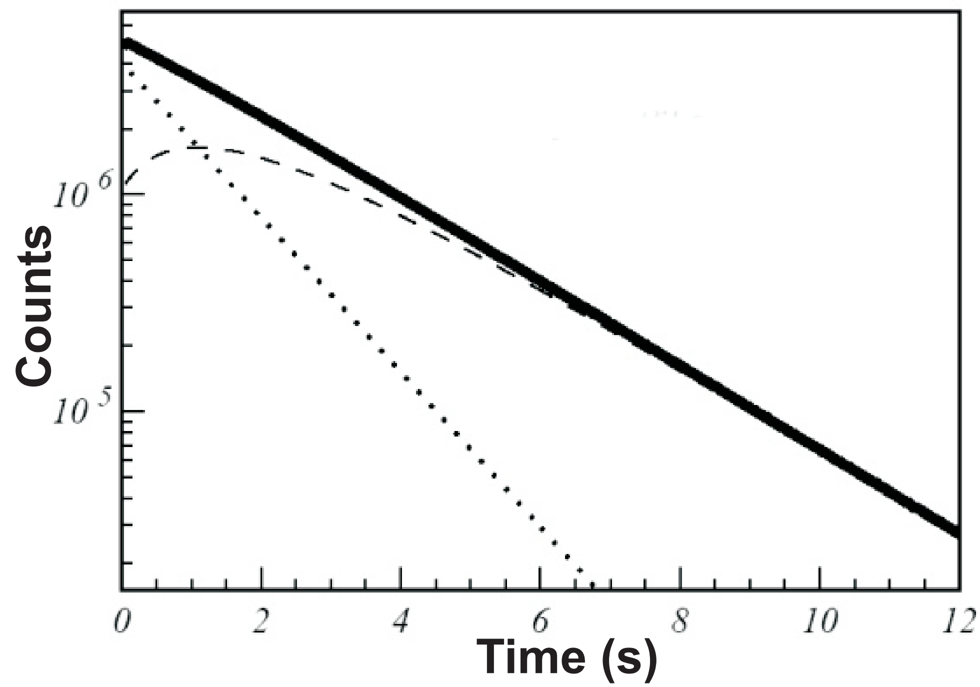


$$_{tot} = C_1 e^{\ _1 t} + C_2 e^{\ _2 t}$$

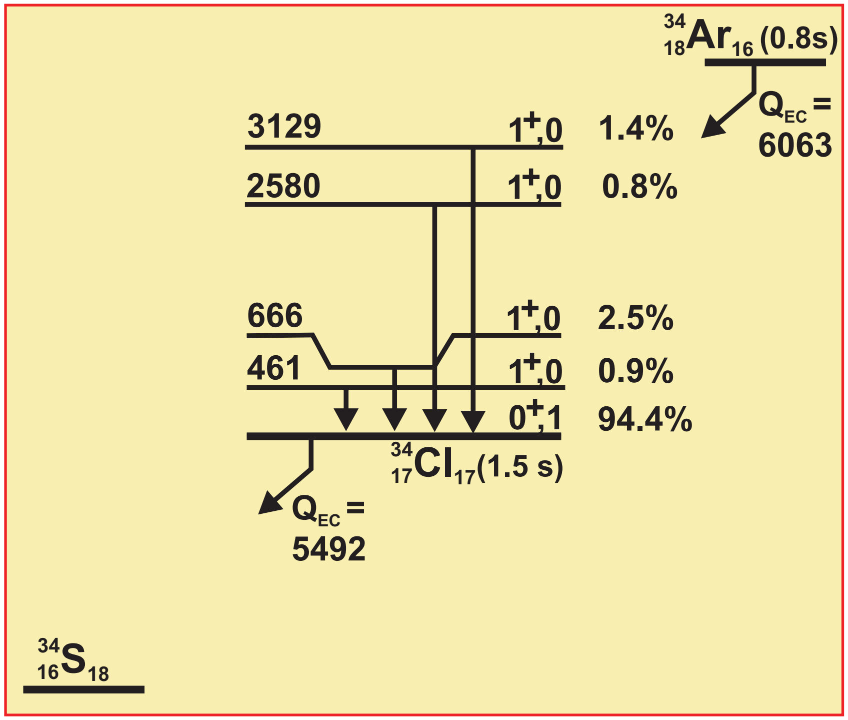
where

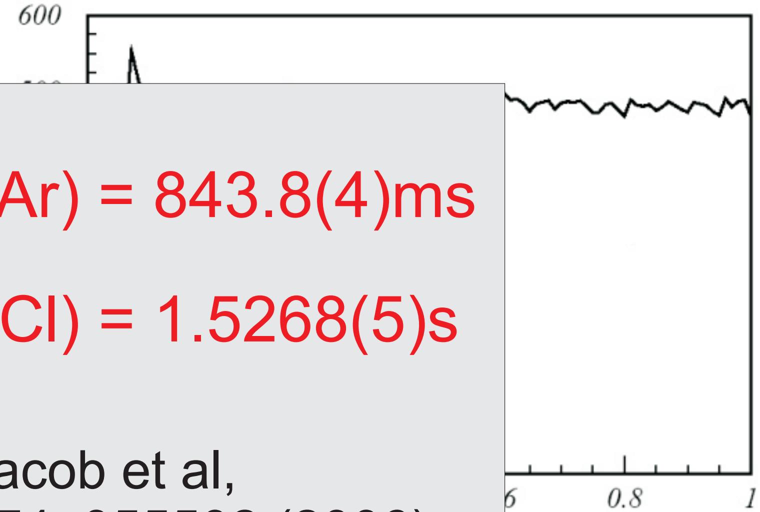
$$C_1 = N_1 \ _1 \frac{2 \ _2 - \ _1}{\ _2 - \ _1}$$

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



HALF LIFE OF ^{34}Ar





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

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

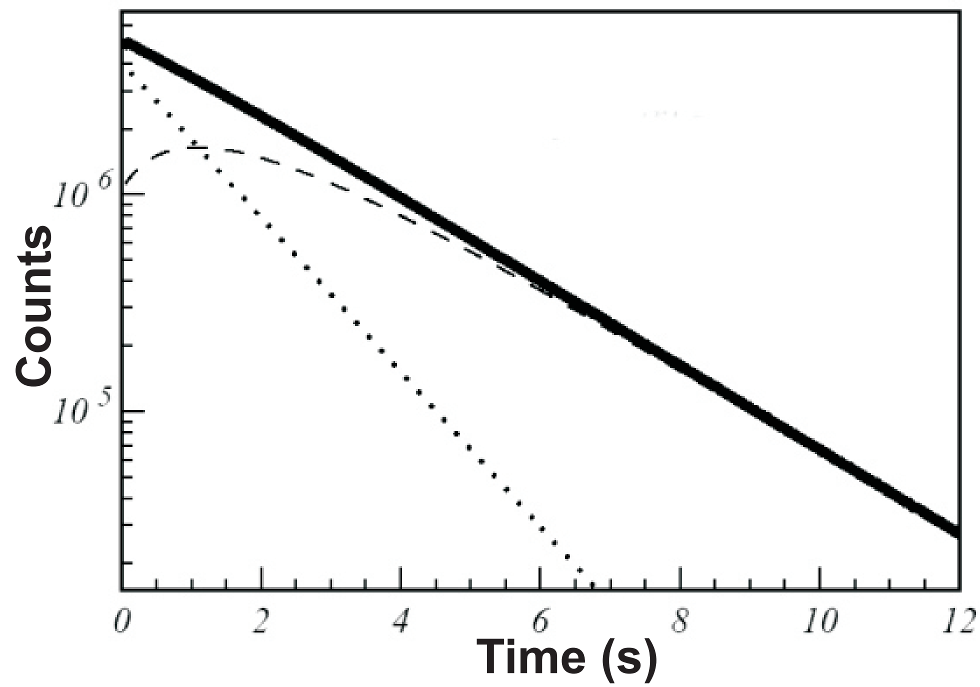
V.E. Iacob et al,
PRC 74, 055502 (2006)

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

where

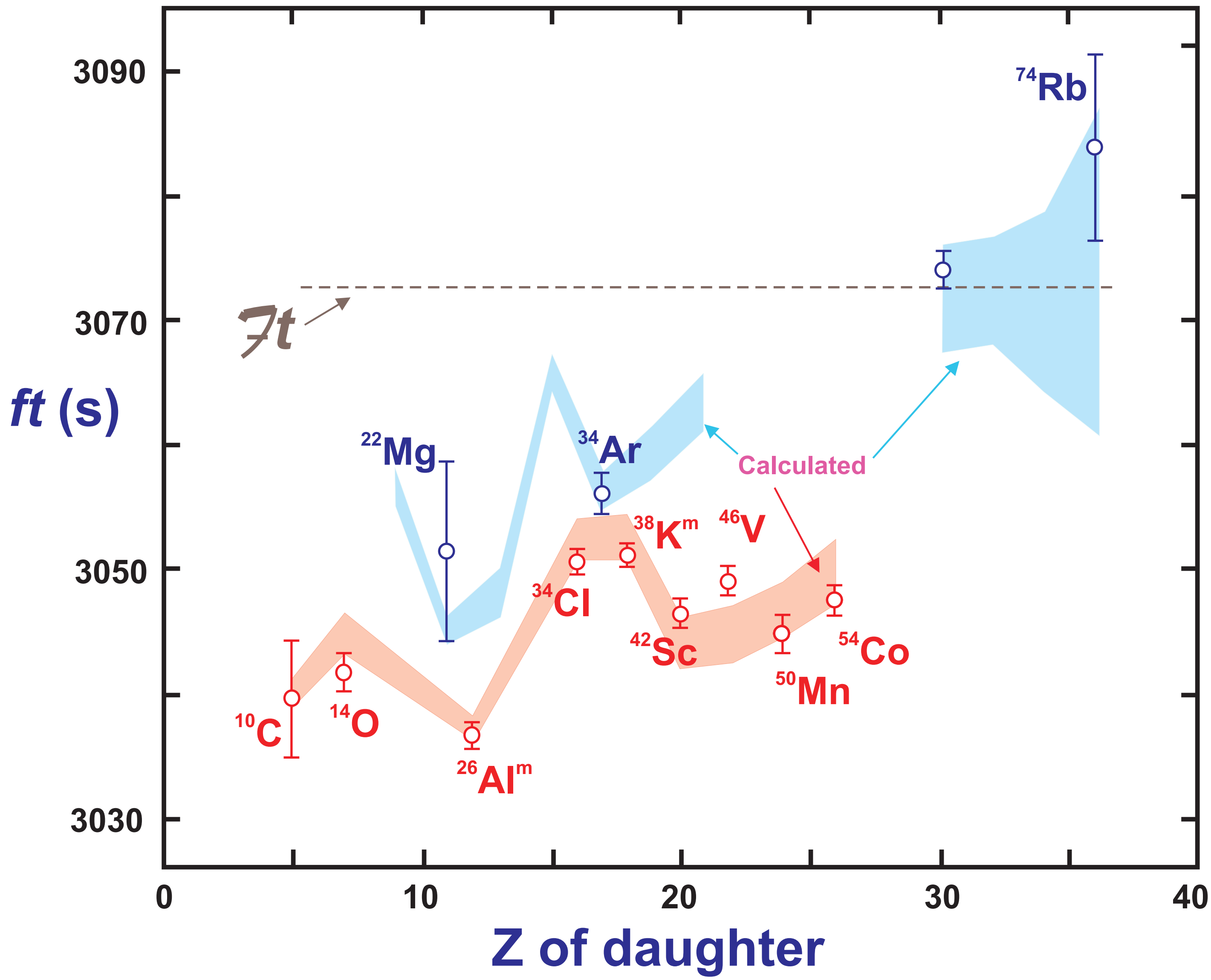
$$C_1 = N_1 \;_1 \frac{2 \;_2 - \;_1}{_2 - \;_1}$$

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



STATUS OF CORRECTION TEST

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



SUMMARY AND OUTLOOK

We know now that ...

1. The weak force (vector component) is constant in nuclei to 0.013%.
2. Universality of the weak force (CKM unitarity) is verified to 0.1%.
3. Nuclear physics is the source of key data for this test, the most precise one available for CKM unitarity.

Within 5 years, expect ...

1. Improved theory for analyzing K_{e3} decay will give more precise value for V_{us}
2. Nuclear measurements will reduce uncertainty on V_{ud}.
3. Weak force universality will be tested to a precision of $\lesssim 0.05\%$.