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Beta decay probing weak interaction properties

Part 2

TU Darmstadt, Sept. 3-5, 2018

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Outline- 1

1. Introduction / 2 lectures

- role of beta decay in weak interaction physics
- beta decay Hamiltonian
- beta decay angular distribution

2. ft-values / 3 lectures

- definition
- corrected ft-values
- test of CKM matrix unitarity
- role of mirror beta transitions and neutron decay

3. Correlation measurements / 5 lectures

- correlation formula
- physics content and opportunities
- testing parity violation
- searching for time reversal violation
- probing the structure of the weak interaction (scalar and tensor currents)

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2. *ft* value of a β transition
and unitarity of the
CKM quark-mixing matrix

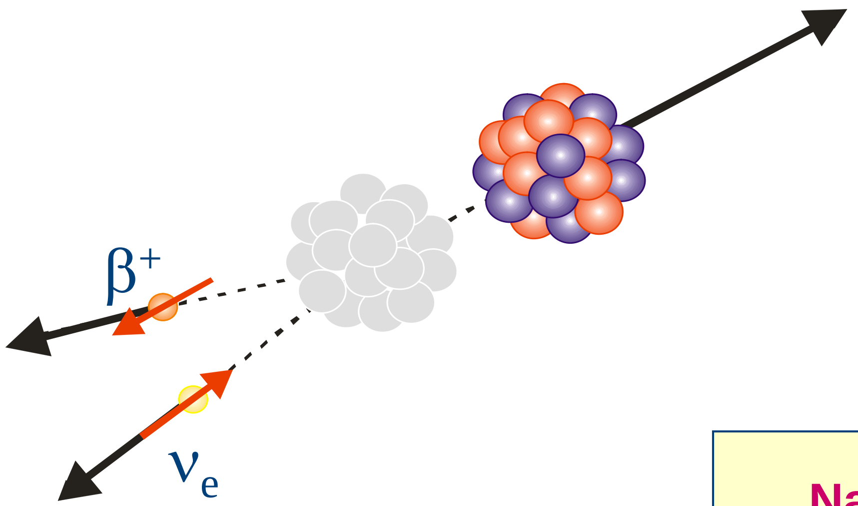

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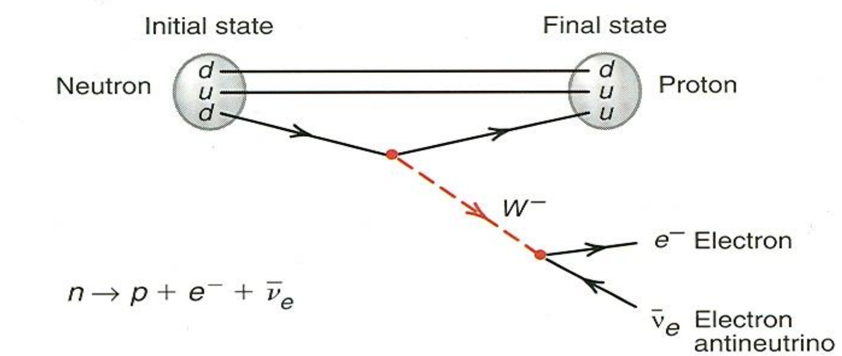
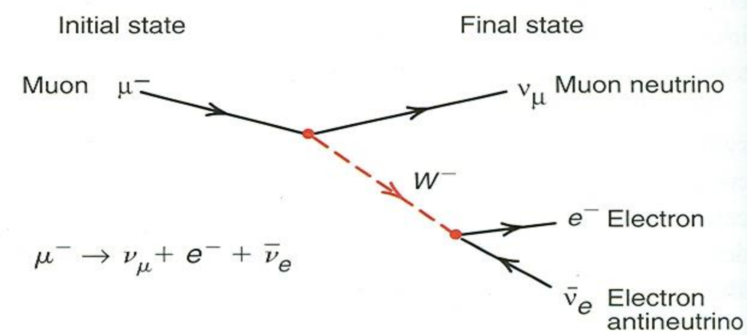
Figure 3. Beta Decay and Other Processes Mediated by the *W*

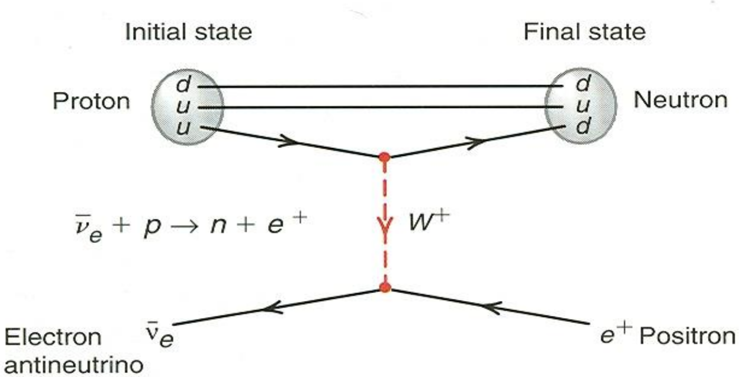
The *W* is the charged gauge particle of the weak force, so processes mediated by the *W* involve the exchange of one unit of electric charge. Quarks and leptons therefore change their identities through the emission or absorption of the *W*. In all the processes shown here, the arrow of time is from left to right, and an arrow pointing backward represents an antiparticle moving forward in time. The arrow on the *W* indicates the flow of electric charge. Note also that in each of these processes, electric charge is conserved at every step.



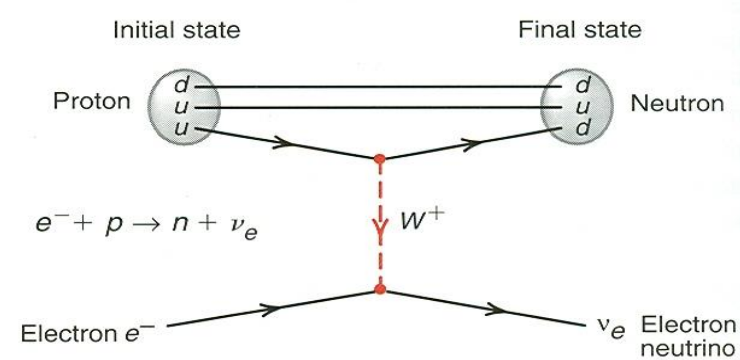
(a) Neutron beta decay. A neutron decays to a proton when a *d* quark in the neutron emits a W^- and transmutes into a *u* quark. Like the photon, the W^- can decay into a particle and an antiparticle, but here the particle is the electron, and the antiparticle is the electron antineutrino.



(b) Muon beta decay. This process is exactly analogous to the beta decay of the neutron. The muon transforms into a muon neutrino as it emits a W^-; the W^- decays into an electron and an electron antineutrino.

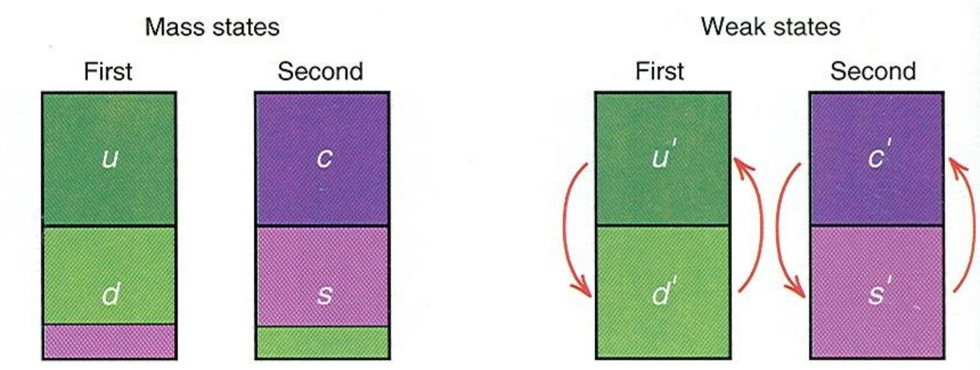


(c) Inverse beta decay. An electron antineutrino interacts with a proton by exchanging a W^+. The *u* quark emits a W^+ and transmutes to a *d* quark (thus the proton turns into a neutron). The electron antineutrino transmutes into a positron as it absorbs the W^+.



(d) Electron capture. This process is similar to inverse beta decay, except that an electron interacts with the proton. The electron transmutes into an electron neutrino as it absorbs the W^+.

Cabibbo-Kobayashi-Maskawa quark-mixing matrix



$$\begin{pmatrix} d \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta_c & -\sin\theta_c \\ \sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d' \\ s' \end{pmatrix}$$

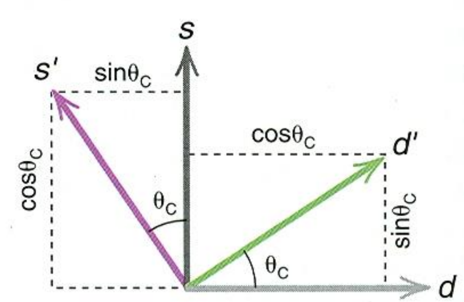
mass states — mixing matrix — weak states

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

weak states — mixing matrix — mass states

Figure 8. Two-Family Mixing among the Quarks

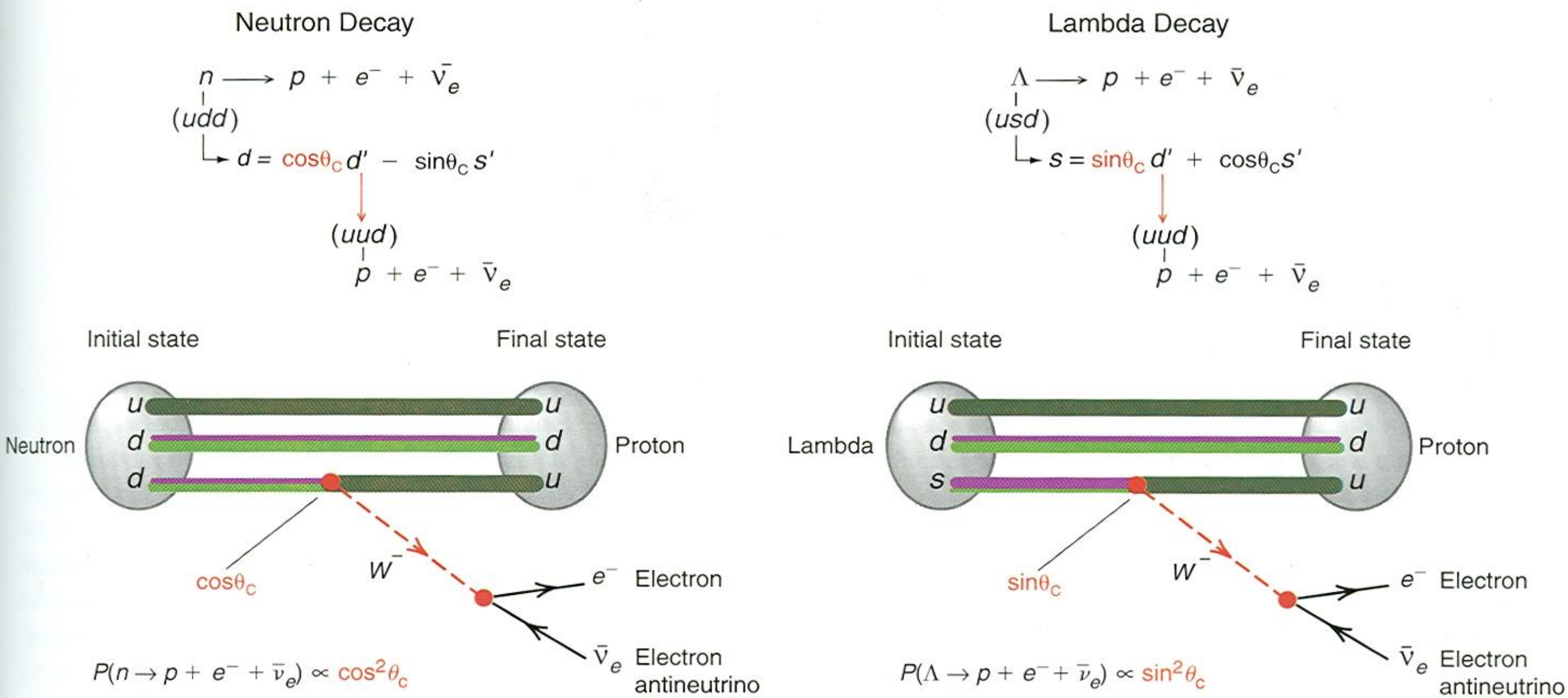
The quark weak states and mass states are like two alternative sets of unit vectors in a plane (see diagram at right) that are related to each other by the rotation through an angle θ_c. In this analogy, one mixing matrix is just a rotation matrix that takes, say, the mass coordinates *d* and *s* into the weak-force coordinates *d′* and *s′*; its inverse is the rotation through the angle $-\theta_c$ that takes the weak coordinates into the mass coordinates.



← 2 generations

3 generations ↓

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

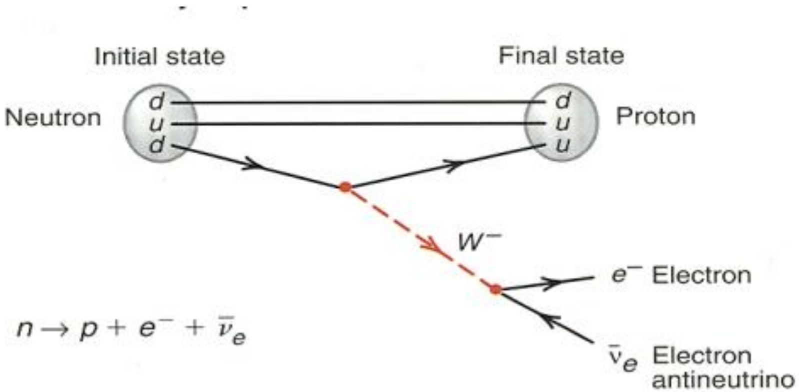


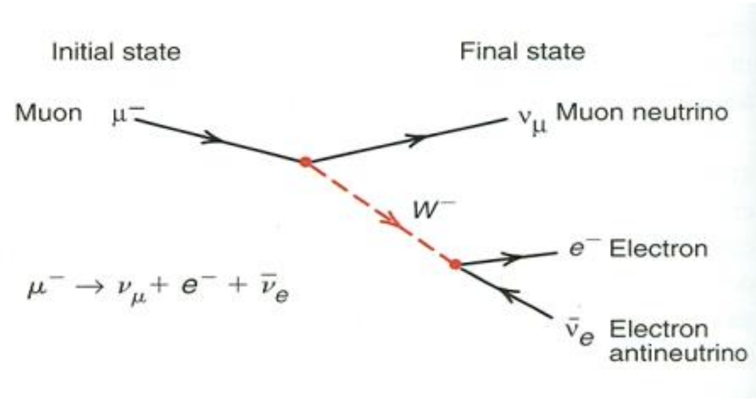
The neutron decay amplitude is proportional to $\cos\theta_c$, the amplitude of the state d' in the d quark. The decay probability is proportional to the square of the amplitude:

The lambda decay amplitude is proportional to $\sin\theta_c$, the amplitude of the state d' in the s quark. The lambda decay probability is proportional to the square of the amplitude.

Figure 9. Neutron and Lambda Beta Decay in the Two-Family Picture

In beta decay, the neutron transforms into a proton through the transition $d \rightarrow u$, and the lambda transforms into a proton through the transition $s \rightarrow u$. However, in both cases, the W acts between members of the quark weak isospin doublets in the first family, that is, the W causes the transition $d' \rightarrow u$. So, only the fraction of the d in the state d' takes part in neutron decay, and only the fraction of the s in the state d' takes part in lambda decay. The multicolored lines for d and s show their fractional content of d' (green) and s' (purple).





$G_\beta = G_V = G_F V_{ud}$

$G_\mu = G_F$

$$G_\beta^2 / G_\mu^2 = G_V^2 / G_F^2 = \frac{1.2906(13) \text{ x } 10^{-10}\,\text{GeV}^{-4}}{1.36047(2) \text{ x } 10^{-10}\,\text{GeV}^{-4}} = 0.9486(10) = V_{ud}^2$$

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

$$V \cong \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

with : $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

With $e^{\pm i\delta_{13}} \cong 1$
and the values of V_{ud}, V_{ub} and V_{ts}
→ $s_{13} \cong s_{23} \cong 0$ (i.e. $\theta_{13} \cong \theta_{23} \cong 0$)
→ $c_{13} \cong c_{23} \cong 1$

$$\longrightarrow \quad V \cong \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Beta decay transition probability :

distribution in energy, emission angle and polarization of β-particles for allowed β-decay of polarized nuclei

$$dW = dW_0\,\xi\left\{ 1 + \frac{\bar{p}\cdot\bar{q}}{E_e E_\nu}\,a + \frac{\Gamma m}{E_e}\,b\right.$$

βν-correlation

Fierz interference term

$$+ \bar{J}\cdot\left[\frac{\bar{p}}{E_e}A + \frac{\bar{q}}{E_\nu}B + \frac{\bar{p}\,\mathrm{x}\,\bar{q}}{E_e E_\nu}D\right]$$

β-asymmetry ν-asymmetry

$$\left. + \bar{\sigma}\cdot\left[\frac{\bar{p}}{E_e}G + \hat{p}\,(\bar{J}\cdot\hat{p})\,Q' + \bar{J}\,\mathrm{x}\,\frac{\bar{p}}{E_e}R\right] \ldots\right\}$$

longitudinal polarization transversal polarization

$\bar{p}$: momentum of beta particle
$\bar{q}$: momentum of neutrino
E: energy
m: electron rest mass
$\bar{J}$: spin of nucleus
$\Gamma = \sqrt{(1-(\alpha Z)^2}$

(Z of daughter nucleus)

with

$$dW_0 \propto G_F^2\; \underbrace{F(\pm Z, E_e)}_{\text{Fermi function}}\; \underbrace{(E_e - E_0)^2\, p\, E_e\, dE\, d\Omega_e\, d\Omega_\nu}_{\text{phase space}}$$

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J.D. Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206 & Phys. Rev. 106 (1957) 517

ft- value of a beta transition

$W = \frac{E_e^{tot}}{m_e}$

$p = \sqrt{W^2 - 1}$

$\gamma = \sqrt{(1 - \alpha^2 Z^2}$

- **decay rate** for allowed beta decay from an unpolarized nucleus :

$$d\Gamma = d\Gamma_0 \ \xi \ \left[1 + \frac{\gamma}{W} b\right]$$

with :

$$d\Gamma_0 = \frac{G_F^2 V_{ud}^2}{(2\pi)^5} \frac{1}{(m_e c^2)^5} F(\pm Z, W) \ S(\pm Z, W) \ (W - W_0)^2 \ p \ W \ dW \ d\Omega_e \ d\Omega_\nu$$

phase space factor: $(W - W_0)^2 \ p \ W \ dW \ d\Omega_e \ d\Omega_\nu$

$$G_F/(\hbar c)^3 = (1.16639 \pm 0.00001) \times 10^{-5} \ \mathrm{GeV}^{-2}$$ (from muon decay)

Note: - shape-correction factor $S(\pm Z, W) = 1$ for allowed beta-transitions

- the Fermi function $F(\pm Z, W)$ describes the main part of the Coulomb interaction between the outgoing beta particle and the daughter nucleus

$$\xi = 2\left[M_F^2 C_V^2 + M_{GT}^2 C_A^2\right]$$ (neglecting Scalar and Tensor type weak interactions)

with M_F and M_{GT} the Fermi and Gamow-Teller matrix elements
and C_V and C_A the coupling constants for the vector and axial-vector currents

(N.S. et al., Physical Review C 78 (2008) 055501)

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$$d\Gamma = d\Gamma_0 \; \xi \left[1 + \frac{\gamma}{W} b\right]$$

$$d\Gamma_0 = \frac{G_F^2 V_{ud}^2}{(2\pi)^5} \frac{1}{(m_e c^2)^5} F(\pm Z, W) \; S(\pm Z, W) \boxed{(W - W_0)^2 \; p \; W \; dW \; d\Omega_e \; d\Omega_\nu}$$

→ **the lifetime of a decaying state** $\tau = \frac{\hbar}{\Gamma}$ **(with Γ the width of decaying state)**

is given by:

$$\hbar/\tau = \int d\Gamma = \int \frac{G_F^2 V_{ud}^2}{2\pi^3} \frac{1}{(m_e c^2)^5} \xi \; F(\pm Z, W) \; S(\pm Z, W) \; (W - W_0)^2 \; p \; W \left[1 + \frac{\gamma}{W} b\right] dW$$

(integrating over neutrino and electron directions)

Fierz interference term; zero in Standard Model

$$\hbar/\tau = \int d\Gamma = \int \frac{G_F^2 V_{ud}^2}{2\pi^3} \frac{1}{(m_e c^2)^5}\, \xi\, F(\pm Z, W)\, S(\pm Z, W)\, (W - W_0)^2\, p\, W \left[1 + \frac{\gamma}{W} b\right] dW$$

for a specific β transition from a nuclear state, the partial half-life is (setting *b* = 0) :

$$1/t = \frac{G_F^2 V_{ud}^2}{2K}\, \xi\, f$$ **with** $$G_F/(\hbar c)^3 = (1.16639 \pm 0.00001) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

and $t = t_{1/2}\left(\frac{1 + P_{EC}}{BR}\right)$ **,** $K/(\hbar c)^6 = \frac{2\pi^3\ \ln 2\ \hbar}{(m_e c^2)^5} = (8120.271 \pm 0.012) \times 10^{-10}\ \mathrm{GeV}^{-4}\ \mathrm{s}$

and $t_{1/2} = \ln 2\ \tau$ **,** $f = \int F(\pm Z, W)\, S(\pm Z, W)\, (W - W_0)^2\, p\, W\, dW$

which leads to : $$ft = \frac{2K}{G_F^2\ V_{ud}^2} \frac{1}{\xi} = \frac{K}{G_F^2\ V_{ud}^2} \frac{1}{[M_F^2 C_V^2 + M_{GT}^2 C_A^2]}$$

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ft- value of $0^+ \rightarrow 0^+$ superallowed beta transitions

- **in general:** $$ft = \frac{K}{G_F^2 \; V_{ud}^2} \frac{1}{[M_F^2 C_V^2 + M_{GT}^2 C_A^2]}$$

- **for $0^+ \rightarrow 0^+$ transitions:** **only vector current present (selection rules; $M_{GT} = 0$)**

$$ft = \frac{K}{G_F^2 \; V_{ud}^2} \frac{1}{M_F^2 C_V^2}$$

in reality (see next slide):

$$\mathcal{F}t^{0^+\rightarrow 0^+} \equiv f_V t^{0^+\rightarrow 0^+} \left(1 + \delta_{NS}^V - \delta_C^V\right)\left(1 + \delta_R'\right) = \frac{K}{2G_F^2 \; V_{ud}^2 \; C_V^2 \left(1 + \Delta_R^V\right)}$$

Note: $|M_F|^2 = T(T+1) - T_i T_f$ $\qquad T = \frac{|N-Z|}{2}$

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$$\mathcal{F}t^{0^+\to 0^+} \equiv f_V t^{0^+\to 0^+} \left(1+\delta_{NS}^V - \delta_C^V\right)\left(1+\delta_R'\right) = \frac{K}{2G_F^2\; V_{ud}^2\; C_V^2\; \left(1+\Delta_R^V\right)}$$

- **radiative correction** $\delta_R' = \delta_1 + \delta_2 + \delta_3$ **(order α, $Z\alpha^2$, $Z^2\alpha^3$)**

  leading order α: exchange of γ or Z-boson between p and e^-

- **nucleus independent radiative correction $\Delta_R = 0.02361(38)$**
- **nuclear structure dependent radiative correction δ^V_{NS}**
- **Coulomb (isospin) correction $\delta^V_c = \delta^V_{c1} + \delta^V_{c2}$**
  - **difference in configuration mixing**
  - **difference in radial part of wave functions**

I.S. Towner & J.C. Hardy, Rep. Prog. Phys. 73 (2010) 046301

W. J. Marciano and A. Sirlin Phys. Rev. Lett. 96 (2006) 032002 (for Δ_R)

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Cabibbo-Kobayashi-Maskawa quark-mixing matrix

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

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with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

With $e^{\pm i\delta_{13}} \cong 1$
and the values of V_{ud}, V_{ub} and V_{ts}
→ $s_{13} \cong s_{23} \cong 0$ (i.e. $\theta_{13} \cong \theta_{23} \cong 0$)
→ $c_{13} \cong c_{23} \cong 1$

→

$$V \cong \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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J. Berlinger et al., Phys. Rev. D 86 (2012) 010001 ("Review of Particle Properties")

Unitarity of CKM quark-mixing matrix

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

$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1 \ \ ??$$

if not unitary → possible indication for 4th generation of quarks, or other types of new physics (requiring extra bosons)

Physics information from the $0^+ \rightarrow 0^+$ Fermi transitions

(e.g. I.S. Towner & J.C. Hardy, Rep. Prog. Phys. 73 (2010) 046301)

1. V_{ud} matrix element (→ test of unitarity)
2. test of CVC (constancy of $Ft^{0^+ \rightarrow 0^+}$ values)
3. right-handed currents:

$$\mathcal{F}t = \frac{K}{2G_F^2 V_{ud}^2 (1-2\zeta)(1+\Delta_R^V)}$$

$\zeta = 0.00004\ (28)$

Ad 3: Left Right Symm.-models

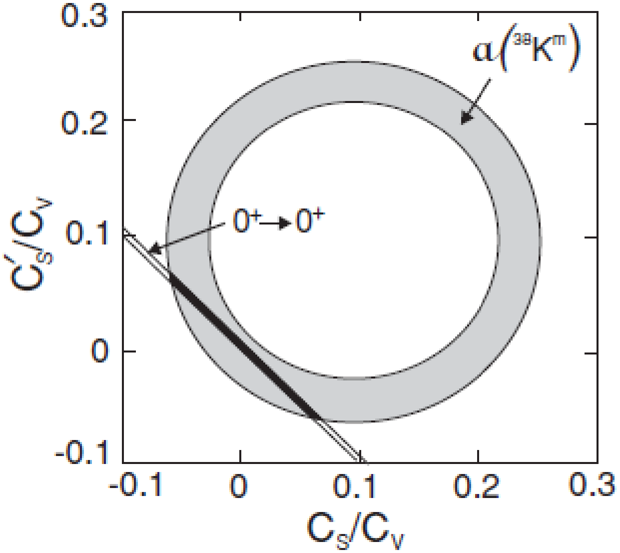
$W_1 = W_L \cos\zeta - W_R \sin\zeta$

$W_2 = W_L \sin\zeta + W_R \cos\zeta$

$\delta = m_1^2 / m_2^2$

4. scalar currents: $\mathcal{F}t = \dfrac{K}{2G_F^2 V_{ud}^2 (1+\Delta_R^V)} \dfrac{1}{1+\langle b_F' \rangle}$

$$-0.005 < \mathrm{Re}\left(\frac{C_S + C_S'}{C_V}\right) < 0.011 \quad \text{(90\% CL)}$$



Ad 4: scalar currents

5. extra Z-bosons (would contribute to radiative correction Δ_R^V)

$$m_{Z_\chi} > 460\ \text{GeV/c}^2$$

- First row of CKM marix:

V_{ud} - nuclear transitions
  ($0^+ \rightarrow 0^+$ superallowed Fermi transitions)
- mirror beta decays
- neutron decay
- pion decay

V_{us} - K-decay

V_{ub} - B-decay

- Other rows and columns

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$0^+ \rightarrow 0^+$ superallowed Fermi beta transitions and CKM unitarity

for $0^+ \rightarrow 0^+$ transitions: only vector current (selection rules) :

$$ft = \frac{K}{G_F^2 V_{ud}^2} \frac{1}{M_F^2 C_V^2}$$

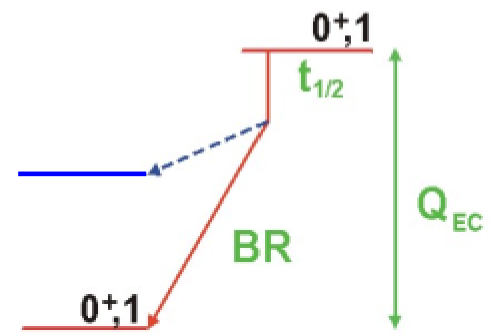
(assuming Fierz interference term *b* = 0)

with :

$$f = \int F(\pm Z, W)\, S(\pm Z, W)\, (W - W_0)^2\, p\, W\, dW$$

Q_{EC}

$$t = t_{1/2} \left(\frac{1 + P_{EC}}{BR} \right),$$



in reality:

$$\mathcal{F}t^{0^+ \rightarrow 0^+} \equiv f_V t^{0^+ \rightarrow 0^+} \left(1 + \delta_{NS}^V - \delta_C^V\right)\left(1 + \delta'_R\right) = \frac{K}{2 G_F^2\, V_{ud}^2\, C_V^2\, \left(1 + \Delta_R^V\right)}$$

from experiment

nucleus dependent corrections

nucleus independent

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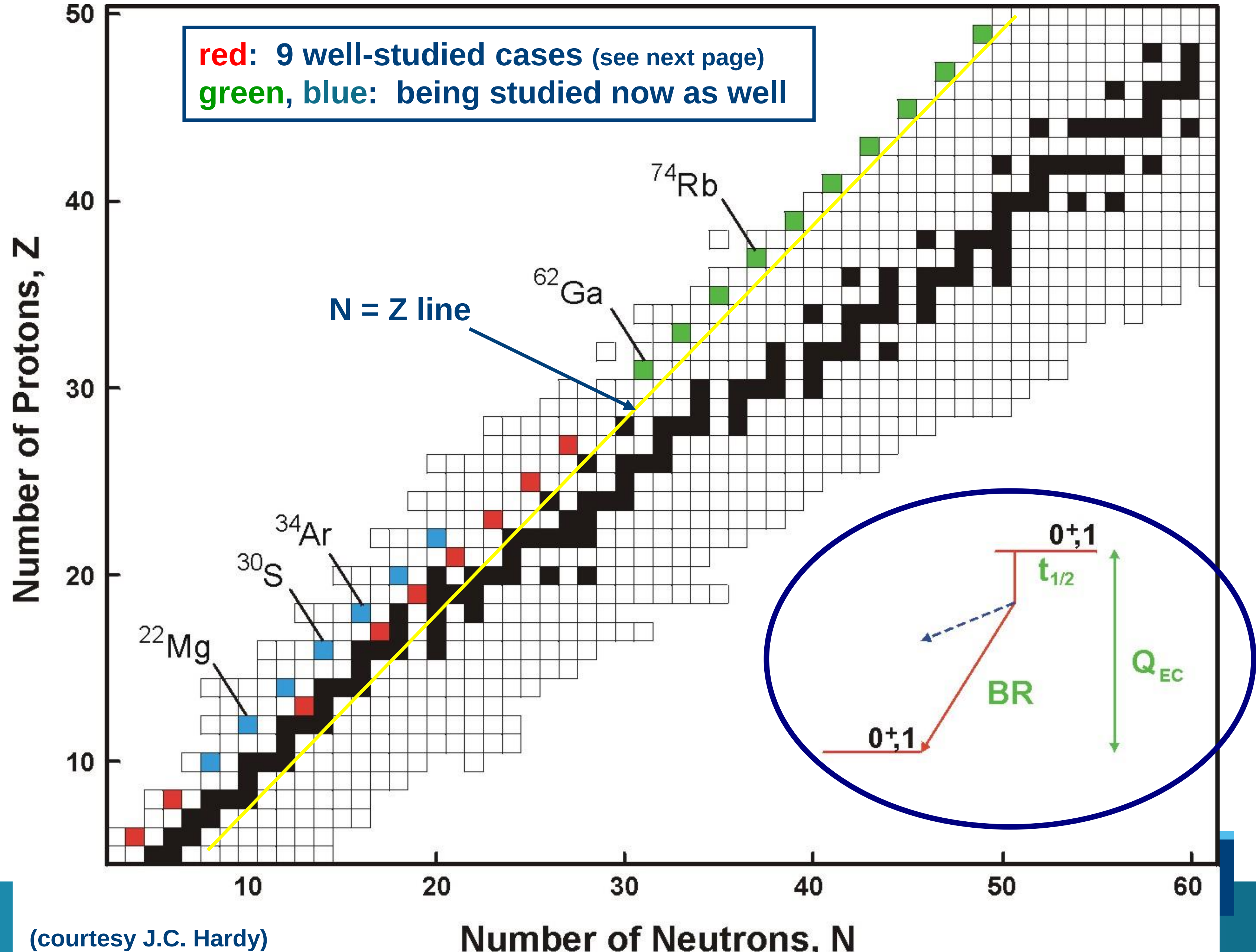
the 0⁺ → 0⁺ pure Fermi transitions:



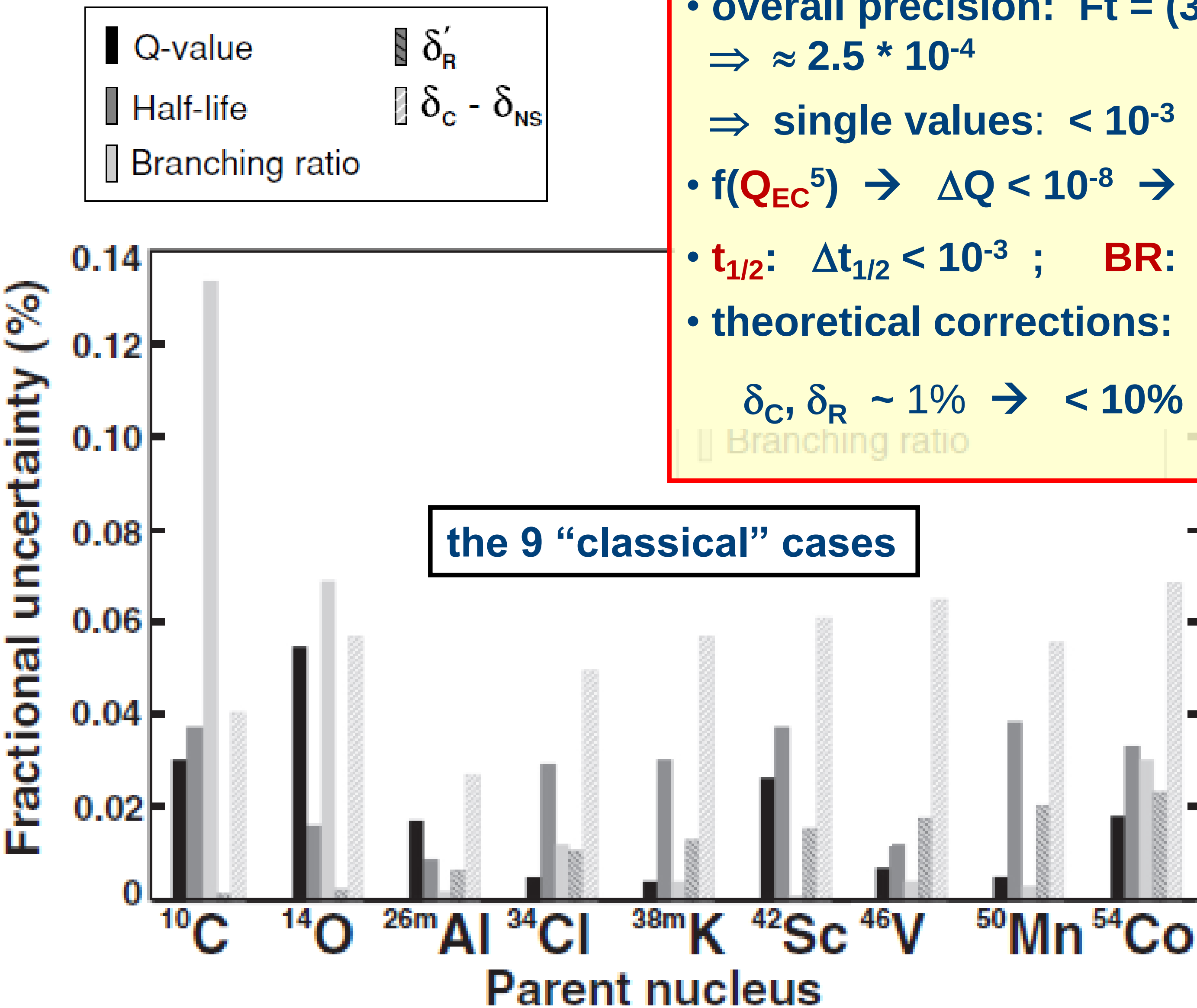
(courtesy J.C. Hardy)

Required precision

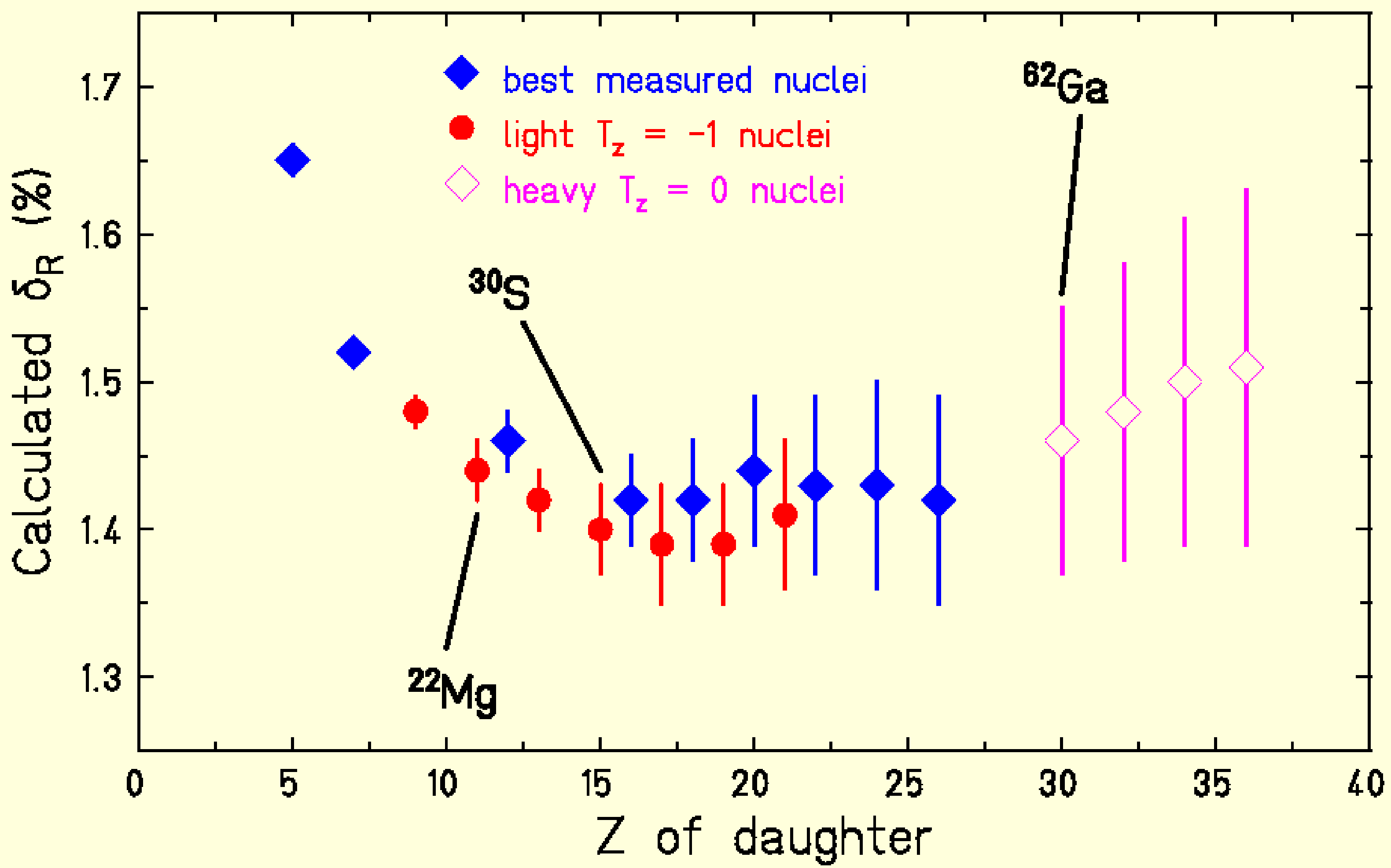
J.C. Hardy and I.S. Towner, Phys. Rev. C 91 (2015) 025501

- overall precision: Ft = (3072.27 ± 0.72) s
  $\Rightarrow$ ≈ 2.5 * 10^{-4}
  $\Rightarrow$ single values: < 10^{-3}
- $f(Q_{EC}^5)$ → $\Delta Q < 10^{-8}$ → < 1keV
- $t_{1/2}$: $\Delta t_{1/2} < 10^{-3}$; BR: $\Delta BR < 10^{-3}$
- theoretical corrections:

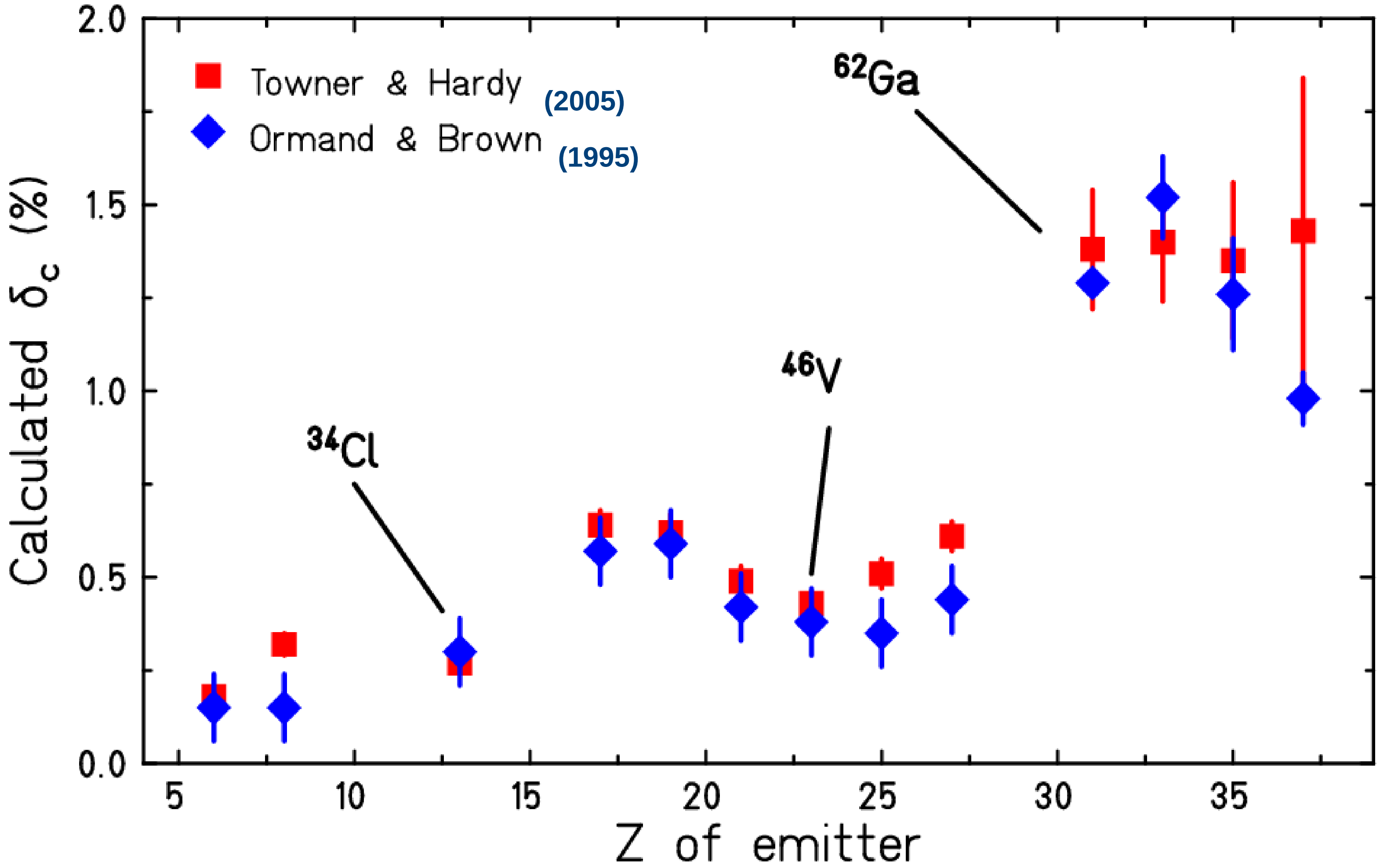
  δ_C, δ_R ~ 1% → < 10%



The inner radiative correction δ_R

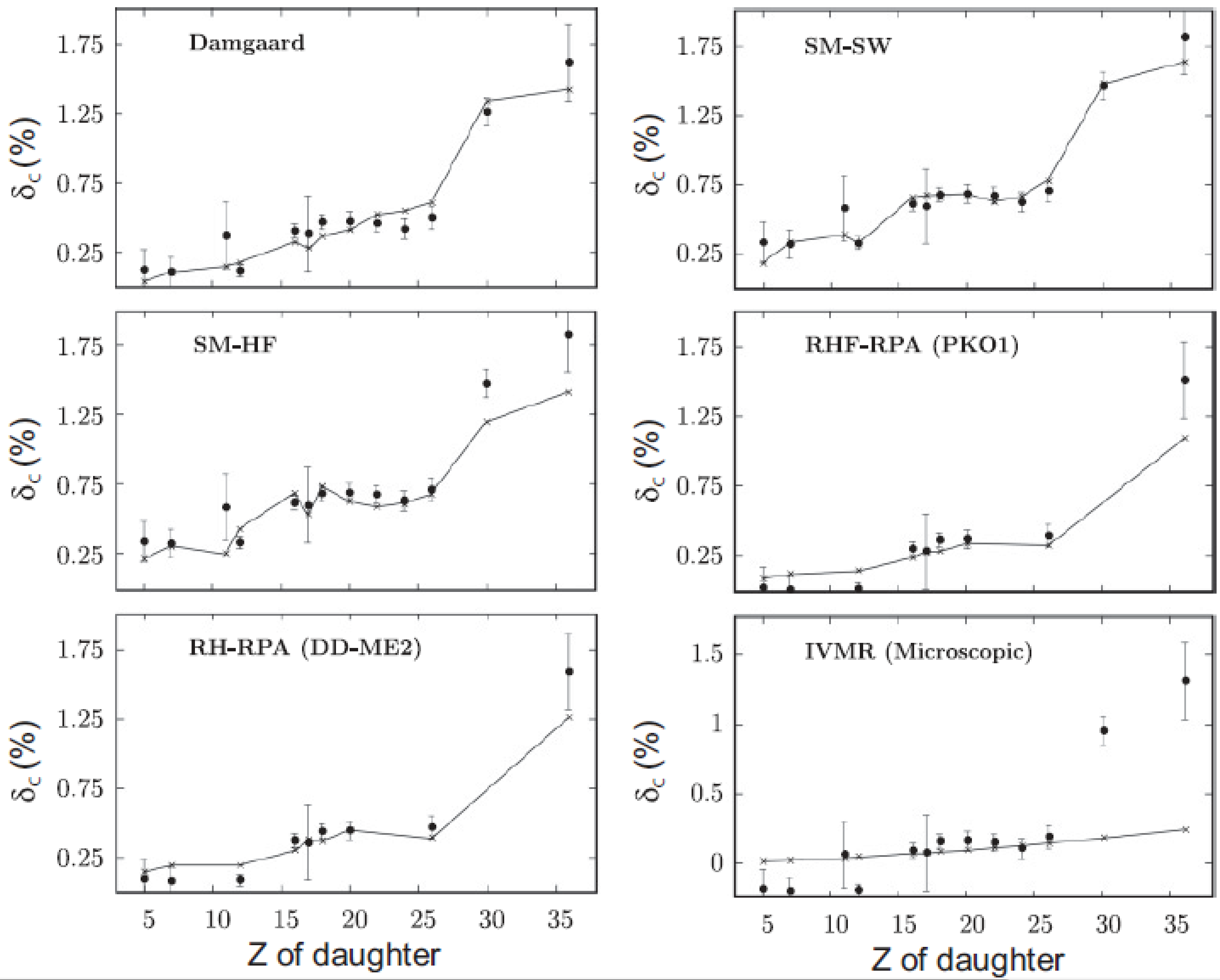


The isospin-mixing correction δ_C

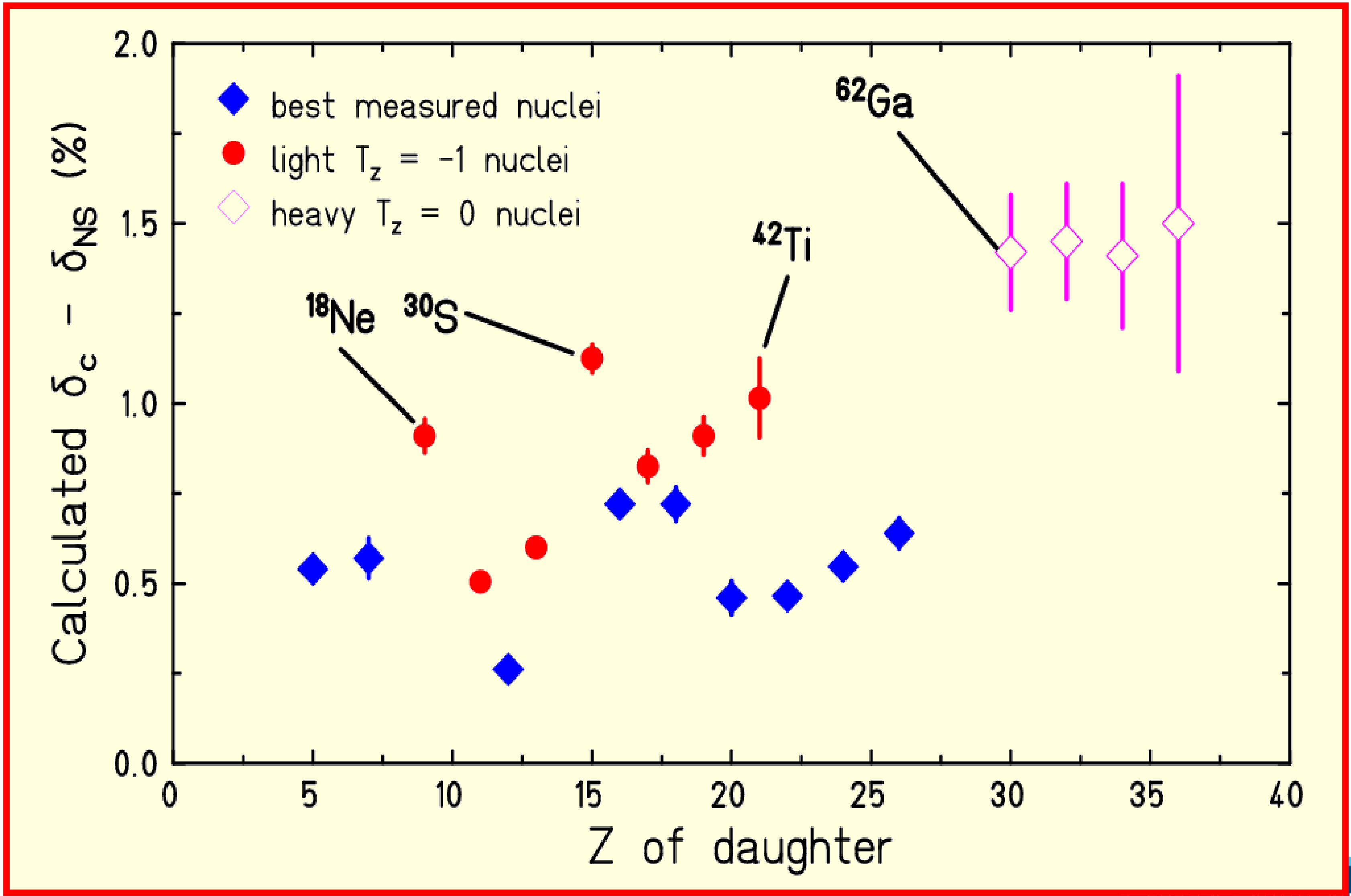


Isospin-mixing corrections

I.S. Towner and J.C. Hardy
Phys. Rev. C 82 (2010) 065501

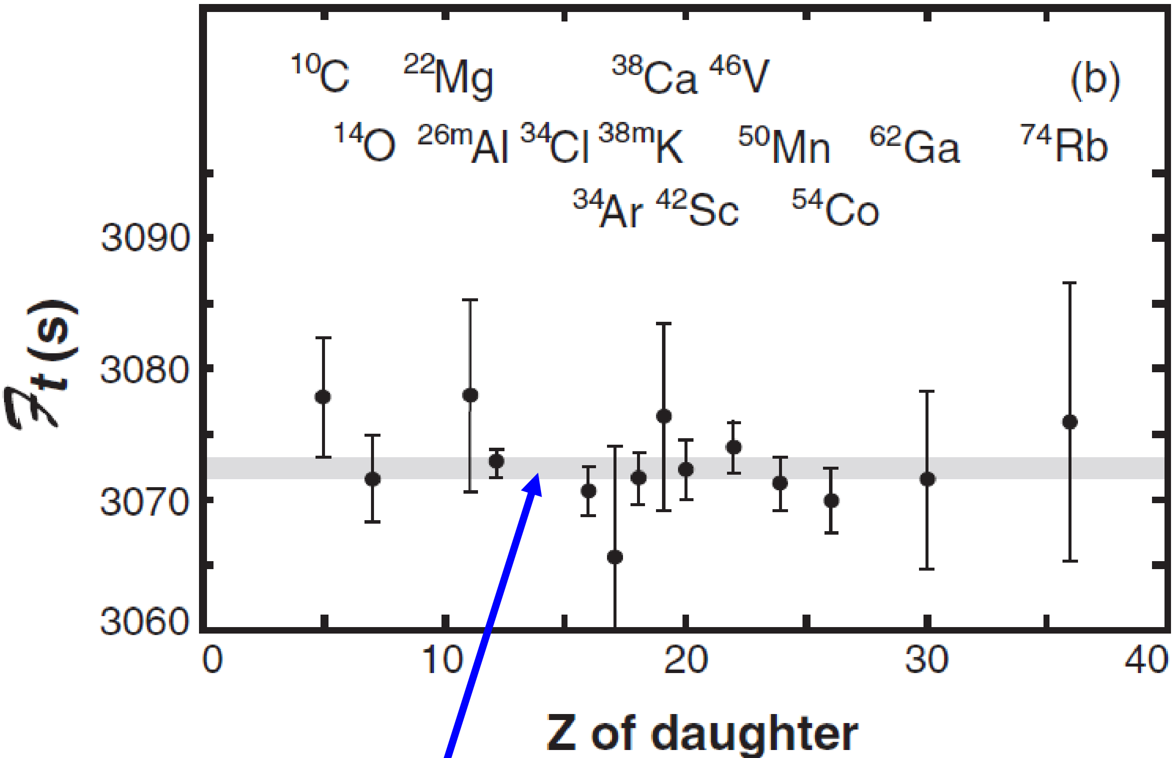


Isospin-mixing corrections and Nucl.Struct. δ_{NS} radiative corrections



J.C. Hardy and I.S. Towner, Phys. Rev. C 91 (2015) 025501

Present situation



$<Ft> = (3072.27 \pm 0.72)$ s

$\Rightarrow |V_{ud}| = 0.97417(21)$

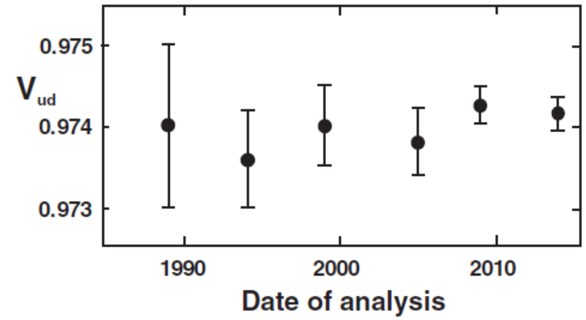


FIG. 6. Values of V_{ud} as determined from superallowed $0^+ \rightarrow 0^+$ β decays plotted as a function of analysis date, spanning the past two and a half decades. In order, from the earliest date to the most recent, the values are taken from Refs. [4], [210], [211], [5], [6], and this work.

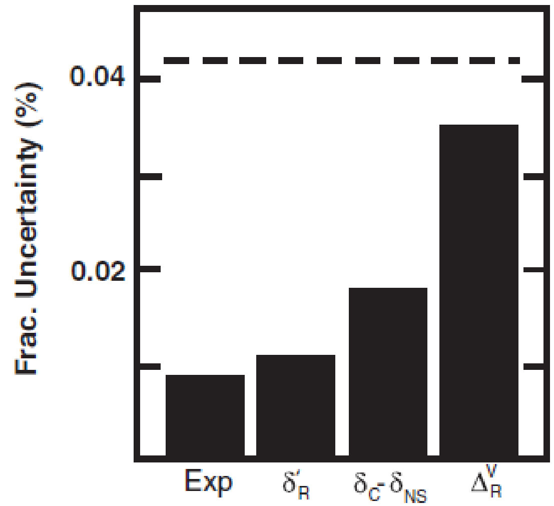


FIG. 8. Uncertainty budget for $|V_{ud}|^2$ as obtained from superallowed $0^+ \rightarrow 0^+$ β decay. The contributions are separated into four categories: experiment, the transition-dependent part of the radiative correction (δ'_R), the nuclear-structure-dependent terms ($\delta_C - \delta_{NS}$), and the transition-independent part of the radiative correction Δ_R^V.

J.C. Hardy and I.S. Towner, Phys. Rev. C 91 (2015) 025501

some recent experimental data (post-2000; not complete)

^{14}O	$T_{1/2}$	*Leuven, Auckland, Berkeley*
	Q_{EC}	*Auckland*
^{18}Ne	$T_{1/2}$	*TRIUMF*
	Q_{EC}	*ISOLDE*
^{22}Mg	$T_{1/2}$, BR	*Texas A&M*
	Q_{EC}	*CPT Argonne, ISOLDE*
^{26}Si	Q_{EC}	*JYFL*
$^{26}Al^m$	Q_{EC}	*JYFL*
^{34}Ar	$T_{1/2}$, BR	*Texas A&M*
	Q_{EC}	*ISOLDE*
^{38}Ca	Q_{EC}, T_{12}	*ISOLDE*
	Q_{EC}	*MSU*
$^{38}K^m$	$T_{1/2}$	*Auckland*
^{42}Sc	Q_{EC}	*JYFL*
^{42}Ti	Q_{EC}	*JYFL*
^{46}V	Q_{EC}	*JYFL, CPT Argonne*
^{50}Mn	Q_{EC}	*JYFL*
	$T_{1/2}$	*Auckland*
^{62}Ga	$T_{1/2}$, BR	*GSI, JYFL, TRIUMF, Texas A&M*
	Q_{EC}	*JYFL*
^{74}Rb	$T_{1/2}$,BR	*TRIUMF, ISOLDE*
	Q_{EC}	*ISOLDE*

and many, many more ....

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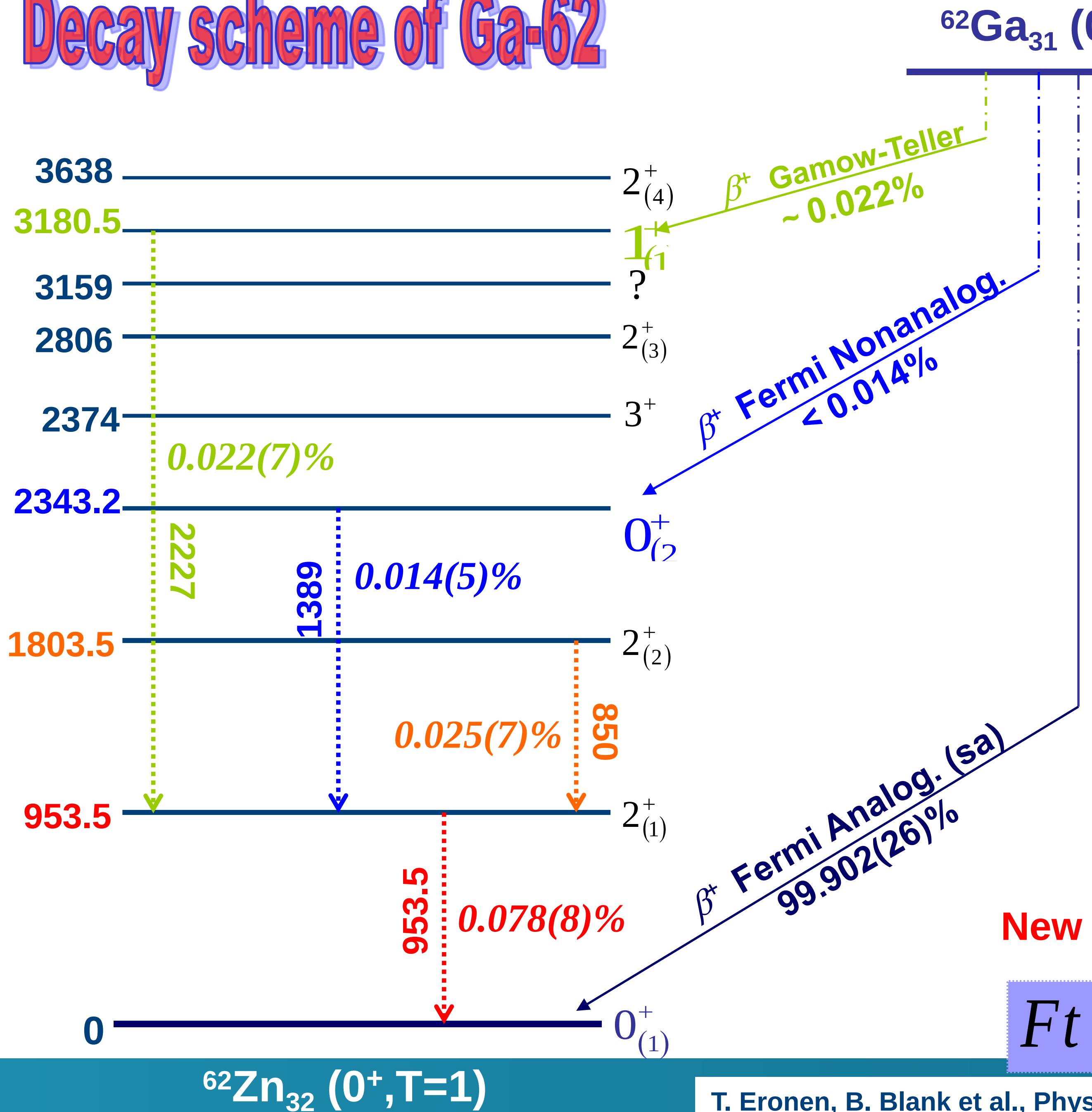
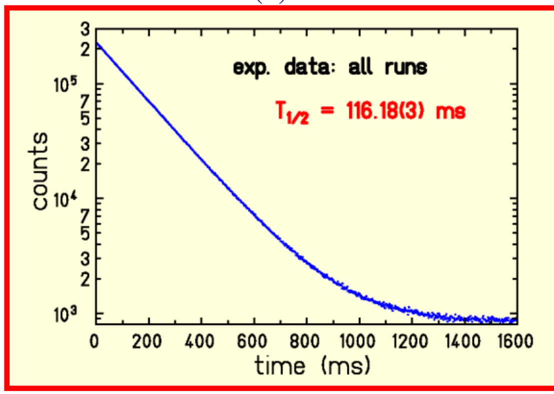
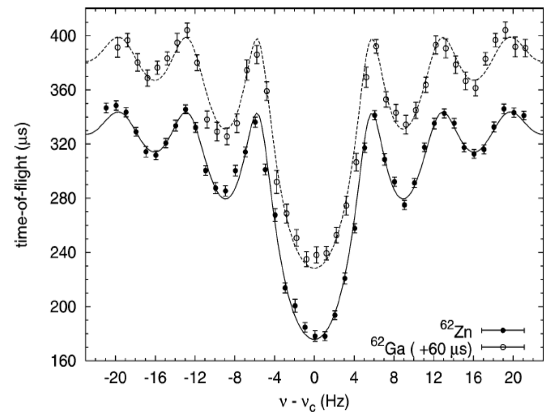
Decay scheme of Ga-62





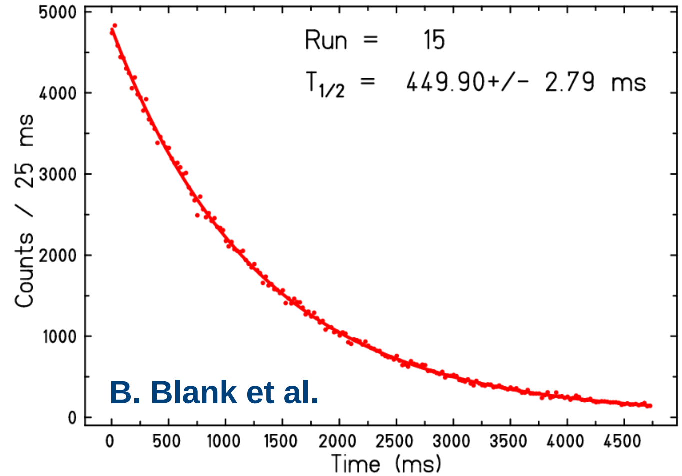


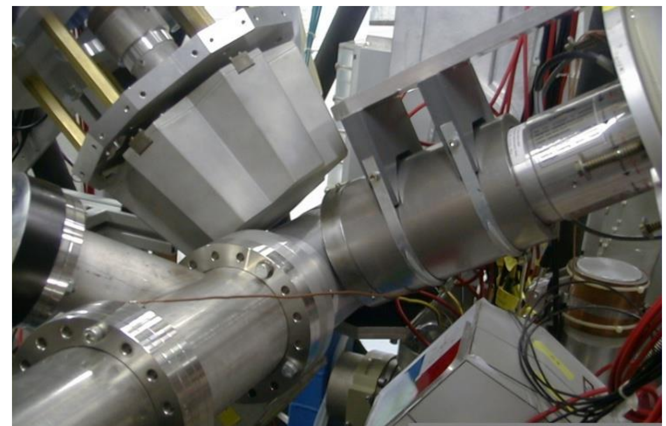
$$ft = (3076.0^{+2.1}_{-4.8})\ \mathrm{s}$$

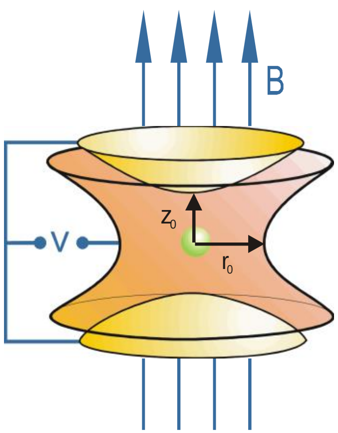
New *Ft* value for ^{62}Ga:

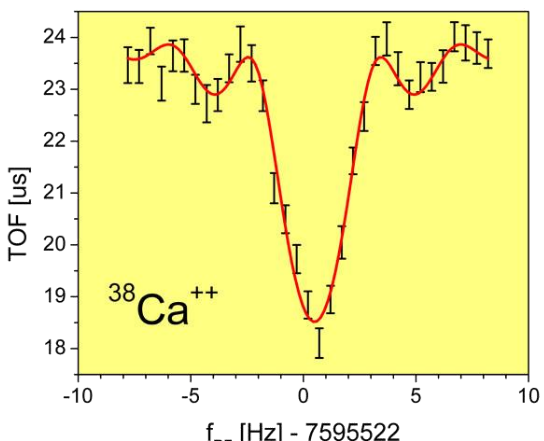
$$Ft = (3076.2^{+6.0}_{-7.4})\ \mathrm{s}$$

T. Eronen, B. Blank et al., Phys. Lett. B 636 (2006) 191

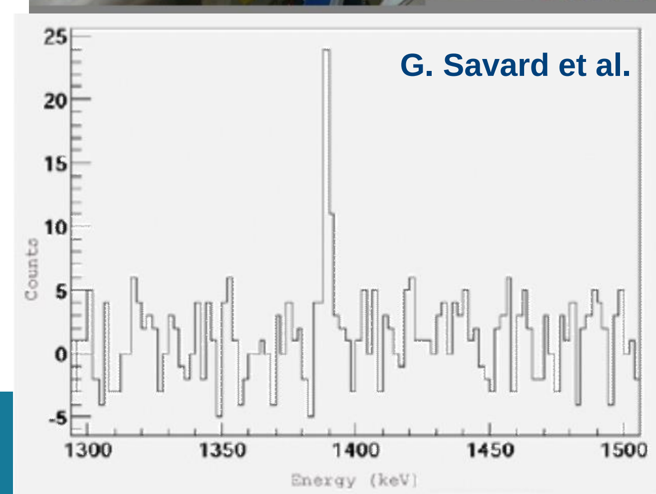




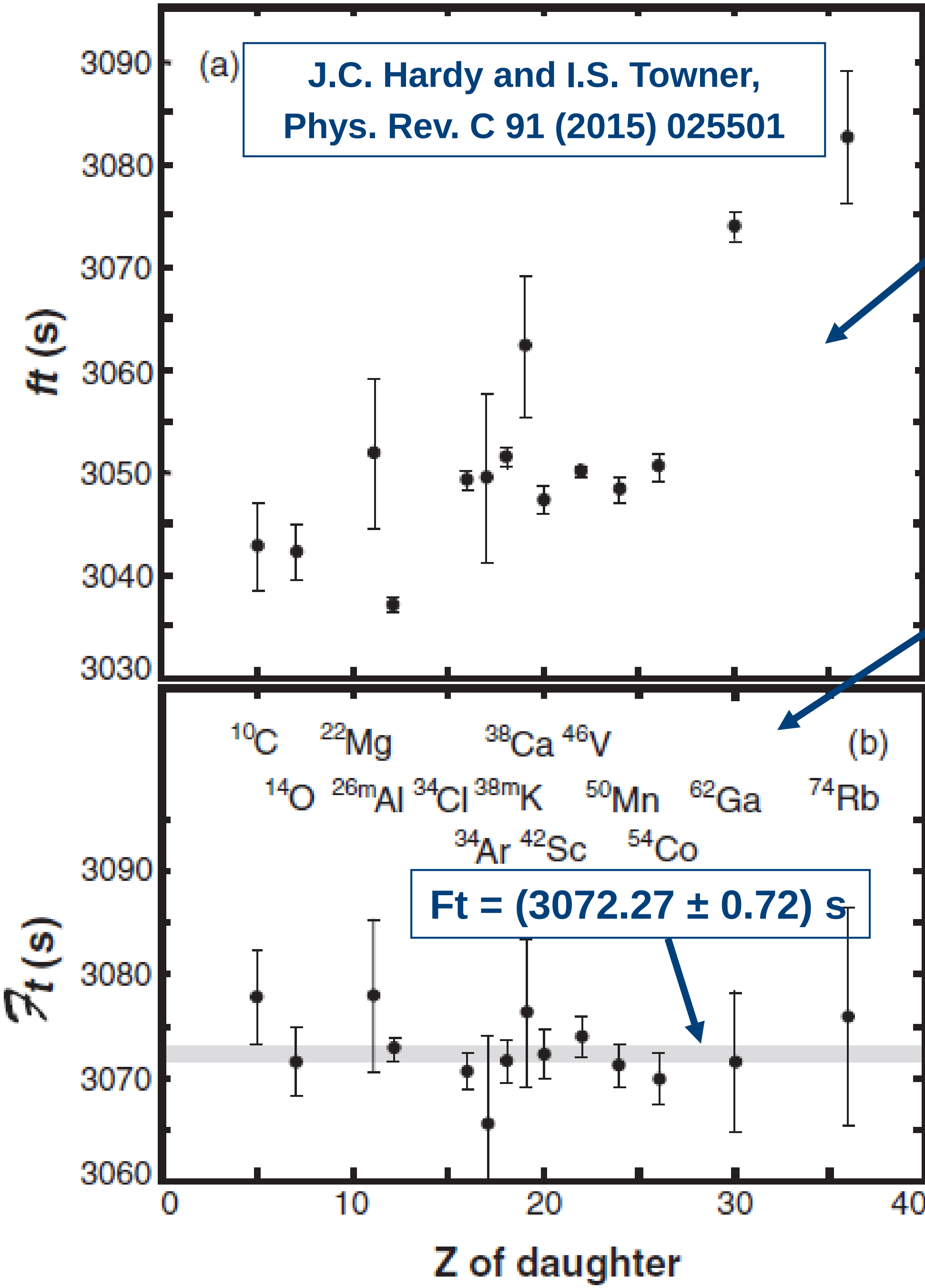




G. Bollen et al.



Test of nuclear corrections



- **ft value + QED corrections**
  (no δ_R', δ_c or δ_{NS})

$$Ft = ft\,(1 + \delta_R')\,(1 - \delta_c + \delta_{NS})$$

- **ft value with all corrections ➔**

$$Ft = ft\ \ (1 + \delta_R')\,(1 - \delta_c + \delta_{NS})$$

→ nuclear corrections seem to be OK, but they contribute significantly to uncertainty

→ new calculations needed
+ measurements for nuclei with large corrections

FIG. 2. (a) In the top panel are plotted the uncorrected experimental ft values as a function of the charge on the daughter nucleus. (b) In the bottom panel, the corresponding $\mathcal{F}t$ values are given; they differ from the ft values by the inclusion of the correction terms δ_R', δ_{NS}, and δ_C. The horizontal gray band gives one standard deviation around the average $\overline{\mathcal{F}t}$ value.

Error budget

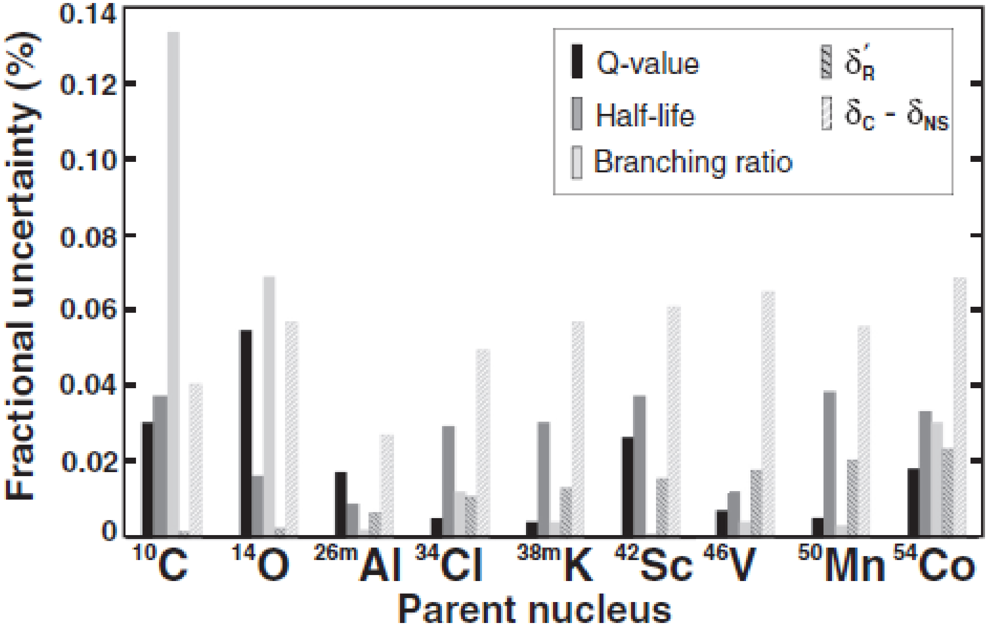


FIG. 3. Summary histogram of the fractional uncertainties attributable to each experimental and theoretical input factor that contributes to the final $\mathcal{F}t$ values for the "traditional nine" superallowed transitions. The bars for δ'_R are only a rough guide to the effect on each transition of this term's systematic uncertainty. See text.

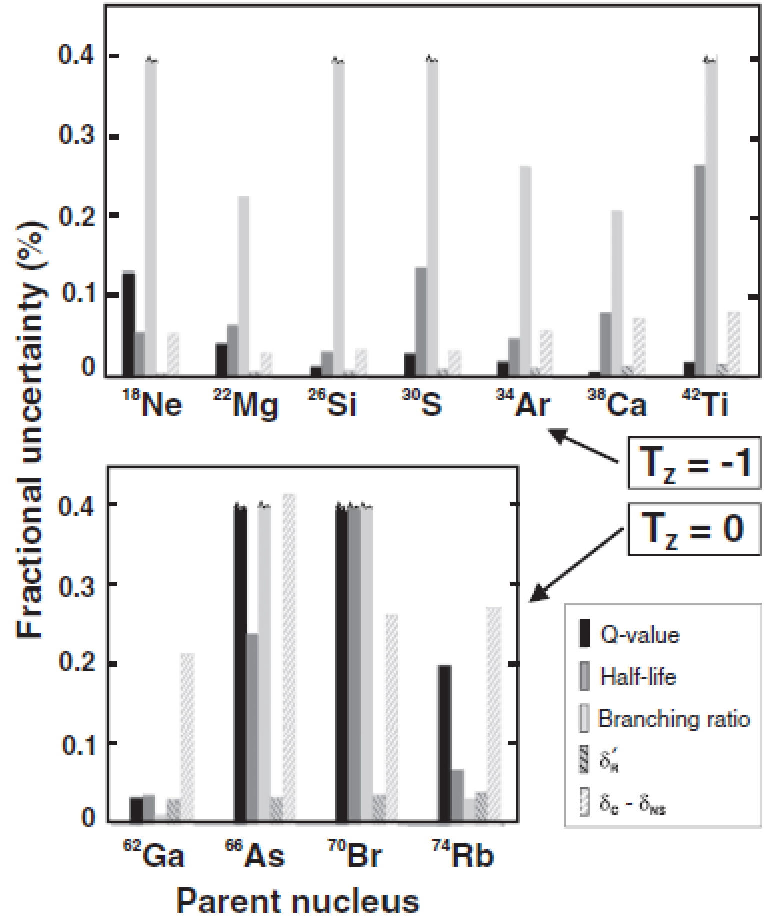


FIG. 4. Summary histogram of the fractional uncertainties attributable to each experimental and theoretical input factor that contributes to the final $\mathcal{F}t$ values for the 11 other superallowed transitions. Where the error is cut off with a jagged line at 40 parts in 10^4, no useful experimental measurement has been made. The bars for δ'_R are only a rough guide to the effect on each transition of this term's systematic uncertainty. See text.

Other possibility:

if CVC accepted (Ft-values constant for superallowed $0^+ \rightarrow 0^+$)

→ measurement of Ft can test calculation of δ_c - δ_{NS} in different models

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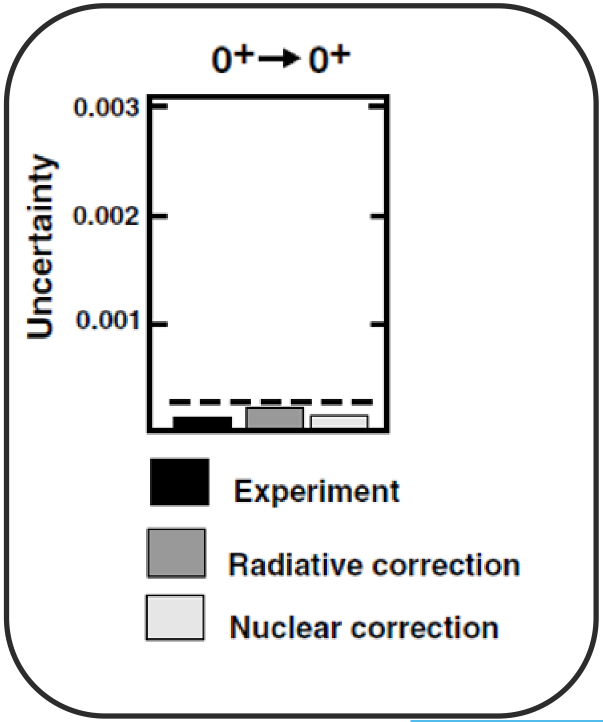
Conclusion for extracting V_{ud} from the $0^+ \rightarrow 0^+$ pure Fermi transitions

Value obtained for V_{ud} from:

$$\mathcal{F}t^{0^+\rightarrow 0^+} \equiv f_V t^{0^+\rightarrow 0^+} \left(1 + \delta_{NS}^V - \delta_C^V\right)\left(1 + \delta'_R\right) = \frac{K}{2G_F^2\ V_{ud}^2\ C_V^2\ \left(1 + \Delta_R^V\right)}$$

is $|V_{ud}| = 0.97417(21)$

Comparing the different contributions to the error bar it turns out that the precision of this value is currently limited by the precision of the correction $\Delta_R = 0.02361(38)$.



Free neutron decay and CKM unitarity

$$ft = \frac{K}{G_F^2\, V_{ud}^2} \frac{1}{[M_F^2 C_V^2 + M_{GT}^2 C_A^2]}$$

$$f_n \tau_n (1 + \delta_R) = \frac{K/\ln 2}{G_F^2 V_{ud}^2 (1 + \Delta_R^V)(1 + 3\lambda^2)}$$

$M_F^2 = 1$
$M_{GT}^2 = 3$
$C_V \equiv 1$

with $f_n(1+\delta_R) = 1.71489(2)$ and $\lambda = g_A/g_V = C_A/C_V$

$$\rightarrow \quad V_{ud}^2 = \frac{4908.7 \pm 1.9}{\tau(1 + 3\lambda^2)}$$

with λ from $A_n = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$

Neutron lifetime, anno 2006

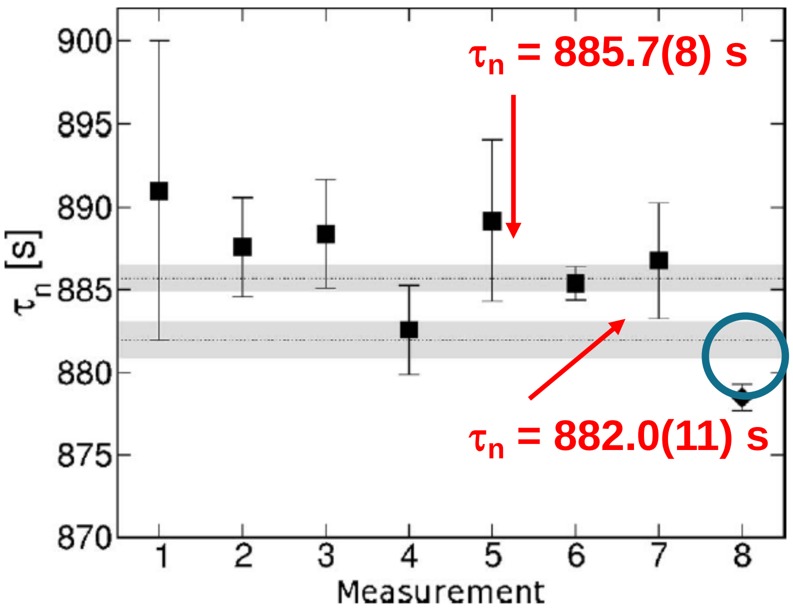
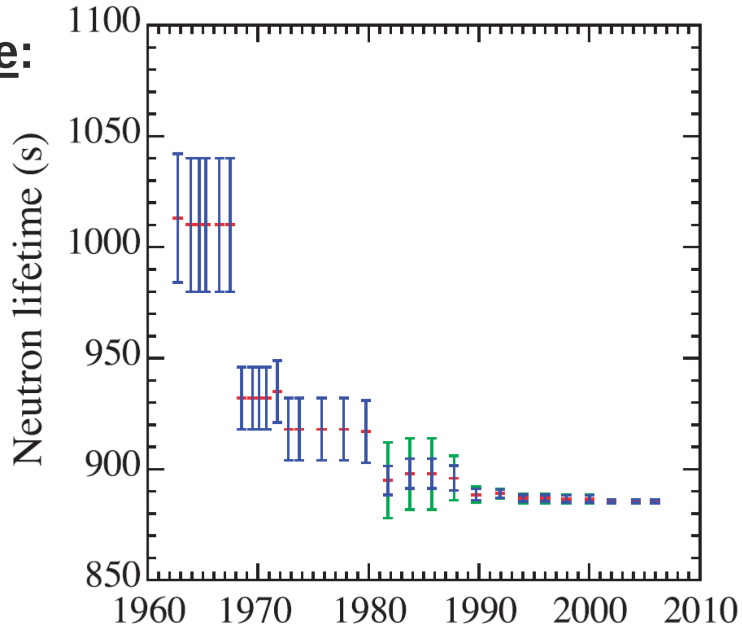


FIG. 12. Input data for the world average value of τ_n (see also Table IV). 1, Spivak (1988); 2, Mampe *et al.* (1989); 3, Nesvishevsky *et al.* (1992); 4, Mampe *et al.* (1993); 5, Byrne *et al.* (1996); 6, Arzumanov *et al.* (2000); 7, Dewey *et al.* (2003); and 8, Serebrov *et al.* (2005a). The upper band shows the weighted average of the first seven values and the lower band the weighted average of all values.

NS, O. Naviliat-Cuncic, M. Beck, Rev. Mod. Phys. 78 (2006) 991

Note:



Particle Data Group, Patrignani et al., Chin. Phys. C 40 (2016) 100001

all neutron → $0.9716 < |V_{ud}| < 0.9807$

recent neutron → $|V_{ud}| = 0.9758(13)$

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Neutron lifetime, anno 2018

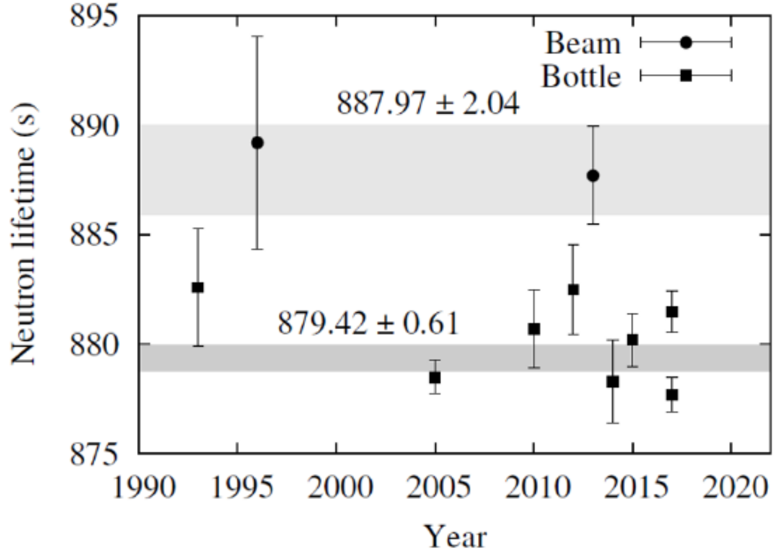
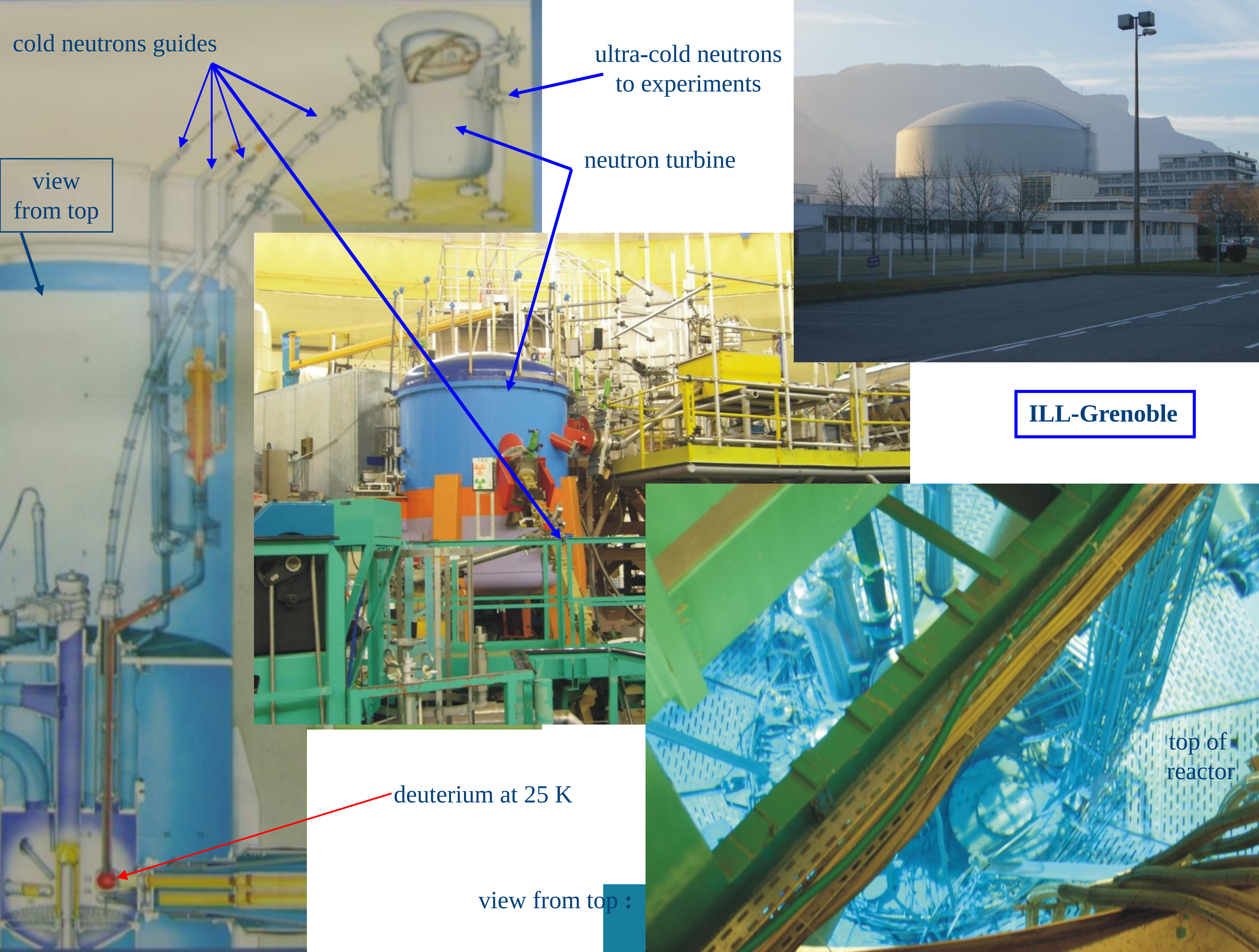


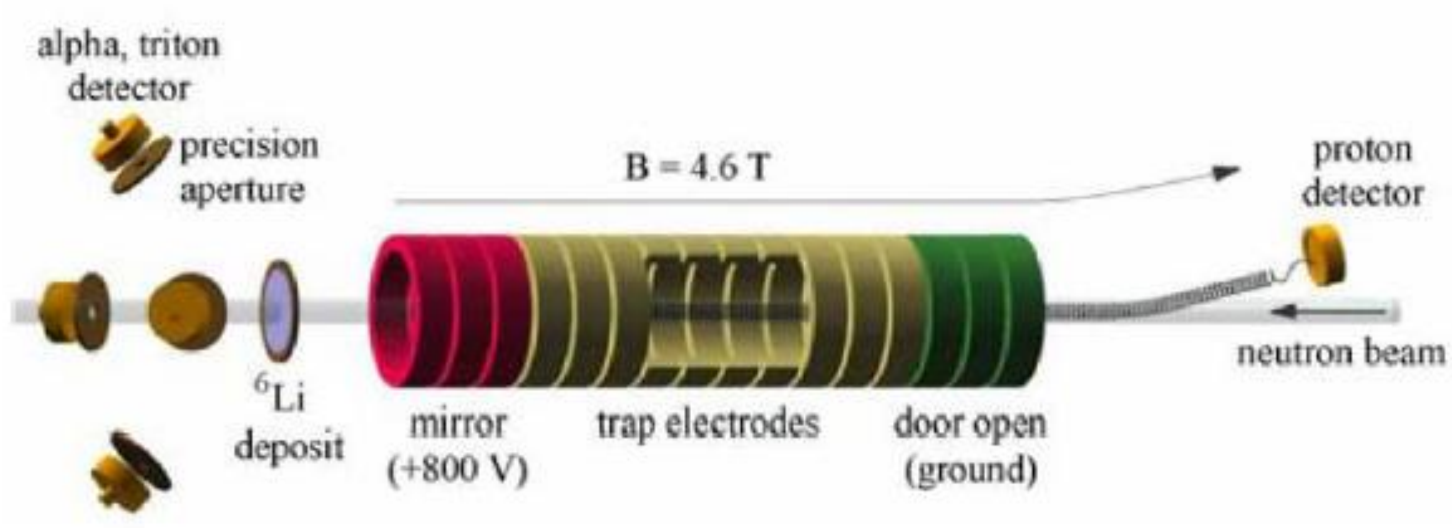
Figure 2: Overview of neutron lifetime results, separated into "beam" and "bottle" experiments (see also Table 7). The "bottle" experiments are performed with ultracold neutrons (UCN) stored in either a material bottle, a gravitational trap, or recently also a magneto-gravitational trap. Note the about four standard deviations tension between the weighted average values of both types of experiments. The uncertainty of the average of the "trap" measurements was scaled by a factor $\sqrt{\chi^2/\nu} \approx 1.52$ following the PDG prescription (Section 4.1).

Coefficient	Value	Year/Method	Reference
τ_n (s)	882.6 ± 2.7	1993/Bottle	[198]
	$889.2 \pm 3.0 \pm 3.8$	1996/Beam	[191]
	$878.5 \pm 0.7 \pm 0.3$	2005/Bottle	[197]
	$880.7 \pm 1.3 \pm 1.2$	2010/Bottle	[199]
	$882.5 \pm 1.4 \pm 1.5$	2012/Bottle	[200]
	$887.7 \pm 1.2 \pm 1.9$	2013/Beam	[192]
	878.3 ± 1.9	2014/Bottle	[201]
	880.2 ± 1.2	2015/Bottle	[202]
	$877.7 \pm 0.7 \pm 0.4$	2017/Bottle	[189]
	$881.5 \pm 0.7 \pm 0.6$	2017/Bottle	[203]
	879.75 ± 0.76		Average ($S = 1.9$)

M. Gonzalez-Alonso, O. Naviliat-Cuncic, N. Severijns, arXiv:1803.08732, and Prog. Part. Nucl. Phys. available on-line


cold neutrons guides
ultra-cold neutrons
to experiments
neutron turbine
view
from top
ILL-Grenoble
deuterium at 25 K
top of
reactor
view from top :

Measuring the neutron lifetime - beam method



J. Byrne *et al.*, Europhys. Lett. 33, 187 (1996)
M.S. Dewey *et al.*, Phys. Rev. Lett. 91, 152302 (2003)

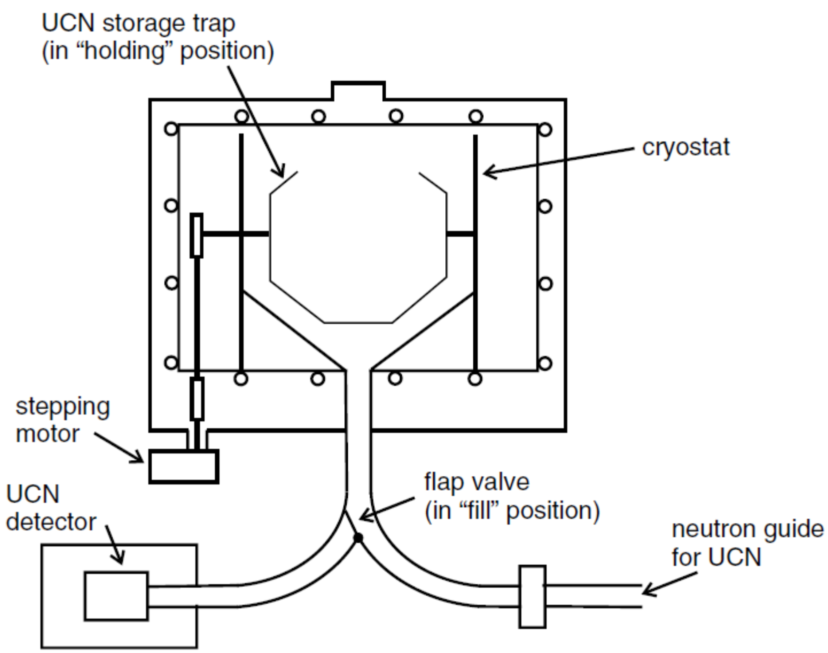
$$\tau_n = \frac{N}{\frac{dN}{dt}}$$

with N = # of neutrons present in decay volume
dN / dt = # of neutron decays in same volume

precision limited by:

- exact knowledge of mass of LiF deposit
- ^{6}Li(n,t)α neutron capture cross section

Measuring the neutron lifetime - bottle method



- trap is filled from bottom
- rotated to holding position
- kept there for a certain time (used two values)
- then rotated back to downward position
  in 5 steps with n's being counted
- storage times up to 800 s were reached !

- walls are covered with 'Fomblin' oil
  at low temperature to avoid wall losses

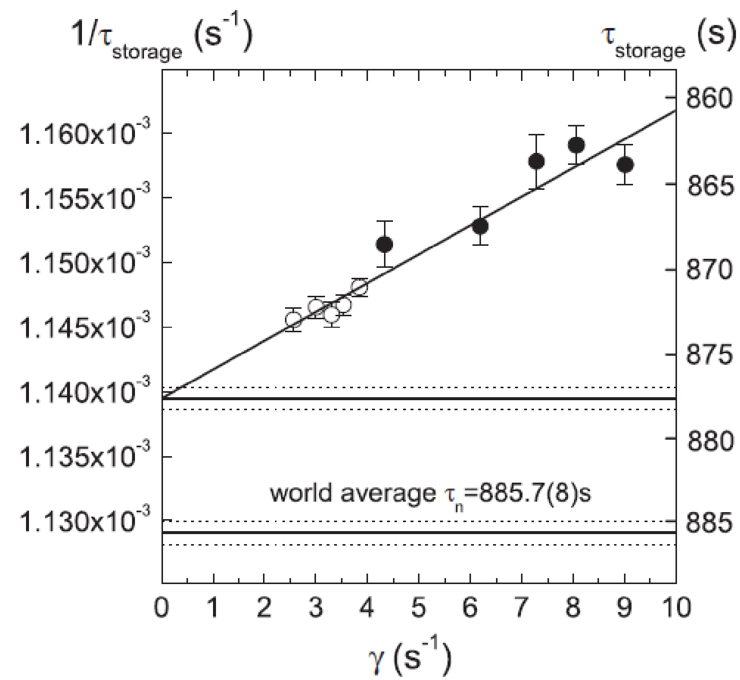


FIG. 12. Result of extrapolation to the neutron lifetime when combined energy and size extrapolations are used. The open circles represent the results of measurements for a quasispherical trap, and the full circles the results of measurements for a cylindrical trap.

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A.P. Serebrov et al., Phys. Lett. B 605 (2005) 72; Phys. Rev. C 78 (2008) 035505

Neutron asymmetry parameter, anno 2013

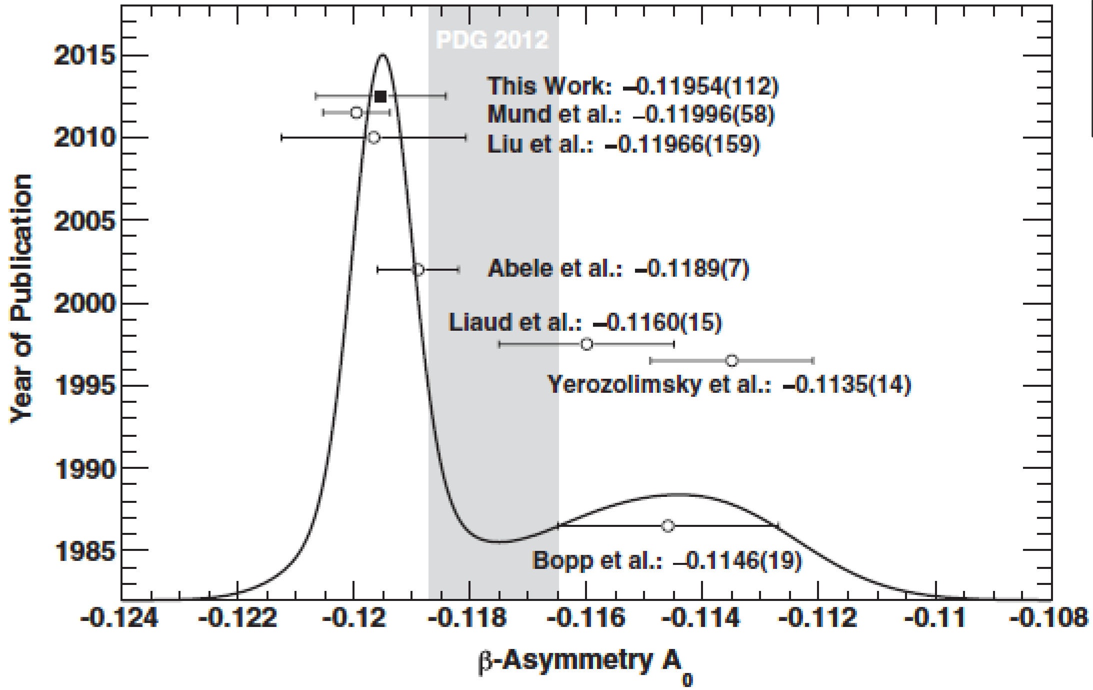


FIG. 2. Ideogram of values for A_0 from this work (filled square) and recent measurements (open circles) [7,9,28–32], arranged by year of publication. To account for correlated systematic errors in sequential measurements, the ideogram (solid curve) was constructed using the combined result from [31] and [32] of −0.11951(50) reported in [32], and the combined result of [7,9] and this work of −0.11956(110), as discussed in the text. The gray band indicates the PDG 2012 average value of $A_0 = -0.1176(11)$ [33], which includes the results of [7,9,28–31], but does not include [32] or the work reported here.

$$A_0 \equiv A_n = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$$

$$\text{with} \quad \lambda = \frac{g_A}{g_V} = \frac{C_A}{C_V}$$

M.P. Mendenhall et al.,
Phys. Rev. C 87, 032501(R) (2013)

Neutron asymmetry parameter, anno 2018

$\tilde{A}_n$	$-0.1146(19)$	1986	Bopp
	$-0.1160(9)(12)$	1997	Liaud
	$-0.1135(14)$	1997	Yerozolimsky
	$-0.11926(31)(42)$	2013	Mund - PERKEO
	$-0.12015(34)(63)$	2018	Brown - UCNA
	$-0.11869(99)$		Average ($S = 2.6$)

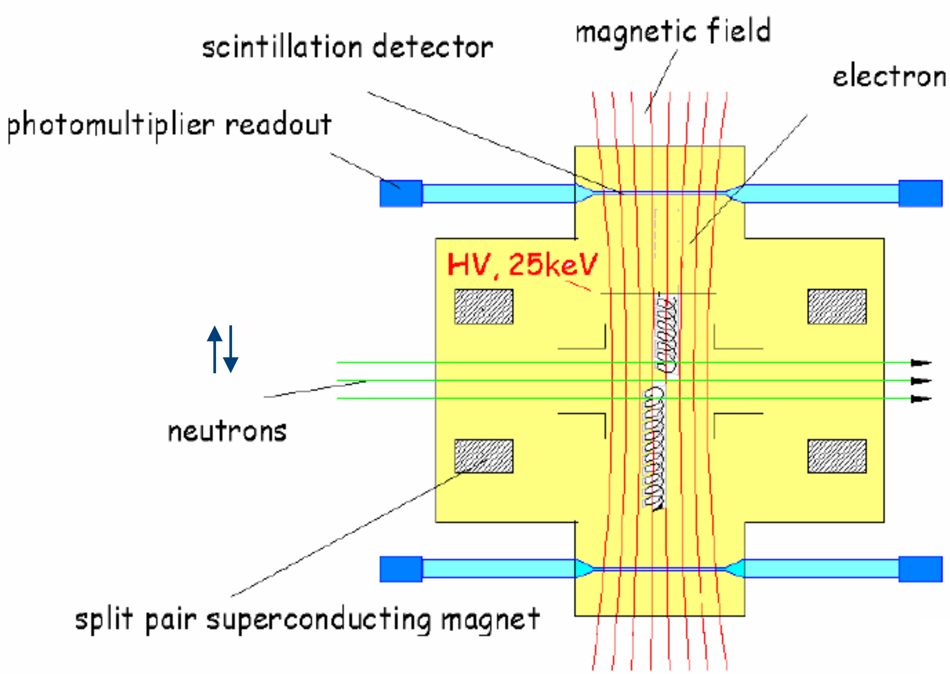
Pre-2000 experiments had large corrections (up to 15%)

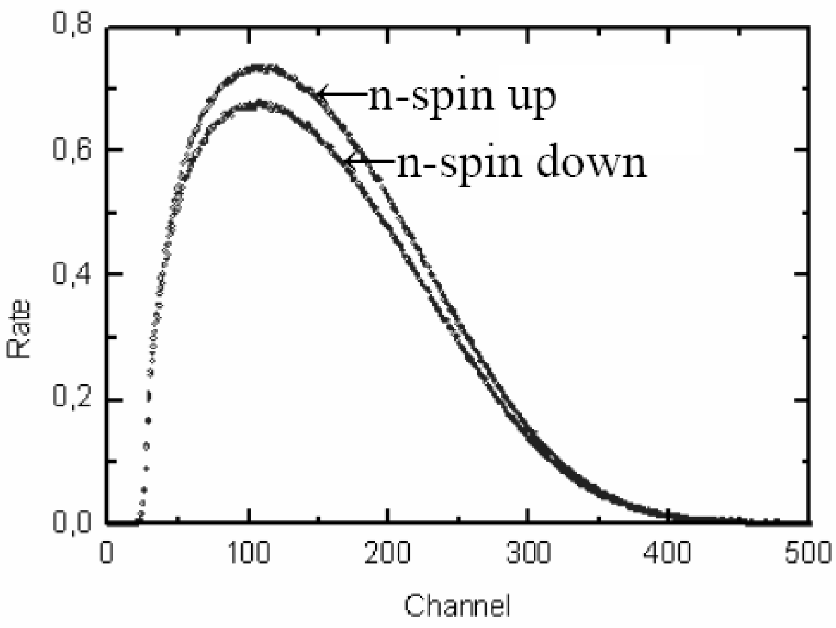
(e.g. H. Abele, Prog. Part. Nucl. Phys. 60 (2008) 1)

M. Gonzalez-Alonso, O. Naviliat-Cuncic, N. Severijns, arXiv:1803.08732, and Prog. Part. Nucl. Phys. available on-line

KU LEUVEN

Neutron beta-asymmetry parameter - PERKEO set-up (Heidelberg)

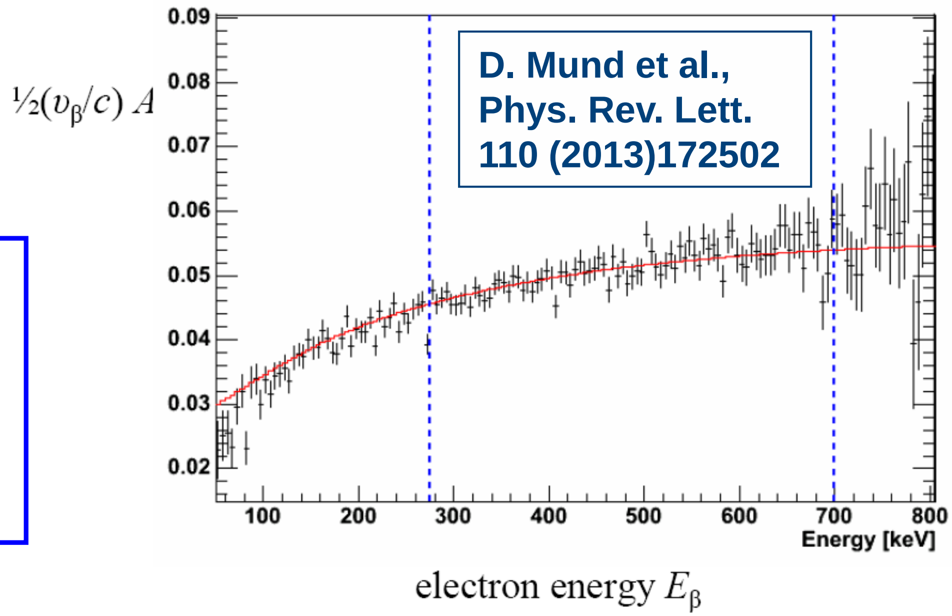




$$A_n = -2\frac{\lambda^2+\lambda}{1+3\lambda^2} \quad \text{with} \quad \lambda = \frac{g_A}{g_V} = \frac{C_A}{C_V}$$

$$dW = dW_0 \; \xi \left\{ 1 + \frac{\mathbf{p}}{\mathrm{E}} \cdot \mathbf{J} \, A \right\} \qquad (\text{with } b = 0)$$

$$\Rightarrow \quad \frac{dW(\mathbf{p},\mathbf{J}) - dW(\mathbf{p},-\mathbf{J})}{dW(\mathbf{p},\mathbf{J}) + dW(\mathbf{p},-\mathbf{J})} = \frac{\mathbf{p}}{\mathrm{E}} \cdot \mathbf{J} \; A = \frac{v}{c} \, \mathrm{J} \, A \cos\theta$$



D. Mund et al.,
Phys. Rev. Lett.
110 (2013)172502

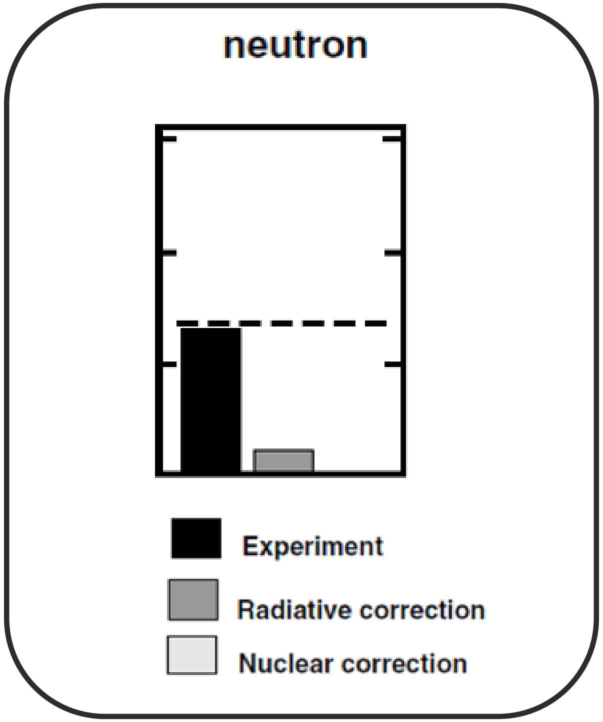
Conclusion for extracting V_{ud} from neutron decay

Value obtained for V_{ud} from neutron decay requires precise values for the neutron lifetime and the factor $\lambda = C_A/C_V$, which is obtained from the beta-asymmetry parameter *A* in neutron decay.

The values obtained for λ from the experiments performed since the year 2000 are an order of magnitude more precise and are also more reliable (smaller corrections required) than previous results. The value of λ can therefore be considered as established and has good precision.

The values obtained for the neutron lifetime from the beam method and the bottle method currently do not agree by more than 5 stand. dev. This problem has to solved before any precise value for V_{ud} can be obained from neutron decay .

Thus, the precision of a value for V_{ud} from neutron decay is currently limited by the experimental precision



T = 1/2 superallowed mirror beta transitions and CKM unitarity

$$\mathcal{F}t^{\mathrm{mirror}} \equiv f_V t\left(1+\delta'_R\right)\left(1+\delta^V_{NS}-\delta^V_C\right) = \frac{K}{G_F^2 V_{ud}^2}\,\frac{1}{|M_F^0|^2 C_V^2\left(1+\Delta_R^V\right)\left(1+\frac{f_A}{f_V}\rho^2\right)} = \frac{2\mathcal{F}t^{0^+\to 0^+}}{\left(1+\frac{f_A}{f_V}\rho^2\right)}$$

= 1 = 1

with $\rho = C_A M_{GT} / C_V M_F$

Parent nucleus	$\mathcal{F}t$ (s)	$\delta\mathcal{F}t$ (%)
^{3}H	1135.3 ± 1.5	0.13
^{11}C	3933 ± 16	0.41
^{13}N	4682.0 ± 4.9	0.10
^{15}O	4402 ± 11	0.25
^{17}F	2300.4 ± 6.2	0.27
^{19}Ne	1718.4 ± 3.2	0.19
^{21}Na	4085 ± 12	0.29
^{23}Mg	4725 ± 17	0.36
^{25}Al	3721.1 ± 7.0	0.19
^{27}Si	4160 ± 20	0.48
^{29}P	4809 ± 19	0.40
^{31}S	4828 ± 33	0.68
^{33}Cl	5618 ± 13	0.23
^{35}Ar	5688.6 ± 7.2	0.13
^{37}K	4562 ± 28	0.61
^{39}Ca	4315 ± 16	0.37
^{41}Sc	2849 ± 11	0.39
^{43}Ti	3701 ± 56	1.51
^{45}V	4382 ± 99	2.26

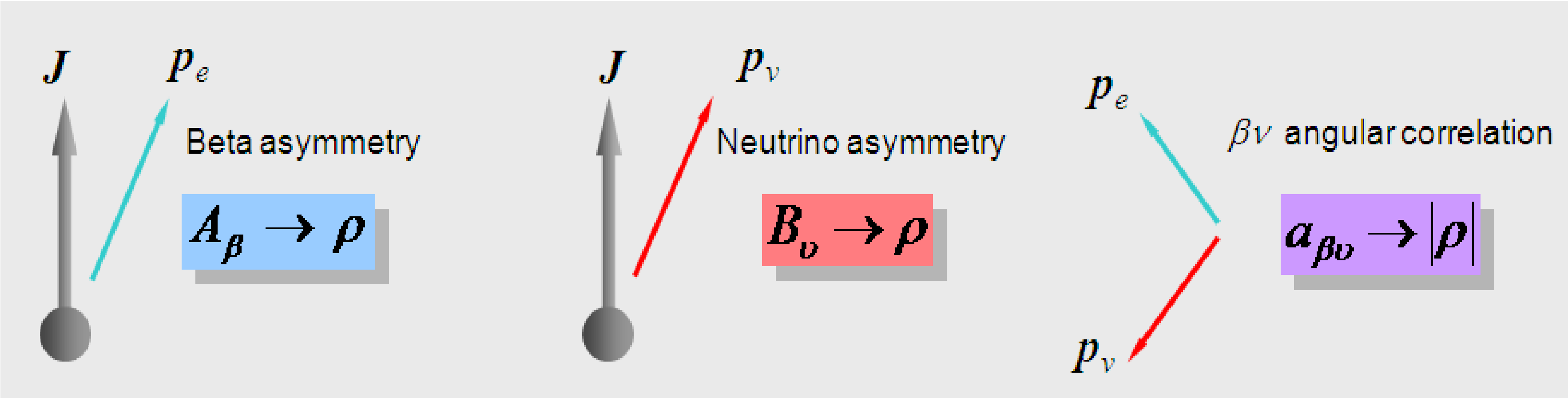
$$Ft_0 = Ft^{mirror}\left(1+\frac{f_A}{f_V}\rho^2\right) = 2Ft^{0^+\to 0^+}$$

$$= \frac{K}{G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

← accuracy of 0.1 % to 0.4 % for most cases

N.S., I.S. Towner et al., Phys. Rev. 78 (2008) 0555501

- extract mixing ratio $\rho = G_A M_{GT} / G_V M_F$ from correlation measurements:



- there are 35 candidates between ^{3}H and ^{83}Mo, near the N = Z line

(best are the ones with A < 45 about)

- correlation measurements have been carried out for:

^{17}F, ^{19}Ne, ^{21}Na, ^{29}P, ^{35}Ar and ^{37}K

2. Status

correlation measurements have been carried out for:

^{17}F, ^{19}Ne, ^{21}Na, ^{29}P, ^{35}Ar and ^{37}K

	^{19}Ne	^{21}Na	^{29}P	^{35}Ar	^{37}K
J	1/2	3/2	1/2	3/2	3/2
$\mathcal{F}t$ [s][a]	1720.3(30)	4085(12)	4809(19)	5688.6(72)	4562(28)
f_A/f_V[b]	1.0143(29)	1.0180(36)	1.0223(45)	0.9894(21)	1.0046(9)
E_0 [MeV][c]	2.728 31(17)	3.036 58(70)	4.431 45(60)	5.455 14(70)	5.636 46(23)
E [MeV][d]	0.511	1.60	2.39	3.14	3.35
M [amu][e]	19.000 141 99(9)	20.995 750 9(4)	28.979 147 65(30)	34.972 055 1(4)	36.970 076 11(12)
b[f]	−148.5605(26)	82.6366(27)	89.920(15)	−8.5704(90)	−44.99(24)
$a_{\beta\nu}$		0.5502(60)[g] ***a***			
A_β	−0.0391(14)[h] ***A***		0.681(86)[i] ***A***	0.430(22)[j] ***A***	−0.5707(19) ***A***
B_ν					−0.755(24)[k] ***B***
ρ	1.5995(45)	−0.7136(72)	−0.593(104)	−0.279(16)	0.561(27)
$\mathcal{F}t_0$ [s]	6184(30)	6202(48)	6537(606)	6128(49)	6006(146) 6137(28)

O. Naviliat-Cuncic and N.S., Phys. Rev. Lett. 102 (2009) 142302

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Status mirror nuclei

$$\mathcal{F}t_0 = \mathcal{F}t^{mirror}\left(1+\frac{f_A}{f_V}\rho^2\right) = \frac{K}{G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

$$(\mathcal{F}t_0)_{avg} = 6159(17)\ \mathrm{s}$$

$|V_{ud}| = 0.9730(14)$

(mirror transitions)

O. Naviliat-Cuncic & N.S., PRL 102 (2009) 142302

M. Gonzalez-Alonso, O. Naviliat-Cuncic, N.S., arXiv:1803.08732 (Prog. Part. Nucl. Phys.)

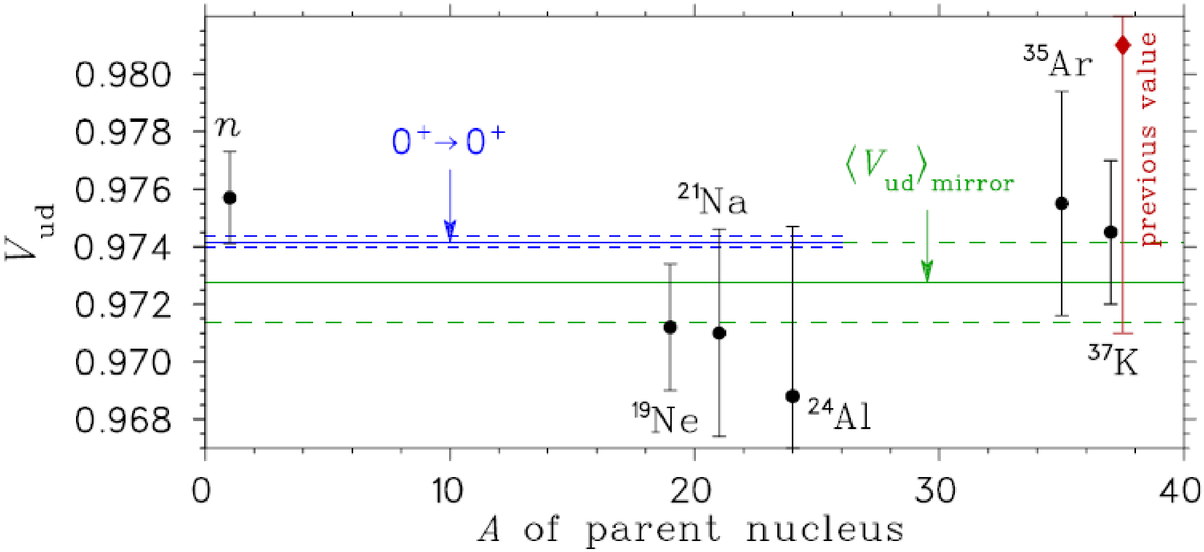


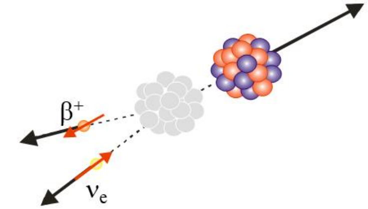
FIG. 6. (Color online) Measurements of V_{ud} comparing the value from the neutron [34], ^{24}Al [46], and the $T = 1/2$ mirror nuclei: ^{19}Ne [37], ^{21}Na [47], ^{35}Ar [38], the previous value for ^{37}K [12], and the present work. The averages (uncertainties) in V_{ud} determined from $0^+ \rightarrow 0^+$ [16] and mirror transitions are shown as the solid (dashed) lines.

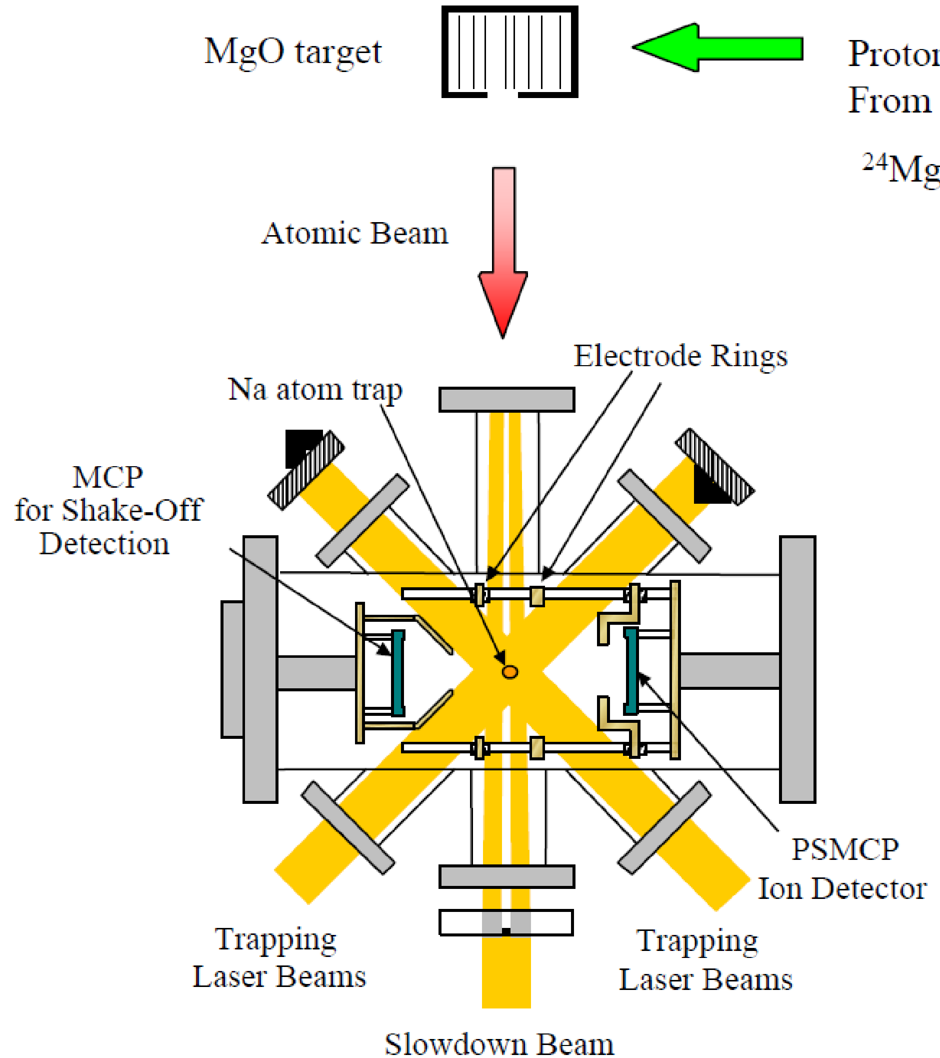
Fenker, Behr, Melconian et al., PRL 120 (2018) 062502

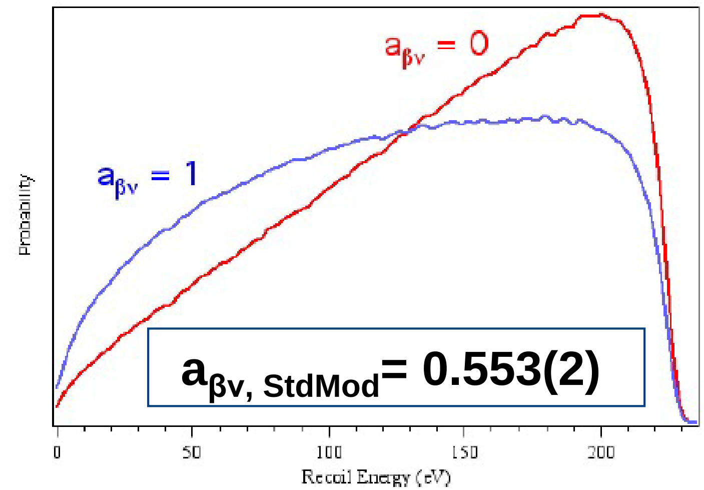
$$\text{Note: } 2\mathcal{F}t^{0^+0^+} = 6144.5(14)\ \mathrm{s}$$

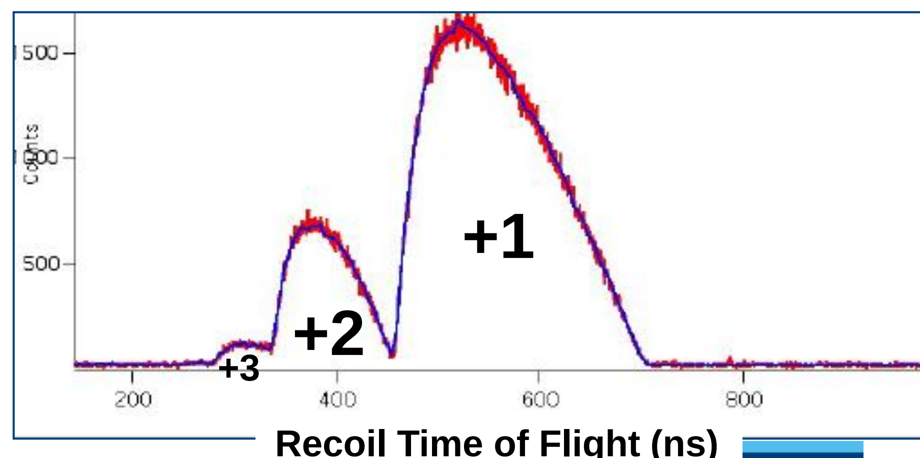
Beta-neutrino correlation in ^{21}Na

$$^{21}\mathrm{Na} \rightarrow {}^{21}\mathrm{Ne}\, e^{+} \nu_{e}$$









N.D. Scielzo et al., Phys. Rev. Lett. 93 (2004) 102501
P.A. Vetter et al., Phys. Rev. C 77 (2008) 035502

Initial result: $a_{\beta\nu,\,exp}$ = 0.524 (9)

3σ off SM !?! (**large** trap population!)

N.D. Scielzo et al., Phys. Rev. Lett. 93 (2004) 102501

New result (**low** trap population!) **:**

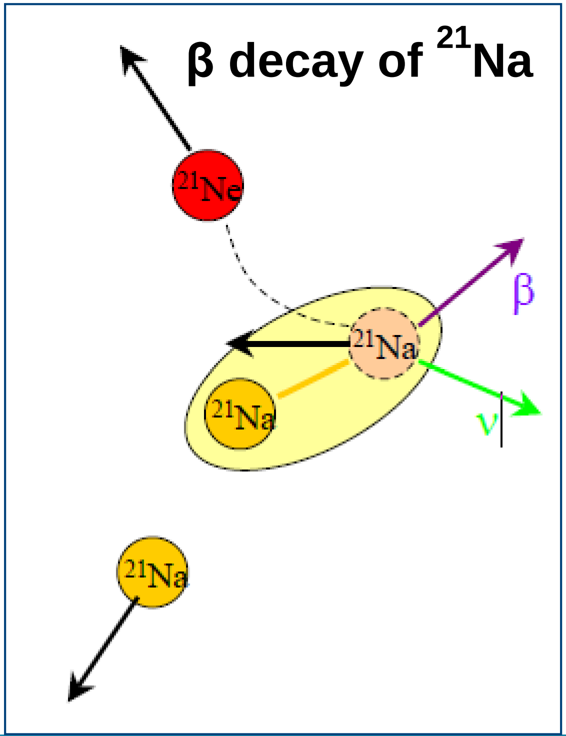
$a_{\beta\nu,\,exp}$ = 0.5502 (38) (46) (20)

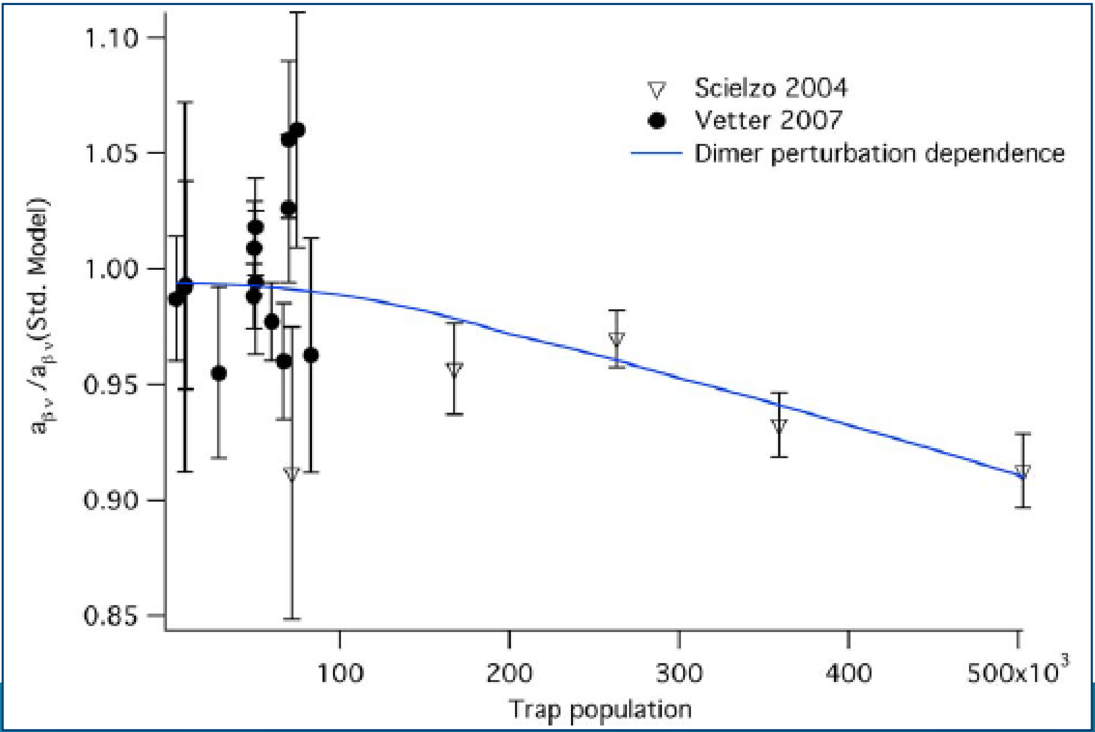
[stat] [sys] [model]

P.A. Vetter et al., Phys. Rev. C 77 (2008) 035502

$a_{\beta\nu,\,SM}$ = 0.553(2)

- **Problem: ^{21}Na formation rates in MOT are high;**
- **Recoil ion scatters off molecule, and changes momentum;**
- **Initial momentum, energy distribution of ^{21}Ne is lost, and depends on scattering parameters.**





Beta-asymmetry parameter in ^{37}K decay

^{37}K @ ISAC-TRINAT: A = $-0.5707(13)_{stat}(12)_{syst}(5)_{pol}$ = $-0.5707(18)$

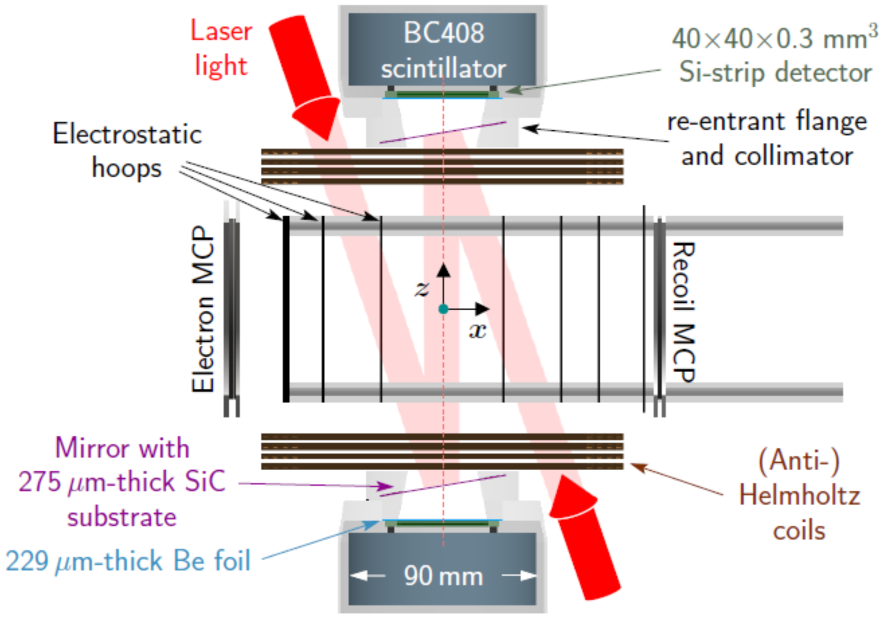
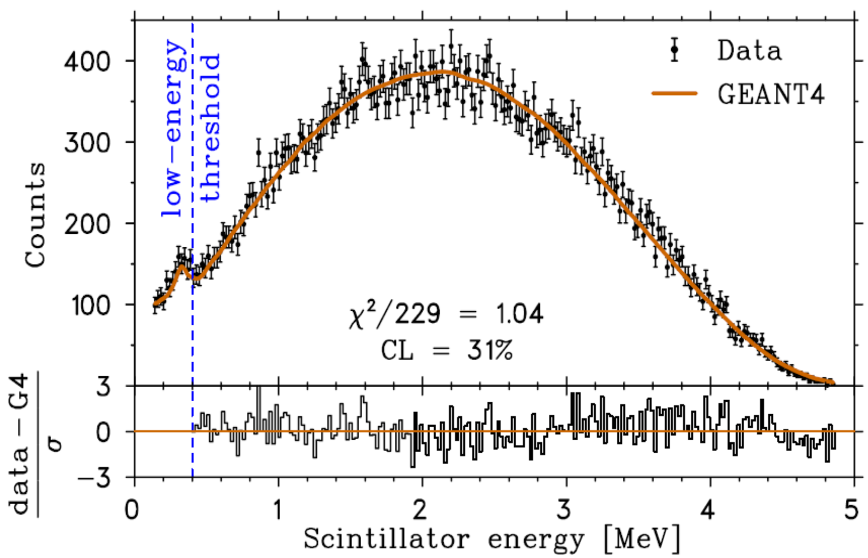


FIG. 1. The TRINAT detection chamber (color online). To polarize the atoms along the β-detection ($\hat{z}$-) axis, optical pumping light is brought in at a 19° angle with respect to the $\hat{z}$-axis and reflected off thin mirrors mounted within a β collimator on the front face of the re-entrant flanges. Thin Be foils behind the mirrors separate the Si-strip and scintillator β detectors from the 1×10^{-9} Torr vacuum of the chamber. Magnetic field coils provide the Helmholtz (optical pumping, 2 Gauss) and anti-Helmholtz (MOT) fields. Glassy carbon and titanium electrostatic hoops produce a uniform electric field of 150 to 535 V/cm in the $\hat{x}$ direction to guide shakeoff electrons and ions towards microchannel plate detectors.



reached 99.12(9)% nuclear polarization by optical pumping in the MOT magneto-optical trap

Fenker, Behr, Melconian et al., PRL 120 (2018) 062502

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T = 1/2 mirror β transitions:

$$Ft^{mirror}\left(1+\frac{f_A}{f_V}\rho^2\right) = 2Ft^{0^+\rightarrow 0^+} = \frac{K}{G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

$$\rho = \frac{C_A M_{GT}}{C_V M_F}$$

Currently the precision of V_{ud} from mirror beta transitions is limited by the precision with which the GT/F ratio can be obtained from correlation experiments.

Further improvements require:

- **new and precise measurements of correlation coefficients,**
  (e.g. βν-correlation coefficient *a* and beta-asymmetry parameter *A*)
- **improved corrected Ft-values for T=1/2 mirror transitions**
- **new calculations of nucleus independent radiative correction Δ_R**

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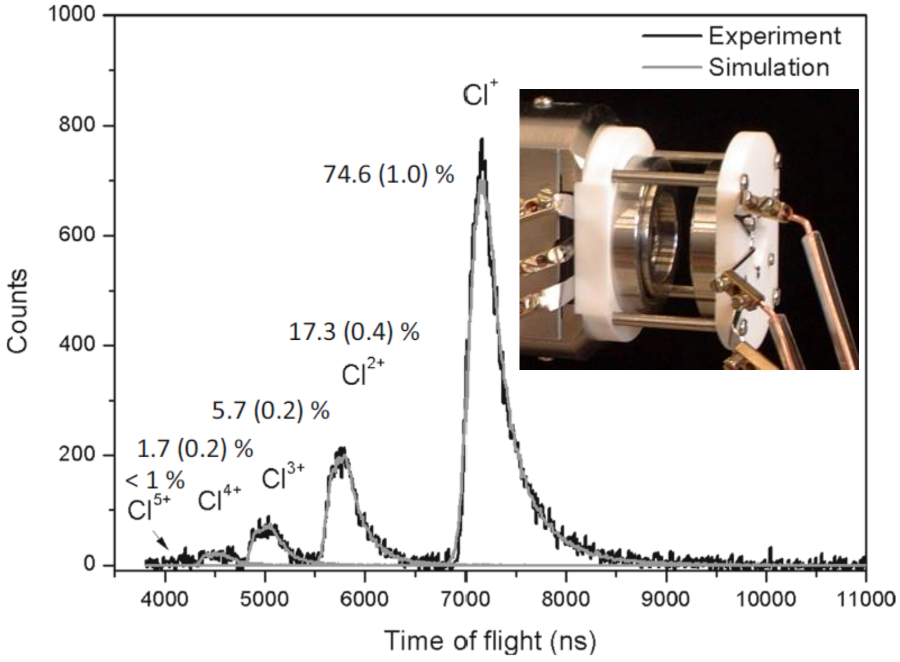
new measurements using mirror transitions, e.g. :

^{35}Ar @ LPCTrap



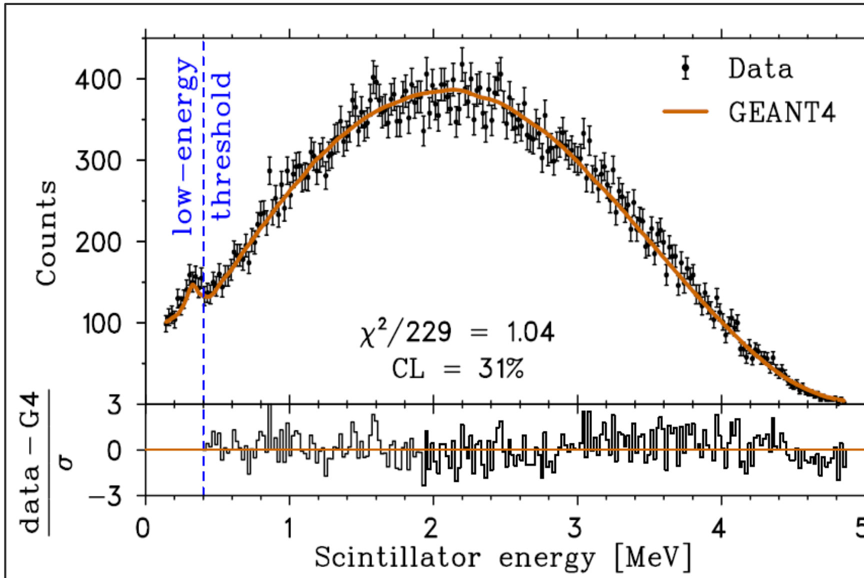
ToF distribution of the ^{35}Cl RI resulting from $^{35}Ar^{1+}$ decay

C. Couratin et al., PR A 88 (2013) 041403(R)
E. Lienard, et al., Hyperfine Interact. 236 (2015) 1

^{37}K @ ISAC:

3 times better precision possible

Fenker, Behr, Melconian et al., PRL 120 (2018) 062502

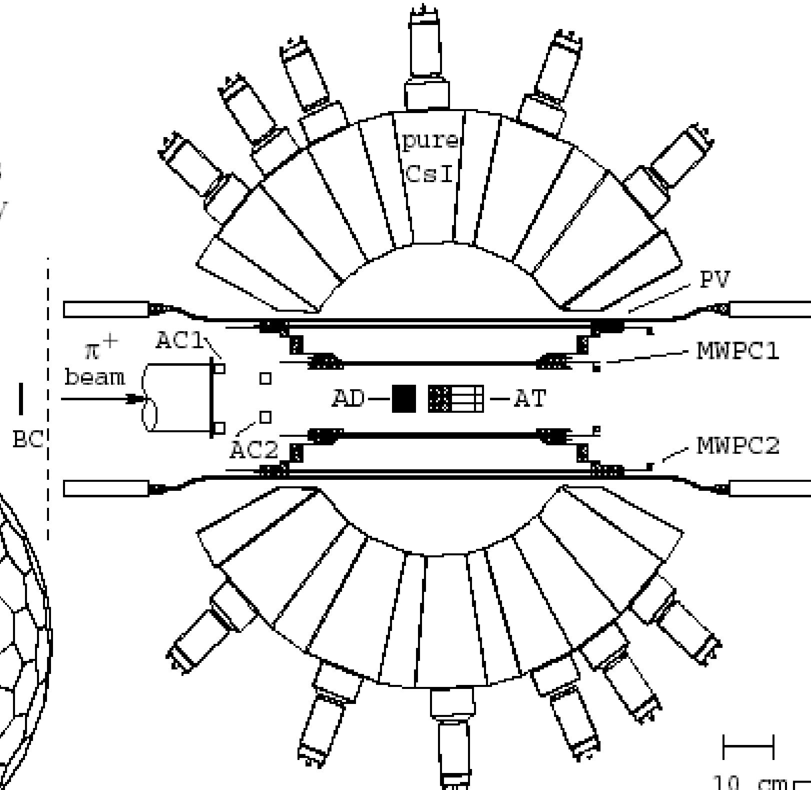


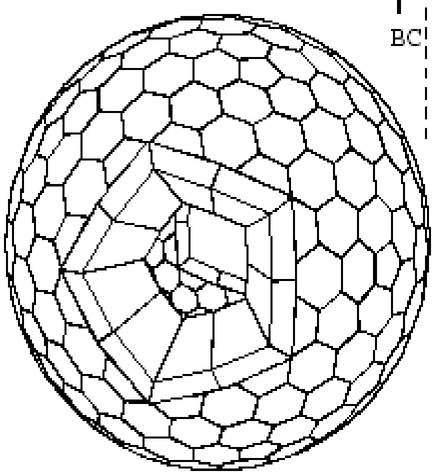
Pion decay $\pi^+ \to \pi^0 e^+ \nu$ and CKM unitarity

pure Vector decay

The PIBETA Experiment:

- stopped π^+ beam
- segmented active tgt.
- 240-det. CsI(p) calo.
- central tracking
- digitized PMT signals
- stable temp./humidity
- cosmic μ antihouse





D. Pocanic et al., PRL (2004)

BR($\pi^+ \to \pi^0 e^+ \nu$)=[1.036±0.006]x10^{-8}

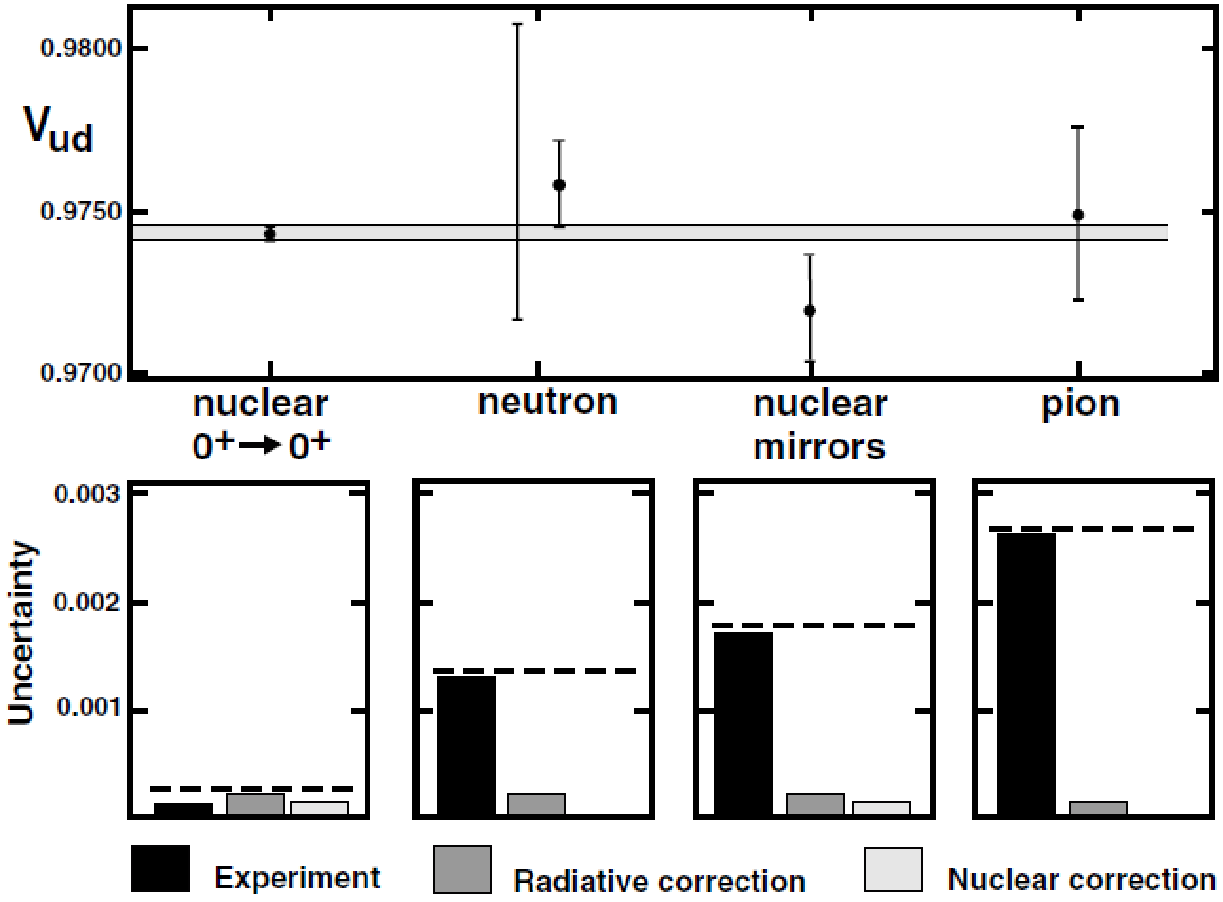
Towner & Hardy, Rep. Prog. Phys.72(2010)046301

$\to$ $|V_{ud}{}^{\pi}|$ = 0.9742(26)

Paul Scherrer Institute, Villigen, CH

KU LEUVEN

V_{ud} status overview



<u>Note</u>: weighted average at present equal to result from nuclear Fermi decays

I.S. Towner and J.C. Hardy, Rep. Prog. Phys. 73 (2010) 046301

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V_{us} from K-decay

TABLE IX. Results for $|V_{us}|$ obtained from the recent measurements of $|V_{us}|f_+(0)$ in neutral and charged kaon decays.

Experiment	Decay	$\|V_{us}\|f_+(0)$[a]	$\|V_{us}\|$[b]
E865	$K^+, e3$	0.2243(22)(7)[c]	0.2284(23)(20)
KTeV	$K_L, e3, \mu3$	0.2165(12)[d]	0.2253(13)(20)
NA48	$K_L, e3$	0.2146(16)[e]	0.2233(17)(20)
KLOE[f]	$K_L, e3, \mu3$	0.21673(59)	0.2255(6)(20)[g]
Weighted average			0.2254(21)

[a] For K^+ decay $f_+(0)=0.982(8)$, while for K_L decay $f_+(0) = 0.961(8)$ (see text).

[b] The first error is due to experimental uncertainties; the common error of 0.0020 is related to the uncertainty of $f_+(0)$.

[c] Sher *et al.* (2003).

[d] Alexopoulos *et al.* (2004).

[e] Lai *et al.* (2004).

[f] A result obtained at KLOE for the $K_S, e3$ decay is not included here as only a preliminary value, i.e., $|V_{us}| = 0.2254(17)$ (Franzini, 2004), is available to date.

[g] Ambrosino *et al.* (2006a).

NS, O. Naviliat-Cuncic, M. Beck, Rev. Mod. Phys. 78 (2006) 991

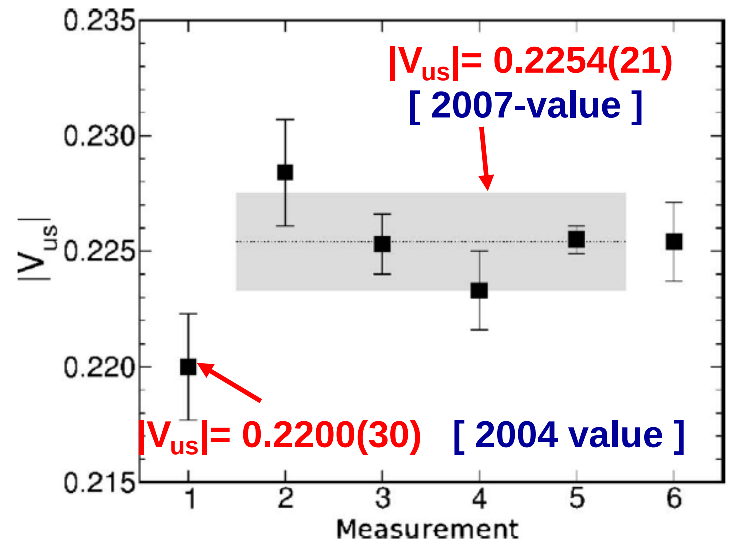

FIG. 14. Values for $|V_{us}|$ from the Particle Data Group analysis [1, Eidelman *et al.* (2004)] and from recent results in K decays [2, Sher *et al.* (2003); 3, Alexopoulos *et al.* (2004); 4, Lai *et al.* (2004); 5, Ambrosino *et al.* (2006a); 6, preliminary result from KLOE, Franzini *et al.* (2004)]. The shaded band indicates the weighted average of the published new results from K decays (measurements 2–5). See also Table IX.

2016-value : $|V_{us}|$= 0.2253(8)

Particle Data Group, Patrignani et al., Chinese Phys. C 40 (2016) 100001

(form factor $f_+(0)$ takes into account SU(3) breaking and isospin symmetry breaking effects)

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Unitarity of CKM quark mixing matrix

- **coupling of quark weak eigenstates to mass eigenstates in the Standard Model**

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

unitarity condition:

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

V_{ud} = 0.97417 (21) ~ 95 %
V_{us} = 0.2253(8) ~ 5 %
V_{ub} = 0.00415(49) ~ 0 %

➔ $\sum V_{ui}^2$ = 0.99978(55) PRESENT

Hardy & Towner, Phys. Rev. C 91, 025501 (2015)

Note: previously *(2004):* ***V_{ud} = 0.9736(3)***
V_{us} = 0.2200(23)

➔ $\sum V_{ui}^2$ = 0.9967(13) OLD

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Unitarity test for all rows and columns of the CKM matrix

CKM-matrix elements from experimental data :

Particle Data Group, Patrignani et al., Chinese Phys. C 40 (2016) 100001

$$\begin{pmatrix} 0.97417(21) & 0.2248(6) & 0.00409(39) \\ 0.220(5) & 0.995(16) & 0.0409(39) \\ 0.0082(6) & 0.0400(27) & 1.009(31) \end{pmatrix} \begin{matrix} \rightarrow 0.99956(51) \\ \rightarrow 1.04 \\ \rightarrow 1.020 \end{matrix}$$

$$\begin{matrix} \downarrow & \downarrow & \downarrow \\ 0.9975 & 1.042 & 1.020 \end{matrix}$$

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