BETA DECAY: A WINDOW ON FUNDAMENTAL SYMMETRIES

J.C. Hardy

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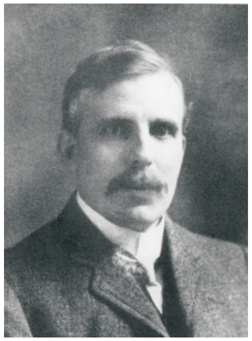
BRIEF HISTORY OF THE WEAK INTERACTION



1899 Rutherford first identifies (and named) two different types of radiation – and – emitted from uranium.

1933 Fermi derives theory for beta decay incorporating vector interaction. Coupling constant, G_V, is presumed to be universal. Three years later, Gamow and Teller add axial-vector interaction.

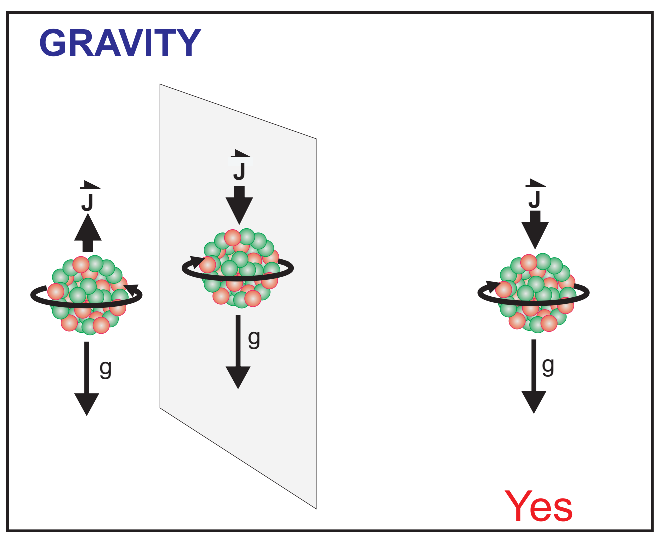
1953 Sherr and Gerhart test vector-current universality by measuring superallowed beta decay of ^{10}C and ^{14}O to ± 30%.

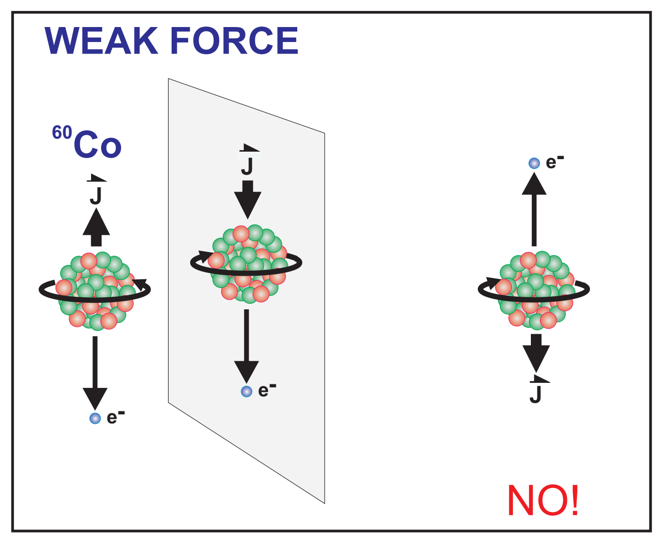
1954 Feynman and Gell-Mann put forward the Conserved Vector Current hypothesis.

BRIEF HISTORY OF THE WEAK INTERACTION

1956 Lee and Yang suggest that the weak interaction might not conserve parity. That could explain the “ puzzle”. They suggest experiments to test for parity violation.

1957 Wu and collaborators observe preferential direction for emission of electrons in the beta decay of polarized ^{60}Co. This demonstrates parity non-conservation.





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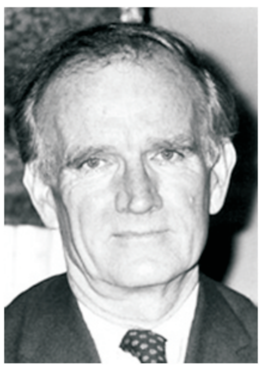
1960-63 G_V from superallowed decays found different from G , the constant from muon decay. Also the coupling strength for kaons and pions differed depending on whether their decays changed strangeness or not.

BRIEF HISTORY OF THE WEAK INTERACTION

1963 Cabibbo resolves discrepancy by recognizing that universality was only manifest by the total strength of the strangeness-changing and -conserving decays. Thus $G_V = \cos \quad G$. In modern terms, he recognized mixing between the first two generations of quarks via a unitary rotation.



1964 Cronyn and Fitch observe long-lived neutral kaon decay into two pions, violating CP symmetry. Source of CP violation remained puzzle for next 10 years.

1974 Kobayashi and Maskawa propose third generation of quarks as simplest solution to CP violation. The corresponding 3X3 rotation (mixing) matrix became known as the CKM matrix.

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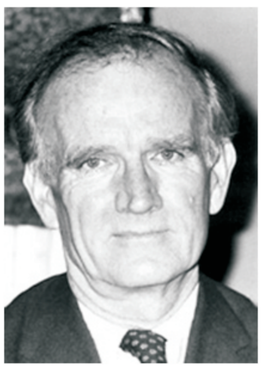

…-lived …ons, violating …olation …ars.

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

weak eigenstates — Cabibbo Kobayashi Maskawa (CKM) matrix — mass eigenstates

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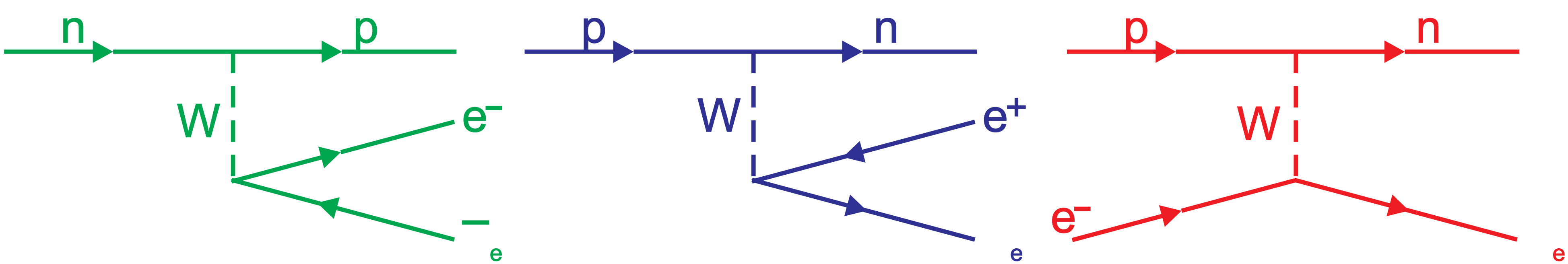
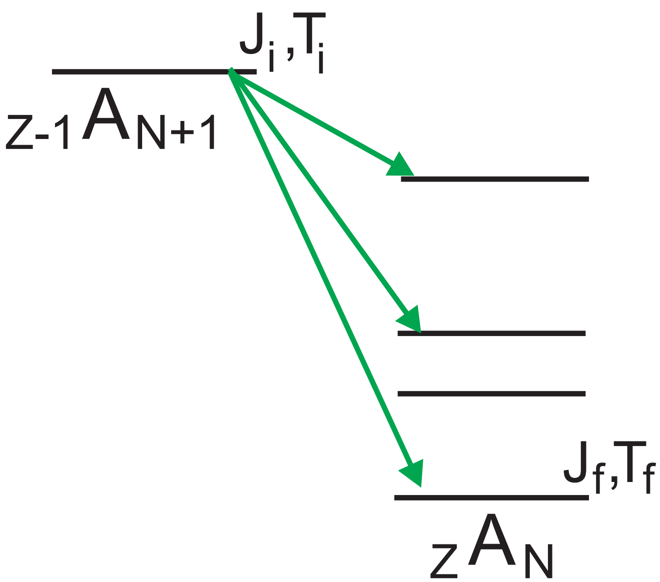
BETA DECAY



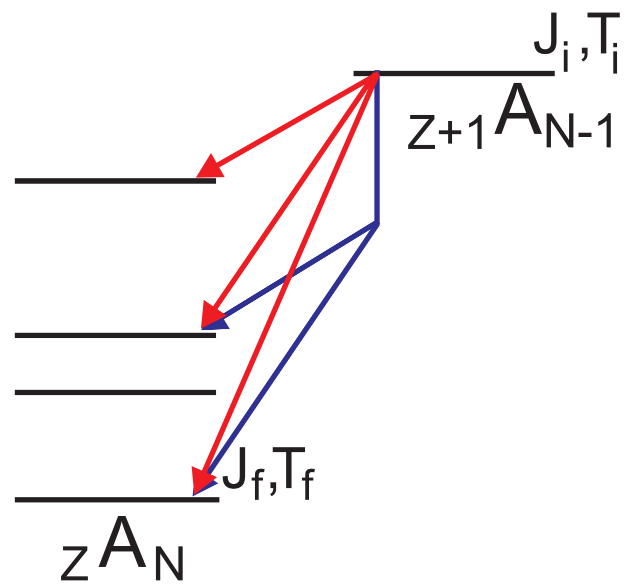


$\vec{J}_i = \vec{J}_f + \vec{L} + \vec{S}$

"Allowed" decay: $L = 0$

Vector current: $S = 0$

Axial-vector current: $S = 1$



Selection rules: Vector current $J = 0$, $T = 0$

Axial vector current $J = 0, \pm 1$; $T = 0, \pm 1$; no $0^+ \rightarrow 0^+$

Standard model: Conserved vector current (CVC)

Scalar, tensor and preudoscalar currents = 0

OVERVIEW OF BETA-DECAY POSSIBILITIES

Decay rate from oriented nuclei:

Jackson, Treiman, Wyld, NP 4, 206 (1957)

$$d^5 \;\propto\; F(\pm Z, E_e)\, p_e E_e (E - E_e)^2\, dE_e\, d\;\; {}_e\, d \quad \left(G_V^2 < \;\, >^2 + G_A^2 < \;\; >^2\right)$$

$$\times \left\{1 + a\frac{\vec{\mathbf{p}}_e \cdot \vec{\mathbf{p}}}{E_e E} + b\frac{m}{E_e} + \frac{\vec{\mathbf{J}}}{J} \cdot \left(A\frac{\vec{\mathbf{p}}_e}{E_e} + B\frac{\vec{\mathbf{p}}}{E} + D\frac{\vec{\mathbf{p}}_e \times \vec{\mathbf{p}}}{E_e E}\right)\right\}$$

only occur because parity is not conserved

only occurs if time-reversal invariance is violated

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$$\times \left\{1 + a\frac{\vec{\mathbf{p}}_e\cdot\vec{\mathbf{p}}}{E_e\, E} + b\frac{m}{E_e} + \frac{\vec{\mathbf{J}}}{J}\cdot\left(A\frac{\vec{\mathbf{p}}_e}{E_e} + B\frac{\vec{\mathbf{p}}}{E} + D\frac{\vec{\mathbf{p}}_e\times\vec{\mathbf{p}}}{E_e\, E}\right)\right\}$$

1) If E_e, $\quad_e$ and $\quad$ are not measured

$$\frac{1}{t} \quad \propto \quad \underbrace{\int F(\pm Z, E_e)\, p_e E_e (E - E_e)^2 dE_e}_{f} \left(G_V^2 < \quad >^2 + G_A^2 < \quad \quad >^2\right)\left\{1 + b\,\frac{m}{E_e}\right\}$$

= 0 in Standard Model

So

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

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≠ 0 if scalar or tensor currents exist

So

$$ft \; = \; \frac{\mathbf{K}}{G_V^{\,2} < \; >^2 + G_A^{\,2} < \quad >^2}$$

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2) If $\vec{p}_e$ is measured, then A can be obtained and $\frac{G_A < \quad >}{G_V < \ >}$ determined.

for J ⟶ J $\qquad A = \dfrac{\mp \frac{1}{J+1} \quad ^2 - 2\sqrt{\frac{J}{J+1}}}{1 + \quad ^2}$

+ more terms if scalar or tensor currents exist

where $\quad = \dfrac{G_A < \quad >}{G_V < \ >}$

Examples: neutron decay

decay between mirror nuclei (e.g. $^{19}Ne \rightarrow {}^{19}F$)

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3) If $\vec{p}_e$ and $\vec{p}$ are measured, *a* and *B* can be obtained, also yielding .

$$a = \frac{1 - \frac{1}{3}\;\;^2}{1 + \;\;^2}$$

+ more terms if scalar or tensor currents exist

for J ⟶ J $\quad B = \frac{\pm\frac{1}{J+1}\;\;^2 - 2\sqrt{\frac{J}{J+1}}}{1 + \;\;^2}$

where $= \frac{G_A < \;\; >}{G_V < \; >}$

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To summarize:

- There are three ways to determine $\dfrac{G_A <\ \ >}{G_V <\ >}$ experimentally: measure *a*, *A* or *B*.

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To summarize:

- There are three ways to determine $\frac{G_A <\ \ >}{G_V <\ >}$ experimentally: measure *a*, *A* or *B.*
- The standard model excludes scalar and tensor currents. A non-zero measured value for *b* would indicate their presence.

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To summarize:

- There are three ways to determine $\frac{G_A < \;\; >}{G_V < \; >}$ experimentally: measure *a*, *A* or *B.*
- The standard model excludes scalar and tensor currents. A non-zero measured value for *b* would indicate their presence. Unexpected values for *a*, *A* and *B* would also be a signal.
- The standard model assumes time-reversal invariance. A non-zero measured value for *D* would demonstrate a violation of this assumption.

SAMPLE OF RECENT EXPERIMENTS

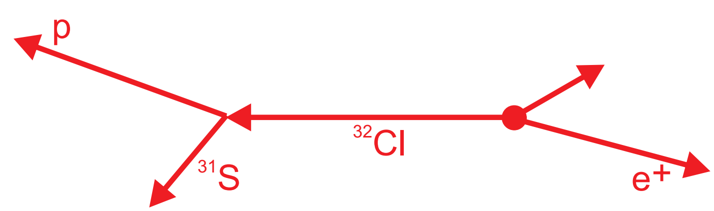
VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

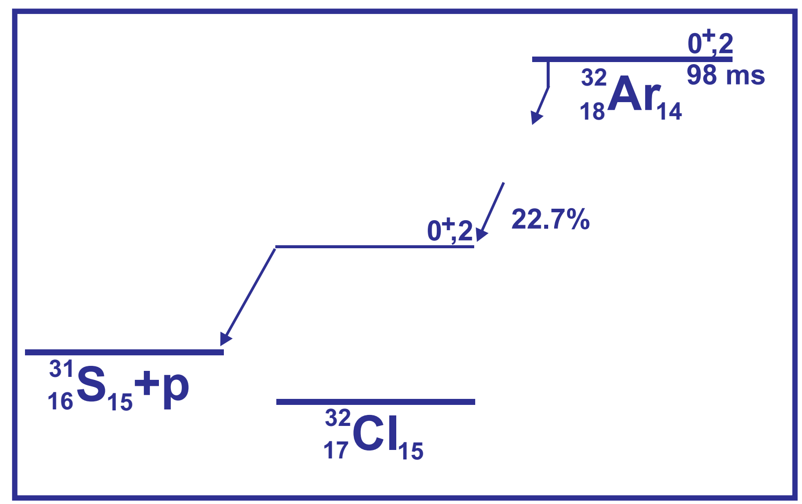
Positron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ Decay of ^{32}Ar

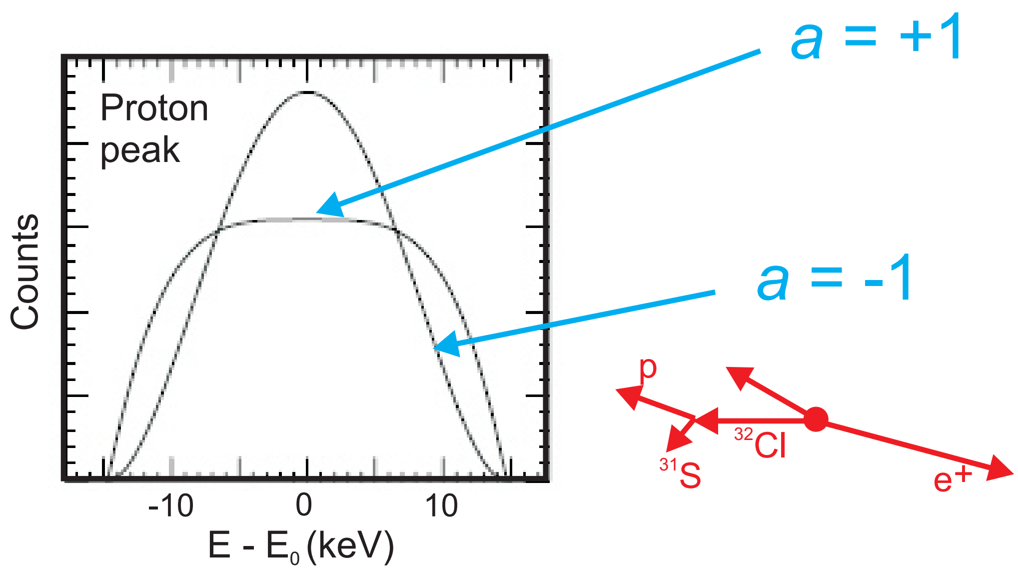
E. G. Adelberger,[1] C. Ortiz,[2] A. García,[2] H. E. Swanson,[1] M. Beck,[1] O. Tengblad,[3] M. J. G. Borge,[3] I. Martel,[4]
H. Bichsel,[1] and the ISOLDE Collaboration[4]

"Superallowed" transition:

- J=0, T=0 (analog states), $0^+ \rightarrow 0^+$
- pure vector decay (S =0)







Beta-neutrino correlation ($\vec{p}_e \cdot \vec{p}$):

$$a = \frac{2 - \frac{(C_S^2 + C_S'^2)}{G_V^2}}{2 + \frac{(C_S^2 + C_S'^2)}{G_V^2}}$$

a = 0.9989(65)

SAMPLE OF RECENT EXPERIMENTS

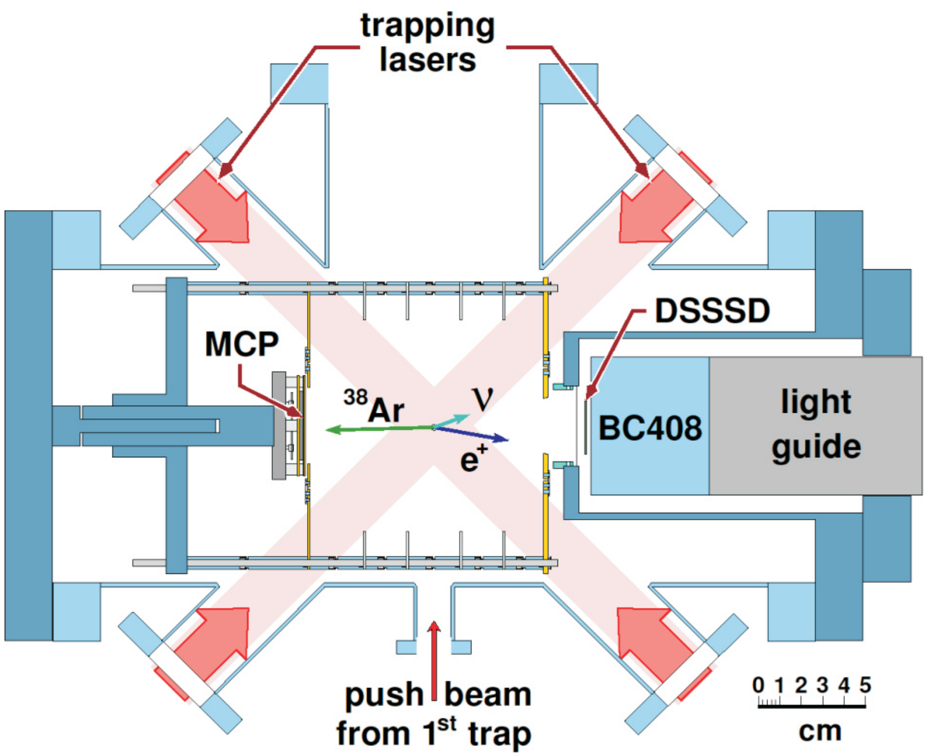
PRL 94, 142501 (2005) PHYSICAL REVIEW LETTERS week ending 15 APRIL 2005

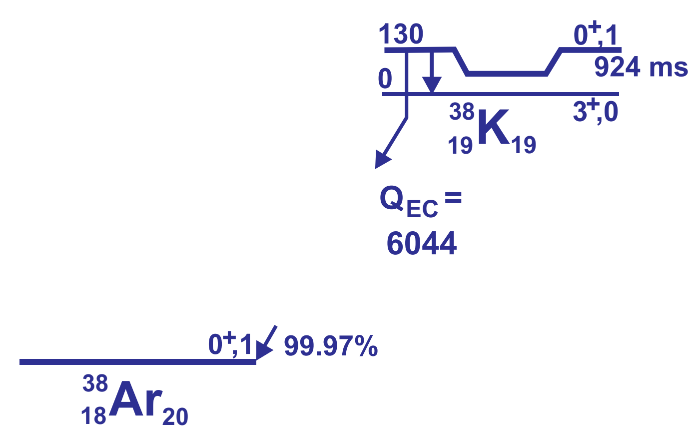
Scalar Interaction Limits from the β-ν Correlation of Trapped Radioactive Atoms

A. Gorelov,[1] D. Melconian,[1] W. P. Alford,[2] D. Ashery,[3] G. Ball,[4] J. A. Behr,[4] P. G. Bricault,[4] J. M. D'Auria,[5] J. Deutsch,[6] J. Dilling,[4] M. Dombsky,[4] P. Dubé,[1] J. Fingler,[4] U. Giesen,[4] F. Glück,[7] S. Gu,[4] O. Häusser,[1,*] K. P. Jackson,[4] B. K. Jennings,[4] M. R. Pearson,[4] T. J. Stocki,[1] T. B. Swanson,[5] and M. Trinczek[5]

"Superallowed" transition:

- J=0, T=0 (analog states), $0^+ \to 0^+$
- pure vector decay (S =0)





Beta-neutrino correlation ($\vec{p}_e \cdot \vec{p}_\nu$):

$$a = \frac{2 - \frac{(C_S^2 + C_S'^2)}{G_V^2}}{2 + \frac{(C_S^2 + C_S'^2)}{G_V^2}}$$

a = 0.9981(46)

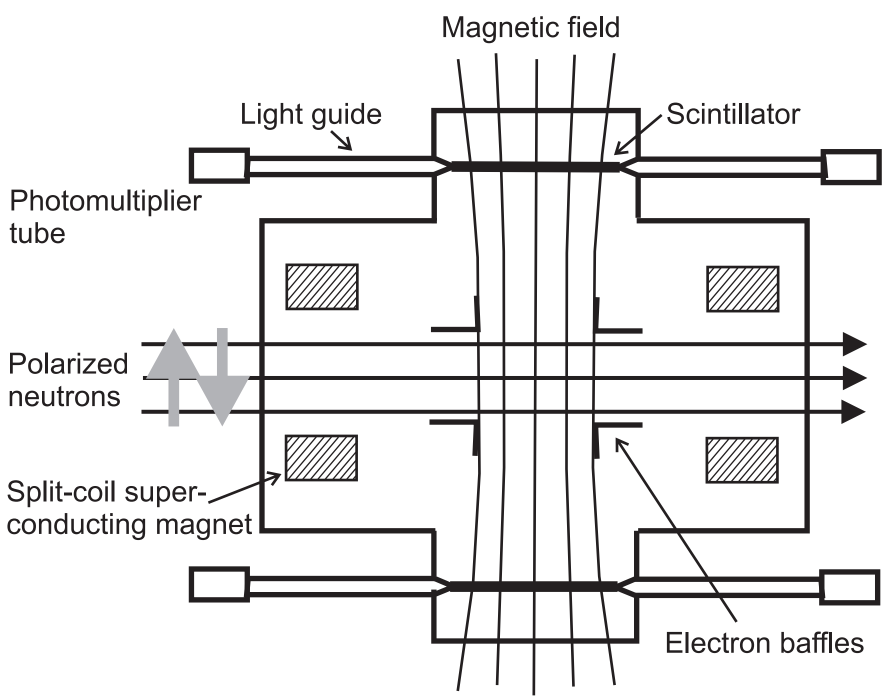
SAMPLE OF RECENT EXPERIMENTS

arXiv:1204.0013v1 (2012)

Determination of the Weak Axial Vector Coupling $\lambda = g_A/g_V$ from a Measurement of the β-Asymmetry Parameter A in Neutron Beta Decay

D. Mund,* B. Märkisch,† M. Deissenroth, J. Krempel,‡ M. Schumann,§ and H. Abele¶
Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, 69120 Heidelberg, Germany

A. Petoukhov and T. Soldner**
Institut Laue-Langevin, BP 156, 6, rue Jules Horowitz, 38042 Grenoble Cedex 9, France



Beta-asymmetry parameter $(\vec{J} \cdot \vec{p}_e)$:

$$A = \frac{\mp \frac{1}{J+1} \;^2 - 2\sqrt{\frac{J}{J+1}}}{1 + \;^2} \quad \text{where} \quad = \frac{G_A < \quad >}{G_V < \; >}$$

For neutron decay: J = ½ , < > = $\sqrt{3}$, < > = 1

$$A = -2\frac{(\quad + 1)}{1 + 3 \;^2} \quad \text{where} \quad = \frac{G_A}{G_V}$$

***A* = -0.11996(58)**

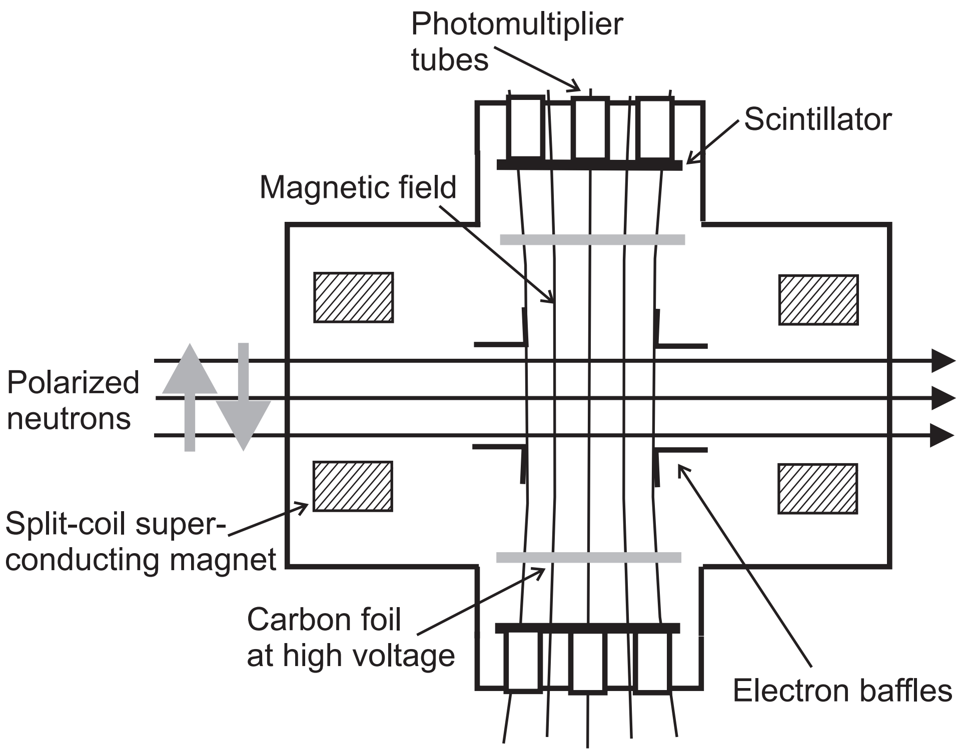
= -1.2767(16)

SAMPLE OF RECENT EXPERIMENTS

PRL 99, 191803 (2007) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2007

Measurement of the Neutrino Asymmetry Parameter *B* in Neutron Decay

M. Schumann,[1,*] T. Soldner,[2] M. Deissenroth,[1] F. Glück,[3,4] J. Krempel,[1,2] M. Kreuz,[2] B. Märkisch,[1] D. Mund,[1]
A. Petoukhov,[2] and H. Abele[1,†]



Neutrino-asymmetry parameter ($\vec{J} \cdot \vec{p}$):

$$B = \frac{\pm \frac{1}{J+1} \ \ ^{2} - 2\sqrt{\frac{J}{J+1}}}{1 + \ \ ^{2}} \quad \text{where} \quad = \frac{G_A < \ \ >}{G_V < \ \ >}$$

For neutron decay: J = ½ , < > = $\sqrt{3}$, < > = 1

$$B = 2\,\frac{(\ \ - 1)}{1 + 3\ \ ^{2}} \quad \text{where} \quad = \frac{G_A}{G_V}$$

Standard model:
= 0.9870(1) with = -1.2767(16)

***B* = 0.9802(50)**

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

PHYSICAL REVIEW C 79, 055502 (2009)

Superallowed $0^+ \rightarrow 0^+$ nuclear β decays: A new survey with precision tests of the conserved vector current hypothesis and the standard model

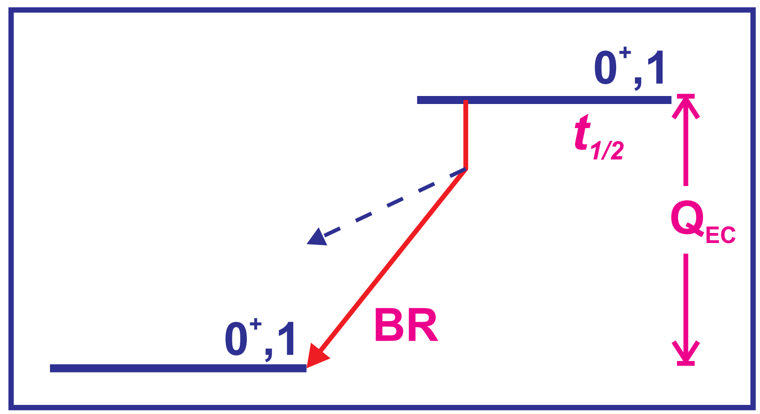
J. C. Hardy* and I. S. Towner

$$\frac{1}{t} \propto \underbrace{\int F(\pm Z, E_e)\, p_e E_e (E - E_e)^2 dE_e}_{f} \left(G_V^2 < \;>^2 + G_A^2 < \;>^2\right)\left\{1 + b\,\frac{m}{E_e}\right\}$$

= 0 by angular momentum selection rules (for the $G_A^2 < \;>^2$ term)

$$ft\left\{1 + b\left\langle\frac{m}{E_e}\right\rangle\right\} = \frac{K}{G_V^2 < \;>^2}$$

where $b \propto \frac{C_S}{G_V}$ **= 0 in standard model**



Standard model: *ft* values constant $\longrightarrow G_V$

Scalar current searched by energy dependence