The crucial role of neutron β-decay experiments in establishing the fundamental symmetries of the (V-A) description of weak interactions.

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Why the Neutron?

1. Neutrons are available in huge numbers with fluxes up to 10^9 cm^{-2} sec^{-1}
2. Neutrons come in a wide range of energy from thermal (~0.025 eV) through cold (<5.10^{-5} eV) to ultra- cold neutrons (<2.10^{-7} eV). Ultra-cold neutrons (UCN) can be stored in bottles made from material such as quartz which have a positive scattering length, or in inhomogeneous magnetic fields
3. Neutrons are uncharged but have magnetic moments allowing easy manipulation of the spin and production of ~100% longitudinal or transverse polarization.
4. ***Neutrons decay weakly with a lifetime of order 15 minutes***

Neutron Decay Parameters

The main kinematic parameters governing neutron decay are:

1. $\Sigma = (m_n+m_p)c^2 = 1877.83704$ MeV
2. $\Delta= (m_n-m_p)c^2 = 1.29332$ MeV
3. Kinetic energy of electrons, $T_e< 783$ keV
4. Kinetic energy of protons, $T_p< 751$ eV. Such low energy protons may be stored in Penning traps with well depth < 1kV
5. Recoil parameter $\delta= \Delta/ \Sigma<10^{-3}$. Because δ is so small the momentum transfer dependence of all form factors may be neglected

The Weak Interaction in Nuclei

Within the Standard Model the charged current weak interaction is constructed from a purely left-handed equal admixture of polar vector (V) and axial vector (A) currents of quarks and leptons.

In the language of nuclear physics

1. V-interactions give rise to allowed Fermi β- transitions with coupling constant g_V and spin/parity selection rule

   $\Delta I=0$, no parity change

2. A-interactions give rise to allowed Gamow/Teller β-transitions with coupling constant g_A and spin/parity selection rule:

   $\Delta I=0, \pm 1$, no), no $0 \rightarrow 0$, no parity change

β-decays within isospin multiplets

1. The importance of such decays is that, within CVC theory, the vector current V_μ***(x)*** is conserved neglecting:

(a) multiplet mass splittings contributing corrections of order $(\delta m/m)^2$ (***Behrends and Sirlin 1960***)

(b) Coulomb and radiative corrections at the level of a few %.

2. The net result is that the vector coupling constant in such hypercharge conserving weak decays ($\Delta Y=0$) is given by

$$g_V = G_F V_{ud}$$

G_F is the universal Fermi coupling constant and V_{ud} is the largest element in the unitary CKM matrix which rotates the quark mass eigenstates (d,s,b) into the weak eigenstates (d’,s’,b’)

The CKM Quark Mixing Matrix

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

The Cabibbo-Kobayashi-Maskawa quark mixing matrix is a unitary matrix which rotates the quark mass eigenstates (d, s, b) into the weak eigenstates (d', s', b'). It follows that, ***to ensure unitarity***

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

The element $|V_{us}| = 0.2254+.0020$ determined from K^+_{e3} and K^+_{e0} decays and the element $|V_{ub}| = 0.00367+0.00047$.(Severijns et al 2006)

The leading matrix element $|V_{ud}|$ may be determined independently from (a) the ft values of $0^+ \rightarrow 0^+$ β-decays, (b) neutron β-decay.

β-decays within isospin multiplets

1 By far the most important of such decays is neutron decay which is a 1/2 →1/2 β-transition within an isospin doublet.The mass splitting correction is of order $\delta^2 \sim 10^{-6}$. The electromagnetic corrections are of order 1% and have been studied in detail.

2. Neutron decay is allowed by both Fermi and Gamow/Teller selection rules giving rise to easily observable parity-violating effects associated with polar vector/axial vector interference

3.Also of great importance are the seven pure Fermi $0^+ \rightarrow 0^+$ β^+-transitions within isospin triplets which lead to a direct evaluation of $G_F V_{ud}$ allowing for the symmetry-breaking corrections.(Hardy and Towner 2005)

The Axial Current

1.The axial current $\boldsymbol{A_\mu(x)}$ is not conserved since this would forbid the decay of pseudo-scalar pions into leptons. Therefore the ratio

$$\Lambda = g_A/g_V = |\lambda| \; e^{i\phi}$$

is a function of the strong interactions and ***must be determined experimentally***

2. However various field-theoretic results exist (PCAC theory), e.g. the Goldberger-Treiman relation $|\lambda| = f_\pi g_{\pi NN} / mc^2$

which relate $|\lambda|$ to the charged pion decay constant f_π, the mean nucleon mass m and to the pion-nucleon coupling constant $g_{\pi NN}$.

3. As shown from experiments on the β-decay of polarized neutrons, $\phi=\pi$ and λ is real and negative. If λ were complex this would signal a ***violation of time reversal invariance*** in β-decay

Neutron Decay and Solar Astrophysics

The β-decay of the free neutron

$$n \rightarrow p + e^- + \underline{\nu}_e$$

is essentially the inverse of the weak interaction initiating the proton-proton cycle of thermonuclear interactions in the sun

$$p + p \rightarrow {}^2H + e^+ + \nu_e$$

However, since the deuteron ^2H can exist only in the triplet state, and the protons can scatter only in the singlet state, it follows that the leptons must carry off one unit of spin and only the axial current can contribute .

Therefore the rate of the process is proportional to $|\lambda|^2$

The Neutron Lifetime.

Within the standard model the neutron lifetime τ_n is given by:

$$ft=\{2\pi^3\ln(2)(h/2\pi)^3/(m_e^5c^4)\}/\{G_F^2|V_{ud}|^2[1+3|\lambda|^2]\}$$

where $t=\tau_n\ln(2)$ and $f(1+\delta_R)=1.71489\pm 0.00002$ is the Coulomb corrected integrated Fermi phase space factor and $\delta_R>0$ is a term ~1-2% which takes account of the ***outer radiative corrections***

It follows that, in order to determine the fundamental quantities $|V_{ud}|^2$ and $|\lambda|^2$, together with the ***sign of λ, the neutron lifetime*** τ_n must be measured accurately plus at least ***one other parameter*** determined from neutron decay.

The Neutron Lifetime and Big Bang Cosmology.

The neutron lifetime is itself of direct interest in big-bang cosmology since it determines the rate at which hydrogen is converted into helium in the early Universe.

Using the current world average value of the neutron lifetime , τ_n ***= 885+0.8 sec*** results in a relative helium abundance in the present day Universe of about 25% in good agreement with observation

Measuring the Neutron Lifetime

1. ***The Measurement Problem.*** Given a thermal flux of 2.10^9 neutrons cm^{-2} sec^{-1} one may estimate a count rate of ~10 decays sec^{-1} per cm^3 of neutron beam, which will be unobservable against background without the application of special methods. In the ~60 years which have elapsed since Robson first determined the lifetime to an accuracy of 20% at Chalk River(1950) ***two quite distinct techniques*** have survived.

2. These are ***(a) "bottle" methods*** which rely on measuring the decay rate of ultra-cold neutrons trapped in material or magnetic bottles, and ***(b) "Penning trap"*** methods which measure the number of decay protons stored in a given time in a variable length of neutron beam of known neutron density.

"Bottle" Methods for Measuring τ_n

1. ***Bottle methods*** which rely on storing ultra-cold neutrons over a periods of time ***t*** determine the ***number of survivors after time t***

2. ***Magnetic bottles:*** These rely on the force

$$\underline{F}=-\text{grad}[(\underline{\mu}_n.\underline{B}(\underline{r})]$$

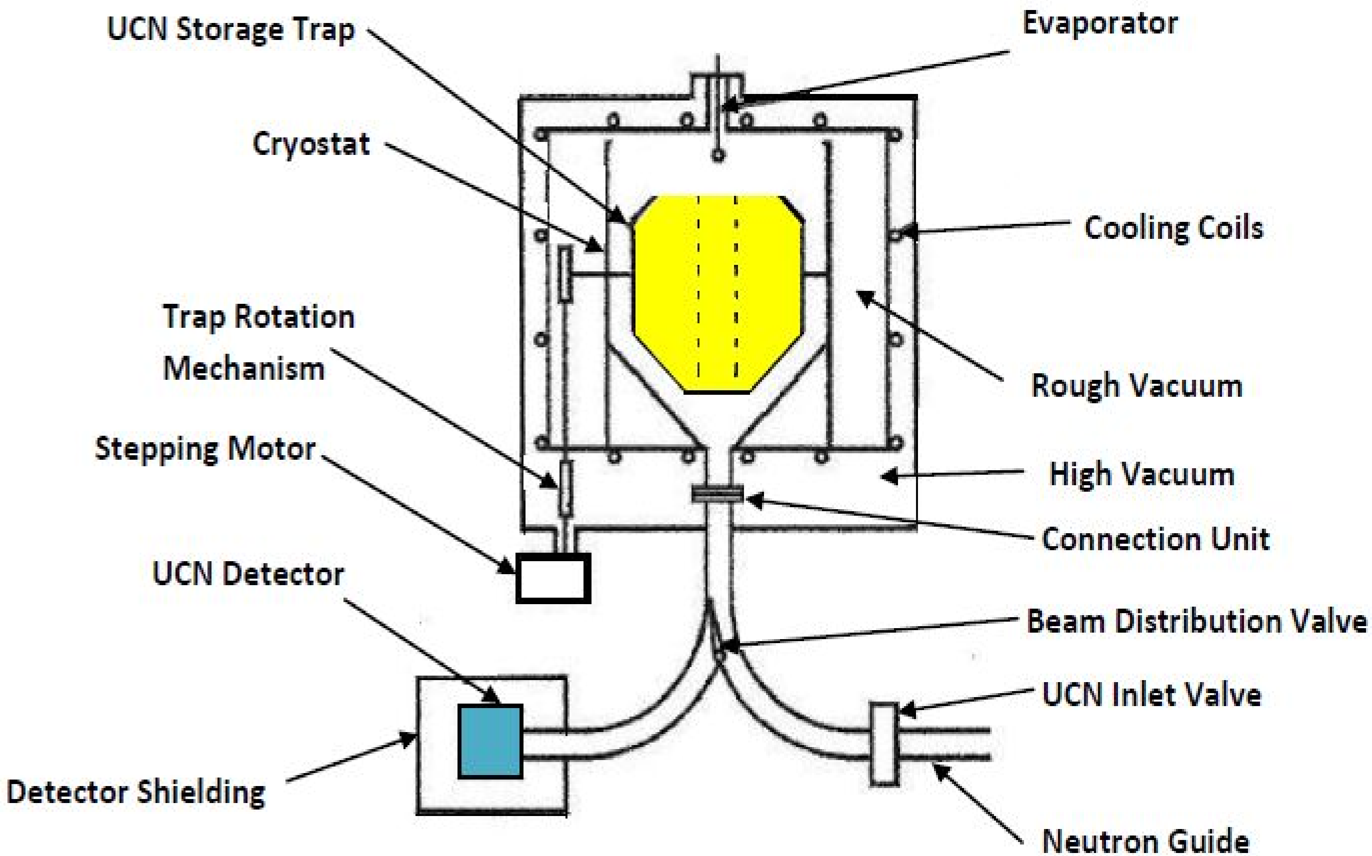
exerted on the neutron magnetic moment $\underline{\mu}_n$ in an inhomogeneous magnetic field $\underline{B}(\underline{r})$. Since the force acts to trap only one sign of the spin, it follows that spin-flipping of the trapped ultra cold neutrons could be recorded as β-decay.

To date the technique, which is exceptionally difficult, has yet to prove competitive

“Bottle” Methods for Measuring τ_n

3. ***Material bottles***: These rely on the fact that, in a material (e.g.quartz) with positive scattering length the Fermi pseudo-potential is repulsive for neutrons and totally reflects ultra-cold neutrons of energy <2.10^{-7}eV. The method applies the law of exponential decay $N(t)=N(0) \exp[-\lambda_n t - \lambda_w t]$ where $\lambda_n = 1/\tau_n$ and λ_w represents the loss-rate at the bottle walls

4. The method has been gradually refined by (a)***Altering*** the collision rate be varying the volume, (b)***Coating*** the surface with hydrogen-free fomblin oil (c)***Scaling*** the storage times in proportion to the mean free path (d) using ***gravity*** to effect trapping in the vertical dimension (e) ***Counting*** the number of neutrons escaping from the trap by up-scattering at the walls



Gravitational trap for storing ultra cold neutrons

(Serebrov et al 2005)

Penning Trap Method for Measuring τ_n

1. In this method protons from neutron decay with energy < 0.8 keV are stored in a ***Penning trap*** for a period ~10 msec. On release from the trap they are accelerated to an energy~30 keV and counted for a period ~100 μsec in a silicon surface barrier detector. This ratio of storage to counting time brings about a suppression of background by a ***factor of about 100***
2. The Penning trap is composed from a uniform axial magnetic field of ~5T from a superconducting magnet superimposed on an electrostatic quasi-square well potential of depth~1kV and variable length. The magnetic field at the exit point is bent through a 9^o angle so that the proton counter sits outside the neutron beam.

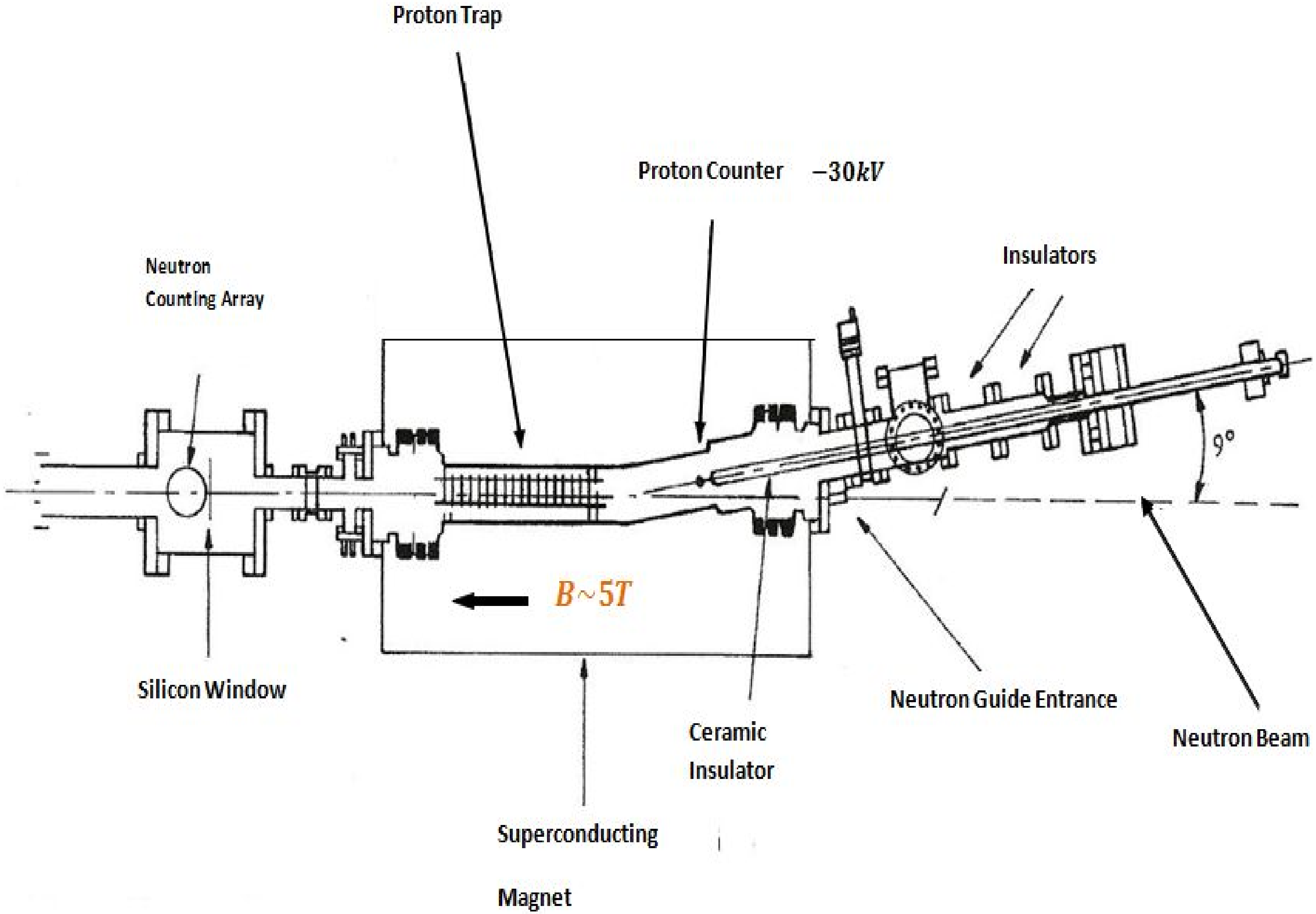
Penning Trap Method for Measuring τ_n

3 . The neutron lifetime measurement is based on the differential relation

$$dn(t)/dt = -n(t)/\tau_n$$

Its application in detail involves making accurate measurements of ; (a) ***proton counting rate*** as a function of measured beam length, and (b) ***detection efficiency*** and collection ***solid angle*** for the emerging neutrons.

4. The number of incident neutrons is determined by counting the emerging neutrons in an ***assayed*** target of a 1/v neutron capture reaction $^{10}B\,(n,\alpha)^{7}Li$ or $^{6}Li\,(n,\alpha)^{3}H$ which provides a measure of the mean neutron density in the beam. This is the main weakness in the technique since the (n,α) capture cross-sections must be known to better than 0.25%



The Penning Trap for storing protons of energy < 1keV from neutron decay (Byrne 1995)

Selected Measured Values of τ_n

Bottle Methods*	τ_n
Mampe et al (1989)	887.6 $\pm$ 3 sec
Mampe et al (1993)	882.6 $\pm$ 3.3 sec
Arzumanov et al (2000)	885.4 $\pm$ 1.0 sec
Serebrov et al (2009)	878.5 $\pm$ 0.78 sec

Penning Trap Methods*	τ_n
Byrne et al (1996)	889.2 $\pm$ 4.8 sec
Dewey et al (2003)	886.8 $\pm$ 3.4 sec
Nico et al (2005)	886.3 $\pm$ 3.4 sec

Statistical and systematic errors combined in quadrature

Determination of the g_A/g_V Ratio λ

To determine the ***sign of λ*** it is necessary to observe a pseudo-scalar interference effect between vector and axial vector matrix elements. To do this one must study a spin/momentum correlation coefficient for ***polarized neutrons***.

Once the sign of λ is known there are various ways of determining the ***magnitude of λ***. The most accurate of these methods rely on making a measurement of the ***anomaly in λ*** i.e. $(|\lambda|-1)$

Decay Rate of a Polarized Neutron

The decay rate of a polarized neutron is given by the famous Jackson-Treiman-Wyld equation (1957)

$dW(\sigma_n, \sigma_e\, p_e, p_{\underline{\nu}}, E_e) \sim F(E_e) d\Omega_e d\Omega_{\underline{\nu}} \{1 + a\, p_e \,.\, p_{\underline{\nu}} / E_e E_{\underline{\nu}} + b m_e / E_e + \ldots$

$+ \langle\sigma_n\rangle . [A\, p_e / E_e + B\, p_{\underline{\nu}} / E_{\underline{\nu}} + D\, p_e \times p_{\underline{\nu}} / E_e E_{\underline{\nu}} + R\, \sigma_e \times p_e / E_e + \ldots]\}$

where the $p_e \,.\, p_{\underline{\nu}}$ angular correlation coefficient a is given by

$a = (1-|\lambda|^2) / (1+3|\lambda|^2)$.

The Fierz interference coefficient b vanishes in the absence of scalar or tensor couplings as in the standard model, but ***is sensitive to the coupling of a right handed lepton to either handedness of quark.***

A new program of measurements is under way.(Pocanic et al 2009)

Decay Rate of a Polarized Neutron

The coefficients A and B of the parity-violating spin/momentum correlations $A\langle\sigma_n\rangle\, p_e / E_e$ and $B\langle\sigma_n\rangle.\, p_{\underline{\nu}} / E_{\underline{\nu}}$ ***are given by***

$A = -2[|\lambda|^2 + \mathbf{\mathit{Re}}(\lambda)]/(1+3|\lambda|^2)$, $B = 2[|\lambda|^2 - \mathbf{\mathit{Re}}(\lambda)]/(1+3|\lambda|^2)$,

The best value of A using ***cold*** neutrons available to date is:

$A = -0.1189 \pm 0.0007$, (Abele et al 2002)

giving $\lambda = -1.274 \pm 0.002$ in conformity with (V-A) theory

A ***first*** measurement using ***ultra-cold*** neutrons gives the value

$A = -0.1138 \pm 0.0051$ (Pattie et al 2009)

The coefficient B is not sensitive to $(|\lambda| - 1)$ the ***anomaly in*** λ .

Decay Rate of a Polarized Neutron

The two remaining terms in the transition rate of a polarized neutron

$\langle \sigma_n \rangle . [D\, p_e \times p_{\underline{\nu}} / E_e E_{\underline{\nu}}]$ ***(P-conserving)***

$\langle \sigma_n \rangle . [R\, \sigma_e \times p_e / E_e]$ ***(P-violating)***

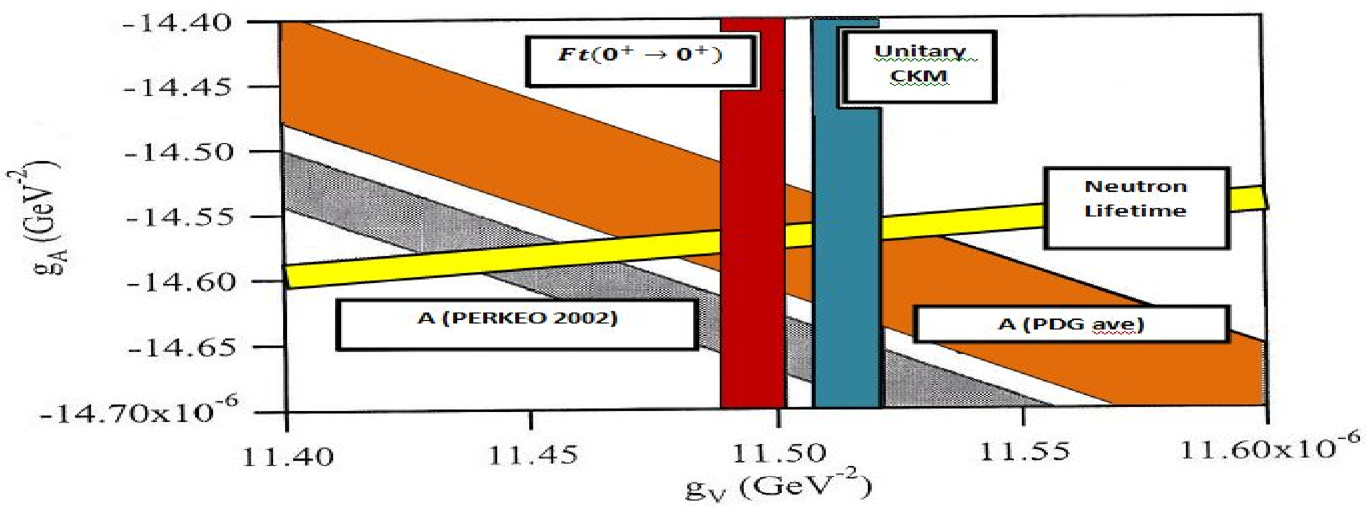
are ***T-violating*** correlations which vanish in the standard model.

The R-correlation has not been measured in neutron decay.However the coefficient $D= 2\, \boldsymbol{Im}(\lambda) /(1+3|\lambda|^2)$ has measured values

$D= (-0.6 \pm 1.3).10^{-3}$ (Lising et al 2000)

$D=(-2.8+7.1).10^{-4}$ (Soldner et al 2004)

Thus the ratio λ is real and β-decay is Time Reversal Invariant



Consistency plot for g_A vs g_V determined from (a) ***neutron lifetime***, (b) ***electron asymmetry coefficient A and*** (c) ***ft-values of super-allowed $0^+ \rightarrow 0^+$ β-transitions.***

According to this plot which is <u>not exactly up to date</u> there is no consistency although the details are a matter of some dispute.

The question is whether there exists an additional source of information which has yet to be exploited ?

Determination of $|\lambda|$ using Unpolarized Neutrons

The $p_e \cdot p_{\underline{\nu}}$ angular correlation coefficient given by

$$a = (1-|\lambda|^2) / (1+3|\lambda|^2)$$

provides another route to $|\lambda|$ which is hampered by the fact that, since the antineutrino is unobservable, one has to rely on detecting the proton.

However the proton spectrum contains a term directly proportional to a and the possibility exists to measure a from the proton spectrum alone

Measurements of |λ| from the proton spectrum in unpolarized neutron decay (*Wietfeldt 2005*)

	a	|λ|
Grigor'ev et al 1967	– 0.091 ± 0.039	1.22 ± 0.08
Stratowa et al (1978)	– 0.1017 + 0.0051	1.259+0.018
Byrne et al (2002)	– 0.1054+0.0055	1.271+0.018

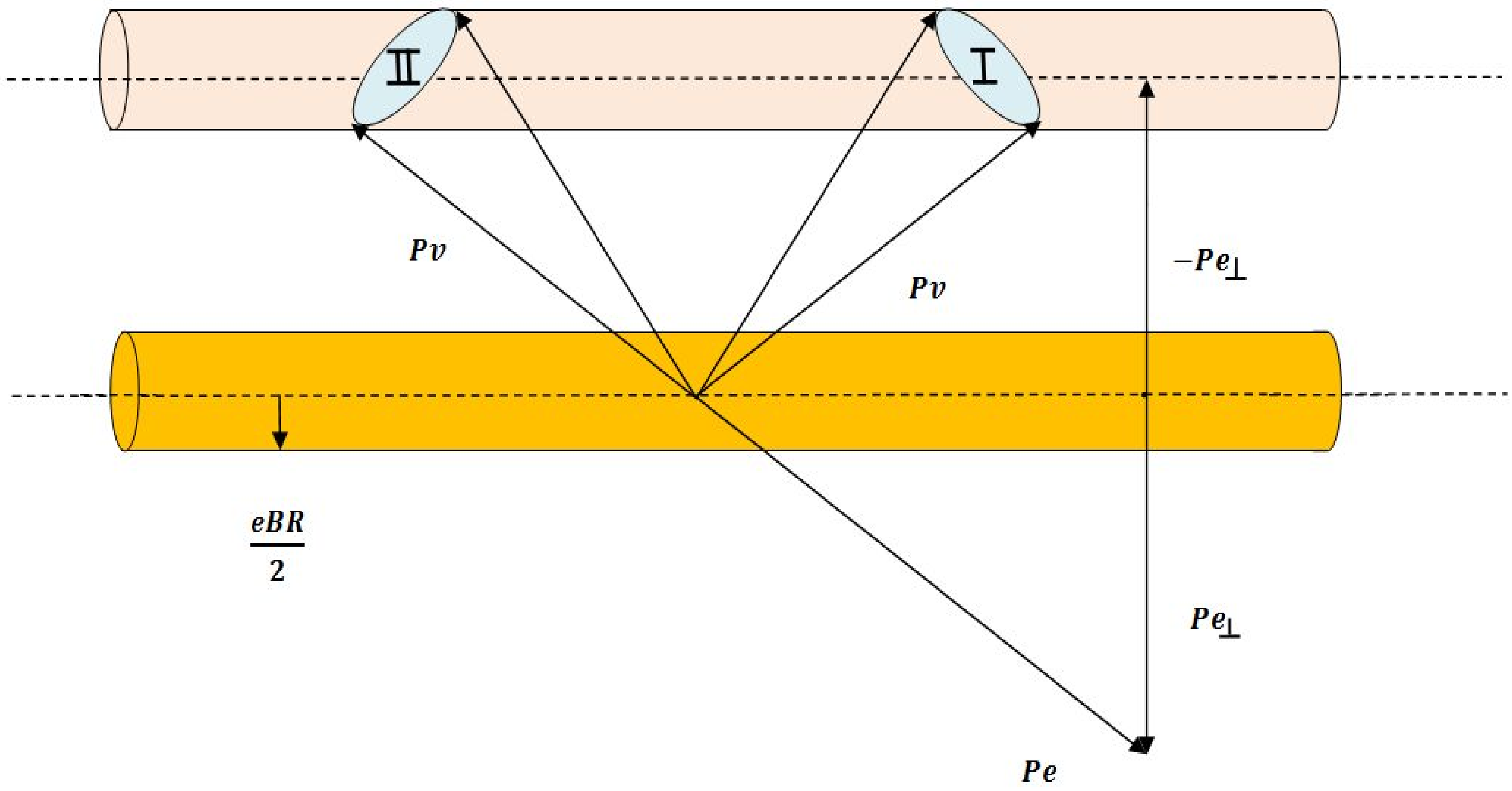
aSPECT ***No published result.*** (***Konrad 2010***)

aCORN: A measurement of ***a*** and $|\lambda|$ from an electron-proton coincidence experiment.

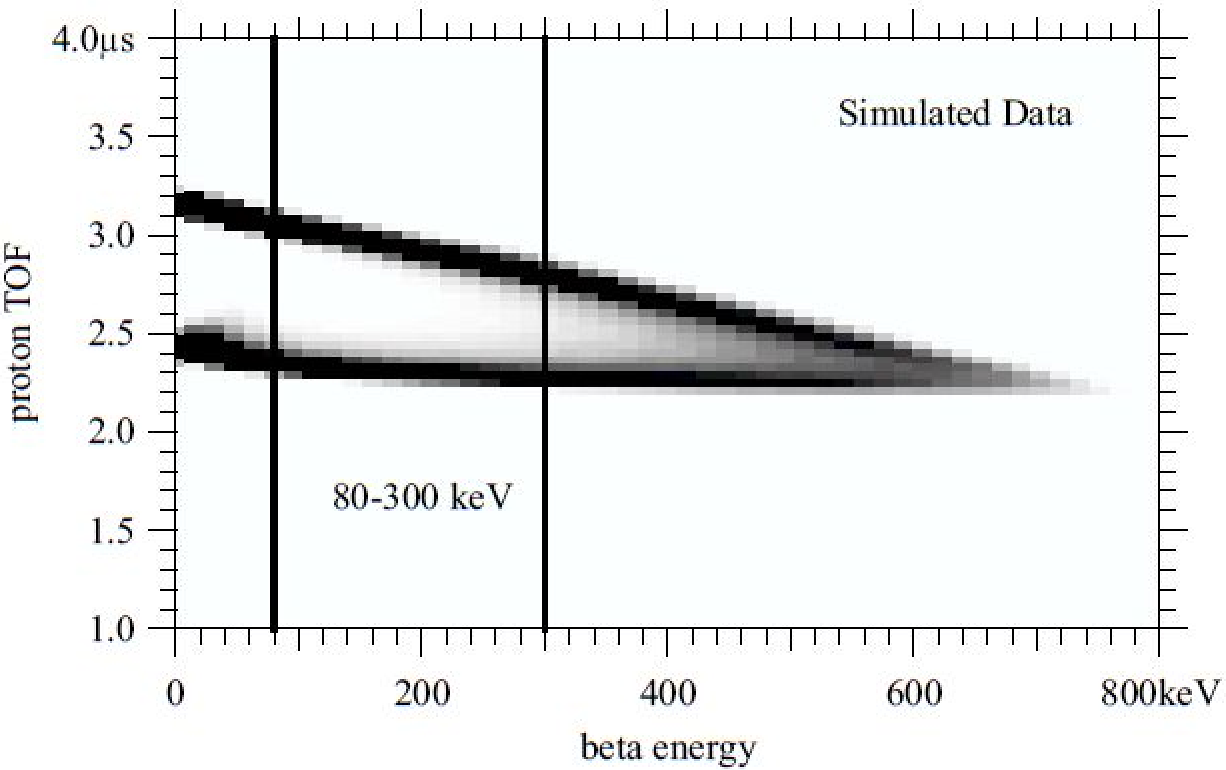
In this method the two solid angles corresponding to $p_e \cdot p_{\underline{\nu}} >$ 0 and $p_e \cdot p_{\underline{\nu}} < 0$ are made equal by limiting the transverse component of the proton momentum in a strong axial magnetic field . The longitudinal momenta for both angles can be recorded in coincidence with the corresponding electron, by reflecting the protons for which $p_e \cdot p_{\underline{\nu}} < 0$ in an electrostatic mirror.For an electron kinetic energy >250 keV the time delay incurred is then detected by time-of-flight.

(Balashov and Mostovoy 1995, Wietfeldt et al 2005)

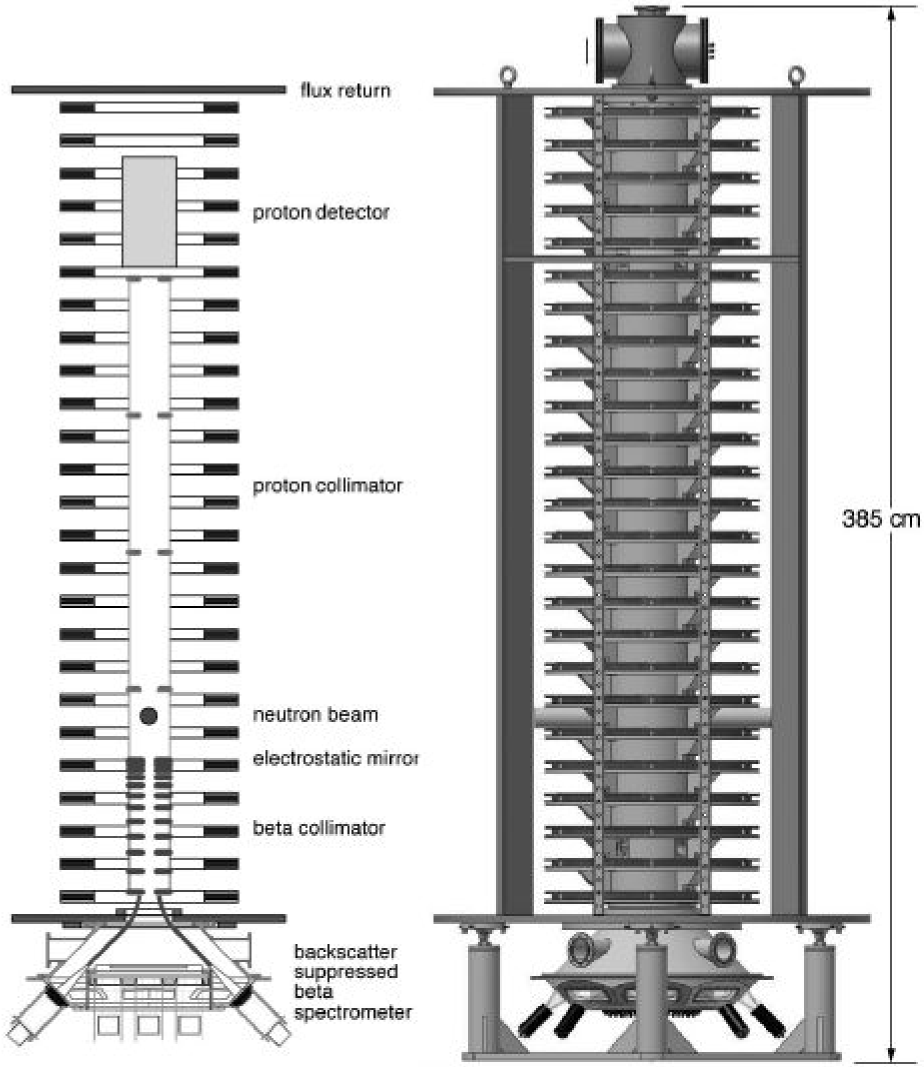
The principle is illustrated in the momentum diagram below

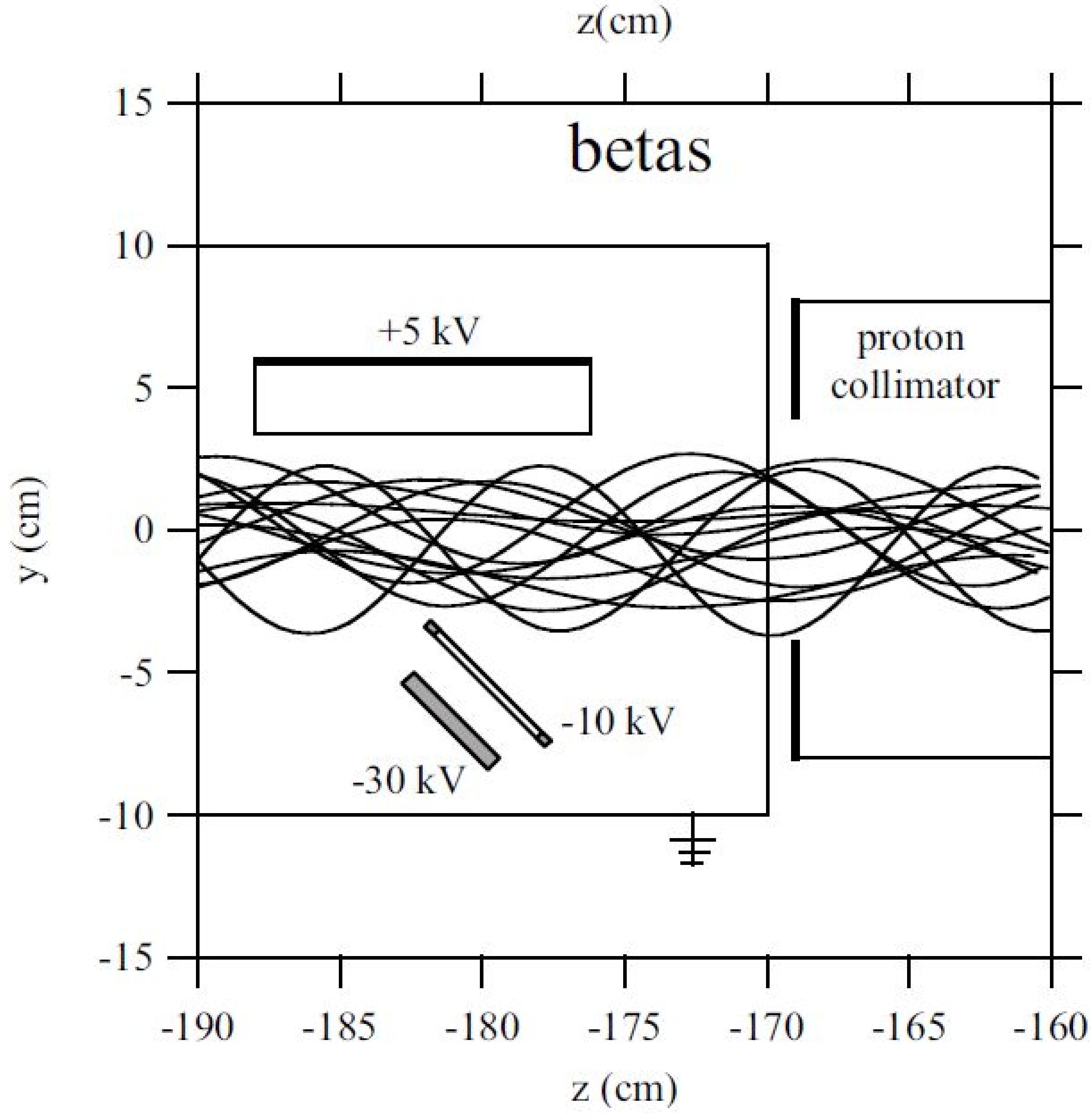


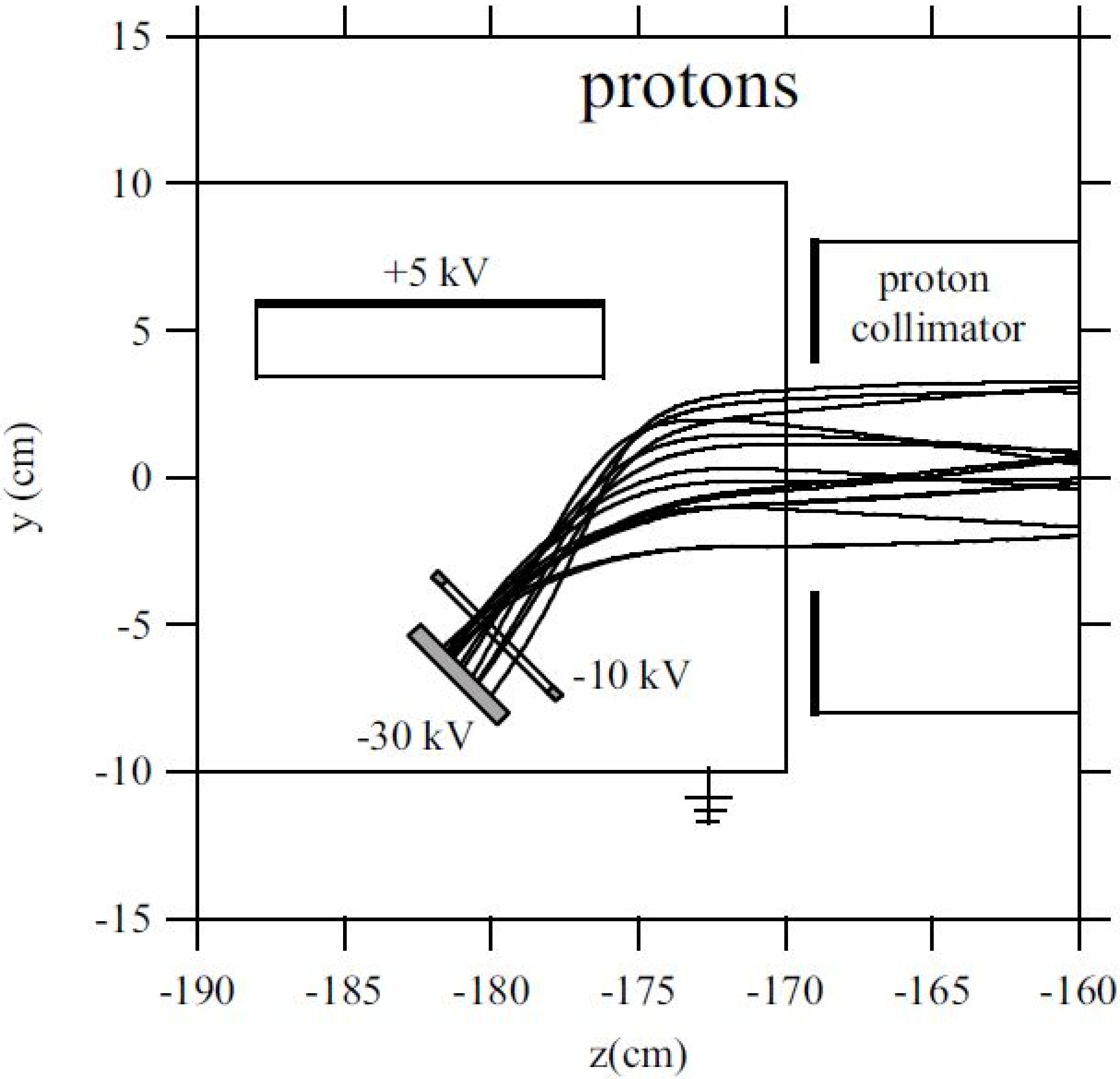
Momentum diagram for the aCORN project to measure a.For a decay on the axis of the lower cylinder of electron momentum p_e and proton momentum p_p <eBR/2 the antineutrino momentum p_ν must lie in the upper cylinder in cone I. If the ***transverse*** component of p_e, and the ***longitudinal*** component of p_p are reversed, p_ν moves into cone II and ***p_e. p_ν changes sign***



4.0µs
3.5
3.0
2.5
2.0
1.5
1.0
proton TOF
Simulated Data
80-300 keV
0
200
400
600
800keV
beta energy


flux return
proton detector
proton collimator
neutron beam
electrostatic mirror
beta collimator
backscatter
suppressed
beta
spectrometer
385 cm


z(cm)
betas
+5 kV
proton
collimator
-10 kV
-30 kV
y (cm)
15
10
5
0
-5
-10
-15
-190
-185
-180
-175
-170
-165
-160
z (cm)



protons
+5 kV
proton
collimator
-10 kV
-30 kV
15
10
5
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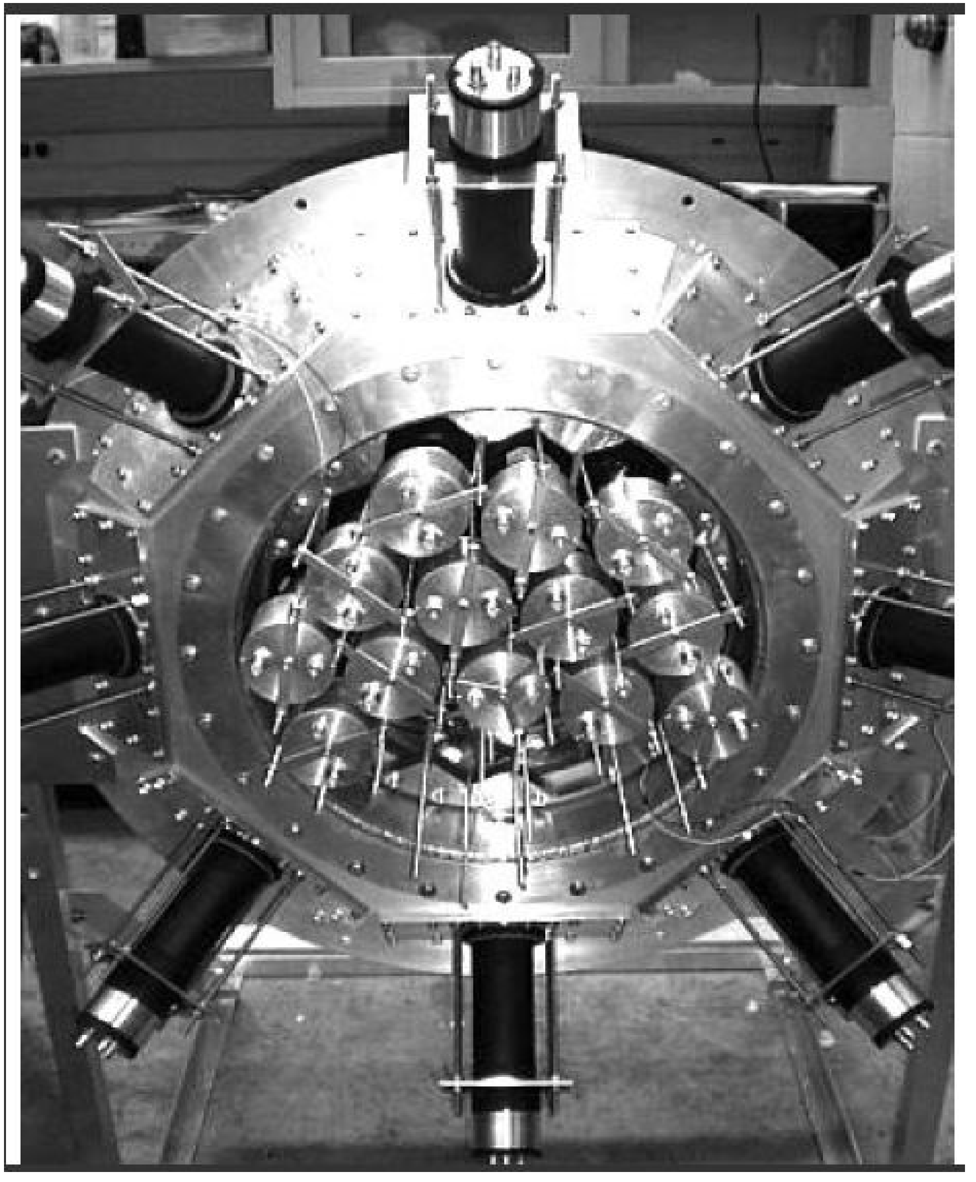
-5
-10
-15
y (cm)
-190
-185
-180
-175
-170
-165
-160
z(cm)



The beta-spectrometer for the* aCORN *experiment (Wietfeldt et al 2009)

In addition to its normal three-body decay process

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

the neutron also undergoes two further weak decay processes:

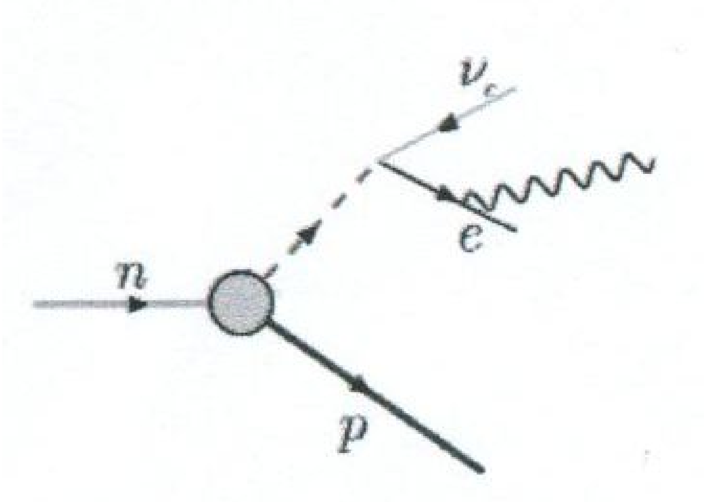
1. **Radiative Neutron Decay**.

$$n \Rightarrow p + e^- + \bar{\nu}_e + \gamma, \qquad BR \sim 10^{-3}$$

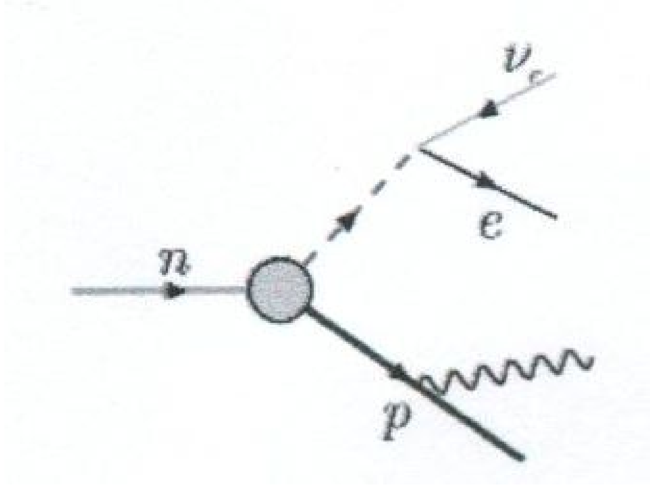
2. Decay into an Antineutrino and a Hydrogen Atom

$$n \Rightarrow H + \bar{\nu}_e, \qquad BR \sim 4.10^{-6}$$

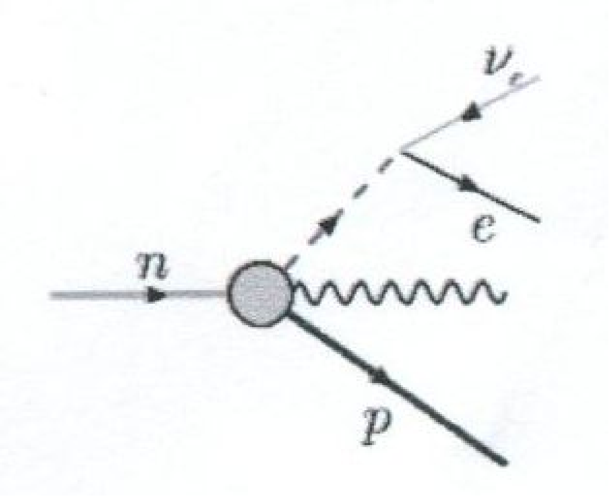
Radiative Neutron β–Decay



Electron Bremsstrahlung



Proton Bremsstrahlung

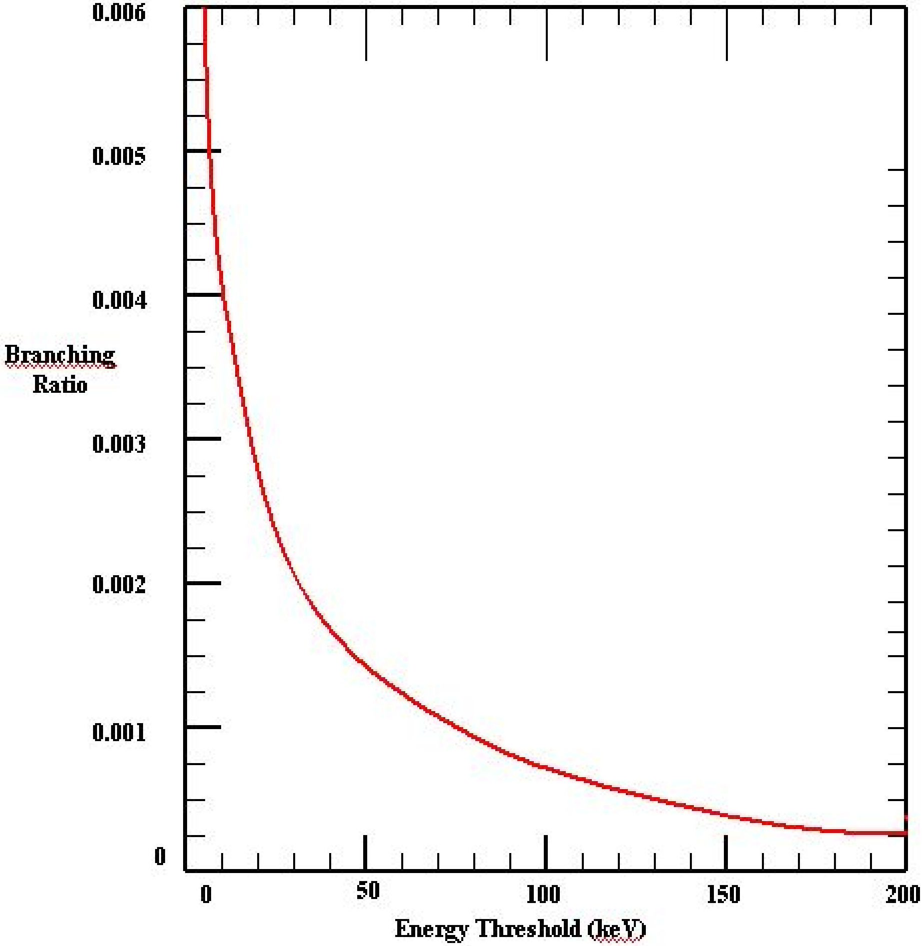


Direct Emission from Weak Vertex

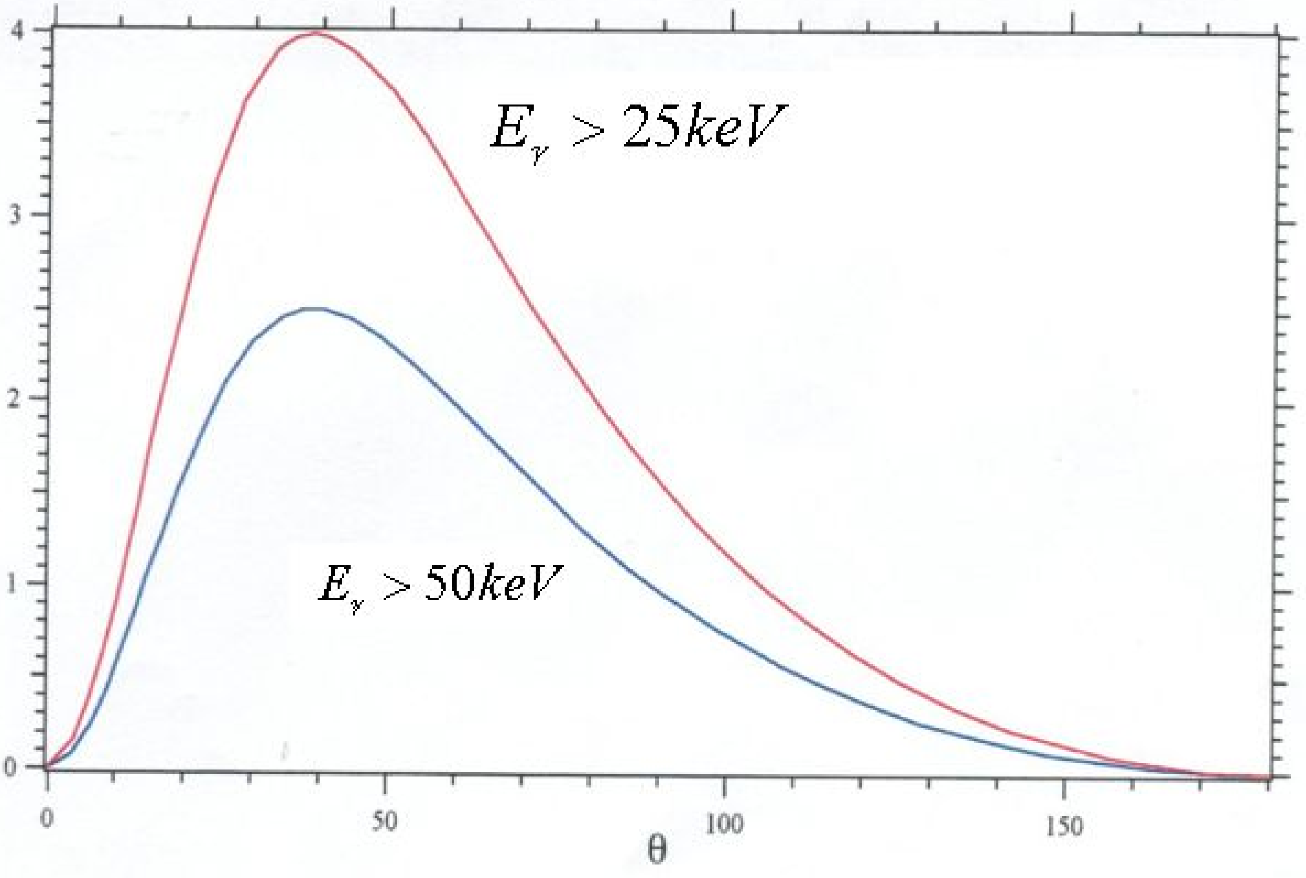
Radiative Neutron β-Decay

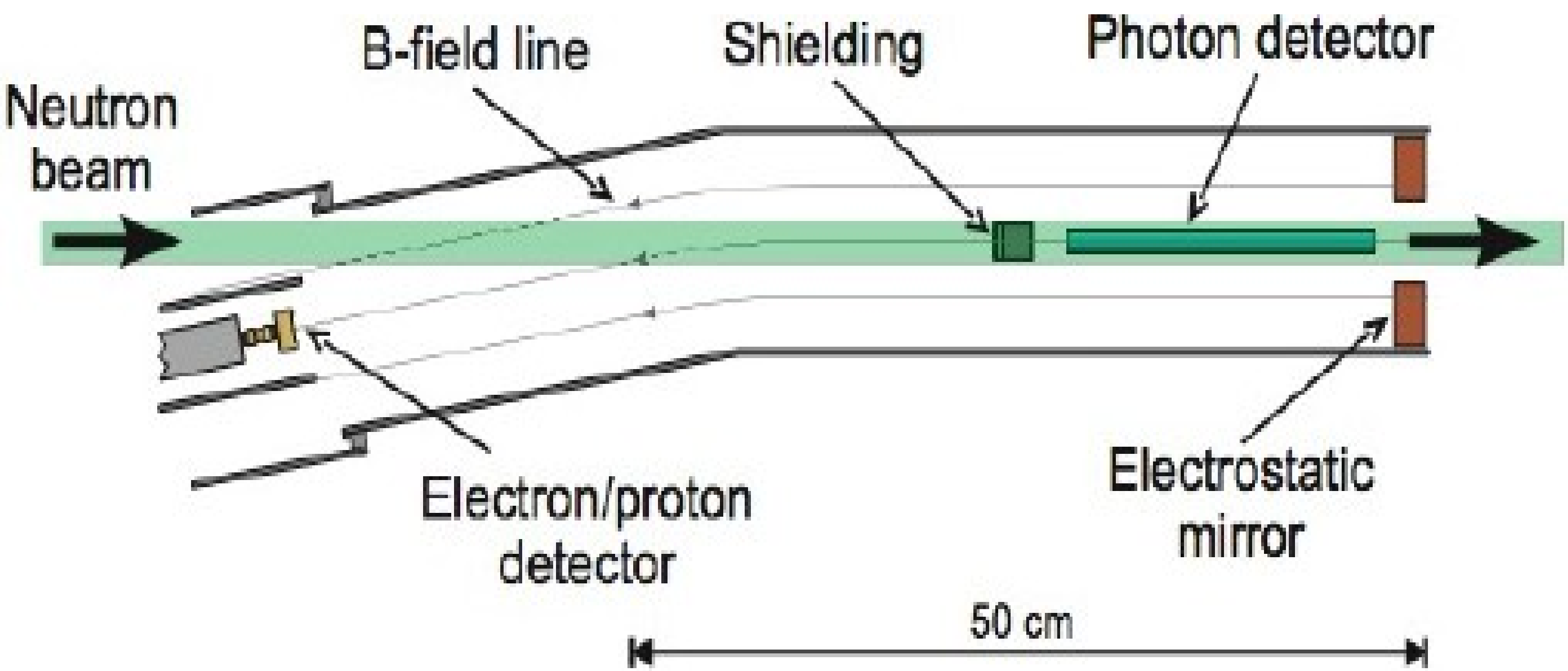
- The process of radiative neutron β-decay is represented by the three diagrams shown above.
- The contributions from the electron and proton inner bremsstrahlung diagrams have been computed by Gaponov and Khafisov (1996). This process is included in Sirlin's universal outer radiative correction formula.
- The contribution from the diagram describing direct emission from the weak vertex has recently been computed by Bernard et al. (2004) together with a calculation of the circular polarization
- An upper limit of 6×10^{-3} for the branching ratio was set by Beck et al (2002)

Energy Spectrum in Radiative Neutron Decay

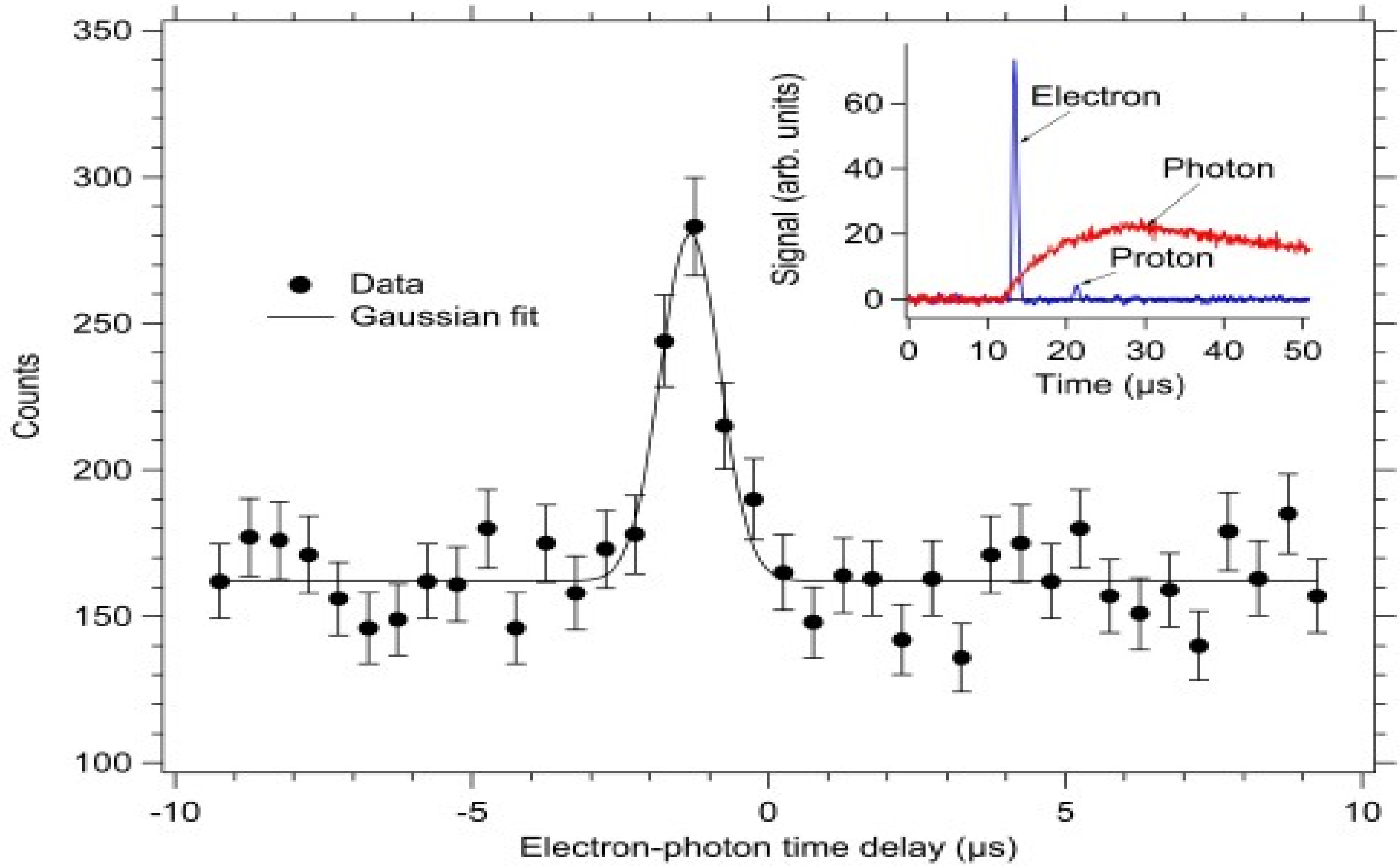


Angular Distribution in Radiative Neutron Decay

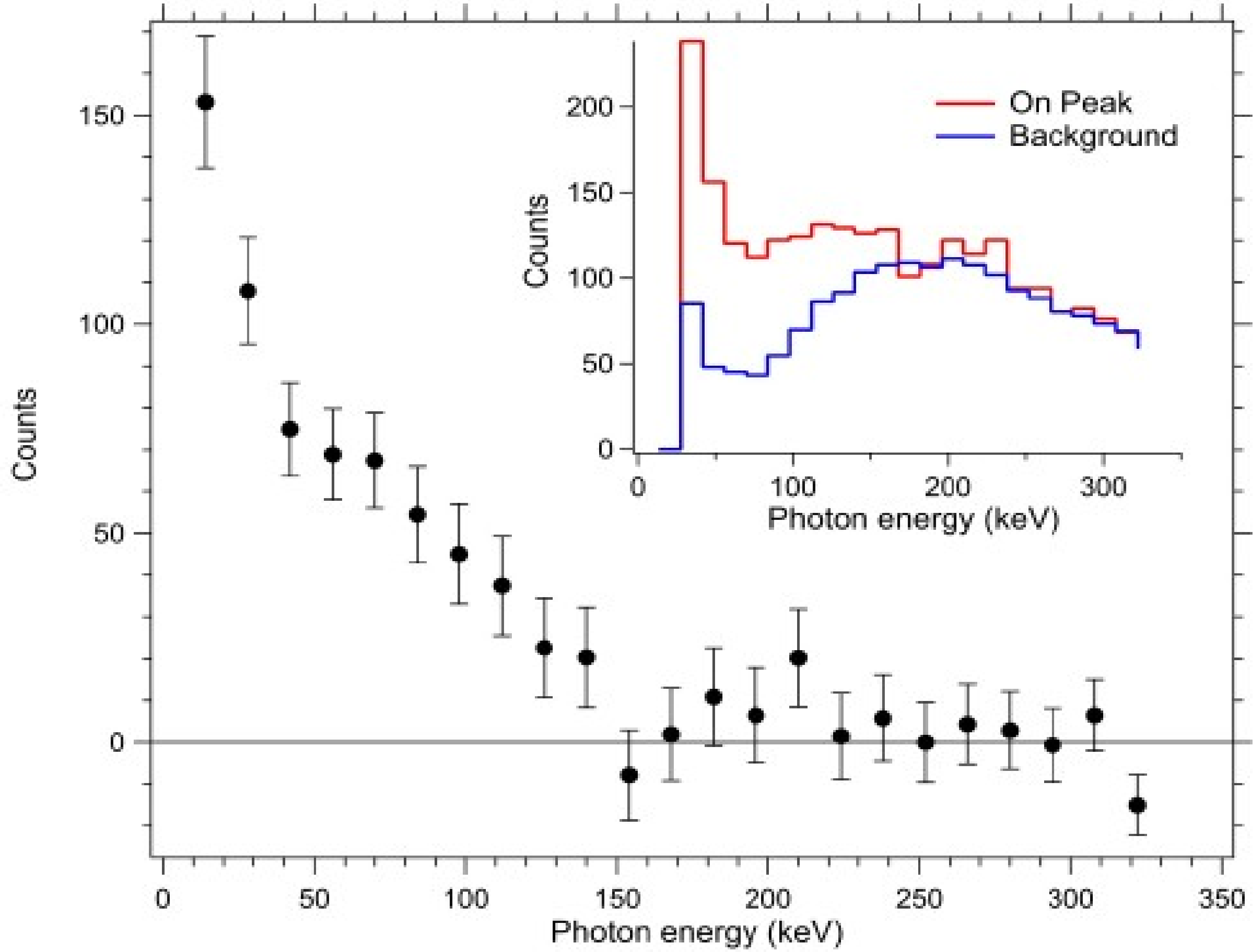




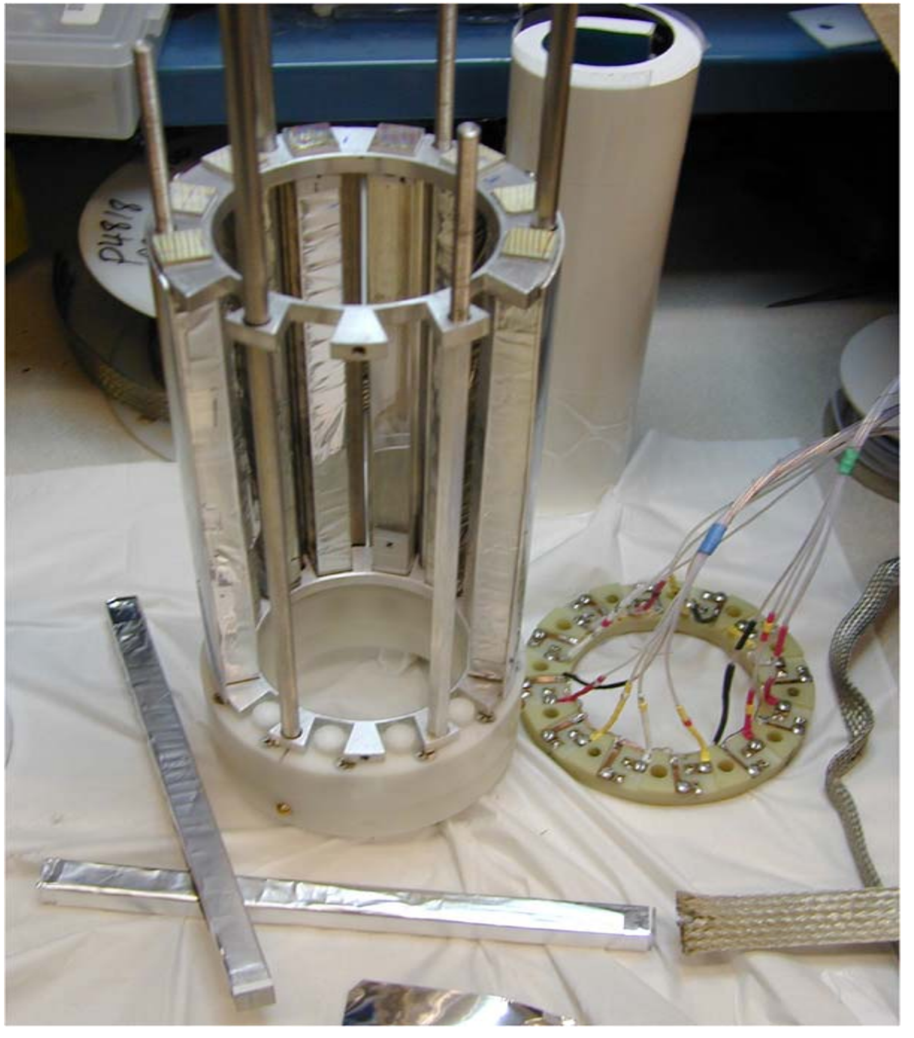
The* NIST *radiative neutron decay experiment. The combination of ~* 4T *magnetic field and* < 1kV *electrostatic mirror allows for nearly* 2π *solid angle coverage for* electrons *and up to* 4π *coverage for* protons*.



Observation of electron-photon-proton triple coincidences from radiative neutron decay ***([Nico et al 2006](#))***



The energy spectrum of inner bremsstrahlung photons from radiative neutron decay, recorded in a single (BGO) bismuth germanate crystal ***and viewed by a*** silicon avalanche photodiode



The measured branching ratio for radiative decay in the single crystal measurement RDKI ***was*** $(3.13+0.34) \times 10^{-3}$**.**
In the updated version RDKII ***the*** 12 element detector***, shown being assembled above, is used.***

Two-Body Decay of the Neutron

- In the case of two-body neutron decay conservation of momentum requires that

$$\mathbf{p}_{\bar{\nu}_e} + \mathbf{p}_H = 0$$

- The antineutrino and the H-atom therefore have the unique energies

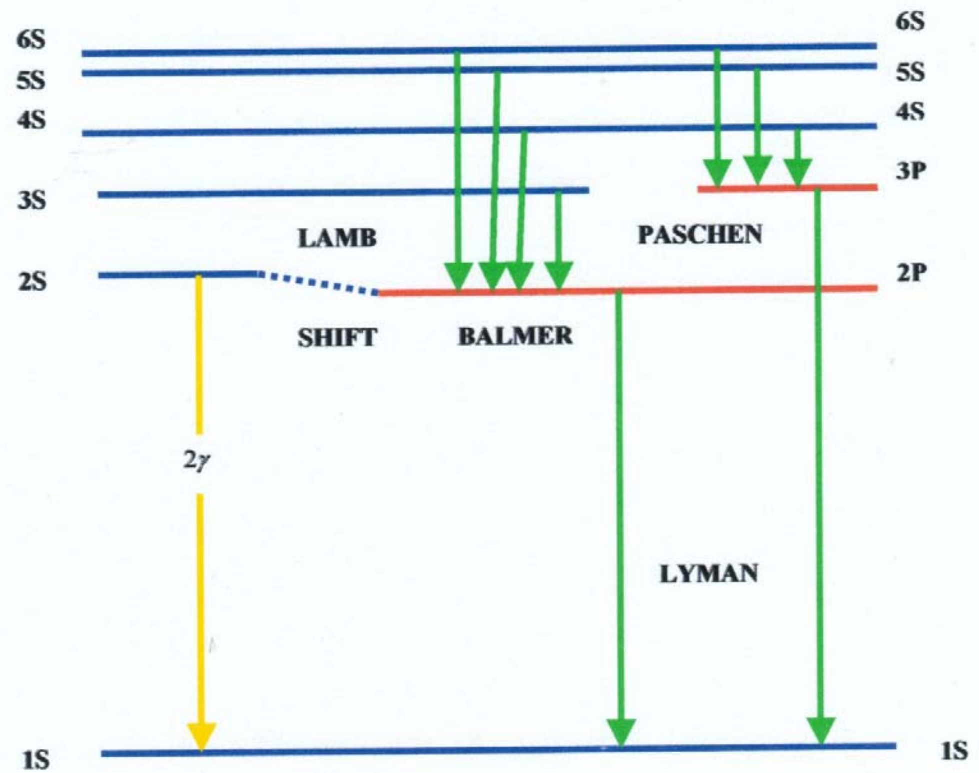
$$E_{\bar{\nu}_e} = 783\, keV, \qquad E_H = 326.5\, eV$$

Decay Scheme of the Hydrogen Atom

- Only the S-states of the hydrogen atom are populated since only these states have a non-zero position probability at the proton where the electron is created

- The 2S level is metastable with a lifetime of 0.143 sec. for decay by 2γ emission to the 1S ground state. Since all other S-states have lifetimes in the range $\tau_{n>2} < 3.10^{-7}$sec. only the 2S state survives.

Decay Scheme of the Hydrogen Atom



Relative Populations of the S-levels in the Hydrogen Atom

nS-level	1S	2S	3S	4S	5S
Population (%)	84.35	10.54	3.12	1.32	0.67

Hyperfine Splitting in the 2S level

- Due to the magnetic coupling between electron and proton the 2S state splits into a $^1S_0$ **singlet** level |0,0> with quantum numbers F=0, m=0, and a three-fold degenerate $^3S_1$ **triplet** level |1,1>,|1,0> and |1,-1> with quantum numbers F=1, m= 1,0 and -1. The $^1S_0$ and $^3S_1$ states are separated in frequency units by an amount ν_h= 177.14 MHz.

- If f_n, ($0< f_n<1$), represents the degree of neutron polarization and $\boldsymbol{\sigma}_n$ is the neutron spin vector, then, referred to an **axis of quantization along $\mathbf{p}_H$,** the relative populations of the hyperfine levels are given by

$$\frac{dW(0,0)}{d\Omega} = Kn^{-3}.|1-3\lambda|^2(1-\langle\boldsymbol{\sigma}_n\rangle.\hat{\mathbf{p}}_H)$$

$$\frac{dW(1,1)}{d\Omega} = Kn^{-3}.2|1+\lambda|^2(1+\langle\boldsymbol{\sigma}_n\rangle.\hat{\mathbf{p}}_H)$$

$$\frac{dW(1,0)}{d\Omega} = Kn^{-3}.|1+\lambda|^2(1-\langle\boldsymbol{\sigma}_n\rangle.\hat{\mathbf{p}}_H)$$

$$\frac{dW(1,-1)}{d\Omega} = 0$$

where

$$\hat{\mathbf{p}}_H = \mathbf{p}_H / |\mathbf{p}_H|,$$

$$\langle \boldsymbol{\sigma}_n \rangle . \hat{\mathbf{p}}_H) = f_n \boldsymbol{\sigma}_n . \hat{\mathbf{p}}_H) = f_n \cos\theta$$

$$\lambda = G_A / G_V = -1.2695 \pm 0.0029$$

and

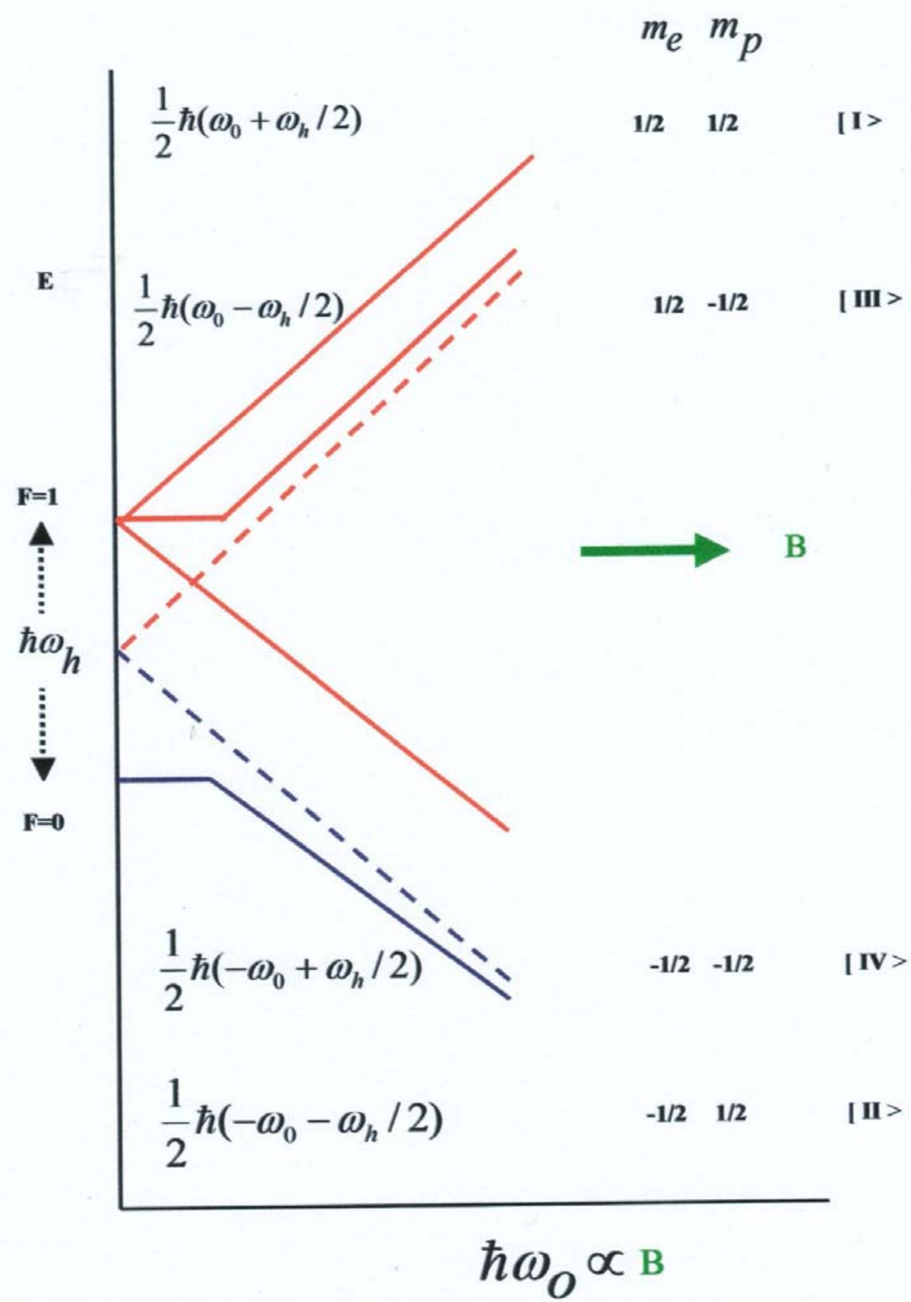
$$K = (G_F^2 V_{ud}^2 / 8\pi^2)(\alpha \mu_e^2 c^2)^2 (\mu_p / \mu_n)(1 + \mu_p / \mu_n)^{-3} (E_{\bar{\nu}_e} / c)^2$$

Zeeman Splitting in a Magnetic Field B = 0.0575 T

- The 177.14 MHz hyperfine splitting in the 2S level corresponds to a magnetic field B=0.000634 T, and, in a strong magnetic field B=0.0575 T, F is no longer a good quantum number.

- In this case the hyperfine states go over into the Paschen-Back states |I>,|II>,|III> and |IV>, in which m_e and m_p are good quantum numbers, referred to an axis of quantization along **B**.

- Thus, to exploit the Zeeman splitting to separate the Paschen-Back states in energy, the momentum vector $\mathbf{p}_H$ must be parallel, or anti-parallel to **B**.



m_e m_p
$\frac{1}{2}\hbar(\omega_0 + \omega_h/2)$
1/2 1/2
[I >
E
$\frac{1}{2}\hbar(\omega_0 - \omega_h/2)$
1/2 -1/2
[III >
F=1
B
$\hbar\omega_h$
F=0
$\frac{1}{2}\hbar(-\omega_0 + \omega_h/2)$
-1/2 -1/2
[IV >
$\frac{1}{2}\hbar(-\omega_0 - \omega_h/2)$
-1/2 1/2
[II >
$\hbar\omega_o \propto$ B

Quantum Numbers of Paschen-Back States

State	n	p	e^-	ν_e	m_e+m_ν	Fermi or Gamow/Teller ?
|I>	1/2	1/2	1/2	-1/2	0	F+G/T
|II>	-1/2	1/2	-1/2	-1/2	-1	G/T
|III>	-1/2	-1/2	1/2	-1/2	0	F+G/T
|IV>	-3/2	-1/2	-1/2	-1/2	-1	F+ G/T

Relative Populations of Paschen-Back States

$$W_I = 2|1+\lambda|^2(1+\langle\boldsymbol{\sigma}_n.\hat{\mathbf{p}}_H\rangle)/[4(1+3\lambda^2)] = 0.62\% \quad (\,for\ \langle\boldsymbol{\sigma}_n\rangle = 0)$$

$$W_{II} = 8\lambda^2(1-\langle\boldsymbol{\sigma}_n\rangle.\hat{\mathbf{p}}_H)/[4(1+3\lambda^2)] = 55.24\% \quad (\,for\ \langle\boldsymbol{\sigma}_n\rangle = 0)$$

$$W_{III} = 2|1-\lambda|^2(1-\langle\boldsymbol{\sigma}_n\rangle.\hat{\mathbf{p}}_H)/[4(1+3\lambda^2)] = 44.14\% \quad (\,for\ \langle\boldsymbol{\sigma}_n\rangle = 0)$$

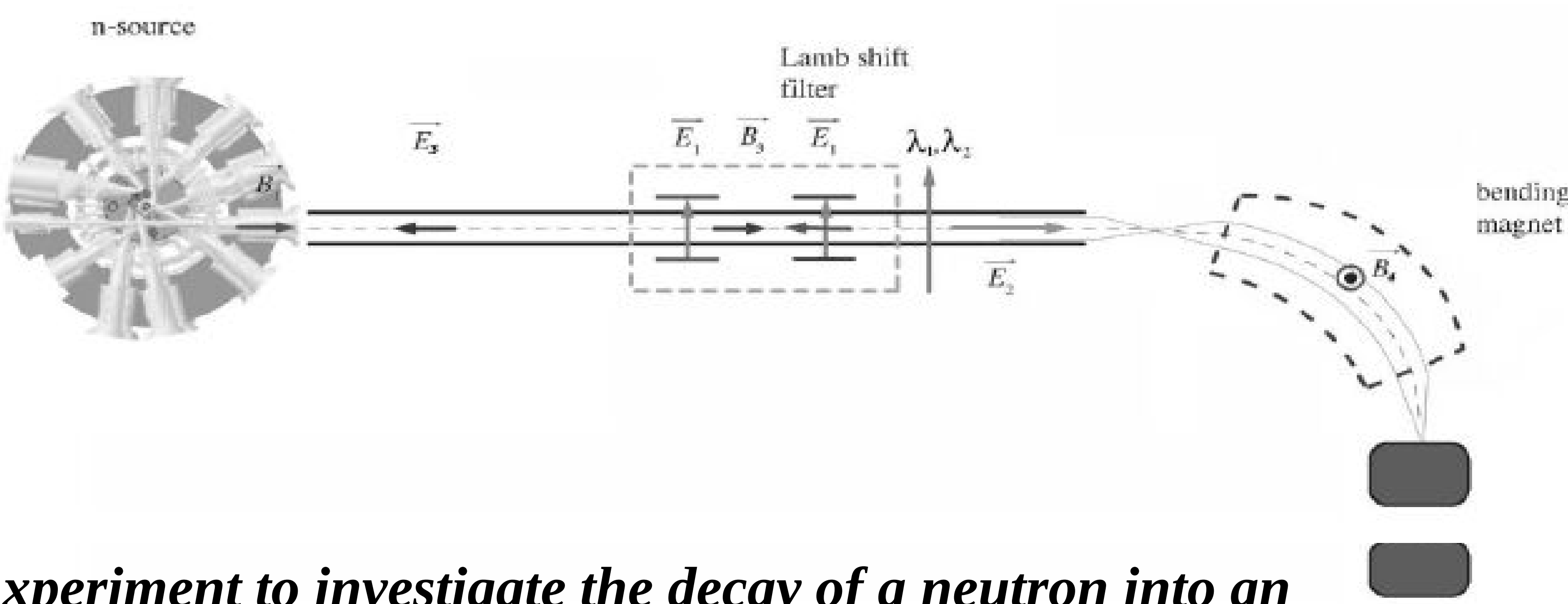
$$W_{IV} \equiv 0$$

State Separation and $2S_{1/2}$-$2P_{1/2}$ Level Crossing at B>0.05 T

- The question is: how to separate the populations in the different Paschen-Back states? This is done by exploiting the phenomenon of **level crossing**.

- In a zero magnetic field **B**=0 the 2S and 2P states are separated in energy by the Lamb shift ν_L=1057.8 MHz. However, for values of **B** in the range 0.05 to 0.062 T, the upper two $2P_{1/2}$ levels with m_e=1/2 cross the lower two $2S_{1/2}$ levels |IV> and |II> which have m_e= -1/2

- This allows the possibility of 2P-2S mixing through application of the linear Stark effect.



Experiment to investigate the decay of a neutron into an antineutrino and a hydrogen atom (Schott et al 2006)

Neutrons from a through-going beam tube decay into hydrogen atoms at about 3 sec^{-1}. These are state-selected in a Lamb shift spin filter, ionized by a pair of CW lasers $\lambda_1(2S \rightarrow 10P)$ and $\lambda_2(10P \rightarrow 27D)$ into protons which are subsequently detected

Table 2. $W_i(\%)$ for various g_S and g_T.

config. i	$g_S = 0, g_T = 0$	$g_S = 0.1, g_T = 0$	$g_S = 0, g_T = 0.02$
1	44.114	46.44	43.40
2	55.24	53.32	55.82
3	.622	.238	.780
4	0.	0.	0.

Sensitivity of the relative populations of the Paschen–Back hyperfine states to small admixtures of scalar and tensor weak interactions. A finite population of state 4 would indicate the presence of a small right handed component in the weak current (Schott et al 2009)

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