Precision Tests of the Standard Model with trapped atoms, 2nd lecture

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Two recent developments that use traps for the understanding of fundamental processes:

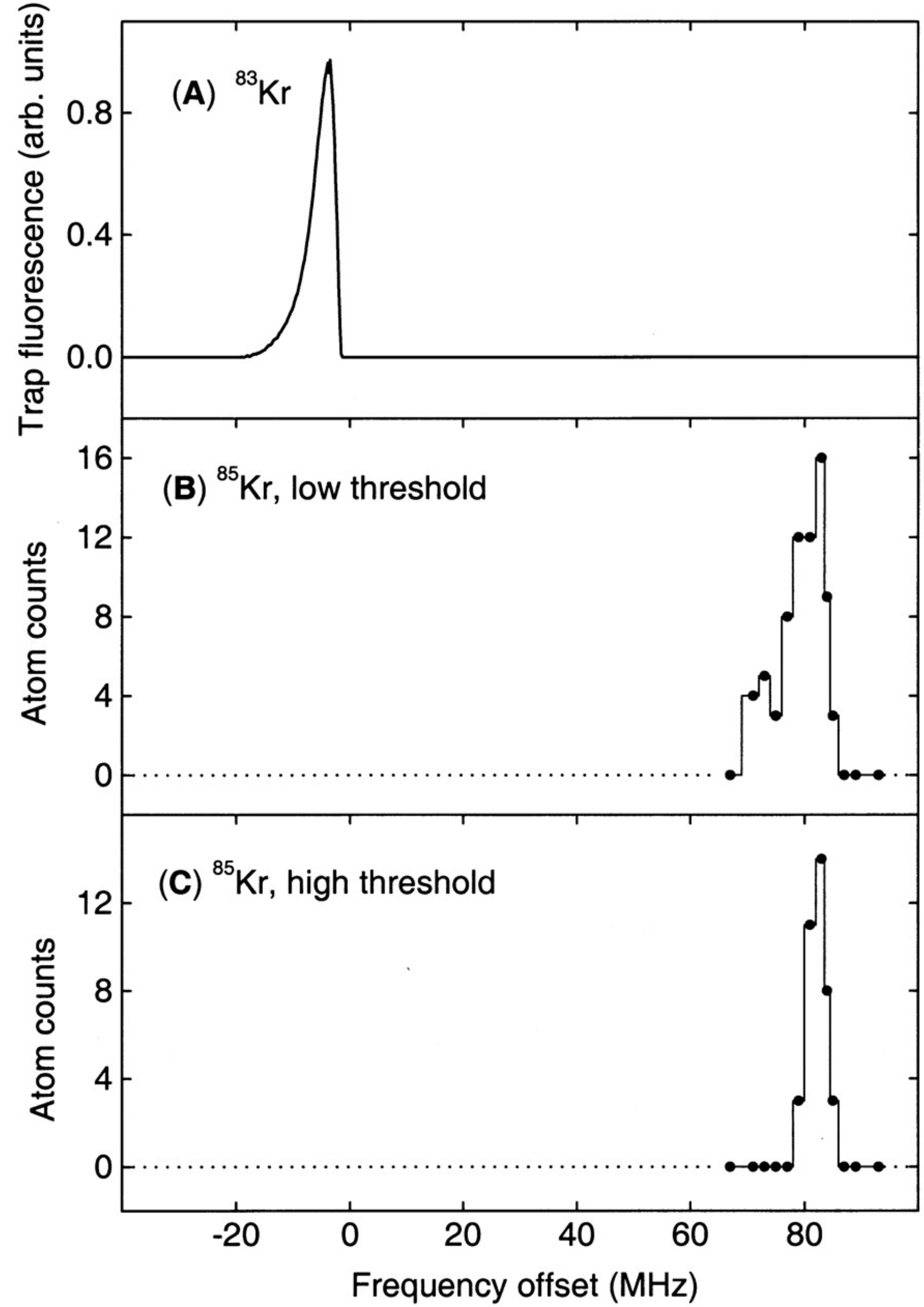
Isotope abundance analysis with single atom detection in a MOT; gives ratios of isotopes important for dating samples. Tested with Krypton. Science **286**, 1139.

Magnetic trapping of neutrons for a lifetime measurement. It is a proof of principle. Capture the neutrons in a magnetic trap filled with superfluid ^{4}He and watch them decay. There are scintillations in the fluid. Nature **403**, 62 (2000).

C. Y. Chen, Y. M. Li, K. Bailey, T. P. O'Connor, L. Young, Z.-T. Lu “Ultrasensitive Isotope Trace Analyses with a Magneto-Optical Trap” Science **286**, 1139.

Laser manipulation of neutral atoms has been used to count individual krypton-85 and krypton-81 atoms present in a natural krypton gas sample with isotopic abundances in the range of 10^{-11} and 10^{-13}, respectively. This method of isotope trace analysis is free of contamination from other isotopes and elements and can be applied to several different isotope tracers for a widerange of applications. The demonstrated detection efficiency is 1×10^{-7}. System improvements could increase the efficiency by many orders of magnitude.

Figure 4. (A) Fluorescence of trapped ^{83}Kr atoms versus laser frequency. Fluorescence was measured with a low-gain photodiode detector. (B and C) Number of ^{85}Kr atoms counted versus laser frequency. Each data point represents number of atoms counted in 20 min, with 10 min each for loading and counting. Fluorescence threshold, over which an atom is counted, was set at 3 kcps (B) and 10 kcps (C).



P. R. HUFFMAN, C. R. BROME, J. S. BUTTERWORTH, K. J. COAKLEY, M. S. DEWEY,S. N. DZHOSYUK, R. GOLUB, G. L. GREENE, K. HABICHT, S. K. LAMOREAUX, C. E. H. MATTONI, D. N. MCKINSEY, F. E. WIETFELDT & J. M. DOYLE, “Magnetic trapping of neutrons”, Nature **403**, 62 (2000)

Accurate measurement of the lifetime of the neutron (which is unstable to beta decay) is important for understanding the weak nuclear force and the creation of matter during the Big Bang. Previous measurements of the neutron lifetime have mainly been limited by certain systematic errors; however, these could in principle be avoided by performing measurements on neutrons stored in a magnetic trap. Neutral-particle and charged-particle traps are widely used for studying both composite and elementary particles, because they allow long interaction times and isolation of particles from perturbing environments. Here we report the magnetic trapping of neutrons. The trapping region is filled with superfluid ^{4}He, which is used to load neutrons into the trap and as a scintillator to detect their decay. Neutrons in the trap have a lifetime of 750+330-200 seconds, mainly limited by their beta decay rather than trap losses. Our experiment verifies theoretical predictions regarding the loading process and magnetic trapping of neutrons. Further refinement of this method should lead to improved precision in the neutron lifetime measurement.

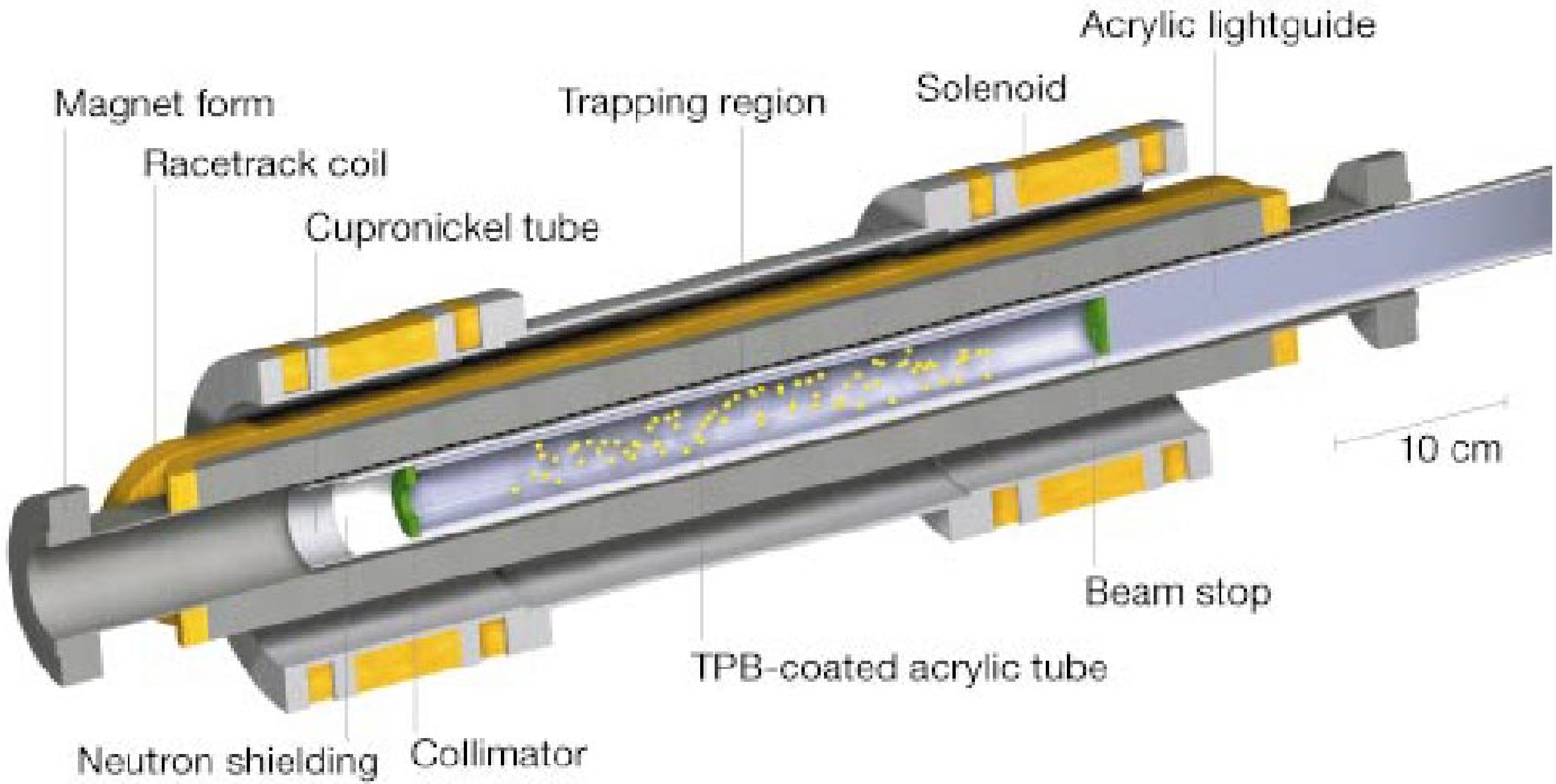
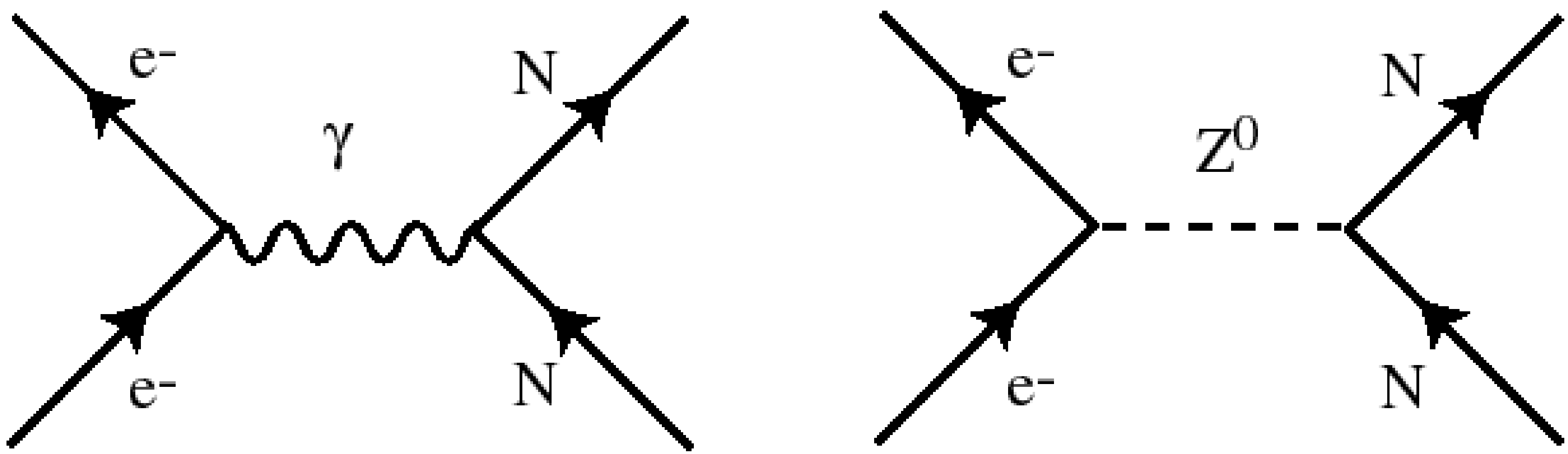
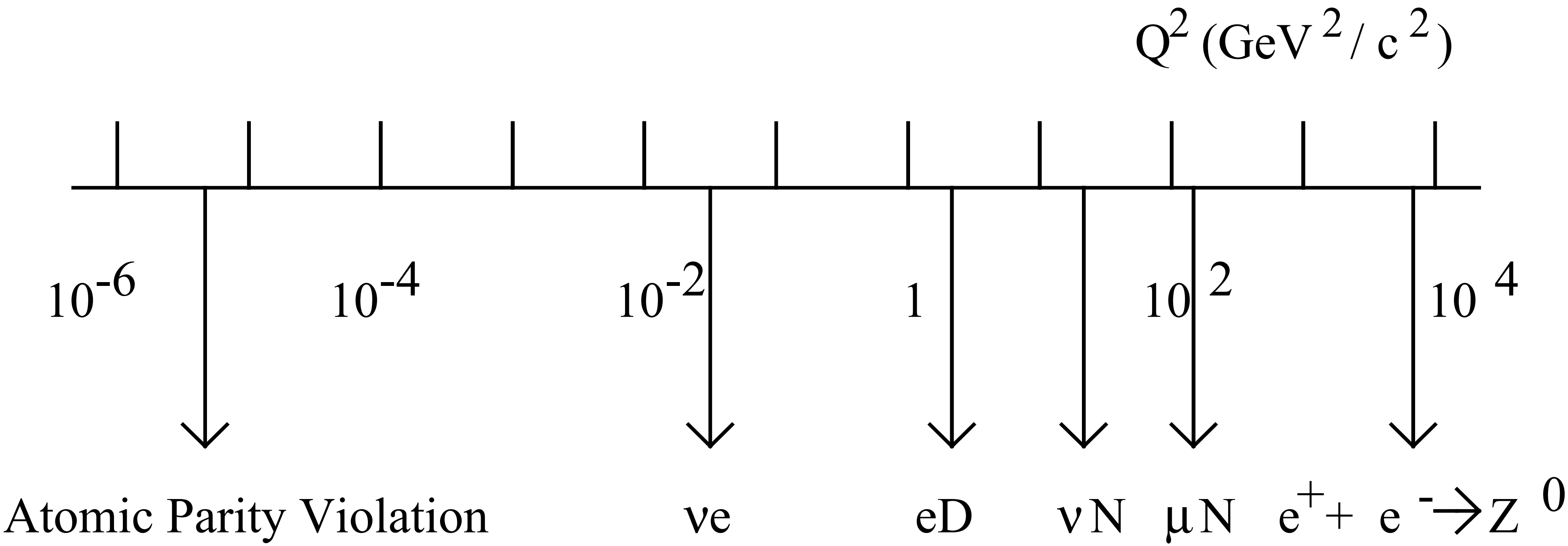


Figure 1 Half-section view of the neutron trapping apparatus. The trapping region is filled with isotopically pure ^{4}He at a temperature 250 mK. The helium is contained within a cupronickel tube. A beam of cold neutrons passes through a series of teflon windows and enters the helium from the left. It is collimated by a boron carbide ring, passes through the trapping region and is absorbed by a boron carbide beam stop. Approximately 1% of the 11 K neutrons scatter in the superfluid helium. Those neutrons (yellow) in the low-field-seeking spin state and with energy below the trap depth are magnetically confined. The rest of the scattered neutrons are absorbed by neutron-shielding material (boron nitride) surrounding the trapping region. The magnetic trapping field is created by an assembly of superconducting magnets. Radial confinement is provided by a quadrupole constructed from four racetrack-shaped coils and axial confinement is provided by two sets of solenoids. Electrons from neutron beta-decay cause extreme-ultraviolet scintillations in the superfluid helium which are wavelength-shifted to the visible by a thin film of TPB-doped polystyrene coated on the inside of an acrylic tube surrounding the trapping region. This tube is optically coupled to an acrylic light guide which transports the blue light to the end of the 250-mK region (to the right).

"In the Glashow Weinberg Salam theory of the electroweak interaction, for each channel there is always a Z channel accompanying it. At low energy, the Z channel is suppressed by a factor of $Q^2/M^2(Z)$ where Q is the momentum transferred and M(Z) is the mass of the Z particle. Nevertheless, this tiny effect can be detected if it is enhanced by some mechanism."

Langacker





Domain of Q^2, square of the four-momentum transfer, explored by different experiments.

C. S. Wood, S. C. Bennett, D. Cho, B. P. Masterson, J. L. Roberts, C. E. Tanner, C. E. Wieman, “Measurement of Parity Nonconservation and an Anapole Moment in Cesium” Science **275**, 1759 (1997).

The amplitude of the parity-nonconserving transition between the 6S and 7S states of cesium was precisely measured with the use of a spin-polarized atomic beam. This measurement gives $\mathrm{Im}(E1_{pnc})/\beta$ = 1.5935(56) millivolts per centimeter and provides an improved test of the standard model at low energy, including a value for the S parameter of 1.3(3)exp (11)theory. The nuclear spin-dependent contribution was 0.077(11) millivolts per centimeter; this contribution is a manifestation of parity violation in atomic nuclei and is a measurement of the long-sought anapole moment.

The anapole moment measurement is a 7σ result.

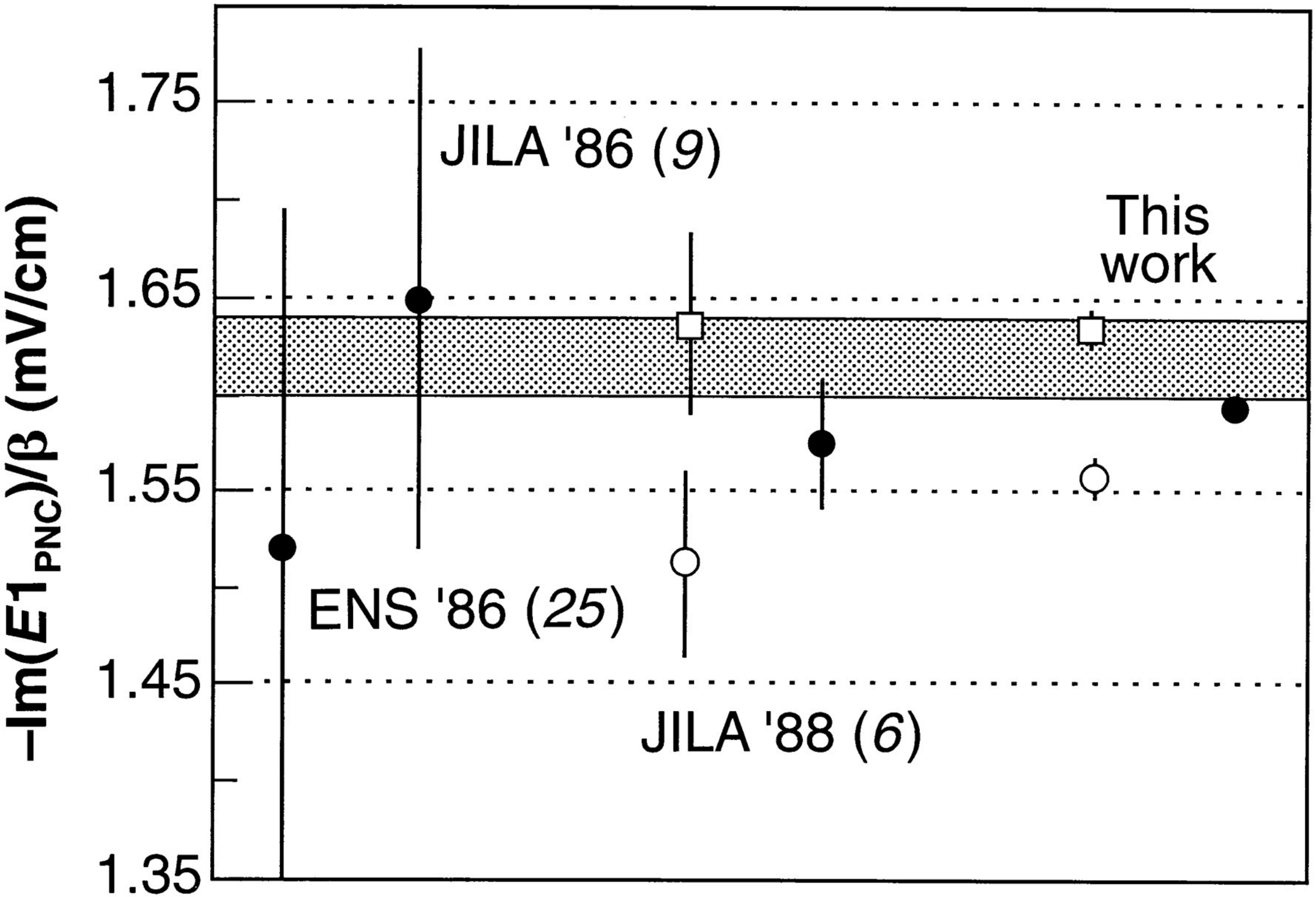


Figure 4. Historical comparison of cesium PNC results. The squares are values for the 4-3 transition, the open circles are the 3-4 transition, and the solid circles are averages over the hyperfine transitions. The band is the standard-model prediction for the average, including radiative corrections. The $\pm 1\sigma$ width shown is dominated by the uncertainty of the atomic structure.

S. C. Bennett and C. E. Wieman "Measurement of the 6S 7S Transition Polarizability in Atomic Cesium and an Improved Test of the Standard Model" Physical Review Letters **82**, 2484 (1999)

The ratio of the off-diagonal hyperfine amplitude to the tensor transition polarizability (M_{hf}/β) for the 6S7S transition in cesium has been measured. The value of $\beta = 27.024$ (43) expt. (67) theor. $\times a_0^3$ is then obtained using an accurate semiempirical value of M_{hf}. This is combined with a previous measurement of parity nonconservation in atomic cesium and previous atomic structure calculations to determine the value of the weak charge. The uncertainties in the atomic structure calculations are updated (and reduced) in light of new experimental tests. The result $Q_W = -72.06$ (28) expt. (34) theor. differs from the prediction of the standard model of elementary particle physics by 2.5σ.

Theory: $Q_w(^{133}Cs) = -73.2 - 0.7965S - 0.11T \pm 0.2$

Experiment: $Q_W = -72.06 \pm 0.44$ (adding in quadrature the errors).

Erratum: Measurement of the $6S \rightarrow 7S$ Transition Polarizability in Atomic Cesium and an Improved Test of the Standard Model [Phys. Rev. Lett. 82, 2484 (1999)]

S. C. Bennett and C. E. Wieman

TABLE I. Fractional differences ($\times 10^3$) between measured and calculated values of quantities relevant for testing PNC calculations in atomic cesium. We only list the most precise experiments. The second column lists the most relevant aspects of the wave functions that are being tested. $\langle 1/r^3 \rangle_{nP}$ is the average of $1/r^3$ over the wave function of the electronic state nP. Where the experiment has improved or changed significantly since the publication of Ref. [12], the difference from the old experiment is listed in brackets.

Quantity measured	Calculation tested	Difference ($\times 10^3$) Dzuba *et al.*[a,b]	Blundell *et al.*[c]	$\sigma_{\rm expt}$
$6S \rightarrow 7S$ dc Stark shift[d]	$\langle 7P \Vert \boldsymbol{D} \Vert 7S \rangle$	−3.4[19]	−0.7[22]	1.0[4]
$6P_{1/2}$ lifetime[e]	$\langle 6S \Vert \boldsymbol{D} \Vert 6P_{1/2} \rangle$	−4.2[−8]	4.3[1]	1.0[43]
$6P_{3/2}$ lifetime[e]	$\langle 6S \Vert \boldsymbol{D} \Vert 6P_{3/2} \rangle$	−2.6[−41]	7.9[−31]	2.3[22]
α[f]	$\langle 7S \Vert \boldsymbol{D} \Vert 6P_{1/2} \rangle$, and $\langle 7S \Vert \boldsymbol{D} \Vert 6P_{3/2} \rangle$	...	−1.4	3.2
β[g]	same as α	...	−0.8	3.0
$6S$ hfs[h]	$\psi_{6S}(r = 0)$	1.8	−3.1	...
$7S$ hfs[i]	$\psi_{7S}(r = 0)$	−6.0	−3.4	0.2
$6P_{1/2}$ hfs[j]	$\langle 1/r^3 \rangle_{6P}$	−6.1	2.6	0.2
$7P_{1/2}$ hfs[k]	$\langle 1/r^3 \rangle_{7P}$	−7.1	−1.5	0.5

[a]The value for $k_{\rm PNC}$ of Dzuba *et al.* is obtained using "energy rescaling" so we have used the corresponding "rescaled" values in the table for consistency. Blundell *et al.* do not rescale $k_{\rm PNC}$ and so we use their pure *ab initio* values in the table. [b]Refs. [13,14]. [c]Refs. [6,12]. [d]Ref. [8]. [e]Ref. [18]. [f]Using present work's value of β and α/β from Ref. [19]. [g]Present work. [h]Defined. [i]Ref. [20]. [j]Ref. [21]. [k]Ref. [22].

Recent papers that analyze the atomic parity non-conservation measurement in Cs result in the context of extensions of the standard model:

VOLUME 84, NUMBER 2 PHYSICAL REVIEW LETTERS 10 JANUARY 2000

Indications for an Extra Neutral Gauge Boson in Electroweak Precision Data

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Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104-6396

(Received 15 October 1999)

A new analysis of the hadronic peak cross section at LEP 1 implies a small amount of missing invisible width in Z decays, while the effective weak charge in atomic parity violation has been determined recently to 0.6% accuracy, indicating a significantly negative S parameter. As a consequence, the data are described well if the presence of an extra Z' boson, such as predicted in grand unified theories, is assumed. Moreover, the data are now rich enough to study an arbitrary extra Z' boson and to determine its couplings in a model independent way. An excellent fit to the data is obtained in this case, suggestive of a family nonuniversal Z' similar to those predicted in a class of superstring theories.

Precision Observables and Electroweak Theories

Jonathan A. Bagger, Adam F. Falk, and Morris Swartz
Department of Physics and Astronomy, The Johns Hopkins University, 3400 North Charles Street, Baltimore, Maryland 21218
(Received 12 August 1999)

We compute the bounds from precision observables on alternative theories of electroweak symmetry breaking. We show that a cutoff as large as 3 TeV can be accommodated by the present data, without any new particles or unnatural fine tuning.

R⁻ contains atomic PNC information.

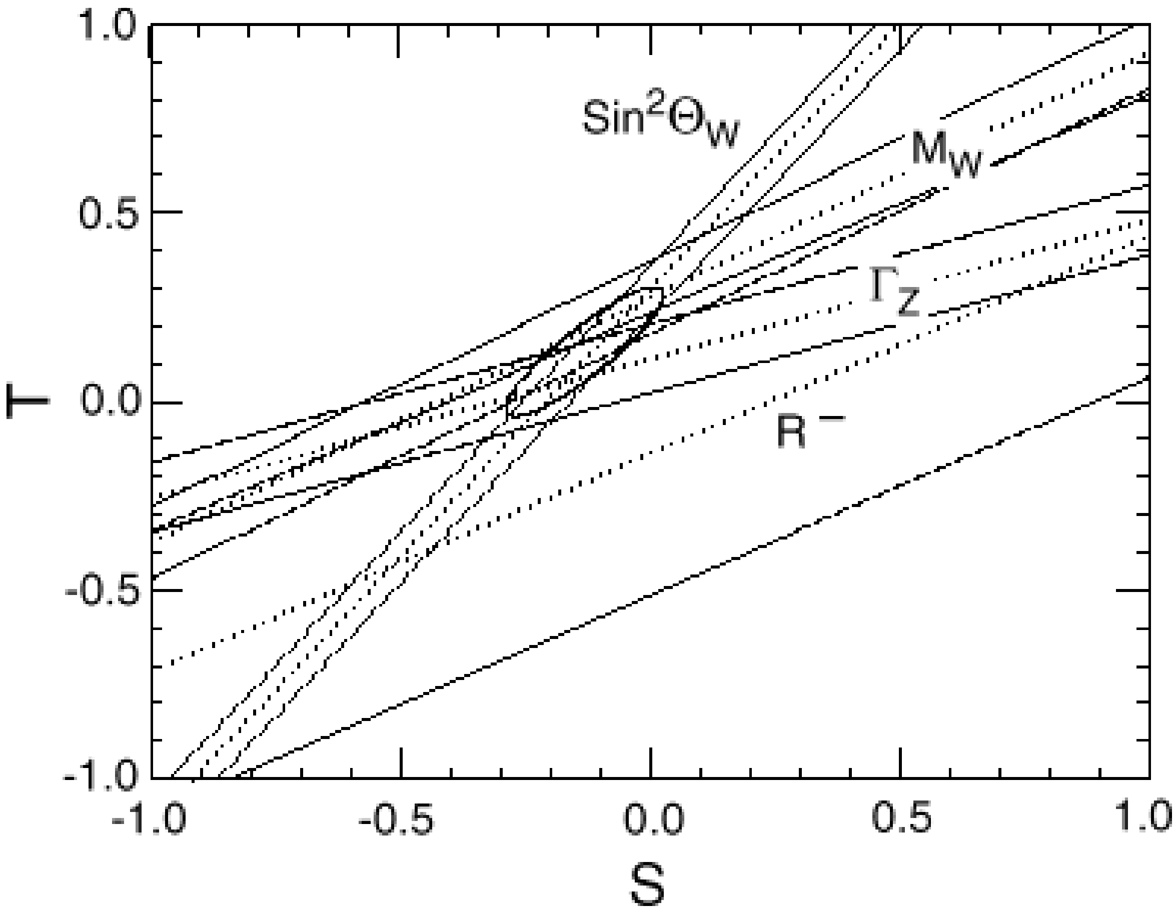

FIG. 1. Fit to S and T from electroweak observables, with $M_H^{\rm ref} = 500$ GeV and $m_t^{\rm ref} = 175$ GeV.

PHYSICAL REVIEW D, VOLUME 61, 016006

Atomic parity violation and precision electroweak physics — An updated analysis

Jonathan L. Rosner

These are the global fits to all the data. Note the sensitivity to the new Cs atomic PNC measurements

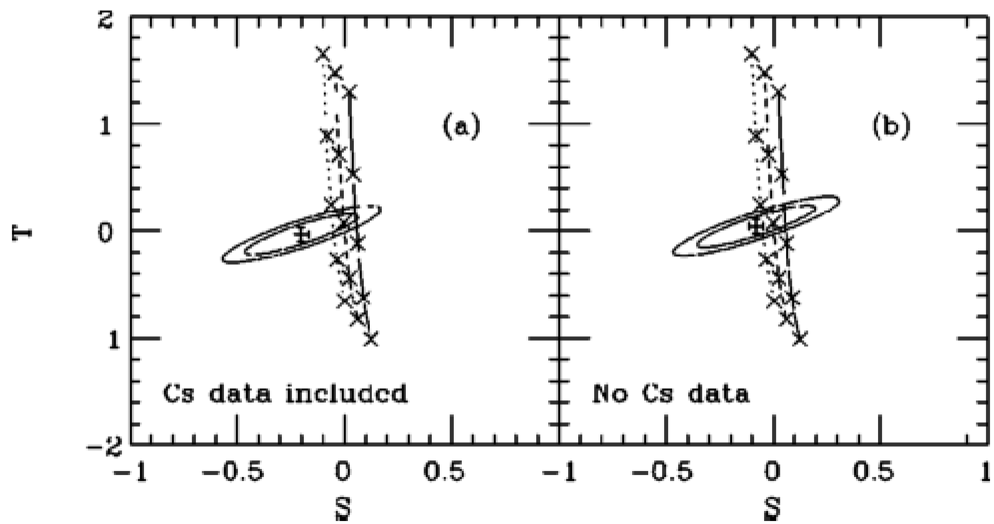

FIG. 1. Allowed ranges of S and T at 68% (inner ellipses) and 90% (outer ellipses) confidence levels, corresponding to $\chi^2=2.3$ and 4.6 above the minima (crosses at the center of ellipses). Dotted, dashed, and solid lines correspond to standard model predictions for $M_H=100$, 300, and 1000 GeV/c^2. Symbols $\times$, from bottom to top, denote predictions for $m_t=100$, 140, 180, 220, and 260 GeV/c^2. (a) Fit including APV experiments with present errors; (b) fit excluding new Cs measurement.

TABLE I. Electroweak observables described in the fit.

Quantity	Experimental value	Theoretical value
Q_W (Cs)	-72.06 ± 0.46 [a]	-73.19 [b] $-0.80S - 0.007T$
Q_W (Tl)	-115.0 ± 4.5 [c]	-116.8 [d] $-1.17S - 0.06T$
M_W(GeV/c^2)	80.394 ± 0.042 [e]	80.315 [f] $-0.29S + 0.45T$
"M_W" (GeV/c^2)	80.36 ± 0.21 [g]	80.315 [f] $-0.29S + 0.52T$ [h]
"M_W" (GeV/c^2)	80.24 ± 0.11 [i]	80.315 [f] $-0.54S + 0.70T$ [h]
$\Gamma_{ll}(Z)$ (MeV)	83.958 ± 0.089 [j]	83.92 [f] $-0.18S + 0.78T$
$\sin^2\theta_{\text{eff}}$	0.23195 ± 0.00023 [j]	0.23200 [f] $+0.0036S - 0.0026T$
$\sin^2\theta_{\text{eff}}$	0.23099 ± 0.00026 [k]	0.23200 [f] $+0.0036S - 0.0026T$
m_t(GeV/c^2)	174.3 ± 5.1 [l]	$173.9 + 241S + 82T$

Note how the different electroweak observables contribute to the S and T parameters. S for isospin preserving and T for isospin violating extensions of the standard model.

The mass of the extra Z' boson with the limits from atomic parity non-conservation in Cs.

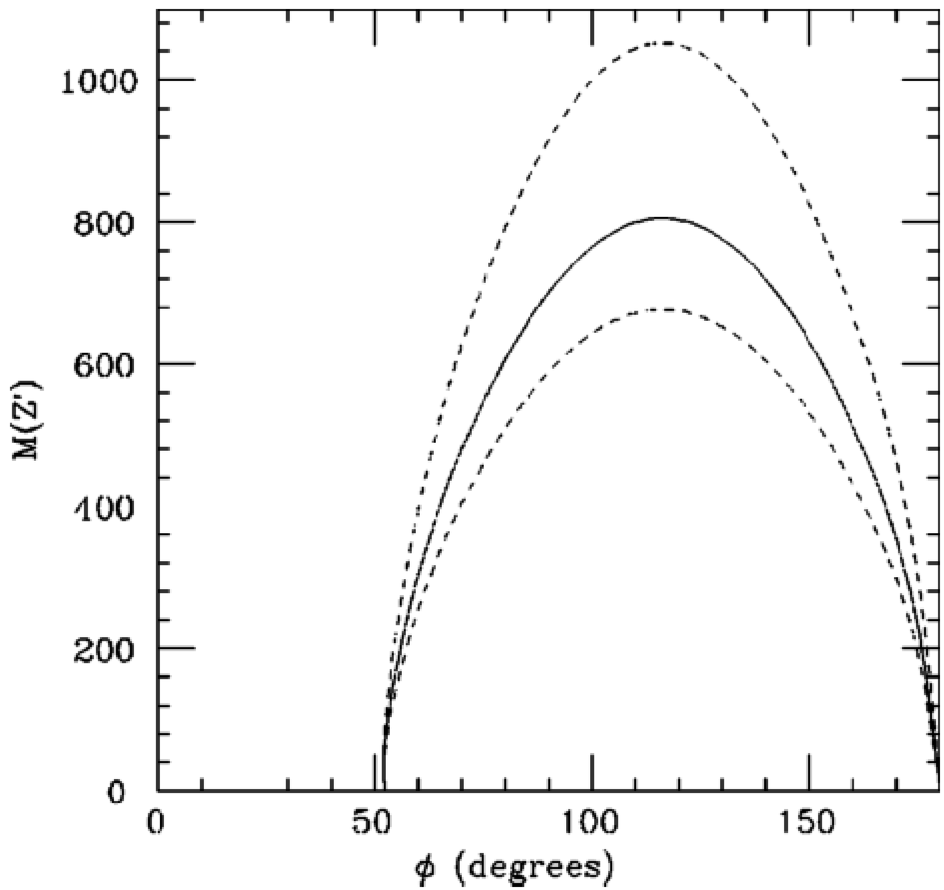

FIG. 3. Values of $M(Z')$ corresponding to central value (solid line) and $\pm 1\sigma$ errors (dashed lines) of $Q_W(\mathrm{Cs})$ in a model where the discrepancy with respect to the standard electroweak prediction is due to the exchange of a new unmixed Z'.

Historical development of Atomic Parity Non Conservation

1959 Zel'dovich suggests to look for the effect in Optical Rotation. (Rotation of the polarization of the light as it passes through some medium).

1967 The Wimberg-Salam theory of electroweak interactions includes a neutral boson Z^0 (The exchange of a W^+ or W^- changes the charge state).

1974 M. A. Bouchiat and C. Bouchiat suggest using heavy atoms.

1978 Novosibirsk experiment in Bi shows a 4.5σ result; Berkeley experiment in Tl shows a 2.1σ result.

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Experiments at Seattle, Oxford, Paris, Boulder working with Tl, Bi, Pb, Cs and more recently with rare earths.

Recent theory for Cs at Novosibirsk/South Wales and Notre Dame

For a vector-axial vector type weak force, the Lagrangian for the parity violating quark-electron interaction in the low energy limit is:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_{i=u,d} \left[C_{1i} \bar{e} \gamma^{\mu} \gamma^5 e \bar{q}_i \gamma_{\mu} q_i + C_{2i} \bar{e} \gamma^{\mu} e \bar{q}_i \gamma_{\mu} \gamma^5 q_i \right]$$

$A_e - V_N$ $\quad$ $V_e - A_N$

$C_{1u,d}$ strength of the interaction of the electronic axial vector with the hadronic vector current. $C_{2u,d}$ has the hadronic axial vector with the electronic vector current. At tree-level the standard model predicts with [$x=\sin^2\theta_w(M_z)\approx 0.2323$]

$$C_{1u} = \frac{1}{2}\left(1 - \frac{8}{3}x\right)$$

$$C_{1d} = -\frac{1}{2}\left(1 - \frac{4}{3}x\right)$$

Electromagnetic interactions bind nuclei and electrons that do not violate parity. The accompanying Z^0 channel has both a vector piece and an axial-vector piece that violate parity.

Because there is a finite probability that the electron overlaps with the nucleus, an exchange of a Z^0 boson between the electrons and the neutrons or protons can take place. This interaction produces a parity non-conserving neutral current and because parity is violated, the interaction mixes the parity eigenstates of an atom, for example the S states have a very small amount of a P state mixed with them.

$$|S\rangle \rightarrow |S\rangle + \delta_{pnc}|P\rangle$$

In order to measure this small effect one interferes the PNC amplitude with an allowed electromagnetic transition.

$$| S> + \delta_{pnc}|P> \longrightarrow |S> + \delta_{E}|P> + \delta_{pnc}|P>$$

In PNC experiments the weak charge is related to the transition rate δ_{pnc} (measurable quantity) via an atomic matrix element $<\gamma^5>$ which can only come from atomic theory calculations.

$$Q_W = -2[(2Z+N)\, C_{1u} + (Z+2N)\, C_{1d}] + small\ C_{2u,d} \approx \text{-N+Z}[1\text{-}4\sin^2\theta_W]$$

$$Q_w = \frac{\delta_{pnc}}{<\gamma^5>_{nucleus}}$$

The question is to see if Q_w is as predicted by the Standard Model.

The parity violating effect has an approximate Z^3 (number of protons) dependence (Bouchiat):

$$<\Psi_s|\, Q_w\gamma^5 \,|\, \Psi_p>$$

We can think of the operator $Q_w\gamma^5$ in the non-relativistic limit as simply a parity violating operator such as:

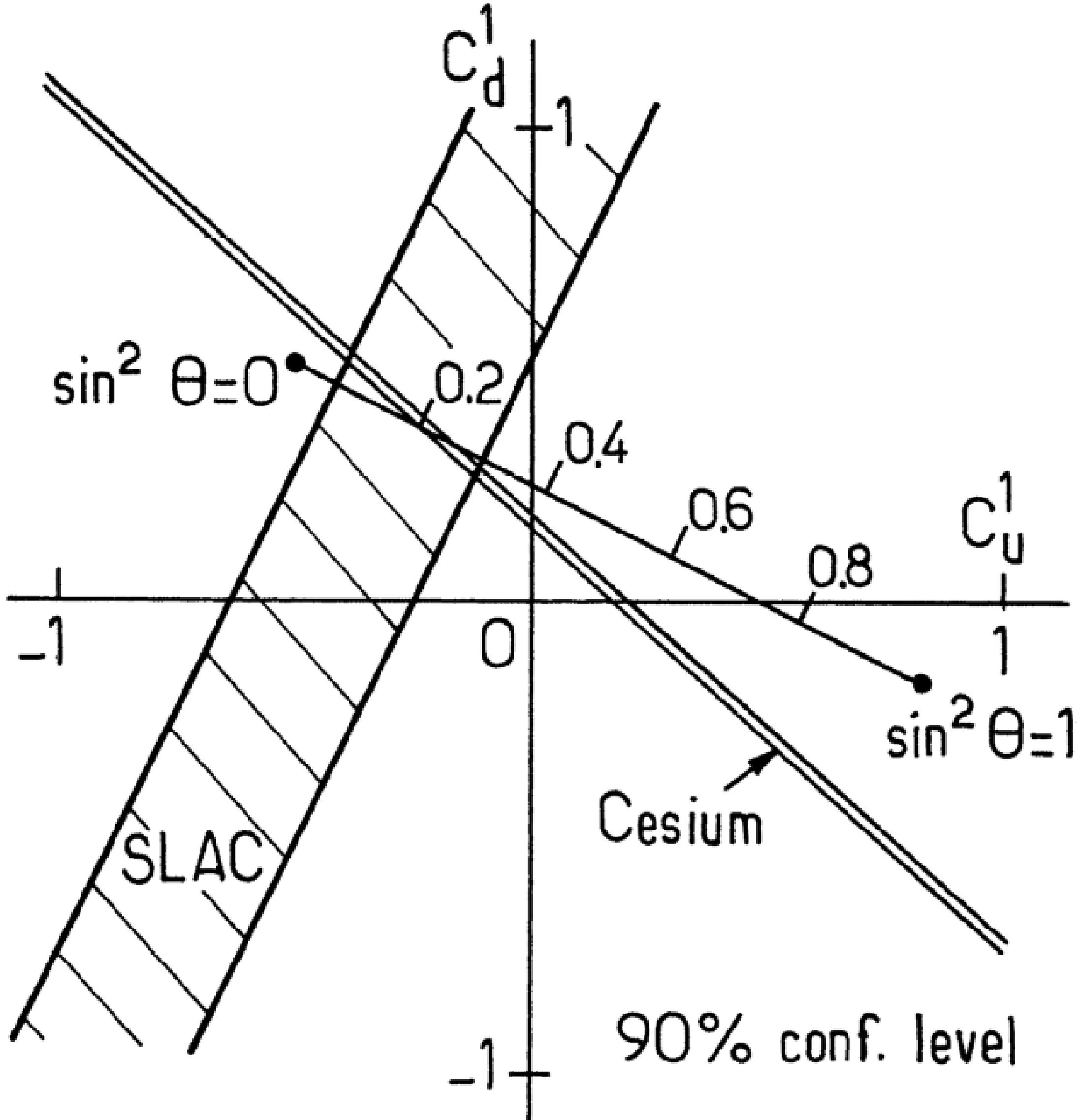
$$\vec{\sigma}\cdot\vec{p} \rightarrow \vec{\sigma}\cdot\frac{\partial}{\partial r}$$

Then we can see why the Z^3 dependence since:

1.- $(A_e\text{-}V_N)$ There are more nucleons for the electron to exchange a Z^0: $Q_w \sim Z$

2.- $(A_e\text{-}V_N)$ The electron has an overlap with the nucleus $\Psi_s(0) \sim Z^{1/2}$

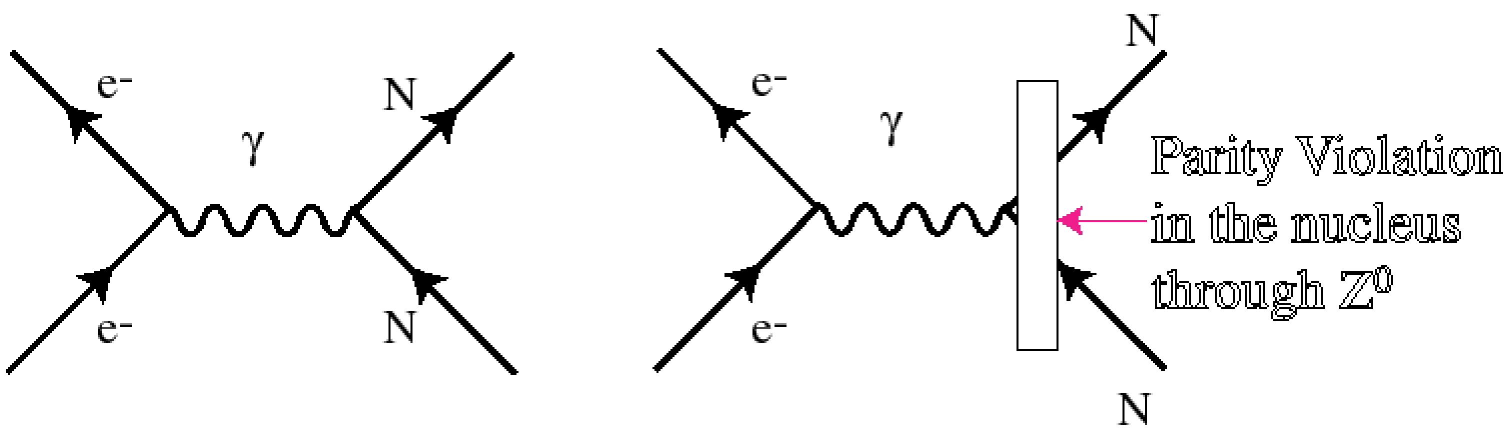
3.- It has higher momentum $d\Psi_p/dr\,(0) \sim Z^{3/2}$



Experimental, model-independent determination of the weak charges of the u and d quarks. The two bands represent the domains allowed by the high-energy SLAC and by the cesium experiments. The graduated segment represents the prediction of the standard model for values of the parameter $\sin^2\theta_w$ from 0 to 1.

The Anapole Moment

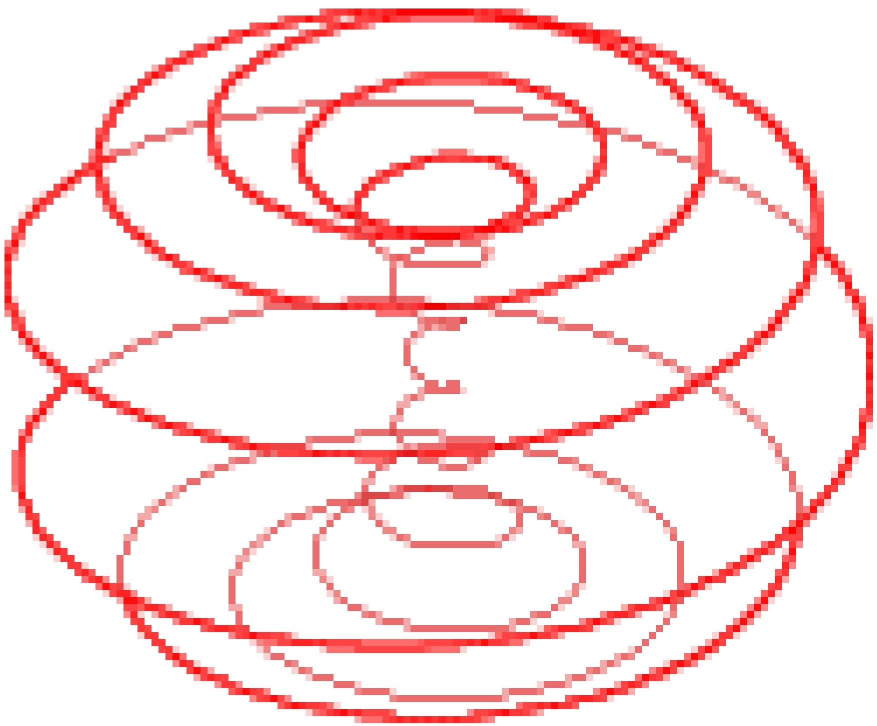
1958 Zel'dovich, Vaks
1980 Khriplovich, Flambaum
1997 Boulder experiment



It can be thought as a "weak radiative correction". The nuclear wave function has parity violating components (V_e A_N). It has to be probed inside the nucleus by an electromagnetic interaction.

The anapole moment contribution to the measured atomic PNC violation is larger than that from $C_{2u,d}$ which is incoherent, only the last nucleon contributes; it is suppressed by a factor of $(1\text{-}4\sin^2\theta_w)$. The anapole moment grows proportional to the nuclear surface: $A^{3/2}$. In Cs the first contribution is of the order of 0.01 while the anapole is about 0.13

The anapole moment comes from the hadronic interactions of Z^0, that is nucleon-nucleon. One can then use parity violation to separate it from the strong and electromagnetic interactions.

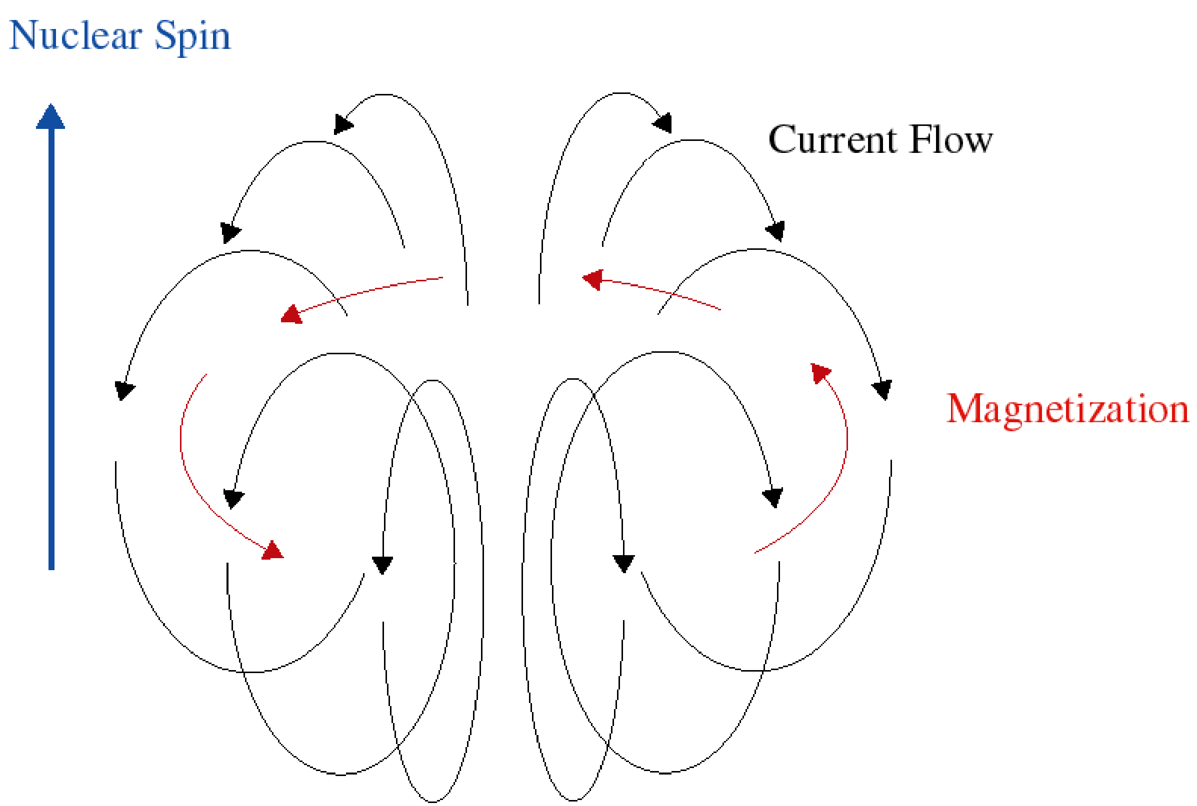


The chirality of an atom arising from the neutral current weak interaction between the electron and a nucleon can be shown by plotting the electron probability current density for a given atomic state, shown here for the 2p1/2 state in hydrogen. Under a parity transformation, or equivalently under mirror reversal, the helicity of the streamlines is reversed: the atom is fundamentally handed. (After R. A. Hegstrom et al, Am. J. Phys. 56 p1086, 1988).

See: Fortson Group - Atomic Chirality

http://www.phys.washington.edu/~fortson/chiral.html

Take the image from the previous slide and apply it to the nucleus. The wavefunction of a nucleon violates parity and so its current has a certain chirality. The current can be separated in two components. One an axial rotation and the second a current flowing in a torus. It is this last part that generates a magnetic field inside the nucleus. It changes the magnetization in a chiral form and manifests itself differently depending on the hyperfine state of the interacting nucleus-electron.



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