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Search for Parity Nonconservation in Hydrogen

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1. Theory

Weak interactions are mediated by the exchange of virtual W^+, W^- and Z^0 particles, which together with the photon are the gauge bosons of the standard electroweak theory of Glashow, Weinberg and Salam [1]. In stable atoms the electrons have no charged interactions (exchange of W^+ or W^-) in first order (that would constitute β-decay) and the second order effects are, of course, very feeble. On the other hand Z^0 exchange does not affect the charges of the constituent particles and contributes in first order to atomic structure. The range of the virtual Z^0 is very short ($\sim 10^{-18}$ m) because it is massive ($\sim$100 GeV/c^2) and for our purposes it is adequate to consider the interaction as a simple current-current interaction at a point. Assume, as in the standard theory, that the currents contain only vector (V) and axial vector (A) components. Then there are four main terms to consider in the effective Hamiltonian

$$H_{eff} = \frac{G_F}{\sqrt{2}} \sum_N (C_{VV}^{eN} \bar{\psi}_e \gamma^\mu \psi_e \bar{\psi}_N \gamma_\mu \psi_N + C_{AA}^{eN} \bar{\psi}_e \gamma^\mu \gamma_5 \psi_e \bar{\psi}_N \gamma_\mu \gamma^5 \psi_N$$

$$+ C_{AV}^{eN} \bar{\psi}_e \gamma^\mu \gamma_5 \psi_e \bar{\psi}_N \gamma_\mu \psi_N + C_{VA}^{eN} \bar{\psi}_e \gamma^\mu \psi_e \bar{\psi}_N \gamma_\mu \gamma^5 \psi_N). \quad (1)$$

ψ_N and ψ_e are the nucleon and electron field operators, the C's are coupling constants, γ_μ and γ_5 are the usual Dirac matrices and G_F is the Fermi constant. Of course the fundamental couplings are to the quarks but at low energy it is convenient to consider the nucleons as fundamental. There are also terms proportional to the momentum transfer but they are small in atoms.

The first two terms in (1) are of even parity because they involve the product of two odd currents (the C_{VV} term) and of two even currents (the C_{AA} term). These interactions cause shifts of the energy levels of an atom. The last two terms are of odd parity and according to first order perturbation theory they do not shift the levels. These are the terms responsible for parity nonconservation in hydrogen. They may be replaced to a good approximation by a non-relativistic potential H_{pv} for an electron interacting with a point proton at $r = 0$. In atomic units [2]

$$H_{pv} = \frac{\alpha G_F}{2\sqrt{2}} \{ -C_{AV}^{ep} (\vec{\sigma}_e \cdot \vec{p}) \delta(\vec{r}) + C_{VA}^{ep} (\vec{\sigma}_e \cdot \vec{p})(\vec{\sigma}_e \cdot \vec{\sigma}_N) \delta(\vec{r}) + \text{h.c.} \}. \quad (2)$$

The matrix of H_{pv} between the $nS_{1/2}$ and $nP_{1/2}$ states of hydrogen is diagonal in the hyperfine quantum numbers F and M and the elements are

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$$<nP_{1/2}FM|H_{pv}|nS_{1/2}FM> = iV(C_{AV}^{ep} - C_{VA}^{ep}[2F(F+1)-3]) \qquad (3a)$$

where

$$V = \frac{\alpha G_F}{2\sqrt{2}} \cdot \frac{Z^4}{\pi n^4}\sqrt{n^2-1}. \qquad (3b)$$

In the case of hydrogen with $n = 2$, V/h is 0.0128 Hz.

Parity nonconservation in hydrogen was discussed as early as 1959 by Zel'dovich [3]. Later many practical aspects of making a measurement were explored by Michel [4], but the subject really came to life with the discovery of weak neutral currents in 1973/74 [5,6]. Almost immediately Feinberg published two important papers on the weak circular polarization of spontaneous decay radiation from hydrogenic atoms [7] and Lewis and Williams discussed the rate of excitation of hydrogen atoms by polarized light [8]. It was subsequently suggested that the best hope of detecting parity nonconservation in hydrogen lay in microwave transitions among the $2S_{1/2}$ levels [9] and the three experiments tried on hydrogen (at Seattle, Michigan and Yale) are all based on such transitions. Dunford [10] has proposed a similar scheme with He^+. As yet there are no results of sufficient accuracy to detect the parity nonconservation. For a fuller and more general account see ref. [11].

2. Principle of the Yale Experiment

The Yale experiment involves the $2S_{1/2}$ and $2P_{1/2}$ states in zero magnetic field. The strength of the parity nonconserving interaction is measured by a study of hyperfine transition from $(2S_{1/2}F = 0)$ to $(2S_{1/2}F = 1)$ at 178 MHz using an atomic beam of hydrogen.

According to first order perturbation theory the usual $(2S_{1/2}F)$ state $|SF>$ is modified by an admixture of the $(2P_{1/2}F)$ state $|PF>$ to become

$$|S'F> = |SF> + \frac{<PF|H_{pv}|SF>}{E_{SF} - E_{PF}}|PF> \qquad (4)$$

where E_{SF} and E_{PF} are the eigenvalues of those two states and we have neglected the smaller effect of $2P_{3/2}$ and other more distant states. Hence the electric dipole matrix element between the states normally labeled $(2S, F = 0)$ and $(2S, F = 1)$ is

$$<S'1|z|S'0> = <S1|z|P0>\frac{<P0|H_{pv}|S0>}{E_{S0} - E_{P0}} + \frac{<S1|H_{pv}|P1>}{E_{S1} - E_{P1}}<P1|z|S0>. \qquad (5)$$

The weak interaction matrix elements are given by (3a) and (3b). The energy denominators are both approximately equal to the Lamb shift S; 969 MHz for $F = 0$ and 1088 MHz for $F = 1$. Consequently the terms involving C_{AV}^{ep} almost cancel and the electric dipole matrix element is approximately

$$<S'1|z|S'0> = \frac{4\sqrt{3}iV}{S}C_{VA}^{ep}. \qquad (6)$$

Of course the main point is that this matrix element is not zero and that an electric dipole hyperfine transition can therefore be excited.

Fig. 1 indicates the main features of the apparatus. A high intensity $2S$ atomic beam is produced by passing a 500 eV beam of protons through a cesium target. The atoms are prepared in the $F = 0$ state using a microwave state selector [12] to stimulate decay of the $F = 1$ atoms through transition to the short lived $2P_{1/2}$ levels. The beam now enters the main interaction region in which it passes sequentially through two separated parallel, coherent oscillating fields. The first field $\vec{\beta}$ is magnetic and drives the normal $F = 0 \rightarrow F = 1$ magnetic dipole transition. The second field $\vec{\epsilon}$ is electric and drives the parity-forbidden electric dipole transition $F = 0 \rightarrow F = 1$ through the transition moment discussed above. The $F = 1$ amplitudes induced at resonance in the two regions may be written

$$\vec{A}_{M1} = \mu\vec{\beta} \qquad \vec{A}_{E1} = id\vec{\epsilon}e^{i(\phi_0+\phi)} \tag{7}$$

where μ and d are real and proportional respectively to the magnetic dipole and (parity-forbidden) electric dipole transition moments. The angle ϕ_0 is a quantum mechanical phase (equal to zero if we ignore the decay of the P states) and ϕ is the phase angle between $\vec{\epsilon}$ and $\vec{\beta}$. The state amplitudes are polarized parallel to the fields because the initial $F = 0$ state is spherically symmetric. Thus the probability of transitions to the $F = 1$ state is

$$\begin{aligned} P &= (\vec{A}_{M1} + \vec{A}_{E1})^* \cdot (\vec{A}_{M1} + \vec{A}_{E1}) \\ &= \mu^2\beta^2 + d^2\epsilon^2 + 2\mu d\vec{\beta}\cdot\vec{\epsilon}\sin(\phi_0 + \phi). \end{aligned} \tag{8}$$

Here we see first the allowed $M1$ term, then the negligible forbidden $E1$ term and last the interference term to be measured, which is proportional to the weak interaction through d and depends on the odd parity combination of fields $\vec{\beta}\cdot\vec{\epsilon}$.

Atoms driven into the $F = 1$ state are picked out by a second state selector (Fig. 1) which stimulates $F = 0$ atoms to decay, but transmits $F = 1$ atoms. The latter are then detected by measuring the flux of emitted Lyman-alpha photons when the beam enters a region of strong static electric field. Thus the number of detected atoms is proportional to P (8). The interference term of interest is modulated by chopping the phase of the rf electric field between ϕ and $\phi + \pi$ and is extracted from the total detector signal by phase sensitive detection.

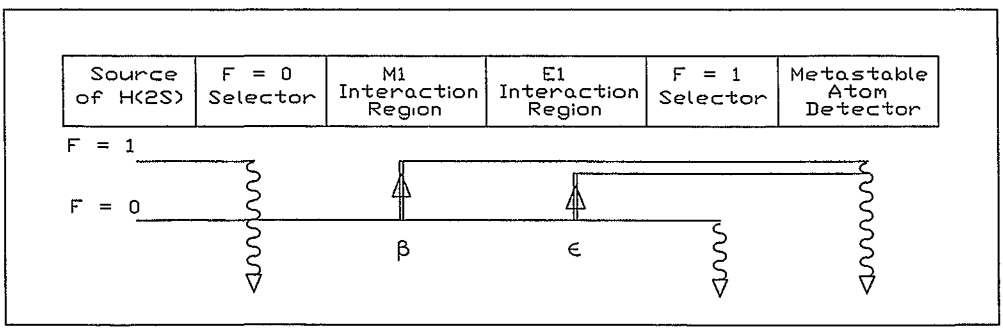

Fig 1. Schematic view of the Yale apparatus

3. Status of the Yale Experiment

At present the apparatus runs with sufficient statistical sensitivity to determine C_{VA}^{ep} with an error of order unity in one day. Unfortunately, there is a relatively large and unexpected transition amplitude that appears to be both proportional and parallel to the electric field $\vec{\varepsilon}$. It is evident from our measurements of the phase and frequency dependence of this amplitude that it is not the interesting $\vec{A}_{E1}$ of (7). We believe therefore that it is the result of some imperfection of our apparatus which so far we have been unable to identify in spite of several years of effort.

The hypotheses that we have tested include the obvious ones such as a small rf magnetic field or a stray static electric field in the $E1$ region. We have also excluded a large class of possible effects that could occur in the fringes of the electric field $\vec{\varepsilon}$ and we have demonstrated that stray magnetic fields are not responsible. In fact we have not found any experimental variable apart from $\vec{\varepsilon}$ that can influence this transition amplitude.

Although this problem prevents us from observing parity nonconservation in hydrogen we are able to determine an experimental upper bound $C_{VA}^{ep} < 300$ which is the most accurate result so far from hydrogen. Of course we hope that the mechanism responsible for the systematic error will come to light, but at present we are not optimistic about the prospects for a large improvement. Similar problems have been encountered in the Seattle and Michigan hydrogen experiments at a similar level of precision.

At present several experiments have determined C_{AV} in various heavy atoms at the 10% level of accuracy or better but C_{VA} has not been detected in any atom. For a review of parity nonconservation in atoms, see [13] or [14].

References

1. E.D. Commins and P.H. Bucksbaum, *Weak Interactions of Leptons and Quarks* (Cambridge University Press, 1983).
2. R.W. Dunford, R.R. Lewis and W.L. Williams, *Phys. Rev.* **A18** (1978) 2421.
3. Ya. B. Zel'dovich, *Zh. Eksp. Teor. Fiz.* **36** (1959) 964.
4. F.C. Michel, *Phys. Rev.* **B138** (1965) 408.
5. F.J. Hasert, *et al., Phys. Lett.* **46B** (1973) 121; *Phys. Lett.* **46B** (1973) 138.
6. A. Benvenutti *et al., Phys. Lett.* **32** (1974) 800.
7. G. Feinberg and M.Y. Chen, *Phys. Rev.* **D10** (1974) 190; Errata **10** (1974) 3145; G. Feinberg and M.Y. Chen, *Phys. Rev.* **D10** (1974) 3789.
8. R.R. Lewis and W.L. Williams, *Phys. Lett.* **59B** (1975) 70.
9. E.A. Hinds and V.W. Hughes, *Phys. Lett.* **B67** (1977) 487.
10. R.W. Dunford, *Phys. Lett.* **99B** (1981) 58.
11. E.A. Hinds, in *The Spectrum of Atomic Hydrogen Advances*, ed. G.W. Series, World Scientific, 1988, p. 245.
12. J. Wm. Edwards, G.L. Greene and E.A. Hinds, *Nucl. Instrum. Methods* **197** (1981) 581.
13. E.N. Fortson and L.L. Lewis, *Phys. Reports* **113** (1984) 290.
14. E.A. Hinds, in *Atomic Physics 11*, eds. J.C. Gay, G. Grynberg and S. Haroche, World Scientific, 1989.