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Parity nonconservation in atoms; past work and trapped atom future

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Parity nonconservation has now been measured in atomic cesium with a fractional uncertainty of 2%. This was done by observing the 6S-7S laser excited transition rate in a "handed" apparatus. When combined with recent precise calculations of the cesium atomic structure, this provides an important test of the Standard Model. Efforts are under way to achieve a more sensitive test by measuring parity nonconservation in a series of radioactive cesium isotopes which have been trapped using laser light.

1. Introduction

The basic process we are studying is the exchange of a Z_0 boson between the electrons and the neutrons or protons in an atom. This gives rise to a parity nonconserving (PNC) neutral current interaction, and the goal of this research is to measure the strength of this interaction and thereby test the Standard Model. Because it is parity violating, this interaction mixes the parity eigenstates of an atom, more specifically, the S states have a very small amount of P state mixed in with them [1]. It is this mixing that is measured in the experiment. The amount of P state δ_{PNC} is equal to the weak charge times an atomic matrix element $\langle \gamma_5 \rangle$, which is found by calculating the electronic structure of the atom. The weak charge is the quantity we are interested in, since it is related directly to the fundamental interactions. This weak charge [2] is

$$Q_w = 2[(2Z + N)C_v^u + (Z + 2N)C_v^d] + \text{ small } C_A^u, C_A^d \text{ terms.} \quad (1)$$

The quantities C_v^u and C_v^d are the fundamental electron quark-neutral-current coupling constants and characterize the quark vector current couplings. There are additional terms involving the axial vector currents for the quarks, as noted, which are much smaller and will be neglected in this discussion. Neglecting radiative corrections, in the Standard Model [2], we have $C_v^u = 1/2 - (4/3)\sin^2\theta_w$ and $C_v^d = -1/2 + (2/3)\sin^2\theta_w$. The primary goal of this work is to see if Q_w, and hence these constants, are as predicted by the Standard Model, or whether there are small corrections to them due to the existence of new physics not included in the Standard Model. The remainder of this paper will discuss how one determines Q_w in atoms.

It should be emphasized that these experiments are measuring very small quantities and therefore are quite difficult. The mixing of S and P states is typically only about one part in 10^{11}. Nevertheless, these experiments have now succeeded in measuring this mixing to a few percent and should reach a few parts in 10^3 in the future.

2. General experimental approaches

This section will discuss the general experimental approaches which are used to measure the quantity δ_{PNC}. It is determined by measuring an electric dipole transition between two S states in an atom (or two P states). Such electric dipole transitions are absolutely forbidden by the parity selection rule, and thus when one measures such an E1 amplitude it directly indicates the amount of P states which are mixed in with the S states. The "brute force" method that first occurs to most people is to measure such an E1 amplitude by looking directly at a "pure" PNC induced rate by simply driving a forbidden S to S transition. The rate in this case is given by the square of the transition amplitude

$$R_{PNC} = |A_{PNC}|^2 \approx (\delta_{PNC})^2 R_{\text{allowed EM}}. \tag{2}$$

The transition rate is proportional to $(\delta_{PNC})^2$ and therefore would be about 10^{-22} times a typical allowed electric dipole transition rate. This is far too small to ever be observed and therefore this experimental approach cannot reach the necessary level of sensitivity.

The method actually used in all successful atomic PNC experiments is to look for an interference between the PNC amplitude and a parity allowed electromagnetic amplitude. In this case, the transition rate is given by

$$R = |A_0 \pm A_{PNC}|^2 = A_0^2 \pm 2A_0 A_{PNC} + A_{PNC}^2. \tag{3}$$

Here, A_0 is an allowed electromagnetic transition amplitude and A_{PNC} is the parity nonconserving amplitude we are interested in measuring. The important point is that the term $2A_0A_{PNC}$ is linear in the parity nonconserving amplitude and therefore can be large enough to measure. The signal of interest is the fractional modulation in the transition rate $\Delta R/R$ when the parity of the experiment (and hence the sign of the interference term) is reversed. In a real experiment, this means carrying out a minor reflection of the experiment and seeing how the transition rate changes.

In the Colorado experiment, we interfere A_{PNC} with an electric field induced E1 amplitude by applying a dc field to the atoms. This field produces a parity conserving mixing of S and P states

$$|S\rangle \to |S\rangle + \delta_E |P\rangle + \delta_{PNC} |P\rangle. \tag{4}$$

Here, δ_E is the electric field or "Stark" mixing term. We observe the interference between the electric field induced mixing and the neutral current induced mixing of P states into the S states. This "Stark interference" method was first used to measure PNC in thallium by the group at Berkeley and in cesium by the group at ENS in Paris. This approach has the advantage that there are a large number of independent reversals which modulate the signal and this makes the systematic errors relatively small and tractable.

We have chosen to study cesium because it is a high Z alkali atom. The weak charge is approximately proportional to the number of neutrons, and the relevant atomic matric element is proportional to the square of the number of protons, so δ_{PNC} increases approximately as Z^3. Being an alkali atom, the atomic structure of cesium is relatively simple, so $\langle \gamma_5 \rangle$ can be accurately calculated.

3. Colorado experiment

We will now discuss the details of the Colorado experiment [3]. We use a tunable dye laser whose green output excites the 6S to 7S transition in cesium as shown in fig. 1. The 7S state then decays to the 6P state and subsequently to the 6S state. We observe the fluorescence on the 6P to 6S transition to monitor the 6S to

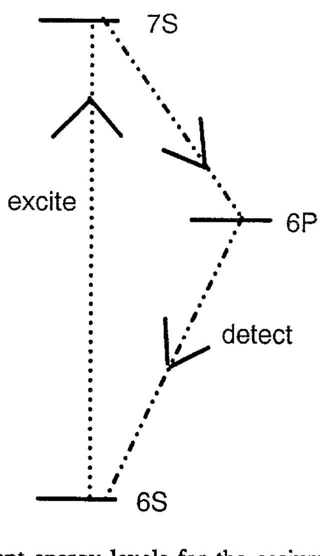

Fig. 1. Relevant energy levels for the cesium atom.

7S rate. The heart of the experimental apparatus is shown in fig. 2. An intense-collimated-cesium beam intersects a standing wave laser field. The laser field is produced by sending light into a Fabry–Perot cavity which is resonant at the frequency of the laser light. This produces a very intense field in the cavity. This

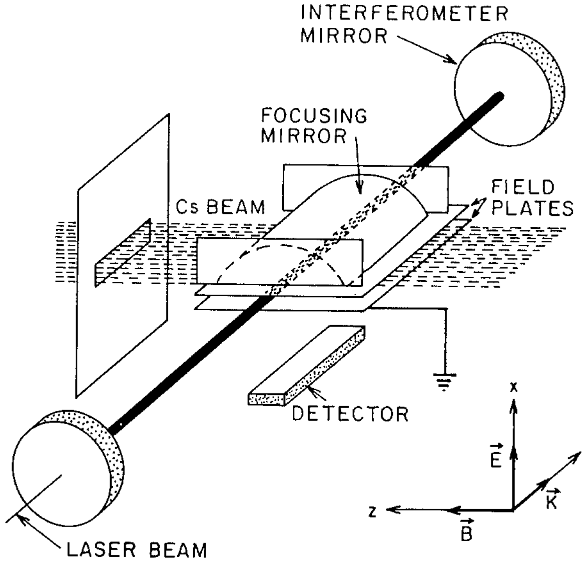

Fig. 2. Interaction region of Colorado PNC experiment.

field excites the laser beam in a region in which there is a "handedness" produced by having a coordinate system defined by the electric field, magnetic field, and photon angular momentum vectors. We measure a fractional change in the 6S to 7S rate $\Delta R/R$ of about 2×10^{-6} when the handedness of this system is reversed. This reversal is done in four independent ways; $\boldsymbol{E}$ goes to $-\boldsymbol{E}$, $\boldsymbol{B}$ to $-\boldsymbol{B}$, σ to $-\sigma$ (this is done by changing the laser light from right to left circular polarization), and m to $-m$. This m reversal is carried out by changing the laser frequency to excite the opposite m or Zeeman quantum level. Having four independent reversals puts in a tremendous amount of redundancy since, in principle, only one reversal is necessary to observe the parity violation. This redundancy greatly suppresses systematic errors.

4. Results

In fig. 3, we show the results of all the experimental measurements of parity nonconservation in atomic cesium which is the most thoroughly measured atom. At the top are the two measurements of the Paris group [4], and at the bottom is our 1985 result and our 1988 result [3].

In order to obtain useful elementary particle physics from the experimental numbers, however, it is necessary to know the atomic structure. This comes about because of the fact

$$Q_{\mathrm{W}} = \frac{\delta_{\mathrm{PNC}}}{\langle \gamma_5 \rangle_{\mathrm{nucleus}}},$$

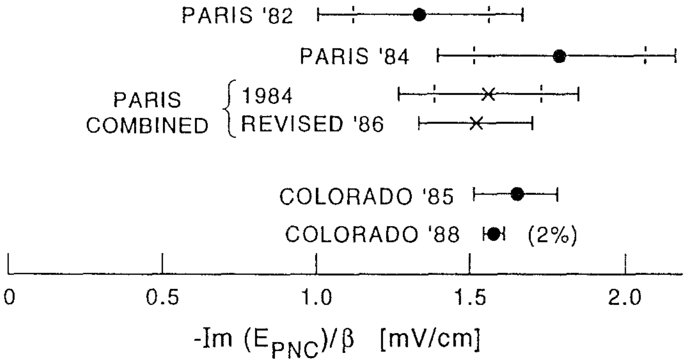

Fig. 3. Results of PNC measurements in cesium. This shows the parity nonconserving electric dipole transition amplitude between the 6S and 7S states in units of the amount of dc electric field which would be needed to give a Stark induced amplitude of the same size.

where δ_{PNC} is the experimentally measured quantity and $\langle\gamma_5\rangle_{nucleus}$ is an atomic matrix element which can only come from atomic theory calculations.

The most recent and most accurate calculation of $\langle\gamma_5\rangle$ has been done by the group at Notre Dame, and they have achieved a 1% uncertainty [5]. Combining the Notre Dame theory and the Colorado experiment gives

$$Q_w = 71.0 \pm 2\% \pm 1\%,$$

where the first uncertainty is experimental and the second theoretical. Alternatively, this can be expressed in terms of the value of $\sin^2\theta_w$. This is

$$\sin^2\theta_w = 0.223 \pm 0.007 \pm 0.003.$$

If we now compare this value with values obtained from high-energy experiments, we have a precise test of the Standard Model. As shown in fig. 4, this test has a unique sensitivity to a variety of new physics. This figure shows that there is very little experimental data on the C_v^d coupling constant other than atomic PNC. Thus, any new physics which primarily affects this coupling constant can only be tested by comparing atomic PNC and high energy results. A variety of models (particularly ones involving neutral bosons) have been put forth which would affect this coupling constant. These results set the best constraints on the possible masses or coupling constants in most of these models.

5. Future

Since the mass of the Z is known to better than one part in 10^3, any improvement in the determination of Q_w will provide a more sensitive test for "new" physics. In

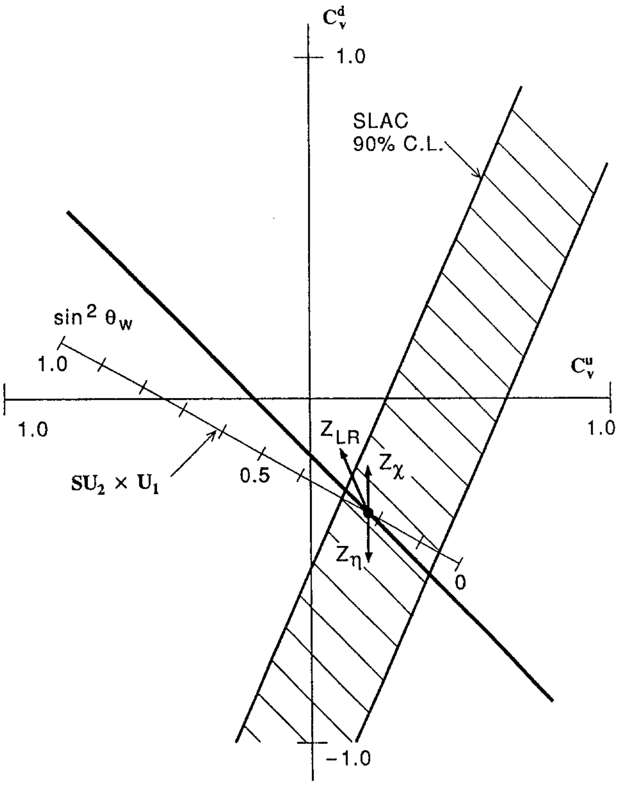

Fig. 4. Plot of quark axial vector–electron vector coupling constants for the up and down quarks with the electron. The cross hatched area is the region allowed by the SLAC deep inelastic electron scattering results. The solid line is the region allowed by the cesium PNC results. The round spot is the Standard Model prediction. while the arrows indicate how the values would change for three different alternative models.

the near term, we will have an improved experiment at Colorado which uses somewhat fancier laser technology and an optically pumped atomic beam. This experiment is now running with a signal-to-noise ratio which is significantly better than was obtained in the 1988 experiment. Since the previous result was limited entirely by statistical uncertainty, we expect to improve our measurement uncertainty to several parts in 10^3 within this year. However, as the experiments get better, the principal limitation will become the uncertainty in the calculated value of $\langle\gamma_5\rangle$. There have been credible speculations that it will be possible to do the theory in cesium to a part in 10^3. However, it is not clear when these calculations will be completed and the question of how to check their accuracy becomes a major issue.

We have begun a longer term experimental project to try to deal with the atomic theory question. The basic idea is to compare precise measurements of atomic PNC for different isotopes of cesium. The weak charge is sensitive to the number of neutrons and hence will change for different isotopes, but the atomic matrix element depends on the electronic structure and hence is almost independent of the number of neutrons. We believe these experiments will be possible because of the new technology of laser trapping which will allow us to collect and hold the isotopes to be measured [6]. If one then looks at appropriate combinations of experimental results, for example

$$\frac{\delta_{\mathrm{PNC}}^{125\mathrm{Cs}} - \delta_{\mathrm{PNC}}^{139\mathrm{Cs}}}{\delta_{\mathrm{PNC}}^{125\mathrm{Cs}} + \delta_{\mathrm{PNC}}^{139\mathrm{Cs}}} = \frac{Q_{\mathrm{w}}^{125} - Q_{\mathrm{w}}^{139}}{Q_{\mathrm{w}}^{125} + Q_{\mathrm{w}}^{139}},$$

the atomic matrix element will drop out, leaving a ratio of weak charges as shown, which can be directly compared with Standard Model prediction. To achieve adequate sensitivity in a PNC experiment, it is necessary to have a relatively high density of atoms with a low velocity spread. Because of the small number of short-lived (as short as 1 minute) isotopes which can be produced, this experiment is only feasible if these atoms can be efficiently collected and held. We have been developing laser trapping technology which we believe will accomplish this. The laser trap we use [7] is based on the force exerted on the atoms by laser photons scattering off them. An inhomogeneous magnetic field acts to regulate the scattering rate, and hence this force, in a spatially dependent manner. The result is that the atoms are pushed to one point in space and held there by the light pressure. Using this approach, we have achieved atomic densities of $10^{10}/\mathrm{cm}^3$ and, with minor modifications, have been able to cool these atoms to as low as 1 μK [6].

The proposed trapped atom PNC experiment will work as follows. First, the cesium isotopes will be produced at a facility which is currently under construction at LAMPF. These isotopes will be inserted into a small cell which is filled with the laser beams which make up the optical trap. The efficient trapping of atoms in such a cell is a complicated problem and is discussed in detail by Michelle Stephens in another paper in this volume.

After the atoms have been collected in the laser trap and cooled to $\leqslant 1$ mK, they will be transferred into a second trap for the PNC measurement. The second trap will probably be either a purely magnetic trap or a far off resonance dipole force optical trap. These traps are rather shallow but they avoid the perturbations on the atoms due to frequent excitation and decay by trapping light. In the PNC measurement trap, the 6S $\rightarrow$ 7S transition will be excited in the presence of electric and magnetic fields, similar to our past experiments.

Using this approach, we expect to measure the fractional change in Q_{w} between ^{125}Cs and ^{139}Cs to about 2 parts in 10^3. This will provide a stringent test of the Standard Model, and may well reveal new physics beyond it.

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