PARITY NONCONSERVATION IN ATOMIC PHYSICS

Carl E. Wieman

Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology, and Physics Department, University of Colorado, Boulder, CO 80309

ABSTRACT

Measurements of parity nonconservation (PNC) in atoms have now reached a precision comparable with the two most precise measurements of electroweak neutral currents. The standard model of electroweak unification predicts a relationship between the three quantities measured in these experiments: the W mass, the inelastic neutrino scattering cross sections, and the weak atomic charge. Precise measurements of these three quantities probe different ways the standard model may fail. Atomic physics measurements are interesting in particular because they are sensitive to the low energy behavior of the theory and they are uniquely sensitive to the electron-quark coupling constants $C_{1u}$ and $C_{1d}$.

Parity nonconservation has now been observed in a number of atoms.\textsuperscript{1) It has been measured with a fractional uncertainty of 10-20\% in bismuth by a number of groups, and to about 20\% in lead and thallium. The atomic physics theory needed to interpret these results is known to about 10\% in thallium and much worse in lead and bismuth. In cesium, PNC has been measured to 2\% at Colorado\textsuperscript{2) and 12\% by the Paris group.\textsuperscript{3)}} Since the atomic theory is also known much more accurately for cesium (1-5\%) than for other atoms, cesium provides the most precise atomic measurement of neutral currents. This paper discusses the basic ideas behind the cesium PNC experiment, the experimental apparatus, and finally some of the implications of the results.

A parity nonconserving neutral current interaction between nucleons and electrons mixes the S and P states of an atom.\textsuperscript{4) The amount of P state which is mixed into the S state is given by
\[ |S\rangle \rightarrow |S\rangle + \delta_{\text{PNC}} |P\rangle \]
\[ \delta_{\text{PNC}} \approx 5 \times 10^{-18} Z^3 \approx 10^{-11} \]

where \( Z \) is the atomic number. The dependence on atomic number makes it desirable to study heavy atoms. Since the size of the mixing is determined by the relative sizes of the weak and electromagnetic interactions, \( \delta_{\text{PNC}} \) is extremely small -- on the order of 1 part in \( 10^{11} \). For comparison, this is about the same as the ratio of the thickness of a hair to the diameter of the earth. We observe this mixing by finding an electric dipole transition amplitude between two \( S \) states in an atom. The parity selection rule strictly forbids electric dipole transitions between two \( S \) states with different principal quantum numbers, so the observation of such an amplitude determines the amount of \( P \) state contamination in the \( S \) state.

One might naively think of observing this amplitude by simply irradiating an atom with the appropriate frequency of light to excite such a transition and then measuring the transition rate. This experiment would be doomed to failure because the transition rate would be proportional to the square of the mixing term \( \delta_{\text{PNC}} \), making the signal impossibly small. Instead, all atomic PNC experiments use a "heterodyne" approach in which one provides some additional, much larger, parity conserving transition amplitude between the two \( S \) states. Now the transition rate is given by

\[ R = |A_0 + A_{\text{PNC}}|^2 = A_0^2 \pm 2 A_0 A_{\text{PNC}} \]

where \( A_{\text{PNC}} \) is the PNC amplitude, and \( A_0 \) is the heterodyne amplitude. In this case the PNC amplitude contributes linearly to the transition rate and thus can be observed. The very small quadratic contribution \( A_{\text{PNC}}^2 \) can be ignored. To use this technique one must choose \( A_0 \) properly so that it will be in phase with \( A_{\text{PNC}} \) and there will be a non-zero interference term. One must also worry about how to separate out the \( 2A_0 A_{\text{PNC}} \) term from the much larger \( A_0^2 \) contribution to the rate. This is done by using the fact that this term does not con-
serve parity, and hence will change sign if the parity, i.e., the "handedness" of the experiment is reversed. How this is done in practice will be discussed below.

The two heterodyne amplitudes which have been used in atomic PNC experiments are an allowed magnetic dipole amplitude (bismuth and lead), and a "Stark induced amplitude" (thallium and cesium). Stark induced amplitude refers to the E1 amplitude produced by the application of a static electric field to the atom. This mixes the S and P states in a parity conserving manner and gives rise to a transition amplitude between S states. One complication in using this amplitude is that, if only an electric field is present, the interference term between Stark induced and PNC amplitudes will show up only in the polarization of the upper state, and not in the transition rate. To overcome this, one adds a magnetic field which splits the m levels of the atom. The transition rate between individual $S,m \rightarrow S',m'$ states, where $m$ is the orientational quantum number, will now have a contribution linear in the PNC amplitude. The addition of the B field can either be thought of as something to resolve the different m levels, or it can be thought of as an additional vector, which along with the electric field, and a vector defined by the laser polarization, provide a coordinate system for the experiment, as shown in Fig. 1. The appeal to the latter viewpoint is that one is looking for a quantity with a "handedness"; that is what it means to be parity violating. Thus it is natural that one would need a handed experiment to see it and a coordinate system provides such a handedness.

![Fig. 1. Orientation of the fields in the experiment.](image-url)
In our experiment we excite cesium atoms in an atomic beam using a laser which intersects the beam at right angles. This gives narrow transition linewidths and therefore requires a relatively small magnetic field to sufficiently resolve the different m levels. This approach also provides considerable technical benefits which are beyond the scope of this article. Figure 2 shows the relevant energy levels of the cesium atom.

We tune the laser to excite particular m levels from the 6S F=3 state to particular m levels of the 7S F=4 state, and also measure the corresponding 6S F=4 to 7S F=3 transitions. As discussed later, it is quite important to measure both these hyperfine transitions. We excite the 6S to 7S transitions using 540 nm (green) light and

![Cesium energy level diagram](image)

Fig. 2. Cesium energy level diagram.
monitor the excitation rate by observing the 850 and 890 nm light which is emitted as the 7S state decays. To perform the experiment, we set the laser to the frequency which excites one of the m levels, and measure the modulation in the transition rate as the various parity reversals are carried out. Most of the reversals can be understood by considering the coordinate system defined by the vectors in Fig. 1. The reversal of any of the three vectors transforms the handedness of this coordinate system and hence constitutes a parity reversal. Reversing the sign of the E and B fields and changing the laser polarization from right-handed to left-handed each gives a reversal of the PNC contribution to the rate. A fourth reversal comes from changing the laser frequency so that we excite the m level with the opposite sign. In principle only one of these reversals is necessary, but the effects being studied are extremely small and systematic errors are a very serious problem. Four reversals provide a large amount of redundancy which enormously suppresses the problem of systematic errors, and makes the experiment possible.

A simplified schematic of the apparatus is shown in Fig. 3. Light from a highly stabilized tunable dye laser is sent into a vacuum system where it resonates in a Fabry-Perot cavity. This produces a standing wave with a circulating power of about 1300 times the incident laser power. An intense collimated beam of cesium intersects this standing wave in a region of perpendicular electric and magnetic fields, and is excited to the 7S state. As mentioned earlier, we observe the excitation by detecting the subsequent fluorescence from the 6P state. Although much of the apparatus looks relatively standard, almost all the components must achieve "state of the art" performance in order to observe the very small PNC effect.

The most recent results from this experiment are

\[
\frac{\text{Im} \, \epsilon_{\text{PNC}}}{\beta} = \begin{array}{c|c|c}
\text{F=4 \rightarrow F'=-3} & -1.639 \ (47) \ (08) \ \text{mV/cm} \\
\text{F=3 \rightarrow F'=-4} & -1.513 \ (49) \ (08) \ \text{mV/cm} \\
\text{average} & -1.576 \ (34) \ (08) \ \text{mV/cm} 
\end{array}
\]
Fig. 3. Schematic of the apparatus.

Where $\frac{\text{Im } S_{\text{PNC}}}{\beta}$ gives the PNC amplitude in terms of the size of the dc electric field one would need to produce the same transition amplitude, and the first uncertainty is statistical while the second is systematic. As mentioned earlier, we measure this amplitude for two different hyperfine transitions. These results were obtained after 160 hours of data acquisition. A far larger amount of time was spent in studying and eliminating potential systematic errors. These errors are associated with various combinations of misaligned and stray electric and magnetic fields (both static and oscillating). As one can see, the systematic uncertainties have now been reduced to well below the statistical uncertainty.

In Fig. 4 we compare these results with earlier measurements of PNC in cesium. This figure shows that the measurements have steadily improved up to the present 2% value. It is also important to notice the consistency of the results. This is in contrast to some earlier measurements of atomic PNC, and provides support to the idea that these Stark induced type experiments, with their numerous reversals, are not plagued by unknown systematic errors.

I will now discuss some of the implications of these results. First consider the difference in the PNC amplitudes on the two different hyperfine lines. The difference is 0.126(68) mV/cm which means that there is a 97% probability it is larger than 0. A nonzero difference signifies the existence of a PNC amplitude that depends on the relative orientation of the nuclear and electron spins. Such an
amplitude could arise from charged weak currents in the nucleus which mix the parity of the nuclear eigenstates. This would cause a nuclear "anapole moment" which would couple to the electrons. The possible existence of such an anapole moment was predicted by Zeldovich\(^6\) in 1957, but it has never been observed. Our present experimental results are consistent with estimates\(^7\) for such a nuclear spin-dependent moment.

To obtain numbers that are useful for testing the standard model we average the results for the two hyperfine lines, which eliminates the nuclear spin dependent part. If only one line had been measured, it would be impossible to separate the contributions due to neutral weak currents from those due to charged weak currents in the nucleus. Although this solves one problem in interpretation, another remains. The measured quantity is actually the product of a weak charge, \(Q_w\), times an atomic matrix element. It is the value of \(Q_w\) that is needed for testing electroweak unification, but it can only be obtained if one also has the matrix element, which must be calculated. A great deal of work on the structure of heavy atoms has been directed toward providing a precise calculated value for this quantity. At present the two most precise calculations give uncertainties of 1 and 5\% (Refs. 8 and 9). Using these values we obtain

\[
\sin^2 \theta_w = 0.227 \pm 0.007 \pm 0.004 \text{ (Novosibirsk theory)}^8
\]

\[
\sin^2 \theta_w = 0.213 \pm 0.007 \pm 0.018 \text{ (Notre Dame theory)}^9
\]
which can be compared with the values obtained from neutrino scattering and the measurement of the W and Z masses:

\[
\sin^2 \theta_W = \begin{cases} 
0.228 \pm 0.007 \pm 0.002 & (W \text{ mass}) \\
0.233 \pm 0.003 \pm 0.005 & (\nu \text{ scattering}) 
\end{cases}
\]

For all three values, the first uncertainty is experimental while the second is theoretical. It can be seen that the three values overlap very nicely and have comparable uncertainties. All other measurements of \(\sin^2 \theta_W\) are substantially less precise.

General reviews discussing how this agreement verifies the standard model and constrains alternatives which go beyond it, are given in Refs. 10 and 11. Here we will simply highlight a few aspects in which the atomic physics results are particularly prominent, and which show how the different measurements complement each other.

Figure 5 shows the model-independent experimental limits on the electron axial vector-quark vector coupling constants for the up and down quarks. The vertical cross hatched band is set by the SLAC deep inelastic electron scattering measurements while the narrow solid line is set by the cesium PNC results. It is clear that one obtains far better constraints from the combination of results than from either individually. Note also that the solid line intersects the standard model line at the accepted value of the weak mixing angle.

This severely constrains any alternatives to the standard model which would predict different values for the coupling constants. It turns out that many alternatives that contain extra Z bosons have exactly this effect. As a result atomic PNC measurements set the largest available lower limits on the masses of extra Z's for a large number of such models. These limits range from above 100 GeV up to nearly 1 TeV depending on the model. Reference 12 and references therein discuss these limits in detail; however, these references used the old PNC measurements so one must scale the results by the improvement of the present atomic PNC measurement. The limits one obtains are higher than those that could be set by any accelerator presently in operation or under construction.
Fig. 5. Experimental limits set on the values of the electron-quark coupling constants, $C_{1d}$ and $C_{1u}$. The broad vertical bar is the region allowed by the deep inelastic electron scattering off H and D, and the solid bar is the region allowed by cesium PNC experiments. The arrows show how the values would be shifted off the $SU_2 \times U_1$ line if there were additional neutral bosons of the various types.

The atomic PNC results also set an upper limit on the mass of the top quark.$^{10,13}$ This happens because the top quark mass enters in the radiative corrections to the value of $\sin^2 \theta_W$ which one obtains from the experiments, and the sizes of the corrections are different for the different ways of obtaining the weak mixing angle. The agreement among different values thus constrains $m_t$ to be less than about 160 GeV. Future improvements in the measurement of the Z mass will improve this limit.

Measurements of parity nonconservation in atoms are now providing important tests of the theory of electroweak unification.
Work is presently under way which will lead to significantly more precise measurements, and further test our understanding of fundamental physics.

I am pleased to acknowledge the contributions of M. C. Noecker and B. P. Masterson who carried out the experimental work discussed here. Masterson and H. Patrick also assisted in the preparation of this manuscript. This work was supported by National Science Foundation grant PHY86-04504.

REFERENCES

8. V. Flambaum, private communication.
9. W. Johnson, S. Blundell, Z. Liu, and J. Sapirstein, Phys. Rev. A 27, 1395 (1988). The value is $0.95(5)$ in units of $\text{mea} \cdot \left(\frac{Q}{78}\right) \times 10^{-11}$.