WHAT ATOMIC PARITY NON-CONSERVATION CAN TELL US

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Abstract

Atomic parity non-conservation (PNC) is a developing field which has made valuable contributions to our understanding of electroweak theory and the Standard Model. However, despite recent experimental and theoretical advances it appears as though atomic PNC is being left behind by large-scale experiments. Also, there is much debate about *precisely* what information can be deduced from atomic PNC and associated experiments at low momentum transfer (low $|q^2|$). We discuss the future for atomic PNC and ways to interpret the results it produces.

1 Introduction

Atomic PNC (for a recent review see [21]) has been an experimentally viable subject for about 17 years now. During this time it has developed from a demonstration that electroweak theory applies in atoms, at low momentum transfer, to a fairly rigorous test of the Standard Model (SM). At first the interest was simply whether or not parity violation occurred in atomic systems but once this had been shown unequivocally work progressed both experimentally and theoretically to provide an accurate measure of the relevant electroweak parameters.

In section 2 we will introduce the basic ideas involved in atomic PNC and how it relates to the SM. We will then discuss in what way it is sensitive to possible new physics, beyond the SM. Section 4 will present an overview of the current status of experiment and theory and we will also look at what progress is expected in the next few years including some comments on new kinds of atomic PNC experiments involving isotopes. In section 5 we will compare the situation of atomic PNC with that from other SM tests.

2 Basics of Atomic PNC

The dominant process in atomic PNC is the exchange of a Z boson between an electron and a nucleon in an atom. This process is implied by electroweak unification where the Z boson can be considered to be acting as a heavy photon. The nature of the exchange is well understood and the effect can be described fairly simply in terms of SM parameters. In order to make a measurement of these parameters it is necessary to have both an accurate measure of the size of the effect and also an accurate calculation of the atomic theory which describes the probability distribution of the valence electrons.

2.1 Atomic PNC in the SM

This rather simplified view immediately tells us several things about the area of the SM in which we are working. Clearly we are interested in

1. neutral current processes,

2. flavour conserving interactions,

3. low momentum transfer, and

4. electron-quark interactions.

The first two items limit us to a small subset of SM physics but this can be regarded as a good thing — it makes our test very direct.

The third point is, perhaps, the key issue and the main argument for atomic PNC tests. We know that, even within the SM, physics at the Z-pole is different from physics measured at low q^2. We can consider tests over a range of q^2 to be tests of our understanding of the radiative corrections to the SM and how to run parameters. However, much more importantly, we expect physics *beyond* the SM to show up differently at low and high momentum transfer. It may be that very high accuracy experiments at the Z-pole are inherently insensitive to certain kinds of new physics.

The last point is also quite important. Again, we are limiting ourselves to a subset of the SM but it is one which is investigated by few experimental probes. In considering the value of atomic PNC we will see that it is not necessarily in competition with high energy experiments so much as other tests of electron-quark physics.

2.2 Dependence of Atomic PNC on SM Parameters

Traditionally the way that atomic PNC has been included in atomic physics is to consider the effect of a small perturbative Hamiltonian

$$H^1_{PNC} = A_{PNC}\gamma_5\rho_n(r) \tag{1}$$

where $\rho_n(r)$ is the nucleon density, γ_5 is the left handed Dirac operator and A_{PNC} includes all the electroweak parameters of relevance. The effect of this Hamiltonian in a particular atom then has to be calculated, and this is one of the major stumbling blocks in interpreting experiments. The accuracy of such calculations will be discussed in section 4. Here we are concerned with A_{PNC}.

Originally (see [2]) A_{PNC} was written in the following way:

$$A_{PNC} = \frac{G_F Q_W}{2\sqrt{2}} \tag{2}$$

where G_F is just the Fermi constant and Q_W is the so-called *weak charge* given (in the absence of radiative corrections) by

$$Q_W = -\rho^*(N - Z(1 - 4\sin^2\theta_W)). \tag{3}$$

Here N and Z are the neutron and proton number respectively and ρ^* is inserted because we will find G_F from charged sector data (muon decay) and we are looking at neutral current processes. If we then replace G_F in equation 2 with $G^*_\mu(q^2 = 0)$ radiative corrections can be included through the starred parameters as in the scheme of Kennedy and Lynn ([11]).

The above process, though, is unnecessarily complicated and it hides much of the physics. Charged sector processes are introduced via G_μ and then removed by ρ. How to include radiative corrections is unclear and the whole thing is related to $\sin^2\theta_W$ which is poorly defined. Also there is actually a general insensitivity to the value of $\sin^2\theta_W$ which is not clear from the form of the equation and the value of A_{PNC} appears to depend on the (unknown) masses of the top quark and Higgs boson through the radiative corrections.

A more revealing approach was suggested by Sandars ([20]) who showed that if we write

$$A_{PNC} = \frac{\pi\alpha P_W}{4M_Z^2} \tag{4}$$

$$P_W = \frac{-(N - Z(1 - 4\sin^2\theta_W))}{\sin^2\theta_W\cos^2\theta_W} \tag{5}$$

then a number of useful properties arise. First of all we can immediately account for radiative corrections by writing explicitly

$$\sin^2\theta_W \rightarrow \sin^2\theta^*_W(q^2 = 0) \tag{6}$$

$$\alpha \rightarrow \alpha^*(q^2 = 0) \tag{7}$$

$$M_Z \rightarrow M^*_Z(q^2 = 0) \tag{8}$$

The value of α is measured at $q^2 = 0$ so this is trivial to include. The form of the equation for P_W is such as to be very insensitive to the exact value of $\sin^2\theta_W$ (mathematically P_W

is simply sitting on a minimum for $\sin^2\theta_W$ near 0.25), making the corrections irrelevant. The equation shows the real physics of the situation, which is that atomic PNC is a direct measurement of the mass of the Z boson at low energy. In principle it could be compared to the high energy mass if we trust the radiative correction calculations (which make a difference of about 8%). These calculations have only a very weak dependence on M_t and M_H, implying that any difference between high and low energy cannot be explained by selecting a particular set of the variables within the SM, but would require physics beyond the SM.

3 Atomic PNC Beyond the SM

We can consider two kinds of physics beyond the SM, so-called *loop level* and *tree level*.

3.1 Loop Level

Loop level new physics is most easily expressed in terms of the parameters S and T introduced by Peskin and Takeuchi ([19]). Atomic PNC in a single isotope is purely a function of the isospin-conserving parameter S and it can be shown that inclusion of this term changes P_W in the following way:

$$P_W^{\mathrm{SM+new}} = P_W^{\mathrm{SM}}\left(1 + \frac{\alpha S}{4\sin^2\theta_W\cos^2\theta_W}\right) \tag{9}$$

If we consider an experiment which looks at the difference in the atomic PNC effects within a series of isotopes then the physics is clearer when expressed in terms of equation 3. The pure *difference* in the PNC effect is a function of T, the isospin-breaking parameter:

$$\Delta Q_W^{\mathrm{SM+new}} = \Delta Q_W^{\mathrm{SM}}(1 + \alpha T) \tag{10}$$

We can see immediately that S and T enter these equations at the 1% level for parameters of order unity.

One quantity of interest is the ratio of these two effects because that could be measured independently of our knowledge of the atomic structure (there are other limitations as we shall discuss in section 4). The ratio is a function of a linear combination of S and T:

$$\left(\frac{\Delta Q_W}{P_W}\right)^{\mathrm{SM+new}} = \left(\frac{\Delta Q_W}{P_W}\right)^{\mathrm{SM}}(1 + 0.011(S - 0.66T)) \tag{11}$$

This combination is exactly the same as the combination of S and T measured in the far more accurate experiments at LEP, a coincidence which comes about because, in taking the ratio, we are really looking at $\sin^2\theta_W$. As this can be run from high to low energy in a way independent of new physics, the only new physics that would show up is that already revealed in the high energy experiments. It appears then that an atomic PNC ratio experiment is of little interest for examing loop level corrections to physics beyond the SM.

3.2 Tree Level

If we consider the effect of new physics at tree level (new particles for example), things look a little more hopeful. There are many reviews of this subject and the exact dependence of the new physics depends on its nature (see for example [12],[9] and [15] and references therein). We shall consider just one example here, the possibility of the existence of a second Z boson.

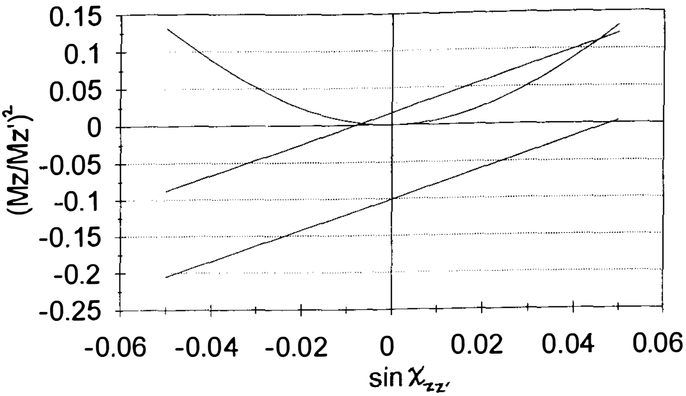

Figure 1: Plot of allowed values of mass of second Z boson (a Z') against mixing angle. Values below the curve and outside the lines are excluded.

Again, we find a multiplicity of effects depending on the exact model but we shall consider a simple case and consider the effect of a Z' which has a different mass to the Z and which mixes in to it with some mixing angle. Then experiments conducted at the Z-pole, for example measuring the Z width, Γ_Z, are sensitive to:

$$\left(1 - \frac{M_Z}{M_{Z'}}\right) \sin^2 \theta_{ZZ'} \tag{12}$$

whereas atomic PNC would measure

$$a \left(\frac{M_Z}{M_{Z'}}\right)^2 + b \sin \theta_{ZZ'} \tag{13}$$

Physically the situation is that the extra Z boson is capable of being exchanged in the atom regardless of its mixing into the standard Z boson, but with a reduced probability which depends on its mass. At the Z-pole the Z' would only show through its mixing into the Z. If its mass is sufficiently high it may never be observed directly and if its mixing angle is zero it would only show up in a low energy experiment. An example, taken from [15], is plotted in figure 1. The area below the curve is excluded by data from LEP and CDF, whereas atomic PNC Cs data excludes the area outside the two lines.

It is clear, however, that if a difference is observed between physics at high and low energy it will require a number of tests in various systems to say whether such a difference arises from an error in running parameters between the two regimes or some new physics. Even if we are assured that there is new physics involved, its nature and size would only be susceptible to analysis from a wide range of experiments including atomic PNC.

Element	Experimental Accuracy	Theoretical Accuracy	References
Caesium	2.4%	1%	[18],[1]
Thallium	1.2%	3%	[22],[4]
Lead	1.2%	8%	[17],[5]
Bismuth	2.0%	12%	[14],[6]

Table 1: Current situation of atomic PNC experiments and theory

4 Current and Future Status

Experiments were started in the late 1970s, spurred by the introduction of the tuneable dye laser and by the realisation in [2] that an otherwise unmeasureable effect would scale as Z^3, where Z is the atomic number. Studies of heavy atoms have been the only successful work to date. The current situation is summarised in table 1 where the accuracy with which we can recover the SM parameters is determined by the quadrature sum of the experimental and theoretical errors.

Within the year we expect some improvement on the caesium experimental result to 0.5% or better ([23]) and there is the hope for improved accuracy on the thallium calculation, perhaps to the 1% level ([16]). These best results are quite recent and the history of the subject tells us it will be many years before they are improved again.

4.1 New Atomic PNC Experiments

There are a number of proposals for new kinds of atomic PNC expts (for example [7],[3]) but they have not yet even been started so it will be a long time before any results can be expected. Even if there are new experiments accurate to better than 1%, it is not clear that atomic theory will ever be good enough to keep up. A way round this was proposed by Fortson *et al* in [8] who suggested comparing the difference in atomic PNC in a range of isotopes to the single isotope effect. Whilst this essentially eliminates the atomic theory it simply makes the measurement susceptible to the poorly known neutron distribution in the nucleus. This can be expressed in terms of the neutron radius and distribution given by the size and shape factors ([10]):

$$\delta_{np} = \frac{\left(\langle r_n^2\rangle - \left\langle r_p^2\right\rangle\right)}{\left\langle r_p^2\right\rangle} \tag{14}$$

$$\eta_{n,p} = \frac{21}{25}\frac{\left\langle r_{n,p}^4\right\rangle}{\left\langle r_{n,p}^2\right\rangle} \tag{15}$$

Currently there is an 85% uncertainty on δ_{np} and 25% on $\eta_{n,p}$. Both errors would have to be reduced to 10% in order to measure the atomic PNC isotope difference to 0.2%.

Given the difficulty of measuring or modelling neutron distribution it seems more likely that such isotopic measurements could be a source of neutron distribution data (or, rather, a means of selecting between different nuclear models) than ***vice versa***.

4.2 Future Accuracy

Considering both the experimental and theoretical difficulties involved, we conclude that it is unlikely that atomic PNC tests will improve beyond a combined accuracy of 0.5% in the next 5 years. In the longer timescale 0.1% seems unfeasibly small even for a best case test because of the difficulty of improving both experimental and theoretical accuracies.

5 How Does Atomic PNC Measure Up?

5.1 Comparison with High Energy

Current LEP data ([13]) produces a value for S with an error of ± 0.30 and T with an error of ± 0.34. The best atomic PNC tests only measure S, with an accuracy of ± 2.2. We might expect this to improve to ± 0.9 with the new results expected this year but even in 5–10 years it will not compete with the high energy measurements for measurements of S and T.

5.2 A Different Approach

As has been remarked, the physics involved in atomic PNC, the physics away from the Z-pole, is quite different from that measured in accelerators. Regardless of the limits on experiments, low energy tests are potentially considerably more sensitive to some tree level new physics than high energy tests. It seems a sensible approach is to combine data from a series of low energy experiments to create a complete test of the SM. These would include atomic PNC, neutrino-nucleon and neutrino-electron scattering, polarized electron deuteron scattering in the neutral sector and muon lifetime in the charged sector. These would measure M_Z, $\sin^2\theta_W$ and G_F all independently of input from high energy results. Currently we take a measurement at low energy and try to compare it to the high energy equivalent. If one parameter can be singled out independently of the rest, this is fine. However, it is usually the case that the comparison requires an input of other parameters of the SM, hiding the origin of any difference which may arise.

It seems less ambiguous that a complete low energy SM should be compared to that derived from high energy data and examined for differences beyond the radiative corrections. Any such difference would be a clear indication of physics beyond the SM and the nature of the difference would be a clue as to the kind of new physics being observed.

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