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Atomic parity non-conservation: Present status and future prospects

B P DAS
Non-Accelerator Particle Physics Group, Indian Institute of Astrophysics, Bangalore 560 034, India

Abstract. The general features of parity nonconservation (PNC) in atoms arising from neutral weak currents and the nuclear anapole moment are discussed. The theoretical approaches used to calculate PNC observables are briefly mentioned. A brief review of the present status of atomic PNC is presented and its potential as a probe of physics beyond the standard model is highlighted.

Keywords. Parity nonconservation; standard model; neutral weak currents; nuclear anapole moment.

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1. Introduction

The discovery of parity non-conservation in the beta decay of ^{60}Co by Wu and co-workers [1] about forty years ago marked an important landmark in the history of physics. This phenomenon which suggests the lack of mirror or left-right symmetry has now been observed in several physical systems. An important case in point is parity non-conservation in atoms [2]. Indeed parity non-conservation has now been observed in several atoms [3]. The latest measurement on caesium has yielded a result of unprecedented accuracy (0.35%) and has led to the discovery of the nuclear anapole moment [4].

It does appear that atomic parity non-conservation can serve as an important probe of physics beyond the standard model (SM) of particle physics if the present accuracy of the atomic theory is improved, or the uncertainties associated with it can be removed by comparing very accurate parity non-conservation measurements on several isotopes of the same element [5]. It has been pointed out that atomic parity non-conservation can provide significant constraints on models that suggest the possible observation of leptoquarks in the events that were recently observed at the HERA collider [6].

This article first presents the general features of parity non-conservation in atoms and then focuses on its present status and future prospects.

2. General features of parity nonconservation in atoms

The dominant contribution to parity non-conservation in atoms comes from the neutral weak current (NWC) interaction between the electrons and nucleons [7]. The effective Hamiltonian describing the interaction consists of two parts; one of which is nuclear spin independent (NSI) [7] and the other is nuclear spin dependent (NSD) [8]:

$$H_{\rm NWC}^{\rm NSI} = \frac{G_{\rm F}}{2\sqrt{2}} Q_W \sum_e \gamma_5^e \rho(r_e),$$

$$H_{\rm NWC}^{\rm NSD} = \frac{G_{\rm F}}{2\sqrt{2}} R_W \sum_e \vec{\alpha}_e \cdot \vec{I} \rho(r_e),$$

where

$$Q_W = 2[Zc_{1p} + Nc_{1n}].$$

Z and N are respectively the number of protons and neutrons, c_{1p} and c_{1n} are the vector (nucleon)–axial vector (electron) coupling coefficients, $\vec{\alpha}$ and γ_5 are the usual Dirac matrices, $\rho(r_e)$ is the normalized nucleon number density, $G_{\rm F}$ is the Fermi coupling constant and $\vec{I}$ is the nuclear spin R_W depends on the axial vector (nucleon)–vector (electron) coupling coefficients.

The parity nonconserving weak interaction between the nucleons can lead to a nuclear anapole moment [8, 9], which in turn can interact with the atomic electrons via the electromagnetic interaction. The effective Hamiltonian describing such an interaction is [8]

$$H_{\rm anapole}^{\rm NSD} = \frac{G_{\rm F}}{2\sqrt{2}} k_a \frac{2\chi}{I(I+1)} \sum_e \vec{\alpha}_e \cdot \vec{I} \rho(r_e),$$

where

$$\chi = (I + \tfrac{1}{2})(-1)^{I+(1/2)-l}.$$

l is the orbital angular momentum of the valence nucleon, k_a is a quantity which depends on various nuclear parameters. It is interesting to note that $H_{\rm anapole}^{\rm NSD}$ has the same form as $H_{\rm NWC}^{\rm NSD}$ and so they both lead to the same observable effects. However, in the case of heavy atoms, the contributions of $H_{\rm anapole}^{\rm NSD}$ is larger than that of $H_{\rm NWC}^{\rm NSD}$ [8].

The parity non-conserving electric dipole transition amplitude between atomic states of the same parity, ψ_i and ψ_f, is given by

$$E_1^{\rm PNC} = \sum_{I \neq i} \frac{\langle \psi_f | D | \psi_I \rangle \langle \psi_I | H_{\rm PNC} | \psi_i \rangle}{E_i - E_I} + \sum_{I \neq f} \frac{\langle \psi_f | H_{\rm PNC} | \psi_I \rangle \langle \psi_I | D1 | \psi_i \rangle}{E_f - E_I}.$$

Note that $H_{\rm PNC}$, which can arise from parity non-conserving NSI or NSD interactions has been treated as a perturbation. The matrix element of this operator scales as Z^3 and Z^2 for the NSI and NSD interactions respectively [2, 10]. It is primarily because of this reason that the heavy atoms are considered to be the best candidates for a parity non-conservation experiment. The quantity that is measured in such an experiment depends on the interference of $E_1^{\rm PNC}$ and an allowed electromagnetic transition amplitude [3]. The experiments that have been fruitful so far are based on fluorescence and optical rotation [4, 11]. In the former case the interference is between $E_1^{\rm PNC}$ and a Stark-induced electric dipole transition amplitude, while in the latter it is between $E_1^{\rm PNC}$ and an allowed magnetic dipole transition amplitude. An accurate calculation of $E_1^{\rm PNC}$ must be based on a suitable relativistic many-body theory. Indeed a variety of *ab initio* and semi-empirical methods have been employed to calculate this quantity [12]. The most widely used method is many-body perturbation theory (MBPT). In this approach, apart from the parity non-conserving interaction, the residual interaction (difference of the two-electron Coulomb interactions and the one-electron Hartree–Fock potential) is also treated as a perturbation. The wave function can be calculated either order-by-order or to all orders for particular types of excitations (singles, doubles, etc.) if one uses the coupled cluster (CC) approach.

For atoms with strongly interacting configurations, it would indeed be appropriate to use a hybrid approach consisting of the configuration interaction (CI) and the MBPT or CC approaches. Examples of such atoms are bismuth and ytterbium.

By combining the results of atomic parity non-conservation experiments and calculations it is possible to extract Q_W and quantities characterizing the NSD interaction. The extraction of Q_W has important implications for physics beyond the standard model. One can express the deviation of this quantity from its standard model values as

$$\Delta Q_W = Q_W - Q_W^{\rm SM},$$

where the standard model value of Q_W is given by

$$Q_W^{\rm SM} = (1 - 4\sin^2\theta_W)Z - N.$$

Z and N are respectively the number of protons and neutrons and $\sin^2\theta_W$ is the Weinberg mixing angle.

After the inclusion of radiative corrections

$$Q_W^{\rm SM} = (0.9793 - 3.8968\sin^2\theta_W)Z - 0.9793N.$$

It is possible to parametrize Q_W and hence ΔQ_W in terms of the isospin conserving and breaking parameters, S and T [13].

$$Q_W = (0.9857 \pm 0.0004)\rho - N + Z[1 - (4.012 \pm 0.010)\bar{x}],$$

where $\rho = 1 + 0.00782T$ and $\bar{x} = 0.02323 + 0.00365S - 0.00261T$.

If $S \sim 1$ as predicted by certain models [14], then Q_W clearly must be determined to at least an accuracy of one per cent. In other words, the combined accuracy of atomic parity non-conservation experiment and theory has to be at least one per cent to test physics beyond the standard model.

An interesting point to note is that the uncertainty arising from atomic calculations can be circumvented by measuring the fractional difference of Q_W, but that could give rise to nuclear structure uncertainties [15].

As mentioned earlier, it is possible to get information about the quantities that characterize the NSD interactions by combining atomic experiments and calculations. In particular, the value of k_a which will give quantitative information about the nuclear anapole moment can be extracted.

3. Present status and future prospects

The present status of NSI atomic parity non-conservation is summarized in the table below:

Atom	Transition	Accuracy of experiment	Accuracy of theory
Caesium	$5p^6 6s_{1/2} \rightarrow 5p^6 7s_{1/2}$	0.35%	~1%
Thallium	$6s^2 6p_{1/2} \rightarrow 6s^2 6p_{3/2}$	~ 1%	~3%
Thallium	$6s^2 6p_{1/2} \rightarrow 6s^2 7p_{1/2}$	~ 15%	~5%
Lead	$6p^2, J = 0 \rightarrow 6p^2, J = 1$	~ 1%	~10–15%
Bismuth	$6p^3, J = 3/2 \rightarrow 6p^3, J = 3/2$	~ 2%	~30%
Bismuth	$6p^3, J = 3/2 \rightarrow 6p^3, J = 5/2$	~ 2%	~30%
Barium+	$5p^6 6s_{1/2} \rightarrow 5p^6 5d_{3/2}$		~10%
Ytterbium	$6s^2 \rightarrow 6s5d, J = 1$		15%
Francium	$6p^6 7s_{1/2} \rightarrow 6p^6 8s_{1/2}$		~1%

It is clear that one can only use the caesium results at this stage to make predictions about physics beyond the standard model. Using the results of the latest experiment and theory for that atom, we find that

$$Q_W = (-72.11 \pm 0.27 \pm 0.89).$$

Assuming the standard model to be correct, i.e. $\Delta Q_W = 0$, we get

$$\sin^2 \theta_W = (0.2261 \pm 0.0012 \pm 0.0041).$$

However, if we assume that there can be physics beyond the standard model, i.e. $\Delta Q_W \neq 0$, then we deduce the following limit

$$S = (-1.3 \pm 0.3 \pm 1.1).$$

For all the three quantities that have been extracted above, the first and second errors correspond to experimental and theoretical errors respectively. The latter must clearly be improved in order to make definitive predictions about physics beyond the standard model. This is a difficult but very worthwhile task. In order to achieve this one must go beyond the linearized coupled-cluster approach used by Blundell *et al* who have considered single, double and only a class triple excitations [16]. This would mean including several non-linear effects; for example two simultaneous pair excitations. If one can exploit the tremendous power of modern computers, then this may not be beyond the realm of possibility.

Two new parity non-conservation experiments – one on singly ionized barium and the other on neutral ytterbium deserve special mention. The former experiment involves the use of laser cooling and trapping [17] while the latter is a fluorescence experiment [18]. Relativistic many-body calculations on these two systems have been carried out by the author and his co-workers [19–21]. We have also carried out preliminary studies on singly ionized radium and find that it is a promising candidate for carrying out a parity non-conservation experiment [22].

The recent discovery of the nuclear anapole moment in caesium [4] has profound implications for nuclear and atomic physics and perhaps even particle physics. The quantity indicating the size of the nuclear anapole moment was obtained from this experiment. Its value is

$$k_a = 0.127 \pm 0.019.$$

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Several of the other parity non-conservation experiments could also provide useful information on the nuclear anapole moment in the foreseeable future. The theory in this area needs to be greatly improved. One can indeed expect exciting developments in the area of atomic parity non-conservation in the coming decade.

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