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Atomic theory in cesium, implications for searches for physics beyond the standard model

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Summary. — The goals of high-precision atomic parity violation (APV) studies are to search for new physics beyond the standard model of the electroweak interaction by accurate determination of the weak charge and to probe parity violation in the nucleus. Interpretation of all past APV experiments and some of the ongoing ones requires theoretical calculations. The current status and future prospects of atomic parity violation studies and the implications for searches for physics beyond the standard model are discussed. Recent accurate calculation of the nuclear spin-dependent parity-violating amplitude is described. New result still leads to the discrepancy between constraints on weak nucleon-nucleon coupling obtained from the cesium anapole moment and those obtained from other nuclear PV measurements.

PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.
PACS `21.30.Fe` – Forces in hadronic systems and effective interactions.
PACS `31.15.ac` – High-precision calculations for few-electron (or few-body) atomic systems.

1. – Overview of atomic parity violation

Recent advancements in the experimental atomic physics, development of the high-precision methodologies to study atomic physics quantities, and remarkable increase in computational power lead to possibilities of further advances in the study of fundamental symmetries with heavy atoms and ions. The parity-nonconserving (PNC) effects in atoms lead to a non-zero amplitude for atomic transitions otherwise forbidden by the parity selection rule, such as the $6s-7s$ transition in cesium. Several different effects contributing to the PNC amplitude in atoms may be separated into two groups: nuclear spin-independent and nuclear spin-dependent effects. The Boulder experiment [1], which yielded the most precise atomic PNC study to date, resulted in the measurement of the quantities $R = \mathrm{Im}(E_{PNC})/\beta$ for the $6s_{F=4}-7s_{F=3}$ and $6s_{F=3}-7s_{F=4}$ transitions in ^{133}Cs. Here, F is the total angular momentum ($I=7/2$ for ^{133}Cs nucleus) and β is

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a vector transition polarizability [2]. The resulting values $R_{4-3} = -1.6349(80)$ mV/cm and $R_{3-4} = -1.5576(77)$ mV/cm allowed to infer data for these two different types of PNC effects. The dominant spin-independent PNC interaction effect in atoms is caused by the exchange of a virtual Z^0 boson between atomic electrons and the nucleus. In Cs experiment, the *average* of R_{4-3} and R_{3-4} gives PNC amplitude that does not depend on the nuclear spin (divided by β). This result is combined with theoretical E_{PNC} amplitude which treats weak charge Q_W as a parameter and either experimental or theoretical value of β to infer the value of the weak charge [3]. In 2009, new developments in atomic methodologies led to significant improvement in the accuracy of the theoretical calculations needed for such an analysis [3]. Cs APV study tested the standard model of the electroweak interactions at very low energies and led to restrictions on its possible extensions.

The *difference* of R_{4-3} and R_{3-4} gives spin-dependent PNC amplitude, divided by β. The main PNC interaction that depends on the nuclear spin arises from the electromagnetic coupling of atomic electrons to the nuclear anapole moment, which is a parity-violating nuclear toroidal magnetic moment described in Ref. [4]. The experimental result is combined with theoretical value of the spin-dependent PNC amplitude to probe weak hadronic integrations. Boulder Cs experiment is the only one at the present time that yielded non-zero value of the anapole moment. The resulting constraints on PNC meson coupling constants [5] were found to be in severe disagreement with the ones obtained from nuclear parity violating experiments [5]. Recently, a high-precision relativistic all-order calculation of the spin-dependent PNC amplitude in Cs [6] was carried out in an attempt to understand this discrepancy, but the new result [6] was found to be consistent with the older atomic physics value of the anapole coupling constant. Therefore, the disagreement between atomic and nuclear physics PNC studies remains unexplained until further APV experiments are completed.

Other PNC experiments carried out to date include Tl (1.7% accuracy [7, 8]), Bi (2 % [9]), Pb (1.2 % [10, 11]), as well as Sm [12] and Dy [13]. The electronic structure of all these systems is significantly more complicated in comparison with Cs, leading to problems with theoretical part of APV studies that allow to infer the weak charge. The most recent calculation of the PNC amplitude in Tl [14] was estimated to be accurate to about 3%. The accuracy of theory is even lower in the other systems where PNC experiments have been completed. More PNC experiments in other atomic systems, such as Yb [15], Fr [16, 17, 18], and Ra^+ [19] are currently in progress. Fr and Ra^+ electronic structure is similar to Cs (one valence electron above the closed shell). New methods are presently under development [6, 20] to improve theoretical accuracy for more complex systems. Further review of other PNC studies and prospects for improvement of theory accuracy is given in [21, 22].

2. – Cs APV study and implications for searches for physics beyond the standard model

The weak electron-nucleus interaction that violates parity but conserve time-reversal is written as the product of vector (V) and axial-vector (A) currents:

$$H = -\frac{G}{\sqrt{2}} \sum_n \left[C_{1N} \bar{e} \gamma_\mu \gamma_5 e \bar{N} \gamma_\mu N + C_{2N} \bar{e} \gamma_\mu e \bar{N} \gamma_\mu \gamma_5 N \right], \tag{1}$$

where G is the Fermi weak constant, e and N are electron and nucleon field operators, respectively, and γ are Dirac matrices. The sum runs over all protons and neutrons in the nucleus. The Z^0 boson exchange between electrons also contributes to the atomic parity violation, but very weakly. Its contribution to PNC amplitude in Cs is only 0.03% [23]. The time-like component of the first term in Eq. (1), which is a product of axial-vector electron current A_e and vector nucleon current V_N, gives nuclear spin-independent PNC Hamiltonian in the electron sector [22, 24]:

$$H_{PNC} = -\frac{G}{\sqrt{2}}\gamma_5 \left[ZC_{1p}\rho_p(r) + NC_{1n}\rho_n(r)\right], \tag{2}$$

where $\rho_p(r)$ and $\rho_n(r)$ are proton and neutron densities, respectively, and Z and N are the number of protons and neutrons. In the calculations, the neutron density is assumed to be the same as the proton density $\rho_n(r) = \rho_p(r) = \rho(r)$, and the above Hamiltonian reduces to

$$H_{PNC} = -\frac{G_F}{2\sqrt{2}}Q_W\gamma_5\rho(r), \tag{3}$$

The issue of the nuclear density functions and the corresponding "neutron skin" correction was discussed in detail in Ref. [25]. The quantity Q_W is the weak charge. To lowest order in the electroweak interaction, it is $Q_W = -N + Z(1 - 4\sin^2\theta_W)$. Since $\sin^2\theta \approx 1/4$, it follows that $Q_W \approx -N$. The Standard Model [26] prediction for the value of the weak charge in ^{133}Cs is $Q_W^{SM} = -73.16(3)$.

There are two approaches to calculating the PNC amplitude, via the direct solution of the perturbed Dirac equation and subsequent evaluation of the forbidden dipole matrix element and using the sum-over-states method. In the direct solution approach, certain classes of the dominant all-order corrections may be are incorporated using correlation-potential method [27, 28].

In the sum-over-states approach [24], one considers the sum

$$E_{PNC} = \sum_n \frac{\langle\Psi_w|D|\Psi_n\rangle\langle\Psi_n|H_{PNC}|\Psi_v\rangle}{E_v - E_n} + \sum_n \frac{\langle\Psi_w|H_{PNC}|\Psi_n\rangle\langle\Psi_n|D|\Psi_v\rangle}{E_w - E_n}, \tag{4}$$

where D is the dipole operator and E_i is the energy of the atomic level i. The sum is over all possible atomic states that satisfy the selection rules for the above operators. In Cs, $v = 6s$, $w = 7s$, and $n = np_{1/2}$ states.

Therefore, the calculation of the PNC amplitude reduces to the calculation of the matrix elements of the one-body operators D and H_{PNC} for a few dominant terms and evaluation of the small remainder contribution. We refer the reader to recent review [21] and references therein for historical overview of previous calculations of the PNC amplitude in Cs. The most recent calculation of the PNC amplitude in Cs that includes Coulomb correlation in the most complete way has been carried out using relativistic coupled-cluster method including single, double, and valence triple excitations terms [3, 29]. The improved accuracy resulted from addition of the non-linear terms, full valence triple excitations, and restoring all fourth-order contributions to the matrix elements. Incorporating other non-Coulomb corrections to this most recent calculation of the PNC amplitude [3], that include Breit (0.6%) [30, 31], QED (0.3%)[32], neutron skin [25] (0.2%), and e-e weak interaction corrections (0.03%) [23] lead to combined value $E_{\rm PNC} =$

$0.8906(26)\ i|e|a_0 Q_W/(-N) \times 10^{-11}$ that is accurate to 0.3% [3]. In these calculations, Q_W is treated as a parameter. Combining the final theoretical value of E_{PNC} with the value of vector transition polarizability $\beta = -26.957(51)a_0^3$ [28] and experimental measurement of Ref. [1] (average of 3-4 and 4-3 transitions) yielded the value of the weak charge [3] $Q_W(^{133}\mathrm{Cs}) = -73.16(29)_{expt}(20)_{theor}$. It is in agreement with the value predicted by the Standard Model [26] given above. Combined with the results of high-energy collider experiments, the Cs PNC study [1, 3], confirmed the energy dependence (or "running") of the electroweak force over an energy range spanning four orders of magnitude (from ∼10 MeV to ∼100 GeV). APV study in Cs provided the most accurate low-energy test of the electroweak sector of the the Standard Model to date [1, 3, 29] by precision determination of ^{133}Cs weak charge. The Cs APV result placed constraints on a variety of new physics scenarios beyond the SM, including the lower limit on the masses of extra Z bosons [3, 29].

3. – Cs APV study: anapole moment and PNC meson coupling constants

Three effects contribute to the nuclear spin-dependent PNC amplitude: the nuclear anapole moment, the Z exchange interaction from space-like component of the nucleon axial-vector current ($A_n V_e$), and the combined action of the hyperfine interaction and spin-independent Z exchange from nucleon vector ($V_n A_e$) current [22]. The nuclear anapole moment characterized by the dimensionless constant κ_a [33] arises due to parity violation inside the nucleus and interacts with atomic electrons via electromagnetic interaction. It is the dominant spin-dependent PNC effect. The nuclear anapole moment and the Z exchange interaction from nucleon axial-vector currents ($A_n V_e$) interactions can be represented by the same Hamiltonian

$$H^{(i)} = \frac{G}{\sqrt{2}}\kappa_i\, \boldsymbol{\alpha} \cdot \boldsymbol{I} \rho(r), \tag{5}$$

where subscript $i = a, 2$ refers to the anapole moment and the axial-vector contributions, respectively; $\boldsymbol{I}$ is the nuclear spin, $\alpha_i = \gamma_0\gamma_i$ and $\rho(r)$ is a normalized nuclear density function. The constant $\kappa_2 = 0.0140$ was calculated in Ref. [33]. The third contribution is small and was calculated in Ref. [34]. The spin-dependent PNC amplitude is calculated in the same way as the spin-independent amplitude, but using the Hamiltonian given by Eq. (5). Study of parity nonconservation in cesium allowed to place constraints on PNC meson coupling constants [5] which were found to be in disagreement with the ones obtained from nuclear parity violating experiments [5, 33]. The analysis of Haxton and Weiman [5] was based on the calculations of the spin-depended PNC amplitude from Refs. [35, 36] that was not expected to be of high precision. In Ref. [6], spin-depended E_{PNC} was calculated using relativistic all-order method to about 1% precision. The value of the anapole coupling constant $\kappa_a = 0.88(12)$ calculated in [6] is only 5% lower than the value used by Haxton and Wieman [5]. Therefore, more accurate evaluation of the spin-depended PNC in Cs did not resolve the discrepancies in the constraints on PNC meson coupling constants. Further experiments capable of accurate measurement of the spin-depended PNC interaction effects are needed for further understanding of the discrepancies between nuclear and atomic PNC studies.

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