Reevaluation of the role of nuclear uncertainties in experiments on atomic parity violation with isotopic chains

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In light of new data on neutron distributions from experiments with antiprotonic atoms [Trzcinska *et al.*, Phys. Rev. Lett. **87**, 082501 (2001)], we reexamine the role of nuclear-structure uncertainties in the interpretation of measurements of parity violation in atoms using chains of isotopes of the same element. With these new nuclear data, we find an improvement in the sensitivity of isotopic chain measurements to "new physics" beyond the standard model. We compare possible constraints on "new physics" with the most accurate to date single-isotope probe of parity violation in the Cs atom. We conclude that presently isotopic chain experiments employing atoms with nuclear charges $Z \lesssim 50$ may result in more accurate tests of the weak interaction.

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I. INTRODUCTION

Atomic parity nonconservation [1,2] (PNC) provides powerful constraints on extensions to the standard model of elementary particles in the low-energy electroweak sector. For example, a deviation in the observed weak charge of an atomic nucleus, Q_W, from the prediction of the standard model may hint at the existence of extra neutral-gauge Z boson. Other possible "new physics" scenarios are discussed, e.g., in Ref. [3].

The most accurate to date measurement of atomic PNC has been carried out by Wieman and co-workers [4,5] using a single isotope of atomic cesium, ^{133}Cs. In such measurements one determines a parity-violating signal E_{PNC}, related to the weak charge as $E_{\mathrm{PNC}}=k_{\mathrm{PNC}}Q_W$. The parameter k_{PNC} is supplied from sophisticated atomic-structure calculations. Even for the relatively well-understood univalent Cs atom, the accuracy of the calculation of k_{PNC} remains the limiting factor in the determination of the weak charge.

There is an ongoing discussion in the literature [5–12] about whether the ^{133}Cs weak charge deviates from the prediction of the standard model. This possible deviation may be interpreted as an indication for an extra neutral-gauge boson Z' [13,14]; there were numerous discussions in the literature about implications of the possible deviation. It is clear that independent tests of parity violation in atoms are required at least at the level of the present 1% accuracy for Cs. It is worth mentioning that PNC measurements were also carried out in Tl [15,16], Pb [17], and Bi (see, e.g., [18]). Among these, the simplest atom is Tl, but even for Tl the theoretical uncertainty for k_{PNC} is a factor of a few larger than that for Cs [19,20].

An alternative approach allowing one to circumvent the difficulties of atomic-structure calculations was proposed by Dzuba *et al.* [21]. The main idea was to form a ratio $\mathcal{R}$ of PNC amplitudes for two isotopes of the same element, thus canceling out the associated uncertainties of the atomic theory. However, Fortson *et al.* [22] pointed out a conceptual limitation of this method—an enhanced sensitivity of possible constraints on "new physics" to uncertainties in the neutron distributions. As an example, the differences between neutron and proton root-mean-square radii for ^{133}Cs differ by a factor of four in relativistic and nonrelativistic nuclear-structure calculations and depend on nuclear models. Unfortunately, at the present level of theoretical understanding of neutron distributions, such large nuclear-structure uncertainties would preclude an extraction of useful information on weak interactions from isotopic ratios measured for heavy atoms.

Given the inadequate accuracy of nuclear-structure calculations for the analysis of PNC measurements based on isotopic ratios, here we investigate the role of uncertainties in neutron distributions using *empirical* data. Recently, Trzcinska *et al.* [23] deduced differences between root-mean-square radii R_n and R_p of neutron and proton distributions from experiments with antiprotonic atoms. A wide range of stable nuclei were investigated and the differences were approximated by a linear dependence suggested in Ref. [24],

$$\Delta R_{np}=\left((-0.04\pm0.03)+(1.01\pm0.15)\frac{N-Z}{N+Z}\right)\mathrm{fm}. \tag{1.1}$$

Here $\Delta R_{np}=R_n-R_p$, Z is the nuclear charge, and N is the number of neutrons. Recently, this result was employed to estimate the nuclear-structure uncertainty for parity-violating amplitude in Cs [10]. In light of the new nuclear data we reexamine the suitability of isotopic chain measurements for studies of parity violation in atoms. We find that the nuclear-structure uncertainty in possible probes of "new physics" with isotopic chains is reduced by the new antiprotonic-atom data. We compare constraints on the direct "new physics" with what is currently the most accurate single-isotope probe of parity violation in ^{133}Cs. We conclude that presently isotopic chain experiments with atoms having $Z \lesssim 50$ may be competitive with this single-isotope determination.

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II. BACKGROUND

In a typical atomic PNC setup, one considers a transition between two atomic states $|i\rangle$ and $|f\rangle$ of the same nominal parity. The weak interaction admixes the states $|n\rangle$ of the opposite parity, leading to the otherwise forbidden parity-violating amplitude

$$E_{\mathrm{PNC}}=\sum_n \left[\frac{\langle f|D_z|n\rangle\langle n|H_W|i\rangle}{E_i-E_n}+\frac{\langle f|H_W|n\rangle\langle n|D_z|i\rangle}{E_f-E_n}\right], \tag{2.1}$$

where D is the electric-dipole operator and H_W is the Hamiltonian of the electron-nucleus weak interaction. As demonstrated by Pollock *et al.* [25], matrix elements of H_W may be represented as

$$\langle j|H_W|i\rangle=\frac{G_F}{2\sqrt{2}}C_{ji}R_p^{2\gamma-2}Q_W(N,Z), \tag{2.2}$$

where factor C_{ji} depends on atomic wave functions and $\gamma=\sqrt{1-(\alpha Z)^2}$.

Including the dependence on nuclear shapes, the nuclear weak charge $Q_W(N,Z)$ may be represented at the tree level as

$$Q_W=-Nq_n+Zq_p(1-4\sin^2\theta_W)+\Delta Q_{\mathrm{new}}. \tag{2.3}$$

Here $\sin^2\theta_W=0.231\,17(16)$ [3] and quantities q_n and q_p, introduced in Ref. [22], depend on neutron and proton distributions inside a nucleus. It should be noted that quantities q_n and q_p are numerically very close to one. For example, in the "sharp edge" model of nuclear density distribution [22]

$$q_n=1-\frac{3}{70}(\alpha Z)^2\left[1+5\left(\frac{R_n}{R_p}\right)^2\right]. \tag{2.4}$$

More sophisticated expressions may be found in Ref. [26], but the accuracy of the above formula is sufficient for the goals of the present work. We omitted radiative corrections in the definition of the weak charge, Eq. (2.3). These contributions are important in the studies of "oblique" corrections, discussed, e.g., in Refs. [25,27]. Here, motivated by possible deviation of the Cs weak charge from the prediction of standard model, we analyze constraints on direct tree-level "new physics." The term ΔQ_{new} in Eq. (2.3) characterizes "new physics." Following [28], we represent it as a combination of couplings to up (u) and down (d) quarks, i.e.,

$$\Delta Q_{\mathrm{new}}=(2Z+N)h_u+(Z+2N)h_d\equiv Zh_p+Nh_n, \tag{2.5}$$

where $h_p=2h_u+h_d$ and $h_n=2h_d+h_u$ are couplings to protons and neutrons. Various elementary-particle scenarios for these interactions were reviewed in Ref. [28]. Finally,

$$Q_W=Nh_0+Zh_p+Nh_n, \tag{2.6}$$

with

$$h_0\equiv -q_n+\frac{Z}{N}q_p(1-4\sin^2\theta_W)\approx -q_n. \tag{2.7}$$

As an outcome of the analysis of PNC experiments one would like to set bounds on "new physics" couplings h_p,h_n or equivalently h_u,h_d; below we summarize the relevant analysis from Refs. [22,25,28]. The PNC amplitudes E_{PNC} and E'_{PNC} are measured for two isotopes of the same element with neutron numbers N and $N'=N+\Delta N$, and the ratio is formed,

$$\mathcal{R}=\frac{E_{PNC}}{E'_{PNC}}=\frac{Q_W}{Q'_W}\left(\frac{R_p}{R'_p}\right)^{2\gamma-2}. \tag{2.8}$$

Here all quantities with primes are for the isotope with N' neutrons. Using Eq. (2.6) one obtains

$$\mathcal{R}=\mathcal{R}_0\left\{1+\frac{Z\,\Delta N}{N\,N'}\frac{h_p}{h_0}+\left(\frac{Z}{N'}h_p+h_n\right)\frac{h'_0-h_0}{h'_0h_0}\right\} \tag{2.9}$$

with $\mathcal{R}_0\equiv(R_p/R'_p)^{2\gamma-2}N\,h_0/(N'h'_0)$. The last term in the above expression may be safely neglected and we determine a contribution of "new physics,"

$$\mathcal{F}=\frac{h_p}{h_0}=\left(\frac{\mathcal{R}}{\mathcal{R}_0}-1\right)\frac{N\,N'}{Z\,\Delta N}. \tag{2.10}$$

In the absence of new couplings $\mathcal{F}=0$. It may seem counterintuitive that the isotopic ratios are sensitive to the new physics encapsulated in couplings to protons (h_p) instead of those to neutrons (h_n). The dependence on h_p may be easily demonstrated with an alternative ratio $(Q_W/N-Q'_W/N')/(Q_W/N+Q'_W/N')$; this ratio is straightforwardly reduced to $Z\Delta N/(2NN')h_p$.

The constraints on h_p, Eq. (2.10), are affected by (i) the experimental error bar in $\mathcal{R}$ and (ii) uncertainties in $\mathcal{R}_0$ which are induced by insufficient knowledge of nuclear distributions. Explicitly,

$$\delta\mathcal{F}=\frac{N\,N'}{Z\,\Delta N}\left\{\frac{\delta\mathcal{R}}{\mathcal{R}_0}+\delta(\Delta q_n)\right\}. \tag{2.11}$$

Here $\Delta q_n\equiv q_n-q'_n$ and we assumed $R_p\approx R'_p$. The radii of proton distributions are known with sufficient accuracy [29] and we disregarded associated uncertainties. Finally,

$$\delta\mathcal{F}=\frac{N\,N'}{Z\,\Delta N}\left\{\frac{\delta\mathcal{R}}{\mathcal{R}_0}+\frac{3}{7}(\alpha Z)^2\frac{\delta\Delta R_n}{R_p}\right\}, \tag{2.12}$$

with $\Delta R_n=R'_n-R_n$. The above expression is similar to the results of Ref. [25].

III. RESULTS AND DISCUSSION

We assume below that in Eq. (2.12) the experimental errors $\delta\mathcal{R}$ may be neglected in comparison to nuclear-structure uncertainty. In contrast to the previous discussions [22,25,28] of atomic parity violation in isotope chains, we employ the empirical Eq. (1.1) to estimate radii of neutron distributions; this relation was deduced from experiments with antiprotonic atoms [23]. To estimate the error bar in the differences $\Delta R_{np}-\Delta R'_{np}$, we formed all possible isotope pairs from the original 21-point data set of Ref. [23] and obtained with the least-square method $\Delta R'_{np} - \Delta R_{np} = [(0 \pm 0.003) + (1.01 \pm 0.04)\{(N'-Z')/(N'+Z') - (N-Z)/(N+Z)\}]$ fm. Instead of a single-parameter fit, we performed a two-parameter fit because there is no strong theoretical reason to believe that the difference $\Delta R'_{np} - \Delta R_{np}$ should vanish for two distinct nuclei with the same relative neutron excess, $(N'-Z')/(N'+Z') = (N-Z)/(N+Z)$. Such obtained (statistical) error bars are very small. However, given insufficient information on systematic errors in Ref. [23], in our subsequent analysis we retained more conservative uncertainties from Eq. (1.1). Based on error bars in Eq. (1.1), we set

$$\delta \Delta R_n \approx \delta(\Delta R'_{np} - \Delta R_{np}) \approx \left[(0.03)^2 + \left\{ 0.15 \left(\frac{N'-Z}{N'+Z} - \frac{N-Z}{N+Z} \right) \right\}^2 \right]^{1/2} \text{ fm.} \tag{3.1}$$

The first (isotope-independent) term in this expression dominates for $Z > 20$; for heavy atoms $\delta \Delta R_n \approx 0.03$ fm. It is worth emphasizing that the Eq. (1.1) for differences between neutron and proton rms radii was obtained in Ref. [23] with data for *stable* isotopes; it is expected that nonstable isotopes may exhibit anomalous ΔR_{np}.

We require the nuclear-structure uncertainty in $\delta\mathcal{F}$ be lower than the current limits deduced from the most accurate to date single-isotope ^{133}Cs determination. The single-isotope measurements are sensitive to a different combination of new h_u and h_d, u-e and d-e couplings. For illustration, we parametrize $h_u = \lambda h_d$. For example, $\lambda = 0$ arises in analyses of extra neutral-gauge Z bosons in E_6 theories and $\lambda = 1$ corresponds to pure isoscalar couplings [28]. We obtain

$$\delta\mathcal{F}(^{133}\text{Cs}) = \frac{\delta h_p}{h_0} \approx \frac{\delta Q_W}{Q_W} \frac{N}{Z + \frac{2+\lambda}{2\lambda+1} N}. \tag{3.2}$$

We set $\delta Q_W / Q_W \approx 0.01$, i.e., the present 1% precision of the determination of the weak charge in ^{133}Cs, and find

$$\delta\mathcal{F}(^{133}\text{Cs}) = \begin{cases} 3.7 \times 10^{-3}, & \lambda = 0, \quad h_u = 0, \\ 5.9 \times 10^{-3}, & \lambda = 1, \quad h_u = h_d, \\ 8.3 \times 10^{-3}, & \lambda = \pm\infty, \quad h_d = 0, \\ \infty, & \lambda = -\frac{Z+2N}{2Z+N}, \quad h_u \approx -1.22 h_d. \end{cases} \tag{3.3}$$

In our illustrative example, the single-isotope bounds set on "new physics" encapsulated in h_p are clearly model dependent. We note that the single-isotope ^{133}Cs measurement is insensitive to a particular scenario $h_u \approx -1.22 h_d$, which may be directly probed by the measurements with chains of isotopes or constrained by other electroweak observables.

TABLE I. Contribution of nuclear-structure uncertainty to a constraint on "new physics" $\delta\mathcal{F}$ for representative isotope pairs.

Atom	Mass numbers A		10^3 $\delta\mathcal{F}$
Ba ($Z=56$)	130	138	6.2
Sm ($Z=62$)	144	154	6.5
Yb ($Z=70$)	168	176	12
Pb ($Z=82$)	204	208	39
^{133}Cs ($Z=55$)[a]	133		3.7
^{133}Cs ($Z=55$)[b]	133		5.9

[a]Single-isotope constraint for extra neutral-gauge Z-boson scenario, Eq. (3.3).
[b]Single-isotope constraint for isoscalar scenario, Eq. (3.3).

Given an experimental precision $\delta\mathcal{R}/\mathcal{R}$ in determination of PNC amplitudes, the uncertainty (2.12) may be minimized by using a pair of isotopes with the maximum possible spread of neutron numbers ΔN. Based on Eqs. (3.1) and (2.12), we calculated $\delta\mathcal{F}$ for such stable isotope pairs for Ba, Sm, Yb, and Pb. We have chosen these atoms mostly because PNC experiments were carried out for them, or at least discussed in the literature [30–35]. From the results compiled in Table I, it is clear that the present nuclear-structure uncertainty still may cloud a competitive extraction of "new physics" from isotopic chain experiments for these atoms. Compared to single-isotope ^{133}Cs determination, measurements with isotopes of Ba and Sm would be two times less sensitive to extra neutral-gauge Z bosons and would have a comparable sensitivity to new isoscalar physics [see Eq. (3.3)]. Possible constraints from heavier Yb and Pb would be affected by the nuclear uncertainty to a larger extent.

Now we proceed with a search for atoms suitable for isotopic ratio experiments given the present nuclear-structure uncertainties. In Fig. 1, we summarize results for atoms with nuclear charges $40 < Z \leq 82$. To minimize the effect of experimental error $\delta\mathcal{R}$ in $\delta\mathcal{F}$, the spread in neutron numbers ΔN should be chosen as large as possible; we only considered atoms with stable isotopes so that $\Delta N \geq 8$ ($\Delta N = 4$ for Pb). We approximate $N \approx 1.5 Z$, $R_p \propto Z^{1/3}$, and the error

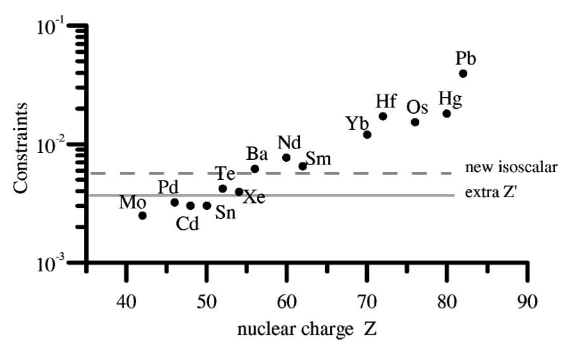

FIG. 1. Contribution of nuclear-structure uncertainty to possible constraints on "new physics" $\delta\mathcal{F}$ for atoms with nuclear charges $40 < Z \leq 82$. Horizontal lines represent limits derived from single-isotope ^{133}Cs PNC analysis in the isoscalar (dashed line) and extra neutral-gauge boson Z' (solid line) scenarios.

$\delta \Delta R_n \approx 0.03$ fm. Thus the nuclear-structure uncertainty in the determination of "new physics" $\delta \mathcal{F}$ grows as $Z^{8/3}$, explaining a general trend in Fig. 1. We compare the uncertainties to constraints set by the Cs determination (horizontal lines). We conclude that the isotopic chain measurements in atoms with nuclear charges $Z \lesssim 50$ may provide comparable limits on couplings for the interesting extra Z scenario. For these elements an interpretation of the measurements in terms of direct new physics may be relatively free of nuclear-structure uncertainties. It is worth emphasizing that extra Z' were discussed recently in connection with a possible deviation of ^{133}Cs weak charge from the prediction of the standard model.

We would like to briefly comment on the required experimental accuracy in determination of ratio $\mathcal{R}$ of the parity-violating amplitudes. Approximating $N \approx 1.5Z$, we find

$$\frac{\delta \mathcal{R}}{\mathcal{R}} \lesssim 0.4 \frac{\Delta N}{Z} \delta \mathcal{F}.$$

We set $\delta \mathcal{F}$ to constraints derived from the determination of ^{133}Cs weak charge, Eq. (3.3). We arrive at

$$\frac{\delta \mathcal{R}}{\mathcal{R}_0} \lesssim 0.4 \frac{\Delta N}{Z} \delta \mathcal{F}(^{133}\mathrm{Cs}) \approx 0.02 \frac{\Delta N}{Z}. \tag{3.4}$$

The required accuracy in the ratio of PNC amplitudes $\mathcal{R}$ is in the order of 0.3% for Ba and Sm, 0.2% for Yb, and 0.1% for Pb. The required experimental error is less demanding for lighter atoms.

So far the most accurate measurement of parity-violating amplitude was carried out in Cs [4]; the achieved accuracy was 0.35%. As first noted by [36], the matrix elements of the weak interaction scale as Z^3; the parity-violating amplitude may be weaker for atoms with nuclear charges $Z \lesssim 50$, which are lighter than Cs ($Z=55$). However, the required experimental error in ratios of PNC amplitudes, Eq. (3.4), is less demanding for lighter atoms. Also, an enhancement of PNC amplitude may arise due to an admixture to the initial/final atomic state of an energetically close intermediate state of an opposite parity by the weak interaction. For example, calculations [37,38] demonstrated that the PNC amplitude for the $6s^2\,{}^1S_0 \rightarrow 5d\,6s\,{}^3D_1$ transition in Yb is approximately 100 times larger than in Cs.

We conclude that at the present level of understanding of neutron distributions, atoms with nuclear charges $Z \lesssim 50$ may be suitable for competitive tests of parity violation with isotopic ratios. If parity-violating enhancement scenarios would be realized for such atoms, the experiments may become feasible. It is worth carrying out a systematic search for enhanced PNC amplitudes for atoms and ions with $Z \lesssim 50$. Such an atomic-structure search is certainly a nontrivial task, requiring in most of the cases an accurate account of correlations. For example, Xiaxing *et al.* [39] argued that the PNC amplitude for the $6s^2\,{}^1S_0 \rightarrow 5d7s\,{}^3D_1$ transition in Ba is an order of magnitude larger than in Cs. Their semiempirical calculation was based on the assumption that an intermediate state $6s7p\,{}^1P_1^o$, which is only 258 cm^{-1} deeper than the $5d7s\,{}^3D_1$ state, provides the main contribution to the PNC amplitude. To verify their conclusion, we have carried out the accurate calculation of this amplitude with combined method of configuration interaction and many-body perturbation theory [40]. Our determination resulted in the PNC amplitude 30 times smaller than the prediction [39]. The main reason for the discrepancy is the strong interaction of the configurations forming $5d7s\,{}^3D_1$ and $6s7p\,{}^1P_1^o$ states, which was not accounted for in Ref. [39]. This configuration interaction leads to significant cancellations of different contributions to the matrix element $\langle 5d7s\,{}^3D_1|H_W|6s7p\,{}^1P_1^o\rangle$ and decreases the contribution to the PNC amplitude by an order of magnitude.

To reiterate, with the new data from experiments with antiprotonic atoms [23] we reevaluated the role of nuclear-structure uncertainties in the interpretation of atomic parity violation with chains of isotopes of the same element. We find that the nuclear-structure uncertainty is reduced by these new data. We compared possible constraints on the direct "new physics" with the most accurate to date single-isotope probe of parity violation in Cs atom. We conclude that presently isotopic chain experiments with atoms having $Z \lesssim 50$ may be competitive with this single-isotope determination. As the neutron distribution measurements become more refined (see, e.g., Ref. [41]), we expect that competitive probes of parity violation with isotopic ratios of the same element may become feasible for heavier atoms.

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