Parity-nonconserving optical rotation on the $6s6p\,^3P_0 \rightarrow 6s6p\,^1P_1$ transition in atomic ytterbium

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A new scheme to measure parity-nonconserving effects in atomic ytterbium is proposed. This method entails measuring parity-nonconserving optical rotation on the 1.28 μm $6s6p\ ^3P_0 \rightarrow 6s6p\ ^1P_1$ transition, for which optical rotation per unit absorption length is predicted to be an order of magnitude larger than that for transitions experimentally studied in thallium, lead, and bismuth. In the proposed experiment using a vapor cell filled with buffer gas, the lifetime of the lower metastable $6s6p\ ^3P_0$ state is limited by collisional deexcitation. Atoms are excited to the lower metastable state by, e.g., short (~ 10 ns) near-resonant light pulses and spurious optical rotation is subtracted on a pulse by pulse basis. The potential sensitivity of this technique may enable precise measurements of electroweak parameters.

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Ever since it was noted that parity nonconserving effects due to neutral weak interactions were considerably enhanced in heavy atoms [1], measurements of atomic parity nonconservation (PNC) have been important tests of the standard model of electroweak interactions [2]. Early measurements [3,4] confirmed the existence of parity-violating neutral weak currents, and more recent precision measurements in thallium [5,6] and especially cesium [7,8] are stringent quantitative tests of the standard model in the regime of low-momentum transfer. Nuclear spin-dependent PNC effects, primarily due to the nuclear anapole moment [9], were first observed in the Boulder Cs PNC experiment [7]. Measurements of nuclear anapole moments are unique probes of the electroweak interaction in the hadron sector. In fact, both the detection of the Cs anapole moment [7] and the null result in Tl [5] provide important information on the weak meson coupling constants. Atomic PNC measurements also constrain many possible extensions of the standard model (see, e.g., Refs. [10–15]). In order to provide improved tests of the standard model, the next generation of atomic PNC experiments (for recent reviews, see, e.g., Refs. [16–18]) aims to increase the precision of nuclear spin-independent atomic PNC measurements and to measure nuclear spin-dependent PNC effects in a variety of atoms.

The ability of atomic PNC measurements to probe fundamental physics is limited both by experimental precision and by the accuracy of theoretical calculations of atomic structure. The uncertainties in atomic theory can be circumvented by comparing PNC effects in a chain of isotopes [19]. However, uncertainties due to incomplete knowledge of nuclear structure, in particular the neutron distribution, are not eliminated in an isotopic comparison and may eventually limit interpretation of atomic PNC measurements with respect to the standard model [20]. The nuclear spin-independent PNC effect is proportional to the weak charge Q_W, given by

$$Q_W(Z,N) = -N + Z(1 - 4\sin^2\theta_W), \tag{1}$$

where Z is the atomic number, N is the number of neutrons, and θ_W is the weak mixing angle. Thus the sensitivity to fundamental parameters of the ratio of PNC measurements for different isotopes is reduced by $\sim \Delta N/N$ compared to the sensitivity of a single isotope measurement, where ΔN is the difference between the numbers of neutrons for the isotopes. It is therefore advantageous to measure PNC effects in isotopes with the largest possible difference in neutron numbers.

Atomic Yb has been identified as a promising system for measurements of atomic PNC effects [21]. Ytterbium has a pair of close-lying (separated by $\approx 589\ \mathrm{cm}^{-1}$) opposite parity states ($6s5d\,^3D_1$, $6s6p\,^1P_1$) which are expected to be strongly mixed by weak neutral current interactions [21–23]. Ytterbium has seven stable isotopes with maximum $\Delta N = 8$, two of which (^{171}Yb, ^{173}Yb) have nonzero nuclear spin, permitting both isotopic comparison of PNC effects and measurement of nuclear anapole moments. It is interesting to note that since ^{171}Yb and ^{173}Yb have valence neutrons, measurements of the Yb anapole moments provide constraints on the weak meson coupling constants that are orthogonal to those obtained from anapole measurements in Cs and Tl.

An atomic beam experiment currently in progress in this laboratory will measure PNC effects in Yb using the Stark-PNC interference technique with the 408-nm $6s^2\,^1S_0 \rightarrow 6s5d\,^3D_1$ transition [21,24,25]. This experiment will detect an asymmetry in transition rates arising from the interference of the PNC-induced and Stark-induced electric dipole transition amplitudes, $A(E1)_{\mathrm{PNC}}$ and $A(E1)_{\mathrm{Stark}}$, respectively. Recently, the possibility of performing such an experiment in a vapor cell has been explored [26]. An Yb PNC experiment in a vapor cell could take advantage of higher atomic densities and offer a potential improvement in statistical sensitivity to PNC effects. In particular, PNC measurements in less abundant isotopes, such as ^{168}Yb (0.14% natural abundance), could be significantly improved by using isotopically pure Yb contained in a vapor cell.

Here we consider an alternative scheme for measuring PNC effects in Yb using a vapor cell, which may offer several advantages. The proposed experiment would measure PNC-induced optical rotation (rotation of the polarization plane of linearly polarized light as it propagates through the atomic vapor) on the 1.28-μm $6s6p\,^3P_0 \rightarrow 6s6p\,^1P_1$ transi-

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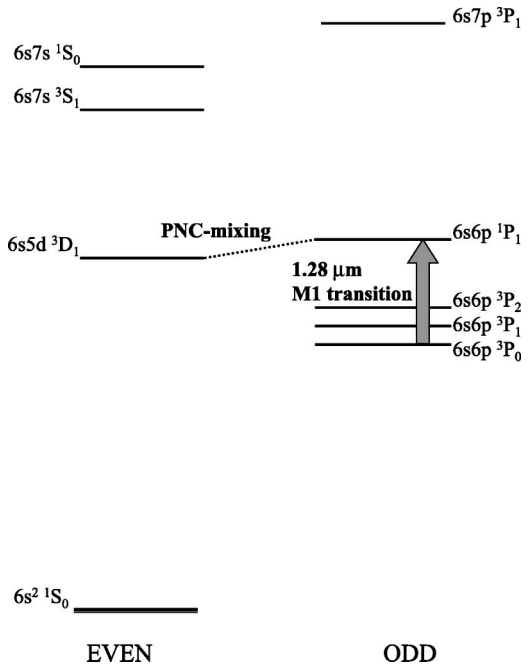

FIG. 1. Partial energy-level diagram (not to scale) of Yb showing the states strongly mixed by the parity-nonconserving neutral weak interaction and the 1.28 μm magnetic dipole transition.

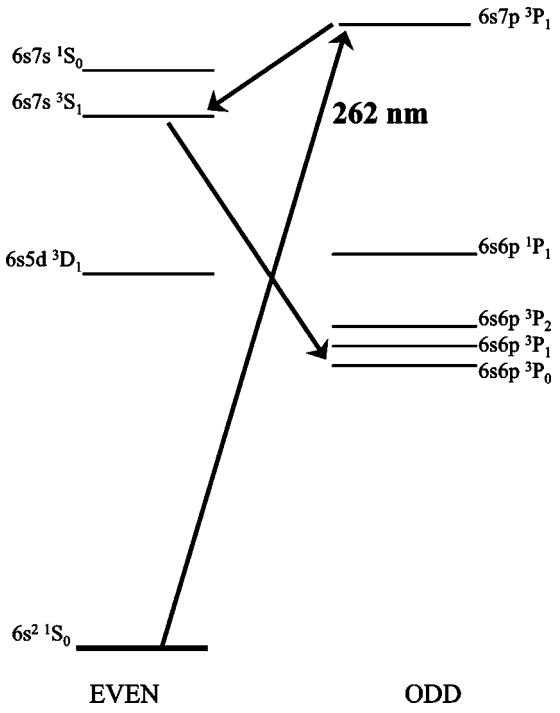

FIG. 2. Partial energy-level diagram (not to scale) of Yb showing the population scheme using nonlinear optical processes to populate the metastable $6s6p\ ^3P_0$ state, discussed in Ref. [30].

tion [27] (Fig. 1). PNC-induced optical rotation arises due to the interference of $A(E1)_{\mathrm{PNC}}$ with the magnetic dipole transition amplitude $A(M1)$, which causes the indices of refraction for left- and right-circularly polarized light to differ (see, e.g., Ref. [29] for a discussion of the basic principles of PNC-induced optical rotation experiments).

This approach circumvents possible limitations due to the ac-Stark effect on the statistical sensitivity of the Stark-PNC interference technique. In the atomic beam experiment using the 408-nm $6s^2\ ^1S_0 \rightarrow 6s5d\ ^3D_1$ transition [21,24,25], a power buildup cavity will be employed to increase the light intensity at 408 nm (similar to the technique developed for the Cs PNC experiment [7]). Atoms interacting with the 408-nm standing wave at different locations will experience different ac-Stark shifts, effectively broadening the transition. This effect could limit the light intensity that can be used in the experiment and thus limit the achievable statistical sensitivity of the Stark-PNC interference method. An optical rotation experiment on the 1.28-μm $6s6p\ ^3P_0 \rightarrow 6s6p\ ^1P_1$ transition would be free from this particular limitation, since it would employ relatively weak light (no power buildup cavity).

In recent, precise measurements of PNC-induced optical rotation using thallium [5,6], lead [28], and bismuth [30], it was necessary to subtract spurious light wavelength-dependent background rotation produced by imperfections in the apparatus by comparing optical rotation in empty cells to rotation in cells filled with the atom of interest. Since the Yb 1.28 μm transition is between excited states, there is a convenient method for subtraction of such spurious background rotation. Namely, the optical rotation can be measured as a function of the density of atoms in the metastable $^3P_0$ state, and rotation that is independent of the $^3P_0$ population can be subtracted. In a pulsed experiment, since atoms excited to the metastable $^3P_0$ state will decay between pulses due to atomic collisions [26] (discussed below), this background subtraction can be performed rapidly (for each pulse) without using empty cells or different cell temperatures. This approach, like the recent proposal to use electromagnetically induced transparency in measurements of PNC-induced optical rotation [31], would eliminate systematic uncertainties associated with the slow drift of background rotation.

This method of measuring PNC effects in Yb requires efficient population of the lower state of the 1.28 μm transition (the metastable $6s6p\ ^3P_0$ state). This can be accomplished using nonlinear optical processes (such as amplified spontaneous emission) generated when light at 262 nm is tuned to resonance with the $6s^2\ ^1S_0 \rightarrow 6s7p\ ^3P_1$ transition [32] (Fig. 2). For 262-nm light pulses of sufficient intensity, experiments have shown that $\sim$20% of the atoms can be transferred to the $^3P_0$ state by nonlinear optical processes [32]. Efficient population of the $^3P_0$ state may also be possible using two-step excitation from the ground state (e.g., $6s^2\ ^1S_0 \rightarrow 6s6p\ ^3P_1 \rightarrow 6s7s\ ^3S_1$ or $6s^2\ ^1S_0 \rightarrow 6s6p\ ^3P_1 \rightarrow 6s5d\ ^3D_1$) and spontaneous decay to the metastable $^3P_0$ state (Fig. 3). Another possibility is to use a pulsed electric discharge to populate the metastable state. It may also be important that the chosen population scheme selectively populates the $^3P_0$ state, and not the $6s6p\ ^1P_1$ state. Since the total angular momentum $J=0$ for the $^3P_0$ state, there can be no atomic polarization-related optical rotation due to the population of this state. However, polarization of the $6s6p\ ^1P_1$ state induced during the population of the metastable state could cause an optical rotation signal that would mimic the time dependence of PNC-induced optical rotation.

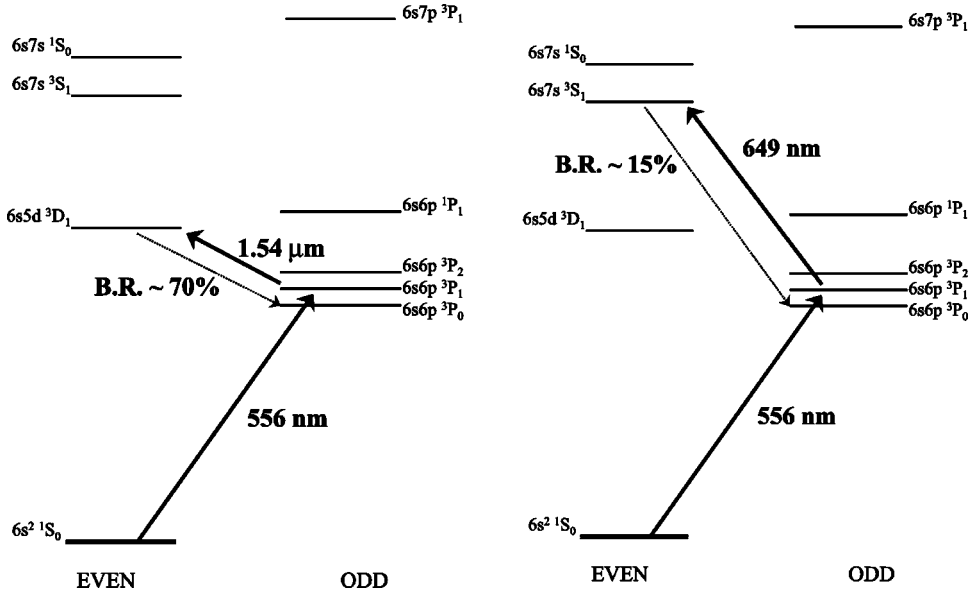

FIG. 3. Partial energy-level diagrams (not to scale) of Yb showing alternative methods of populating the metastable $6s6p\ ^3P_0$ state using two step excitation followed by spontaneous decay.

Although the lifetime of the $6s6p\ ^1P_1$ state is relatively short ($\approx$5.5 ns, see Ref. [33] and references therein), the population of the $6s6p\ ^1P_1$ state will exist for a longer period of time under the conditions of our experiment due to radiation trapping, since it will be necessary to work at relatively high Yb densities (discussed below).

The PNC-induced optical rotation $\phi_{\rm PNC}$ arises due to the difference in the indices of refraction for left- and right-circularly polarized light (n_+ and n_-, respectively):

$$\phi_{\rm PNC}=\frac{\pi l}{\lambda}{\rm Re}(n_+-n_-), \tag{2}$$

where l is the path length of the vapor and λ is the wavelength of the light in vacuum. The difference of the indices of refraction arising due to PNC is described by (see, e.g., Ref. [29])

$${\rm Re}\left(\frac{n_+-n_-}{n-1}\right)\approx 4\frac{{\rm Im}[A(E1)_{\rm PNC}]}{A(M1)}, \tag{3}$$

where $n\approx(n_++n_-)/2$. Thus for $\phi_{\rm PNC}$ we have

$$\phi_{\rm PNC}\approx\frac{4\pi l}{\lambda}{\rm Re}(n-1)\frac{{\rm Im}(A(E1)_{\rm PNC})}{A(M1)}, \tag{4}$$

for which the maximum rotation amplitude is given by

$$\phi_{\rm PNC}^{max}\approx 2\frac{l}{l_0}\frac{{\rm Im}[A(E1)_{\rm PNC}]}{A(M1)}, \tag{5}$$

where l_0 is the absorption length.

The upper state of the 1.28 μm transition, nominally $6s6p\ ^1P_1$, has a relatively large admixture (about 0.16 in amplitude) of $^3P_1$ [34]. The $M1$ amplitude for the 1.28 μm transition, primarily due to this term mixing, is given by

$$\begin{aligned}A(M1)&=\langle 6s6p\ ^1P_1|A(\hat{\mu}1)|6s6p\ ^3P_0\rangle\\&\approx -0.16\mu_B\langle 6s6p\ ^3P_1|L_z+2S_z|6s6p\ ^3P_0\rangle\\&\approx 0.13\mu_B,\end{aligned} \tag{6}$$

where we consider light linearly polarized along the z axis, $\hat{\mu}$ is the magnetic dipole operator, and L_z and S_z are the projections along z of orbital angular momentum and spin, respectively.

The PNC-induced electric dipole amplitude $A(E1)_{\rm PNC}$ is estimated from

$$\begin{aligned}A(E1)_{\rm PNC}&=\langle 6s6p\ ^1P_1|ez|6s6p\ ^3P_0\rangle\\&\approx b\frac{\langle 5d_{3/2}6s_{1/2}|H_w|5d_{3/2}6p_{1/2}\rangle}{\Delta E}\\&\quad\times\langle 6s5d\ ^3D_1|ez|6s6p\ ^3P_0\rangle,\end{aligned} \tag{7}$$

where H_w is the PNC weak-interaction Hamiltonian in the nonrelativistic limit, e is the electron charge, $b\approx 0.26$ is a coefficient given by an estimate in Ref. [21] that describes the configuration mixing amplitude and relevant angular mixing coefficients for the state with nominal configuration and term $6s6p\ ^1P_1$ with the $|5d_{3/2}6p_{1/2}\rangle$ state, and $\Delta E\approx 589\ {\rm cm}^{-1}$ is the energy separation of the $6s5d\ ^3D_1$ and $6s6p\ ^1P_1$ states. The mixing of the $6s5d\ ^3D_1$ and $6s6p\ ^1P_1$ states by the weak interaction was estimated in Ref. [21], so in order to find $A(E1)_{\rm PNC}$, we need only calculate $\langle 6s5d^3D_1|ez|6s6p^3P_0\rangle$. This matrix element can be estimated from the lifetime $\tau=380(30)$ ns [33] of the $6s5d\ ^3D_1$ state and branching ratio $\xi\approx 0.7$ to the $6s6p\ ^3P_0$ state with the formula [35]

$$|\langle 6s5d\ ^3D_1|ez|6s6p\ ^3P_0\rangle|^2=\frac{\xi}{\tau}\frac{3\hbar}{4}\left(\frac{\lambda}{2\pi}\right)^3. \tag{8}$$

From Eqs. (7) and (8), we find that

$$|{\rm Im}[A(E1)_{\rm PNC}]|\approx 7\times 10^{-10}ea_0, \tag{9}$$

where a_0 is the Bohr radius. From these estimates, we obtain from Eq. (5) that the amplitude of the PNC-induced optical rotation is

$$\phi_{\mathrm{PNC}}^{max} \approx (3\times 10^{-6})\frac{l}{l_0} \text{ rad.} \tag{10}$$

Note that this value for the Yb PNC-induced optical rotation per unit absorption length is about an order of magnitude larger than that for thallium, lead, and bismuth. Part of this enhancement is due to the fact that the $A(M1)$ amplitude for the Yb transition is smaller, meaning also that it is more difficult to achieve an absorption length at 1.28 μm.

The optimal statistical sensitivity to optical rotation is achieved for about two absorption lengths at the wavelength of interest. Indeed, as can be seen from Eq. (5), the optical rotation angle increases linearly with the path length through the vapor l while the transmitted light power (due to resonant absorption) falls as e^{-l/l_0}, so the signal (the product of transmitted light intensity and rotation angle) is proportional to le^{-l/l_0}. The shot-noise limit for any polarimeter is proportional to the square root of the number of photons incident on the analyzer [36]. It follows that the signal-to-noise ratio is optimal when

$$\frac{\partial}{\partial l}(le^{-l/2l_0}) = \left(1-\frac{l}{2l_0}\right)e^{-l/2l_0} = 0, \tag{11}$$

or when $l = 2l_0$.

The density of atoms in the metastable $6s6p\,^3P_0$ state n_m required to obtain an absorption length at 1.28 μm can be estimated from a calculation of the resonant absorption cross section σ_{abs} using the relation

$$\frac{l}{l_0} = n_m \sigma_{abs} l\left(\frac{\gamma_0}{\gamma_D}\right), \tag{12}$$

where γ_0/γ_D describes the fraction of atoms resonant with the light, where γ_0 is the natural width of the transition and γ_D is the Doppler width ($\sim 2\pi\times 400$ MHz). The resonant absorption cross section is given by (see, e.g., Ref. [35]):

$$\sigma_{abs} \approx \frac{\lambda^2}{2\pi}\frac{\gamma_p}{\gamma_0}, \tag{13}$$

where γ_p is the partial width of the 1.28 μm transition, estimated from (see, e.g., Ref. [35]):

$$\gamma_p = \frac{4}{3}\frac{(2\pi)^3}{\hbar\lambda^3}\frac{\|\hat{\mu}\|^2}{2J+1}, \tag{14}$$

where $\|A(\hat{\mu})\|$ is the reduced matrix element for the 1.28 μm transition and $J=1$ is the total angular momentum of the upper state. From these considerations, we estimate that $n_m l \sim 10^{19}$ cm^{-2} for an optimal experiment. For a cell length of 100 cm, this would require a metastable state density of $n_m \sim 10^{17}$ cm^{-3}.

Both the statistical sensitivity of this method and the effectiveness of the technique for subtracting spurious background rotation depend on the lifetime of the metastable $^3P_0$ state. At Yb densities of $\gtrsim 10^{17}$ cm^{-3}, the lifetime of the metastable $^3P_0$ state may be limited by Yb-Yb collisions, for which upper limits for the de-excitation cross sections (those for both the ground state and excited states) were found to be $\sim 10^{-14}$ cm^2 in Ref. [26]. In Ref. [26], Yb atoms contained in a tantalum-lined stainless steel vapor cell were excited to the $^3P_0$ state by 262-nm light resonant with the $6s^2\,^1S_0 \rightarrow 6s7p\,^3P_1$ transition followed by cascade decay. The experiment used noble buffer gases (helium and neon) to limit diffusion of excited Yb atoms to the cell walls, and the population of the metastable $^3P_0$ state was monitored by detecting absorption of a weak, cw probe beam at 649 nm (resonant with the $6s6p\,^3P_0 \rightarrow 6s7s\,^3S_1$ transition, see Fig. 3). The upper limits on Yb-Yb quenching cross sections were estimated from the dependence of the quenching rate on vapor cell temperature. The Yb-Yb quenching cross sections may be smaller than the reported upper limits since there may have been a relatively high concentration of impurities (with large quenching cross sections) following nearly the same dependence on vapor cell temperature as the Yb density. Additionally, it is possible that de-excitation of the $^3P_0$ state may have been primarily due to collisions with atoms in the metastable $6s6p\,^3P_2$ state, so the Yb-Yb collisional quenching of the metastable state could be reduced in a different population scheme. In fact, similar states in mercury (which has ground-state electronic configuration $[\mathrm{Xe}]6s^2 4f^{14}5d^{10}$, analogous to Yb's $[\mathrm{Xe}]6s^2 4f^{14}$) have three orders of magnitude smaller cross sections for quenching by collisions with ground-state atoms [37]. In the most optimistic case, the lifetime of the metastable state would be limited primarily by collisions with buffer gas atoms (such as He), which would be used in a PNC experiment to limit the diffusion rate of excited Yb atoms from the probe region. The cross sections for collisional quenching of the $^3P_0$ state by noble gases are very small, $\lesssim 10^{-21}$ cm^2 [26], so metastable Yb atoms may be able to survive many ms at buffer gas pressures of several hundred Torr. It is crucial to accurately determine the Yb-Yb $^3P_0$ quenching cross sections in order to gauge the feasibility of the proposed PNC experiment.

To illustrate the potential of this method for measuring PNC effects in Yb, the statistical sensitivity of the proposed experiment can be estimated, for one particular set of parameters, as follows. Here we employ the population scheme discussed in Ref. [32] (illustrated in Fig. 2) and assume the Yb-Yb quenching cross sections are $\sim 10^{-17}$ cm^2 (like those for the Hg states). For each 262 nm pulse about 20% of the Yb atoms end up in the metastable state (roughly corresponding to the expectations from measurements of nonlinear emissions in Ref. [32]). For a cell length $l \approx 100$ cm, the required Yb density to achieve two absorption lengths for the 1.28 μm transition is $\sim 5\times 10^{17}$ cm^{-3}.

In order to sufficiently populate the metastable state, the energy per pulse at 262 nm must be ~ 400 mJ for a laser beam cross-sectional area of 0.02 cm^2 (achievable with available commercial lasers). We assume a repetition rate of $R \sim 10$ pulses/s. Continuous wave diode lasers at 1.28 μm with powers of 25 mW are also commercially available. The

shot-noise-limited sensitivity to optical rotation $\delta\phi$ can be estimated from these parameters:

$$\delta\phi \approx \frac{1}{\sqrt{N_\gamma \tau_m}} \frac{1}{\sqrt{RT}} \approx (4\times 10^{-7}) \frac{1}{\sqrt{T}} \text{ rad}, \qquad (15)$$

where $N_\gamma \sim 5\times 10^{16}$ is the number of photons at 1.28 μm incident on the polarization analyzer per second, $\tau_m \sim 5\times 10^{-6}$ s is the Yb-Yb collision-limited lifetime of the metastable state, and T is the measurement time in seconds. Using these parameters, for $T\sim 10^6$ s, the expected fractional uncertainty $\delta\phi/\phi_{\rm PNC}$ in a measurement of PNC-induced optical rotation is $\sim 10^{-4}$. A measurement of PNC effects in different isotopes of Yb at this level of sensitivity would complement the Cs [7,8] and Tl [5,6] PNC results as significant probes of electroweak interactions and new tree-level physics [11]. Of course, it is important to note that if the Yb-Yb collisional de-excitation cross sections are significantly larger than $\sim 10^{-17}$ cm^2, this technique would not be as favorable.

If the Yb-Yb $^3P_0$ quenching cross sections turn out to be rather large, then it still may be possible to perform a Yb optical rotation PNC experiment by employing a multipass cavity (see, e.g., Ref. [29] and references therein). In Ref. [38], it was found that the most significant sources of systematic errors for a PNC experiment employing a multipass cavity arose from birefringence of the mirror coatings, windows, and birefringence due to off-normal incidence of the light beam. It appears that all of these effects can be corrected for in our experimental scheme, since they are all independent of the density of atoms in the $^3P_0$ state. Thus the path length l can reach at least 10^4 cm, lowering the required metastable state density for an optimal experiment to $n_m \sim 10^{15}$ cm^{-3}.

In conclusion, we have proposed a new approach to the study of parity-nonconserving effects in atomic Yb, namely, measuring PNC-induced optical rotation on the 1.28 μm (metastable) $6s6p\,^3P_0 \rightarrow 6s6p\,^1P_1$ transition. Estimates given above indicate that optical rotation per unit absorption length in Yb is an order of magnitude larger than for Tl [5,6], Pb [28], or Bi [30]. Spurious frequency-dependent background rotation caused by the apparatus, a significant problem in most optical rotation PNC experiments, can be effectively subtracted in an individual pulse by measuring the optical rotation as a function of the $6s6p\,^3P_0$ state population. Since the experiment will be performed in a vapor cell, this approach is suitable for PNC measurements on purified Yb isotopes with low natural abundance. In order to determine the merits of the proposed experiment more accurately, it is crucial to experimentally determine Yb-Yb collisional de-excitation cross sections, which may limit the Yb density. This approach, due to the effective mechanism for subtraction of apparatus rotation, may also permit use of a multipass cavity to enhance the PNC signal.

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