Atomic Tests of Discrete Symmetries at Berkeley

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Abstract. Recent and ongoing experiments testing various fundamental discrete symmetries are discussed, including search for parity nonconservation in dysprosium and ytterbium, investigation of possibilities of searches for parity and time-reversal invariance violation in samarium, and a test of permutation properties of photons in a two-photon transition in barium.

EUGENE COMMINS AND ATOMIC TESTS OF DISCRETE SYMMETRIES

Professor Eugene Commins is a pioneer in a very tough business – testing fundamental symmetries of Nature with table-top atomic physics. A typical experiment of this kind takes anywhere from 8 to 15 years (and in some cases, even longer), which is a time scale not particularly well matched to that of funding agencies, or the time expected for a graduate student to complete his or her thesis. Unfortunately, not many experiments discover something unexpected, or even set limits for “new physics" at a desired level. Nevertheless, when such a result is eventually achieved, it is often of a scientific value that is hard to overestimate.

Professor Commins has succeeded in bringing several experiments of this kind to fruition, starting from the first measurement of atomic parity violation in a highly forbidden atomic transition [1, 2, 3], and culminating in the most stringent limit on the P,T-violating dipole moment of the electron (discussed in B. C. Regan’s contribution elsewhere in these Proceedings).

In this paper, we review some of the recent and ongoing atomic tests of fundamental symmetries carried out at Berkeley by Eugene’s colleagues, former students and “grand-students." Eugene has participated in much of this work either directly, or as an unlimited source of practical advice and theoretical expertise.

P- AND P,T-VIOLATION IN HEAVY ATOMS WITH CLOSELY SPACED OPPOSITE PARITY LEVELS

P- and P,T-violating interactions mix atomic levels of opposite parity. According to perturbation theory, the mixing is proportional to the matrix element of the symmetry-violating interaction, and inversely proportional to the difference in the energies of the two states (the energy denominator). This suggests an enhancement mechanism – the use of opposite-parity states that are nearly degenerate. Thus, many experimental attempts and proposals of atomic symmetry tests have concentrated on hydrogen (e.g. [4] and references therein) and hydrogenic ions (e.g. [5] and references therein).

Another enhancement, first pointed out by P. G. H. Sandars for P,T-odd interactions back in 1960's, and by M.-A. Bouchiat and C. Bouchiat for P-odd interactions in the 1970's, is present in heavy atoms. In fact, for neutral atoms, both the atomic electric-dipole moment (EDM) due to an EDM of the electron, and the dominant (nuclear-spin-independent) part of the parity-nonconserving (PNC) interaction scale approximately like Z^3, where Z is the atomic number.

Since mid-1980's [6, 7] there has been considerable interest in studying P- and P,T-odd effects in the rare-earth atoms, which seemed to have offered the best of both worlds – large $Z \sim 60-70$, and many cases of small spacing between opposite-parity states. Eugene Commins became interested in experimental work that was carried with samarium at Novosibirsk [8] during his visit to Siberia in the Summer of 1987, where he attended the Vavilov conference [3]. This is how this research eventually got transplanted from Novosibirsk to Berkeley.

PARITY NONCONSERVATION IN DYSPROSIUM

The idea of an enhancement due to closely spaced, opposite-parity levels is most compelling in the case of dysprosium (Dy; $Z = 66$). Here there are two levels whose energy separation is on the order of hyperfine-structure splittings and isotope shifts. These two states of even and odd parity (and designated as A and B, respectively) both have $J = 10$ and lie 19797.96 cm^{-1} above the $J = 8$ ground state (Fig. 1). Spectroscopic properties of Dy, and particularly of these states were studied in Refs. [9, 10, 11], including lifetimes which were found to be 7.9 μs for A and > 200 μs for B.

The smallness of the level separation grants one the opportunity (as well as dictates the necessity) of performing an entirely different kind of PNC measurement as compared to the traditional optical-rotation and PNC-Stark-interference-induced-dichroism PNC experiments. We apply a relatively weak magnetic field (~ 1.4 Gs), which brings energy separation between certain Zeeman sublevels of A and B close to zero, and observe quantum beats due to the presence of an external electric field of a few V/cm. Because the PNC effect is T-even, the electric field has to be time varying (for co-linear electric and magnetic fields) in order for there to be Stark-PNC interference [12]. For an oscillating electric field, the interference term in transition probability contributes at the same frequency as the the electric-field frequency (whereas the dominant signal due to the Stark-induced mixing oscillates at twice the frequency). Another PNC signature is

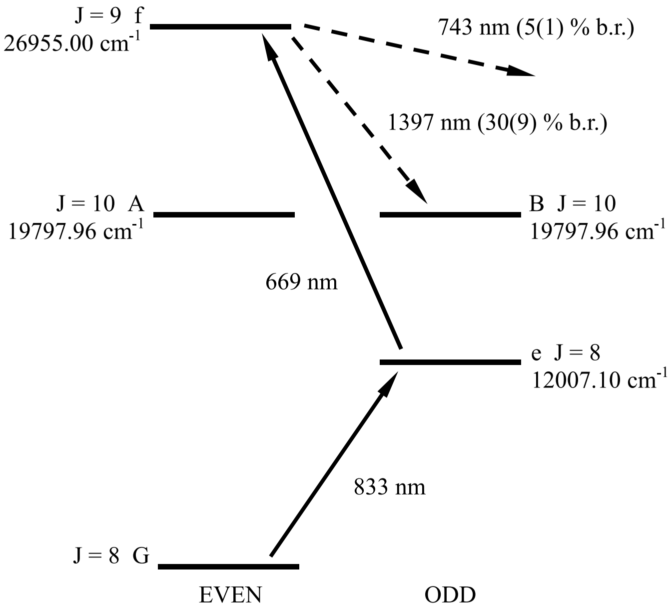

FIGURE 1. Partial level diagram of Dy showing the transitions in the current population scheme. Solid arrows indicate excitation; dashed arrows indicate spontaneous decay.

that it reverses with the sign of the residual energy separation (decrossing) as described by the P-odd, T-even rotational invariant:

$$\frac{d\mathbf{E}}{dt}\cdot(\mathbf{B}-\mathbf{B_c}), \tag{1}$$

where $\mathbf{B_c}$ is the magnetic field required to cross the levels.

Our most recent PNC search [12] was originally motivated by theoretical estimates [13] predicting a substantial enhancement due to the small energy separation of the opposite-parity levels. These estimates had large uncertainties due to extreme complexity of the structure of the atomic states involved. Unfortunately, despite the fact that the experimental sensitivity to the PNC matrix element (H_w) considerably exceeds other PNC experiments performed so far (see, e.g., Ref. [14] for a review), no PNC effect was detected, and an upper limit of $|H_w| < 5$ Hz (68% C.L.) was established. This statistics-limited experiment used pulsed lasers with repetition rate of 10 Hz, which led to a low effective duty cycle ($\sim 10^{-4}$). Using cw lasers, we have developed an efficient population method of the nearly degenerate states [15] which will significantly improve the sensitivity of the PNC measurement (see below).

The basic setup for the current PNC measurement is depicted in Fig. 2. Atoms emerge from an effusive oven source operating at $T \sim 1500$ K and pass through several collimators. Then, they enter the electric- and magnetic-field interaction region where they are excited by laser beams and end up populating the odd-parity state B (the role of the cylindrical lenses will be described below). A sinusoidally varying electric field is applied with two grids consisting of $\sim 5\times10^{-3}$ cm diam. Be-Cu wire. Wire grids were chosen instead of plates in order to minimize stray surface charge. The magnetic field

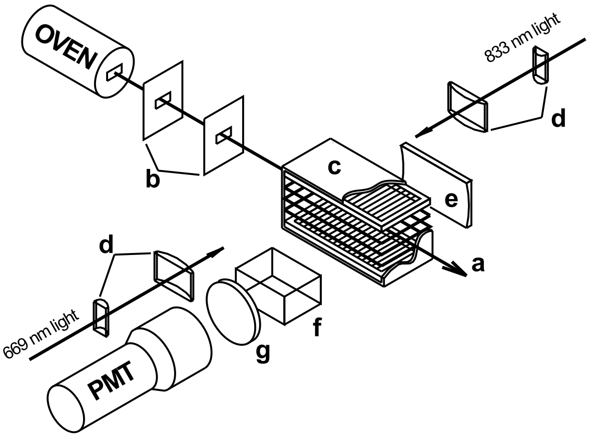

FIGURE 2. Current Dy PNC setup: a) atomic beam produced by effusive oven source at T= 1500 K; b) atomic beam collimators; c) interaction region of atoms with E-field ($\sim$ 4 V/cm) produced between wire grids and B-field ($\sim$ 1.4 Gs) produced by wire turns; mu-metal yoke provides high homogeneity; entire region is enclosed in a magnetic shield (not shown); d) cylindrical lens to diverge laser beams; e) mirror; f) light pipe; and g) interference filter.

is produced by wires forming a rectangular solenoid whose magnetic flux is “shorted" by a CO-NETIC yoke. The mirror currents due to the yoke add to the field produced by the coil, and the entire configuration leads to a rather homogeneous magnetic field in the interaction region similar to that of an infinitely long solenoid. The electric- and magnetic-field homogeneity is $\sim 10^{-3}$ within the volume of ~ 100 cm^3 where atoms interact with the laser beams, experience quantum beats and fluoresce. The interaction region is enclosed by a single layer of magnetic shielding (not shown). Fluorescence is directed by a light pipe onto a photomultiplier tube.

In the current population scheme, three transitions are required to reach the longer-lived, odd-parity state B (Fig. 1). The atoms are first excited by 833-nm and then by 669-nm light. The final step involves spontaneous decay at 1397 nm, with a measured branching ratio of $0.30(9)$ [16]. In order to populate a large fraction of the weakly collimated atomic beam, the laser frequency is effectively broadened by using a cylindrical lens to diverge the laser beam. For sufficiently large light intensities, this leads to an efficient and robust population inversion analogous to adiabatic passage used in magnetic resonance [17]: as the atoms pass through the beam, they experience a sweep in light frequency due to the Doppler effect that is slow compared to Rabi oscillations. In our case, the adiabatic criterion requires that the Rabi frequency be much larger than the transverse Doppler width [15].

With this scheme, we have achieved population transfer over a large fraction of the transverse-atomic-velocity distribution. For the 833-nm transition, a substantial portion of the transverse-velocity distribution underwent adiabatic passage. Although the second transition at 669 nm did not exhibit adiabatic passage, the transfer efficiency into state B is nevertheless large due the short lifetime of state f (Fig. 1) [15]. Further improvements are possible by increasing the power of the lasers used and by utilizing a laser at 1397 nm to stimulate the f $\rightarrow$ B transition. The achieved population efficiency translates into

$\sim\ 10^4$ times higher counting rate compared to the pulsed PNC experiment[12]. With a similar technique and a total integration time of 20 hours, this should allow us to reach a statistical sensitivity to the weak matrix element of $\sim$10 mHz.

The future of dysprosium as a laboratory for PNC studies depends crucially on the results of the current phase of the experiment. If the effect is “around the corner," (i.e. $|H_w| \sim 1$ Hz) Dy can still contribute to the study of both nuclear-spin-independent effects (via isotopic comparisons of the PNC effect), and to the study of the nuclear-spin-dependent PNC (via comparison of the effect on different hyperfine transitions). If the effect is suppressed even more strongly, it appears that Dy would not have sufficient advantages over other systems for PNC studies. However, the unique situation in Dy could also be applied in other studies that benefit from near-degeneracy of long-lived opposite parity Zeeman sublevels, forming a well isolated two-level system with adjustable parameters (level spacing, projection of angular momenta of the crossing sublevels, their effective width, etc.).

PARITY NONCONSERVATION IN YTTERBIUM

Ytterbium (Yb; $Z = 70$) is another example of a unique system in which to study atomic PNC. Yb was first proposed as a system for studying PNC by one of Professor Commins former graduate students, David DeMille [18], while he was at Berkeley.

Like Dy, Yb is a rare-earth atom and has seven stable isotopes, including two isotopes with non-zero nuclear spin. However, because the ground state of Yb has a closed $4f$ shell (in addition to a closed $6s$ shell), the low-lying energy levels more closely resemble those found in alkaline-earth atoms such as Ba and Ca. This makes the calculations significantly more reliable than those done in other rare-earth atoms such as Dy and Sm.

In Yb, the weak interaction mixes the even-parity $5d6s\ ^3D_1$ state with the odd-parity $6s6p\ ^1P_1$ state (see Fig. 3). The mixing between these two states is expected to be large due to relatively small energy separation between the two states ($\approx 600\,cm^{-1}$) and favorable configurations among the states (the $^1P_1$ state is not a pure $6s6p$ configuration and contains $\approx$ 15% $5d6p$; allowing mixing between the $6s$ electron in the $^3D_1$ state and the $6p$ electron in the $^1P_1$ state).

This mixing leads to a small electric-dipole ($E1$) transition amplitude between the $6s^2\ ^1S_0$ ground state and the $5d6s\ ^3D_1$ state. The size of this PNC-induced transition amplitude was estimated in DeMille’s original proposal to be $\approx 10^{-9} e a_0$ ($\approx$ 100 times larger than in Cs) [18]. This estimate has been confirmed by more elaborate calculations of M.G. Kozlov, S. Porsev, and Yu. Rakhlina, [19] and B. P. Das [20].

In addition to the large enhancement of the PNC effect, the transition also has a highly suppressed magnetic-dipole ($M1$) amplitude ($\approx 10^{-4}\mu_B$ [21]), and a moderately sized Stark-induced amplitude ($2.18(33) \times 10^{-8} e a_0/(V/cm)$ [21]) allowing the use of the Stark-interference technique in an atomic beam, which has been successfully employed for cesium [22].

A schematic of the apparatus is shown in figure 4. A dc electric field mixes opposite-parity states and creates a Stark-induced $E1$ transition amplitude between the $^1S_0$ and

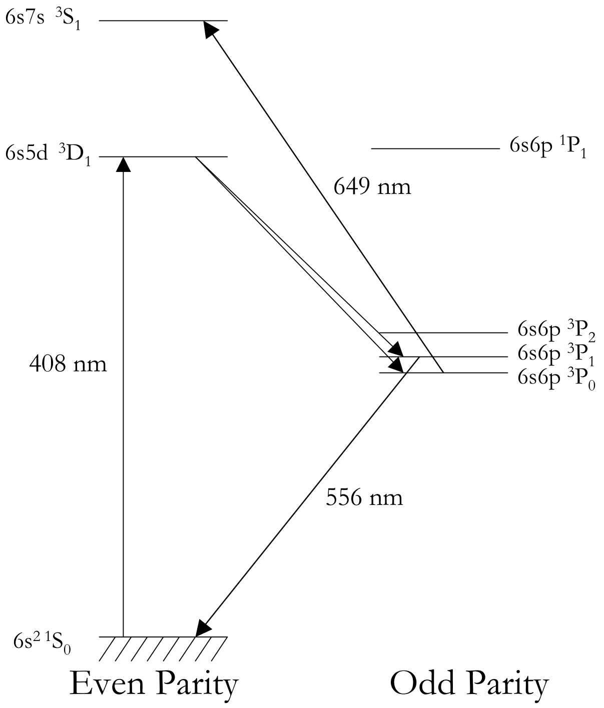

FIGURE 3. Low-lying energy levels for Yb.

$^3D_1$ states (see Fig. 3). This amplitude interferes with the PNC-induced $E1$ transition amplitude. A magnetic field is applied to separate the magnetic sublevels of the upper state to prevent the cancellation of the interference terms for the different sublevels. The atoms are excited using resonant laser light at 408 nm which is coupled into a power-build-up cavity. Changing the handedness of the geometry (reversing the electric field or the polarization angle) changes the sign of the interference term, which is proportional to the P-odd rotational invariant

$$(\varepsilon \cdot \mathbf{B})\ ((\varepsilon \times \mathbf{E}) \cdot \mathbf{B}), \tag{2}$$

where ε is the light polarization vector. This leads to a change in the number of atoms excited to the upper state. The excited atoms decay predominantly to the $^3P_1$ and the metastable $^3P_0$ states ($\approx$ 35% and 64%, respectively) as indicated in figure 3. The atoms which decay to the $^3P_1$ state can be detected through fluorescence from the subsequent decay to the ground state at 556 *nm*, while the atoms decaying to the metastable $^3P_0$ state can be probed downstream by exciting them to a higher-lying state and observing the subsequent fluorescence. Thus, it is possible to achieve high-efficiency detection of the number of atoms undergoing the transition.

The geometry described above was first employed by Professor Commins in his PNC experiments in thallium (Tl) (see [2]; those experiments were done in a vapor cell rather than an atomic beam). This geometry differs slightly from that used in the Cs experiment [22]. Calculations done by Professor Commins in the early stages of the experiment

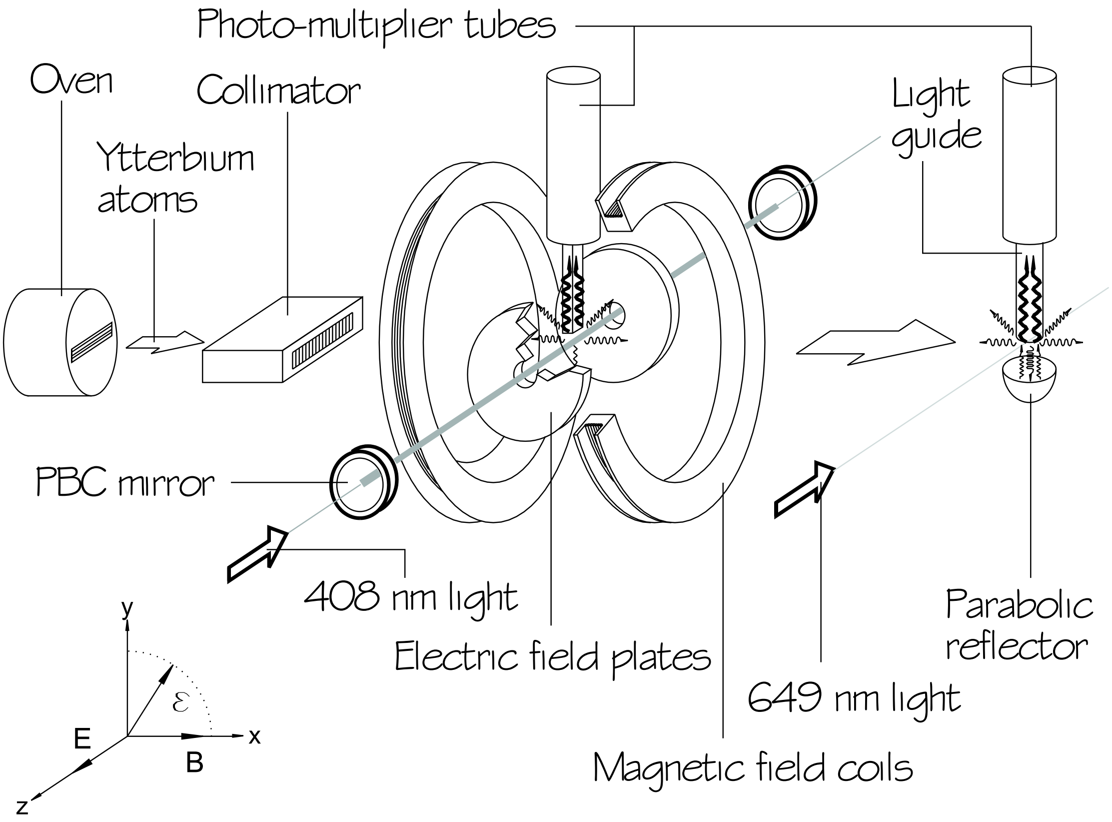

FIGURE 4. Experimental Apparatus for Yb PNC measurement.

suggest that this geometry is less sensitive to systematic effects associated with the nonzero $M1$ transition amplitude between the $6s^2\,{}^1S_0$ and $5d6s\,{}^3D_1$ states.

During the past several years, we have pursued a detailed study of the spectroscopic parameters relevant to performing a PNC experiment in atomic Yb. These preliminary investigations included measurements of the lifetimes of many relevant states, dc-Stark shifts, hyperfine and isotope shifts, and the Stark-induced amplitudes for both the $6s^2\,{}^1S_0 \to 5d6s\,{}^3D_1$ transition and the $6s^2\,{}^1S_0 \to 5d6s\,{}^3D_2$ transition, another candidate for a PNC experiment [23, 21]. Most recently we have completed a measurement of the highly forbidden $M1$ transition amplitude between the $6s^2\,{}^1S_0$ state and the $5d6s\,{}^3D_1$ state using the Stark-interference technique [24]. All of these measurements have confirmed our understanding of the system and lead us to believe a high-precision test of PNC in Yb using the Stark-interference technique in an atomic beam is feasible.

One remaining question for the Stark-interference atomic beam experiment concerns the use of the power-build-up cavity in order to increase the number of atoms making the transition. The ac-Stark shifts resulting from the high-intensity standing wave inside the power-build-up cavity serve to broaden the atomic resonance. At high powers, some of the atoms are shifted out of resonance, decreasing the overall signal. Because the ac-Stark shift depends on the intensity of the light and the signal depends only on its power, it is desirable to have a transverse-cavity-mode spot size which is as large as experimentally feasible. Unfortunately, as the cavity-mode size increases the cavity becomes more sensitive to misalignment and is less stable. Thus there is a practical limit on the size of a single cavity mode. Another approach that we are pursuing is to use a confocal power-build-up cavity. In this case, each transverse mode is degenerate with either the fundamental transverse mode (with a different longitudinal index), or its eigenfrequency falls exactly between two fundamental modes [25]. Thus, instead of coupling into just one transverse mode, it is possible to use a beam with a large spot size and excite many modes at once. The size of the ac-Stark shifts is the final quantity that must be measured before proceeding with the PNC experiment.

In addition to the experiment described above we have investigated the possibility of measuring the PNC effect in a vapor cell, which may allow for higher atomic densities and higher statistical sensitivity [26, 27]. As with the atomic beam experiment the atoms would be excited in the presence of crossed electric and magnetic fields and a change in the transition rate would be detected with a change in the handedness of the fields. The atoms undergoing the transition would be detected by using probe light at $649\,nm$ resonant with a transition from the metastable $6s6p\ ^3P_0$ state to a higher-lying $6s7s\ ^3S_1$ state. A possible limiting factor in this experiment is the collisional de-excitation of the atoms in the metastable $6s6p\ ^3P_0$ state by other Yb atoms as well as buffer gas atoms. We have measured the collisional perturbations of the $6s6p\ ^3P_0$ state, including pressure broadening and de-excitation cross sections, due to quenching with possible buffer gases (He, Ne) and with Yb atoms [26]. These experiments suggest that indeed it may be possible to perform a Yb PNC experiment in a vapor cell with greater statistical sensitivity than is possible with an atomic beam. However, there are many questions yet to be answered concerning the feasibility of such a measurement such as collisional broadening of the transition, ionization of the Yb atoms in the high-intensity light fields required for the experiment, and collisionally assisted transition rates.

Another possibility for a PNC experiment is an optical-rotation experiment in a vapor cell [28]. In this case the transition studied would be the $M1$ transition between the metastable $6s6p\ ^3P_0$ state and the $6s6p\ ^1P_1$ state. This transition amplitude is relatively large ($\approx 0.1\,\mu_B$) due to spin-orbit coupling. The PNC mixing described above again creates a $E1$ transition amplitude between states of nominally the same parity. The interference between the $M1$ transition amplitude and the PNC-induced $E1$ transition amplitude leads to optical rotation of linearly polarized light in the absence of external fields. The magnitude of the optical rotation per unit absorption length is about an order of magnitude larger than in the transitions in Tl, Bi, and Pb, where this effect had been measured (this is partially due to a smaller $M1$ amplitude for Yb). Because the lower state is not the ground state, it is possible to measure spurious optical rotation by monitoring optical rotation as a function of time while the population of the $6s6p\ ^3P_0$ state decays. While quenching of the $6s6p\ ^3P_0$ state in Yb-Yb collisions may be a limiting factor in this experiment, it appears possible that a highly complementary measurement to Stark-interference measurements could be performed this way.

SPECTROSCOPY AND POSSIBLE TESTS OF P,T-VIOLATION IN SAMARIUM

There are several parameters of importance in judging the merits of a system in which an EDM is measured. In addition to the large enhancement factor, it is also necessary to have a long spin-relaxation time (a parameter that enters directly into sensitivity to an EDM). Correspondingly, the majority of studies so far have been performed in atoms or molecules in their ground electronic states (e.g. [29]). The use of excited metastable states (as pioneered by Player and Sandars in 1970 [30]) may offer significant advantages, including the possibility to access the potential enhancement afforded by level degeneracy. The development of this idea for molecules is discussed in a contribution by D. P. DeMille et. al. in these Proceedings.

Another potentially useful system for an EDM experiment with metastable states is atomic samarium (Sm; $Z = 62$). In order to evaluate the feasibility and merit of an EDM search in samarium, an experimental study was undertaken, the results of which were reported in Ref. [31]. A systematic measurement of the lifetimes and tensor polarizabilities of the lowest-lying odd-parity levels was performed. The lifetimes were measured by detecting time-resolved fluorescence following pulsed laser excitation of atoms in an atomic beam; polarizabilities were measured employing the method of Stark-induced quantum beats. An analysis of the data was undertaken to find the best even-parity candidate states for an EDM measurement. For the most favorable candidate state (nominally $4f^6 5d6s\ ^7G_1$ at 15639.80 cm^{-1} which has an opposite-parity "partner" state only ~ 11 cm^{-1} away), the electron EDM enhancement factor was estimated to be $R = \pm 1100 \pm 800 \pm (1300 \text{ to } 1900)$. Here the three factors come from the contributions of various constituent electronic configurations and terms of the nearly degenerate states. Unfortunately, relative signs in the configuration and term decomposition, although they must have been known to the workers whose analysis contributed to the compilation [32], have been apparently lost. This considerable remaining uncertainty in the enhancement factor has put further work on the EDM search in Sm on hold pending further theoretical or experimental input regarding the sign ambiguity. If it turns out that the terms in the enhancement factor are of the same sign, the enhancement factor could exceed that of Tl by as much as an order of magnitude.

The spectroscopic investigations in Sm [31] also led to a somewhat unexpected additional result. Critical analysis of the obtained lifetime and polarizability data along with earlier results in Sm showed quite unambiguously that terms were incorrectly listed in [32] for a class of odd-parity states. The term reassignment cleared some long-standing discrepancies between theory and spectroscopic data in Sm. It also allowed to revise (namely, reduce by a factor of about 40) an estimate of the PNC amplitude in a transition from the ground state of Sm to the $^7G_1$ state originally made by the Oxford group [7] (see also Ref. [33] where experimental possibilities of measuring PNC in this transition were investigated). Our revised estimate showed that while the PNC amplitude in this Sm transition is still much larger than in Cs, it is probably somewhat smaller than that in Yb (see above), and no obvious advantages of Sm were found.

SEARCH FOR PERMUTATION SYMMETRY VIOLATION FOR PHOTONS

The notion that an N-particle wave function describing identical particles should be either symmetric (in the case of integer-spin particles), or antisymmetric (in the case of half-integer-spin particles) with respect to permutation of any two particles constitutes one of the fundamental pillars of our current understanding of Nature. This permutation symmetry postulate (PSP) and the spin-statistics connection (SSC) are of similar importance as, and closely related to the CPT theorem, an important cornerstone of modern physics. In spite of the very general assumptions underlying the proof of the spin-statistics theorem, the argument leading to it is far from being straightforward, and involves some subtle assumptions (see E. Wichmann's contribution in the current Proceedings). An attempt of an intuitive explanation was given by Feynman in his 1986 Dirac memorial lecture [34], which subsequently was vigorously dismissed by a number of authors (see [35] for a review of theory and experiments related to PSP and SSC). It is precisely the fundamental nature of PSP and SSC that makes it worthwhile to evaluate how well it can be checked experimentally. The discoveries of P- and CP-violation give us examples of how it can be fruitful to perform tests of a seemingly solid physical law.

While sensitive searches for violations of PSP and SSC were performed for the electrons and some composite bosons, direct experimental data for important fundamental bosons – the photons – turn out to be surprisingly scarce (see [36] for a detailed review).

Atomic spectroscopy offers a possibility of testing quantum statistics for photons via the use of a powerful (but not widely known) selection rule for two-photon transitions [37, 23]: while two-photon transitions between an F=0 and F'=1 state (where F, F' are total angular momenta) are generally allowed for *non-degenerate* photons, the transition is strictly forbidden for *degenerate* photons. This rule is closely related to the well-known Landau-Yang theorem in particle physics [38, 39] which states that a vector particle cannot decay into two photons. Bose-Einstein statistics is at the core of the proof of this theorem.

The idea of the experiment is to apply a strong laser field to atoms in the ground F=0 state, and look for forbidden excitation events to a two-photon resonant, high-lying F'=1 state. The sensitivity of the experiment can be calibrated by using two laser fields of appropriate polarizations whose photon energies add up to the two-photon transition energy, but which are non-degenerate.

The first experiment based on this approach was described in Ref. [40], and reported a limit on the relative fraction (ν) of anti-symmetric photon pairs present in the laser field of $\nu \leq 10^{-7}$. This experiment used barium atoms in a vapor cell and pulsed lasers and was limited by their final bandwidth.

Currently, we are pursuing a new version of the experiment that is using barium atomic beam and a narrow-band cw laser [41]. This is expected to reach the level of sensitivity of $\nu \lesssim 10^{-11}$ with eventual further improvements by several orders of magnitude.

Simultaneously, we are also performing auxiliary spectroscopic measurements with Ba using the pulsed lasers and the atomic beam apparatus of Ref. [31]. These measurements are aimed at choosing the optimal F=0→F′=1 transition and detection scheme [41], and a better understanding of the configuration and term composition of the levels involved. They include determination of lifetimes and branching ratios of even-parity excited states, and measurements of their tensor electric polarizabilities. In addition, we will look for auto-ionizing resonances at energies corresponding to three-photon absorption from the ground state, the presence of which could, in principle, degrade the sensitivity of the forbidden two-photon transition Bose-Einstein statistics test [40, 36].

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