New Search for T-Violating Forces in Atomic Thallium

A proposal submitted to the
National Institute of Standards and Technology
Precision Measurement Grants Program

for the period 1 October 1999 - 30 September 2000

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May 1999

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Abstract

An experiment is proposed which will provide a stringent new test of time reversal-violating (but parity-conserving) interactions in atoms. New calculations of such long-range "T-odd, P-even" forces in thallium indicates that our experiment should improve by four to five orders of magnitude current experimental atomic limits. We will use a thallium atomic beam and high-finesse laser ring cavity to search for a T-violating interaction of the form $\hat{k} \cdot \vec{E}$ (where the vectors represent laser propagation and a static electric field direction respectively). By detecting the differential cavity phase shift for counter propagating laser beams, sensitivity to sources of mechanical noise is substantially reduced. The cavity finesse both amplifies the size of the experimental observable and enhances sensitivity to the T-odd phase shift. An independent set of experiments, underway using the newly constructed atomic beam apparatus, focuses on high-precision electromagnetic measurements in thallium. These measurements provide crucial tests of ongoing thallium parity nonconservatic (PNC) calculations. They also serve as an ideal experimental foundation from which to develop and carry out the proposed T-violation experiment.

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1. Project Overview

We seek support to complete a new atomic physics experiment which would provide an exacting test of time-reversal symmetry. In particular, the proposed measurement would improve limits on possible long-range time reversal-violating (but parity conserving) electron-nucleon forces by four to five orders of magnitude. All of the experimental work described here will make use of a recently-completed high-flux thallium atomic beam system, as well as a laser system already in use in this laboratory. These experimental systems are presently being used to complete a series of precise atomic structure measurements in atomic thallium. These measurements[1] provide crucial cross-checks of thallium wavefunctions calculations now underway. Improved calculations will complement an existing 1% measurement of parity nonconserving (PNC) optical rotation in thallium[2] and will enhance the role of this element in testing the electroweak standard model. Several of these atomic structure experiments have either been completed[1] or are in progress[3]. As they each require the use of a key experimental tool which will also be required for the "T-violation" experiment, their intrinsic importance is complemented by their value as developmental tools for the measurement which is the central focus of this proposal.

A decade ago, a scheme was proposed[4] to search for a "T-odd, but P-even" (TOPE) interaction in atomic thallium, and initial theoretical estimates for interpretation of the atomic observable were carried out. With several key experimental modifications to the original proposal, we describe here an experiment realization which has the potential for very high precision, while retaining a simplicity that will be of great benefit in achieving a scientifically significant result within the three-year time frame of the NIST grant. At its essence the proposed experiment will search for a TOPE interaction in the thallium atom that would be manifested by a laser ring-cavity phase shift induced by atoms passing through the cavity. The laser here would be tuned and locked near the 1283 nm $6P_{1/2} \rightarrow 6P_{3/2}$ M1 transition in thallium. As will be shown, in the presence of a large static electric field, an atomic thallium beam would reveal the existence of such an interaction by producing a component of the total cavity phase shift which would change sign under either electric field or laser propagation reversal. Detection of the *differential* ring-cavity phase shifts for counter-propagating laser beams, then, would retain sensitivity to such a TOPE effect while substantially reducing sensitivity to common-mode fluctuations due to laser frequency or mechanical noise.

Recently, we have completed a precise laser spectroscopy/polarimetery measurement of the electric quadrupole component amplitude within this same 1283 nm transition[1]. Having now completed construction and testing of our atomic beam apparatus, the 1283 nm laser and the high-voltage/electric-field plate system will be used to measure the Stark shift and Stark-induced amplitude within this transition. To enhance the very small atomic beam absorption expected for this M1 transition, we will incorporate the ring cavity design into this preliminary experiment prior to its implementation in the TOPE experiment.

Currently, our group at Williams College consists of this PI, one or two senior undergraduate thesis students per year, and a postdoctoral research associate. Funding from N.S.F. for both personnel and equipment ("RUI" and "MRI" programs, each with College matching funds) supports the ongoing atomic structure measurements. Over recent years, we have built up substantial infrastructure in terms of hardware, group personnel, and expertise, and we are now poised to undertake this new project. The NIST grant would not only provide the specific optical, vacuum, and electronic hardware required to undertake the new TOPE experiment, but would also support the hire of an *additional* full-time research assistant to help carry it out. The research program in this laboratory, whose scope would be further broadened with aid of this grant, plays the important role of providing excellent research training opportunities for numerous talented Williams College undergraduates, 90% of whom in recent years have pursued graduate study in science or engineering.

In a very important recent development, a collaborative association has been initiated between our experimental group and the theory group at PNPI, St. Petersburg, Russia which includes the original authors of the thallium TOPE proposal[4]. Theory calculations are obviously necessary to provide a direct connection between the magnitude of experimental observables and the corresponding TOPE coupling constants. Indeed, preliminary new calculations have recently been undertaken (see below). We anticipate an ongoing dialogue with the theory group as additional TOPE models are explored and the full-scale calculation of our experimental observable becomes necessary. Travel funds have been sought through the NATO Linkage Grant program to allow collaborative institutional visits by members of our groups.

In the following section we discuss the status of the search for T-odd, P-even forces, placing the proposed experiment in context. In Section 3 of the proposal, we outline current experimental systems and motivate and discuss our atomic structure work, focusing specifically on the atomic beam-based spectroscopy experiments. The new TOPE experiment is then discussed in Section 4.

2. Background and Motivation

2.1 T-violation and TOPE forces

Atomic physics experiments have long provided exacting tests of fundamental physics through searches for violations of discrete symmetries. For example, experimental searches for permanent electric dipole moments (EDM's) in atomic and molecules[5] have yielded remarkably stringent limits on the size of possible time reversal- and parity-violating (T-odd, P-odd) fundamental interactions. At the same time, recent precise measurements[2,6] of atomic parity nonconservation (PNC) have helped to provide sensitive tests of electroweak (P-odd, but T-even) forces which complement accelerator-based measurements[7,8].

Considering more broadly the history of T-violation experiments, the nonconservation of (CP) symmetry was first observed 35 years ago in kaon decays[9] (the CPT theorem states that CP-violation implies T-violation). Very recently, the KTeV collaboration at Fermilab has established 'direct' evidence of CP-violation in the kaon system[10]. The magnitude of the violation is in only marginal agreement with predictions from the standard model, which has fueled speculation about possible extensions to the model. The lack of observed T- or CP - violation in *any other physical system* reflects the comparatively poor state of knowledge concerning the underlying mechanisms of T-violation. There is a need for new experimental results, probing a broad range of physical systems, which would yield insight into the fundamental character of time-reversal noninvariance.

What do we know about the nature of T-odd, but P-even interactions in particular? Over the past two decades, limits have been placed on possible TOPE forces in nucleon-nucleon interactions through studies of so-called 'triple correlation' decays[11,12], and modest limits have been set in the purely leptonic positronium system[13]. However, this proposal specifically focuses on the nature of *electron-nucleon* TOPE forces such as would be detected in stable atoms. In contrast to atomic EDM and electroweak tests, there exist no direct experimental limits in atomic systems concerning possible forces which would violate time reversal but *not* parity symmetry. Atomic physics work in this area has consisted of theoretical proposals[4,14], and exploratory (*but not ongoing*) experimental investigations[15,16].

It has been pointed out[11,17] that existing limits on atomic and electron electric dipole moments (EDMs) coupled with known electroweak effects, can provide sensitive (albeit indirect) limits on TOPE forces (electroweak and TOPE interactions together would yield an 'EDM-like' observable; the non-observation of any atomic EDM thus limits the potential size of any TOPE mixing). However, EDM experiments are most sensitive to a short-range (contact) interaction between the electron and nucleon. As the mass of the particle responsible for the TOPE interaction decreases, the force acquires a long-range character to which indirect EDM limits become rapidly less sensitive[17]. Within this project we intend to concentrate our efforts on the investigation of a long-range TOPE electron-nucleon interaction, for which there are no significant existing experimental limits.

2.2 Preliminary results of new thallium TOPE calculations

Theoretical calculations are necessary to provide a direct connection between the magnitude of experimental observables and the corresponding TOPE coupling constants. Preliminary calculations have recently been carried out by our collaborators at PNPI[18]. The potential, H_T, of the proposed long-range TOPE electron-nucleus interaction, was written down assuming a stationary nucleus with one valence nucleon. Specifically, they considered an interaction mediated by a light boson of mass $< \alpha m_e$, where $\alpha = 1/137$ and m_e is the electron mass. Since atomic thallium will be used in the experiment the matrix element $\langle 6P_{1/2} | H_T | 6P_{3/2} \rangle$ (where $6P_{1/2}$ and $6P_{3/2}$ are ground and first excited states of thallium) was calculated to estimate the limits that could be established for coupling constants. The angular part of this matrix element was calculated analytically, while radial integral was calculated numerically. The result is: $\langle 6P_{1/2} | H_T | 6P_{3/2} \rangle = (\beta_{eN} + \beta_{Ne})\ 2 \times 10^{11}$ Hz. The predicted experimental sensitivity to this matrix element is $\sim 10^4$ Hz (see Sect.4 below) and thus would yield limits on the coupling constants of β_{eN} and $\beta_{Ne} < 10^{-7}$. A rough estimate shows when one applies the model suggested in [16] to the case of a *long-range* interaction, one can establish indirect EDM-based limits on these constants of no better than β_{eN}, $\beta_{Ne} < 10^{-2} - 10^{-3}$. It is clear that for the case of a *long-range* TOPE electron-nucleon interaction, the proposed experiment will set substantially more stringent limits on the relevant coupling constants.

One can also consider mechanisms whereby, through 'ordinary' weak interaction mixing, the addition of the TOPE interaction would provide a T-odd, P-odd amplitude to which the EDM experiments would in general be sensitive. In such a model, this sensitivity would not have the same dependence on the range of the TOPE force as that which characterizes the model considered in [16]. An important aspect of the ongoing exploratory theoretical work will be the exploration of such mechanisms and calculations of corresponding sensitivity of indirect EDM limits to potential TOPE forces versus those that would result from a direct experimental search. Work is now underway to perform the necessary calculations of TOPE mixing in thallium that will allow us to relate the particular TOPE observable which we intend to measure to models such as that discussed here.

3. Experimental Systems and Atomic Structure Measurements

In this section we both present motivation for, and a summary of, ongoing thallium spectroscopy work in our laboratory. We then outline design and operating parameters of the new atomic beam apparatus to be used for the proposed work, and briefly discuss the M1 Stark-induced amplitude measurement that will serve as an ideal bridge between the current work and the proposed TOPE experiment.

3.1 Testing electroweak physics with atoms

In contrast to the situation described above, there is a quarter century-long history of parity nonconservation experiments in atoms[19]. Experiments in several atoms have now reached the 1% level of precision or better[2,6,20]. The electroweak quantity of interest in atomic experiments is the weak charge, Q_w. In an atomic experiment, the PNC observable, E_{pnc}, can be expressed as: $E_{pnc} = Q_w * C(Z)$, where C(Z) depends on the details of the relevant atomic structure. Thus, the precision with which fundamental electroweak physics can be tested in atoms depends not only on the precision of the PNC experiment itself, but *equally* on the accuracy of theoretically-calculated wavefunctions required to translate the measured PNC effect into a test of fundamental physics. Future improvements in atomic electroweak tests will require advances on both fronts. For the case of atomic cesium, in addition to a precise PNC measurement[6], there exists a wealth of precise independent atomic structure measurements. These provide valuable independent tests of current cesium atomic wavefunction calculations[21]. Indeed, the very recent 0.35% cesium PNC measurement, coupled with a new assessment of the precision of atomic theory[8] have led to a provocative 2.5 standard deviation discrepancy between Cs PNC results and the predictions of the standard model.

In thallium, the recent precise PNC measurement[2] has encouraged a new round of atomic structure calculations. In particular, a new calculational technique has been developed[22,23] which better accounts for electron correlations in non-alkali systems. In the thallium system, a preliminary new calculation[24] shows promise of surpassing the existing 3% level of wavefunction precision. Finally, work is ongoing[25] towards a next-generation thallium PNC experiment which could lead to experimental precision below the 1% level. Unlike cesium, independent atomic structure measurements in thallium *simply do not exist* at the level of precision now required to check the accuracy and guide the further refinement of thallium atomic theory work. Therefore, ongoing work in this laboratory focuses on high-precision determinations of transition amplitudes, frequency splittings, and Stark-induced effects in the two lowest ground-state transitions of thallium.

Despite continuing advances in high-energy experimental tests of the standard model, it is quite remarkable that in certain areas, the atomic experiments equal or surpass the ability of accelerator-based experiments to set limits on possible standard model extensions. Indeed, one interpretation of the Cs PNC result would be to infer the existence of an 'extra' Z-boson of mass roughly 1 TeV[7]. Modest improvements in the precision of the thallium calculations and (PNC experiment) would be of great value as these low-energy atomic physics experiments continue to probe the limits of the standard model.

3.2 Vapor cell results at 1283 nm

The $6P_{1/2}$ - $6P_{3/2}$ 1283 nm transition in thallium which will be the focus of the TOPE search (see Fig. 1 below) has recently been the subject of a recent precision measurement in our group. This experiment used an external cavity diode laser system, optical polarimeter, and thallium atoms contained in a heated, sealed vapor cell. Precise lineshape analysis of optical transmission and Faraday rotation spectra resulted in a 1% measurement of the relative electric quadrupole to magnetic dipole (E2/M1) amplitude ratio within this transition[1]. This measurement provides a useful check of the accuracy of the relevant atomic wavefunctions. An accurate value for the E2 amplitude is also essential for precise measurements (both existing and future) of thallium PNC within this transition. Our new E2 value agrees well with a preliminary measurement done in conjunction with the Seattle thallium PNC work. However, as described in [1], lineshape simulations demonstrate that use of an older, incorrect value in the Oxford PNC work[26] for the E2 amplitude is at least partially responsible for the ~2σ disagreement between published PNC results. Thorough characterization of the residual frequency noise, intensity noise, as well as the tuning properties of the laser were an essential feature of this work, and become a valuable asset for the TOPE experiment which will utilize the same laser.

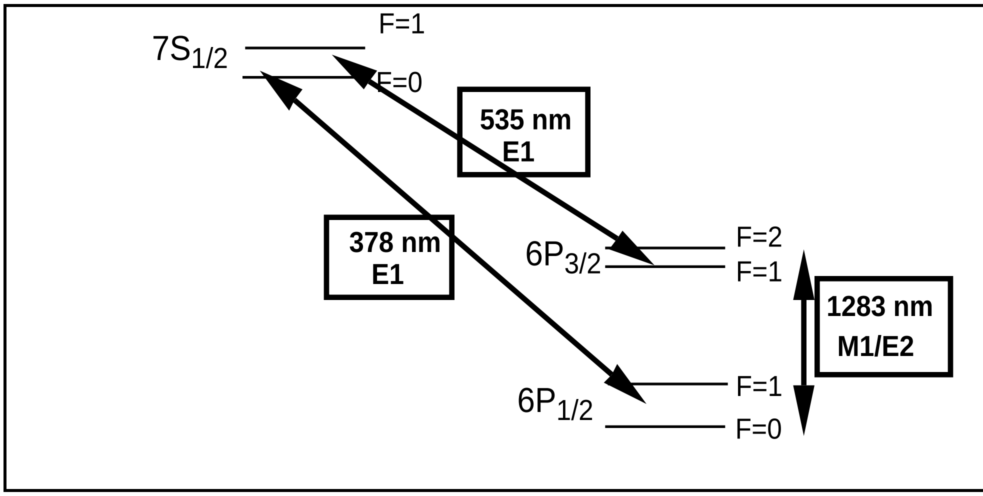


Figure 1.

Relevant low-lying energy levels of atomic thallium with hyperfine substructure (not to scale), and transition wavelengths. The recent high-precision PNC measurement and proposed TOPE measurement both utilize the 1283 nm transition.

3.3 Spectroscopy of thallium at 378 nm

There is particular need for measurements of improved precision within the 378 nm $6P_{1/2}$ - $7S_{1/2}$ E1 transition in thallium since the mixing between these states provides the dominant term in PNC mixing of the $6P_{1/2}$ state. To this end, a second external cavity diode laser, operating near 755 nm with power of 5 mW, is being used in our laboratory as a frequency-doubling source. We have installed a commercial external resonant frequency-doubling cavity[27] from which we have obtained roughly 1 microwatt of UV light at 377.6 nm. Initially we have incorporated this laser into our existing vapor cell apparatus. Figure 2 shows a typical 30-second scan in which we observe each of the three hyperfine transitions (for each of the two isotopes) within this transition. Fitting the Doppler-broadened spectrum to an appropriate theoretical lineshape allows us to extract excited-state hyperfine splitting and isotope shift information. Two confocal Fabry-Perot cavities, whose free-spectral ranges (roughly 300 and 500 MHz respectively) were independently calibrated with the aid of a 0.1 ppm wavemeter (Burleigh WA-1500), are used for frequency calibration and scan linearization. The presence of the very well-known 21 GHz ground-state hyperfine splitting within the scan provides a valuable alternative frequency calibration. Even without the aid of Doppler-narrowing techniques, analysis of a single spectrum such as this can determine splittings to 10 MHz or better. Our goal of ±1 MHz isotope shift and $7S_{1/2}$ state hyperfine splitting measurements would represent improvements over existing experimental results[28] and provide valuable new atomic structure information.

Spectroscopy of a strongly-allowed transition such as this is an ideal way to initially probe and characterize the atomic beam system (see immediately below). We intend as a first test of this new system to use our 378 nm laser system to measure the Stark shift within this transition, improving upon an existing 5% measurement[29]. Here we would lock the laser to a stable reference cavity and use and acousto-optic modulator (AOM) to tune to particular frequencies within the Doppler-narrowed atomic beam transmission profile. By determining the AOM frequency shift which compensates for the application of a large, well-known static electric field within the atomic beam interaction region, the magnitude of the shift will be measured, providing an ideal test of thallium atomic wavefunctions.

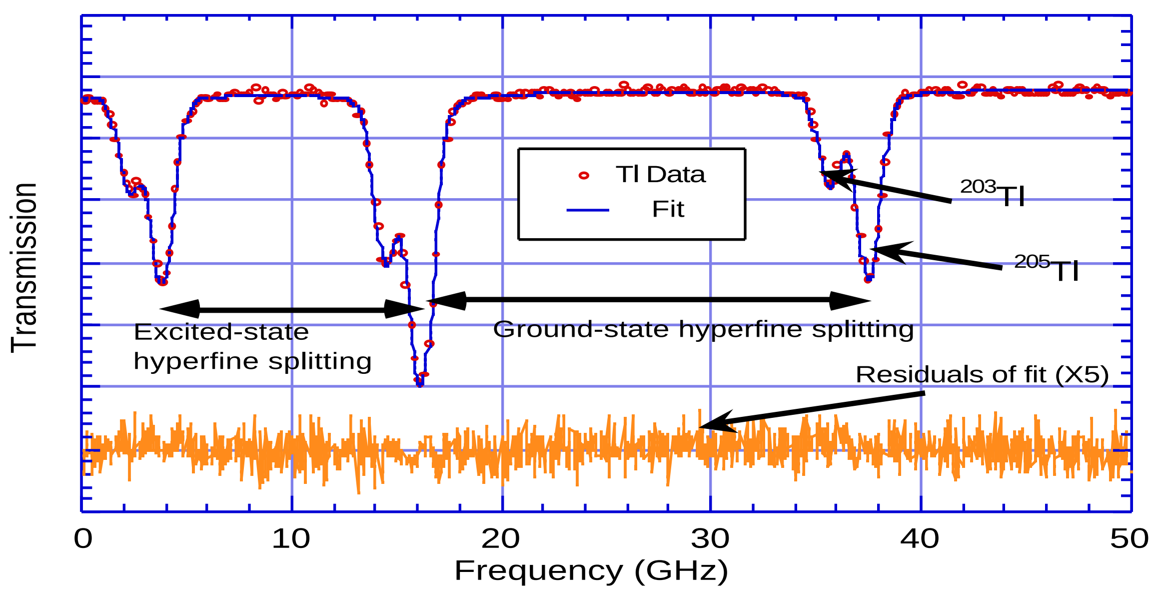


Fig. 2 A scan of the six individual transitions (2 isotopes x 3 hyperfine transitions) within the 378 nm E1 transition in thallium. A single 30 second scan such as this is fit to a lineshape model (data-fit residuals shown below spectra) which incorporates known isotopic abundances relative linestrengths, and ground-state hyperfine splittings. The simultaneous transmission data from two calibrated Fabry-Perot cavities (not shown) are used for frequency calibration and linearization.

3.4 Atomic beam design and characterization

We have recently completed construction of a high-flux atomic beam apparatus. In our system, a radiation-shielded oven capable of containing 1 kg of thallium is heated to ~800ºC. Pre-collimated thallium atoms exit the oven through a nozzle consisting of multiple parallel channels. The beam travels into a collar, mounted off of the main chamber, containing various ports for beam collimation, insertion of electric field plates and high voltage, and laser transmission. Included in this design is a fast chopping wheel for atomic beam modulation and lock-in detection. The ability to "chop" the atomic sample at ~100 Hz, something impossible for the vapor cell experiments, will allow us to use a transmission geometry to detect the very weak atomic beam absorption expected for the 1283 nm M1 transition (see below). Our atom/field interaction region includes polished stainless steel high-voltage field plates of known separation so that, with the aid of a high-precision high-voltage divider, we can achieve at least part per thousand absolute electric field knowledge. From kinetic theory and geometric considerations, for the case of an atomic beam source consisting of an oven with an exit slit of height h much less than its width w, one can express the beam density a distance D downstream as: $n_b = (n_0)wh/4\pi D^2$, where n_0 is the oven density[30]. In the effusive limit, n_0 is limited by the mean free path condition. For our atomic beam apparatus, with D=20 cm and w = 2 cm, one finds $n_b \approx 10^{11} / cm^3$. For a 2-cm wide beam at the interaction region, geometric considerations imply a ~ 70 (20) MHz residual transverse Doppler width for thallium E1 (M1) transition. Our oven nozzle consists of 30 parallel, 0.02" wide x 0.25" deep slits providing a favorable combination of large throughput and transverse collimation. Recent experience with this design for a Yb atomic beam have yielded results consistent with this model[31].

3.5 Atomic beam spectroscopy of the 1283 nm $6P_{1/2}$-$6P_{3/2}$ M1 transition

A key feature in many of these thallium measurements, is the existence of a ground-state transition which is **magnetic dipole** in character. Since the M1 matrix element can be calculated to high-precision *without the need for detailed wavefunction knowledge* (it requires only knowledge of atomic spins), the M1 absorptivity can be used as a direct measure of atomic number density. Thus, measurement of relative absorptivity using the M1 transition for normalization greatly simplifies the design of the experiments and will remove a wide variety of potential systematic errors. This feature was used to great advantage in the E2 amplitude measurement discussed above, and will greatly facilitate the Stark-induced amplitude measurement described here.

It is important to estimate the expected absorptivity of the atomic beam for the case of this 'forbidden' M1 transition. The number of optical depths, N, for a laser interacting over a length L with a gas of atoms of density n_b is given by $N = n_b \sigma L$, where σ is the (resonant) cross-section for the absorption of the Doppler-broadened sample. Estimating the M1 cross-section[32] to be ~ 10^{-16} cm^2 (in reasonable agreement with measured absorptivity in our vapor cell), and assuming a tenfold Doppler-narrowing in our beam, then for $n_b \approx 10^{11} / cm^3$ and L=2 cm , we expect atomic beam absorption of 'single-pass' laser light to be roughly 0.05% for the M1 transition.

We will complete a precise measurement of Stark-induced amplitude within the 1283 nm M1 transition, providing an excellent test of atomic structure theory within the same transition used to measure atomic PNC. The experiment involves measurement of the fractional change in M1 transition rate upon application of the static field. Given the precise calculability of the M1 amplitude, the fractional absorptivity change is *directly interpretable* in terms of the square of the Stark-induced amplitude. The Stark-mixed-E1 transition amplitude for E = 50 kV/cm is expected to be comparable to the M1 amplitude. Lock-in detection of the transmission signal using the chopped atomic beam should largely eliminate low-frequency intensity noise in the optical system. The transmission geometry provides the distinct advantage of 100% photon collection efficiency.

Assuming a 5×10^{-4} fractional M1 absorption, a high-precision measurement of the Stark-induced absorption (to 1 part in 10^3) would be possible in principle without approaching the shot noise limit on atoms or photons. However, there is an excellent opportunity here to make use of the same ring-cavity enhancement scheme proposed for the TOPE experiment, and thus benefit from a greatly enhanced absorption signal. We plan therefore to construct a three mirror ring-cavity similar to that shown in Fig. 3 below, except that here the electric field plates would be oriented horizontally so as to allow the laser beam to pass *between* them. By sending counter-propagating laser beams around the vertical cavity of even modest finesse, we would substantially enhance the M1 and Stark-induced absorption. The 1283 nm laser would in this case be independently locked and AOM-tuned to a particular hyperfine transition. One of the two output-coupled ring-cavity laser beams would be used to lock the *ring-cavity itself* onto resonance. The second cavity output beam would then provide the atomic absorption signal. By tuning the laser and ring-cavity to a number of fixed frequencies we will be able to simultaneously measure the Stark shift and the Stark-induced amplitude within this transition. The completion of this measurement will also serve as the ideal developmental foundation for the TOPE measurement described next.

4. The Thallium T-odd, P-even (TOPE) Experimental Search

4.1 Overview of experimental scheme

The schematic in Fig. 3 below depicts a relatively simple experiment designed to search for evidence of a T-odd, P-even force in atomic thallium. It has excellent potential for very high precision and effective suppression of many possible systematic errors. The experimental scheme originally envisioned for this search[4] suggested the use of a high-density vapor cell in a conventional interferometer. In this atomic beam proposal, the four order-of-magnitude *reduction* in OD compared to the cell is more than compensated by the ability to use much larger static electric fields and a high-finesse cavity. The Doppler-narrowed beam geometry also facilitates clean tuning to a particular resolved hyperfine transition as required by this scheme. The experimental signature for T-violation here is a cavity phase shift which depends on the direction of laser beam propagation *and* the direction of the static electric field.

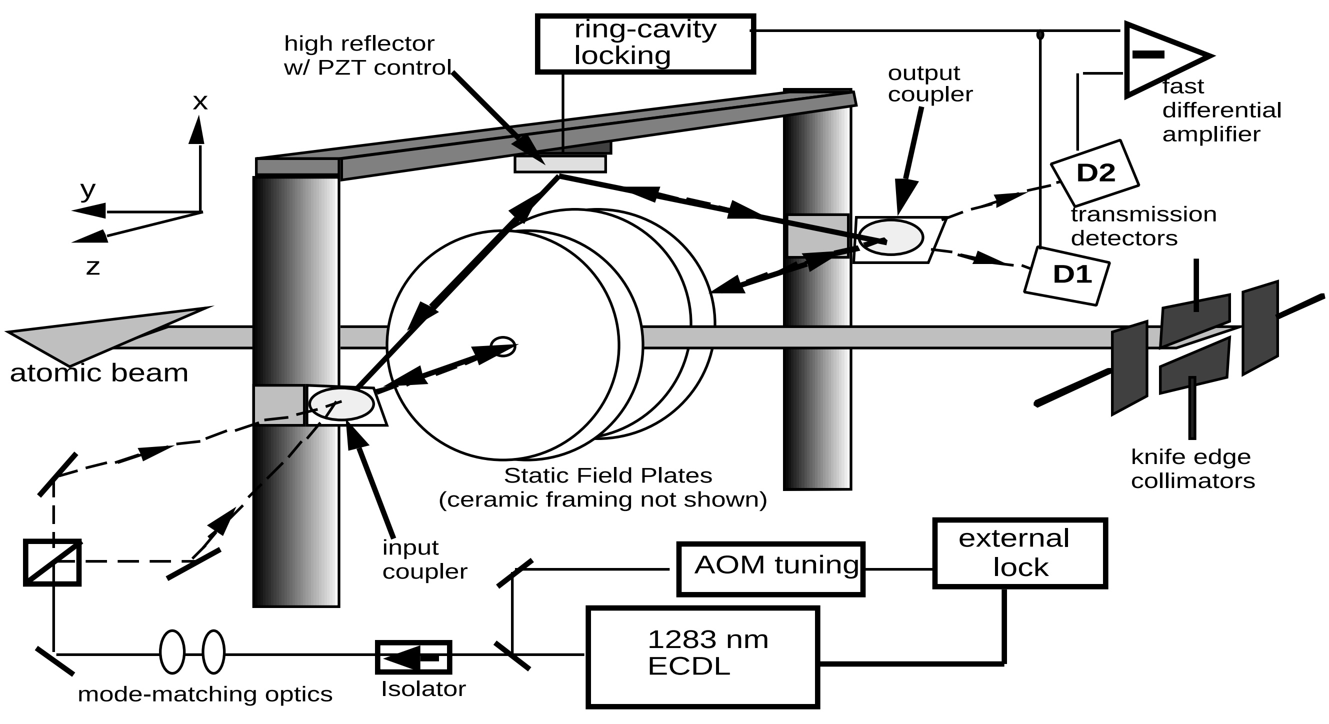


Figure 3. Schematic of setup for proposed TOPE atomic beam experiment.

Experimentally, we will first lock the frequency of our 1283 nm laser with the use of a stable external high-finesse cavity. Our specific ring cavity design and estimate statistical precision (sect. 4.3 below) assumes that the residual frequency fluctuations can be reduced to 10 kHz or less.

Incorporating an AOM into the lock loop allows a convenient, precise method of laser tuning. The interaction region consists of a longitudinal electric field ($\vec{E} \equiv E\hat{z}$) oriented perpendicular to the atomic beam propagation. As shown in Fig. 3, an appropriately mode-matched laser beam is injected into a high-finesse ring cavity such that it travels both parallel and antiparallel to the static electric field. The ring cavity mirrors will be rigidly mounted in a plane normal to the atomic beam. The linearly polarized laser drives $\Delta m = \pm 1$ (σ^+/σ^-) transitions in this geometry. An output coupler allows us to sample a small amount of circulating power for each counterpropagating component. The resonance condition for each beam depends on the exact optical path length. With appropriate piezoelectric cavity tuning to the steep edge of a ring cavity resonance peak, monitors D1 and D2 would be extremely sensitive to any changes in this optical path length. In order to keep the ring cavity locked to the side of a fringe, we will use the transmission signal from a single detector to provide servo control to the cavity PZT element. A key feature of this experimental scheme is the use of a fast differential amplifier to detect the differential transmission signal, and hence the differential cavity phase shift. This technique will greatly reduce sensitivity to common-mode sources of fluctuations such as those do to laser frequency, intensity, or ring cavity mechanical noise. Yet, as will now be shown, the differential signal provides the ideal readout for any potential TOPE observable.

4.2 Derivation of the experimental TOPE observable

As described in ref. [4], we search for a new T-odd contribution to the total transition probability, $|a_\eta|^2$, from the thallium $6P_{1/2}(F=0,m_F=0)$ state to the $6P_{3/2}(F=1,m_F=\eta)$ state [η = helicity of light = ±1] within the 1283 nm M1 line. For the moment we assume an ideal geometry, with the cavity laser beams exactly counterpropagating and that the direction of propagation parallel to the static electric field. By introducing the static field, we create a Stark-induced E1 amplitude which adds to the existing M1 amplitude. In the circular polarization basis, the laser fields are related by: $\beta_\eta = i\kappa\,\eta\,\varepsilon_\eta/c$ [here $\kappa = \hat{k}\cdot\hat{z} = \pm 1$ refers to the propagation direction of the laser]. Because of the relative factor of *i*, the two electromagnetic amplitudes do not interfere. We now make the key observation that the T-odd, P-even matrix elements are *purely imaginary*[4,14], as can be seen by noting that in this case taking 't' to '-t' in the atom amounts to exchanging initial and final states (*i.e.* complex conjugating the matrix element). Regarding selection rules, the T-odd, P-even Hamiltonian mixes states of the *same* parity within the atom, and its scalar nature enforces the selection rules: $\Delta F=0$, $\Delta m_F=0$. Thus, a TOPE interaction leads to first-order 'corrections' to both the M1 and Stark-induced amplitudes. Figure 4 indicates the four possible types of amplitudes, where in many cases particular diagrams represent infinite sums over intermediate states. Noting the relative phases indicated in the figure, it is clear that after adding and squaring all terms, two cross-terms within $|a_\eta|^2$ survive which are *linear* in the T-odd amplitude. Unlike the purely electromagnetic terms, each of these interference terms is linear in E, and change sign with the laser propagation direction. That is, they are proportional to $\hat{k}\cdot\vec{E}$, a manifestly T-odd, P-even quantity. As expected, there is no difference here between $|a_{\eta=1}|^2$ and $|a_{\eta=-1}|^2$, *i.e.* no "dichroism" as would be induced by a PNC interaction. Defining δ and α to be the T-odd and T-even contributions to amplitude respectively, we can write $\left|a_\eta\right|^2 \approx \alpha^2 + 2\alpha\delta$.

The complex index of refraction near the atomic absorption is proportional to the linestrength factor, $|a_\eta|^2$, as well as a frequency-dependent factor which here would reflect both Lorentzian and residual Doppler broadening. The *real* part of the index, n_r, produces a dispersive phase shift whose

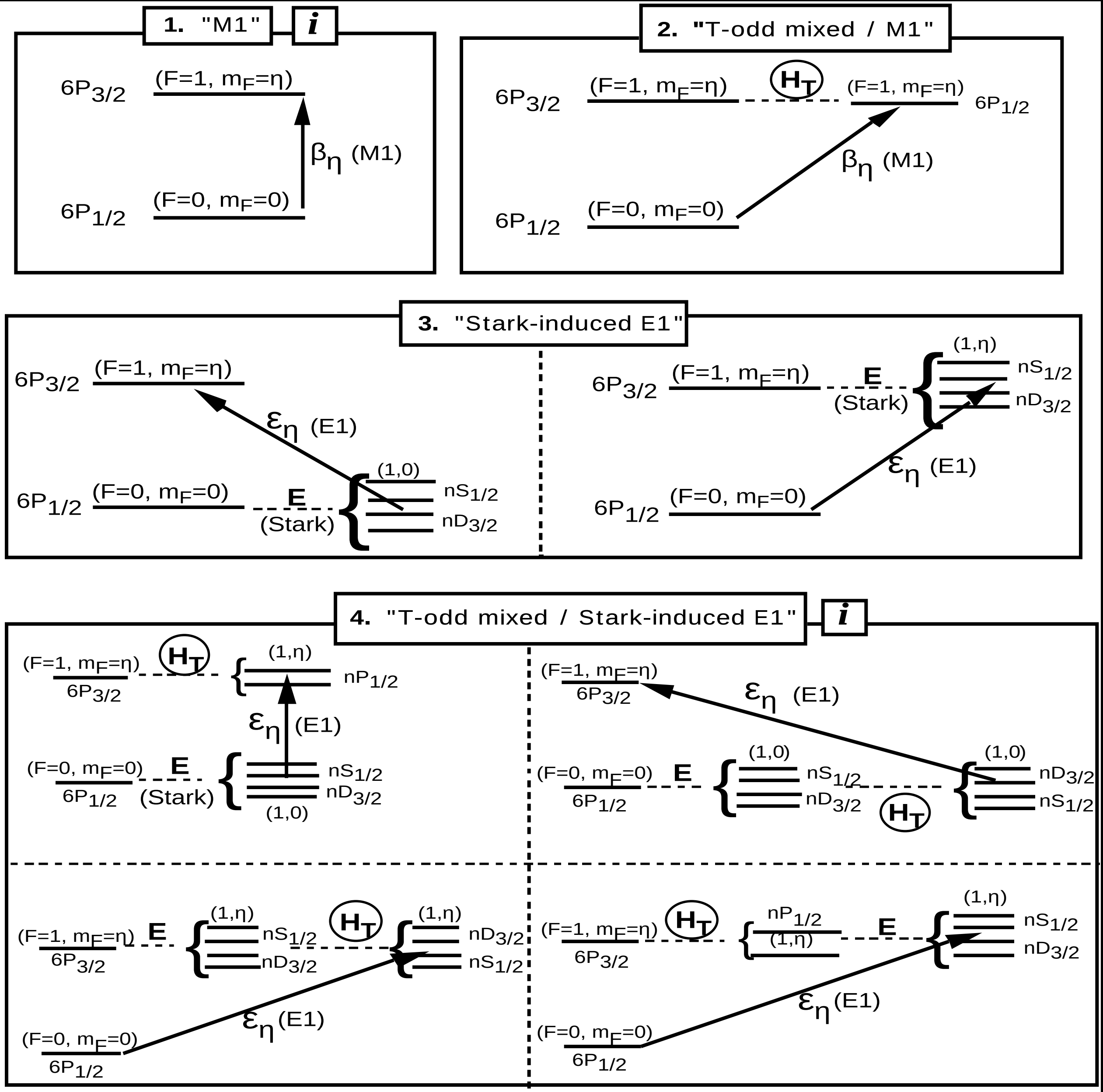


Figure 4. Summary of the four classes of amplitudes relevant to the TOPE experiment. β and ε refer to the laser fields, η to the laser helicity (±1), **E** to the static field, and $\mathbf{H_T}$ to the T-odd interaction. The relative phase of each type of amplitude is indicated by the presence or absence of the factor of ***i*** next to the label. Interference terms exist between #1-#4 and #2-#3. Each such term contains exactly one factor of each of the four quantities responsible for state-mixing.

magnitude depends on the interaction length, $\varphi = n_r(2\pi l/\lambda)$. The quantity in parentheses can easily be re-expressed as the ratio of measured optical depth (OD) to the imaginary part of the index, n_i. Finally, since the phase shift is much less than unity, using a ring cavity would simply amplify the net shift by a factor given by the finesse, $\mathcal{F}$. Noting that the sign of δ above changes with reversal of laser propagation direction, and recalling that experimentally we intend to measure the *difference* in cavity phase shifts $\Delta\varphi_T \equiv \varphi_{cw} - \varphi_{ccw}$ between counterpropagating beams, we have:

$$\Delta\varphi_T = 4\mathcal{F}(OD)(n_r/n_i)(\delta/\alpha). \qquad (1)$$

4.3 Experimental details and estimate of experimental precision

In addition to enhancing the size of any effect, the high-finesse of the cavity allows for great sensitivity in *detecting* any potential cavity phase shift. Assuming that the circulating cavity power does not lead to optical saturation (not a serious limitation for this 'forbidden' M1 transition), the statistical phase shift resolution in the experiment thus scales with $\mathcal{F}^2$ where $\mathcal{F}$ is the cavity finesse. With the laser locked independently and the ring cavity PZT-tuned appropriately, the ultimate phase resolution depends on the cavity finesse and our fringe-splitting ability. In particular, a phase shift $\delta\varphi$ would be revealed by an associated (fractional) voltage change such that $\delta\varphi \approx (\pi/8)(\delta V/V)(1/\mathcal{F})$. We define the quantity $\Delta V = V_{D1} - V_{D2}$ as the voltage difference signal which will become our experimental TOPE observable. **The quantity $\Delta\varphi_T$ is linear in the electric field; we will therefore search for a change in ΔV associated with a reversal of the static electric field direction.** Any residual differential 'optical' phase shift due to imperfect beam overlap, mirror birefringence, etc. should not survive this electric field reversal. We note that this differential measurement is not compromised by the need to lock the ring-cavity to one of the individual transmission signals.

To establish a statistical noise baseline, we begin by estimating the expected flux of atoms and photons and compute that the *shot-noise limited* value for $(\delta V/V)$ on a single voltage channel would be of order $10^{-7}/\sqrt{\text{Hz}}$. If we assume a reasonable value of $\mathcal{F} = 300$ for a ring cavity of 1 GHz free spectral range, a much more realistic value for $(\delta V/V)$ would be $\sim 10^{-3}$ (reflecting residual frequency and mechanical noise). If the differencing technique removes the common-mode noise to 1 part in 10^3 (*i.e.* $[\delta(\Delta V)] \approx 10^{-3}\,\delta V$), the residual noise level would still be at least one order of magnitude *above* the shot noise limit -- equivalent to a statistical sensitivity of $\Delta\varphi_T \sim 3\times10^{-9}$ radians/$\sqrt{\text{Hz}}$. The atomic beam chopping facility discussed above will further remove sensitivity to low-frequency laser intensity variations. The details of the mode-matching optics and the ring cavity optical design (precise cavity geometry, mirror curvature…) will follow standard criteria enabling single mode stable operation for ring-cavity beams .

Using Eq. 1 above, assuming that the frequency is detuned by roughly one Doppler halfwidth, and inserting our estimate for achievable atomic beam OD, we find that the corresponding limit which can be placed on the T-odd quantity **(δ/α)** is $\sim 3\times10^{-8}/\sqrt{\text{Hz}}$. To extract a limit on a typical T-odd atomic *matrix element*, $\langle b|H_T|a\rangle$, we note that **(δ/α)** is also proportional to the ratio of the Stark-induced electric to the magnetic dipole, which can be near unity for the E-fields achievable in this experiment. Taking a typical value of the energy denominator resulting from the T-odd mixing, we find that in one second we can establish limits on $[\langle b|H_T|a\rangle / h]$ of $\sim 3\times10^6$ Hz. Modest integration times of order days should lower this limit to the $\sim 10^4$ Hz level or below. We note that an accurate estimate of our sensitivity to H_T requires the evaluation of numerous infinite sums of dipole matrix elements which are contained within both quantities δ and α – a task currently being undertaken by our theory collaborators[18].

An additional experimental tool to limit potential systematic errors is the ability to tune the laser to the opposite side of the resonance thus reversing the sign of $\Delta\varphi_T$. Tuning the laser to the vicinity of the nearby $6P_{1/2}(F=0) \rightarrow 6P_{3/2}(F=2)$ pure electric quadrupole line would provide yet another systematic check in that the T-odd component of that transition is identically zero.

4.4 Consideration of potential systematic errors

We will first address the potential systematic errors of greatest concern in this experiment. The hyperfine interaction is responsible for observed splittings within the fine-structure states of thallium. However, it also mixes states in *exactly the same fashion* as the TOPE interaction, though with the crucial absence of the relative phase factor of "*i*" associated with the latter. The hyperfine interaction matrix element which mixes the $6P_{1/2}(F=1)$ and the $6P_{3/2}(F=1)$ can be estimated as the geometric mean of the "diagonal" matrix elements responsible for the observed splittings, or roughly: $\langle 6P_{3/2} | H_{HF} | 6P_{1/2} \rangle \approx 3 \times 10^{9}\, Hz$. In this TOPE search, our goal is to reach a limit on the TOPE matrix element at least five orders of magnitude smaller than this. In our ideal geometry, there can be no contribution of the hyperfine amplitude to a "TOPE-type" interference term, due to its relative phase. The question thus becomes, in what imperfect experimental situation can a spurious phase factor appear which could allow what is effectively a hyperfine-induced $k \cdot \vec{E}$ interference term? After extensive exploration of the effect of both geometric misalignments and imperfect polarization, it is clear that three or more of these non-idealities must exist simultaneously to produce a hyperfine systematic error. For example, with (i) some degree of circular polarization in the laser beam and (ii) a misalignment of the static field (so that a component of the laser polarization exists along E) and (iii) imperfect counterpropagation ($\vec{k}_{CW} \neq \vec{k}_{CCW}$), there can be a component of absorptivity which is independently odd under k and E reversal. The known extinction properties of the calcite crystals which we use to polarize the laser beam are useful for setting limits on the first item of at least 10^{-3}. With care the electric field and laser propagation directions can be aligned to better than 10^{-2} radians also. Fringing fields at the location of the atomic beam associated with the very small laser beam propagation holes will not cause effective misalignment which exceeds this limit. One obvious experimental test of the presence of these imperfections would be to purposely introduce fully circularly-polarized light into the ring cavity. Measurement of the size of any observable systematic error can then be used to improve the geometrical alignment of other offending vectors and to insure that the size of any possible 'false' signal is kept well below the expected experimental sensitivity.

Another potential systematic error would result from motional magnetic fields which would naturally change sign with changing static electric field direction. The size of such fields would be below the milligauss level, and the orientation would be transverse to the laser propagation direction. When one considers possible magneto-optical effects (the so called 'Voigt' effect) due to such transverse fields, any potential effect on absorptivity that would be "*k*-dependent" would again require multiple misaligned vectors. In this case the vectors are that of the electric (motional magnetic) field, the CW vs. CCW propagation directions, as well as the CW vs. CCW laser polarizations. Given the intrinsically small size of such transverse field effects, we conclude that such a contribution can again be kept well below the project level of statistical sensitivity.

The quantity α in the above expressions depends quadratically on the static field. Though a small imperfection in electric field reversal would indeed cause a change in the individual directional phase shifts, its only effect on the *difference* would be to change the quantity $\Delta\varphi_T$ itself by the same small fractional amount. Possible complicating effects of optical saturation or optical pumping associated with the cavity-enhanced laser field and Doppler-narrowed atomic beam should not present a problem for this E1-forbidden transition. We will explore this experimentally by changing the laser input power or focusing characteristics.

4.5 Optical system design and testing

We have already begun initial design and some prototype testing of the optical ring cavity design in our lab. To demonstrate a proof-of-principle with regard to the common-mode rejection of noise afforded by the subtraction technique, we have locked our 1283 nm laser to the side of a stable reference cavity (Burleigh RC-110). Figure 5 shows the simultaneous transmission measurements of this and a second Fabry-Perot cavity located next to the first. As can easily be seen, even for the case of two *independent* cavities, a substantial component of the residual fluctuations are of a common-mode variety. Transmission signals from CW and CCW beams within a *common* ring cavity (prototype now under construction) would certainly exhibit a far greater degree of common-mode behavior. The potential for eventual part-per-thousand common-mode subtraction of ring cavity noise is clearly evident. During the summer of 1999 and the following academic year, we plan to continue with optical and electronics testing of our prototype ring cavity. We have requested NIST funds beginning in the summer of 2000 for a full-time research assistant to carry forward this initial phase of design and testing.

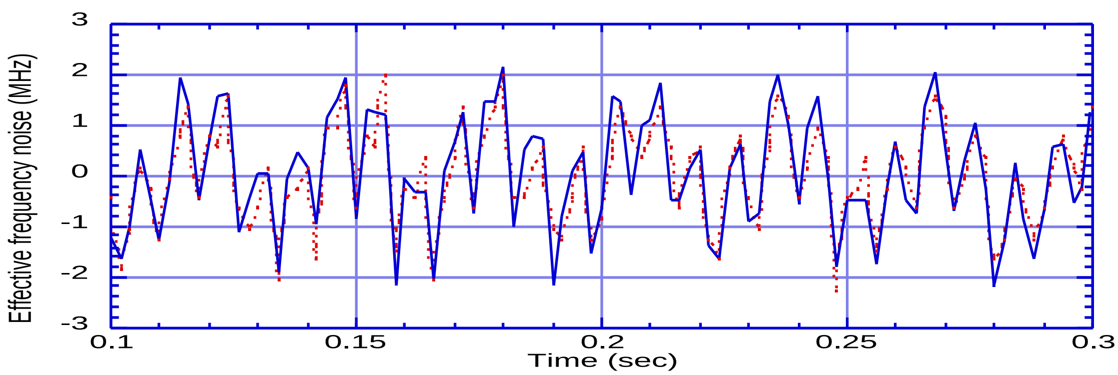


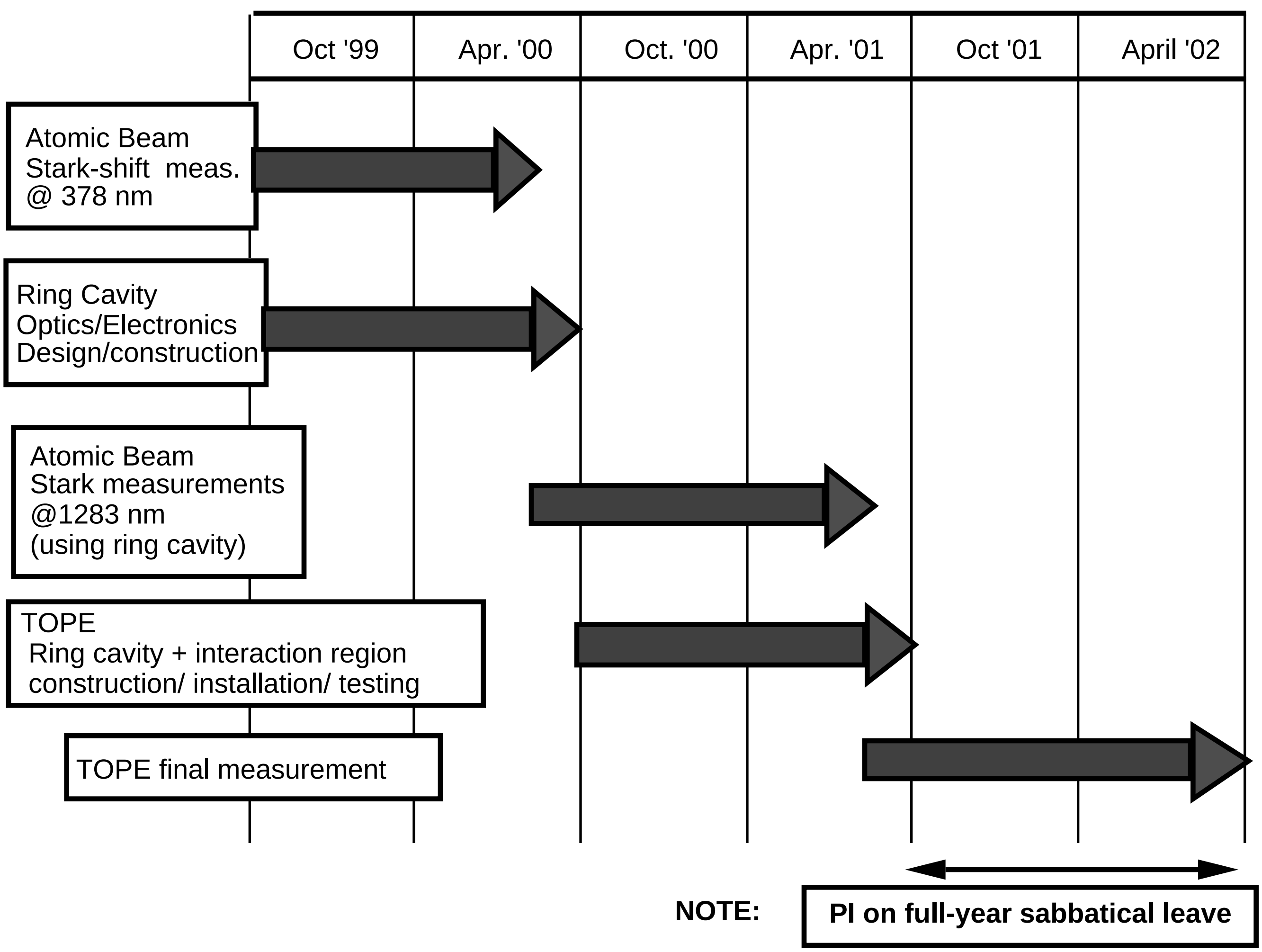
Fig. 5 Comparison of side-by-side confocal cavities each tuned to the half-maximum point of a Fabry-Perot transmission fringe. The y-axis was inferred from the measured transmission noise and fringe width. Noise reflects both residual frequency fluctuations and mechanical vibrations.

4.6 Concluding remarks

We conclude by reiterating that any information which we learn on the size of possible TOPE effects in this thallium experiment will represent the first such direct experimental evidence concerning long-range electron-nucleon T-odd, P-even interactions. As we pursue this experimental work, we look forward to an ongoing collaborative involvement with the PNPI theory group. A key contribution from the theory side will be the continuing exploration of possible models in which TOPE forces can be manifested in atomic systems, and quantitative calculations relating our experimental observable to coupling constants in these theories. As has been outlined, NIST funds would allow us to capitalize on a unique opportunity to extend ongoing precision measurements of thallium atomic structure in a new direction, providing fundamental and valuable new information concerning time reversal-violating, parity-conserving forces in atoms.

Proposed Timeline

The timeline shown here highlights the fact that the two lines of experimental work will begin in parallel, with at least one group member working on the atomic beam spectroscopy experiments while another designs, tests, and constructs the optics, electronics, and mechanical components for the new ring-cavity interaction region. The first test of the ring cavity design will be in the atomic beam measurement of the Stark shift and Stark-induced amplitude within the E1-forbidden 1283 nm transition. Experience gained here will directly benefit the TOPE experiment which shares much of the experimental equipment and technique. During the final of the three years outlined below (2001-2002 academic year), the PI will have a full-year sabbatical leave, during which he will remain at Williams and devote his full-time efforts towards completion of the TOPE experiment.



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Relevant Recent Publications

Atomic Parity Nonconservation/Atomic Structure:

"Measurement of the Electric Quadrupole Amplitude within the 1283 nm $6P_{1/2}$ - $6P_{3/2}$ Transition in Atomic Thallium," P.K. Majumder and Leo L. Tsai, Phys. Rev. **A60** *(to appear July 1999).*

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Kyle F. Downey '96
" An Atom-Laser Interaction Region and Electromagnetic Structure Measurements in Atomic Thallium"

Paul F. Boerner '96
" Construction of an Optical System for Use in Precise Measurements of Thallium Atomic Structure"

Julie R. Rapoport '97
" The Design, Construction, and Application of an Atomic Beam Apparatus"

Peter C. Nicholas '98
" The Design and Construction of an Atomic Beam Apparatus for Precise Spectroscopy of Thallium"

Leo L. Tsai '98
" Precise Measurement of the Electric Quadrupole Amplitude within the $6P_{1/2}$-$6P_{3/2}$ Transition in Thallium

Robert N. Lyman '99
" Spectroscopy of the 378 nm $6P_{1/2}$-$7S_{1/2}$ Transition in Atomic Thallium"

Andrew L. Speck '00 (project to begin June, 1999)
" Stark shift measurement within the 378 nm $6P_{1/2}$-$7S_{1/2}$ Transition in a Thallium Atomic Beam"