Search for T-Odd, P-Even Interactions with a Three-level, Directional Clock

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Introduction. In this discussion we consider a new class of T-violation experiments, that are sensitive to the presence of parity-conserving time-reversal violating interactions in atoms. The neutral K mesons, whose CP violating properties were discovered nearly thirty years ago[1] remain the only system where T-violation has been demonstrated; and even there the evidence is indirect, in that CPT is experimentally shown to be conserved while CP is violated. Since the Standard Model of strong and electroweak interactions can accommodate T-violation by means of complex quark mixing angles,[2] there is good motivation to search for other examples which might, in conjunction with the K-meson results, either confirm this connection, or point unambiguously to new physics beyond the Standard Model. Assuming CPT to be conserved, the mass matrix[3] in the $K^\circ + \bar{K}^\circ$ (C=+1, P=-1) and $K^\circ - \bar{K}^\circ$ (C=-1, P=-1) basis is

$$M = \begin{pmatrix} \mu - \frac{\Delta}{2} & H_{int} \\ -H_{int} & \mu + \frac{\Delta}{2} \end{pmatrix} \quad . \tag{1}$$

Here μ is the strong interaction mass of K°, ϵ is the usual CP-violation parameter, and $\Delta = m_L - m_S - \frac{i}{2}(\Gamma_L - \Gamma_S)$ is the complex mass difference. The CP-violating interaction $H_{int} = \epsilon\Delta = [-0.048(45) + i2.797(45)]$ MHz is experimentally Hermitian and thus consistent with a C-odd, P-even, T-odd ($\not{C}P\not{T}$) superweak mixing. Observation of direct CP-violation in K° decays as evidenced by a non-zero ϵ' parameter[4] would preclude superweak models but experimentally ϵ' is now consistent with zero.[4]

The most precise tests of time-reversal invariance are measurements of the permanent electric dipole moment (EDM) of the electron,[5,6] ($d_e < 1\times10^{-26}$ e-cm) or the neutron[7] ($d_n < 5\times10^{-26}$ e-cm). An EDM violates parity as well as T. Its presence would suggest a small P-odd T-odd ($\not{P}\not{T}$) term in the total atomic Hamiltonian. Parity conserving T-violation is far more difficult to test. Here, the current best limits also come from EDM measurements, since higher order weak corrections would produce a small EDM even for $P\not{T}$.[8] Naively one might suppose that these "second order" effects should be suppressed relative to T-and P-violating contributions to the EDM by the strength of weak interactions in atoms, which might be as small as $G_F \times Ry^2 \sim 10^{-21}$. However, Khriplovich has argued that the contact nature of the supposed T-violating interaction already accounts for most of the suppression, so that P-conserving effects would be only further suppressed by α in EDM measurements.[9]

These model estimates suggest that a direct test of parity conserving time reversal violation in atoms would be of considerable value, even if it were less precise than the edm measurements by a factor of α. Furthermore, it is conceivable that T-violation might present itself in the long range Coulomb interaction, or in some new interaction mediated by a very light weakly-coupled gauge boson. In this case EDM measurements would not be a sensitive test, but direct $\not{T}$P measurements far less precise than current EDM experiments would set valuable limits on these interactions. In any case, new high precision tests of time reversal invariance might give us our first glimpse of the low energy behavior of new physical interactions beyond the Standard Model.

Direct Atomic Tests for P$\not{T}$ *interactions.* Time-reversal tests search for the presence of a nonvanishing T-odd combination of observables. We seek T-odd scalars (P$\not{T}$) that arise in the cycling behavior of atomic state populations; several may be constructed for an atom with nuclear, electronic, and orbital angular momenta $\mathbf{I}, \mathbf{S}, \mathbf{L}$, in the presence of static, $\mathbf{E}$ and $\mathbf{B}$ or time-varying, ϵ and b fields. Three such $\not{T}$P combinations are $i\Gamma\mathbf{\Sigma} \cdot \mathbf{B}$,[10] $\mathbf{E} \cdot \epsilon \times \mathbf{b}$, and $\mathbf{b}_1 \cdot \mathbf{b}_2 \times \mathbf{b}_3$, where $\mathbf{\Sigma}$ is the photon angular momentum and Γ is a decay width.

Various T-odd Lagrangians involving interactions between the electron and hadron currents and applied electromagnetic fields may be responsible for the presence of this T-odd scalar. We consider two classes of such interactions: 1) a current-current interaction, Fig. 1a, that has a non-relativistic form

$$\mathcal{L}^{cc}_{\not{T}\mathrm{P}} = \mathbf{L} \cdot \mathbf{S} \times \mathbf{I} \tag{2a}$$

for atoms or

$$\mathcal{L}^{cc}_{\not{T}\mathrm{P}} = \mathbf{L} \cdot \mathbf{S}_+ \times \mathbf{S}_- \tag{2b}$$

for positronium, and 2) a current-current-field interaction, Fig. 1b, with a non-relativistic

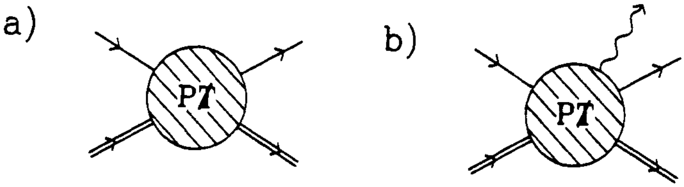

Fig. 1. a) Four fermion interaction $\mathcal{L}^{cc}_{\not T P}$. The fermions can be nucleons or electrons (positrons). b) Four fermion plus one photon interaction $\mathcal{L}^{ccf}_{\not T P}$.

form

$$\mathcal{L}^{ccf}_{\not T P} = i\omega(\rho_e \mathbf{S} + \rho_n \mathbf{I})\cdot \mathbf{b} \quad , \tag{3}$$

where ρ_e and ρ_n are constants, $\mathbf{S}_\pm$ are the positron and electron spins, and b and ω are RF magnetic field and angular frequency, respectively. Examples of phenomenological interactions that lead to these forms, have been explored for $\mathcal{L}^{cc}_{\not T P}$ [8] and for $\mathcal{L}^{ccf}_{\not T P}$.[11] The atomic tests considered here are especially sensitive if the $\not T$ interaction is long range. In both cases, the Hamiltonian does not contribute in first order to the self-energy of the states: the interactions are strictly non-diagonal, only coupling together different states with imaginary (Hermitian) coupling constants, as in the kaons (Eq.1). Note that $\mathcal{L}^{ccf}_{\not T P}$ introduces a phase shift in the magnetic dipole transition moment which vanishes entirely for static electromagnetic fields.

Several experiments to search for P$\not T$ interactions are presented in the columns of Table 1. Row 1 is the atomic state employed while row 2 gives the scalar combinations of observables that is measured. Each atomic system in Table 1 is sensitive to $\not T$ scalar combinations of internal variables of form $\mathcal{L}^{cc}_{\not T P}$ or $\mathcal{L}^{ccf}_{\not T P}$ as seen in row 3.

A possible $\not C$P$\not T$ interference experiment in the $2^3S_1 \to 2^1P_1$ transition in positronium (Ps), column 1, is detailed in Ref. 10. A *direct* C-violation search in this state, sensitive to

atomic	Ps	H	Be	Rb
transition	$2^3S_{1\pm1} \rightarrow 2^1P_{10}$	$\beta_0 \rightarrow \beta_{-1}$	$2^3P_j \rightarrow 2^3P_{j'}$	$2^3S_{1/2}(m_F \rightarrow m'_{F'})$
observables	$i\Gamma\mathbf{\Sigma}\cdot\mathbf{B}$	$\mathbf{E}\cdot\epsilon\times\mathbf{b}$	$\mathbf{b}_1\cdot\mathbf{b}_2\times\mathbf{b}_3$	$\mathbf{b}_1\cdot\mathbf{b}_2\times\mathbf{b}_3$
non-	$\mathbf{L}\cdot\mathbf{S}_+\times\mathbf{S}_-$	$\mathbf{L}\cdot\mathbf{S}\times\mathbf{I}$	$\mathbf{L}\cdot\mathbf{S}\times\mathbf{I}$	
relativistic		$i\omega\mathbf{I}\cdot\mathbf{b}$	$i\omega\mathbf{I}\cdot\mathbf{b}$	$i\omega\mathbf{I}\cdot\mathbf{b}$
models		$i\omega\mathbf{S}\cdot\mathbf{b}$	$i\omega\mathbf{S}\cdot\mathbf{b}$	$i\omega\mathbf{S}\cdot\mathbf{b}$

Table 1. Atomic tests of $P\not{T}$.

$\mathcal{L}^{cc}_{\not{T}P}$, has been recently completed[12] yielding a limit

$$| < 2^1P_1|\mathcal{L}^{cc}_{\not{T}P}|2^3P_1 > | < \ 65\text{MHz} \ . \tag{4}$$

In normal atoms (much more abundant than Ps) C is not a good quantum number, thus a direct C-violation test is not possible and the more difficult T-violation tests must be made. An experiment employing the $\beta_0 \rightarrow \beta_{-1}$ transition in hydrogen, column 2, involves a magnetic-dipole, electric-dipole interference in a two state transition amplitude, but suffers from short coherence times due to P-state radiative decay. The experiment in beryllium 2^3P metastable, column 3, should exhibit long coherence times and is sensitive to both classes of the $P\not{T}$ interaction, but it presents considerable technical challenges. A three-level directional clock experiment ($\mathbf{b}_1\cdot\mathbf{b}_2\times\mathbf{b}_3$) in ^{87}Rb is the most promising in the short term and will be treated in detail below.

The Three Level Directional Clock. Three levels, labeled A, B, and C, may be coherently driven in a variety of complicated ways by three driving fields with angular frequencies $\omega_{AB}+\omega_{BC}+\omega_{CA}=0$, each of which is on or near a resonance between two of the levels. We will simplify our analysis for this presentation in order to illustrate the essential T-violating effects: we consider only systems driven by three resonant RF magnetic fields, so that the detunings Δ_{AB}, Δ_{BC}, and Δ_{CA} are all zero. Furthermore, we will adjust the field amplitudes so that the individual 2-state Rabi rates $R_{AB}=R_{BC}=R_{CA}=R$ are equal. The remaining parameter governing the behavior of the state populations is the overall phase Φ, defined by $\Phi\equiv\phi+\theta+\delta$. Here $\phi\equiv\phi_{BC}-\phi_{CA}-\phi_{AB}$ is the RF relative phase; $e^{i\theta}\equiv i\hat{\mathbf{b}}_1\cdot\hat{\mathbf{b}}_2\times\hat{\mathbf{b}}_3$ defines a phase θ due to the geometrical relationship between the three magnetic field operators; and δ is the T-violating phase. The principal challenge of this experiment is to separate the phase effects of δ from those of ϕ and θ.

To illustrate the phase response of this coupled three-state system, let $\delta = 0$, $\theta = -\frac{\pi}{2}$, and $\phi = 0$, thus $\Phi = \frac{\pi}{2}$. The populations of the three states respond as in Fig. 2, cycling from initial state A in the sense $A \rightarrow B \rightarrow C \rightarrow A \cdots$. The response of the populations is clearly time-directional. If the time-reversal operator is applied to this system then the RF phase is reversed, $\phi = 0 \rightarrow 0$ *and* the sense of all magnetic fields is reversed and thus $\theta = -\frac{\pi}{2} \rightarrow \frac{\pi}{2}$ and $\Phi = 0 \rightarrow \pi$. The populations then respond with the opposite time dependence $A \rightarrow C \rightarrow B \rightarrow A \cdots$ as in Fig. 2b, because the *boundary conditions* are explicitly T-odd. This demonstrates that the directionality of this system can be sensitive to phase.

If the RF phase is instead set to $\phi = \frac{\pi}{2}$ ($\Phi = 0$), then the boundary conditions are T-even and the system responds as in Fig. 2c. No temporal sense to the oscillations is observable (in this it mimics a two state system). Any slight deviation, due to a nonzero δ for example, will lead to a gradual modulation, or "sloshing", of the population of the three states. Two examples of this are shown in Figs. 3b and 3c. For $|\Phi| << 1$, the probability of finding the atom in an initially unpopulated state B is modulated according to

$$P_B(t) = \frac{1}{3} - \frac{2}{9}\cos\left[\frac{2\sqrt{3}}{3}\Phi Rt + \frac{\pi}{3}\right] - \frac{4}{9}\cos 3Rt \cos\left[\frac{-\sqrt{3}}{3}\Phi Rt + \frac{\pi}{3}\right] \ . \qquad (5)$$

Extremely accurate phase shifts of $\Phi \rightarrow \Phi + \pi$ are possible and lead to a response of the system as if $\Phi \rightarrow -\Phi$ in Eq.5.

The experiment is executed as follows: 1) The system is polarized in state A, 2) with the externally controllable phases set to $\phi = \frac{\pi}{2}$, $\theta = -\frac{\pi}{2}$ and the atoms evolve as in Eq.5, and 3) the population P_0 of B is sampled at an extremum of the fast Rabi oscillation $\omega_F t = 3Rt = m\pi$ ($m = 1, 2, \ldots$) for maximum sensitivity. The same measurement P_π is made with Φ augmented by π. An asymmetry

$$A_p \equiv \frac{P_0 - P_\pi}{P_0 + P_\pi} \qquad (6)$$

can be defined and for $\Phi << 1$

$$A_p = \frac{S/N}{1 + S/N}\frac{\Phi}{3}\omega_F t \qquad (7)$$

where S/N is the signal-to-noise for the B state detection. In order to maximize sensitivity, long coherence times t should be sought and ω_F, and thus the RF power, should be maximized. The analysis above depends on the rotating wave approximation. At sufficiently

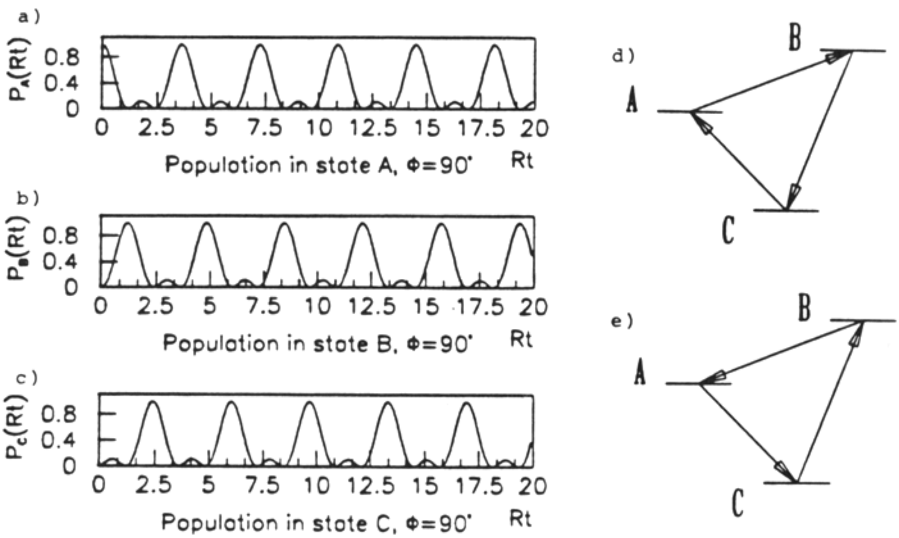

Fig. 2. Probability of finding atom in state a) A, b) B, and c) C as a function of time. State A is initially populated, detunings are all zero, and the two-state Rabi rates are equal. For $\Phi = \pi/2$ the cycling behavior in inset d) indicates the state evolution $A \rightarrow B \rightarrow C \rightarrow A \rightarrow \ldots$ while for $\Phi = 3\pi/2$ e) indicates $A \rightarrow C \rightarrow B \rightarrow A \rightarrow \ldots$.

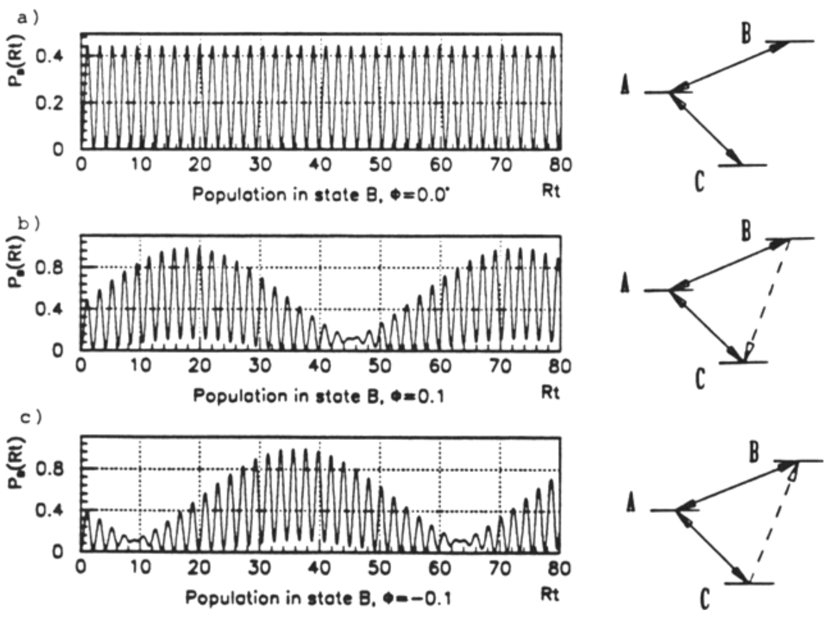

Fig. 3. Probability of finding atom in state B for a) $\Phi = 0$, b) $\Phi = 0.1$, and c) $\Phi = -0.1$.

high RF intensity RWA will break down and AC Stark effects will dominate. It is possible that under these conditions of classical RF fields that the three state coupled system will exhibit chaotic behavior.

Static Magnetic Field Dependence. It now remains to express δ in terms of $i\rho_e\omega\mathbf{S}\cdot\mathbf{b}$ and $i\rho_n\omega\mathbf{I}\cdot\mathbf{b}$, and to separate its effect from the other components of Φ. This is best done in the context of a specific atomic system, rubidium, although it applies similarly to all other alkalis. The relevant atomic energy levels for ^{85}Rb ($I = 5/2$, hyperfine splitting $\nu_{85} = 3035.74$ MHz, $g_{85} = 2.936\times10^{-4}$) and ^{87}Rb ($I = 3/2$, $\nu_{87} = 6834.70$ MHz, $g_{87} = 9.951\times10^{-4}$)[13] are shown in the Breit-Rabi diagram in Fig. 4. For ^{87}Rb (^{85}Rb) the initial state A is the $[F,m_F]$=[2,-2] state ([3,-3] state) while B and C correspond to the [1,-1] ([3,-2]) and [2,-1] ([2,-2]) states, respectively.

To separate the effect of δ from those of ϕ and θ we execute measurements of A_p and thus of Φ, for each Rb isotope, under conditions of identical RF frequencies $\nu_{AB}(85) = \nu_{AB}(87) = 5305$MHz, $\nu_{BC}(85) = \nu_{BC}(87) = 6030$MHz, and $\nu_{CA}(85) = \nu_{CA}(87) = 725$MHz. This can be achieved at static magnetic fields $B_{85} = 2720$G and $B_{87} = 805$G. The ϕ and θ phases should remain unchanged when B is switched between values that bring either isotope into resonance, however, δ will, in general, differ. In the rotating wave approximation, as for Eq. (5), the overall response phase Φ is given by

$$e^{i\Phi} = \frac{M_{AB}}{|M_{AB}|}\frac{M_{BC}}{|M_{BC}|}\frac{M_{CA}}{|M_{CA}|} \tag{8}$$

where $M = M_{\rm em} + M_{\not T}$ is the total transition amplitude including the normal electromagnetic terms M_{em} and all P$\not T$ ones $M_{\not T}$. At these static magnetic fields, M_{em} is dominated by the electron magnetic dipole moment $g_e\mu_B$. If we assume that the nuclear magnetic dipole moment $g_{85}\mu_B$ or $g_{87}\mu_B$ and the $\not T$ moments $\omega\rho_{n85}I$ or $\omega\rho_{n87}I$ and $\omega\rho_e S$ are much smaller than $g_e\mu_B$ then the $\not T$ phase is given by

$$\delta_{85} = \frac{12\pi(\nu_{AB}^2-\nu_{CA}^2)}{\nu_{85}}\times\frac{(\rho_{n85}+\rho_e g_{85}/g_e)}{g_e\mu_B} = 2\pi(-27.3\ \text{GHz})\times\frac{(\rho_{n85}+\rho_e g_{85}/g_e)}{\mu_B} \tag{9}$$

or

$$\delta_{87} = \frac{8\pi(\nu_{AB}^2-\nu_{CA}^2)}{\nu_{87}}\times\frac{(\rho_{n87}+\rho_e g_{87}/g_e)}{g_e\mu_B} = 2\pi(-8.1\ \text{GHz})\times\frac{(\rho_{n87}+\rho_e g_{87}/g_e)}{\mu_B}\ . \tag{10}$$

In general, δ_{85} and δ_{87} differ if any or all of the ρ's are non-zero. The exceptions in which

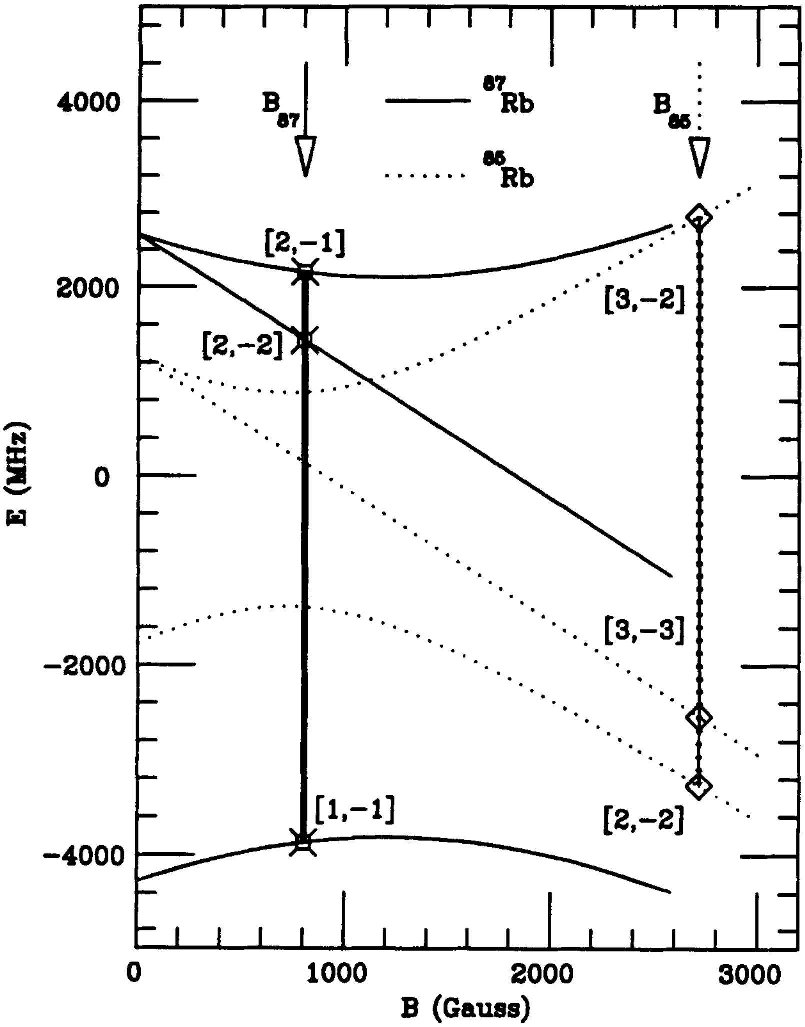

Fig. 4. Breit-Rabi diagram for ^{85}Rb and ^{87}Rb. Levels are labeled according to $[F, m_F]$.

$\delta_{85} = \delta_{87} \neq 0$ (*eg.* $3\rho_{n85}/\nu_{85} = 2\rho_{n87}/\nu_{87}$), are *a priori* unlikely. These experiments are not sensitive ($\delta = 0$) to any model in which $\rho_n/g_n = -\rho_e/g_e$.

Since the two isotopes are measured at identical RF frequencies possible shifts in ϕ and θ therefrom are avoided. However, to obtain equal two-state Rabi frequencies as required above, the RF intensities b_i must be changed when switching isotopes. Shifts stemming from this change are technically much easier to eliminate than those from changing the transition frequencies. In addition, this same technique of comparing two different δ's with the same transition frequencies can be extended to other alkalis and even mixtures of alkalis. Thus, combinations of isotopes requiring different or small RF intensity changes can be measured.

Experimental techniques. The choice of an atomic ground state for the initial experiments was governed by the long coherence times available in the absence of radiative decay. We can maximize coherence times in two ways 1) cool and confine the atom using optical molasses techniques, or 2) localize the atom by collision with a buffer gas. Both techniques can obtain coherence times approaching 0.1s. The initial state can be polarized via optical pumping and this would occur automatically as part of the molasses cooling. The RF magnetic fields are supplied by three orthogonal transmission lines in each region, as shown in Fig. 5. A low impedance load on each line generates standing waves in the interaction region. The RF intensity can be modulated and the RF phase precisely reversed by changing the position of the reflecting load. The static magnetic field must be precisely maintained and can be provided by a solenoid or an NMR magnet. The final state detection can be achieved by resonant flourescence or resonant photo-ionization using a short pulse ($5 \rightarrow 20$ ns) laser.

Conclusions. The three state directional clock method provides a new approach to the investigation of CP- and T-nonconservation. We have begun experiments at the University of Michigan to measure any $\not{T}$ phase in Rb. Limits on δ at the 10^{-4} level should be readily attainable. Prospects for much higher precision are good, but depend upon maintaining highly stable fields. In order to probe interactions of the type $\mathcal{L}^{cc}_{\not{T}P}$, we will attempt the more difficult experiments in Be(2^3S) but only after gaining experience with the alkalis.

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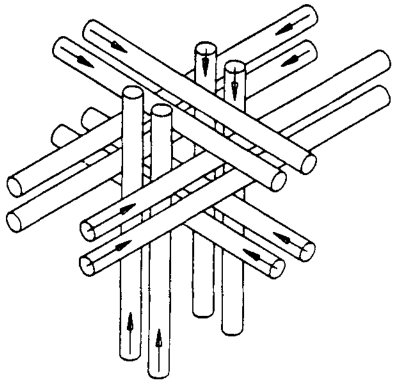

Fig. 5. Interaction region. Three orthogonal doubled pairs of transmission lines generate the three RF magnetic fields. The current in each conductor is indicated by an arrow.

to the search for $\not{C}P\not{T}$ interactions in atomic systems. This conference is in honor of his devotion to investigating the fundamental processes of nature, including the discrete symmetries C, P, and T. Were he still with us he would undoubtedly be intimately involved in the present T-violation experiments.

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