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SEARCH FOR AN ELECTRIC DIPOLE MOMENT IN THALLIUM*

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The atomic-beam magnetic-resonance technique has been used to search for a linear Stark effect, which would violate parity and time-reversal invariance, in the $6\,^2P_{1/2}$ ground state of thallium. The motional magnetic field effect $(\vec{v}\times\vec{E}/c)$ was accounted for by comparison experiments between Tl and Na and K. The electric dipole moment of the thallium atom is $D_{\rm Tl}=[(1.3\pm2.4)\times10^{-21}\ {\rm cm}]e$, where the error is the standard deviation.

In a recent paper,[1] Carrico, Stein, Lipworth, and Weisskopf report the possible observation of a small linear Stark effect (LSE) in the ground state of thallium, which is consistent with an atomic electric dipole moment (EDM) of $D_{\rm Tl} = (5\times10^{-19}\ {\rm cm})e$. We wish to report here the results of a recent measurement yielding an upper limit to the EDM of the thallium atom which is several orders of magnitude smaller and is consistent with zero.

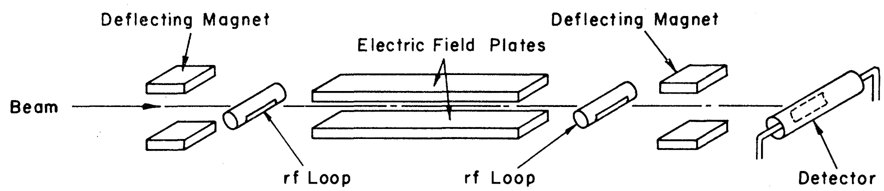
If the atom possessed a permanent EDM, then the interaction of the EDM with a uniform external electric field $\vec{E}$ would produce an LSE. The observation of an LSE in a nondegenerate system would be direct evidence of a violation of both parity (P) and time-reversal (T) invariance. Sachs[2,3] has pointed out that an atomic EDM arising from a violation of invariance under T and P in the electromagnetic interactions would involve a $\vec{J}\cdot\vec{E}$ interaction, where $J=L+\frac{1}{2}\sigma$. In searching for such a violation, thallium offers the advantage (over the alkali atoms) of an $L\neq0$ ground state.

It was first shown by Salpeter[4] and Sandars[5] that an atomic EDM would arise from the interaction of an EDM of the (valence) electron with the rest of the atom. The ratio R of an atomic EDM to an electron EDM (called the enhancement factor) has been calculated for a number of atomic systems.[6-9] The interaction involves terms in $Z^2\beta^2$, where Z is the nuclear charge and β the atomic polarizability.[6] R will be largest in atomic systems with high Z and large β. An R of about 200 has been estimated[9] for thallium.

We examined the relative shift between the $F=1$, $m_F=0$ and the $F=1$, $m_F=-1$ sublevels of the $6^2P_{1/2}$ ground state of Tl caused by a uniform electric field of 50 kV/cm. The measurement was made in the presence of a magnetic field of 1 G parallel to the electric field. A diagram of the atomic beam apparatus appears in Fig. 1. It is described in Gould, Lipworth, and Weisskopf.[10] The quadratic Stark effect (caused by the interaction of the electric field with an induced EDM) was subtracted out by periodically reversing the direction of the electric field. The technique of slope detection[10] was used to achieve a resolution of one part in 10^4 of the 230-Hz linewidth.

The motional magnetic field effect $(\vec{v}\times\vec{E}/c)$ is accounted for by performing comparison experiments[11] between thallium and an atom with a small value of R such as sodium ($R=0.32$) or potassium ($R=2.4$). (The motional magnetic-field effect is significant to the experiment in that the interaction of the magnetic moment of the atom with this field will result in an effect, linear in the applied electric field $\vec{E}$, if $\vec{E}$ is not parallel to the magnetic field. See Fig. 1.)

A small current I_x is passed through a Helmholtz pair approximately perpendicular to $\vec{E}$ and



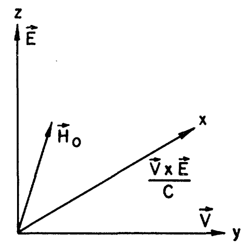


FIG. 1. If $\vec{E}$ and $\vec{H}_0$ are not parallel, then the motional magnetic field $(\vec{v}\times\vec{E}/c)$ will have a component along $\vec{H}_0$ which is linear in $\vec{E}$. Components perpendicular to $\vec{H}_0$ enter only quadratically.

the 1-G field $\vec{H}_0$. This produces a resultant magnetic field $\vec{H}$ which can be rotated relative to the direction of $\vec{E}$. For small rotations, the angle of rotation is proportional to I_x. The experiment is performed using Na or K; as these atoms have a small enhancement factor, we assume that any observed signal is due to the motional magnetic field effect. The signal is measured for several values of I_x, and the value of I_x for which $\vec{E}$ and $\vec{H}$ are aligned is determined by a least-squares fit of the data. The experiment is repeated using thallium. Any difference in the value of I_x for which the signal equals zero may be interpreted as an LSE. The results of comparison No. 6 are shown in Fig. 2.

The results of seven alkali-thallium comparisons, comprising 5×10^4 electric-field reversals, is given in Table I. The average alkali-thallium intercept difference is 0.058 ± 0.104, where the error is the standard deviation. A chi-squared test indicates a confidence interval of 99% that the data are consistent with a Gaussian distribution of the same mean and standard deviation.

Writing the LSE as $\Delta\nu = kE$, we find from the data in Table I that $k=(3.3\pm6)\times10^{-7}$ Hz $(\mathrm{V/cm})^{-1}$. The relation between the EDM of the atom and the LDE is given by $D=hkF/e$, where h is in erg cm, k in Hz/esu, and e in esu. We find for thallium, $D_{\mathrm{Tl}}=[(1.3\pm2.4)\times10^{-21}\ \mathrm{cm}]e$. We take the upper limit of the electron EDM as $D_e=D_{\mathrm{Tl}}/200$ or $D_e=[(6\pm12)\times10^{-24}\ \mathrm{cm}]e$. Using Cs-Na comparisons, Weisskopf et al.[12] have established an upper limit of $D_e=(\pm3\times10^{-24}\ \mathrm{cm})e$.

The fact that the intercept differences are larg-

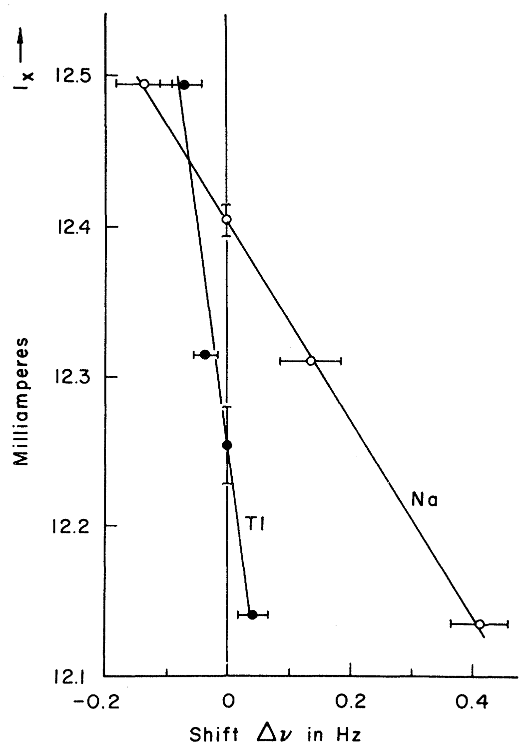


FIG. 2. Tl-Na comparison; experiment No. 6. The shift in the frequency of the Zeeman "flop-in" transition caused by a reversal of the direction of the electric field as a function of the current I_x. Horizontal error bars are one standard deviation; vertical error bars are the standard deviation of the least-squares fit. The LSE in this comparison was 0.06 Hz or 1.1 $\times10^{-6}$ Hz $(\mathrm{V/cm})^{-1}$. The slope of the graph is -3.4 mA/Hz.

Table I. Thallium-alkali intercepts.

Comparison No. and Alkali Used	Slope (ma/Hz) Alkali	Tl	Intercepts (ma) Alkali	Tl	Intercept Difference (ma)
1. K	-1.23	-3.7	13.045±.005	12.984±.01	.061
2. Na	-0.88	-3.7	13.043±.0015	12.97±.006	.073
3. Na	-0.75	-3.2	12.636±.004	12.469±.015	.167
4. Na	-0.76	-3.3	12.607±.0004	12.463±.018	.144
5. Na	-0.74	-3.0	12.366±.0035	12.426±.01	-.06
6. Na	-0.67	-3.4	12.405±.0007	12.255±.022	.15
7. Na	-0.60	-3.4	12.360±.0085	12.487±.016	-.127
Na	-0.66		12.354±.001		
Na	-0.67		12.359±.008		

er than the errors to the least-squares fit in Table I suggests that the sensitivity of the experiment is being limited by instrumental effects, probably trajectory effects. A smaller magnetic moment and a higher beam temperature cause Tl atoms to undergo smaller deflections than alkali atoms in the deflecting magnets, giving rise to differences in the trajectories through the interaction region. If the electric field plates are not perfectly parallel, then atoms very near to one plate will experience a different $\vec{v}\times\vec{E}/c$ effect than atoms very near to the other plate. A nonparallelism of a few ten-thousandths of a radian is sufficient to account for the difference between Tl and alkali intercepts. As the trajectory effects depend upon the position of the beam source, which varied between comparisons, intercept differences averaged out over the seven comparisons.

We are currently constructing a new interaction region which will use much stronger electric fields. It is hoped that we can partially remove the degeneracy between the substates via the quadratic Stark interaction, thus eliminating the need for a magnetic field. This, in turn, would remove the contribution from the $\vec{v}\times\vec{E}/c$ effect.

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