tion actually leads to an unbound state.

[6]Footnote f in Table I of Ref. 4.

[7]B. M. Smirnov, Teplofiz. Vysokikh Temperatur, Akad. Nauk SSSR 3, 775 (1965) [translation: High Temp. 3, 716 (1965)].

[8]A. C. Riviere and D. R. Sweetman, Phys. Rev. Letters 5, 560 (1960).

[9]B. Donnally, to be published.

[10]The Wien filter construction is based in part on the more sophisticated design by L. Wählin, used by the University of Colorado cyclotron group.

[11]C. E. Kuyatt and J. A. Simpson, Rev. Sci. Instr. 38, 103 (1967).

[12]We have used 755.1 mV as the affinity for hydrogen, taken from the calculation by C. L. Pekeris, Phys. Rev. 112, 1649 (1958).

[13]An additional experiment was done with an rf ion source. Unfortunately, no direct measurement of the ion energy was made; the value of 920 eV determined from the H-D splitting gives 78 mV for the helium affinity.

[14]S. Geltman, Astrophys. J. 136, 935 (1962).

[15]These differential cross sections are measured essentially in the direction of the optical electric vector.

ELECTRIC DIPOLE MOMENT OF THE CESIUM ATOM. A NEW UPPER LIMIT TO THE ELECTRIC DIPOLE MOMENT OF THE FREE ELECTRON*

T. S. Stein, J. P. Carrico, E. Lipworth, and M. C. Weisskopf
Brandeis University, Waltham, Massachusetts
(Received 5 September 1967)

A few years ago, experiments were begun to search for an electric dipole moment (EDM) of the cesium atom.[1,2] The importance of these experiments lies in the fact that the observation of an EDM in an atomic system of well-defined angular momentum would be direct evidence for a violation of both space-inversion and time-reversal invariance.[3]

The experiments were performed on an atomic beam magnetic resonance apparatus. The transition between the levels (4, −4) and (4, −3) of cesium was induced in a Ramsey double hairpin in a weak uniform magnetic field $\vec{H}$. A set of parallel electric field plates was situated between the rf loops. A small resonance shift, linear in the applied electric field $\vec{E}$, was observed. This effect could possibly have been interpreted as due to the interaction of an EDM of the cesium atom with this field. Stated as an upper limit on the existence of an EDM of the cesium atom, the result of these experiments was $d_{Cs} = (2.2 \pm 0.1) \times 10^{-19}$ cm$\times e$.

As was pointed out at the same time, there was an alternative explanation for this effect. As the atom moves with velocity $\vec{v}$ through the electric field it experiences a motional magnetic field $\vec{v} \times \vec{E}$. A resonance shift, linear in $\vec{E}$, due to the interaction of the atom's magnetic dipole moment with this motional magnetic field results if $\vec{E}$ is not parallel to $\vec{H}$. The experiments are very sensitive to this alignment as a misalignment of 0.01 rad would explain the result above.

The possibility that a $\vec{v} \times \vec{E}$ effect was causing the linear shift was indirectly taken into account in later work by comparing shifts in various alkalies. This led to a new upper limit for the cesium atom of $d_{Cs} = (5.1 \pm 4.4) \times 10^{-20}$ cm$\times e$.[4,5] King,[6] using a square-wave phase-modulation technique to eliminate $\vec{v} \times \vec{E}$, found $d_{Cs} = (0.8 \pm 8.0) \times 10^{-20}$ cm$\times e$. Sandars,[7] in a recent experiment where $\vec{v} \times \vec{E}$ was taken into account by comparing results from beams in opposite directions, found as an upper limit $d_{Cs} = (9 \pm 10) \times 10^{-21}$ cm$\times e$.

In this Letter we wish to report the results of experiments in which $\vec{v} \times \vec{E}$ is measured directly on the Zeeman transitions $(F, m_F = -I \pm \frac{1}{2}) \leftrightarrow (F, -I - \frac{1}{2})$ of several of the alkali atoms. The approach differs from that used in the previous work in the following ways:

(1) A new, longer resonance region is used in which the $\vec{H}$ field (horizontal field) is produced by rectangular Helmholtz coils mounted on a cylindrical form enveloping the electric field plates and rf loops.[8] An additional pair of coils was mounted at right angles to the $\vec{H}$-field coils in order to produce a magnetic field (vertical field) perpendicular to $\vec{H}$. Adjustment of the current in this latter pair of coils allows us to vary the alignment of $\vec{E}$ and $\vec{H}$ electronically, and thus manipulate the $\vec{v} \times \vec{E}$ effect. The entire resonance region is magnetically shielded by three concentric Hipernom cylinders to minimize noise due to fluctuations in the ambient field.

(2) Digital signal-processing techniques are used. The direction of the $\vec{E}$ field is reversed periodically and the resonance signal is accumulated in two counters gated synchronously

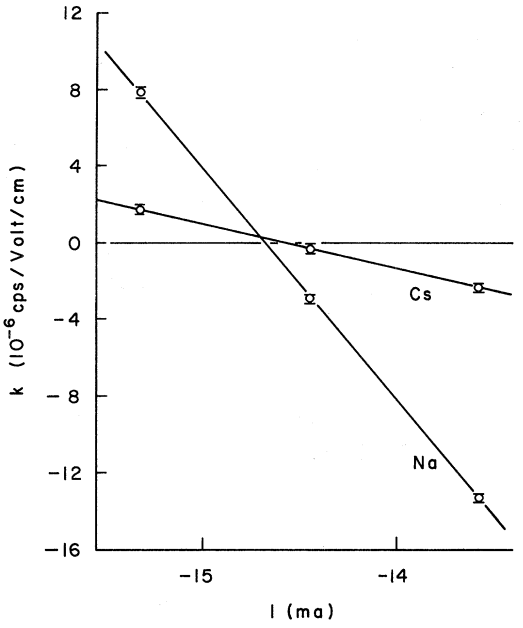

FIG. 1. $k = \Delta\nu(E)/E$ is plotted. $\Delta\nu(E)$ is the resonance shift due to the $\vec{E}$ field; I is the current in the vertical C-magnet coil. A change of 1 mA in I produces a change in the angle between $\vec{E}$ and $\vec{H}$ of approximately 0.08°.

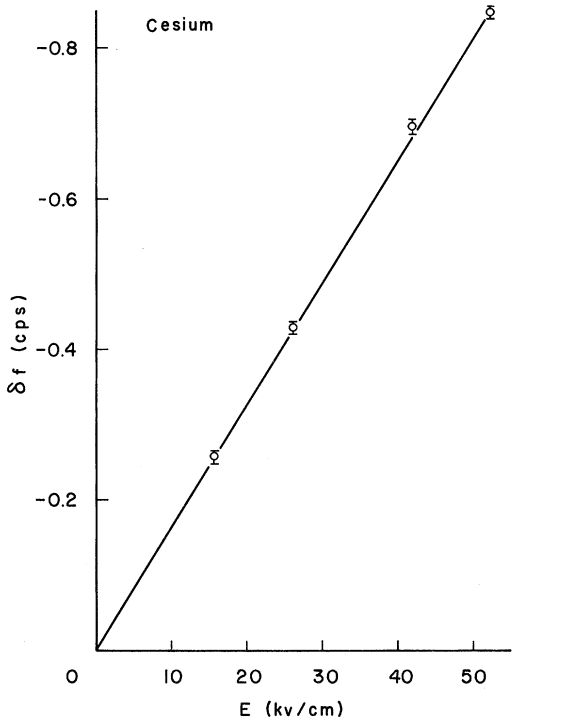

FIG. 2. The resonance shift $\Delta\nu(E)$ plotted as a function of the electric field E for a constant angle between $\vec{E}$ and $\vec{H}$.

with the switching frequency. In this way the quadratic Stark effect subtracts out and any remaining signal indicates the presence of an effect which is linear in $\vec{E}$. By introducing the appropriate delays into a counting cycle, a steady $\vec{E}$ field is insured during the time when data are taken. This eliminates possible transient effects (e.g., that caused by a displacement current).

(3) A phase-locked frequency synthesizer is used. This and the magnetic shields give us a very stable resonance. Noise is then limited to that associated with beam production and the detection electronics.

(4) Several beams are prepared simultaneously so that comparisons between different alkalies can be made in short periods of time. This insures as similar environmental conditions as possible.

Experiments consist of studying the signal linear in $\vec{E}$ as a function of the current through the vertical field coils and determining the point of zero signal (intercept) in each element. The intercepts of several alkalis are compared. The importance of making comparisons between different elements stems from the fact that the initial misalignment (i.e., vertical field = 0) of $\vec{E}$ and $\vec{H}$ is not known a priori. If only one element is studied this information would be required to determine whether linear effects other than $\vec{v}\times\vec{E}$ are present. In a comparison, however, the initial misalignment subtracts out. If the intercepts are not the same for different elements then an interaction other than $\vec{v}\times\vec{E}$ is also contributing to the linear signal.

Experiments were conducted comparing Na with Cs and Na with K. A typical result of a Na-Cs comparison is shown in Fig. 1. The linearity of the resonance shift as a function of the applied electric field is shown in Fig. 2. The intercepts do not coincide for either the Na-Cs or the Na-K comparisons. Although these differences could be due to EDM interactions, we have not been able to rule out the possibility that instrumental effects are responsible.

If, for example, the $\vec{E}$ field does not reverse exactly when the high voltage is switched, the quadratic Stark interaction can give rise to an effect that is not subtracted out by our data-processing technique. Use was made of the measured values of the quadratic Stark shifts[9] to see if the zero-signal differences could be explained by such an effect. However, an ana-

lysis of the data shows that a quadratic Stark effect cannot completely account for the differences between intercepts. Comparison of results of linear shift measurements on the cesium hyperfine doublet $(4, 0) \leftrightarrow (3, 1)$ and $(4, 1) \leftrightarrow (3, 0)$ with measurements made on the Zeeman transition support this conclusion. This doublet was studied because any quadratic Stark effect which interferes with the linear shift measurements on the Zeeman levels would show up 200 times larger on the hfs line. This doublet and the Zeeman line have the same magnetic dependence. If the largest observed intercept difference (Cs_{hfs}-Cs_{Zeeman}), which corresponds to 0.32 cps at 5.25×10^5 V/cm, is attributed entirely to a quadratic Stark effect it would lead to a correction of 24% of the Na-Cs difference.

The data were also analyzed to see if a magnetic effect (e.g., that due to a magnetic field arising from leakage current) could account for the differences. The analysis shows that the differences between intercepts cannot be completely attributed to a magnetic effect.

A third possible source of intercept difference results if the average misalignment between $\vec{E}$ and $\vec{H}$ is different for each alkali. This occurs if the spatial distribution of velocities is different for each element and there are inhomogeneities in the electric and/or magnetic fields. In this case the initial misalignment would not be the same for each element and differences in the intercepts would be observed. Furthermore, the previous analyses concerning spurious magnetic and quadratic Stark effects would be incorrect.

There was reason to suspect that trajectory effects were present in the Na-K comparisons. These elements were placed in separate ovens along the beam axis of the apparatus. Experiments were conducted with the ovens in their original positions and again with these positions reversed. The results based on a small number of such experiments showed an effect dependent on the relative oven positions.

Sodium and cesium, however, were formed in the same oven using a charge of CsCl and Na. The oven was rotated in an attempt to change the spatial distribution of velocities. The Na-Cs difference remained constant independent of the oven rotation. Therefore, it is reasonable to conclude that the Na-Cs difference suffered less from trajectory problems than the Na-K comparisons. We thus limit our discussion to the Na-Cs data. Furthermore, as we do not completely understand the extent to which trajectory effects influence the Na-Cs data we confine the discussion below to the observed (uncorrected) Na-Cs difference.

Schiff[10] has shown that it is not possible to observe an EDM in an electrically neutral nonrelativistic system. However, Salpeter,[11] and elsewhere Sandars,[12] have shown that it is possible to observe such a moment in a relativistic system. Furthermore, a calculation by Sandars[12,13] has shown that if the electron possesses an EDM then the EDM of the cesium atom is approximately 100 times larger, whereas that of the sodium atom is 0.3 times as large. Attributing the observed difference between sodium and cesium entirely to an EDM of the cesium atom we find as an upper limit $|d_{Cs}| = (2.0\pm0.6)\times10^{-21}$ cm$\times e$. This result together with Sandars's calculation applied to cesium can be used to set a new upper limit to the EDM of the electron $|d_e| = (1.7\pm0.5)\times10^{-23}$ cm$\times e$.

At present, experiments are in progress to investigate in detail the effects described above.

The authors wish to acknowledge the contributions of the Brandeis University Machine Shop under the supervision of Mr. Arthur Larsen in the construction of the apparatus, and of Dr. Asher Adler who aided in the design of the detection electronics.

*Work supported by the National Science Foundation.

[1]P. G. H. Sandars and E. Lipworth, Phys. Rev. Letters 13, 718 (1964).

[2]E. Lipworth and P. G. H. Sandars, Phys. Rev. Letters 13, 716 (1964).

[3]T. D. Lee and C. N. Yang, Brookhaven National Laboratory Report No. BNL-443 (F91), 1957 (unpublished), p. 17.

[4]E. Lipworth, A. Adler, J. P. Carrico, T. S. Stein, and P. G. H. Sandars, Bull. Am. Phys. Soc. 11, 403 (1966).

[5]J. P. Carrico, E. Lipworth, P. G. H. Sandars, and T. S. Stein, to be published.

[6]C. O. Thornburg, Jr., and J. G. King, Bull. Am. Phys. Soc. 11, 329 (1966).

[7]J. R. P. Angel, P. G. H. Sandars, and M. H. Tinker, Phys. Letters 25A, 160 (1967).

[8]J. G. King, private communication.

[9]J. P. Carrico, E. Lipworth, P. G. H. Sandars, and T. S. Stein, to be published.

[10]L. I. Schiff, Phys. Rev. 132, 2194 (1963).

[11]E. E. Salpeter, Phys. Rev. 112, 1642 (1958).

[12]P. G. H. Sandars, Phys. Letters 14, 194 (1965).

[13]P. G. H. Sandars, Phys. Letters 22, 290 (1966).