The second and third term in the bracket in eq. (5) are proportional to N and depend on the temperature as $T^{-\frac{3}{2}}$ and T^{-2}. For low temperatures the total correction will be negative, whereas above $T \approx 3000^{\circ}$K the opposite is true. Recalling that very dense gases will be highly ionized only if the ratio of the thermal energy and the ionization potential are not too small, we conclude that under such a condition the second term will dominate the third one. Of course, at high temperatures quantum effects are significant only in extremely dense systems. Thus, for instance, at a thermal energy of 1 eV the condition $Nv_0 = 1$ will be fulfilled for $N \approx 3 \times 10^{21}$. On the other hand, in the low temperature regions the correction terms may be of interest in considering the conduction band of an impurity semiconductor. Owing to the fact that the electron effective mass is usually much less than m, the quantum effect may become more pronounced in this case.

A similar calculation may be carried out for the low frequency solution of the dispersion relation in an electron-ion plasma

$$1 + 4\pi\, \alpha_{\mathrm{rpa}}(q,\omega) + 4\pi\, \alpha_{\mathrm{ex}}(q,\omega) = 4\pi\, e^2 ZN/M\, \omega^2, \tag{6}$$

$Z|e|$ and M being the ionic charge and mass, respectively. Then proceeding as before and neglecting in the course of integration the phase velocity ω/q compared with the mean electron velocity, one finds

$$\omega^2 = (q^2 ZkT/M)[1 + 0.1786\, Nv_0 - 0.1073(\hbar\omega_{\mathrm{p}}/kT)^2], \quad q \ll q_{\mathrm{D}}. \tag{7}$$

The comparison with eq. (5) shows that the quantum corrections are now of greater importance. This especially refers to the Pauli exclusion contribution, which represents the leading correction term in eq. (7) for all temperatures below 70 000°K.

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OBSERVATION OF A $v \times E$ EFFECT IN AN ELECTRIC DIPOLE MOMENT EXPERIMENT USING A REVERSIBLE ATOMIC BEAM MACHINE

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We have used a reversible atomic beam machine to eliminate the $\boldsymbol{v} \times \boldsymbol{E}$ effect and set a new limit $d_{\mathrm{e}} \leqslant 1 \times 10^{-22}$ e·cm on the electric dipole moment of the electron.

The search for electric dipole moments is of considerable current interest since the observation of such a moment in an atomic system with well defined angular momentum would indicate the violation of both parity and timereversal invariances [1].

A rather sensitive experiment of this type can be carried out using modern atomic beam techniques. In 1964 Sandars and Lipworth [2] carried out such an experiment on the ground state of cesium and found a small but definite frequency shift in the Zeeman resonance $F = 4$, $M = -4 \leftrightarrow M = -3$. This effect was linear in the applied electric field and behaved in all respects in the manner expected from an electric dipole moment.

However Sandars and Lipworth pointed out that there was an alternative explanation which may be termed the $\boldsymbol{v} \times \boldsymbol{E}$ effect. The atom as it moves with velocity $\boldsymbol{v}$ through the uniform electric field $\boldsymbol{E}$ sees an apparent magnetic field

$(v/c)\times \boldsymbol{E}$. The interaction of the atomic magnetic moment with this field leads to a shift of the resonance frequency which is linear in the electric field. One can readily show that the effect would vanish if the electric and magnetic fields in the apparatus were truly parallel. Sandars and Lipworth found that an angle of 0.01 radian between the fields would explain their results.

Preliminary evidence for the correctness of the $\boldsymbol{v}\times\boldsymbol{E}$ interpretation was obtained by Lipworth et al. [3] who found that the apparent dipole moments in a range of alkali atoms were in the ratios to be expected from their magnetic moments and velocities.

In this communication we report the results of an experiment with a new atomic beam machine in which the beam can pass through the deflecting magnets and resonance region in either direction. Since the two beams experience opposite $\boldsymbol{v}\times\boldsymbol{E}$ effects but the same true electric dipole moment interaction the two linear electric field effects can be separated.

While the basic principles of our method are similar to those of Sandars and Lipworth, there are some important differences:

1) A symmetric reversible beam is used.

2) In place of the alternating EHT and conventional lock-in methods used in ref. 2 we use square wave modulation and digital counting techniques. The advantage is that one can gate out all transients and the applied electric field is constant while observations are made.

3) As in ref. 2 the quadratic Stark effect is used for calibration purposes. Our system differs in that the calibration is continuously produced in a mode which is orthogonal to the electric dipole moment signal. The two signals are separated and accumulated by appropriate operation of the counting system. This gives us a continuous calibration signal which serves as a useful check on the operation of the apparatus.

4) In order to allow the apparatus to accumulate data over long periods the oscillator frequency is locked to the appropriate resonance frequency using a digital technique.

For convenience of presentation we interpret our results in terms of the effective Hamiltonian

$$H_{\mathrm{eff}} = -(d_{\mathrm{eff}}/J)\,\boldsymbol{J}\cdot\boldsymbol{E} \tag{1}$$

where d_{eff} is the apparent electric dipole moment of the atom. It is easy to show that eq. (1) leads to a shift of the observed $F = 4$, $M = -4 \leftrightarrow M = -3$ transition in cesium which is given by

$$h\delta\nu = -\tfrac{1}{4}\, d_{\mathrm{eff}}\, E \tag{2}$$

Our results are given as the average of several sets, each set taking about twelve hours of data collection. We find:

With the beam going east to west $d_{\mathrm{eff}} = (+57\pm 20)\times 10^{-21}\ e\cdot$ cm.

With the beam going west to east $d_{\mathrm{eff}} = (-39\pm 8)\times 10^{-21}\ e\cdot$ cm.

The errors quoted are purely statistical and are consistent with the fluctuations to be expected from the number of particles in the beam.

The change in sign of the apparent dipole moment d_{eff} for the two opposite beam directions is convincing evidence for the presence of a $\boldsymbol{v}\times\boldsymbol{E}$ effect. Calculation shows that the corresponding misalignment of the electric and magnetic fields is 2×10^{-3} radian. This corresponds quite closely with the expected accuracy of mechanical alignment of the magnet pole face and the electric field plates.

Assuming that the part of our data which changes sign on reversing the beam can be attributed to the $\boldsymbol{v}\times\boldsymbol{E}$ effect we can deduce a value for the electric dipole moment of the atom. We find

$$d_{\mathrm{A}} = (+9\pm 10)\times 10^{-21}\ e\cdot \mathrm{cm}.$$

The error quoted here is based on our feeling that the velocity distribution and hence $\boldsymbol{v}\times\boldsymbol{E}$ in the two beam directions may differ by as much as 25 per cent.

If we now make use of the theoretical calculation [4] that relativistic antishielding effects make the electric dipole moment of the atom a factor of order 100 bigger than of the free electron we find for the moment of the electron

$$d_{\mathrm{e}} \leqslant 1\times 10^{-22}\ e\cdot \mathrm{cm}.$$

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