ENHANCEMENT FACTOR FOR THE ELECTRIC DIPOLE MOMENT OF THE VALENCE ELECTRON IN AN ALKALI ATOM

P. G. H. SANDARS
The Clarendon Laboratory, Oxford

Received 7 July 1966

The atomic electric dipole moment caused by a moment on the electron is calculated for the alkalis in their ground states. The ratio of the atomic to electronic moments is found to range from 4×10^{-3} for lithium to 10^3 for francium.

It is well known that the existence of an electric dipole moment on an elementary particle would violate both parity and time-reversal invariances. The recent observation of the *CP* violating $K_2^0 \rightarrow 2\pi$ decay [1] implies through the *CPT* theorem the violation of time-reversal invariance. Since parity is well known to be violated there is now no reason why an elementary particle should not have an electric dipole moment. This situation has stimulated considerable interest in the experimental search for such moments.

In two previous communications [2,3] we have pointed out that experiments to look for a linear Stark effect in the ground states of free alkali atoms can form an extremely sensitive test for an electric dipole moment on the electron. In part this sensitivity comes from the ease with which one can carry out precise atomic beam experiments on alkali atoms [2]. But more important is the fact that the polarizability of the alkali atoms can enhance the effect of the electric dipole moment of the electron by several orders of magnitude. As we showed in ref. 3 the electric dipole moment of the Cs atom is larger than the electric dipole moment of the electron by a factor of order 100.

In this paper we report new calculations on the ratio of the atomic moment d_A to the electronic moment d_e for all the alkalis in their ground states. For convenience of calculation we have used a method involving an expansion in $Z^2\alpha^2$ rather than the purely relativistic treatment we reported in ref. 3. We write our expansion in the form

$$d_A/d_e = S = S^0 + S^1 + S^2 + \dots \qquad (1)$$

where S^0 is value of the ratio of the non-relativistic limit, S^1 is the term of order $Z^2\alpha^2$ and so on. One can show on very general grounds [3,4]

Table 1
Calculated values of ratio d_A/d_e for alkali ground states.

Element	Z_1	Relativistic correction factor F	d_A/d_e unshielded (a)	d_A/d_e shielded (b)
Li	3	1.0009	4.5×10^{-3}	4.3×10^{-3}
Na	11	1.012	3.3×10^{-1}	3.18×10^{-1}
K	19	1.036	2.65	2.42
Rb	37	1.15	27.5	24
Cs	55	1.39	133	119
Fr	87	2.8	1150	-

that $S^0 = 0$; in the non-relativistic limit the atom does not have a moment even if the electron does. We show elsewhere [5] that the higher order terms in eq. (1) do not vanish and that in the approximation where the valence electron is treated as a single particle moving in a central potential $V(r)$ S^1 is given to an adequate approximation by

$$S^1 = -\tfrac{2}{3}\alpha^2 \int R^s(r) R^p(r) \frac{d}{dr}(V(r))^2 \, dr \ . \qquad (2)$$

Here $R^s(r)$ is the radial part of the valence wavefunction and $R^p(r)$ is a perturbed radial function which satisfies a Sternheimer equation

$$\left[\epsilon^s + \tfrac{1}{2}\frac{d^2}{dr^2} - \frac{1}{r^2} + V(r)\right] R^p(r) = rR^s(r) \ , \qquad (3)$$

where ϵ^s is the single particle energy of the unperturbed valence electron. By means of a method analogous to that used by Casimir [6] when considering hyperfine structure one can show that the terms in eq. (1) of higher order in $Z^2\alpha^2$ can be incorporated into a relativistic correction factor given by $F = S/S^1 = 3(2\rho+1)\rho(2\rho-1)$ with $\rho = (1-Z^2\alpha^2)^{\frac{1}{2}}$. By a convenient coincidence F is identical to the hyperfine structure correction factor F_r tabulated by Kopferman [7].

We have obtained numerical solutions for the Sternheimer equation (3) for all the alkalis using the potentials and unperturbed valence wave-functions given by Herman and Skillman [8]. The results for the ratio d_A/d_e, multiplied by the appropriate relativistic correction factor F, are given in table 1 column (a). The value for Cs is in excellent agreement with the provisional value given in ref. 3 which has been used by Lipworth et al. [9] to set the present limit $d_e \lesssim 5 \times 10^{-22}$ $e \times$ cm on the moment of the electron.

An important objection to the calculation above is that it neglects the polarizability of the atomic core. This could be serious since one knows that an electric dipole moment at the nucleus is reduced by a factor $1/Z$ by the shielding effect of the core. To investigate this we have solved eq. (3) with the right hand side multiplied by the shielding factor $(\alpha_c + (Z-1)r^3)/(Z\alpha_c + (Z-1)r^3)$ where α_c is the polarizability of the core given by Dalgarno [10]. The results of these calculations are given in column (b) of the table. It is clear that there are small modifications to the values for the ratio d_A/d_e but that the overall magnitudes are unchanged.

1. Christenson, Cronin, Fitch and Turlay, Phys.Rev. Letters 13 (1964) 138.
2. P.G.H.Sandars and E.Lipworth, Phys.Rev.Letters 13 (1964) 718.
3. P.G.H.Sandars, Physics Letters 14 (1965) 194.
4. L.I.Schiff, Phys.Rev.132 (1963) 2194.
5. P.G.H.Sandars, to be published.
6. H.B.G.Casimir, On the interaction between atomic nuclei and electrons (W.H.Freeman, San Francisco, 1963).
7. H.Kopferman, Nuclear moments, (Academic Press, New York, 1958).
8. F.Herman and S.Skillman, Atomic structure calculations (Prentice-Hall, Englewood Cliffs, New Jersey, 1963).
9. E.Lipworth, A.Adler, J.P.Carrico, T.S.Stein and P.G.H.Sandars, Bull.Am.Phys.Soc.11 (1966) 403.
10. A.Dalgarno, Advances in Physics 11 (1962) 281.

* * * * *

THE VELOCITY DEPENDENCE OF ATOM-ATOM TOTAL SCATTERING CROSS SECTIONS IN THE 7-500 eV ENERGY RANGE

W. NEUMANN and H. PAULY

Institut für Angewandte Physik der Universität Bonn

Received 8 July 1966

Total scattering cross sections for fast alkali metal atomic beams scattered by a thermal Hg beam have been measured for energies of 7-500 eV. Glory-oscillations and the transition to the high energy behavior have been observed.

The velocity dependence of the total scattering cross section for fast Na, K and Cs atomic beams scattered by a thermal Hg beam has been measured for energies of 7 to 500 eV. Glory oscillations in the total cross section which have been reported only for collisions in the thermal energy region [1-3], were observed in these experiments.

The apparatus and measurement procedure are described in detail elsewhere [4], and thus only the main features are mentioned here. To form the primary beam, alkali ions are produced by surface ionization, accelerated to the desired energy, and then neutralized by charge exchange with thermal alkali atoms. The secondary beam is formed by the effusion of Hg from a many-channel oven. It can be turned on and off by an electromagnetically operated shutter. The fast alkali atoms are detected by surface ionization on an unheated 92% W - 8% Pt filament. This method of detection eliminates the thermal alkali atoms, which can reach the detector from the charge exchange chamber. For the present measurements the detector filament was 15 mm high and 25 μ wide. The half-width of the primary beam at the detector was about 130 μ, and the distance from the scattering center to the detector was 55 cm.

The experimental results are shown in fig. 1, where the total scattering cross section $Q(v)$ is plotted as a function of the primary beam velocity v. Clearly seen are both the oscillations in $Q(v)$