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Measurement of alkali-metal polarizabilities by deflection of a velocity-selected atomic beam*

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The electric dipole polarizability of the alkali-metal atoms Na, K, Rb, and Cs are determined by measuring the deflection of a velocity-selected beam by an inhomogeneous electric field. It is shown experimentally that scattering of slower beam atoms by background gas in the apparatus is an important systematic error in measurements of this kind if a beam-velocity selector is not used, and that this scattering is responsible for the discrepancies between different, earlier beam-deflection measurements of polarizability. The polarizability values obtained in this work are $\alpha(\mathrm{Na}) = 24.4 \pm 1.7$ Å^3, $\alpha(\mathrm{K}) = 45.2 \pm 3.2$ Å^3, $\alpha(\mathrm{Rb}) = 48.7 \pm 3.4$ Å^3, and $\alpha(\mathrm{Cs}) = 63.3 \pm 4.6$ Å^3.

I. INTRODUCTION

The dipole polarizability of an atom can be measured by deflecting a beam of the atoms in question with an inhomogeneous electric field. The experiment is shown in Fig. 1. Atoms that have polarizability α are deflected by an amount

$$x_v = \frac{1}{2}\left(\alpha E \frac{dE}{dx}\right) L^2/mv^2$$

as they pass with velocity v through a distance L in which one maintains a transverse electric field with known strength E and gradient dE/dx. The net deflection of atoms at the plane of the detector, s_v, is directly proportional to x_v; so a measurement of the deflection yields a value for the polarizability provided that the atoms in the beam have a known, well-defined velocity. If the atoms have a wide distribution of velocities, however, the extraction of a value for the polarizability from the pattern of deflected atoms requires a knowledge of the velocity distribution of the atoms that comprise the beam in the neighborhood of the detector.

The deflection of atoms in a velocity-selected beam can be measured in either of two ways: (i) For relatively large deflections one measures the beam shape $I(x)$ (i.e., the number of beam atoms detected versus the detector position x) with and without the electric field applied; the net deflection of the beam is then found by comparing the locations of the field-on and field-off beam shapes. (ii) For smaller deflections it is advantageous to position the detector on the side of the beam shape where the detected signal $I(x)$ depends strongly on the relative position of the beam and the detector. If the beam, comprised of atoms with velocity v, is deflected by an amount s_v when the field is applied, then the resultant change in detector signal is $\Delta(x, E) = [dI(x)/dx]\, s_v$. Hence a measurement of $\Delta(x, E)$ and $I(x)$ suffices to determine s_v.

The deflection of atoms in a beam that has a distribution of velocities can be determined provided that one has a knowledge of (or makes an assumption about) the velocity distribution. The analysis appropriate for a Maxwellian distribution has been given in detail elsewhere[1]; the result for that special case is $\Delta(x, E) = [dI(x)/dx]\, s_{\bar{v}}$, where $s_{\bar{v}}$ is the deflection experienced by an atom with velocity $\bar{v} = (2kT/M)^{1/2}$, and where $I(x)$ is the beam shape as measured without velocity selection.

In previous polarizability measurements of this type done by Scheffers and Stark[2] (SS) and by Chamberlain and Zorn[3] (CZ), no velocity selector was employed. Therefore the beams were comprised of atoms that had a broad range of velocities, and the pattern of deflected atoms was interpreted by measuring the source temperature and assuming that the atoms had the corresponding Maxwellian velocity distribution. In particular, CZ had designed their oven source in the way that Miller and Kusch[4] had suggested would be most favorable for production of a Maxwellian distribution.

At about the same time as the CZ research was being done, Salop, Pollack, and Bederson[5] (SPB) measured the alkali atom polarizabilities with an E-H–gradient atomic beam method, the principles of which are described in the immediately preceding article by Molof, Schwartz, Miller and Bederson.[6] As compared with the electric-deflection method, the E-H–gradient balance method has the important advantage of not depending on a knowledge of the atomic velocities. Unfortunately, the agreement between the SS, CZ, and SPB experiments was not as good as one might have expected. Since the weakest link in the electric-deflection experiments was the assumption about the velocity distribution, we undertook the present experiment[7] in which the alkali polarizabilities are determined from the electric deflection of a velocity-selected atomic beam.

II. APPARATUS

The atomic beam apparatus used for this experiment is described in detail in the doctoral dissertation of Hall.[8] The principal dimensions are given in Fig. 1. Oil-diffusion pumps and liquid-nitrogen traps are used to produce a system base pressure of 1×10^{-7} Torr; however, there is also provision to raise the over-all system pressure as high as 3×10^{-5} Torr by the controlled addition of argon gas so that the effect of background gas scattering may be studied.

The atomic beam is generated in an oven of standard design.[4] The knife-edge slit through which the atoms emerge is 0.025 cm wide and 0.5 cm high. A surface ionization detector with effective dimensions of 0.008 cm wide × 0.5 cm high is employed.

A rotating-disk velocity selector[9] can be moved in and out of the beam so that one can work either with the full output of the oven or with atoms whose velocity is within 2% of a mean velocity that is known to an accuracy of 0.5%. The test of this velocity selector by time-of-flight methods has been described elsewhere.[10]

The inhomogeneous electric field is of the two-wire type. Its cross-sectional geometry differs only in minor respects from that shown in Fig. 3 of Ref. 3.

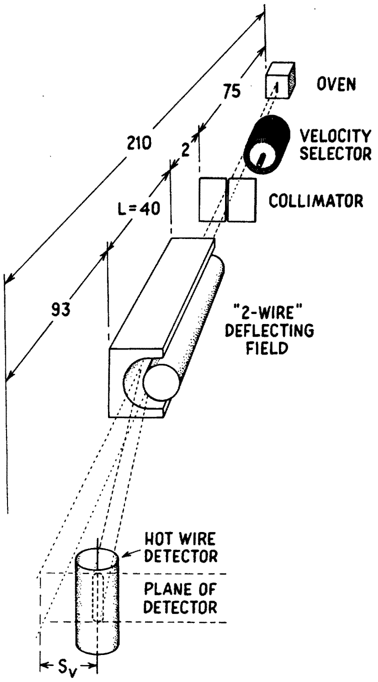

FIG. 1. Schematic diagram of electric-deflection measurement of atomic polarizability. Indicated dimensions are in centimeters.

III. RESULTS

Measurements were made on beams of sodium, potassium, rubidium, and cesium. Unfortunately the velocity selector was not capable of sustained operation at the rate of rotation required for lithium.

Deflection measurements without the velocity selector were done with various pressures of the deliberately added background gas. For direct comparison with the experiments of SS and CZ, the calculations of polarizability were done just as though the velocity distribution were the Maxwellian expected from a source at the measured temperature of the beam oven. The results show a striking dependence of the apparent polarizability on the scattering gas pressure. We show the results for Cs in Fig. 2, and we note that the systematic effect of the scattering seems to be present even at the lowest attainable pressure. Similar dependences on gas pressure are found for the other alkali atoms. For example, the apparent polarizability of K as measured with 3×10^{-5} Torr of argon in the apparatus is 31 Å^3; this may be compared to the value $\alpha(\text{K})=45.2\pm3.2$ Å^3 obtained from measurements on velocity-selected beams. It is interesting to note that the apparent values of polarizability obtained in this experiment from deflection measurements at 10^{-7} Torr without a velocity selector [$\alpha(\text{Na})=22.6$ Å^3; $\alpha(\text{K})=42.5$ Å^3; $\alpha(\text{Rb})=42.3$ Å^3; $\alpha(\text{Cs})=48.1$ Å^3] are quite comparable to the CZ values.

Measurements with the velocity selector in place were done in order to analyze the beam velocity distributions and to measure the deflection of atoms of known velocity. These measurements showed the manner in which the velocity distribution is altered as one adds argon scattering gas to the vacuum system to change the pressure over the range 1×10^{-7}–1×10^{-5} Torr. Even at 10^{-7} Torr there are significant deviations from the Maxwellian distribution at low velocities. Deflection measurements of atomic polarizability were done with selected velocities ranging between $\bar{v}/2$ and $2\bar{v}$ for each atomic species. As seen in Fig. 2 the values of polarizability obtained from velocity-selected beam measurements do not depend significantly on the system pressure. Voltages up to 10 kV were applied to the deflecting field electrodes; the deflections were found to be proportional to V^2, as expected.

The final results from this experiment, derived from an extended series of measurements taken with velocity-selected beams, are as follows:

$$\alpha(\text{Na})=24.4\pm1.7\ \text{Å}^3,$$

$$\alpha(\text{K})=45.2\pm3.2\ \text{Å}^3,$$

$$\alpha(\mathrm{Rb}) = 48.7 \pm 3.4\ \text{Å}^3,$$

$$\alpha(\mathrm{Cs}) = 63.3 \pm 4.6\ \text{Å}^3.$$

The principal sources of uncertainty in these values are (in approximately equal proportions) (i) the uncertainty in the location of the beam within the field electrodes and the values of E and dE/dx within those electrodes, (ii) the uncertainty in the length of the deflecting field because of fringing effects at the ends, and (iii) the statistical scatter in the $\Delta(x, E)$ detector signals.

IV. DISCUSSION

Polarizability measurements done without a velocity selector depend on the background gas pressure because the slower atoms are preferentially scattered out of the beam. The distribution in velocity of the remaining beam atoms is such that the beam as a whole deflects rather less from the electric forces than one would expect from a beam with an ideal Maxwellian distribution.

Although Miller and Kusch have shown that careful construction and operation can yield a beam with an essentially Maxwellian velocity distribution for many kinds of beam experiments, the beams employed in polarizability measurements are long and tightly collimated so that even a very small angle scatter suffices to prevent an atom from reaching the detector. This also affects the interpretation of the electric deflection experiments that test for an inequality between the electron and proton charge magnitudes[1,11]; the actual limits established by these experiments are probably a factor of 2 or so larger than is quoted in the publications.

From these results we conclude that the discrepancy between the SS, CZ, and the present electric deflection measurements of the polarizability of the alkali atoms can be understood as a consequence of the alteration of the beam velocity distribution by scattering from background gas in the apparatus. If a velocity selector is not employed and a Maxwellian distribution is simply assumed, then the apparent value of the polarizability is a very strong function of the pressure within the system.

The discrepancy between the electric-deflection results and the SPB E-H-gradient balance experiment appears to be resolved by the work of Molof, Schwartz, Miller, and Bederson as discussed in their accompanying paper.[6]

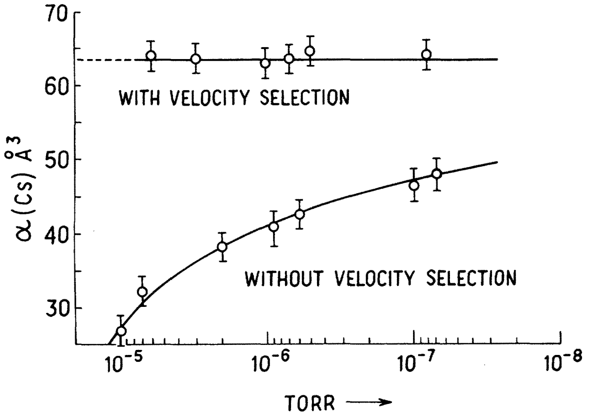

FIG. 2. Polarizability of cesium measured as a function of background gas pressure. Error bars shown on this figure show run-to-run consistency; they do not include all of the systematic errors that could affect the final result for α(Cs). Values labeled "without velocity selection" were obtained by analyzing the data as though the beam-velocity distribution were an undistorted Maxwellian. The values for α(Cs) obtained in earlier deflection experiments without use of velocity selection (shown in Fig. 3) are fully consistent with the data shown here.

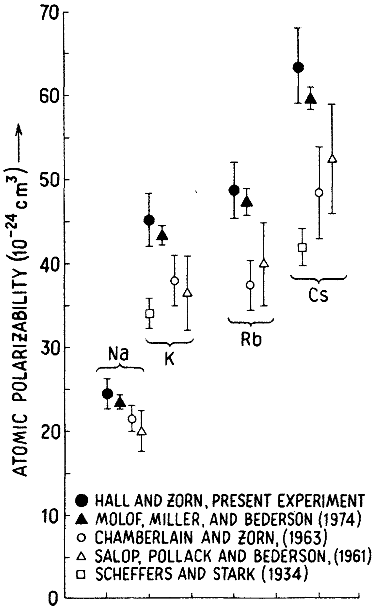

FIG. 3. Results from atomic-beam measurements of alkali-metal polarizabilities. Triangles (open and filled), results from E-H-gradient balance experiments (Refs. 5 and 6); open circles and squares, results from electric deflection experiments that did not employ velocity selection (Refs. 2 and 3). Comparisons with theory are given in the accompanying article by Molof, Schwartz, Miller, and Bederson (Ref. 6). See also the review by R. Teachout and R. Pack, At. Data 3, 195 (1971).

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