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Measurement of the static electric dipole polarizabilities of barium and strontium*

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The static electric dipole polarizabilities of barium and strontium atoms have been measured using an electric deflection technique. The results are normalized to the polarizability of lithium by comparing deflections of the alkaline-earth beams to deflections of a lithium beam passing through an inhomogeneous electrostatic field. The measured polarizabilities are $(39.7\pm 3.2)\times 10^{-24}$ cm^3 for barium and $(27.6\pm 2.2)\times 10^{-24}$ cm^3 for strontium.

I. INTRODUCTION

The static electric dipole polarizability is an important property of an atom particularly in the study of interactions in which the valence electrons dominate. Despite considerable theoretical attention which has been given to the polarizabilities of the elements, the experimental work has been confined almost entirely to the noble-gas atoms and to the alkali-metal atoms.[1] We have undertaken measurements of the polarizabilities of those alkaline-earth atoms which have ionization potentials low enough that they may be detected by surface ionization—barium and strontium. Since the ground states of these atoms are S states the polarizabilities are scalar quantities.

We have previously used the same electric deflection technique to measure the average polarizabilities of the alkali dimers.[2] We have used a different technique on the same apparatus, the E-H-gradient balance method, to make accurate (±2%) measurements of the scalar polarizabilities of the alkali-metal atoms and of the tensor polarizabilities of the $^3P_2$ metastable noble-gas atoms.[3] In the present work we normalize our measurements to the polarizability of lithium, using the value reported in Ref. 3.

II. APPARATUS AND EXPERIMENTAL METHOD

Our apparatus has been described elsewhere[2,3] and the experimental method is the same as used in Ref. 2 so that the description following will be brief. The apparatus consists of a beam source, an interaction region where an electrostatic deflecting field is applied, a beam detector, and a multichannel scaler for data accumulation. The detector is a surface ionizer followed by an electric quadrupole mass spectrometer and particle multiplier. (The mass spectrometer was not used in the work of Refs. 2 and 3.) For barium a platinum wire (950 °C) was used to ionize the beam, and for strontium a rhenium wire (1600 °C) was used in an oxygen atmosphere of 10^{-7} Torr.

The inhomogeneous electrostatic deflecting field in the interaction region is formed by two iron pole pieces at different potentials, as described in Refs. 2 and 3. The electric field strength at the beam position is 11.16 cm^{-1} times the applied potential difference. The field gradient is 6.8 cm^{-1} times the electric field strength for our pole-piece geometry.

The beam source is an oven which may be heated to 1000 °K. In these experiments the oven was loaded with both barium and lithium or with strontium and lithium. Lithium was chosen for normalization of the results because the vapor pressures of barium, strontium, and lithium at 1000 °K are similar and low enough to maintain effusive beams.

The experimental procedure was to fix the detector off the beam axis a distance Z and to scan the potential across the pole pieces of the interaction region to deflect the beam. For some potential V the detected count rate would be a maximum. A plot of V^2 vs Z is found to be linear for large displacements Z as illustrated in Fig. 1. For small displacements ($Z \leq$ beam width) the line deviates toward the origin in a manner determined by the apparatus geometry. In Ref. 2 a detailed analysis of the experiment was given which showed that the ratio of the slopes of the V^2 vs Z lines (Fig. 1) for two atomic species is the inverse ratio of the polarizabilities of the two species, provided that the beams have the same velocity distribution. Therefore, we obtained deflection data first for an alkaline-earth beam and then for lithium, with the source temperature fixed. Figure 1 shows the results of typical data runs from which polarizability ratios were evaluated. (The slope of the deflection line for lithium is not the same in the two cases shown in Fig. 1 because the distance between the interaction region and the detector was 1.2 m for the barium runs and 0.9 m for the strontium runs.)

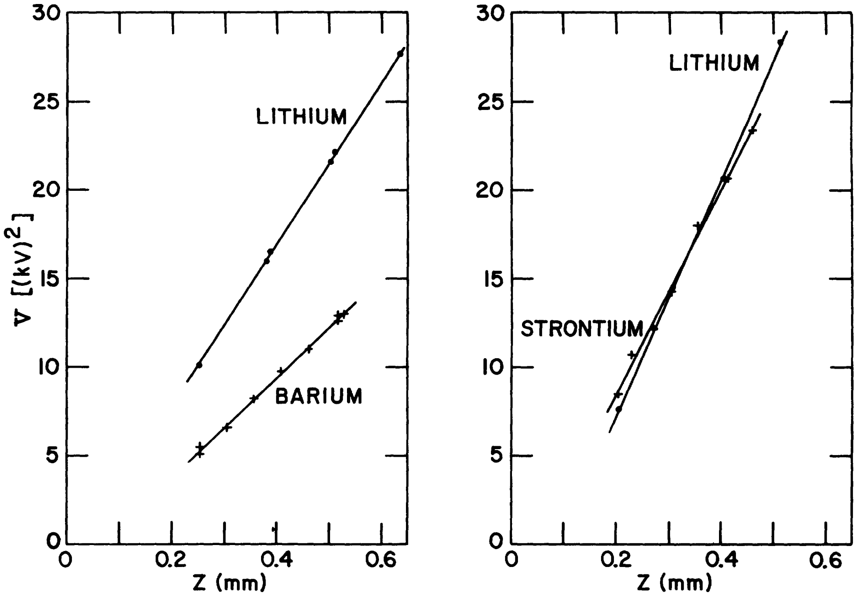

FIG. 1. Typical electric deflection data obtained for barium and lithium at the same beam-source temperature, and similar data for strontium and lithium. The potential V is that for which the beam intensity is a maximum with the detector fixed at a distance Z from the beam axis. The ratio of the deflection slopes in each case yields the inverse ratio of the polarizabilities of the atomic species being compared. The lines for two species can cross, as shown with lithium and strontium, if the active portion of the surface ionizer is wider for one of the species. However, the slopes of the lines are unaffected. Both cases shown correspond to a beam-source temperature of ~ 1000 °K. The flight path after the interaction region is different for the two cases shown; in the left-hand figure it is 1.2 m and in the right-hand figure it is 0.9 m.

III. RESULTS

Several sets of data as typified by Fig. 1 were obtained for barium and lithium, and for strontium and lithium, each set yielding a value for the ratio of the polarizability of the alkaline earth under study to that of lithium. The measured ratios are tabulated in Table I. Using the known[3] polarizability of lithium, $(24.3 \pm 0.5) \times 10^{-24}$ cm^3, we find the polarizability of barium to be 39.7×10^{-24} cm^3 and the polarizability of strontium to be 27.6×10^{-24} cm^3.

IV. DISCUSSION OF UNCERTAINTIES

As with our earlier experiment[2] the normalization procedure eliminates most uncertainties in the results except for the uncertainty in the polarizability of the "standard," the uncertainty in the relative potential measurements, and statistical fluctuations in the data. The lithium polarizability is known[3] to within 2%. Relative values of the squares of the electric potentials are good to better than 1%. Statistical fluctuations in the data (~5%) are caused mostly by shifts in the beam alignment

TABLE I. The results of all of our data runs for barium and strontium. Each data run yielded a value of the ratio of the polarizabilities (α) of barium and lithium, or of strontium and lithium.

Barium run number	α(Ba)/α(Li)	Strontium run number	α(Sr)/α(Li)
1	1.617	1	1.121
2	1.606	2	1.090
3	1.761	3	1.182
4	1.517	4	1.076
5	1.639	5	1.145
6	1.649	6	1.149
7	1.756	7	1.182
8	1.508		

TABLE II. A comparison of our measured polarizabilities with the semi-empirical calculations of Altick (Ref. 5) and Cohen (Ref. 6) and the self-consistent–field calculation of Thorhallson, Fisk, and Fraga (Ref. 7). Both Altick and Cohen state that their lower bound should be closer to the correct polarizability α. The values are all in units of 10^{-24} cm^3.

Research	Barium polarizability	Strontium polarizability
Present experiment	39.7 ± 3.2	27.6 ± 2.2
Altick	$31.9 \le \alpha \le 44.5$	$24.0 \le \alpha \le 31.4$
Cohen	$30.6 \le \alpha \le 34.7$	$23.3 \le \alpha \le 26.2$
Thorhallson *et al.*	49.7	33.4

which occur during data runs. Some of these shifts are believed to be due to work-function changes on the surface of the hot-wire detector. Overall, we assign an 8% uncertainty to the final results.

We have made consistency tests in which we deliberately offset the rear of the interaction region enough to decrease the slopes of the deflection data lines by 15%, and the polarizability ratios remain the same within the statistical uncertainty.

V. CONCLUSIONS

We have measured the static electric dipole polarizability of barium and find $(39.7 \pm 3.2) \times 10^{-24}$ cm^3. For strontium we obtain $(27.6 \pm 2.2) \times 10^{-24}$ cm^3. The only other experimental result with which we may make a comparison is from the unpublished electric deflection work of Hall, Hoeberling, and Zorn,[4] who measured $(25 \pm 3) \times 10^{-24}$ cm^3 for the polarizability of strontium.

The simplest theoretical estimates of the polarizability result from the summation of experimentally determined oscillator strengths. Altick[5] and Cohen[6] have obtained upper and lower bounds on atomic polarizabilities using this method, but with different sets of experimental data. Their results for barium and strontium are given in Table II. Both Altick and Cohen state that their lower bound should be closer to the true polarizability. Thorhallson, Fisk, and Fraga[7] used self-consistent–field wave functions to calculate atomic polarizabilities for a number of atomic species; their results are also in Table II.

Note added in proof. We have recently been able to obtain data with a calcium beam and find $(25 \pm 2.5) \times 10^{-24}$ cm^3 for the polarizability of the calcium atom. The details will be reported in a later note. Earlier we had not attempted to run a calcium (40 amu) beam because of a very large potassium (39 and 41 amu) background from our rhenium surface ionizer, but after several months at 1600 °C the background has mostly disappeared.

In regard to the self-consistent-field calculations of the alkaline-earth polarizabilities,[7] a more recent calculation for barium has been reported by K. M. S. Saxena and S. Fraga [J. Chem. Phys. 57, 1800 (1972)] using improved wave functions. Their result $(68.0 \times 10^{-24}$ cm$^3)$ is considerably larger than the other values given in Table II.

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