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Measurements of electric dipole polarizabilities of the alkali-metal atoms and the metastable noble-gas atoms*

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The E-H-gradient balance technique has been used to measure the static electric dipole polarizabilities of the alkali-metal atoms and the tensor polarizabilities of the $^3P_2$ metastable noble-gas atoms. All of the measurements are normalized to the scalar polarizability of $^3S_1$ metastable helium, a value which has been accurately calculated. The scalar polarizabilities of the alkali atoms, in units of 10^{-24} cm^3, are for lithium, 24.3 ± 0.5; sodium, 23.6 ± 0.5; potassium, 43.4 ± 0.9; rubidium, 47.3 ± 0.9; cesium, 59.6 ± 1.2. For the $^3P_2$ metastable noble-gas atoms we measure the zz components of the polarizability tensors for $m_J = 1$ and 2, which completely determines the polarizability tensors for all m_J. For $\alpha_{zz}(m_J)$ we find, in units of 10^{-24} cm^3, for neon, 28.4 ± 0.6 $(m_J = 1)$ and 26.7 ± 0.5 $(m_J = 2)$; argon, 49.5 ± 1.0 $(m_J = 1)$ and 44.7 ± 0.9 $(m_J = 2)$; krypton, 52.7 ± 1.0 $(m_J = 1)$ and 46.8 ± 0.9 $(m_J = 2)$; xenon, 66.6 ± 1.3 $(m_J = 1)$ and 57.4 ± 1.1 $(m_J = 2)$. The rare-gas results, while more precise, are in good agreement with earlier work. The alkali-metal results are in excellent agreement with recent theory and the experiment of Hall and Zorn.

I. INTRODUCTION

The static electric dipole polarizabilities of the alkali-metal atoms and of the $^3P_2$ metastable noble-gas atoms have been previously measured.[1-4] These highly polarizable systems are interesting because they may be treated approximately as one-electron atoms. In addition, the similarity in the gross structure of each of the metastable noble-gas atoms to that of the adjacent alkali atom in the periodic table invites comparisons. The ns valence electron accounts for most of the polarizability in each case, but one expects the metastable noble-gas atom to have a larger polarizability than its alkali neighbor because the metastable electron is more loosely bound. For the alkali metals the electronic core consists of closed spherical shells which contribute less than 10% to the polarizability, but for the metastable noble-gas atoms the core contains a p hole which introduces a small anisotropy in the charge distribution and the polarizability.

Atomic polarizabilities are important because of the role of induced electric dipole moments in low-energy interactions of neutral atoms with other neutral systems, with charged particles, and with electromagnetic fields, such as in chemistry, plasmas, and atmospheres. Measured values of polarizabilities provide sensitive checks on the outer part of atomic wave functions, which is crucial in describing low-energy interactions.

The best previous measurements of the alkali polarizabilities were those of Salop, Pollack, and Bederson[1] and of Chamberlain and Zorn[2] about 12 years ago, aside from the thesis work of Hall.[5] Salop *et al.* in this laboratory used the E-H-gradient balance technique while Chamberlain and Zorn used an electric-deflection method. The results of the two groups agreed within experimental uncertainty, and the measured polarizabilities were about 10% less than theoretical values based on oscillator strengths[6,7] and about 22% below a perturbation calculation of Sternheimer,[8] which included core effects approximately. A detailed discussion of the experiments and the theory existing at the time is given in a review article by Bederson and Robinson.[9] We now find the earlier alkali measurements to be too low by about 18%. The probable reasons will be discussed in Sec. V and in the following article by Hall and Zorn,[10] where their electric-deflection results for the alkalis are presented.

The only previous measurements of the polarizabilities of the $^3P_2$ metastable noble-gas atoms were those of Pollack, Robinson, and Bederson[3] for argon, and Robinson, Levine, and Bederson[4] for neon, krypton, and xenon. These measurements were made using the E-H-gradient balance technique on the same apparatus as used by Salop *et al.*[1] for the alkali measurements with an important difference: the metastable polarizabilities were normalized to the scalar[11] polarizability of $^3S_1$ metastable helium, a value which has been accurately calculated.[12] Robinson *et al.*[4] found good agreement between the measured polarizabilities and estimates they made from oscillator strengths using the Coulomb approximation of Bates and Damgaard.[6] We have remeasured the tensor polarizabilities of the $^3P_2$ metastable noble-gas atoms with an apparatus capable of greater accuracy and find good agreement with the earlier measurements of Pollack *et al.* and Robinson *et al.* Furthermore, our results agree with recent measurements of the polarizability anisotropy in the metastable noble-gas atoms by Player and Sanders.[13]

The *E-H*–gradient balance technique has also been used to measure polarizabilities of metastable mercury.[14] An electric-deflection experiment with our apparatus has been performed to measure the average polarizabilities of the diatomic alkali molecules.[15]

II. APPARATUS

Figure 1 is a diagram of our apparatus showing relevant dimensions and a cross-sectional view of the *E-H* pole pieces. The beam source is a conventional alkali oven but with a flexible metal tube attached to the side of the oven to permit us to flow gases through the oven cavity. The oven temperature was such as to cause an alkali vapor pressure in the oven of a few hundred millitorr. The rear of the oven had flexible metal tubes attached to allow quick air cooling of the oven. In order to excite the noble-gas atoms in the beam, two filaments were mounted on either side of the beam axis and electrons were accelerated from these filaments forward towards the oven, through a coarse grid, and backward towards a plate containing a beam collimating slit. The filaments were located 3 cm downstream of the oven and 1 cm away from the collimating slit. The electron accelerating potential was typically 100 V and an emission current of 200 mA was common.

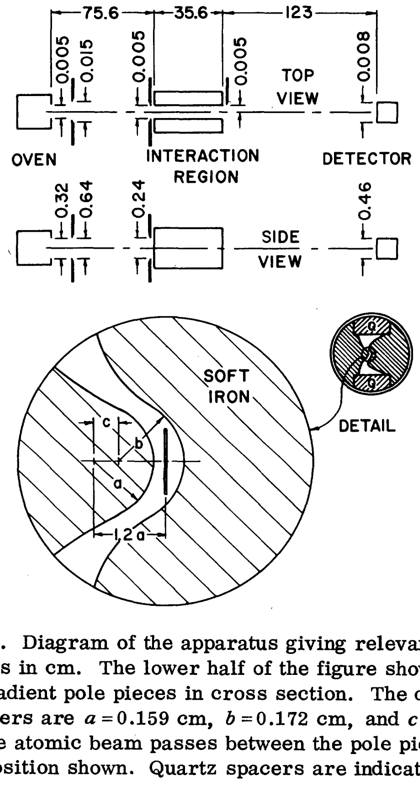

FIG. 1. Diagram of the apparatus giving relevant dimensions in cm. The lower half of the figure shows the *E-H*–gradient pole pieces in cross section. The design parameters are $a = 0.159$ cm, $b = 0.172$ cm, and $c = 0.066$ cm. The atomic beam passes between the pole pieces at the position shown. Quartz spacers are indicated by Q.

In the interaction region the beam passes between two soft iron pole pieces which are insulated from each other. The pole pieces (Fig. 1) are used to apply congruent inhomogeneous electric and magnetic fields across the atomic beam. The design is similar to the "two-wire" configuration described by Salop, Pollack, and Bederson[1] except for the size and mounting. With this configuration it can be shown analytically that the ratio of the field gradient to the field is reasonably constant over the height of the beam when the beam passes at the position shown in Fig. 1. The ratio of the field gradient to the field has been measured to be 6.8 cm^{-1} (Sec. VII). The yoke and coil of the electromagnet are external to the vacuum system. The pole pieces have a beam-defining slit mounted at the entrance to the interaction region and a half-slit mounted at the exit end. The potential applied across the pole pieces was monitored with a 10^6:1 voltage divider consisting of 0.07% resistors with negligible voltage coefficients. The reduced potential was measured with a digital voltmeter.

In the detector chamber the beam passes through a slit and is then intercepted by an array of platinum wires strung perpendicular to the beam axis and perpendicular to the slit. The array consisted of 125 wires, each 0.0025 cm in diameter, with their centers separated by 0.0050 cm. Thus, roughly half of the alkali atoms in the beam will strike the platinum wire array and surface ionize. The ions are then detected via secondary-electron emission from an aluminum surface using a scintillator and photomultiplier system. When a metastable atom beam is being run, roughly half of the atoms pass through the wire array and strike an aluminum surface, and Auger electrons are detected with the scintillator-photomultiplier system. The wire array was designed as one solution to the problem of detecting both the alkali and metastable atom beams with the same geometry and using our existing secondary-electron-emission and scintillator-photomultiplier ion detector.

The detected-particle-count rate was stored in successive channels of a 400-channel multiscaler as the multiscaler varied the electric field strength in the interaction region.

The vacuum system was of stainless-steel construction with copper gaskets except for Viton gaskets on the beam source chamber. The apparatus was pumped by oil diffusion pumps with sorption traps and the background gas pressures were typically 5×10^{-7} Torr in the beam-source chamber (with a beam running) and 10^{-8} Torr in the remainder of the apparatus.

III. EXPERIMENTAL METHOD

In the interaction region of our apparatus we apply an inhomogeneous magnetic field H across the beam which acts on the effective magnetic moment $\mu(m_F)$ of a beam particle in the magnetic substate m_F. The magnitude of the transverse magnetic force is $\mu(m_F)\,\partial H/\partial z$, where $\partial H/\partial z$ is the transverse component of the gradient of the magnitude of the magnetic field. If we also apply an inhomogeneous electric field E across the beam, there is an electric force which for a scalar polarizability α is simply $\alpha E\,\partial E/\partial z$. The induced electric force is always directed toward the direction of stronger field, while the direction of the magnetic force depends on the sign of $\mu(m_F)$. If $\mu(m_F)$ is negative it is possible to adjust the field strengths so that the electric and magnetic forces are equal and opposite. When the forces are so balanced,

$$\alpha E\frac{\partial E}{\partial z}=\mu(m_F)\frac{\partial H}{\partial z}\,, \tag{1}$$

and since atomic magnetic moments are known, it is possible to obtain α by determining E and H when the balance condition of Eq. (1) prevails. The null condition indicated in Eq. (1) is independent of the velocity distribution in the beam and the specific values of the field gradients if the electric and magnetic fields are congruent. This was the method used by Salop *et al.*[1] to measure the alkali polarizabilities. In their case the magnetic field strength at the beam position was determined from the knowledge of the field value at which $\mu(m_F)=0$ for some m_F, and the electric field strength E at the beam position was obtained from the potential V applied across the pole pieces and a geometrical factor K, where $E=KV$, which was calculated from the measured slit position and pole-piece geometry.

In the present remeasurement of the alkali polarizabilities we instead normalize our results by making nearly simultaneous observation of the applied potentials needed to balance first an alkali substate m_F and then the $m_J=1$ substate of ${}^3S_1$ metastable helium with the magnetic field strength unchanged. The alkali polarizability α is then given by

$$\alpha=\alpha_{\mathrm{He}}[\mu(m_F)/\mu_{\mathrm{He}}(1)](V_{\mathrm{He}}/V)^2\,, \tag{2}$$

where $\mu(m_F)$ and V refer to the alkali atom in question and α_{He}, $\mu_{\mathrm{He}}(1)$, and V_{He} refer to metastable helium in the $m_J=1$ substate, and where we have used the fact that the electric field gradient is proportional to the electric field strength and that the electric field strength is proportional to the applied potential. However, none of these proportionality constants enters into the expression for α given by Eq. (2). If we choose the alkali substate $m_F=F$, then Eq. (2) becomes simply

$$\alpha=\tfrac{1}{2}\alpha_{\mathrm{He}}(V_{\mathrm{He}}/V)^2\,, \tag{3}$$

where the factor $\frac{1}{2}$ is correct to better than 0.1% (Sec. IV).

The normalization technique summarized by Eq. (2) or (3) is primarily important because it removes the need to know the geometrical factor K; without normalization the polarizability depends on K^2 and errors in the shapes of the pole pieces, their spacing, and in the beam position are amplified. In addition, the normalization technique eliminates the need for an absolute calibration of the voltmeter used to measure V, and eliminates the need to know H. We will show in Sec. VII that even large misalignments of the apparatus lead to small errors in the normalized polarizability.

In the case of the ${}^3P_2$ metastable noble-gas atoms the polarizability for each m_J substate is a tensor with two independent components[3,4,9] $\alpha_{zz}(m_J)$ and $\alpha_{xx}(m_J)=\alpha_{yy}(m_J)$, where the z axis is established by the direction of the applied fields. The magnitude of the induced dipole moment in our experiment is $\alpha_{zz}(m_J)E_z$, and we measure $\alpha_{zz}(m_J)$ for $m_J=1, 2$. (The magnetic moment is zero for $m_J=0$; so this state cannot be balanced with nonzero potentials.) The two measured quantities $\alpha_{zz}(1)$ and $\alpha_{zz}(2)$ are sufficient to completely determine the diagonalized polarizability tensors for all m_J[4,9]:

$$\begin{aligned}
&\alpha_{zz}(0)=\tfrac{1}{3}[4\alpha_{zz}(1)-\alpha_{zz}(2)]\,,\\
&\alpha_{xx}(0)=\alpha_{yy}(0)=\tfrac{1}{3}[\alpha_{zz}(1)+2\alpha_{zz}(2)]\,,\\
&\alpha_{xx}(1)=\alpha_{yy}(1)=\tfrac{1}{2}[\alpha_{zz}(1)+\alpha_{zz}(2)]\,,\\
&\alpha_{xx}(2)=\alpha_{yy}(2)=\alpha_{zz}(1)\,.
\end{aligned} \tag{4}$$

The polarizabilities are independent of the sign of m_J; so Eq. (4) also applies to the $m_J=-1, -2$ substates. It is frequently convenient to express the polarizability tensors in terms of the average polarizability $\overline{\alpha}$ and the polarizability anisotropy $\gamma(m_J)$ by defining

$$\begin{aligned}
&\overline{\alpha}=\tfrac{1}{3}[\alpha_{xx}(m_J)+\alpha_{yy}(m_J)+\alpha_{zz}(m_J)]\,,\\
&\gamma(m_J)=\alpha_{zz}(m_J)-\alpha_{xx}(m_J)\,.
\end{aligned} \tag{5}$$

The average polarizability $\overline{\alpha}$ is the same for all m_J. Following Angel and Sandars[16] we define a quantity α_t by

$$\alpha_{zz}(m_J)=\overline{\alpha}+\alpha_t(\tfrac{1}{2}m_J^2-1)\,, \tag{6}$$

for $J=2$. In terms of our measured quantities,

$$\alpha_t = \tfrac{2}{3}[\alpha_{zz}(2) - \alpha_{zz}(1)]. \quad (7)$$

IV. EXPERIMENTAL PROCEDURE

With a beam operating, we align the pole pieces of the interaction region by scanning the front of the assembly across the beam to maximize the beam intensity. From the beam-intensity patterns, the position of the rear of the assembly (with half-slit attached) is determined. This procedure positions the beam along the proper path through the interaction region. Then the detector slit is scanned across the beam to check the beam profile and center position. The magnetic field is set to some suitable value and a coarse scan of the potential across the pole pieces is made to examine the spectrum of E-H balance maxima. Many maxima may occur at intermediate magnetic field strengths as the electric field strength is scanned because of the different $\mu(m_F)$ and because more than one isotope may be present. An example of such a coarse scan of the potential across the pole pieces is given in Fig. 2 for cesium at a magnetic field strength of 1.01 kG. The multiscaler has incrementally swept the potential from 1.62 to 11.0 kV and has recorded the detector count rate for each step, repetitively. To obtain the actual balance potentials we make fine scans of the maxima of interest. An example is given in Fig. 3 of one of the maxima chosen from Fig. 2 for the $(F, m_F) = (4, 4)$ substate of cesium. Also shown in Fig. 3 is a fine scan of the balance maximum for the $m_J = 1$ substate of $^3S_1$ helium. It is the square of the ratio of the two potentials corresponding to the respective maxima which determines the polarizability ratio [Eq. (2)]. Each point in Fig. 3 corresponds to an increment of the potential of 8.1 V. The fine scans typically required 0.4 h each.

With potassium and lithium we were not able to clearly resolve the $m_F = F$ substate in the fashion described above. In these two cases we operated at sufficiently high magnetic field strengths that the values of $\mu(m_F)$ for all m_F were close to one Bohr magneton (μ_B); the balance spectrum under this condition showed only one peak. The evaluation of the polarizabilities of potassium and lithium from the data required a slight modification[1,17] of Eq. (2). For each datum we determined the magnetic field strength H from the measurement of the helium balance potential and used H to calculate the average magnetic moment $\bar{\mu}$ for potassium or lithium. At the lowest values of H used, $\bar{\mu}$ was $0.90\mu_B$ and at the highest values of H, $\bar{\mu}$ was $0.99\mu_B$.

A coarse scan of the E-H balance spectrum for $^3P_2$ metastable krypton at a magnetic field strength of 313 G is given in Fig. 4, showing the $m_J = 1$ and $m_J = 2$ balance maxima.

In collecting balance data for the metastable noble-gas atoms, one simply turned off the gas under study and turned on helium to obtain the normalization data. When working with the alkali atoms, the normalization data were obtained by cooling the oven by about 30 K to reduce the vapor pressure, and then turning on the helium gas and the electron bombardment current. We parenthetically note that the presence of alkali vapor greatly enhanced electron emission from the filaments.

All of the data were normalized to the polarizability of the $m_J = 1$ substate of $^3S_1$ metastable helium using the quantities [Eq. (2)] $\mu_{\text{He}}(1) = g_s\mu_B$, where $g_s = 2.0023$ and $\mu_B = 9.2732 \times 10^{-21}$ erg/G, and $\alpha_{\text{He}} = 46.767 \times 10^{-24}$ cm^3, obtained from a variational

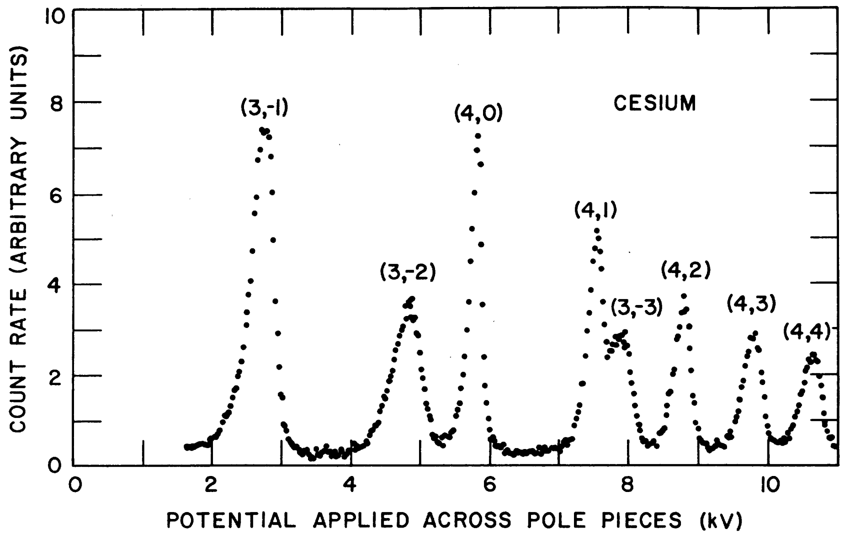

FIG. 2. Coarse scan of the potential applied across the E-H-gradient pole pieces at a fixed magnetic field strength of 1010 G. The peaks result from a balancing of the electric and magnetic forces acting on cesium atoms in different (F, m_F) sublevels. The polarizability determination is made using the (4, 4) balance peak since the magnetic moment for that case is independent of the magnetic field strength.

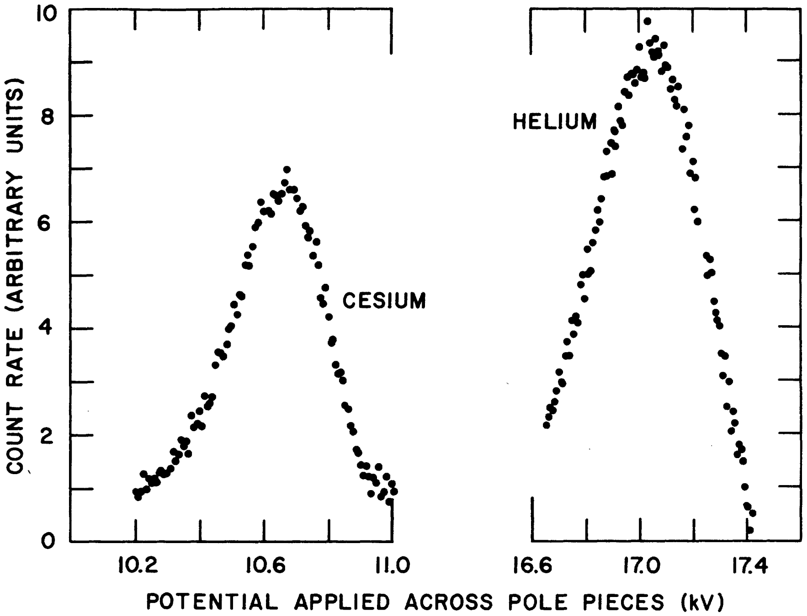

FIG. 3. Fine scans of a cesium $(F, m_F) = (4, 4)$ balance peak and a balance peak for the $m_J = 1$ sublevel of $^3S_1$ metastable helium, at a fixed magnetic field strength of 1010 G. The determination of the cesium polarizability involves the measurement of the ratio of the potentials corresponding to the maxima of the balance spectra [Eq. (2)]. The true zero levels have been suppressed in this figure.

calculation by Chung and Hurst[12] using a 72-term wave function. The effective magnetic moments used by us for the alkali atoms included the nuclear contribution, which was at most 0.1%.

Measurements were made for a wide range of magnetic field strengths for all of the alkali atoms and the metastable noble-gas atoms. In addition, with each species diagnostic tests were made, as will be discussed in Sec. VII.

V. ALKALI-ATOM RESULTS AND DISCUSSION

Our data for the alkali polarizabilities are shown in Fig. 5, plotted as a function of magnetic field strength. The average of the data for each case is given in Table I along with the polarizabilities measured by Salop *et al.*,[1] by Chamberlain and Zorn,[2] and by Hall and Zorn,[10] and with a number

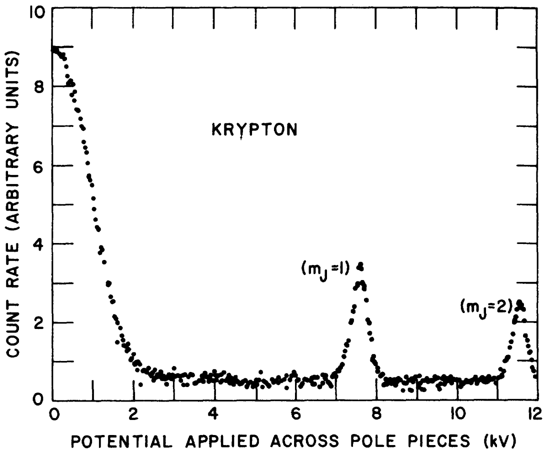

FIG. 4. Coarse scan of the potential applied across the *E-H*-gradient pole pieces at a fixed magnetic field strength of 313 G, for krypton. The peaks to the right result from a balancing of the electric and magnetic forces acting on $^3P_2$ krypton atoms in different m_J sublevels. The beam intensity around zero potential is due to the $m_J = 0$ sublevel. The background contains contributions from ^{83}Kr. The components of the polarizability tensor for all m_J are completely determined by a measurement of the potentials corresponding to the maxima of the $m_J = 1$ and $m_J = 2$ balance peaks.

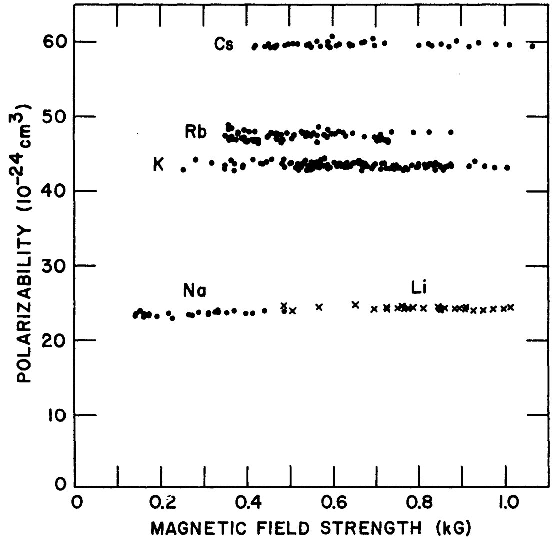

FIG. 5. Our alkali-metal atom polarizability determinations plotted vs the magnetic field strength at which the measurement was made.

TABLE I. Comparison of experimental and recent theoretical values for the electric dipole polarizabilities of the alkali-metal atoms. The polarizabilities are expressed in units of 10^{-24} cm^3.

Research	$\alpha_{\rm Li}$	$\alpha_{\rm Na}$	$\alpha_{\rm K}$	$\alpha_{\rm Rb}$	$\alpha_{\rm Cs}$
Present experiment; *E*-*H*-gradient balance	24.3 ± 0.5	23.6 ± 0.5	43.4 ± 0.9	47.3 ± 0.9	59.6 ± 1.2
Hall and Zorn, Refs. 5, 10; electric deflection		24.4 ± 1.7	45.2 ± 3.2	48.7 ± 3.4	63.3 ± 4.6
Chamberlain and Zorn, Ref. 2; electric deflection	22 ± 1.5	21.5 ± 1.5	38 ± 3	37.5 ± 3	48.5 ± 5.5
Salop, Pollack, and Bederson, Ref. 1; *E*-*H*-gradient balance	20 ± 3.0	20 ± 2.5	36.5 ± 4.5	40 ± 5.0	52.5 ± 6.5
Sternheimer, Ref. 27; perturbation theory	24.74	22.33	42.97	45.49	61.19
Adelman and Szabo, Ref. 26; Coulomb-like approximation	24.6	23.8	43.2	48.2	61.0
Rapp, Ref. 29; pseudopotential model	24.6	24.5	47.3	50.2	62.6
Hameed, Ref. 31; double-perturbation theory	25.5	31.5			
Chang, Pu, and Das, Ref. 21; Brueckner, Goldstone	24.84				
Stevens and Billingsley, Ref. 25; coupled Hartree-Fock	25.37				
Norcross, Ref. 28; semiempirical-model potential					59.3

of theoretical values. A more complete listing has been compiled by Teachout and Pack.[18] A great deal of theoretical work has been done for the alkali polarizabilities in an effort to understand the various approximations which have been used and to develop a rapid and reasonably accurate method of calculating polarizabilities.

The earliest calculations were based on experimental and theoretical oscillator strengths.[7] In 1962 Dalgarno[19] applied the coupled Hartree-Fock (CHF) method to the helium-lithium-beryllium isoelectronic sequence. The CHF method includes all intrinsic and self-consistency effects but ignores correlation (except for that due to the Pauli principle), which is second order and higher in the $1/r_{ij}$ interaction, where r_{ij} is the distance between the ith and jth electrons. The result of omitting correlation is to produce orbitals which are too large and therefore a polarizability which is too large. Because the equations for the first-order orbitals are coupled, extensive computations are required and the method has seen limited usage. Uncoupled Hartree-Fock (UHF) approximations have been devised in attempts to reduce the computations. Comparisons of the UHF approximations have been given by Langhoff, Karplus, and Hurst,[20] by Chang, Pu, and Das,[21] and by Tuan and Davidz.[22] Perturbation corrections to UHF methods have been discussed by Tuan, Epstein, and Hirschfelder,[23] Musher,[24] and Tuan and Davidz.[22] A coupled multiconfigurational self-consistent field method has been devised by Billingsley, Krauss, and Stevens.[25] The many-body Brueckner-Goldstone approach is exact to the extent that it includes all perturbation terms and thus provides a standard to which one can compare the other methods. A calculation by Chang, Pu, and Das[21] for lithium using the Brueckner-Goldstone approach is interesting since it sheds light on the physical content and errors of the Hartree-Fock calculations.

The best agreement between our work and theory is found with the Coulomb-like approximation used by Adelman and Szabo[26] and the perturbation calculations of Sternheimer.[27] Adelman and Szabo give an analytic expression for the polarizability. A comparison of all theoretical values shows the greatest variation for cesium—in fact, only one calculation falls within our uncertainty limits for cesium, a recent one by Norcross.[28] Norcross used a semiempirical-model potential involving two adjustable parameters based only on the lowest few spectroscopic term values. He included spinorbit effects and allowed for coré polarization. Norcross compares his result to Sternheimer's[27] and shows that the 3% agreement is partly fortuitous—that the partial contributions calculated for the valence electron only, the core polarization only, and the reverse polarization of tne core by the valence electron differ by considerably more than do the over-all results. Rapp[29] has calculated alkali-atom polarizabilities using wave functions based on a pseudopotential model.

On the experimental side, we feel that the results of Salop *et al.*[1] are most likely too low because the geometrical constant K, which relates the applied potential to the electric field strength at the beam position, was overestimated by about 9%. Several factors influence K. These include the shapes of the pole pieces, their spacing, and the beam width and placement in the interaction region. The electric deflection results of Chamberlain and Zorn[2] and of Hall and Zorn[5,10] are discussed in the following article.

It is interesting to note that the tensor polarizability of the first excited state has been measured for cesium and rubidium by Marrus, McColm, and Yellin,[30] and for potassium by Marrus and Yellin.[30] They measured the polarizability difference between the $n_0\,^2S_{1/2}$ ground state and sublevels of the $n_0\,^2P_{1/2,3/2}$ states, where n_0 is the principal quantum number. In stating their full polarizability results Marrus *et al.* added the ground-state polarizabilities of Salop *et al.*[1] We have adjusted their P-state polarizabilities to reflect the higher ground-state polarizabilities determined by us, and we present these values in Table II.

VI. $^3P_2$ NOBLE-GAS-ATOM RESULTS AND DISCUSSION

Our data for the polarizability tensor components $\alpha_{zz}(m_J=1)$ and $\alpha_{zz}(m_J=2)$ for $^3P_2$ metastable neon, argon, krypton, and xenon are shown in Fig. 6, plotted against the magnetic field strength at which they were measured. All other tensor components for all m_J may be obtained from $\alpha_{zz}(1)$ and $\alpha_{zz}(2)$ via Eq. (4). In Table III we give the average of the data for each case. The experimental results of Pollack *et al.*[3] and Robinson *et al.*[4] are included in Table III. Those experimenters used the E-H-gradient balance method described in Sec. III in this laboratory on an earlier apparatus, including normalization to helium. The better accuracy in our case is attributed to the higher spatial resolution of the present apparatus and to the use of a multichannel scaler to accumulate large quantities of data, such as illustrated in Figs. 2–4 and summarized in Fig. 6.

TABLE II. Polarizabilities of the $(n_0\,^2P_J m_J)$ excited states of cesium, rubidium, and potassium, measured by Marrus, McColm, and Yellin (Ref. 30), where n_0 represents the principal quantum number in each case. Their original data have been adjusted by us to reflect the present improvement in the values of the ground-state polarizabilities given in Table I. Experimental uncertainty limits given in Ref. 30 (in parentheses) have not been altered. The polarizabilities are expressed in units of 10^{-24} cm^3.

Atom	$\alpha(n_0\,^2P_{1/2}\pm\frac{1}{2})$	$\alpha(n_0\,^2P_{3/2}\pm\frac{3}{2})$	$\alpha(n_0\,^2P_{3/2}\pm\frac{1}{2})$
Cesium	194(29)	203(30)	280(42)
Rubidium	119(17)	109(15)	155(23)
Potassium	94(13)	121(16)	75(10)

There have been two calculations of the average polarizabilities of the $^3P_2$ metastable noble-gas atoms, both by Robinson.[4] He used a modified Sternheimer method without core polarization in one case, and he also used oscillator strengths calculated by the Coulomb approximation of Bates and Damgaard.[6] Robinson's results for both calculations are given in Table IV with average polarizabilities obtained from our data with Eq. (5). There has been no calculation of the polarizability anisotropy for these atoms.

In Table IV we give values of α_t obtained from our data with Eq. (7) and compare them to accurate

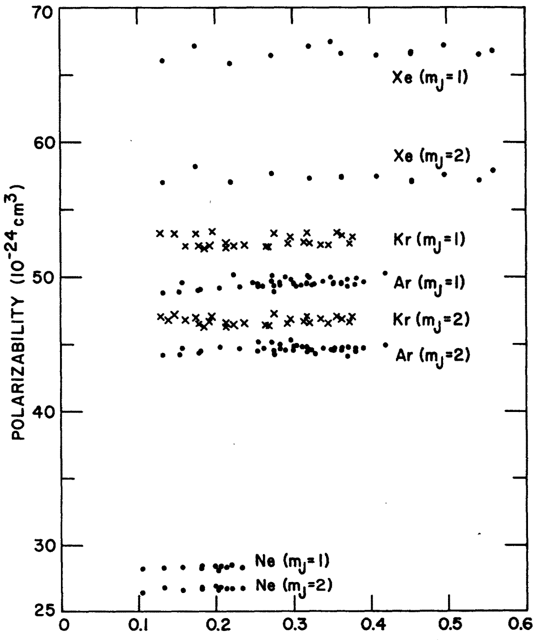

FIG. 6. Our determinations of the $\alpha_{zz}(m_J)$ components of the polarizability tensors for the $^3P_2$ metastable noble-gas atoms plotted vs the magnetic field strength at which the measurement was made. The zero level has been suppressed in this figure.

TABLE III. Comparison of our results for the tensor polarizabilities $\alpha_{zz}(m_J=1)$ and $\alpha_{zz}(m_J=2)$ of the $^3P_2$ metastable noble-gas atoms with the results of Pollack, Robinson, and Bederson (PRB, Ref. 3) for argon, and of Robinson, Levine, and Bederson (RLB, Ref. 4) for neon, krypton, and xenon. The polarizabilities are expressed in units of 10^{-24} cm^3.

		Present experiment	PRB and RLB
Neon	$\alpha_{zz}(1)$	28.4 ± 0.6	28.0 ± 1.4
	$\alpha_{zz}(2)$	26.7 ± 0.5	26.7 ± 1.3
Argon	$\alpha_{zz}(1)$	49.5 ± 1.0	50.5 ± 3.5
	$\alpha_{zz}(2)$	44.7 ± 0.9	44.5 ± 3.1
Krypton	$\alpha_{zz}(1)$	52.7 ± 1.0	53.7 ± 2.7
	$\alpha_{zz}(2)$	46.8 ± 0.9	46.7 ± 2.3
Xenon	$\alpha_{zz}(1)$	66.6 ± 1.3	68.2 ± 3.4
	$\alpha_{zz}(2)$	57.4 ± 1.1	56.8 ± 2.8

(5%) values measured by Player and Sanders[13] in an atomic beam resonance experiment. The tensor part of the polarizability is two-thirds of the difference between $\alpha_{zz}(2)$ and $\alpha_{zz}(1)$, and in view of the fact that this difference is so small the agreement with Player and Sanders is surprisingly good.

VII. ANALYSIS OF UNCERTAINTIES

We have made experimental tests of the effectiveness of the normalization technique. We deliberately offset the beam source, the pole pieces of the interaction region, or the detector, and we measure the balance potentials as outlined in Sec. III. The misalignments affect the absolute values of the balance potentials but do not seriously affect the relative measurements. Table V contains examples of the results of these tests. The misalignments alter the apparatus geometric factors, which do not enter the relative polarizability determinations even in second order.

Although knowledge of the geometric factors is not necessary in order to obtain the normalized polarizabilities, we are able to use the known helium polarizability and the known magnetic field dependence of the effective magnetic moments of the atoms under study to determine the two geometric quantities which describe the interaction region of our apparatus. We determine the magnetic field strength H at the beam position from the relative balance potentials of the various m_F substates observed; the squares of the balance potentials are related to the effective magnetic moments. (We have found that the values of H so obtained agree well with the values of H obtained from observations of zero magnetic moment crossings—the method used by Salop *et al.* to determine H.) Once H is known the helium information is sufficient to determine K, and we have done this for the helium part of each datum as a consistency check on the apparatus and alignment. We find an average value $K = 11.16$ cm^{-1}. The ratio of the field gradient to the field strength at the beam position, C, may be obtained from electric deflection of an atom of known polarizability once K is known. We have reported elsewhere[15] electric deflection measurements with alkali atoms and molecules. The atomic data yield a value of 6.8 cm^{-1} for C.

Normalization of the data requires that the metastable helium beam be coaxial with the beam under study, when the electric and magnetic forces are balanced. Two points deserve consideration: (i) the helium gas pressure used (~1 Torr) was generally higher than the alkali vapor pressure used

TABLE IV. Comparison of values for the average polarizability $\bar{\alpha}$ and the tensor part of the polarizability α_t for the $^3P_2$ metastable noble-gas atoms, in units of 10^{-24} cm^3. The values of $\bar{\alpha}$ and α_t for the present experiment were obtained from the measured quantities $\alpha_{zz}(1)$ and $\alpha_{zz}(2)$ using Eqs. (5) and (7). The theoretical values of Robinson (Ref. 4) are theory A, which is a modification of Sternheimer's method, and theory B, which uses estimates made of oscillator strengths from the Coulomb approximation of Bates and Damgaard.

		Present experiment	Player and Sandars, Ref. 13	Robinson Theory A	Robinson Theory B
Neon	$\bar{\alpha}$	27.8		29.6	27.8
	α_t	−1.1	−0.963		
Argon	$\bar{\alpha}$	47.9		50.5	48.1
	α_t	−3.2	−2.95		
Krypton	$\bar{\alpha}$	50.7		59.9	53.5
	α_t	−3.9	−3.90		
Xenon	$\bar{\alpha}$	63.6		78.2	62.5
	α_t	−6.1	−6.03		

TABLE V. Results of a typical experimental test of the normalization technique. The squares of the balance potentials measured for potassium and $^3S_1$ helium are given for cases where (i) the apparatus is aligned as well as possible, (ii) the rears of the pole pieces of the interaction region are offset by 0.005 cm, and (iii) the detector is offset by 0.005 cm. In each case the resulting apparent polarizability is given in units of 10^{-24} cm^3. The potassium polarizability is related to the ratio of the squares of the balance potentials for helium and potassium [Eq. (2)], and an average potassium magnetic moment $\bar{\mu}$ of $0.979\mu_B$ has been used. A random error of about 0.3×10^{-24} cm^3 was observed among the potassium data.

Condition	V_K^2	V_{He}^2	Apparent α_K
Normal alignment	93.82 (kV)^2	177.50 (kV)^2	43.32
Pole pieces offset	94.52	179.08	43.40
Detector offset	92.24	176.12	43.71

(~0.3 Torr) and (ii) electron-bombardment excitation of the helium involves recoil of the helium atoms. We utilized electron bombardment parallel to the beam to minimize recoil scattering out of the beam, and we used a slit following the electron-emitting filaments to limit possible broadening of the metastable helium beam resulting from either (i) or (ii) above. We obtained data with slit widths of 0.75, 0.25, and 0.15 mm and found no change in the normalized polarizabilities. Differences in the beam widths and shapes would not be expected to affect the results. As a test, balance scans for helium and argon were run with gas pressures up to four times normal and no change in the beam shape resulted, nor were any differences greater than 0.3% in the balance potentials observed.

We obtained data for each atomic species during several different runs and before and after the disassembly and relocation of the apparatus in a new laboratory.

We allow for an 0.5% uncertainty in Chung and Hurst's value for the scalar polarizability of $^3S_1$ helium.[12] In our experiment the greatest uncertainty results from beam shifts during data runs (~0.001 cm) or inaccurate centering of the detector to begin with, which causes the balance potentials to be incorrect. The scatter in the data (Figs. 5 and 6) is almost entirely attributable to this problem, but the large quantity of data reduces the uncertainty considerably. The polarizability values quoted in Tables I and III are correct to within about 1.5% for two standard deviations of the data, depending on the particular case.

VIII. CONCLUSIONS

We have used the E-H-gradient balance technique to measure the scalar polarizabilities of the alkali-metal atoms and the tensor polarizabilities of the $^3P_2$ metastable noble-gas atoms, normalized to the scalar polarizability of $^3S_1$ metastable helium. The measured quantities are presented in Tables I and III. The results compare well with theoretical values. Our alkali polarizabilities agree with the experimental values of Hall and Zorn (Ref. 10, following paper), and our $^3P_2$ noble-gas polarizabilities agree with previous measurements of Pollack, Robinson, and Bederson[3] for argon, of Robinson, Levine, and Bederson[4] for neon, krypton, and xenon, and of Player and Sandars[13] for the $^3P_2$ polarizability anisotropies.

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