Determination of the Polarizability Tensors of the Magnetic Substates of $^3P_2$ Metastable Argon*†

EDWARD POLLACK,‡ EDWARD J. ROBINSON,§ AND BENJAMIN BEDERSON
Department of Physics, New York University, University Heights, New York, New York
(Received 8 January 1964)

The atomic beam E-H gradient-balance method has been employed to measure the z-component $\alpha_z(m_J)$ of the electric polarizability tensors of the $m_J=+2$ and $m_J=+1$ magnetic substates of $^3P_2$ metastable argon. The measurements were normalized to the polarizability of $^3S_1$ metastable helium, which is calculable to within an accuracy of 1%. In this method, a metastable beam is passed through a region containing transverse, congruent, inhomogeneous electric and magnetic fields. The condition that atoms in a particular magnetic substate experience no deflection in such a field region is $\alpha_z(m_J)E(\delta E/\delta z)=\mu_{\mathrm{eff}}(\delta H/\delta z)$, where μ_{eff} is the magnetic moment in the field H, and $\delta E/\delta z$, $\delta H/\delta z$ are the z components of the gradients of the magnitudes of the electric and magnetic fields, respectively. Because of the congruency of the E and H fields $(\delta E/\delta z)/E=(\delta H/\delta z)/H$, and therefore $\alpha_z(m_J)=\mu_{\mathrm{eff}}H/E^2$. Because of the normalization, it was unnecessary to find either E or H. The results, in units of 10^{-24} cm^3, are $\alpha_z(\pm1)=50.4\pm3.5$ and $\alpha_z(\pm2)=44.5\pm3.1$. The measured values of $\alpha_z(+1)$ and $\alpha_z(+2)$ can be used to determine the polarizability tensors of each of the magnetic substates. The other components of the diagonalized tensors, with $\alpha_x(m_J)=\alpha_y(m_J)$, in units of 10^{-24}cm^3 are $\alpha_x(0)=46.4\pm2.4$, $\alpha_x(\pm1)=47.2\pm2.3$, $\alpha_x(\pm2)=50.4\pm3.5$, and $\alpha_z(0)=52.4\pm4.8$.

INTRODUCTION

RECENTLY an atomic beam method has been developed to measure the electric polarizabilities of atoms.[1–3] Using this technique, called the "E-H gradient balance method," polarizability determinations are independent of the atomic-beam velocity distribution and specific values of the field gradients and apparatus geometry except where employed in the calculation of the electric field at the beam position from knowledge of the applied voltage and pole-face contour. Salop, Pollack, and Bederson[2,3] used this method to measure the polarizabilities of the alkalis, and the results of this work, as well as those of Chamberlain and Zorn,[4] are in agreement with recent theoretical determinations, to within experimental error.[5,6] For all these systems, the ground states are S states and the polarizability is therefore scalar.

We will here briefly review our basic technique, applied to an atom possessing a tensor polarizability. Consider an atom traversing a region of space containing both an inhomogeneous transverse electric field and an inhomogeneous transverse magnetic field, with both fields possessing large transverse gradients. We assume that these fields are congruent, that is, the electric and magnetic fields as well as their gradients are proportional and in the same direction throughout the interaction region. The atom experiences a transverse force due to its magnetic moment given by

$$F_m=\mu_{\mathrm{eff}}(m_J)(\delta H/\delta z)\,, \tag{1}$$

where $\mu_{\mathrm{eff}}(m_J)$ is the effective atomic magnetic moment of the magnetic substate m_J and $\delta H/\delta z$ is the transverse component of the gradient of the magnitude of the magnetic field.

For an atomic system possessing a tensor polarizability the electric dipole moment $\boldsymbol{\mu}_e$ induced in the atom by the electric field $\mathbf{E}$ is generally not along the field direction. For the case where the polarizability tensor is in diagonal form, $\boldsymbol{\mu}_e$ is given by

$$\boldsymbol{\mu}_e=\hat{\imath}\alpha_xE_x+\hat{\jmath}\alpha_yE_y+\hat{k}\alpha_zE_z\,,$$

where α_x is the xx component of the polarizability tensor α, etc. For S-state atoms, $\alpha_x=\alpha_y=\alpha_z=\alpha$, i.e., the polarizability is a scalar. For the magnetic substates of P-state atoms, this is in general not the case and the polarizability of each of the substates is a tensor. In the present work, the electric and magnetic fields, which are in the z direction, establish the z axis as a symmetry axis in the atom. Thus, α is in diagonal form, with the x and y components being equal. In terms of matrix elements, the polarizability components may be

* This work was supported in part by the Advanced Research Projects Agency, through the U. S. Office of Naval Research, Contract N-ONR-285(15) and by the Defense Atomic Support Agency, through the U. S. Army Research Office, Grant DA-ARO-(D)-31-124-G269, Durham, North Carolina.

† From part of a thesis submitted by E. Pollack to the Graduate Faculty of New York University in partial fulfillment of the requirements for the Ph.D. degree, October 1963.

‡ Present address: Physics Department, University of Connecticut, Storrs, Connecticut.

§ National Science Foundation, Science Faculty Fellow 1963-1964.

1 B. Bederson, J. Eisinger, K. Rubin, and A. Salop, Rev. Sci. Instr. **31**, 852 (1960).

2 A. Salop, Ph.D. thesis, New York University, 1961 (unpublished).

3 A. Salop, E. Pollack, and B. Bederson, Phys. Rev. **124**, 1431 (1961).

4 G. Chamberlain and J. Zorn, Phys. Rev. **129**, 677 (1963).

5 The earlier Scheffers and Stark (Ref. 6) values for lithium and cesium are in error, being about 40% too low for lithium and 20% too low for cesium.

6 H. Scheffers and J. Stark, Phyzik Z. **35**, 625 (1934).

written (in atomic units) as follows[7]:

$$\alpha_x(m_J)=\alpha_y(m_J)=\sum_{k\neq 0}\left[(J^2+J-m_J^2)\delta_{JJ'}+(J^2+m_J^2+3J+2)\delta_{J+1,J'}+(J^2+m_J^2-J)\delta_{J-1,J'}\right]\frac{|\langle 0|\sum_{i=1}^{N} r_i|k\rangle|^2}{E_k-E_0}, \quad (2a)$$

$$\alpha_z(m_J)=2\sum_{k\neq 0}\left[m_J^2\delta_{JJ'}+\{(J+1)^2-m_J^2\}\delta_{J+1,J'}+(J^2-m_J^2)\delta_{J-1,J'}\right]\frac{|\langle 0|\sum_{i=1}^{N} r_i|k\rangle|^2}{E_k-E_0}, \quad (2b)$$

where J and m_J are the total angular momentum and magnetic quantum numbers of the unperturbed state $|0\rangle$, J' is the total angular momentum quantum number of the state $|k\rangle$, $(E_\kappa-E_0)$ the difference in energy between $|k\rangle$ and $|0\rangle$, r_i the radial coordinate of the ith electron, and N the number of electrons. Since the electric field is parallel to the z axis, the induced dipole is

$$\boldsymbol{\mu}_e=\hat{k}\alpha_z E_z.$$

The resulting force is also in the z direction, and is given by

$$F_e=\alpha_z(m_J)E(\delta E/\delta z), \quad (3)$$

where $\alpha_z(m_J)$ is the "effective" polarizability of the atom in the substate m_J and $\delta E/\delta z$ is the transverse component of the gradient of the magnitude of the electric field. (It is assumed throughout that the nuclear spin is zero.) For substates possessing negative atomic moments, the fields can be adjusted so that the electric and magnetic forces given by Eqs. (1) and (3) are equal and opposite. (In the present experiment these are the positive m_J states.) When this is the case, it follows that

$$\mu_{\text{eff}}(m_J)(\delta H/\delta z)=\alpha_z(m_J)E(\delta E/\delta z). \quad (4)$$

Should Eq. (4) apply for several magnetic substates, $\alpha_z(m_J)$ for each substate can be determined separately.

It can readily be shown that the polarizability tensors of all the substates can be uniquely expressed in terms of the effective polarizabilities of the $m_J=+1$ and $m_J=+2$ substates. Thus,

$$\begin{aligned}\alpha_z(0)&=\tfrac{1}{3}[4\alpha_z(+1)-\alpha_z(+2)],\\ \alpha_x(0)&=\tfrac{1}{3}[\alpha_z(+1)+2\alpha_z(+2)],\\ \alpha_x(\pm 1)&=\tfrac{1}{2}[\alpha_z(+1)+\alpha_z(+2)],\\ \alpha_x(\pm 2)&=\alpha_z(+1),\\ \alpha_x(m_J)&=\alpha_y(m_J).\end{aligned} \quad (5)$$

Note that $\bar{\alpha}_x=\bar{\alpha}_y=\bar{\alpha}_z$, where $\bar{\alpha}_x$ is the x component of the polarizability tensor averaged over the five magnetic substates, etc.

Because of the assumed congruency of the electric and magnetic fields, we may write $\delta H/\delta z=kH$ and $\delta E/\delta z=kE$, where k is a geometry factor. Substituting for the gradients in terms of the fields, the balance condition, Eq. (4), can be rewritten as

$$\alpha_z(m_J)=\mu_{\text{eff}}(m_J)H/E^2. \quad (6)$$

The measurement of $\alpha_z(m_J)$ is therefore independent of velocity, and specific values of the field gradients and geometry, except in the determination of E from the applied voltage. H can be accurately determined by means of a "zero-moment" experiment,[8] and $\mu_{\text{eff}}(H)$ is an accurately known function of H.

Relative measurements, using a normalizing element whose polarizability is known, can also be performed. In the present work, $\alpha_z(1)$ and $\alpha_z(2)$ of metastable $^3P_2$ argon were measured in terms of the polarizability of metastable $^3S_1$ helium, which has been calculated[9] (46.6×10^{-24} cm^3) to an accuracy of about 1%. Substituting for the magnetic field in terms of α(He) in Eq. (6) we obtain

$$\alpha_z(m_J)=\mu_{\text{eff}}(m_J)/2\mu_0(V_{\text{He}}/V)^2\alpha(\text{He}), \quad (7)$$

where μ_0 is the Bohr magneton, V_{He} is the voltage at balance for metastable helium and V is the voltage balance for the argon substate.

Although the balance condition is valid for beams of infinitesimal width, Salop *et al.*[3] have shown that it is a good approximation for the narrow beams used in the present experiment.

APPARATUS

Figure 1 is a schematic diagram of the apparatus. The metastable beam is formed by effusion of argon into a region where it is cross fired by an electron beam. It then passes through a narrow collimator into the $E-H$ field region, and is finally incident upon a tungsten surface which serves as the cathode of a Bendix electron multiplier. The metastable $^3P_2$ and $^3P_0$ atoms are capable of ejecting electrons from the tungsten cathode, and these electrons are multiplied

[7] E. U. Condon and G. H. Shortley, *The Theory of Atomic Spectra* (Cambridge University Press, Cambridge, England, 1951). The tensor polarizability is defined on p. 106. Eqs. (2a) and (2b) are obtained by using the T-operator properties tabulated in Eq. (11), p. 63.

[8] V. W. Cohen, Phys. Rev. **46**, 713 (1934).

[9] Charles Schwartz (private communication). Also, A. Dalgarno, Proc. Phys. Soc. (London) **72**, 1053 (1958).

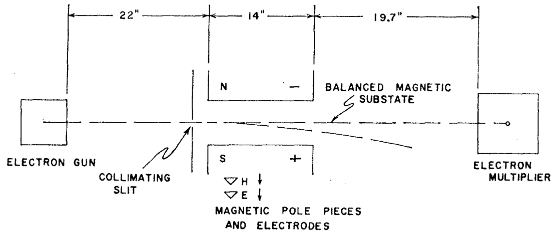


FIG. 1. Schematic diagram of the experiment.

and counted using a preamplifier and scalar. Metastable helium is produced and detected in a similar fashion.

The main chamber contains the magnet pole pieces, which also act as the electrodes for the inhomogeneous electric field. They are insulated from the magnet yoke by a rectangular glass tube which also serves as the vacuum envelope. The electric and magnetic fields between the pole pieces are congruent, since the boundary conditions which they obey are almost identical if the pole pieces are of high permeability and the magnetic fields are sufficiently low to avoid saturation effects.

The pole pieces are 14 in. long, and the ratio of gradient to field is 2.5 cm^{-1} at the beam position, and the gap width is 0.056 in. The beam height as well as its location relative to the pole pieces was fixed by a 0.002-in. $\times$0.050-in. collimating slit mounted directly in front of the pole pieces, at a distance of 0.025 in. from the convex edge. A beam-height limiter 0.060 in. high was mounted at the detector end of the pole piece assembly.

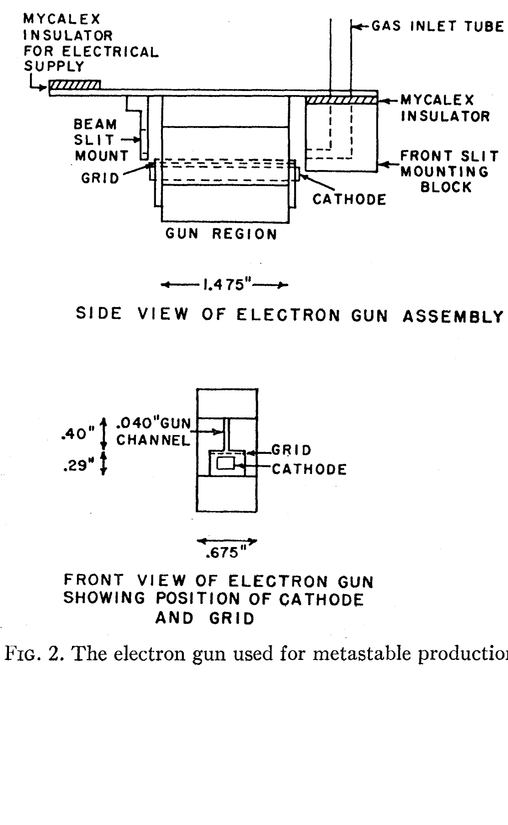


FIG. 2. The electron gun used for metastable production.

A Sensitive Research electrostatic voltmeter was used to measure the applied voltage. Prior to being put into service, its calibration was checked at the National Bureau of Standards. Subsequent calibrations were performed by the manufacturer. The instrument maintained its calibration to within 0.1% throughout the course of the present work.

Figure 2 shows two views of the electron gun.[10]

The gun makes use of a Philips type A cathode, which stands up comparatively well to ion bombardment which results from its operation. The entire gun is mounted between the pole faces of a magnet which produces a field of approximately 1000 G parallel to the electron beam. Recoil broadening was essentially eliminated by the use of a 0.002 in. wide slit mounted at the beam exit of the gun.

The usual operating voltages were 23 V for argon and 26 V for helium, with a current of about 30 mA. At these potentials the photon background was negligible, although it rose rapidly with increasing voltage. For example, at 30 V using argon, about 6% of the detected beam was due to photons. The full beam intensities were typically about 1000 and 200 cpm for argon and helium, respectively. Dark current noise from the multiplier corresponded to only several cpm and so reasonable signal-to-noise was achieved by counting for several minutes, at each pair of E and H field values.

MEASUREMENTS

Measurements were made of the beam intensity as a function of voltage across the electrodes, for a fixed value of magnetic field. Figure 3 presents such a run taken with argon at a field of approximately 260 G. The beam intensity when $V=0$ is due primarily to those atoms with $\mu_{\text{eff}}=0$, namely, those in the $^3P_0$ metastable state, and those with $m_J=0$ in the $^3P_2$ metastable state. As voltage is applied across the pole pieces, the beam intensity decreases at first as the atoms without magnetic moment are deflected out by the electric field. The first peak is in balance at about 11 kV and the second peak at 17 kV, and any further increase in voltage results in a monotonically decreasing beam intensity. The curve shape is similar to that of a "zero-moment" curve.[7] Figure 4 shows the region of the single peak for a similar experiment performed with metastable helium at a magnetic field of about 300 G.

Values of the polarizability ratio for the $m_J=+1$ and $m_J=+2$ substates of argon are obtained using a

[10] In the early stages of the experiment an rf discharge was used for metastable production instead of the electron beam. The discharge was pulsed, and a suitably timed gate circuit was used to discriminate the detector against prompt-arrival photons, in favor of the more slowly traveling metastables. Further development of this method was forestalled by satisfactory operation of the electron gun. Nevertheless, the pulse discharge could certainly be improved, and may ultimately prove superior to the gun method in some cases.

modified form of Eq. (7). Thus,

$$\alpha_z(+1)/\alpha_z(+2)=\tfrac{1}{2}(V_2/V_1)^2, \qquad (8)$$

where the subscripts specify the substates. Absolute values, normalized to helium are

$$\alpha_z(+1)=\tfrac{1}{2}(1.5)(V_{\mathrm{He}}/V_1)^2\times 46.6\times 10^{-24}\ \mathrm{cm}^3, \quad (9)$$

$$\alpha_z(+2)=\tfrac{3}{2}(V_{\mathrm{He}}/V_2)^2\times 46.6\times 10^{-24}\ \mathrm{cm}^3. \qquad (10)$$

The data are sufficient to determine $\alpha_z(m_J)$ only if the magnetic substates associated with the several peaks can be definitely identified. For example, from the positions of the peak in Fig. 3, a ratio $\alpha_{1z}/\alpha_{2z}\approx 1$ can be inferred if α_{1z} represents the $m_J=+1$ substate or $\alpha_{1z}/\alpha_{2z}\approx\frac{1}{4}$ if α_{1z} represent the $m_J=+2$ substate. (Here, the subscripts 1 and 2 refer to the peaks occurring at the lower and higher voltages, respectively.) It is very unlikely that the ratio should differ greatly from unity,

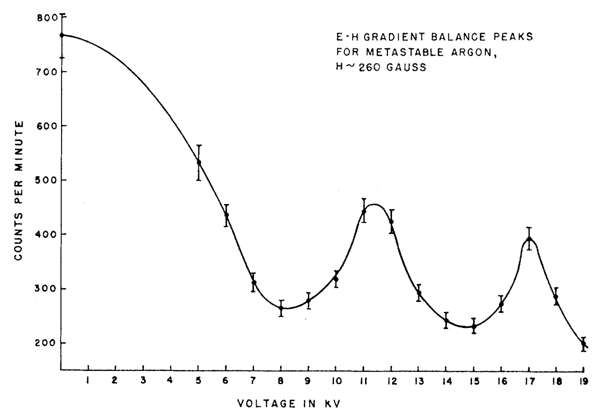


FIG. 3. Beam intensity as a function of applied voltage for metastable argon, at a magnetic field of about 260 G.

since the valence electron, which contributes the principal amount to the polarizability, is in an s state. Nevertheless, a subsidiary experiment was performed in order to definitely identify the substates.

The first peak was brought into balance at a magnetic field of about 260 G and a voltage of 11.1 kV. A beam profile was taken for the balanced substate in steps of 0.001 in. about the beam maximum. The voltage was then dropped to 9.9 kV and a similar profile taken. These two profiles are shown in Fig. 5 The apparatus as used here functioned as a substate selector, and in addition as a relatively crude deflection polarizability spectrometer. A similar deflection experiment was performed on the second balance peak. Beam profiles at balance and at 1.2 kV below balance were taken. Figure 6 shows the results of the second deflection experiment.

An atom experiencing a constant force F transverse to its direction of motion in an atomic beam undergoes a deflection $s=c'F/v^2$, where c' is a constant and v is the

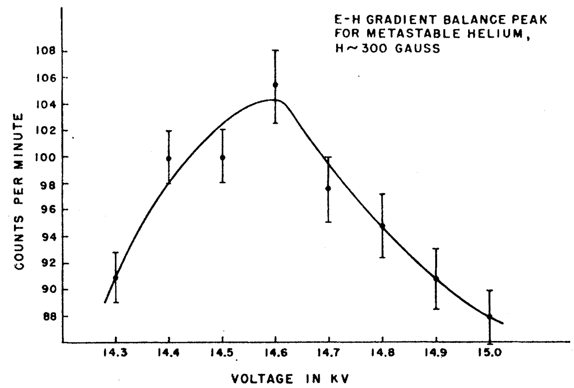


FIG. 4. Beam intensity as a function of applied voltage for metastable helium in the vicinity of the single-balance peak, at a magnetic field of about 300 G.

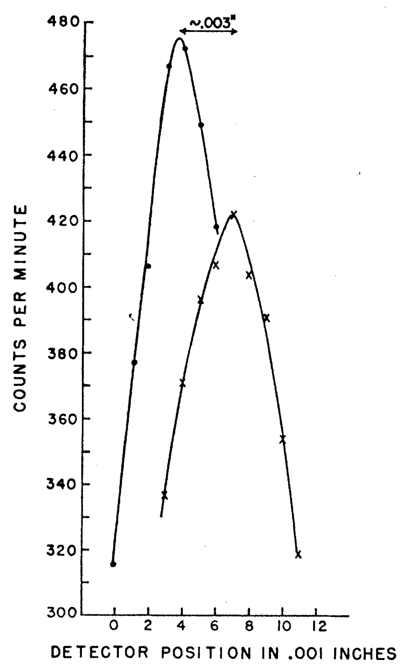
speed of the atom. In the deflection experiment just described, F is proportional to $\alpha_z(E_0+\delta E)^2-\mu_{\mathrm{eff}}H_0$, where E_0 and H_0 are the balance electric and magnetic fields, and δE, the change in electric field. Dropping the second-order term, F is proportional simply to $\alpha_z E_0\delta E$, or $s=c\alpha_z E_0/v^2$, where c is a constant which includes the δE.

Since δE is the same for the first and second deflection experiments, the ratio of the deflections is given by

$$s_1/s_2=(\alpha_{1z}/\alpha_{2z})(V_1/V_2).$$

Now it can be shown[11] that for deflections small compared to the detector width, a triangular beam is dis-

FIG. 5. Beam profiles for metastable argon of the first balance peak, at a magnetic field of about 260 G. The left-hand curve is taken exactly at balance $V=11.1$ kV. The right-hand curve is taken slightly off balance with $V=9.9$ kV. The displacement of the peak of approximately 0.003 in. represents a rough measurement of the polarizability, and therefore serves to identify the balanced substate as $m_J=+1$.



[11] George E. Chamberlain, Ph.D. thesis, Yale University, 1961, p. 83 ff. (unpublished).

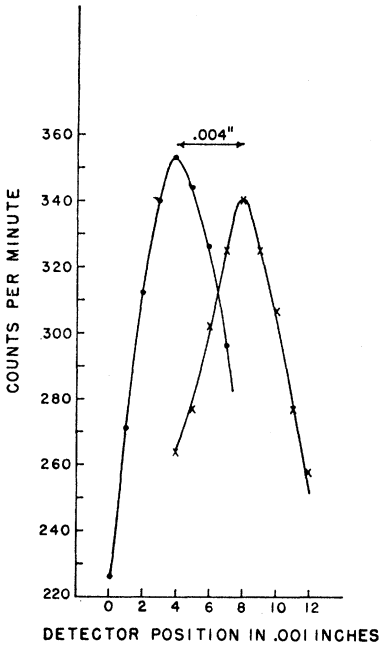


FIG. 6. Beam profiles for metastable argon of the second balance peak at a magnetic field of about 260 G. The left-hand curve is taken exactly at balance with $V=16.9$ kV. The right-hand curve is taken slightly off balance, with $V=15.7$ kV. The displacement of the peak of approximately 0.004 in. represents a rough measurement of the polarizability and therefore serves to identify the balanced substate as $m_J=+2$.

placed with an unaltered profile. That is, velocity broadening of the beam shape is negligible. Our deflections are actually comparable to the beam width, so that some velocity broadening should occur. Nevertheless, the beam shape will be only slightly altered, and it should be possible to determine whether the ratio is of the order of unity or four. Figure 5 shows that the first peak is displaced by approximately 0.003 in. as a result of the unbalanced force, and Fig. 6 shows that the second peak is displaced by about 0.004 in. These values are consistent with the assumption that the $m_J=+1$ substate comes into balance at the lower voltage.

Detailed measurements were made in the vicinity of the balance peaks. A normal run consisted of counting for several minutes at 100-V intervals, usually so as to register several thousand counts. The results are presented in Table I, where the balance voltages for each of the measurable substates of argon at 200, 260, and 300 G, and for the single measurable substate of helium at 260 and 300 G are tabulated. Also tabulated are the values of the polarizability ratios calculated by means of Eq. (8), at the three magnetic fields used, and of the absolute values normalized to helium at the two higher fields, calculated using Eqs. (9) and (10).

SUMMARY AND DISCUSSION OF RESULTS

The results of our measurements of the z component of the electric polarizability tensor of the $m_J=+1$ and $m_J=+2$ substates of $^3P_2$ metastable argon are presented below. The absolute values represent a combined average of the results taken at magnetic fields of 260 and 300 G. The ratio measurement represents a combined average of the results taken at magnetic fields of 200, 260, and 300 G. We find

$$\alpha_z(+1)=(50.4\pm3.5)\times10^{-24}\ \text{cm}^3,$$
$$\alpha_z(+2)=(44.5\pm3.1)\times10^{-24}\ \text{cm}^3,$$
$$[\alpha_z(+1)/\alpha_z(+2)]=1.13\pm0.08.$$

Inserting the above into Eq. (5), and adding errors by the rms method,

$$\alpha_z(0)=(52.4\pm4.8)\times10^{-24}\ \text{cm}^3,$$
$$\alpha_x(\pm1)=(47.25\pm2.3)\times10^{-24}\ \text{cm}^3,$$
$$\alpha_x(\pm2)=(50.4\pm3.5)\times10^{-24}\ \text{cm}^3,$$
$$\alpha_x(0)=\alpha_y(0)=(46.4\pm2.4)\times10^{-24}\ \text{cm}^3.$$

TABLE I. Summary of experimental results.

Approximate magnetic field (gauss)	Balance voltage (kV)	Magnetic substate and element	$\alpha_z(m_J)$	$\alpha_z(+1)/\alpha_z(+2)$
200	9.9	+1(Ar)		1.13
200	14.9	+2(Ar)		
260	11.2	+1(Ar)	51.5	1.14
260	16.9	+2(Ar)	45.3	
260	13.6	+1(He)		
300	12.3	+1(Ar)	49.3	1.13
300	18.5	+2(Ar)	43.8	
300	14.6	+1(He)	(46.6)[a]	

[a] Calculated by Schwartz and Dalgarno (see Ref. 8).

Because of the generally low counting rate, statistical fluctuations contributed significantly to the over-all error. The range of standard deviations of each point was between 1% and 3%, depending upon the duration of the run and the magnitude of the beam intensity, with the helium data usually having the larger deviations. However, the argon peaks were somewhat broader than the helium peaks, owing to the greater overlapping of the three substates $m_J=+2$, $+1$, 0 of $^3P_2$ argon, combined with the presence of the single substate of $^3P_0$ argon, as compared to the presence of the two substates $m_J=+1$, 0 of the $^3S_1$ state of helium, combined with the presence of the single substate of $^1S_0$.

Among the other causes of experimental error are the following: an apparent shift in the balance peak due to fast atoms from unbalanced substates; fluctuations of electron gun current, source pressure, and magnetic and electric fields during the course of a run; measurement of the voltage using the NBS calibrated voltmeter; lack of perfect parallelism of the beam with respect to the pole face; and deviations from the balance condition over the finite beam width. A detailed discussion of most of these errors is contained in Ref. 3.

We make an over-all assignment of $\pm7\%$ to the error in measuring $\alpha_z(+1)$ and $\alpha_z(+2)$, based upon conservative estimates of the above error sources.

It was to be expected that the polarizabilities of

$^3P_2$ argon would be quite large, since its structure is grossly similar to that of ground-state potassium, which has a polarizability of about 36×10^{-24} cm^3. Further, since the valence electron contributes the major amount to the polarizability, the polarizability ratio $\alpha_z(+1)/\alpha_z(+2)$ should be quite close to unity. (The valence electron is in an s state.)

The P configuration of the atom is due to the five p electrons of the incomplete M shell, whose contribution to the polarizability should therefore contain a strong anisotropy. However, since the contribution of the core to the total polarizability is small, the net anisotropy should also be small.

ACKNOWLEDGMENTS

We wish to thank Professor Arthur Salop for his continued interest, and for many useful discussions and suggestions during the course of the work. We also wish to thank Judah Levine for his assistance during the latter part of the experiment.

PHYSICAL REVIEW VOLUME 134, NUMBER 5A 1 JUNE 1964

Studies of the Mechanism of Electron-Ion Recombination. II

WILLIAM A. ROGERS* AND MANFRED A. BIONDI†
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania
(Received 13 January 1964)

Microwave, optical spectrometric, and interferometric techniques have been used to investigate the nature of the electron-ion recombination process in low-pressure, pure helium afterglows at 300 and 77°K. To determine whether dissociative capture of electrons by helium molecular ions, i.e., $He_2^+ + e \rightarrow He^* + He + (KE)$, is the recombination reaction taking place, we have attempted to detect the kinetic energy of dissociation of the excited atoms produced in the recombination process by a study of the widths of the emitted afterglow lines. A model of the low-pressure helium afterglow which reasonably accounts for our electron density, line intensity, and linewidth observations involves principally the creation of He^+ ions and electrons by the collisions of pairs of helium metastable atoms, the three-body conversion of He^+ ions to He_2^+ ions, the ambipolar diffusion of He^+, He_2^+, and electrons, and the diffusion of helium metastable atoms to the walls. The λ5876 radiation (3^3D-2^3P transition) from the later part of the afterglow, when recombination of He_2^+ and electrons is expected to be the source of the excited atoms, exhibits a substantial broadening over the approximately thermal width observed during the discharge and in the early afterglow, when the radiation is expected to originate from electron impact excitation of helium atoms. It is concluded that the dissociative recombination process is the likely source of the observed afterglow line broadening.

I. INTRODUCTION

NUMEROUS experimental studies of the afterglows of pulsed microwave discharges[1–4] have shown that volume electron-ion recombination appears to be an important or dominating process in the removal of free electrons from ionized gases for several different gases. The principal technique in these experiments has involved the determination of spatially averaged electron densities during the afterglow by means of microwave probing techniques (see part I of this paper,[5] hereinafter referred to as I) and an analysis of the time dependence in terms of solutions of the equation of continuity for electrons subject to losses by recombination and diffusion. This analysis, as commonly employed, is outlined in Eqs. (3)–(6) of I.

In the rare gases neon and argon, it has been possible to obtain experimental data consistent with the recombination solution, $1/n_e=[1/n_e(0)]+\alpha t$, and thus to evaluate the recombination coefficient α with reasonable precision. In helium, however, due to the larger ratio of diffusion loss to recombination loss it has not been possible to obtain such a clear distinction. In addition, the helium measurements have been complicated by the fact that at pressures of only a few mm Hg the atomic spectra, which are presumably related to the recombination process, give way to molecular spectra of excited He_2. Thus, serious doubts have been cast on the validity of measurements of the recombination coefficient in helium by means of the afterglow time dependence studies.[6]

By means of a set of controlled mixture experiments in helium and argon, it has been shown (see I) that the large recombination coefficients observed in the pure gases do not appear under circumstances that inhibit

* Present address: Physics Department, Thiel College, Greenville, Pennsylvania.
† Physics Department, University of Pittsburgh, Pittsburgh, Pennsylvania.
[1] M. A. Biondi and S. C. Brown, Phys. Rev. **76**, 1697 (1949).
[2] R. B. Holt, J. M. Richardson, B. Howland, and B. T. McClure, Phys. Rev. **77**, 239 (1950).
[3] M. A. Biondi and T. Holstein, Phys. Rev. **82**, 962 (1951); M. A. Biondi, *ibid.* **83**, 1078 (1951).
[4] A. C. Faire and K. S. W. Champion, Phys. Rev. **113**, 1 (1959).
[5] M. A. Biondi, Phys. Rev. **129**, 1181 (1963).
[6] C. S. Leffel, M. N. Hirsch, and D. E. Kerr, Ann. Phys. (N. Y.) (to be published).