Cause of the Observed Polarization of Electron-Induced Radiation from Helium

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Recent improved measurements of threshold excitation and polarization of radiation from helium excited by electrons have led to the conclusion that previously reported "anomalies" are of experimental origin. Helium lines, $\lambda=4922$, 4388, and 5016 Å, exhibit polarization energy dependencies similar to that previously reported for $\lambda=3889$ Å. Helium lines $\lambda=4922$ and 4388 Å have excitation probability energy dependencies through limited energy ranges as predicted by theory. A tentative explanation of earlier results involves the contribution to both the excitation probability and the polarization of radiation caused by radially directed electrons elastically scattered from the electron beam. Attempts to reduce the radial travel of electrons have resulted in threshold and near-threshold polarization measurements which approach expected magnitudes.

INTRODUCTION

A PROBLEM involving basic understanding of the interaction of electrons with atomic systems has existed since the mid-twenties when Skinner[1] and Skinner and Appleyard[2] first observed that radiation emitted by mercury bombarded by a beam of electrons was polarized. Subsequent theoretical studies[3,4] showed that the threshold measurements observed were not in agreement with simple theory. Numerous authors[5–14] have written concerning this apparent anomaly. A second theoretical prediction[15–18] of the square-root energy dependence of excitation of atomic systems by electrons has never been convincingly demonstrated by direct experiment.

Recent innovations[19] in the measurement of radiation emanating from helium gas when bombarded by a beam of low-energy electrons have included improvements in the electron energy resolution, in the optics leading to greater available light intensities, and in the measurement of the scattered electron intensity.

Figure 1 shows a view of the electron gun, the interaction region, and the electron collector used for the work described in this report. While all surfaces seen by the electron beam in prior measurements were gold or gold-plated, there was evidence of surface charging. Differential pumping during the experiment with Vacsorb pumps emphasized this effect. Apparently the pumping of the hydrocarbons and water vapor so reduced the low-ionization-potential impurities that surface neutralization by positive ions below the ionization onset of helium was less probable. For this reason, the triple carbonate cathodes previously used were replaced by barium-impregnated tungsten cathodes. With metal being constantly evolved from the cathodes, evidence considered indicative of surface charging of the accelerating electrodes was reduced.

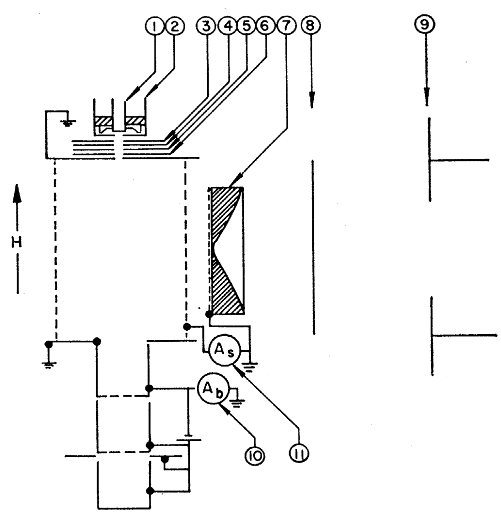

FIG. 1. Schematic diagram of the electron gun, interaction chamber, beam current analyzer, and optics. A square-wave, electron-beam-interrupting voltage was applied to the fourth accelerating electrode. (1) Cathode, $-V_C$; (2) first accel. electrode, $-V_C+5$; (3) second accel. electrode, $-V_C+50$; (4) third accel. electrode, ground; (5) fourth accel. electrode, $-V_C+5+$⊔⊓; (6) fifth accel. electrode, ground; (7) cylindrical lens; (8) Polaroid analyzer; (9) B & L 500-mm monochromator; (10) beam current electrometer; (eleven) scattered current electrometer.

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A retarding potential analysis of the electron beam's energy was made indicating a half-breadth of less than 0.5 V at 25 V, but the author considers this measurement to be unreliable. Surface effects including low-energy electron reflection[20] and charging combined to produce this breadth irrespective of the actual energy resolution of the beam. Atomic structure resolution was considered a more reliable indication of the energy resolution.

The major improvement in the experiment, however, involves the use of a cylindrically ground, fused quartz lens placed to focus the light excited by the electron beam onto the slit of the monochromator. Geometrically, it has the faculty of increasing the light collected from the beam by a factor of 100. The insulated cylindrical gold grid around the interaction region and the metallic coating and the gold grid at the front surface of the lens reduced the light transmission by a factor of 2. A further reduction was effected by the reduced volume from which light could reach the monochromator slit so

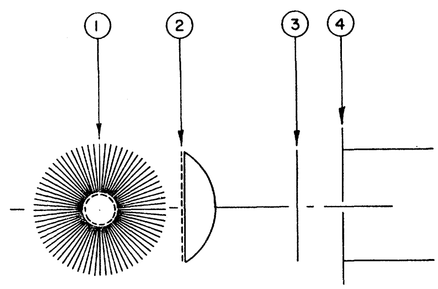

FIG. 2. An axial view of a special interaction region and optics designed to minimize the effect of elastically scattered electrons. The 72 radial fins were gold-plated before being electrolytically coated with platinum black. ① Interaction region surrounded by gold grid and electron collecting fins; ② cylindrical lens; ③ Polaroid analyzer; ④ B & L 500-mm monochromator.

that a final gain in intensity of about 10 was observed over that with the lens removed.

An extension of the initial experiment resulted from the replacement of the gold grid surrounding the interaction region as seen in Fig. 1 by a system of fins or plates as seen in Fig. 2. Its purpose was to reduce the radial motion of electrons elastically scattered from the beam as a magnetic field parallel to the electron beam caused the electrons to be partially collected at these plates. Various central apertures of from 0 to $\frac{3}{8}$ in. in diameter could be produced by adjusting the radial position of the plates.

Results of these experiments are shown by the curves of Figs. 3 through 7 where the relative excitation efficiency and/or the polarization at threshold of selected helium lines is plotted versus the potential applied to the cathode. Potential differences were measured by a Fluke 801 HR differential voltmeter. In all measurements the interaction region including the end plates and grid or plates was held at ground potential. Specifi-

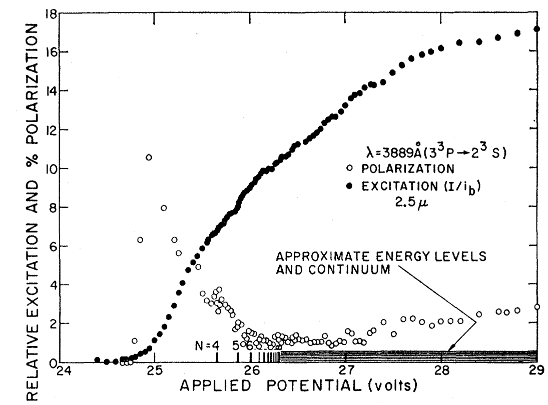

FIG. 3. The relative excitation, I/i_b, and polarization, $\pi=(I_{\parallel}-I_{\perp})\times(I_{\parallel}+I_{\perp})^{-1}\times 100\%$, of helium, $\lambda=3889$ Å.

cally, the accelerating potentials have not been corrected to spectrographically correct threshold values as they indicate the extent of surface and space charge effects. Ironically, when the Vacsorb pumping was terminated, the onset potentials were observed to coincide with the spectrographic values. The approximate energy levels shown are in relation to the observed onset potential but should not be considered absolute since the degree of surface charging changes as the helium ionization potential is approached.

In a separate experiment in which the Polaroid was removed from the optical path, the excitation efficiency versus energy dependence was examined by a direct measurement of total intensity rather than by a determination of $I_{\parallel}$ and $I_{\perp}$. Of the 10 lines measured, the sharp series lines exhibit the most structure near threshold. $\lambda=4121$ Å corresponding to the transition $5\,^3S\rightarrow 2\,^3P$ was measured to have an initial spike in intensity of 0.2-V half-breadth. This would appear to set a limit on the energy resolution of the system. How much of this breadth is characteristic of the transition is not known at this time, however. Curves comparable to those shown for $\lambda=4922$ Å have also been completed using the retarding potential difference method, $\Delta V=0.05$ V. The results were comparable to those shown except that greater errors were inherent in the measurements.

The curves of Fig. 3 are similar to prior measurements for $\lambda=3889$ Å.[5,13] The theoretical threshold polarization of $\lambda=3889$ Å is 36.6%. The polarization for $\lambda=3889$ Å, like that for the $\lambda=5016$-Å line shown in Fig. 4, does not reach its theoretical polarization magnitude. Both lines, however, have excitation and polarization curves which imply that the first light intensity observed is not due to direct excitation to the respective $3P$ level. This is best seen in Fig. 4 where a tentative assignment has been that the initial unpolarized light is due to excitation of the $3\,^1S$ level.

The polarization of the helium lines $\lambda=4388$ and 4922 Å, represented in Figs. 5 and 6, is also observed to dip in magnitude immediately above the threshold

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energy. At threshold, the polarization approximates the theoretical value of 60% within experimental error, which is estimated to be about 10%. Experimental error drops to 1 or 2% at a few tenths of a volt above threshold. Previous measurements have missed the low energy dip in these lines as well as that for 5016 Å. This is not surprising, for the energy breadth of decreasing phase of the dip is of the order of 0.2 V wide. In addition, Fig. 6 shows the results of a series of measurements in which the interaction region was surrounded by scattered electron stopping plates or fins as shown in Fig. 2. Also drawn in Fig. 6 is a straight-line extension of the polarization curve as measured at higher energies. While the theoretical polarization magnitude is 60% at threshold, it does not include the depolarizing effect of pressure. At 2.5 μ, a straight-line extrapolation of experimental measurements yields approximately 50% as a threshold value. Thus some indeterminacy exists near threshold concerning the magnitude of the polarization. On the other hand, the reduction of electron motion normal to the beam direction causes the measured values to converge toward those which may be assumed more nearly correct.

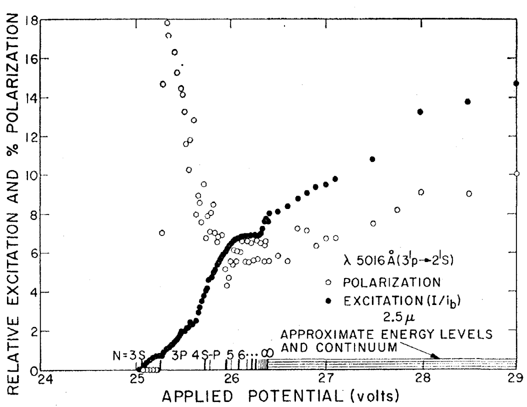

FIG. 4. The relative excitation and polarization of helium, $\lambda=5016$ Å.

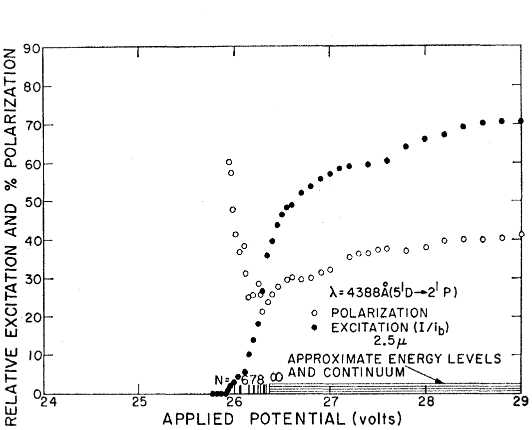

FIG. 5. The relative excitation and polarization of helium, $\lambda=4388$ Å.

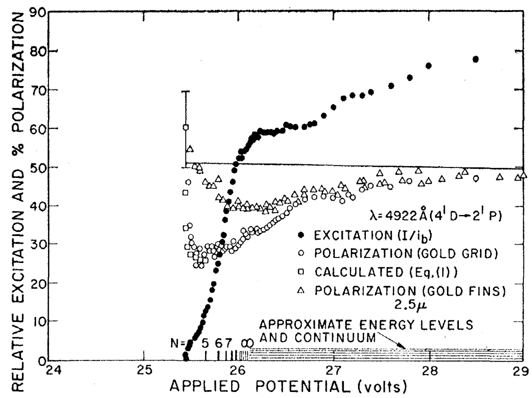

FIG. 6. The relative excitation and polarization of helium, $\lambda=4922$ Å. The solid curve represents a straight-line extrapolation toward threshold of the polarization as measured at the higher energies. The gold-fin polarization measurements are the results of three separate runs representing magnetic fields of 10, 30, and 60 G.

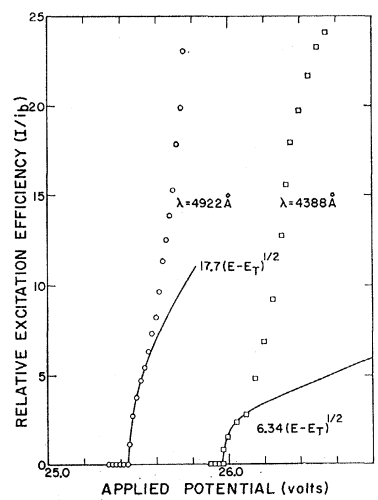

FIG. 7. Relative excitation efficiency curves for $\lambda=4388$ and 4922 Å on an expanded scale. The solid lines are empirical fits of the uncorrected data near threshold.

Figure 7 shows that for a limited energy range adjacent to threshold the excitation efficiency of both $\lambda=4388$ and 4922 Å seems to have a square-root excess energy dependence. Although not shown here, the sharp triplet $\lambda=4713$ Å was observed to have zero polarization independent of energy.

A final result involves the scattered electron current. With an axial magnetic field of 15 G, a pressure of 10^{-7} Torr, and an accelerating potential of 25 V, the ratio of currents through A_s and A_b of Fig. 1 was 0.5%. With 2.5 μ of helium in the system this ratio became 6.6%. Thus, in terms of the transmission of the cylindrical grid (57%), 15% of the beam current was elastically scattered to be collected at the cylindrical walls of the interaction chamber. At 30 V, the corrected ratio dropped to 12%. These must be considered lower limits in the measurement of the scattered current as both internally grounded end plates of the interaction chamber were recipients of scattered electrons.

DISCUSSION AND CONCLUSIONS

With the knowledge that the energy dependence of the polarization of electron-induced radiation can be measured to approach that expected from theoretical considerations and that elastically scattered electrons are to be associated with its departure from theory, one can qualitatively explain experimental observations as follows: Assuming the observations for the $\lambda=4388$- and 4922-Å lines are most nearly typical of direct excitation of a level without contributions from collision and cascade transfers, threshold polarization and the excitation must be due to beam electrons which are collected and measured by A_b. Elastically scattered electrons, having lost finite energy in the collision, are ineffective. For these diffuse singlets, the 60% polarization expected implies that 80% of the photons produced and observed at 90°, $I_{\parallel}$, have electric vectors parallel to the electron's direction of motion. Twenty percent, $I_{\perp}$, will have electric vectors perpendicular to the motion. This condition should exist for a limited energy range of less than 0.005 V, equivalent to the maximum energy lost by an electron in an elastic collision.

Above this energy, radial motion of the elastically scattered electrons contributes more to the intensity of $I_{\perp}$ than to $I_{\parallel}$, tending to decrease the polarization. Analysis of this effect requires knowledge of the cross section and angular distribution for the scattered electrons as well as the cross section for excitation as a function of voltage. In terms of an overly simplified model, one can arrive at a relationship for the polarization,

$$\pi=\frac{3B\bar{\sigma}_x(V)i_b-\frac{3}{2}S\bar{\sigma}_{xs}(V)i_s}{5B\bar{\sigma}_x(V)i_b+\frac{7}{2}S\bar{\sigma}_{xs}(V)i_s}\times 100\%. \quad (1)$$

B and S are geometry factors for the beam and scattered electrons to account for their path lengths. $\bar{\sigma}_x(V)$ and $\bar{\sigma}_{xs}(V)$ are the respective cross sections for the production of photons by beam and scattered electrons averaged over their respective energies; i_b and i_s are the respective currents.

At threshold $\bar{\sigma}_{xs}(V)$ is zero and the polarization magnitude is 60%. As the energy of the electrons increases, $\bar{\sigma}_{xs}(V)$ increases to approximate $\bar{\sigma}_x(V)$. Assuming Bi_b and Si_s to be constant and in the ratio of 0.7 as indicated below, $\bar{\sigma}_x(V)=A(\Delta V)^{\frac{1}{2}}$, and $\sigma_{xs}(V)=A(\Delta V-0.005)^{\frac{1}{2}}$, one can calculate an approximate fit to the experimental points near threshold as seen in Fig. 6.

The denominator of Eq. (1) is the total intensity at the voltage for which the polarization is being measured. Assuming $\bar{\sigma}_{xs}(V)=\bar{\sigma}_x(V)$, a polarization of 25% at the minimum as observed for $\lambda=4922$ Å would require that Si_s equal 0.73 Bi_b. This seems high but may not be since the measured $i_s/i_b=15\%$ includes only a portion of the scattered electrons. Further, we know relatively little of the reflection of the electrons at the surfaces and the contact potential at the grid. Twenty-five-volt electrons with scattering angles less than 30° or greater than 150° have circular paths of diameter less than the radius of the interaction chamber in the applied magnetic field. This, obviously, increases the magnitude of S relative to B.

The increase in polarization at voltages greater than that for which minimum polarization occurs for each of the lines is at least as difficult to explain as the decrease. With $\lambda=5016$ and 3889 Å both changes are less abrupt than for $\lambda=4922$ and 4388 Å. This may be due to relative effective magnitudes of the respective $\bar{\sigma}_x(V)$'s as determined by cascading. Over the voltage range of observation, the ratio i_s/i_b decreases with increasing voltage by 20%. Further, the scattering observed should involve smaller scattering angles. At 29 V, one may use Eq. (1) and the observed total intensity to show that $Si_s=0.3Bi_b$. This is more change than expected from the change in the ratio i_s/i_b, but may only serve to indicate how inexact our knowledge is of what happens within the interaction chamber in terms of electron paths and surface effects.

The excitation curves of Fig. 7 are interesting and reproducible. Obviously, the individual intensity measurements indicated correspond to integrations of the product of electron energy distribution functions and excitation cross section between the energy limits from threshold to the maximum electron energy. Since thermal energies of electrons from the cathode are of the order of 0.1 V, the apparent energy resolution observed in Fig. 7 is extreme unless focusing has improved the energy resolution. The parameters of the square root functions which have been empirically fitted to the experimental points are not to be confused with the parameters of the corrected curves which would result from knowing the actual electron energy distribution. Note also that the energy range fitted is only about half that for which the polarization decreases. When the factor $\frac{7}{2}S\bar{\sigma}_{xs}(V)i_s$ becomes appreciable with respect to $5B\bar{\sigma}_x(V)i_b$ in Eq. (1), the error in considering i_b as the total current effective in producing excitation becomes apparent in terms of increased I/i_b.

Previously reported magnetic field effects[21] can be explained in terms of scattered electrons. The abrupt lessening of the polarization for the diffuse singlets observed as the magnetic field is increased occurs at magnetic fields required to prevent the orbit of the electrons scattered at roughly 90° from intersecting the wall.

The data presented in Fig. 6, which were taken with the interaction chamber shown in Fig. 2, support the tentative explanation of the polarization effects as presented in this paper. That this device reduced the observed polarization dip was considered as tending to confirm this explanation.

At least one other method of accomplishing a similar

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reduction has been considered. It involves a system of concentric grids around the interaction region biased in such a fashion that the scattered electrons would travel and be collected at an energy less than required for excitation.

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Repulsive Interaction Potentials between Rare-Gas Atoms. Heteronuclear Two-Center Systems*

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A theoretical expression, previously applied only to homonuclear pairs of rare-gas atoms, has been used to calculate the interaction energies $U(R)$ for the corresponding heteronuclear two-center systems at internuclear separations R ranging from $0.01a_0$ to $\sim 6.0a_0$ ($a_0=0.529$ Å). These results are compared with: (a) empirical data; (b) other calculations; (c) the geometric-mean rule $U_{AB}=(U_{AA}U_{BB})^{1/2}$; (d) the corresponding united-atom energies. With regard to (a) and (b), this comparison supports conclusions drawn previously from a study of the homonuclear pairwise interactions. That is, the present calculations, too, generally agree more closely with experiment than does either Bohr's screened Coulomb potential or Firsov's Thomas-Fermi type potential. Relation (c) is found to be satisfied, generally, to within a few percent. As for (d), calculations for the He-Ne and Ar-Kr systems indicate that, as $R\to 0$, the electron energy of each system tends, approximately, to the appropriate empirical united-atom value. A similar study of other systems, including the light gases, metals, and certain diatoms, is in progress.

I. INTRODUCTION

A DETAILED knowledge of the interatomic potential $U(R)$ is essential to the solution of a large variety of problems arising in the study of the solid,[1] liquid, and gaseous states.[2–4] At very small interatomic distances $R\lesssim 0.2a_0$ ($a_0=0.529$ Å), Bohr's[5] screened Coulomb potential is a good representation,[6] and at the very much larger near-equilibrium separations, the empirically fitted potentials of the Lennard-Jones (12-6) type (LJ), and of the modified Buckingham (exp-6) type (MB), etc., are applicable.[2] Comparatively little is known concerning $U(R)$, however, in the *intermediate* range of separations, particularly important in the study of phenomena involving close atomic encounters[6–12] or very high pressures and/or temperatures.[13–18] For this reason it seemed worthwhile to examine the reliability of a theoretical expression, U_{TFD}, derived elsewhere[19] on the basis of the Thomas-Fermi-Dirac (TFD) statistical model of the atom[20,21]

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