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Intensity Relations in the Low Voltage Helium Arc

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The linear amplifier photo-cell unit from a Razek-Mulder spectrophotometer is used with a high speed monochromator to measure the relative intensity of helium spectrum lines under various conditions of excitation; the discharge is developed in a copper ball 10.5 cm in diameter. A linear relation is found between arc current and line intensity for a series of voltages between the excitation potential and 100 volts, and from this family of curves a family of excitation functions is drawn for a range of currents up to thirty milliamperes. The voltage intensity relation for eight helium lines (4388, 4438, 4471, 4713, 4922, 5016, 5876, 6678) was determined directly. The results check those of Razek up to 50 volts and those of Elenbaas over the entire range, although secondary maxima are indicated in the region between the ionization potential and 45 volts. Additional experiments show that the cathode surface plays a part in determining the character of the discharge, and that the rise in Razek's curves was caused by the discharge changing to the self-maintaining form; the hysteresis observed by him is eliminated by the use of a two-grid electron source.

THE function which describes the relation between the intensity of a spectral line and the accelerating voltage of the exciting electrons is called the "optical excitation function" of the line. This function in helium has been the subject of considerable investigation.[1–8] If the results of these investigations are to be interpreted in the light of the usual microscopic theories it is necessary to insure that (1) the electrons are homogeneous as to velocity, (2) each electron produces a single photon emission, (3) the number of electrons projected into the gas can be obtained from the measured current, and (4) the energy of the electrons is truly indicated by the voltage measuring device. These conditions will not be met if (1) the mean free path of the electrons is too short, (2) if large space charge effects are present, (3) if the atoms are excited by more than one collision, or by the combined absorption of energy from electrons and photons, (4) if the structures in the tube alter the character of the discharge, (5) if there is self-absorption of the radiation by the gas, or (6) if secondary electrons are present. A linear relation between intensity and both current and pressure is usually accepted as evidence that the conditions enumerated above have been met.

The photographic method of intensity measurement has been used by all previous investigators except Razek.[8] The greatest accuracy claimed for a photographic determination of intensity is 5 percent.[9] However, Hanle[4] reports that variations on the plates used in his work were between 10 and 20 percent, consequently irregularities in the functions he investigated which are of an order of magnitude less than 10 or 20 percent cannot be considered significant. Furthermore, the inherent slowness of the photographic method detracts from its usefulness in excitation function determinations where the "fine structure" of the phenomenon is being studied, since it is difficult to keep constant the discharge tube currents and voltages for a sufficient length of time. Most of the curves in the literature for which data are given indicate a lack of smoothness, but the limited accuracy of the photographic photometry does not justify the drawing of anything but a smooth curve through the points. Furthermore, the number of voltages used is usually insufficient to make the curves which are drawn really indicative of the detailed character of the function.

The spectrum tubes used by other workers[2, 4–7] were usually of small dimensions and were furnished with nonequipotential cathodes, the inequality ranging from 0.3 volts to 5 volts. The envelopes were of glass and the electrodes and shields were large and placed unsymmetrically with respect to the discharge. It is well

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[1] Elenbaas, Zeits. f. Physik **59**, 289 (1929).
[2] Hughes and Lowe, Proc. Roy. Soc. **A104**, 480 (1923).
[3] Bazzoni and Lay, Phys. Rev. **23**, 327 (1924).
[4] Hanle, Zeits. f. Physik **56**, 94 (1929).
[5] Michels, Phys. Rev. **36**, 1362 (1929).
[6] Thieme, Zeits. f. Physik **78**, 412 (1932).
[7] Lees, Proc. Roy. Soc. **137**, 173 (1932).
[8] Razek, Phys. Rev. **37**, 1252 (1931).
[9] Lay and Cornog, J. Opt. Soc. Am. **24**, 149 (1934).

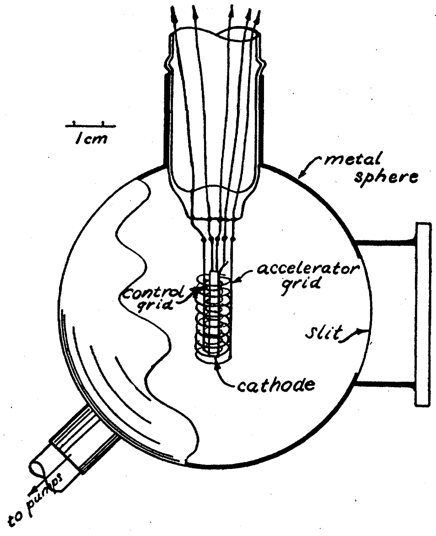

FIG. 1. Diagram of discharge tube for low voltage helium excitation.

known in vacuum tube practice that the disposition of the electrodes plays an important part in determining the tube characteristics, owing to the accumulation of surface charges and similar effects, consequently it might be expected that the behavior of a small discharge in a relatively large system of electrodes would be strongly influenced by the geometry of the system.

Razek used a photoelectric spectrophotometer[10, 11] the response of which was shown to be linear with intensity; this instrument, with which the inherent slowness of the photographic method may be overcome, was shown by him to be applicable to the problem in hand. The linear amplifier from Razek's spectrophotometer and a spectrum tube similar to his were used in the work here reported. From the description of this tube it will be seen that the discharge takes place in a "hohlraum" relatively free from electrodes. The present work was undertaken with the idea of using this kind of tube to determine in greater detail the character of the excitation function, as well as to demonstrate that the sources of error listed above were not present at the relatively high pressures used in this type of equipment. The pressure of the helium was 0.27 mm of mercury.

DESCRIPTION OF THE DISCHARGE TUBE

The discharge takes place in a spun copper ball 10.4 cm in diameter, the inside surface of which is silvered and polished. A slit, over which is placed a tube and a glass plate, allows observation of the discharge. The electron source (Fig. 1) was mounted on the press from a commercial vacuum tube by spot welding to the leads a heater-type oxide coated cathode (diameter 1.7 mm) such as is used in the type '27 tube, a grid from the same type tube (diameter 4 mm) and a second grid from a type '24 tube (diameter 7 mm). The grid nearer the cathode is the "control-grid" and the other is the "accelerator-grid." The wiring is shown in Fig. 2.

The electrons are emitted by the cathode, and the number which is admitted into the space between G_1 and G_2 is determined by the potential difference between G_1 and C; the sense of this potential difference may be changed by means of the reversing switch. Thus the number of electrons available for acceleration by the field between G_1 and G_2 may be regulated without changing the temperature of the cathode; the cathode temperature is maintained by the usual insulated filament heated by a storage battery. A radio B battery supplies the potential difference between G_1 and C, which potential controls the arc current; a bank of storage batteries is used to supply the accelerating potential between G_1 and G_2. The discharge takes place in the equipotential space between the ball and G_2, and the current in the arc is measured by the milli-

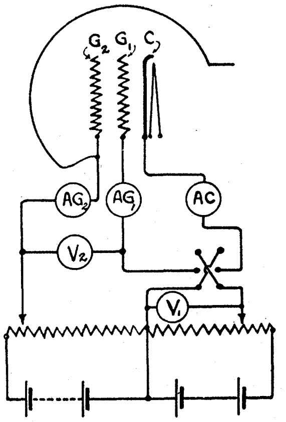

FIG. 2. Wiring diagram of discharge tube for low voltage helium excitation.

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[10] Mulder and Razek, J. O. S. A. and R. S. I. **18**, 466 (1929).

[11] Razek and Mulder, J. O. S. A. and R. S. I. **19**, 390 (1929).

ammeter AG_2. For each observation in the course of the experiment a reading of each meter was taken so as to follow the behavior of the discharge tube as closely as possible. It was thought that a study of the relations between the various currents and voltages might yield information as to the function of the parts of the electron gun; as a matter of fact data were obtained (to be mentioned later) which apparently shed light upon the action of the control grid G_1.

Description of Experimental Set-Up

The discharge tube was permanently connected to the vacuum system through a stopcock; between this stopcock and the ball was a charcoal trap which was immersed in liquid air. The initial pumping was continued for several hours, during which time the cathode material was activated. The presence of waxed joints prevented degassing, and the system was considered clean when the electron current between the elements showed no luminosity and when the characteristics of the tube remained constant. Helium was admitted by the conventional arrangement of bulb and stopcocks, having been allowed to stand in two liquid-air traps for a half-hour before admission to the ball. Examination of the discharge by means of a direct vision spectroscope showed no trace of impurity such as mercury or hydrogen.

The large aperture (f : 1.4) double prism monochromator was designed by Dr. Joseph Razek and was constructed in this laboratory with funds provided by the Faculty Research Committee of the University of Pennsylvania. The entrance slit of this monochromator was placed as close as possible to the slit in the discharge tube, leaving just enough room for the sliding shutter S_1 (Fig. 3). The spectrum is formed on the exit slit I, which may be moved laterally to admit any desired line to the photocell which, with its amplifier, is attached to the monochromator. The photoelectric current is amplified, and the amplified current is indicated by a galvanometer. A 6–8 volt headlight lamp provided a standard of intensity; its brightness was kept constant by the Richardson's bridge arrangement indicated in Fig. 3 and described in detail by Razek.[8] A piece of plate glass P reflected a portion of the light into the system so that the lamp was virtually in the same position with respect to the collimator lens as the entrance slit E. Opening the shutter S_2 resulted in the formation of an image at I of the filament of the same color as the line whose intensity was being measured.

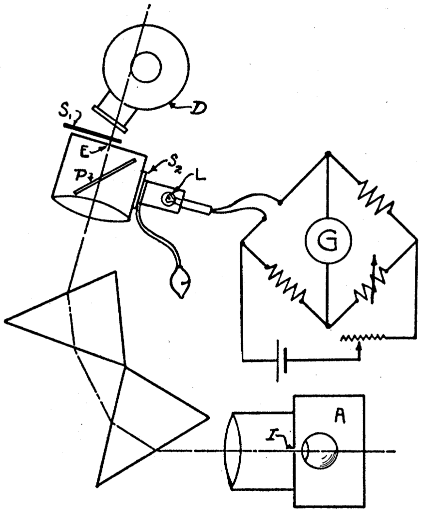

FIG. 3. Optical arrangement for comparison of helium line intensities with standard source.

The experimental procedure was simply to open shutter S_1 and to note the galvanometer current in the photo-cell amplifier, then having closed S_1, to open S_2 and to make a similar reading for the standard intensity. The relative intensity plotted in the results is the ratio between these two galvanometer currents. Such intensity determinations were made (1) for constant voltage and varying arc current and (2) for constant arc current and varying accelerating voltage. The constant voltage determinations were made to test the assumption that the arc current was a reliable measure of the number of collisions occurring in the field-free space and to test the reliability of the photometry. The constant current determinations gave the optical excitation functions of the lines under the conditions of the experiment.

Previous workers have controlled the arc current by varying the temperature of the cathode, but in this work the distribution of the potentials on the grids was used as the controlling agent. This method was deemed ad-

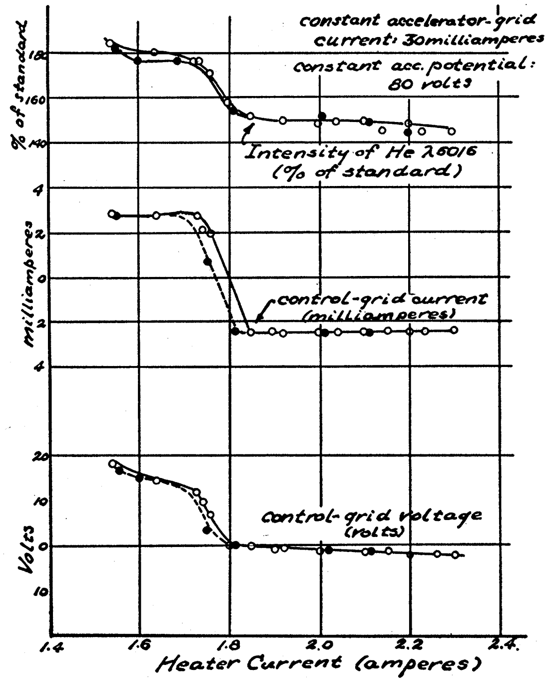

FIG. 4. Behavior of helium discharge tube with changing cathode temperature.

visable since it seemed that the form of the discharge changed with cathode temperature; "hot-spots" formed on the cathode as the result of operating at low temperatures and high accelerating voltages. Improved technique in the matter of applying and forming the cathodes resulted in such active coatings that above certain accelerating voltages the arc became self-sustaining and continued to operate with the cathode cold. This tendency to become self-sustaining began to show itself in most cases when the accelerating voltage was in the neighborhood of sixty volts.

Introduction of the control grid made it necessary to conduct a series of experiments to show that the intensity was not a function of the distribution of the potentials on the grids, but depended solely upon the current to the accelerator grid. Although the temperature of the cathode was varied it was possible to keep the current and voltage between G_1 and G_2 constant by changing the control voltage between G_1 and C. Having decided upon a constant current and voltage, the heater current was varied so as to change the initial supply of electrons; the intensity of a line was measured as a function of cathode temperature. The results are shown in Fig. 4. The curves show that as long as the cathode was kept at a moderately high temperature, the intensity remained constant, regardless of the control grid voltage or the initial supply of electrons, but an increase in intensity was noted when the cathode temperature decreased to the point where a self-sustaining arc began as evidenced by instability in the arc current. In the subsequent work, the cathode was always heated to a temperature well above that at which instability became evident.

By making the control grid positive, the

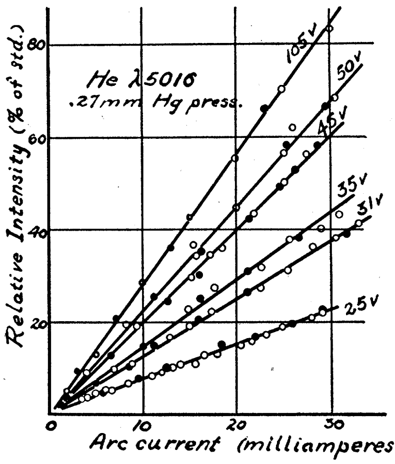

FIG. 5. Current intensity relations in the low voltage helium discharge.

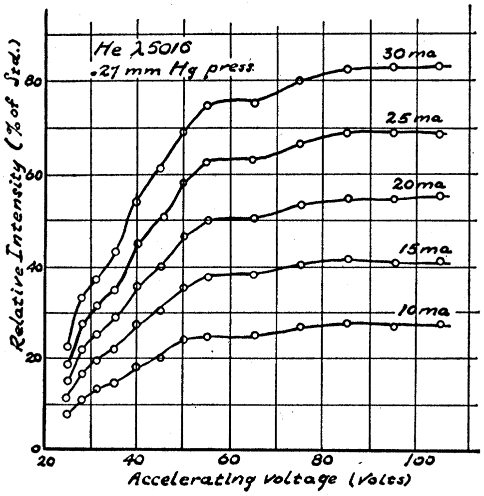

FIG. 6. Family of voltage intensity relations derived from current intensity curves.

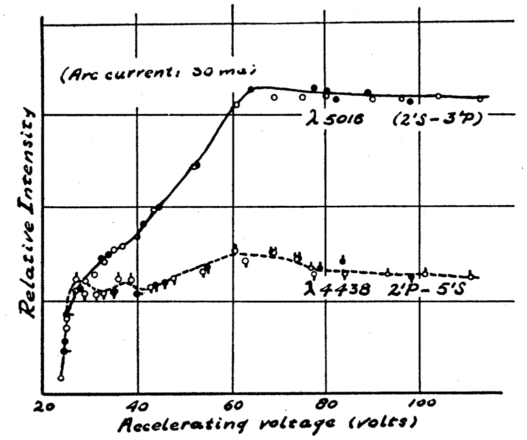

FIG. 7. Voltage-intensity relations in the low voltage helium discharge: lines 5016 (2^1S-3^1P) and 4438 (2^1P-5^1S).

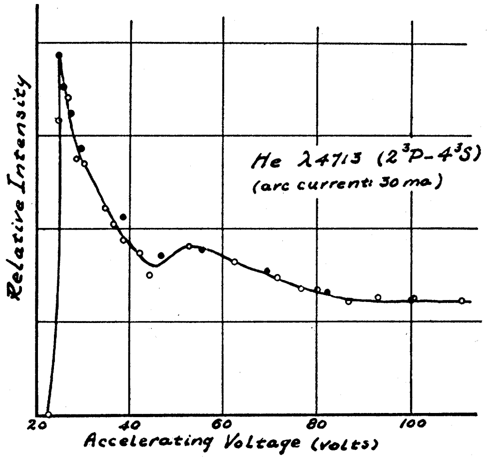

FIG. 8. Voltage intensity relations in the low voltage helium discharge: line 4713 (2^3P-4^3S).

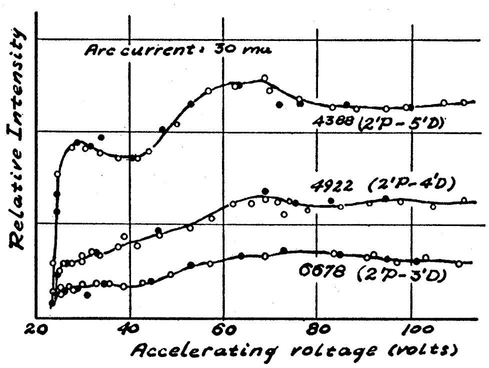

FIG. 9. Voltage intensity relations in the low voltage helium discharge: lines 4922 (2^1P-4^1D), 4388 (2^1P-5^1D), 6678 (2^1P-3^1D).

electrons arrived in the field-free space with the energy corresponding to the sum of the potential drops between the two grids, and the full spectrum always appeared when these two voltages added to 24.5, the ionization potential of helium. Characteristic curves were plotted in which the "breaks" were found to occur very close to the ionization potential, regardless of the distribution of the potentials on the grids. These experiments were considered as indicating that the voltages read on the meters were the voltages applied to the electrodes and that the introduction of the control grid gave rise to no significant complication. The drop across the milliammeters was read by the voltmeters, but this was less than the least count of the meters and could be neglected. The absence of contact potentials of notable magnitude was indicated by the agreement between the accepted value of the first ionization potential and the voltage at which the full spectrum appeared. The absence of voltages due to oscillations was ascertained by checking the readings of the voltmeters against a vacuum tube voltmeter; the check was within the precision of the instruments.

RESULTS

The linear relation between current and intensity is demonstrated by the curves in Fig. 5; the open circles represent data taken with increasing current and the solid circles with decreasing current. This linearity shows, as has

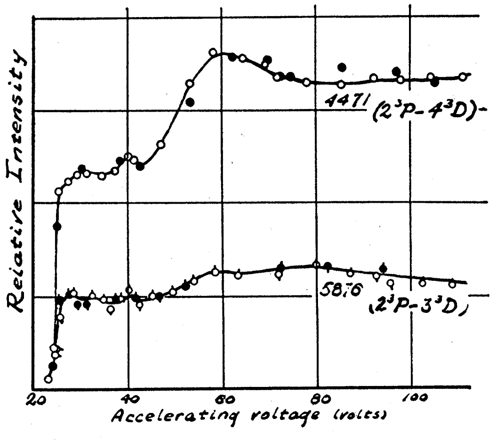

FIG. 10. Voltage intensity relations in the low voltage helium discharge: lines 4471 (2^3P-4^3D) and 5876 (2^3P-3^3D).

been mentioned, that the current to the accelerator grid is a measure of the number of electron collisions and that the photometry is reliable. By making the measurements at a number of voltages, the fact that the linear relation holds for all voltages between the ionization potential and 100 volts is demonstrated. A family of curves such as is shown in part in Fig. 5 may be used to plot a similar family of voltage intensity curves by simply using the ordinates corresponding to the constant current value of the excitation function. The curves shown in Fig. 6 were drawn from the data supplied by the curves in Fig. 5.

Although the linearity is demonstrated to well within the limits of precision of the measurements, the greatest deviations occur in the vicinity of 55 volts, where peak intensities of considerable magnitude have been reported by Cornog.[12] The curves indicate good linearity up to current values of thirty milliamperes, beyond which a slight tendency to saturation is noticed, as might be expected; this would indicate that currents as great as 30 ma may be used without changing the character of the excitation function.

The excitation functions (Figs. 7–10) check the work of Razek as far as 60 volts; where Razek's curves show an increase in intensity, the present results show either a decrease or a flattening. The increase in Razek's functions is probably related to the effect noted above, *viz.*, that at low cathode temperatures the arc tends to change its character; as a result of this change the intensity increases. The collisions which produce the light whose intensity is being measured are presumably in the positive column of the discharge, and should be caused solely by electron-atom encounters, but when the arc tends to become self-sustaining, other light producing mechanisms are involved, as is evidenced by the so-called "negative glow" in the cold discharge. In the present arrangement, in which a dense cloud of electrons is maintained around the cathode, the positive ion bombardment of the cathode is minimized, consequently the negative glow should not be observed. The unusually long life of the cathodes in the two-grid electron source as compared to the one-grid type also indicates that destructive positive ion bombardment has been considerably reduced. The "hysteresis" effect observed by Razek has also been eliminated; this is indicated in the curves, where the solid circles represent intensities measured during a run of decreasing voltages, while the open ones represent increasing voltages. It was in the hope of eliminating this hysteresis effect that the two-grid electron gun was developed, since it would then be possible to carry the tube through a voltage cycle without changing the cathode temperature and consequently without disturbing the condition of the cathode surface. That the cathode surface has something to do with the character of the discharge is evidenced by the fact that there was no hysteresis as long as the cathode was unchanged during a measurement.

The action of the control-grid may be visualized by reference to the curves in Fig. 4. In this experiment the grid was used to keep the supply of electrons in the accelerating field constant; it will be noticed that the current to this grid is constant and that the grid serves to regulate the concentration-gradient between itself and the cathode so as to keep constant the electron density in the acceleration space.

The voltage intensity curves are in good agreement with those of Elenbaas which show maxima in the vicinity of sixty volts as well as a dip around forty volts. This sixty volt maximum was attributed by Lees[7] to a change in the shape of the beam, and the inability of Elenbaas' apparatus to integrate the intensity. The present apparatus is not open to this objection since the silvered sphere does accomplish the integration, so that the sixty volt maximum seems to be real. Some significance may attach to the fact that Elenbaas' apparatus is in general similar to that used in the present work; the cylindrical anode with a slit for observation constitutes a kind of "hohlraum" as does the sphere in the present work, and the entire current to the anode is also measured by Elenbaas. Although the results given here are only in general agreement with the results of the other workers,[4, 5, 7] it will be noticed that a tendency toward an inflection at forty volts is exhibited by the data; the curves are drawn smoothly however, since the precision of the photographic method is not great enough to warrant attaching significance to the indicated irregularities. There

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[12] Cornog, Phys. Rev. **32**, 746 (1928).

is also in the present results a marked indication of secondary maxima between the ionization potential and about 45 volts; this is most noticeable in the lines 4471 (2^3P-4^3D) and 5876 (2^3P-3^3D) (Fig. 10). A somewhat similar effect has been reported for mercury by Siebertz;[13] there is a possibility, however, that this effect in mercury is of a different order of magnitude from the effect reported here.

The sudden changes which occur in the neighborhood of the ionization potential make it rather difficult to set the currents and voltages simultaneously, consequently no attempt was made to set the current at the indicated constant value, but intensities corresponding to the indicated value could be calculated on the basis of the experimentally proved linear relation between current and intensity. Beyond about 35 volts these corrections amounted to less than the precision of the measurements.

CONCLUSIONS

From these results it may be concluded that the discharge tube used by Razek, modified so as to control the supply of electrons without changing the cathode temperature, gives excitation functions which check with those determined by other workers who used the photographic method. The hypothesis that the "hysteresis" effect noticed by Razek is associated with changes in the condition of the cathode surface is substantiated, since keeping the cathode at a constant temperature and protecting it from positive ion bombardment eliminated the effect.

The linear relation between current and intensity shows that pressures as high as those used do not lead to complications in the large, high intensity source used in this work.

In addition to checking the form of the excitation functions determined by Elenbaas, the present work indicates secondary maxima in the region between the ionization potential and forty-five volts.

The writer wishes to express his thanks to Professor C. B. Bazzoni, under whose guidance the work reported here was done; to Mr. F. R. Banks, who assisted in taking the readings, and to Dr. Joseph Razek for valuable aid and suggestions.

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[13] Siebertz, Physik. Zeits. **31**, 141 (1930).

JUNE 15, 1938 PHYSICAL REVIEW VOLUME 53

The Infra-Red Absorption by $C^{13}O_2^{16}$ at 4.375 μ

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The fundamental vibration-rotation band ν_3 of $C^{13}O_2^{16}$ has been found with its center at a wave-length of 4.375μ or 2284.5 cm^{-1}. The individual lines in the band have been fitted by the formula $\nu_3=2284.5+0.780\ N-0.0027\ N^2$ where N takes the values $-2, -4, -6, \cdots$, etc. for the P branch and $+1, +3, +5, +\cdots$, etc. for the R branch. On applying the appropriate mass correction to ν_3 and to the anharmonic constant x_{33} given by Adel and Dennison, these constants take values of 2295.8 cm^{-1} and -11.4 cm^{-1}, respectively. Together these constants give the position of the center of the band as 2284.4 cm^{-1}, which is virtually in perfect agreement with observation.

I. INTRODUCTION

MEASUREMENTS in the infra-red region near 4.37μ in the atmosphere made by earlier investigators in this laboratory have shown the existence of a weak absorption maximum with resolvable rotation lines on the low frequency side of the very intense fundamental vibration ν_3 of the CO_2 molecule. Since part of this absorption region overlaps with the P branch in ν_3 of CO_2 and the lines appear to

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