The Energy Loss of Low Energy Protons in Some Gases*

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Experimental values for the energy loss of protons in H_2, He, N_2, O_2, A, Kr, H_2O, CO_2, and CCl_4 have been obtained in the region from 10 to 80 kev. The energy loss $(\Delta E/\Delta x)$ can be expressed for the elementary gases measured in terms of a single curve, with two constants $\Delta E/\Delta x = Lf(ME)$. The energy loss per atom is independent of the target density over the range 0 to 1.5-mm Hg, and the energy loss for compound gases is equal to the sum of their components.

I. INTRODUCTION

IN traversing a target, a charged particle has a maximum rate of energy loss in the region where the velocity is comparable with the orbital electron velocities in the target atoms. Although abundant measurements of the energy loss have been made on the high energy side of the maximum, the data are scanty on the low side, and the present work was undertaken to provide data in this region.

In 1942, Crenshaw[1] measured the energy lost by protons and deuterons in some gases above an energy of about 100 kev. More recently, Wilcox[2] and Warshaw[3] have reported measurements on the stopping power for protons in several metals in the energy range from 50 to 400 kev. Also Wenzel and Whaling[4] have measured the energy loss of protons in heavy ice in the energy interval from 18 to 540 kev.

The present experiment was designed to measure the energy loss due to ionization, excitation, and charge exchange but not that due to nuclear scattering. Thus only those particles which entered and left the apparatus in a narrow pencil of angle 2.5° were measured. The apparatus and techniques used for the reaction cross-section experiments completed previously lent themselves rather readily for use in making the energy loss measurements in the same energy range. Since these techniques have been reported elsewhere[5] in detail they

FIG. 1. A schematic diagram of the absorption chamber and decelerator.

will not be fully described here. Measurements were made on H_2, He, N_2, O_2, A, Kr, H_2O, CO_2, and CCl_4.

II. APPARATUS AND PROCEDURE

Analyzed protons of energy 10 to 80 kev from a Cockcroft-Walton accelerator passed through a gas absorption chamber via thin (5 to 10 kev) windows into a decelerator. The decelerator measured the current received, as a function of retarding voltage, and hence the energy and energy distribution in the beam. Changing the gas density in the absorption chamber then gave the energy loss in the gas by difference.

The absorption chamber is shown in Fig. 1. The beam was collimated by an aperture 5 mm in diameter. The front foil was mounted on foil holders of different length so that the path length of the beam in the gas could readily be changed. The back foil was mounted on the sliding vane of a valve.[6] When the valve was opened, the back foil was removed from the beam and the energy loss of the front foil could be measured. The valve then could be closed and a gas-tight chamber obtained. A 5-mm diameter collimator was located immediately in front of the back foil. The absorption chamber was insulated from ground so that the beam current to the chamber could be monitored.

Two lengths of the absorption chamber were used, 11.65 and 4.96 cm. The longer chamber was used at high proton energies and with gases having small stopping powers. At lower energies the scattering of the beam by the foils became serious, and in order to have sufficient intensities at the decelerator, the shorter chamber was used.

The preparation and properties of the SiO foils used as windows have been described elsewhere.[7] In these experiments, the foils were 8 mm in diameter and the beam had a diameter of 5 mm. The foils were strong enough to hold a pressure of 2- to 3-mm Hg and the gas leakage was usually negligible. Because these foils are insulators, it was necessary to expose them to an excess of electrons when a beam passed through them in a vacuum. Thus, the foils were prevented from charging up and destroying themselves.

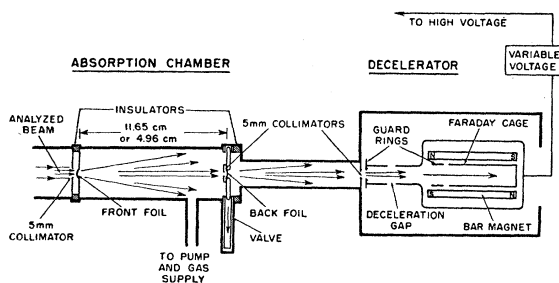Each of the two foils of the absorption chamber scat-

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] C. M. Crenshaw, Phys. Rev. 62, 54 (1942).
[2] H. Wilcox, Phys. Rev. 74, 1747 (1948).
[3] S. D. Warshaw, Phys. Rev. 76, 1759 (1949).
[4] W. Wenzel and W. Whaling, Phys. Rev. 87, 499 (1952).
[5] Los Alamos Report, La-1479 (unpublished).

[6] Wahl, Forbes, Nyer, and Little, Rev. Sci. Instr. 23, 379 (1952).
[7] G. A. Sawyer, Rev. Sci. Instr. 23, 604 (1952).

tered the beam, and only a small part of the beam incident on the front foil passed through to the decelerator. Since the scattering becomes greater, the lower the energy of the beam, it became a serious problem to obtain sufficient beam current at the decelerator without destroying the foils. This set the lower limit of energy in this experiment at which effective measurements could be made. Replacing protons in the beam by deuterons and tritons allowed the lower limit of the energy to be extended downward in the following way: it has been shown by Crenshaw and Warshaw (and this experiment) that isotopes having the same velocity have the same energy loss. Thus, a hydrogen isotope of mass M and energy E will have the same energy loss as a proton of energy $(M_p/M)E$, where M_p is the mass of the proton. The scattering in a foil of the different isotopes at the same energy, however, is the same. Thus, at an incident energy E, the scattering, and consequently, the attenuation, of protons, deuterons, and tritons will be the same, but the differential energy losses observed correspond to protons of energy E, $E/2$, and $E/3$.

The energy of the beam was measured by a decelerator which had been previously developed and is shown in Fig. 1. This device measured the deceleration voltage which was required just to bring the charged ions of the beam to rest. The beam from the absorption chamber was collimated by an aperture 5 mm in diameter before entering the deceleration gap. A guard ring, which was at -300 volts with respect to ground, prevented secondary electrons from entering the deceleration gap (acceleration for electrons). A Faraday cage inside the high voltage terminal collected the beam current. A guard ring and a crossed magnetic field supplied by bar magnets controlled the motion of secondary electrons. The guard ring was -300 volts and the outer shell -2000 volts with respect to the Faraday cage. The current to the Faraday cage was as small as 10^{-10} amp and was measured by an electrometer circuit. A power supply was used to vary the potential of the Faraday cage with respect to the high voltage of the accelerator.

Typical results are shown in Fig. 2. When the beam unobstructed by a foil was passed into the decelerator, it was stopped by a potential about 100 volts lower than the potential on the anode of the ion source. This showed that the plasma in the ion source from which the ions originate was below the ion source anode potential by this amount. It was found that the gas pressure of the ion source was the most important factor in changing the energy of the ions with respect to the anode. However, if the pressure of the ion source was kept relatively constant during an experiment, no appreciable error was introduced. Figure 2 shows that the energy spread of the unobstructed beam was about 150 volts.

When a SiO foil was placed in the beam a deceleration curve was obtained as shown in Fig. 2. For this foil the
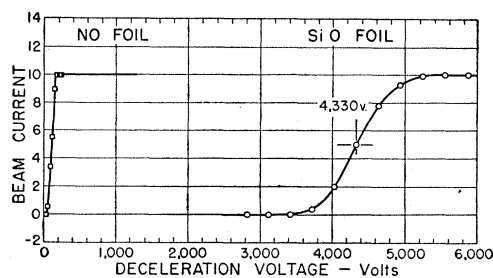

FIG. 2. Deceleration curves showing the energy distribution of the analyzed beam from the accelerator and the energy distribution of the beam after it had passed through a SiO foil.

average energy loss was 4.330 kev. The large straggling was surprising at first. However, since the foils were only about 100 atoms thick and the number of collisions in the foil was only about 50 (there being about 100 ev lost per collision), the statistics of the number of collisions explain the straggling.

Figure 2 shows that the straggle is approximately symmetrical about a mean energy. More sensitively, it was tested to be Gaussian in nature by plotting on probability paper. In such a plot a Gaussian distribution appears as a straight line. This method has the advantage of using the data in an optimum way, and the data gave good straight lines.

By changing the energy of the incident beam, the energy loss of a foil as a function of proton energy was obtained.[5] The relative $\Delta E/\Delta x$ curve for the window material proved to be quite reproducible so that it could be used to predict the energy loss in foils at other energies from a measured loss at one energy. (No very satisfactory method of measuring the mass density of the films is known to us, so that absolute $\Delta E/\Delta x$ values for the foil material remains unknown.)

The gas pressure in the absorption chamber was measured by a Consolidated Engineering Company micromanometer pressure gauge. This all-metal instrument contains a diaphragm which is bowed (to a greater or lesser amount) by pressure. The capacity between the diaphragm and a fixed plate has a value which is a reproducible function of the pressure. The gauge was calibrated by an oil manometer and was found to be stable to within 1 percent during the experiment.

The temperature of the gas was assumed to be the same as the room temperature as measured close to the absorption chamber. With the beam currents used in these experiments a thermocouple placed in the gas of the target chamber showed that the gas temperature was the same as the target chamber walls temperature to within $\pm 0.5°C$.

The gases were handled in the following ways:

1. Hydrogen. Uranium metal absorbers were used to store the hydrogen. A mass spectrographic analysis was made and the gas found to be 99.8 percent hydrogen.

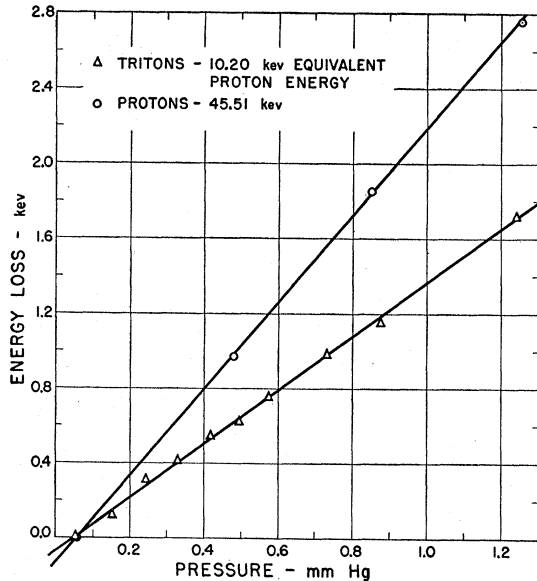2. Water vapor and CCl_4. Distilled water and chemically pure CCl_4 were frozen to dry ice tem-

FIG. 3. The energy lost by a proton and a triton beam in passing through hydrogen gas in the absorption chamber as a function of the pressure.

perature and pumped to remove the air originally absorbed in the samples. This was repeated several times. For the last few times liquid air was used to freeze the liquid to reduce the vapor pressure of the sample to a minimum.

3. Samples of the other gases were as pure as could be obtained, being spectroscopically pure in most instances. A mass spectrographic analysis was performed when there was question of a sample's purity.

III. PROCEDURE

The experiment consisted essentially of measuring the increased energy lost by the beam passing through the absorption chamber as gas was admitted to the chamber. In order to obtain the average energy of the beam at the center of the absorption chamber and to calculate changes in the energy lost in the back foil because of the addition of the gas, the following procedure was adopted:

1. At some incident beam energy E, the energy loss in the front foil was measured. The back foil could be drawn out of the way during this measurement by opening the valve on which it was mounted. Subtracting the energy lost in the front foil from the incident energy of the beam gave the average energy of the beam as it entered the gas.

2. The second foil was placed in position and the energy lost by both foils was measured. The difference between the two measurements gave the energy loss in the back foil. The average energy of the beam passing through the back foil was equal to the energy of the beam after it left the first foil minus one-half the energy loss in the second foil. With a knowledge of the relative energy lost by a proton beam in the foils as a function

of energy, it was possible to calculate the energy lost in the back foil at any energy of the beam emergent from the second foil.

3. Measurements of the foil stopping power were unreliable in a high vacuum, because the window was then cooled by radiation only and became hot enough to change in stopping power by as much as 100 ev. Gas was thus added to the absorption chamber to a pressure of 0.050-mm Hg and used as the reference pressure. Any change in the energy loss of the two foils, when measured in a vacuum and at the reference pressure, was assumed to be the same in both foils.

4. Gas was added to the desired pressures, and at each pressure the energy lost by the beam in passing through the absorption chamber was measured.

5. Finally, the energy lost by the beam at the reference pressure of 0.050-mm Hg was again measured to determine whether the foils had changed during the run. It was usually found that the energy loss of the two foils had increased by as much as 400 ev. It was thought that the loss was due to condensation of oil vapors on the foils. Examination of the data showed that the rate of foil growth was to a good approximation constant, while the beam was passing through the foil.

Since the energy of the emergent beam was known at each pressure, the energy loss in the back foil was calculable from the known stopping power energy curve of SiO. As the pressure of the gas was increased, the average energy of the beam passing through the second foil was decreased, and thus the energy lost by the beam in the back foil was decreased.

The energy lost by the gas at each pressure was then calculated by subtracting the energy lost in the two
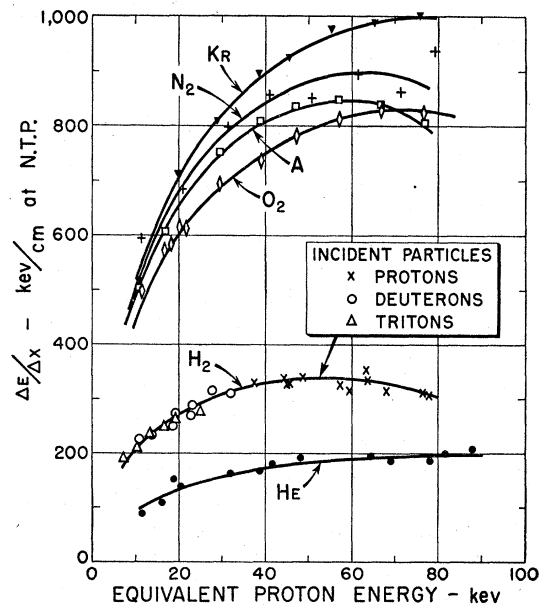

FIG. 4. The experimental values of the energy loss for protons in passing through the gases examined. The smooth curves are calculated from the equation $\Delta E/\Delta x = Lf(ME)$.

foils from the total energy lost by the beam in passing through the absorption chamber.

IV. RESULTS

A. Pressure Dependence

At each energy at least three different pressures were used in the measurement of the energy lost by the beam in the gas. In all cases when the energy loss was plotted as a function of pressure, a straight line was obtained within the experimental error. Typical results are shown in Fig. 3. The straight line passes through zero energy loss at a pressure of 0.050-mm Hg, the reference pressure. These results lead to the conclusion that, in the pressure range 0.050- to 1.50-mm Hg and the energy range examined, the energy loss by a hydrogen beam is proportional to the target density.

B. Effect of Gas on Foil Energy Loss

So far, it has been assumed that a foil stopping power measured in vacuum would continue to apply when gas was present. There is considerable difference in the physical state of the foil in these two cases: in vacuum, the foil is slack and hot enough to radiate the energy lost in it by the beam, but when gas is present, the foil is stretched and cool.

To test this assumption, an experiment was made in which two foils were mounted with a spacing of only 0.3 mm, and the stopping power of the combination was measured with several gases as described above. Within experimental error an energy loss *versus* pressure curve gave a straight line for each gas. Given an approximate value of the energy loss for each gas, calculation showed that as a gas was added to the absorption chamber the foils behaved as if there was a constant separation between the two foils of 2.9 ± 0.3 mm. Since the foil holders were 0.3 mm apart, the bowing of the foils and any diffusion of the gas through them added up to an effective gas length of 2.6 ± 0.3 mm. This correction was added to the measured length of the absorption chamber and the final $\Delta E/\Delta x$ values calculated.

C. Effect of Scattering

In the present experiment, the energy loss of the beam caused by scattering was not to be included. That

TABLE I. Probable errors in determination of $\Delta E/\Delta x$.

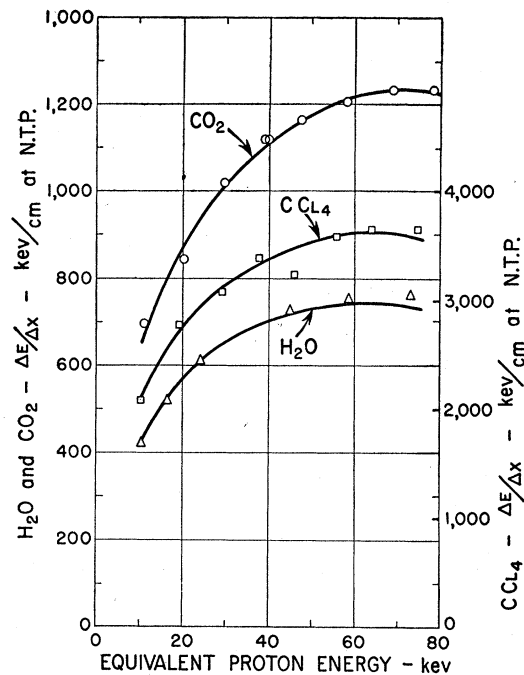|	
1. Energy determination	
The probable error in a deceleration	±25 ev
The probable error of the energy loss in the gas, the result of three decelerations, assuming $\Delta E = 1.5$ kev	±3 percent
2. Gas pressure	±3 percent
3. Gas purity	±1 percent
4. Length of the absorption chamber	±1 percent
5. Temperature	±0.3 percent
Total probable error in $\Delta E/\Delta x$ (rms)	±5 percent

FIG. 5. The experimental values of the energy loss for three compounds. The smooth curves are the sums of the energy loss of the constituents of the compounds calculated from the equation $\Delta E/\Delta x = Lf(ME)$.

scattering did occur in the gas was readily apparent, since as the gas pressure in the absorption chamber was increased, the fraction of the incident beam detected by the decelerator was decreased by as much as 50 percent with some gases. The part of the beam which was scattered by the gas did not pass through the collimator in front of the back foil and into the decelerator and was not included in the measurement.

However, the possibility of inscattering by the gas of the beam scattered by the front foil had to be considered. A calculation of this correction, using the simplifying but comparable assumption that all the gas is condensed on a plane midway between the two foils, gave a value of 0.2 percent, and it was therefore neglected.

D. $\Delta E/\Delta x$ Results

In Figs. 4 and 5 the experimental values of $\Delta E/\Delta x$ are shown for the different gases. The energy loss $\Delta E/\Delta x$ is in units of kev per cm at 0°C and 76-cm Hg. Each of the experimental points is the result of the calculation of the slope of an energy loss *versus* pressure curve as in Fig. 3.

V. ERRORS

The probable errors assigned to the factors which enter into the determination of $\Delta E/\Delta x$ are given in Table I. The total probable error in $\Delta E/\Delta x$ is ±5 percent.
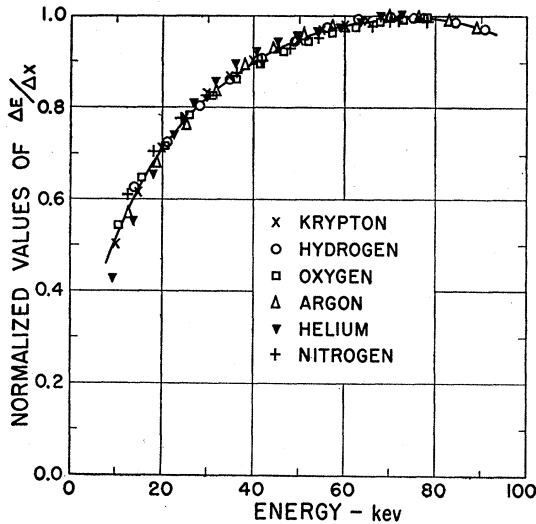
FIG. 6. The energy loss curves of the elementary gases examined normalized to that of krypton. The smooth curve is the average which determines the function f.

With water vapor, it was found difficult to control the pressure in the absorption chamber. When water vapor was added, much of the gas was absorbed in the walls of the chamber requiring a rather long time for the pressure to become stable. When the pressure was then reduced, the water vapor would come out of the walls making it difficult to arrive at a lower pressure. Over the relatively long periods of time which elapsed between decelerations at different pressures there was the possibility that the energy loss of the foils did change. It is expected that the data with water vapor should show a greater scatter than with other gases.

VI. DISCUSSION OF THE RESULTS

1. An examination of the curves of energy loss *versus* energy for the elementary gases reveals a certain similarity in shape. The simplest method of checking this was to match the curves to a standard curve, by linear transformations of the coordinates, i.e.,

$$\left(\frac{1}{L_i}\frac{\Delta E}{\Delta x}\right)=f(M_iE), \qquad (1)$$

where L_i and M_i are constants for gas i.

The function f was determined empirically by drawing smooth curves through the experimental points for each gas and normalizing to that for krypton. Plotting the results for the gases on the same graph gave the result shown in Fig. 6. An average was then drawn through these points to obtain f. The function f and the normalizing constants L_i and M_i are shown in Tables II and III. In Figs. 4 and 5, the experimental points may be compared with the smooth curves for the calculated values. The two agree within the experimental error. The same standard f curve fits equally well with

Warshaw's[3] data for the energy loss in solid targets 50 to 100 kev.

An analytical expression has not been found for the function f which will connect the $E^{\frac{1}{2}}$ dependence[8] at very low energies with the $E^{-1}\log E$ dependence[9] at high energies. Assuming, however, an expression of the form $f(E)=A(E)E^{n(E)}$, $n(E)$ approaches the value 0.5 as E decreases.

No significant regularity in L and M has been found in terms of the atomic constants among the limited number of elementary gases measured. There is, of course, a common reason for a rising $\Delta E/\Delta x$ at low energies, and a falling one at high, but the constants L and M doubtless depend on the properties of the outer electrons of these target gases and on the nuclear charge.

2. The results reported here for H_2 and air are in good agreement (~ 3 percent) with those reported by

TABLE II. Values of the function f in the equation $\Delta E/\Delta x = L_i f(M_i E)$.

E	f	E	f
0.133	0.515	0.600	0.926
0.200	0.627	0.700	0.958
0.300	0.743	0.800	0.980
0.400	0.822	0.900	0.993
0.500	0.881	1.000	1.000

TABLE III. The normalizing constants L and M for the gases measured.

Element	L	M
Hydrogen, $\frac{1}{2}H_2$	169	53.2 kev
Helium	196	82.5
Carbon	404	70.5
Nitrogen, $\frac{1}{2}N_2$	449	62.2
Oxygen, $\frac{1}{2}O_2$	416	72.0
Chlorine, $\frac{1}{2}Cl_2$	807	61.5
Argon	848	59.2
Krypton	999	75.0

Crenshaw.[1] With He and H_2O there is some disagreement with the present values being ~ 18 percent higher. Crenshaw's data have been corrected for a temperature of the target gas in his experiment of 30°C.[10]

3. For water vapor, the vapor has the same stopping power as that calculated from hydrogen and oxygen, indicating that the sum of $\Delta E/\Delta x$ of the constituents equals that of the compound. The results are shown in Fig. 5. Comparison with the results for D_2O ice obtained by Wenzel and Whaling[4] shows that the vapor gives a value for the stopping power 17 percent higher than that for the solid. A density effect in this energy range might thus be indicated.

4. The $\Delta E/\Delta x$ of carbon was obtained from CO_2

[8] E. Fermi and E. Teller, Phys. Rev. **72**, 399 (1947).
[9] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 245 (1937).
[10] C. M. Crenshaw (private communication).

and O_2, assuming the sum of the energy losses of the constituents equals that of the compound. Using this value for carbon one may then obtain chlorine from CCl_4. Calculating the L and M values for carbon and chlorine, it is then possible to calculate, using Eq. (1), the energy loss for the compounds. The calculated results are drawn as the smooth curves in Fig. 5.

5. From data taken with hydrogen for equal velocities, the energy loss of protons, deuterons, and tritons is the same within the experimental error.

The Microwave Absorption Spectrum of $(O^{16})_2$ and $O^{16}O^{17}$*

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The theory of the fine structure of O_2 is made somewhat more complete and fitted to the observed microwave spectrum. This gives $B_0 = 43\ 102 \pm 5$ Mc/sec for $O^{16}O^{16}$. In addition there is evidence for the effect of higher order terms such as centrifugal distortion on the magnetic interaction constants. Magnetic hyperfine structure has been observed in the spectrum of $O^{16}O^{17}$. The spectrum agrees with that predicted on the basis of a perturbation Hamiltonian $b\mathbf{I}\cdot\mathbf{S}+cI_zS_z$, where $b = -102$ Mc/sec and $c = 140$ Mc/sec. The value of 5/2 for the spin of O^{17} is confirmed.

INTRODUCTION

THE oxygen molecule is unusual in having a $^3\Sigma$ ground state; that is, it has an electron spin momentum of unity rather than the value zero which occurs in the ground state of most molecules. This spin angular momentum adds vectorially to the angular momentum K of the "end-over-end" rotational motion of the molecule to give a total angular momentum J which may have the values $K-1$, K, or $K+1$. Transitions between these three different fine structure or ρ-type triplet levels are allowed, because of the magnetic dipole moment associated with the electron spins, with the selection rule $\Delta J = 0, \pm 1$. The transitions with $\Delta J = \pm 1$ give a microwave absorption spectrum in the region of 60 000 Mc/sec.

Since the total orbital angular momentum of the electrons has zero component along the internuclear axis, there should be no multiplet structure of the ordinary type arising from the interaction of the electronic spin with the orbital motion of the electrons. Kramers[1] has shown that the interaction of the two unpaired electron spins, when averaged over the rotation of the molecule, is equivalent to a coupling between the total spin and the figure axis proportional to $3\cos^2\theta - 1$, where θ is the angle between the two. Using this interaction and the $\mathbf{S}\cdot\mathbf{K}$ interaction between total spin and the magnetic moment caused by the end-over-end rotation of the molecule, Kramers derived

an expression for the three energy levels corresponding to $J = K+1$, K, and $K-1$.

Although the Σ-state has a zero average electronic orbital angular momentum, there is an angular momentum component perpendicular to the axis of the molecule and precessing about it. Hebb[2] considered only the interaction between this component and the total spin $S = 1$ and arrived at a formula of exactly the same form as Kramers.[1] This interaction is equivalent to a perturbation of the ground state by neighboring Π-states.

In order to get satisfactory agreement between the fine structure theory and optically obtained data, Schlapp[3] recalculated the energy levels allowing for the fact that the coupling between the electron spin and the molecular rotation is appreciable compared with the rotational energy of the molecule. Schlapp's expressions for the energy differences between the members of a ρ-type triplet are:

$$\nu_+(K) = (W_{J=K} - W_{J=K+1})/h = \lambda - \mu(K+1) \\ - (2K+3)B + [\lambda^2 - 2\lambda B + (2K+3)^2 B^2]^{\frac{1}{2}},$$
$$\nu_-(K) = (W_{J=K} - W_{J=K-1})/h = \lambda + \mu K + (2K-1)B \\ - [\lambda^2 - 2\lambda B + (2K-1)^2 B^2]^{\frac{1}{2}}, \quad (1)$$

where λ is a parameter which gives the magnitude of the interaction proportional to $\cos^2\theta$, and μ is a parameter giving the magnitude of the interaction proportional to $\cos\theta$. From this it is readily seen that

$$\nu_+(K-2) + \nu_-(K) = 2\lambda + \mu,$$

where $2\lambda + \mu$ is presumably a constant.

[1] H. A. Kramers, Z. Physik 53, 422 (1929).
[2] M. H. Hebb, Phys. Rev. 49, 610 (1936).
[3] R. Schlapp, Phys. Rev. 51, 342 (1937).