Letters to the Editor.

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Simultaneous Ionisation and Excitation by Foreign Ions in a Gaseous Mixture.

WE have recently carried out some experiments which indicate that an ion of one kind may, upon collision with a molecule of another gas, ionise that molecule and excite the resulting ion to the degree that the energy required to ionise the one exceeds the energy required to ionise the other. This means that an ion may rob a molecule of an electron, and at the same time give to the resulting ion the excess of energy made available by its recombination with the electron over the amount needed to take that electron out of the molecule. As the energies of excitation are quantised, there is usually still a remnant of the energy of recombination yet to be accounted for, and this probably goes into increased kinetic energy of one or both particles involved in the collision.

The experiments have been limited to mixtures of carbon monoxide and of nitrogen with argon, neon, and helium, but the same process may occur in any mixture of gases and vapours, monatomic or multiatomic. We used carbon monoxide in particular because the energy levels of the CO molecule and the CO^+ ion have recently been experimentally determined in this laboratory [1] and interpreted on the basis of the quantum theory of band spectra.[2] Spectrograms were taken with a Hilger E2 quartz spectrograph of low voltage arcs of 40 milliamperes at 23 volts in a hot cathode discharge tube through mixtures of argon, neon, and helium in turn, each containing ten per cent. of carbon monoxide. The total pressure of the mixture was 2·4 mm. in each case. An auxiliary filament was mounted near the cathode filament so that electrons could be introduced into the discharge from it when desired. The purpose of the auxiliary filament was to enable us to determine whether the carbon monoxide bands were being excited by the rare gas ions or by the electrons from the cathode, and whether the excitation was accomplished simultaneously with the ionisation or was a subsequent event.

The spectrograms show that, in the argon mixtures, none of the negative bands of carbon monoxide or of nitrogen is excited; in the carbon monoxide - neon mixtures the comet tail bands and the first negative bands of CO^+ appear, the former strongly and the latter weakly, but the Baldet-Johnson bands are absent; in the helium mixture all three negative systems of carbon monoxide are strongly developed. The negative bands of nitrogen appear fairly strong in the nitrogen-neon mixture and very strong in the mixture with helium.

Before it could be concluded that these negative bands were being excited simultaneously with the ionisation of the molecule on collision with an ion of neon or of helium, several alternative possibilities had to be tested :

1. The excitation of the ion might follow as a later event after the molecule had been ionised by the rare gas ion. That this process was not operative was demonstrated by introducing into the discharge, electrons from the auxiliary filament at a voltage sufficiently great to excite the CO^+ ions on collision. Although the electron current from this filament was twice as great as from the cathode, no increase in the intensities of the negative bands was produced. Thus, though the current through the discharge was three times as great as before, the negative bands were no more intense. On the other hand, the positive bands of carbon monoxide, which were not present in the original discharge, appeared with moderate strength in the discharge with the auxiliary filament in operation, when the difference of potential between the auxiliary filament and anode was equal to the excitation potentials of these bands. The second positive bands of nitrogen were present even though the auxiliary filament was not used, but their intensities increased enormously when the voltage of the auxiliary filament reached their excitation potential. This suggests a new method for determining the excitation potentials of positive bands and arc lines.

2. The simultaneous ionisation and excitation of the carbon monoxide molecule might be due to direct electron impacts, as has been demonstrated to be possible.[1] That this was not the case was proved by maintaining the voltage of the auxiliary filament higher than the excitation potentials of these bands but below the ionising potential of neon. In this way the possibility of excitation by electron impacts was increased threefold, while the concentration of neon ions was increased very little. A barely perceptible increase in the intensities of the negative bands was observed when the current from the auxiliary filament was twice as great as from the cathode.

3. The ionisation and excitation might be due to an impact of the second kind with an excited neon or helium atom. It was for the purpose of determining whether the ion or an excited atom of the rare gas was responsible for the observed phenomena that nitrogen was substituted for carbon monoxide in the neon mixture. The excitation potential of the negative band system of nitrogen is greater than either of the strong radiating potentials of neon, but is less than the ionising potential of neon. Therefore, an excited neon atom could not ionise the nitrogen molecule and simultaneously excite its negative bands. Hence we must conclude that it is the rare gas ions that were effective.

The interpretation of the observed results on the basis of simultaneous ionisation and excitation by the ions of the inert gases is fairly obvious upon consideration of the excitation potentials of the bands involved and the ionisation potentials of argon, neon, and helium as given in the following table:

Band System.	Excit. Pot.	Gas.	Ionis. Pot.
Comet Tail . .	16·8	Argon	15·4
First Negative .	20·0	Neon	21·5
Baldet-Johnson .	22·9	Helium	24·5
		Carbon Monoxide	14·3

Thus none of the negative bands of carbon monoxide would be expected to appear in the argon mixture, while the comet tail bands and the first negative bands would be excited by neon ions, and all three systems by helium ions, as was observed.

Apparently the neon ions are more efficient in exciting the comet tail bands than they are in exciting the first negative bands. This greater probability that the former would be excited rather than the latter upon a collision between a neon ion and carbon monoxide molecule would seem to indicate that the efficiency of ions in this type of

[1] Duffendack and Fox, *Science*, **64**, p. 277; 1926; *Astrophys. Jour.*, in press.

[2] Birge, NATURE, **117**, pp. 229, 300; 1926; *Phys. Rev.*, **28**, p. 1157; 1926; Johnson, NATURE, **117**, 376; 1926; Duffendack and Fox, NATURE, **118**, 12; 1926.

excitation increases, at least for a time, as the excess energy available increases. This view is supported by the fact that all three systems are strongly developed in the helium mixture. Several bands belonging to the comet tail and Baldet-Johnson systems not previously reported were observed in our spectrograms of the carbon monoxide-helium mixture.

The failure of the Baldet-Johnson bands to appear in the neon mixture and their strong development in the helium mixture is significant. According to Birge,[3] these bands constitute a combination system between the initial states of the first negative and the comet tail systems. If this were true, they would have the same excitation potential as the first negative bands and should be excited by neon ions. Their experimentally determined excitation potential[1] is in agreement with their behaviour in the neon and helium mixtures. This confirms the assignment of this system to a higher initial state of the CO^+ ion as made by Duffendack and Fox.[2] It might be added that Miss Ann Hepburn, at the Chicago meeting of the American Physical Society, corrected her published abstract[4] and reported the excitation potential of this system to be 23·0 volts, in agreement with the value given above.

The appearance of the negative band systems of carbon monoxide and of nitrogen in our discharges is in harmony with their appearance in geissler tube discharges through similar mixtures as observed by Merton and Johnson[5] and by Cameron.[6] Their presence can be accounted for on the basis outlined above, and slight discrepancies can be explained by the less definite limitation of the maximum speeds of the electrons in geissler discharges. Similar discrepancies can be produced in our discharges by increasing the voltage, or the current density, or the percentage of carbon monoxide, or in any way increasing the probability of excitation of the carbon monoxide molecules by direct electron impacts.

There is no reason to believe that this method of excitation of radiation from an ionised molecule is limited to the ions of the rare gases or to multi-atomic molecules. The same process may be expected to occur in any mixture of gases or vapours, and should find application in the production of the first spark spectra of atomic ions to the exclusion of higher spark spectra, and in the approximate determination of the excitation potentials of the spark lines. This process may also explain the enhancement of certain lines in discharges through mixtures of gases and the origin of certain radiations of astronomical interest.

We wish to express our gratitude to Dr. W. E. Forsythe of the Nela Research Laboratory (where these experiments were begun during the summer of 1926) for the argon, and to the U.S. Bureau of Mines for the helium used in these experiments.

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[3] Birge, NATURE, **116**, 207; 1925.
[4] Hepburn, *Phys. Rev.*, **29**, 212; 1926.
[5] Merton and Johnson, *Roy. Soc. Proc.*, A, **103**, 383; 1923; Johnson and Cameron, *ibid.* **106**, 195; 1924; Johnson, *ibid.* **108**, 343; 1925.
[6] Cameron, *Phil. Mag.*, 1, 405; 1926.

Spinning Electron and Wave Mechanics.

IN order to obtain an interpretation of the anomalous Zeeman effect, the multiplet structure, etc., Uhlenbeck and Goudsmit (*Physika*, 1925; *Naturw.*, 953, 1925; NATURE, 117, 264; cf. Thomas, NATURE, 117, 514; Slater, NATURE, 117, 587; London, *Naturw.*, 15, 15, 1927; Darwin, NATURE, 119, 282) assume that the magnetic moment corresponding to the spinning movement of the electron is just twice as great as that of the revolving electric point-charge with the same mechanical angular momentum. In the following, an attempt is made to derive this assumption from the relativistic Schrödinger wave equation in connexion with the electrodynamic meaning of the wave function ψ.

The relativistic wave equation for forceless movement of the electron is:

$$\Delta\psi - \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} - \frac{4\pi^2}{h^2}m_0{}^2c^2\psi = 0. \quad . \quad . \quad (1)$$

(Schrödinger, *Ann. d. Ph.*, 81, 133, and other authors.) The solution, in the rest-system of the electron, may be reduced to the following form (r, z, ϕ being columnar co-ordinates, which are suitable to the purpose):

$$\left.\begin{aligned}\psi &= f(r,z)\ \exp.\ is\phi\ \exp.\ \frac{2\pi i}{h}m_0c^2t\\ &= F(r,z,\phi)\ \exp.\ \frac{2\pi i}{h}m_0c^2t\end{aligned}\right\} \quad . \quad . \quad (2)$$

F satisfies the equation: $\Delta F = 0$, and is therefore harmonic in the rest-system.

The equation of the continuity of electricity is:

$$\text{div.}\left\{\frac{h}{2\pi i}(\psi\ \text{grad.}\ \bar\psi - \bar\psi\ \text{grad.}\ \psi)\right\} + \frac{\partial}{\partial t}\left\{-\frac{h}{2\pi i}\frac{1}{c^2}\left(\psi\frac{\partial\bar\psi}{\partial t} - \bar\psi\frac{\partial\psi}{\partial t}\right)\right\} = 0. \quad . \quad (3)$$

(See W. Gordon, *Zs. f. Phys.*, 41, 117, see p. 121, and O. Klein, *ibid.* 41, 407, see p. 414.)

We multiply the expressions in brackets by the specific charge $\frac{e}{m_0}$ of the electron (the introduction of the factor $\frac{1}{2}$—as introduced by Klein—cannot be justified in our case) and get for the electric density:

$$\rho = \frac{e}{m_0}\left\{-\frac{h}{2\pi i}\frac{1}{c^2}\left(\psi\frac{\partial\bar\psi}{\partial t} - \bar\psi\frac{\partial\psi}{\partial t}\right)\right\}, \quad . \quad . \quad (4a)$$

and for the density of current:

$$j = \frac{eh}{2\pi i m_0}(\psi\ \text{grad.}\ \bar\psi - \bar\psi\ \text{grad.}\ \psi). \quad . \quad . \quad (4)$$

From the non-relativistic form of the wave equation only half the density of current follows (cf. Schrödinger, *l.c.*). From that Fermi (NATURE, 118, 876) and Klein (*Zs. f. Phys.*, 41, 425) have derived the magnetic moment for the revolving movement of an electric point-charge, namely:

$$\mu' = -\frac{e}{m_0}\frac{h}{4\pi}s', \quad . \quad . \quad . \quad . \quad (5')$$

whilst the magnetic moment corresponding to the density of current (4) is:

$$\mu = -\frac{2e}{m_0}\frac{h}{4\pi}s. \quad . \quad . \quad . \quad . \quad (5)$$

μ may be regarded as the magnetic moment of the spinning movement, being twice as great as μ' in agreement with the assumption mentioned in the beginning. The conjectures of Slater and London that the rest-energy m_0c^2 is of rotatory character and that the 'internal phenomenon' of L. de Broglie of the frequency $\nu_0 = \frac{m_0c^2}{h}$ causes it and therefore the magnetism of the electron itself, are supported by this.

The necessary half quantum-numbers for s follow readily if one adapts the Schrödinger conditions for the wave function ψ to our problem.

Only the doublet ($\frac{1}{2}$, $-\frac{1}{2}$) and no higher quantum-states of rotation appear.

We hope, in an early communication, to return to the question of fine structure and analogous problems.

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