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PHYSICS

Origin of Excessive Ionization in Flames

IT has been known for a long time that combustion reactions of the type occurring in flames are sometimes accompanied by an extremely high degree of ionization and excitation of the flame gas[1]. In fact, electron concentrations have been observed which are several orders of magnitude higher than the values given by Lindemann–Saha's equation which presupposes thermodynamic equilibrium. Moreover, to explain the observed radiation emitted from metal vapours introduced into the reacting gas, a considerable number of electrons of energy above the critical energy is required the mean energy of which appears to be well beyond the mean energy of the gas molecules. In short, the electron temperature is expected to exceed the gas temperature.

Measurements of electron temperatures by Calcote[2] with single probes and those that we have made[3] by means of double probes have shown that in certain types or parts of flames the electron gas is at a temperature which is several times larger than that of the gas. The mechanism which leads to this 'overheating', however, has not been satisfactorily accounted for and explanations given so far, such as chemi-ionization, have not attached any importance to the special part which electrons play in conjunction with the combustion reaction itself.

We suggest that the principal effect which causes the mean electron energy to rise above that of the gas molecules is associated with collisions between electrons and products of the combustion process. These products are molecules and radicals which are in states of vibrational and possibly also electronic excitation. In spite of the fact that the nature of the products is not yet known with certainty, an overall picture can be given which will be supported by a numerical estimate.

Let the population of excited states consist of one type of molecules or radicals, all being at the same energy-level. If the concentration of the particles is N^*, the energy-level ε^*, the electron concentration N_e, their average random velocity $\bar{v}_e$, and if the average cross-section of electrons for collisions of the second kind is $\bar{q}_2$, the rate of collisions which increase the electron energy at the cost of the potential energy of the heavy particles can be found. On the other hand, this gain in energy must be balanced by elastic and inelastic losses of the electrons, described by $\varkappa$, the average fractional energy loss per electron collision, and the total collision cross-section for electrons[4], the latter being approximately equal to the elastic cross-section $\bar{q}_1$. If $\bar{\varepsilon}$ is the mean electron energy in excess of that of the ordinary gas molecules of concentration N_0, we have:

$$\varepsilon^* q_2 \bar{v}_e N^* N_e \approx \varkappa \bar{\varepsilon} \bar{q}_1 \bar{v}_e N_e N_0$$

and thus

$$\bar{\varepsilon} \approx (1/\varkappa)(\bar{q}_2/\bar{q}_1)(N^*/N_0)\,\varepsilon^*$$

The relative concentration of excited species can be found thus: in a torch flame the chemical power released is of the order 50 W/cm^3 or 5×10^8 ergs/c.c.sec equal to

$$\varepsilon^*(dN^*/dt) = \varepsilon^* N^*/\tau$$

τ being the relaxation time for vibrational deactivation. Assume all excited states are at a level $\varepsilon^* = 2$ eV; the precise value is, as seen later, of little importance. From these data the rate of production of excited states $dN^*/dt = 10^{20}$/c.c.sec. With a relaxation time[5] of 10^{-5} sec, we obtain $N^* \approx 10^{15}$/c.c. and hence with a flame gas temperature of $\approx 2{,}500°$ K, $N^*/N_0 \approx 10^{-3}$. Finally with $\bar{q}_2/\bar{q}_1 \approx 1$, $\varkappa = 10^{-3}$, we find that $\bar{\varepsilon} \approx 1$ eV or $\approx 10{,}000°$ K. This rough calculation agrees with recently measured values of the electron temperature in flame gases.

The result immediately suggests that the abnormally high electron concentration in flames is a consequence of the high electron temperature. In the flame gas, electrons and positive ions must be conserved in numbers and their rate of production must be balanced by their rate of loss. Since it is known that the electron-ion recombination is very small[4], and that products exist in the flame which form readily negative ions, the rate of ionization must be balanced both by the rate of attachment and by the rate of ion–ion recombination. Starting with the latter and assuming an electron concentration of $N_e = 10^{12}$/c.c., as has been observed, and a recombination coefficient $\rho_i = 10^{-7}$ c.c./sec, a value which allows for the high gas temperature[4], the recombination rate is $\rho_i N_e^2 = 10^{17}$/c.c. sec, which is equal to the ionization rate. The rate of attachment of electrons to form negative ions must be the same, therefore $dN^-/dt = \bar{\sigma}_a \bar{v}_e N_e N_0 = 10^{17}$. With $N_0 = 10^{18}$/c.c., $\bar{v}_e = 6\times10^7$ cm/sec, it follows that $\bar{\sigma}_a \approx 10^{-20}$ cm^2, being the average cross-section for electron attachment. Its value is consistent with published data[6]. Moreover, comparing the rate of ionization (also directly calculable from electron collisions, see ref. 4) with that of excitation we find that the latter is three orders of magnitude larger, again a reasonable result.

It would be possible, in principle, to replace the average magnitudes used by integrals containing the distributions, and to include the dependence of the cross-section on the energy. However, this step seems to be premature, since details of combustion reactions and collision parameters are not sufficiently well known. We conclude that the excessive ionization in flames can be understood in terms of electron collisions of the second kind and the resulting high electron temperature.

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Anti-matter in the Cosmic Radiation

THE question of the amount of anti-matter in the universe is an important one for cosmological theories. The cosmic radiation represents one sample of matter, which is mainly of galactic origin, and it is possible to set a limit to the concentration of energetic anti-matter, in this sample, in the form of anti-protons, from measurements on cosmic ray particles.

At energies up to some tens of GeV the trajectories of the primary cosmic rays are affected by the Earth's magnetic field and, in turn, measurements on the angular distribution of the primary particles enable the sign of charge of the primaries to be determined. The pronounced east–west asymmetry shows that the majority are positively charged, an upper limit of some few per cent being set to the anti-proton intensity. The comparatively high value for this limit arises because of the uncertainty in the contribution to the 'primary' intensity from the