Fast Neutral Particles from Arc Cathode

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The rotating drum method was used to measure the velocity distribution in the vapor jet which emerges from the cathode region in a magnetically stabilized high-vacuum arc discharge maintained between cooled copper electrodes. To obtain sufficient detection sensitivity part of the cathode was made of radioactive copper. The number distribution of copper atoms deposited on the drum as a function of their velocity perpendicular to its surface was measured by a Geiger-Müller counter. An average of about 4×10^4 cm/sec was found for the atomic beam velocity. It is suggested that misinterpretation of earlier observations has led to apparent velocities of up to 10^6 cm/sec.

EARLIEST work[1,2] indicated that vapor emitted from the metal cathode of an arc (spark) in air had an average speed of the order of 10^4 cm/sec. Later Tanberg[3] found that the average velocity of copper evaporated from the cathode of a vacuum arc of 10–20 amp was about 10^6 cm/sec. In his apparatus the cathode vapor was directed against a Pyrex plate suspended as a pendulum. From the deflection was found the average rate of momentum transferred to the plate. From this and the rate of change of mass of the plate, the average velocity of the vapor stream was derived; this assumes that all vapor impinging on the plate condenses. In another experiment, the cathode itself was used as a pendulum, giving essentially the same result. Further measurements with neutral vapor jets emanating from arc cathodes[4–9] have supported partly the lower and partly the higher values.

To clarify these conflicting results, measurements have been made of the velocity spectrum of atoms originating from the cathode region, rather than of the average velocity. A steady arc discharge of about 25 amp dc was maintained in a vessel, evacuated to 10^{-5} mm Hg, between a vertical copper cathode and a hollow copper anode, both water-cooled. Thus copper vapor could pass from the cathode region through the anode and a collimating slit into a vacuum chamber which houses a velocity selector, mounted directly over a fast oil-diffusion pump. The selector consisted of a cylindrical drum (with a narrow slit) which could be rotated at a speed up to 2000 rpm. From the density of copper deposit at different positions on the inside of the drum, the velocity spectrum of the vapor could be derived.

However, preliminary experiments showed only feeble deposits even after long exposures. To increase the sensitivity of detection a radioactive method was used. A sample of 1 g of copper, irradiated to give 76 mc of Cu^{64}, emitting electrons and positrons of about 0.5 Mev and γ rays, was screwed into the center of the cathode tip. Thus radioactive cathode vapor was now deposited on aluminum foil attached to the inside of the drum. The number distribution of particles as a function of their position on the foil was measured by counting the emission from a section of the deposit by means of a Geiger-Müller tube and a narrow slit in a 0.5-cm thick Al plate which was moved over the foil. To allow for background, which originates from a larger section, another count was made using a similar Al plate but without a slit.

In order to achieve a maximum amount of vapor in the small solid angle viewed by the drum, the cathode spot must be kept at the center of the tip. Normally the spot moves randomly over the tip and even along the length of the cathode. By applying an axial magnetic field of about 1000 gauss, produced by a permanent cylindrical magnet surrounding the discharge, the motion was restricted.

The results show that the number distribution of copper atoms as a function of their velocity in the direction perpendicular to the drum surface has a peak at about 3×10^3 cm/sec; measurements could not be extended to velocities much less than 10^3 cm/sec since the errors become too large. The average velocity between this speed and infinity is about 4×10^4 cm/sec. There are apparently no appreciable numbers of atoms with velocities between 10^5 and 10^6 cm/sec; also, the distribution seems to be non-Maxwellian.

The absence of fast particles contradicts Tanberg's findings but his results can be interpreted in a different way—no account has been taken of large aggregates which transfer momentum to the vane but fail to stick on it. Hence, the measured rate of change of mass, found by weighing the vane, is much too small, which may give the apparent large average speeds. This is supported by the fact that large aggregates passed through our collimating slit and were collected in the drum housing. It seems unlikely that magnetic stabilization should have reduced the average velocity by 2 orders of magnitude.

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[1] A. Schuster and G. Hemsalech, Proc. Roy. Soc. (London) **A64**, 331 (1899).
[2] J. F. Mohler, Astrophys. J. **15**, 125 (1902).
[3] R. Tanberg, Phys. Rev. **35**, 1080 (1930).
[4] E. O. Lawrence and F. G. Dunnington, Phys. Rev. **35**, 396 (1930).
[5] J. R. Haynes, Phys. Rev. **36**, 706 (1930).
[6] E. Kobel, Phys. Rev. **36**, 1636 (1930).
[7] H. Nöske and E. Schmidt, Z. Naturforsch **7a**, 667 (1952).
[8] R. Wienecke, Z. Physik **150**, 231 (1958); **151**, 159 (1958).
[9] V. Hermoch, Czech. J. Phys. **9**, 221 (1959).

Experiments[4–9] based, e.g., on light emission or probe currents, give higher average velocities which correspond to those found with shock waves.[10,11] These are to be expected with the large current pulses which have been superimposed on the auxiliary discharge. Such velocities are probably not representative of those in a steady discharge. The velocity spectrum in high-current arcs is still to be investigated. However, it appears that the emission of neutral vapor from low-current arcs cannot be described in terms of classical evaporation theory or expressed in terms of a temperature of the cathode spot.[12]

[10] M. Sakuntala, A. von Engel, and R. G. Fowler, Phys. Rev. **118**, 1459 (1960).

[11] P. F. Little, Proceedings of the Conference on Ionization, Munich, 1961 (North Holland Publishing Company, Amsterdam, 1962), Vol. 2.

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[12] A. von Engel and K. W. Arnold, Nature **187**, 1101 (1960).

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Approach to Equilibrium of Electrons, Plasmons, and Phonons in Quantum and Classical Plasmas*

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The approach to equilibrium of electrons, plasmons, and phonons in finite-temperature plasmas is studied in the random phase approximation. It is first shown that for an electron plasma in equilibrium, the long-wavelength, well-defined, plasmons contribute a term to the free energy which is appropriate to a collection of independent bosons. In order to study nonequilibrium processes, an explicit plasmon distribution function is introduced. The matrix element for plasmon-electron coupling is calculated in the random phase approximation, and second-order perturbation theory is used to write down the equations which couple the electron and plasmon distribution functions. Equilibrium is shown to result from the competition between the spontaneous emission of plasma waves by single fast electrons and the Landau damping of the plasma waves due to the same group of particles. The equation for the time rate of change of the electron distribution function reduces, in the classical limit, to a Fokker-Planck equation in which there appear diffusion and friction terms associated with plasma waves, of the type first considered by Klimontovitch. When an initial arbitrary nonequilibrium electron distribution is considered, it is seen that a plasma wave instability corresponds to coherent excitation of plasma waves by the electrons in contrast to the incoherent excitation associated with spontaneous emission. The method is generalized to two-component electron-ion plasmas in which well defined acoustic plasma waves exist, by introducing an explicit distribution function for the phonons (the acoustic plasmons). The approach to equilibrium and the two-stream instability are derived and discussed for the coupled electron-phonon system; results similar to those obtained for the electron-plasmon system are found.

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THE properties of an interacting electron gas in a uniform background of positive charge have been studied extensively in both the limit of low temperatures and high densities (the quantum plasma) and high temperatures and low densities (the classical plasma). In both these limits, the random phase approximation (RPA) is valid. In general there are two essentially distinct modes of excitation of the plasma: single-particle modes with energies appropriate to a gas of noninteracting electrons, and collective modes, the plasma oscillations, which possess a frequency near the plasma frequency, $\omega_p=(4\pi ne^2/m)^{\frac{1}{2}}$. At long wavelengths the coupling between the plasmons (the quantized plasma modes) and the individual electrons is weak, because there are few electrons which are capable of absorbing the plasmon energy and momentum, so that a long-wavelength plasmon constitutes a well-defined excitation mode. For short wavelengths there are many electrons available to absorb plasmons, so that a short-wavelength plasma mode is highly damped and cannot be usefully regarded as an elementary excitation of the plasma.

Despite the by-now extensive plasma literature,[1] the coupling between electrons and plasmons in a finite-temperature quantum plasma does not seem to have been studied in any great detail. In the present paper we carry out such a study with the aid of explicit plasmon and electron distribution functions and demonstrate its usefulness for an understanding of the way in which the equilibrium between plasmons and electrons comes about in both quantum and classical plasmas.

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[1] Some recent review articles dealing with both classical and quantum plasmas are: Y. Klimontovitch and V. P. Silin, Uspekhi Fiz. Nauk. **70**, 247 [translation: Soviet Phys.—Uspekhi **3**, 84 (1960)], which contains rather complete references to the Russian work in this field, and D. Pines, Physica **26**, 103 (1960).