SOVIET PHYSICS

JETP

A translation of the Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki

Vol. 26, No. 2, pp. 279-482 (Russ. Orig. Vol. 53, No. 2, pp. 417-783) February 1968

FORMATION OF A CESIUM PLASMA BY RESONANCE RADIATION. PHYSICAL PROPERTIES.

N. D. MORGULIS, Yu. P. KORCHEVOI and A. M. PRZHONSKIĬ

Kiev State University

Submitted January 17, 1967

Zh. Eksp. Teor. Fiz. 53, 417—422 (August, 1967)

Cesium vapor in a special detector with a double probe was irradiated by resonance radiation from a discharge in cesium vapor. Under these conditions a quiescent, current-free cesium plasma is produced in the detector. The probe was used to measure the electron density and temperature, typical values being 5×10^{11} cm^{-3} and $\gtrsim 2000$°K. The nature of the processes that can occur in such a plasma are considered, primary attention being given to ionization processes and electron thermalization. The features of these processes are noted. In particular, the basic ionization mechanism under the present conditions is probably a two-step process: 1) $Cs + h\nu \rightarrow Cs^*$ and 2) $Cs^* + Cs^* \rightarrow Cs_2^+ + e$, that is to say, the plasma described here consists primarily of molecular ions. However, this conclusion still lacks direct verification through mass-spectrometer analysis.

Of the various processes by which atoms of a gas or metal vapor can be ionized in order to produce a plasma, at the present time essentially only two have been exploited: these are impact ionization and thermal ionization (gas-discharge plasma and thermal plasma). Other methods cannot be used since the ionization yield in most cases is so small as to be inadequate for obtaining the favorable conditions (variation of potential $d^2V/dx^2 = 0$) required for the formation of the plasma state. In particular, this is the objection to the use of ordinary photo-ionization[1] since the threshold for direct photo-ionization λ_0 usually lies in the extreme shortwave region and the effective cross section for photo-ionization q_{ph} is found to be very small. Even for the case of atomic cesium, which is characterized by a low ionization potential, we find $\lambda_0 = 3200$ Å and $q_{ph} \approx 10^{-19}$ cm^2. The lack of very powerful sources of the appropriate radiation (here we are neglecting lasers) and the problem of housing the system being investigated tend to make it difficult to use methods of this kind.

However, at least with regard to atomic cesium vapor, there is one method which offers the possibility of circumventing these difficulties. Consider the two-step ionization process in which an initially excited cesium atom $Cs \rightarrow Cs^*$ goes to the doublet resonance level $6P_{1/2, 3/2}$ with an excitation energy $V_a \approx 1.4$ eV and then is ionized in accordance with the scheme[2,3] $Cs^* + Cs^* \rightarrow Cs_2^* \rightarrow Cs_2^+ + e$, which leads to the formation of molecular cesium ions. This process does not require a great deal of energy and has an effective cross-section $q = 7 \times 10^{-18}$ cm^2.[4] For this reason we have carried out an experiment designed to produce a plasma through the use of this ionization scheme. In the first stage we have decided to use photo-ionization $Cs + h\nu \rightarrow Cs^*$ by irradiating cesium vapor with an intense source of resonance radiation. The results of this work and the results of an investigation of some of the physical properties of the cesium plasma produced in this way are described below.

A combination glass housing is used to produce the plasma; a schematic diagram of this device is shown in Fig. 1. The system consists of two (1 and 2) individual and independent elements with separate cesium tubulations. Hence, the pressure in each of these elements (P and p) can be adjusted independently. The first element is a discharge tube is in the shape of a dewar and is similar to the tube used by Kondilenko and Vorob'eva.[5] This tube contains a circular anode A, a thermionic cathode K, and a conventional cylindrical probe P by means of which the parameters of the cesium plasma

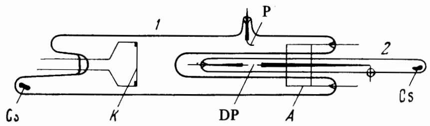

FIG. 1.

in the discharge section are measured. This tube can be covered from the outside by a radiation-reflecting shield.

The second tube, the detector, is 9 mm in diameter and contains only a conventional probe DP; this detector tube with the cesium vapor is introduced into a hollow cavity in the discharge tube. By producing a low-voltage arc in the latter we find it possible to set up in this single two-component system (that is, inside the detector) intense "trapped" resonance radiation of cesium; the double probe is then used to measure the parameters of the cesium plasma produced in this way.

The power supply for the discharge tube provides low-duty-cycle rectangular voltage pulses. The probe characteristics in the discharge tube and the detector were determined by a conventional method, using an S1-8 oscilloscope. By this means, in the discharge tube at a pressure $P \approx 0.1$ mm Hg it is possible to obtain electron densities of $\approx 10^{14}$ cm^{-3} and electron temperatures of $\approx 4000^\circ$K. Under these conditions the density of cesium atoms excited to the 6P level n^* can be determined from the Boltzmann relation through the use of the electron temperature.[6]

We first wish to demonstrate the following: 1) the cesium plasma produced in the detector is actually a result of the resonance radiation ($6S_{1/2} - 6P_{1/2,\,3/2}$ with $\lambda = 8943$ Å and 8241 Å) and 2) the current in the probe circuit in the detector is due to the plasma produced in the detector tube and not to photo effects at the surface of this tube. The first factor was verified by measurements on a separate apparatus using cesium vapor filters and other appropriate optical filters. The second factor is verified from the following: a) the energy of the photons corresponding to this radiation, 1.4 eV, is somewhat smaller than the threshold for the photo effect for a system consisting of tungsten and a cesium film, even under optimum covering conditions; b) the current density achieved at the surface of the probe $\approx 5 \times 10^{-4}$ A/cm^2 is an order of magnitude greater than the largest possible photocurrent from a surface of this kind. Hence, the characteristics of the double probe in the detector system yield a true representation of the cesium plasma that is produced.

An example of the characteristics of the double probe in the detector (one of the symmetric branches) is shown in Fig. 2. These characteristics are completely conventional and are typical of a conventional plasma, allowing us to determine the density n_e and temperature T_e of the plasma electrons in the detector section. The values we obtain is in the range $n_e \approx 10^{10} - 5 \times 10^{11}$ cm^{-3} and $T_e \gtrsim 2000^\circ$K, that is to say, for these values of n_e we are dealing with a conventional plasma. The present plasma is quiescent, like the plasma that is obtained by thermal ionization in a Q-machine,[7] which also has no current flow and avoids many obvious instabilities. However, the plasma obtained in the present device, aside from its method of production, differs from the plasma in a Q-machine in several ways: a) it is weakly ionized ($\beta_i \geq 10^{-4}$) and is composed chiefly of molecular-cesium ions; b) the densities obtained in the present device approach 5×10^{11} cm^{-3} without the requirement of a magnetic field in order to prevent recombination at the walls.

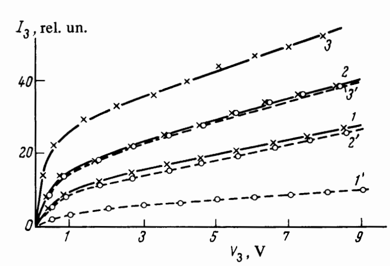

FIG. 2.

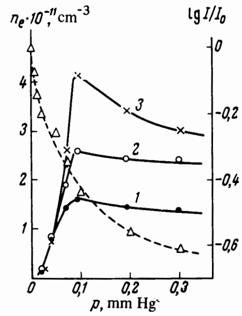

FIG. 3.

Returning to Fig. 2 we see that it depicts two functional relations of the probe characteristics in the detector section on the parameters of the plasma in the outer discharge tube: specifically 1) the dependence on the cesium vapor pressure in the discharge tube P equal to 0.04 (curve 1), 0.08 (curve 2) and 0.2 mm Hg (curve 3) for a fixed density of 4×10^{14} cm^{-3} and a temperature $\approx 4000^\circ$K for the plasma electrons and 2) the dependence on discharge current I, that is to say, the dependence on the density and temperature of the plasma electrons in the discharge device given by 0.7×10^{14} and 3600 (curve 1′) 3×10^{14} and 3900 (curve 2′) and 4×10^{14} cm^{-3} and 4100°K (curve 3′); in this case the quantity P = 0.08 mm Hg remains unchanged. In all of the cases listed above the cesium vapor pressure in the detector section p = 0.09 mm Hg while the electron density n_e and temperature T_e for example, for the uppermost curve in Fig. 2 are 4×10^{11} cm^{-3} and 2100°K.

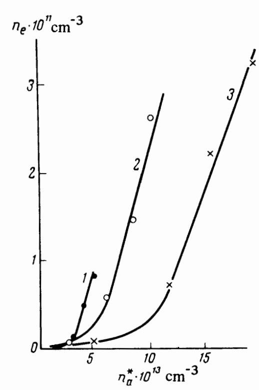

FIG. 4.

These experiments were followed by experiments in which we examined the probe characteristics of the plasma in the detector section for different values of the cesium pressure in the detector section p with fixed parameters for the plasma in the discharge section. Using these data we can determine the quantities n_e and T_e for the plasma in the detector; on the basis of this relation we have obtained the functional dependence $n_e(p)$ shown in Fig. 3 for the cases P = 0.04 (curve 1), 0.08 (curve 2) and 0.2 mm Hg (curve 3). Finally, in Fig. 4 we show the quantity n_e as a function of the density of excited cesium atoms in the detector n_a^* computed from the Boltzmann equation using the values of the parameters for the outer discharge plasma; in this case the pressures p = P were both 0.04 (curve 1), 0.08 (curve 2), and 0.2 mm Hg (curve 3).

An analysis of the data shown in Figs. 2–4 indicates the following characteristics of the cesium plasma; these are purely qualitative and of preliminary nature.

1. The growth in the degree of ionization of the cesium plasma in the detector with increasing pressure P and current I in the discharge device (Fig. 2) is evidently due to the growth in density n_a^* of the excited cesium atoms due to the increase in the total density of atoms n_a in the first case and the increase in electron temperature in the second; under these conditions there is a simultaneous increase in the intensity of the resonance radiation.

2. The strange appearance of an appreciable temperature for the electrons in the detector plasma $T_e \gtrsim 2000^\circ K$ is evidently associated with collisions of the second kind between the excited cesium atoms and the free electrons produced in the ionization processes. In the present experimental conditions the glass wall of the detector section is undoubtedly charged, as is usually the case, to some definite negative potential $V_{wall} \approx (kT/e) \ln \sqrt{M/m}$. For this reason the electrons in the plasma are essentially trapped and the extended interaction between electrons leads to the thermalization.[8] However, direct, and even step-wise, ionization of cesium atoms by plasma electrons with a sufficiently low value of the quantity T_e should presumably not be an important process; it follows from[6] that for this process to be important the value of T_e should be much higher.

3. The functional dependence $n_e(p)$ shown in Fig. 3 (for different values of P) exhibits the existence of a small maximum for the same value p ≈ 0.1 mm Hg. This general tendency is evidently connected with the fact that as the pressure p in the detector increases there is a retardation in the growth of the absorption of the resonance radiation from the discharge section,[3] that is to say, the density of excited atoms in the detector n_a^* on the one hand and simultaneously the usual growth in the recombination coefficient α[9] on the other [cf. Eq. (2)]. The qualitative characteristics of this absorption in the detector can be judged from the dashed curve in Fig. 3, which shows the dependence of the relative weakening of the resonance line of cesium at λ = 8521 Å transmitted through the volume of the detector with neutral vapor, plotted as a function of p.[10] This functional relation, determined by means of a different spectrum analyzer, actually shows completely satisfactory correlation with the growing branch of the basic curve in Fig. 3.

4. The functional dependence $n_e(n_a^*)$ shown in Fig. 4 can be described by the following equation, which relates the balance for the number of charges in the detector plasma:

$$qu_a n_a^{*2} = \frac{D_{amb}}{R_r^{\ 2}} n_e + \alpha n_e^2, \tag{1}$$

where R_r is the reduced radius, while u_a is the rate of excitation of the excited atoms. Thus, it is only in the initial region of the curves in Fig. 4 that the disappearance of plasma is to be associated primarily with diffusion to the walls $n_e \propto n_a^{*2}$; later the principal role is played by volume recombination $n_e \propto n_a^*$. This feature is shown not only by the general behavior of these curves but also by the specific dependence on the vapor pressure of the cesium in the detector, which is associated with the usual reduction in the ambipolar diffusion coefficient D_{amb} and the increase in the recombination coefficient α. In the second region of these curves, which is of primary importance for our case, we have

$$n_e = n_a^* \sqrt{qu_a/\alpha} = \gamma n_a^*. \tag{2}$$

In order to verify this relation we have determined the experimental value of the slope γ, for example from curve 3 in Fig. 4, for which the value of p is largest, that is to say, the approximation for which volume recombination is the only effective mechanism. If we use this value of γ and the value $q = 7 \times 10^{-18}$ cm² indicated in[4] to determine the quantity α we find $\alpha \approx 10^{-7}$ cm³/sec; this value is very close to the value given in[9] for molecular cesium ions in the appropriate pressure range p. However, a direct verification of the specific existence of molecular-cesium ions in the detector sections will require a mass-spectrometer analysis and this, along with related questions, is the subject of our program for the immediate future.

In plotting Fig. 4 we have assumed that with p = P ≈ 0.1 mm Hg the density of excited cesium atoms in the detector n_a^* ($n_a^* \ll n_a$) is approximately equal to this quantity in the discharge tube where it is determined by the Boltzmann equation.[6] The point here is that the discharge tube and the detector form a single field of "trapped" resonance radiation of cesium since they are only separated by the transparent glass partition. Hence, under these conditions the rate of radiation excitation of cesium atoms must be the same in both sections. On the other hand, the rate of radiation deexcitation n_a^*/τ_p must also be the same in this case because a) de-excitation collisions of the second kind are much less likely in the detector and b) in the discharge device, where the quantity n_e is two or three orders of magnitude greater, these inverse collisions of the second kind are compensated by direct excitation due to collisions of the first kind (Boltzmann equilibrium). Since the time for radiation de-excitation in this case τ_{rad} is also the same in both sections then the quantity in question n_a^* must be approximately the same in the overall system.

The experiments described here indicate the possibility of producing a quiescent, current-free, non-magnetic plasma of a new kind; the characteristics of this plasma have also been indicated. Plasmas of this kind in cesium vapor or other media can serve as interesting objects for various investigations.

[1] R. Ditchburn and U. Opik in Coll. Atomic and Molecular Processes, D. Bates ed., 1964, Chap. 3, p. 76.
[2] H. Witting and P. Gyftopoulos, J. Appl. Phys. 36, 1328 (1965).
[3] D. Pollock and A. Jensen, J. Appl. Phys. 36, 1328 (1965).
[4] G. Alfredo and A. Kniazzeh, Bull. Am. Phys. Soc., 11, 634 (1966).
[5] I. Kondilenko and G. Borob'eva, PTÉ No. 2, 142 (1966).
[6] N. Morgulis, Yu. Korchevoĭ and V. Lukashenko, Proc. All-Union Conference on the Physics of Low-Temperature Plasma, Kiev (in Russian) Naukova dumka, 1966 p. 65; Ukr. fix fiz. zhurn. (Ukrainian Journal of Physics) 12, No. 7 (1967).
[7] N. D'Angelo, Nuclear Fusion 3, 147 (1963).
[8] N. Morgulis, Yu. Korchevoĭ and D. Dudko, Proc. All-Union Conference on the Physics of Low-Temperature Plasma, Kiev, Naukova dumka, 1966, p. 64; ZhTF (in press).
[9] P. Dandurand and R. Holt, Phys. Rev. 82, 278 (1951).
[10] L. Biberman and I. Gurevich, Zh. Eksp. Teor. Fiz. 19, 507 (1949).

Translated by H. Lashinsky
44