INVESTIGATION OF SOME PROPERTIES OF A DENSE
HELIUM PLASMA IN THE RECOMBINATION STAGE*

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The recombination mechanisms in the plasma of an afterglow can take different forms depending on the degree of ionization and the partial composition. A weakly ionized plasma, as a rule, decays by means of dissociative processes, which give recombination factors of approximately $10^{-5} \text{ cm}^3/\text{sec}$. For high degrees of ionization the main decay mechanism should be radiational-collisional recombination [1]. Experimental investigations of a decaying helium plasma at low and medium densities ($N_e \lesssim 10^{14} \text{ cm}^{-3}$) confirm the decisive role played by this process at a temperature of approximately 1 eV [2, 3]. So far, however, insufficient experimental data has been obtained on the nature of the decay of a dense plasma ($N_e \gtrsim 10^{16} \text{ cm}^{-3}$). In this paper we present the results of a spectroscopic investigation of a decaying dense helium plasma formed by means of an electrodeless pulsed discharge of medium power.

The capacitor battery which supplies the discharge had a capacitance of 5 µF and was charged up to 35 kV. The period during which the current varied was 3.5 µsec. Its value at the instant of the first maximum reached 200 kA. The discharge tube was a quartz cylinder of diameter 8 cm and length 100 cm. The ends of the cylinder were sealed with plates of optical quartz. The current-carrying coil which surrounded the middle part of the discharge tube had a width of 35 cm. Experiments were made with an initial helium pressure in the tube of 0.25 torr. High-purity helium was used.

To make the measurements we used an ISP-51 spectrograph, at the output of which there was a slit with a microscope from the FEP-1 apparatus. The linear dispersion was 30 Å/mm in the range 4700 Å. Behind the output slit was a unit with an FÊU-11B photomultiplier, the signal from which was applied via a cathode follower to an OK-17 pulse oscilloscope. The resolution time of the apparatus was not worse than 0.3 µsec. The optic axis of the spectrograph was directed along the axis of the discharge tube, and the measurements were made in the region close to the axis. The setting of different parts of the spectrum with respect to the output slit was achieved by means of a micrometer screw attached to the spectrograph prism.

The plasma in an electrodeless high-current discharge experiences a number of successive contractions and expansions in the direction perpendicular to the axis of the discharge tube. Under our experimental conditions this oscillatory process ends approximately 10 µsec after the discharge starts. Starting at this instant, the plasma spreads over the whole volume of the discharge tube and luminesces. This can be clearly seen in photographs obtained with a high-speed camera.

The electron density was found from the value of the Stark broadening of the HeII 4636 Å line [4]. To do this we obtained measurements of the intensities at different parts of the line profile. The profile was shifted successively along the exit slit of the spectrograph, the width of which was taken to be 0.3 Å. This procedure implies good reproducibility of the conditions in the plasma from discharge to discharge, which was in fact the case in our experiments. A check showed that oscillograms of the intensity of the 4686 Å line obtained for different discharges differed from the average by not more than 10%.

Figure 1 shows the profile of the HeII 4686 Å line constructed from three series of measurements 8 µsec after the beginning of the discharge. This determination of the profile was also carried out for successive instants of time up to 50 µsec after the beginning of the discharge. The instrumental and Doppler


The broadening of the line in our case was relatively small (0.3 and 0.4 Å respectively), so their contribution to the profile were ignored. Figure 2 shows values of the electron density determined from the width of the profile during the afterglow phase of the plasma.

The temperature of the electrons in the plasma was found from the ratio of the intensities of the HeII 4636 Å and HeI 4471 Å lines [5]. Figure 3 shows typical oscillograms of these lines. The upper curve shows the change in voltage across the current-carrying coil. These oscillograms clearly illustrate the excitation, ionization, and recombination processes in the plasma. Excitation of the neutral helium occurs 2 μsec after the initiation of the discharge. Then, after the electron energy in the plasma has increased the intensity of the lines of the neutral atoms falls, and intense luminescence of the ionized helium occurs. After 20 μsec, when the discharge current has almost completely decayed, the plasma starts to cool off and recombine.

The particle loss due to ambipolar diffusion can be neglected under these conditions, since their density in the plasma in this phase is still large (~10^16 cm^-3). In addition, as will be shown below, the plasma has a relatively low temperature (< 4.5 eV). Estimates show that the diffusion time of an electron from the axis to the wall of the discharge tube is 0.1 sec, i.e., it exceeds the time of the experiment. Figure 4 shows values of the electron temperature of the plasma determined from several series of measurements. The break in the temperature curve 40 μsec after initiation of the discharge is noteworthy. This may be due to a reduction in the inflow of energy to the electrons, which accompanies electron–ion recombination of doubly charged helium ions. By then, the main mass of doubly charged helium ions has obviously recombined.

Knowing the form of the variation of the density, temperature, and intensity of the 4686 Å line, we can estimate the values of the recombination coefficient of the plasma in the afterglow phase. This estimate is correct for times 20 μsec after the initiation of the discharge, when the currents in the plasma have practically ceased to flow. Taking into account the large collision frequency in the plasma with Ne = 10^16 cm^-3, we can assume that the population of the upper levels of HeII are in Saha equilibrium with the electron continuum. We then have for the ion density in the p level [5]

\[ n(p) = 4.2 \times 10^{-16} \left( \frac{n^2(c) \cdot n(He^{++})}{T^{3/2}} \right) \exp \left( \frac{157890 Z^2}{p^2 T} \right), \]

where \( n(c) \) and \( n(He^{++}) \) are the densities of the electrons and doubly charged helium ions, \( T \) is the temperature, and \( Z \) is the charge on the ion. Taking natural logarithms and differentiating we obtain

\[
\frac{\dot{n}(p)}{n(p)} = \frac{\dot{n}(c)}{n(c)} + 3 \frac{T}{2} \frac{\dot{T}}{T} - \frac{157890 \cdot Z^2}{p^2 T} \frac{\dot{T}}{T}. \tag{1}
\]

Since the intensity of the line

\[ I(p) = n(p) A_p \hbar \nu_p \text{, then } \frac{n(p)}{n(c)} = \frac{I(p)}{I(c)}. \tag{2} \]

Replacing the densities on the left side of Eq. (1) by the intensity (2) and rearranging we finally obtain

\[
\frac{\partial n(He^{++})}{\partial t} = \left( \frac{I(p)}{I(c)} - \frac{n(c)}{n(He^{++})} + \frac{3}{2} \frac{T}{T} + \frac{157890 \cdot Z^2}{p^2 T} \frac{T}{T} \right) n(He^{++}) = - \gamma n(c) \cdot n(He^{++}).
\]

Hence, using the data in Figs. 2–4 we can calculate the recombination coefficient \( \gamma \) of the He^{++} ions at different instants of the plasma afterglow. At instants of time \( t = 20–30, 30–40, \) and 40–50 μsec after initiation.