Argon radiation behind of shock wave front

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Abstract. In this article, the results of an experimental study of non-equilibrium radiation of pure argon are presented. These results were obtained at the Institute of Mechanics of Lomonosow Moscow State University Shock Tube experimental complex. The main attention is focused to the study of the initial phase of radiation take place before the sharp increase electron concentration. The electron number density was determined with using of Stark broadening of Hα hydrogen line method. The panoramic spectra and individual radiation line evolution are presented. It is noted that radiation evolution at the initial stage depends strongly from radiation wavelength.

1. Introduction

The excitation and ionization of atoms by mean of atom-atom collisions and electron impact processes, leading to a subsequent avalanche-like increase in gas radiation, have been considered quite widely in the literature theoretically [1–6] and experimentally [7–8]. At the same time, the initial stage of this process which manifests itself as a period of radiation induction, until recently has not been unambiguously interpreted. If in the classical work [1] and in a number of subsequent works this period is associated with the influence of easily ionizing impurities in shock tubes, then in later studies, for example, in [4], inelastic atomic collisions are considered as the main reason for the ions argon appearance. The difficulties of initial stage studying connected with some experimental problems. For example, the individual argon line radiation at the initial phase is several orders of magnitudes less than this line maximum radiation intensity. Therefore the experimental equipment's sensitivity should be adapted directly to these initial measurements conditions. Wherein the initial phase can gives important information concerning main mechanisms of initial electrons accumulation. In this way the main attention is focused in this paper to the study of the initial phase of radiation that take place before the sharp increase electron concentration.

2. Experimental setup

The experiments were made on the "Shock tube" experimental complex (STEC). The excited levels concentrations were determined with using of the emission spectroscopic technique. To measure the absolute radiation intensities in the spectra of shock-heated gas, all channels were pre-calibrated by a standard procedure of comparison with the radiation of a known calibrated source [9]. The experimental setup scheme with the registration system of the shock-heated gas radiation is presented in Figure 1. The experimental equipment and registration system gives the possibilities to observed the radiation in the wide spectral range and with high time and space resolution. The observed in
experiments spectral region is located between 190nm to 1000nm. The time resolution is 0.1ms approximately. The shock wave velocity can be varied from 4km/s to 12km/s. The moment of the shock front arrival was determined as the middle of the time interval between the signals of the piezoelectric sensors located in the measuring section. The accuracy of these data is ±100 ns. The technique for shock wave front position is described in details in [11].

3. Results and discussion
The example of argon panoramic spectrum is presented in the Figure 2. The shock wave velocity and initial gas pressure are equal 5.81 km/s and 1Torr correspondingly. The pure argon is investigated here, because the pure argon is simple atom without of internal (rotation, vibration) freedom and without of dissociation and others and other complicating factors. As our experimental results shown the spectrum shape is weakly depend on the shock wave speed in the spectral range 200-1000 nm. The intensities of atomic lines and the level of background (bremsstrahlung) radiation are changed only. As well see from this figure the intensity of single atomic line is more high then intensity of background radiation. It should be noted here that this picture represented the cumulative radiation. Namely the values of radiation intensities are summed during all experimental time observation. The integral of this curve over all wavelengths gives information about full gas radiation power during experimental time, but cannot gives information about each individual line at each time step influence to this value. The information about evolution of individual line is needed for this. The next reason for individual line observation is connected with the following. The time evolution of each individual line gives the possibilities to examine of different calculative models and can gives information about ionization mechanism.

![Figure 1. Schematic illustration of experimental setup.](image1.png)

![Figure 2. Argon panoramic spectrum example for shock wave velocity 5.81km/s and initial pressure 1Torr.](image2.png)
3.1. Electron number density determination

As our estimation shown [10] the electron density may have significant influence to the initial stage of individual line radiation evolution. The number electron density was determined on the base of Stark broadening of H_α hydrogen line method [12, 13]. This method makes it possible to determine the electron concentration in the range of $10^{14} - 10^{19}$ cm$^{-3}$.

The Figure 3 demonstrated evolution of radiation of H_α (red curve), D_α (black curve) lines and radiation on the wavelength of 625nm (blue curve). Tuning the wavelength 656.1nm (D_α line) was carried out according to the radiation of the D_α line from the DDS-30 deuterium lamp. As can see from Figure 2 the wavelength 625nm is away from atomic lines radiation and connected with background radiation only. Thus the radiation intensity value on this wavelength (625nm) should be correlated with electron density. The radiation of 625nm and H_α lines was registered with width of the recorded spectral interval 4.0nm, on the other side the D_α line intensity registered with width of the recorded spectral interval 0.16nm. Thus the H_α intensity radiation is accumulating radiation in wider spectral range than D_α line intensity. Where in the center of these lines (D_α and H_α) are close to each other (see Figure 4). Thus the contribution to the radiation recorded at a wavelength of 656.1 (D_α) with a width of 0.16 nm (FWHM) before the onset of avalanche ionization is not significant. An estimate of the electron concentration at the initial stage for the experimental conditions shown in Fig. 4 show that the electron concentration is not more than $10^{14}$ cm$^{-3}$ [13]. Consequently, the measured concentration of electrons with small additions (~ 1%) of hydrogen from the Stark broadening of the H_α line in Fig. 4 allows one to determine only the electron concentration in the avalanche ionization zone.

The example of H_α line shape for shock wave velocity equal 6.4 km/s in argon with the addition of 1% hydrogen is presented into Figure 4. The value of Full Width Half Maximum (FWHM) and electron density for this condition are equal 0.22nm and $4\times10^{16}$cm$^{-3}$ correspondingly [13].
3.2. Temporal dependences of the radiation of shock-heated argon at different wavelengths

The time evolution of individual argon lines are presented on the Figure 5. The shock wave velocity is equal 5.95km/s and initial gas pressure is 1 Torr. It is should be noted that radiation at this initial time interval not investigated in detail and appropriate experimental information is absent in literature. The main attention in experimental studying is connected usually with delay radiation time and degree of ionization. These questions have detail experimental and theoretical description. Should be noted, the radiation intensity at the initial time interval at several orders of magnitude less than intensity maximum, and total duration of this stage is significantly less than full radiation time. Therefore the special customization of experimental equipment should be made before start of this short time interval investigation.

The very interesting evolution of radiations of some lines was observed during shock tube experiments. For example, as can see from Figure 5 the time evolution of line 696 nm is differ then 420nm line. The time evolution of line 696 nm radiation can be divided into three stage 1) After the arrival of the shock wave the radiation intensity almost instantly begin to increase – time interval between 0μs to 0.6μs; 2) Slight decline of intensity – time interval between 0.6μs to 2.5μs; 3) Sharp rise of radiation intensity – time more 2.5μs. Note that radiation on the 696nm wavelength is observed as results of transition from excited energy level 13.328eV to the energy level 11.548eV. The ionization limit for argon is 15.76eV. Wherein the excited levels are exist nearby above the 13.328eV level. Thus it seems intuitively that the decrease in population in the second stage is manifested as a result of a transition to higher excited levels and main mechanism of these transitions should be atom-atom collisions. The electron presences are not taken into account usually at this stage. But as our preliminary estimations shown [10] it is not correct always. The electrons collisions are influence on this and stage 2 cannot be realized without electron influence. Transition from kinetics dominated by heavy particles to electron impact processes was noted in [6] on the based calculative electron temperature behavior.

On the other hand the such three stage evolution not observed at 420 nm line radiation. In this case the radiation intensity increasing smoothly until sharp rise without slight decline of intensity as it was observed for 696nm line radiation. It is interesting that start time of sharp rising for both lines is equal approximately, but slew rate is differ. Note, that radiation on the 420nm wavelength is realized as results of transition between 14.499eV and 11.548eV energy levels. Thus the more higher level (comparison with 696nm radiation) should be populated in this case.
4. Conclusion
The presented in paper experimental results can gives possibilities to make following conclusions:
- the time evolution of different excited level are different at the initial phase before the sharp increase electron concentration and depend on the energy of excited level;
- three stage evolution are not observed for levels with energy equal and higher then 14.499eV.
- the Stark broadening of $H_\alpha$ hydrogen line method can be used to determine the electron concentration in the avalanche ionization zone only

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5. References
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