Pis'ma v ZhETF, vol. 77, iss. 6, pp. 326 – 329 © 2003 March 25

Acoustic impact on superluminescence in argon plasma

A. R. Aramyan[1]

Institute of Applied Problems of Physics NAS RA, 375014 Yerevan, Republic of Armenia

Submitted 19 December 2002
Resubmitted 14 February 2003

It is shown that in the argon discharge plasma it is possible to obtain the overpopulation of certain electronic levels of atomic argon under the influence of acoustic waves. When the specified threshold is overpassed, then a superluminescence (in the form of light flashes) from the overpopulated electronic levels of atomic argon is observed.

PACS: 52.25.Rv

The investigation of properties of low-temperature ionized plasma and of different influences on it is always urgent, since besides the elucidation of new physical mechanisms, the results of these investigations find immediate practical applications. It is noteworthy, however, that the works on the influence of acoustic waves on plasma parameters and on processes in plasma environment are relatively scarce. Besides that, the problem of acoustic wave interactions with thermodynamically nonequilibrium gas such as is the partially ionized gas-discharge plasma, where the electron temperature usually much exceeds that of heavier particles [1 – 3], is lately of high interest. Note that of numerous problems connected with interactions of acoustic waves with partially ionized plasma, the study of an influence of acoustic waves on radiation spectra of gas-discharge plasma appears to be especially promising. Last years, an interesting effect of abrupt change of radiation spectrum under action of sound wave in dense ($p \sim 100$ Torr) argon discharge plasma was observed in our laboratory [4, 5]. Several seconds after cutting out of sound wave, the light flashes were observed during several minutes in different points of the discharge tube in the bulk of positive column that apparently corresponded to some transitions between electronic levels of atomic argon. An assumption was made about the autogeneration (single-pass generation) of appropriate lines in the argon spectrum (the colored photo of this effect is given in [5]).

It was shown as a result of further research of this effect that under certain conditions the change in the plasma radiation at the interaction of acoustic waves with plasma shows not only by flashes, but also by substantial amplification of some spectral lines. Contrary to [4, 5], in the present work the correspondence of the observed spectral lines to transitions between electronic levels of atomic argon was specified.

The studies of the change of a radiation spectrum under the influence of acoustic waves were conducted in low-temperature argon discharge plasma (pressure – 100 Torr, discharge current – 50 mA, voltage on electrodes 2 kV). The experimental set-up (Fig.1) includes a quartz discharge tube with internal diameter of 6 and length of 100 cm. The distance between the electrodes was 85 cm. An electrodynamic transmitter is attached to one of butt ends of the tube. Beforehand, the power from electrodynamic transmitter was calibrated by sound level meter "ROBOTRON 01012" for conditions existing in discharge tube. The light emitted from plasma passes through the second butt and is directed to a monochromator. The investigation of intensity variations of some lines of plasma radiation spectra is curried out under the action of acoustic waves.

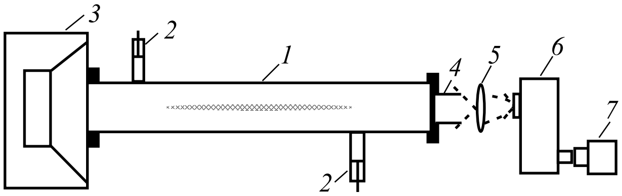

Fig.1. The experimental set up: *1* – is the discharge tube; *2* – electrodes; *3* – the electrodynamic transmitter of sonic waves; *4* – the window; *5* – the lens; *6* – the monochromator; *7* – the photoelectric multiplier tube

The dependence of radiation intensity of $6s \rightarrow 4p$ transition on the acoustic wave intensity on 190 Hz frequency is given in Fig.2 and is seen to show the hysteresis-type behavior. When the intensity of acoustic waves increases (from zero) to $A_{\max}$ (corresponding to 90 dB), no changes in the radiation spectrum is observed and for these acoustic wave intensities a decontraction

---

[1] e-mail: aramyan@web.am

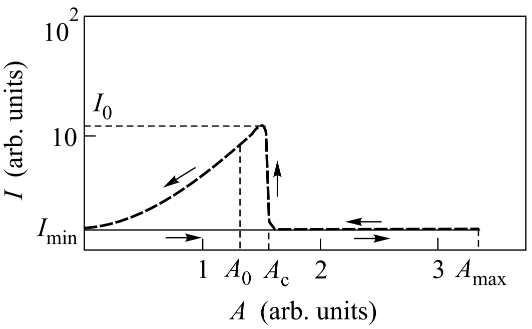

Fig.2. Dependence of the radiation intensity of $6s \to 4p$ transition on the acoustic wave intensity on 190 Hz frequency

of plasma takes place and it completely fills the tube volume. On the return path of acoustic wave intensity, a notable increase in line radiation intensity is observed at the value A_c. The critical value A_c (82 dB) corresponds to the unpinching threshold of discharge. The line intensity is observed to increase after the pinching of discharge. The further reduction of acoustic wave intensity is accompanied with a smooth decrease of the line intensity.

To find the relation between the constant increase of spectral line intensity and flashes we have plotted the dependences to be discussed below. The reduction in acoustic wave intensity on the return path A stays on the value A_o, which is less than A_c and corresponds to 80 dB (Fig.2). In Fig.3a the time dependence of radiation intensity of $6s \to 4p$ transition under constant influence of resonant acoustic waves with 190 Hz frequency and intensity A_0 is shown. It is seen, that in the absence of flashes the intensity of line radiation has the constant value I_o. At the bursting of flashes the line intensity sharply increases (in nearly 100 times) up to $I_{\max}$. After the bursting (with duration of 15–20 ms) the intensity drops to minimum, $I_{\min}$, which corresponds to the value of radiation intensity in the absence of acoustic waves. The rise of intensity from $I_{\min}$ to I_o is rather long, $\sim 1s$. Shown in the second plot (Fig.3b) is the dependence of radiation intensity of an analogous transition after cutting out of acoustic waves, the initial frequency of which was 190 Hertz and intensity – 90 dB. After cutting out of acoustic waves the line intensity keeps on at the minimum initial value of $I_{\min}$ during several seconds (~ 2 s). The value of I_o is reached in to time period and then I_o smoothly decreases to $I_{\min}$ with time in 15–20 s. The pattern of light flashes in this regime is similar to the previous one (Fig.3a).

Thus, summarizing the above experimental data one can draw a qualitative conclusion about the mechanism of this effect.

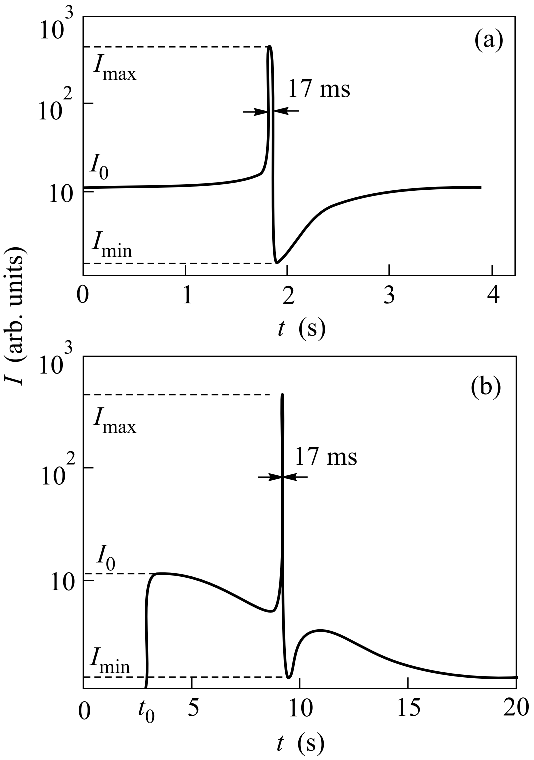

Fig.3. The time dependence of radiation intensity of $6s \to 4p$ transition: (a) under constant action of resonant acoustic waves of frequency 190 Hz and intensity 80 dB, (b) after cutting out of acoustic waves, the initial value of frequency of which was 190 Hz and intensity –90 dB

It is obvious, that low frequency phonon can not influence transitions between electronic levels and processes of radiation. It is possible to tell, that we deal with hydrodynamics, i.e. hydrodynamic flows which can influence stability and configuration of a plasma cloud, and through them on processes of ionization and recombination. As is known [6 – 8], in the presence of inhomogeneity of the acoustic field, there arise vortex-type acoustic flows in the standing sound wave. The velocity of these flows has an order-of-magnitude value $U \sim u_a^2/C$ (u_a is the vibration velocity, C – the sound velocity). In discharge tube the inhomogeneous acoustic field is formed, first of all, due to the existence of strong temperature gradient along the tube radius, and secondly, of a boundary layer near the walls, where the velocity of motion is reduced from its value in the sound wave to zero. The calculations show [7] that the intensity of acoustic flow due to the temperature gradient essentially exceeds that due to the boundary layer. It was shown that sufficiently intense standing acoustic wave may produce vortex-type acoustic flows, the contribution of which to the process of particle transfer in the radial direction may be essential. That was also confirmed experimentally in [9], where a pinched discharge decontracted under the influence of high intensity acoustic waves and the radial temperature gradient considerably smoothed out.

It is also known that at sufficiently high pressures ($P > 10\,\text{mm Hg}$), virtually the only process of bulk neutralization of charged particles in the gas-discharge plasma, which is competitive with the diffusion process, is the dissociative recombination [10] of electrons and molecular ions. In an inert gas discharge the molecular ions are predominant at high pressures ($P > 10\,\text{mm}\cdot\text{Hg}$) and relatively low gas temperatures ($T < 1000\,\text{K}$). So, we may assume that our experiment proceeds via the following processes:

$$\text{Ar}^+ + 2\text{Ar} \to \text{Ar}_2^+ + \text{Ar}, \quad \text{Ar}_2^+ + e \to \text{Ar}^* + \text{Ar}.$$

These processes run at very high rate and lead to efficient formation of excited atoms of inert gas. It is known that highly excited atoms are produced as a result of electron impact dissociation of molecules [11, 12]. This process was widely used in early investigations of Rydberg atoms.

High quantum levels of hydrogen atoms are known from the quantum theory to have large lifetimes. The average lifetime of t_n depends on the value of the first quantum number n as $t_n \sim n^4$.

So, taking into account the aforesaid we may make the following assumptions: The flows formed (Fig.4) are directed in some places to walls and in some places to the center of tube. These flows carry the particles in and out of the discharge range. In this process the particles may be found in the regions of discharge tube, where the temperature of electrons and neutral particles are notably lower than in the discharge range. Hence, hot electrons are quickly cooled mainly due to elastic electron-atom collisions. Then there the recombination of electrons with ions takes place, and basically with molecular ions. An analogous intense recombination occurs also in places, where the acoustic flows are directed to the center of tube. When and where the particles of cool gas get in the discharge, they cause an intense recombination. It turned out that during these recombination events, i.e., during the dissociative recombinations, highly excited long-lived atoms are produced. So, in the indicated places the accumulation of highly excited atoms occurs.

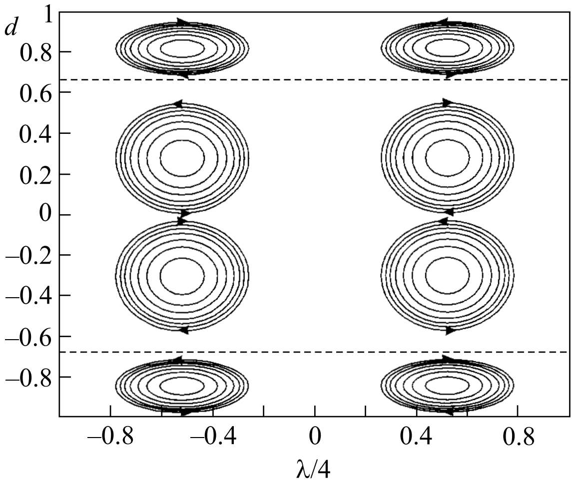

Fig.4. The diagram of "acoustical flows" in the tube

Now consider the destruction of such highly excited long-lived states of the atom as a result of collisions with atoms and molecules.

In conformity with the theory of atomic collisions [13], the probability of transition between two states strongly depends on the Messi parameter ξ (the probability is $\sim \exp(-\xi)$). Let us estimate the value of Messi parameter for transition $nl \to n'l'$, where $n' = n - 1$. The difference in energy for this transition is $\Delta\varepsilon \sim (\delta_l - \delta_{l'})/n^3$, where δ_l is the quantum defect, n – the first quantum number. The Messi parameter is [14]

$$\xi = \Delta\varepsilon a/\nu_a \sim \delta_l/n\nu_a,$$

where a is the size of the strongly excited atom, ν_a – the velocity of nucleus motion. For $n, l \gg 1$ the Messi parameter turns out small due to the smallness of quantum defect δ, and the probability of appropriate transitions is high. The situation is different when the highly excited states have orbital momentum $l \geq 0$. In these cases the Messi parameter $\xi \geq 1$ for moderate values of n. Then the probability of transition at the collision is much less than that in the former case.

Owing to the quenching of highly excited states at collisions with atoms and molecules, the levels with n, $l \geq 1$ are quickly emptied, whereas the levels with $n \gg 1$, $l \geq 0$ are occupied. In this experiment the levels $7s$, $6s$, $7d$ are occupied. Due to this fact an increase in radiation intensity from transitions $7s \to 4p$, $6s \to 4p$, $7d \to 4p$ was observed. As for the flashes and locations of their formation, these are, presumably, due to the superluminescence that takes place when the overpopulation threshold for autogeneration is overpassed.

As was mentioned in the results, the blue flash of $7d \to 4p$ arises only inside the discharge pinch and the orange one ($7s \to 4p$, $6s \to 4p$) – both inside and outside of the pinch boundaries. It is connected with the fact that as a result of quenching at collisions the $7d$ level may be depopulated. Since the concentration of charged particles inside the pinch is much greater than beyond the pinch boundary, one can assume that the recombination of charged particles inside the pinch (in consequence of acoustic flows) proceeds more intensely that beyond the radial boundary of pinch. For this reason the concentration of highly excited atoms inside the pinch is much higher, with the result that the overpopulation threshold between levels $7d \to 4p$ may be overpassed to cause the superluminescence observed as blue flashes. As to the levels $7s$ and $6s$ (orange flashes), they are intensely populated inside and outside the pinch, but the probability of quenching these levels on account of collisions with atoms and molecules is much lower than for the level $7d$. For this reason the orange flashes are observed both inside and outside the pinch.

As is seen in Fig.2, after displaying of superluminescence the intensity of observed lines drops to minimum for sufficiently long periods ($\sim 1s$), that are determined by the velocity of acoustic flow. Under our experimental conditions (tube radius $R \approx 3\,\text{cm}$, the sound wavelength $\lambda = 200\,\text{cm}$, $T \approx 400\,\text{K}$, $P \approx 100\,\text{mm·Hg}$) and 83 dB intensity of sound wave, the velocity of acoustic flow $U \sim 0.1 \div 0.2\,\text{cm/s}$. For these velocities the charged particles cover the distance from the center of discharge (diam. $2 \div 3\,\text{cm}$) to the radial boundary during $\sim 1s$. So, after the superluminescence (i.e., the stimulated depopulation of the levels $7s$, $6s$, $7d$) approximately $1s$ is required to restore the population of these levels that existed prior to flashing.

The hysteresis-type dependence of the intensity of above spectral lines on sound wave intensity is probably connected with the effect of generation of space harmonics of the major acoustic vortex [7].

Finally we arrive at the following conclusion about the dynamics of this effect. The acoustic vortices that arise in case of sufficiently intensive acoustic field transfer cool neutral atoms and charged particles in the radial plane in the discharge tube. At a definite value of the velocity of these motions some regions emerge at specific locations of the tube (either in the discharge pinch or out of it), where an intense recombination of charged particles takes place (in this case the dissociative recombination). As a consequence of this recombination the concentration of highly excited atoms in the mentioned locations abruptly increases. Due to quenching of highly excited atoms at the collisions with atoms and molecules, the population of levels $6s$, $7s$, $7d$ is increased. The observed flashes occur when the overpopulation threshold for superluminescence between levels $6s \to 4p$, $7d \to 4p$, $7s \to 4p$ is overpassed.

From above-stated it is possible to make a following conclusion. For realization of observed effect acoustic vibrations are not essential. Same effect can be caused by vortical flows generated in other way, if the speed of a flow will not result in significant decrease of a temperature radial gradient. The strong flow will result to discharge decontraction [9]. When, in given experiment the speed of flow comes to $\sim 0.2\,\text{cm/s}$.

It is worthwhile to note that such a recombinational superluminescence is observed also in astrophysical objects [15, 16]. One could say that the obtained effect in the gas discharge plasma may be used for modeling similar observed phenomena in astrophysics.

The author deeply grateful to Academician A. R. Mkrtchyan for his continuous attention, discussions and assistance in this work.

---

1. A. I. Osipov and A. V. Uvarov, Sov. Phys. Usp. **35**, 903 (1992).
2. G. A. Galechyan, Sov. Phys. Usp. **165**, 1309 (1995).
3. G. Martaza and M. Y. Yu, J. Plasma Phys. **57**, 835 (1997).
4. A. Aramyan, JETP Lett. **69**, 383 (1999).
5. A. Aramyan, *Influence of Acoustic Waves on Radiation Spectra of Argon Gas-discharge Plasma*, physics/0207014.
6. O. V. Rudenko and S. I. Soulyan, *Theoretical Basis of Nonlinear Acoustics*, M.: Nauka, 1975.
7. K. Z. Hatsagortsyan and G. Galechyan, Laser Phys. **4**, 3 (1994).
8. Quan Qi, R. E. Johnson, and J. G. Harris, J. Acoust. Soc. Am. **97**, 1499 (1995).
9. A. Aramyan, A. Mkrtchyan, and G. Galechyan, Sov. Phys. Acoust. **37**, 213 (1991).
10. A. V. Eletskii, Sov. Phys. Usp. **25**, 13 (1982).
11. W. L. Borst and E. C. Zipf, Phys. Rev. **4A**, 153 (1971).
12. R. S. Frend, J. Chem. Phys. **54**, 3125 (1971).
13. N. Mot and, G. Messi, *Theory of Atomic Collisions*, Oxford, 1933.
14. B. M. Smirnov, *The Excited Atoms*, M.: Energoizdat, 1982.
15. C. Thum, V. S. Strelnitski et al., Astron. Astrophys. **300**, 843 (1995).
16. K. Davidson, D. Ebbets et al., Astron. J. **113**, 335 (1997).