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Nitrogen-plasma continuum emission associated with $N^-(^3P)$ and $N^-(^1D)$ ions

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A possible contribution of negative atomic ions to the continuum radiation in nitrogen plasma is discussed. It is shown that both unstable $N^-(^3P)$ and metastable $N^-(^1D)$ ions may have a significant effect on the total production of the continuum radiation at electron temperatures below 12 000 K. It is also suggested that the theoretical cross sections for the radiative attachments involving the negative ions are more reliable than the available experimental cross sections.

The role of negative atomic ions in production of continuum radiation in nitrogen plasma has been argued by various authors over the last three decades. An excess of continuum radiation has been detected in several shock and arc experiments[1–5] but theoretical estimates neglecting the presence of the negative ions could not account for the excess, especially at electron temperatures $T_e \lesssim 12\,000$ K.[3–5] It was hypothesized[1–4] that the excess of radiation might have been caused by photon emission associated with production of the N^- ions by radiative attachment. It is known now that the ground state $N^-(^3P)$ is unstable and a metastable $N^-(^1D)$ state exists and that another metastable state $[N^-(^1S)]$ may exist[6–11] (see Fig. 1). However, the energies of these states were not accurately known in the early works and some of the conclusions about the stability of these states and their role in production of the continuum radiation were erroneous.

If the negative ion emission is neglected but free-free and free-bound radiation is included in collisional-radiative model,[12] then the frequency-dependent total continuum emission coefficient agrees well with its measured value at $T_e > 12\,000$ K, while at lower electron temperatures the difference is within a factor of 2–3. (Even if the negative ions were present in the plasmas, their role in the production of the continuum radiation at the high temperatures would be negligible because of the low concentration of the ions at these temperatures.)[12,13]

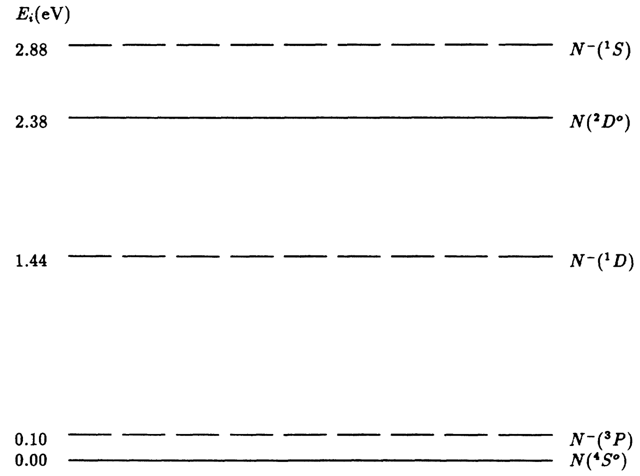

FIG. 1. The electronic configuration of a N ion.

In this paper we study a possibility of production of continuum emission by radiative attachment forming unstable $N^-(^3P)$ and metastable $N^-(^1D)$ ions [the contribution of the $N^-(^1S)$ metastable ion to production of the continuum radiation would be negligible[14]] as follows:

$$e + N(^4S^\circ) \rightleftarrows N^-(^3P) + h\nu \ , \tag{1}$$

and

$$e + N(^2D^\circ) \rightleftarrows N^-(^1D) + h\nu \ . \tag{2}$$

The cross sections for the photodetachments (1) and (2) have been experimentally and theoretically determined.[3–5,15–17] The cross sections for the photodetachment (1) calculated by Asinovskii *et al.*,[3] Moskvin,[16] and Henry[17] agree with each other within a factor of 2 and they show similar agreement with the measurements of D'Yachkov *et al.*[5] and Asinovskii *et al.*[3] The cross sections for the photodetachment (2) calculated by Asinovskii *et al.*[3] and Moskvin[16] agree with each other within a factor of a few, but they are smaller by an order of magnitude than the measured cross sections of Ciffone and Borucki,[4] Asinovskii *et al.*,[3] and Morris *et al.*[15] (the agreement among the measured cross sections is better than a factor of a few). The cross sections used in this work are given in Fig. 2.

Using the approach of Refs. 12 and 13, we calculated the total continuum emission coefficient $j_\nu = j_\nu^{\rm fb} + j_\nu^{\rm ff} + j_\nu^-$ including the radiation produced by the free-free and free-bound transitions and the radiative attachments (1) and (2). We neglected in the calculations the contribution of the following processes:

$$e + N^-(^3P) \rightleftarrows e + N(^4S^\circ) + e \ , \tag{3}$$

$$e + N^-(^1D) \rightleftarrows e + N(^2D^\circ) + e \ , \tag{4}$$

$$N^-(^3P, {}^1D) \rightarrow N(^4S^\circ) + e \ , \tag{5}$$

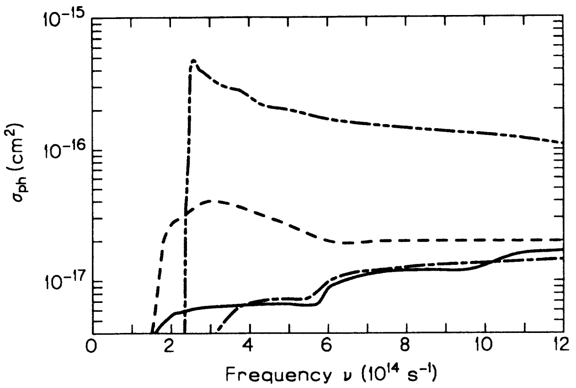

FIG. 2. The theoretical (Ref. 3) (solid line) and experimental (Refs. 4, 5, and 15) (dashed line) photodetachment cross sections of the $N^-(^3P)$ ion [process (1)] and the theoretical (Ref. 3) (dot-dashed line) and experimental (Refs. 3, 4, and 15) (double-dot-dashed line) photodetachment cross sections of the $N^-(^1D)$ ion [process (2)].

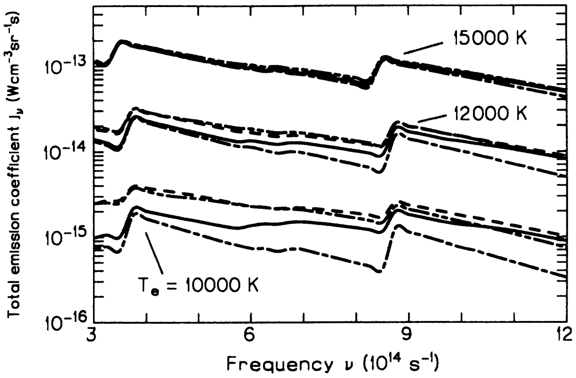

FIG. 3. The total continuum emission coefficients j_ν calculated using different photodetachment cross sections and when there is only one kind of negative ions; either $N^-(^3P)$ [solid (theoretical cross section) and dashed (experimental cross section) lines] or $N^-(^1D)$ [dot-dashed (theoretical cross section) and double-dot-dashed (experimental cross section) lines] is taken into account. The cross sections are those given in Fig. 2.

even though some of them can be quite efficient. This results from the fact that the inclusion of these processes in the model would not change the production of the continuum radiation in plasma considered here. (Also, the rate coefficients for the processes are unknown). Under the experimental conditions discussed here, the populations of electrons and the two lowest atomic states are very high.[12] In addition, the atomic states are close to Boltzmann equilibrium with each other and the electrons are close to Saha equilibrium with these and the other excited atomic states.[12] Therefore the population of the negative ions can be calculated from the Saha equation.[13,18] (The Saha relationship is applicable to both stable and unstable ions.[19]) It should be emphasized that the population of electrons and the $N(^4S^\circ)$ and $N(^2D^\circ)$ states are controlled by processes other than processes (1)–(5) because the population of electrons is very high ($> 10^{16}$ cm^{-3}) and is of orders of magnitude greater than population of the negative ions. As a result, the rate equations for the electrons and atoms can be decoupled from the rate equation for the production of the negative ions. Therefore direct knowledge of the population of the negative ions is not necessary for determination of the intensity of the continuum radiation produced in the plasmas.[13,18]

The calculated frequency-dependent coefficient j_ν taking into account only one radiative attachment process [either (1) or (2)] are given in Fig. 3. As can be seen there, the contributions of the $N^-(^3P)$ and $N^-(^1D)$ ion emission are distinctive at lower electron temperatures and these contributions are comparable to each other. The comparison of the calculated total emission coefficient j_ν [including contributions of both $N^-(^3P)$ and $N^-(^1D)$ ions and using the theoretical photodetachment cross sections] with the experimental values is shown in Fig. 4. As can be seen there, the excess of the continuum radiation in the experiments can be attributed to the formation of the $N^-(^3P)$ and $N^-(^1D)$ ions through the radiative attachments (1) and (2), if the theoretical cross sections used in this work are reliable.

It should be emphasized that the calculated emission coefficients shown in Fig. 4 were obtained assuming *theoretical* cross sections for both attachment processes (1) and (2). The choice of the theoretical cross sections over the experimental ones can be argued as follows. All the measured cross sections were obtained assuming that only *one* of the processes (1) and (2) was responsible for the excess of the detected continuum radiation. Then, the experimental emission coefficients (and consequently the radiative attachment and photodetachment cross sections) were obtained from the difference between the measured and calculated coefficients, with the latter coefficient being a sum of the free-free and free-bound

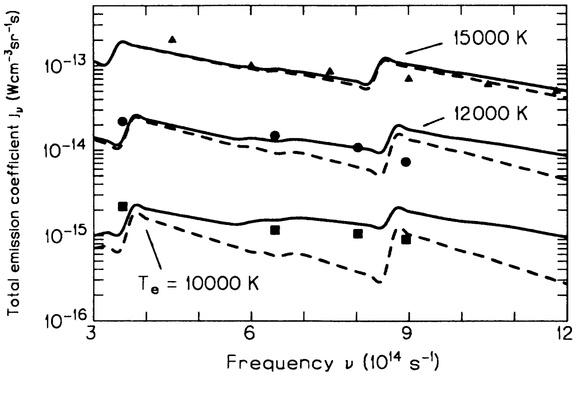

FIG. 4. The comparison of the calculated and measured total continuum emission coefficients j_ν. The solid lines represent the results when the contributions of both $N^-(^3P)$ and $N^-(^1D)$ ions are considered, while the dashed lines represent the results when the contribution of the negative ions is neglected. Experimental results are denoted by squares ($p = 0.61$ atm) (Ref. 4), circles ($p = 0.78$ atm) (Ref. 4), and triangles ($p = 1$ atm) (Ref. 3). The estimated accuracy of the experimental data is better than $\pm 35\%$.

continuum radiation only. Such a procedure, which most likely overestimates the cross sections for processes (1) and (2), is used by experimentalists for two main reasons. First, it is very difficult to measure directly the population of the $N^-(^3P)$ ions during the attachment process (1). [The process of the production of the $N^-(^3P)$ ions can also be viewed as bremsstrahlunglike with the electron in a resonant field of the atoms;[14,20] for example, $N^-(^3P)$ ions are formed through the process (1) and autodetached through the process (5); see discussion in Refs. 21, 22, and 23.] Second, the densities of the $N^-(^1D)$ ions in the experiments were much lower than the background electron and positive ion densities. Thus it seems that the measured cross sections for the photodetachments (1) and (2) were overestimated, especially the cross section for the process (2). Therefore the choice of the theoretical cross sections for the processes (1) and (2) seems to be more justified than the measured cross sections obtained by using the procedure discussed above. This statement would be valid even if the cross sections calculated assuming the correct energy levels of the ions were slightly different from those calculated by Asinovskii *et al.*[3] [The possible difference would certainly be much less than an order of magnitude, which is the discrepancy between the present theoretical and experimental cross sections for the process (2).]

It seems at present that a more reliable cross section for the process (2) would be measured at higher pressure (about 10 atm) and lower temperature ($T_e \lesssim 12\,000$ K). Under such conditions, the process (1) is much less probable[14,24] than the process (2) and the latter process dominates the negative ion emission. One should add that no excess of continuum radiation was detected in the existing higher pressure ($p > 30$ atm) and higher electron temperature ($T_e \gtrsim 13\,000$ K) experiment of Cooper.[25] This, however, is expected because of the negligible contribution of the negative ions to the total continuum radiation[13] in plasmas with high electron temperature.

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