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Johansson, Sveneric; Letokhov, Vladilen

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The Possibility of Resonance-Enhanced Two-Photon Ionization of Ne and Ar Atoms in Astrophysical Plasmas

S. Johansson[1] **and V. S. Letokhov**[2]
[1]*Lund Observatory, Lund, Sweden*
[2]*Institute of Spectroscopy, Troitsk, Russia*

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Abstract—We consider possible schemes for the resonance-enhanced two-photon ionization (RETPI) of Ne and Ar atoms under the action of bichromatic radiation of intense resonance lines of HI, HeI, and HeII in a radiation-rich astrophysical plasma. The ionization rate is comparable to or exceeds the recombination rate in rarified astrophysical plasma, which leads to the accumulation of singly ionized ions with a subsequent transition to the higher ionization state via RETPI. We consider the RETPI reaction chains NeI → ... → NeV and ArI → ... → ArVI. *© 2004 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

In some cases, low-density astrophysical plasma ($N_{\rm H} < 10^{10}$ cm^{-3}) can have a very high radiative-energy density, comparable to the energy density of the free electrons. One example is gas condensations (blobs) near a hot star. The best-known case is the Weigelt blobs near the most massive and brightest star of our Galaxy, η Car [1]. Such blobs can be distinguished from the central star in observations with the Hubble Space Telescope. Such observations show that they are located only a few hundred stellar radii from the central star [1, 2] and that their size and hydrogen density imply a high optical depth to the Lyman continuum [1, 3], and quite possibly to the ionization continuum of helium as well. The photoionization–recombination cycle leads to the formation of intense HI, HeI, and HeII resonance lines with effective spectral temperatures of the order of 10 000 K, close to the photospheric temperature of the star, and with spectral widths of hundreds of cm^{-1} [4]. This unique situation differs radically from the conditions in a typical planetary nebula located orders of magnitude further from the central star, when the main role in exciting and ionizing atoms is played by the electron energy, while the photon density is neglible [5, 6]. Such gaseous blobs located nearby a hot star can be considered "radiation rich."

Another example of a radiation-rich region is the environment of an active galactic nucleus (AGN), although the origin of the high-intensity radiation in these objects has a different nature [6, 7]. In the broad-line regions of AGNs, the ionization parameter (the ratio of the density of the ionizing photons to the density of free electrons) can reach 10^{-2}–10^{-3} [7]. High-intensity lines of H, He, and HeII arise during the photoionizational reprocessing of the bright, short-wavelength radiation of the AGN into recombination lines of these species.

In such radiation-rich regions, photoionization processes can play a more dominant role than electron-collisional ionization (see, for example, [8]). Moreover, the high intensity of the VUV lines of hydrogen and helium can stimulate incoherent nonlinear photonic processes that do not require that the radiation be coherent. One such process is resonance-enhanced two-photon ionization (RETPI), which is well known in nonlinear optics [9, 10]. The possibiity of RETPI in an astrophysical plasma (blobs) near a hot star was considered in [11], including the possibility of a series of RETPI processes $X \to X^+ \to X^{2+}$ etc. under the action of VUV lines of HI, HeI, and HeII [12]. More detailed calculations for atomic C, N, and O are presented by Johansson and Letokhov [13], who considered a scheme for successive RETPI of C, N, and O atoms right to CV, NV, and OV under the action of the radiation of one or two spectral lines from a set of HI, HeI, and HeII lines from HeII Ly$\,\varepsilon$ (234 Å) to HI Ly$\,\alpha$ (1215 Å). In the current paper, we consider an analogous scheme for the successive RETPI of Ne and Ar atoms up to NeV and ArVI, also under the action of the radiation of one or two intense lines of HI, HeI, and HeII. We first supplement the formulas presented in [13] with simple expressions that are useful for estimating the probability of RETPI.

2. PROBABILITY OF RETPI OF AN ATOM SUBJECT TO BICHROMATIC RADIATION

Let us consider an atomic particle X (a neutral atom or ion in ionization state N) in a field of bichro-

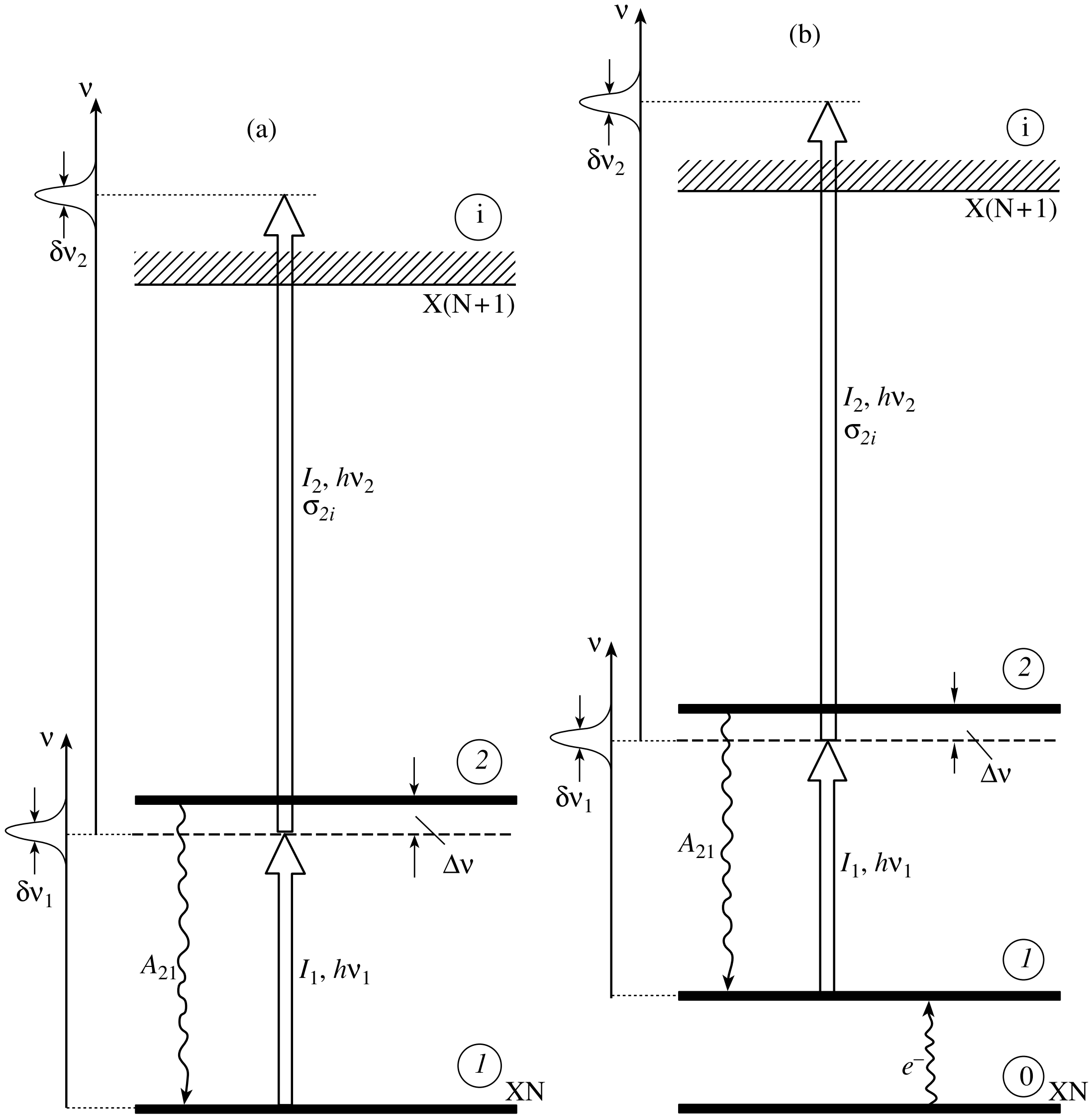

Fig. 1. General schemes for resonance-enhanced two-photon ionization (RETPI) of atomic particles XN under the action of the radiation of two intense spectral lines with widths $\delta\nu_1$ and $\delta\nu_2$ and a frequency offset $\Delta\nu$ relative to the exact intermediate resonance for a permitted spectral transition 1–2. (a) Purely photonic RETPI from the ground state. (b) RETPI from a low-lying state excited by collisions with electrons.

matic radiation with frequencies ν_1 and ν_2 (Fig. 1a), intensities I_1 and I_2 (in photon/cm^2 s), and spectral widths $\delta\nu_1$ and $\delta\nu_2$. The energy of a photon of either frequency, $h\nu_1$ or $h\nu_2$, is not sufficient to ionize the atom, but the energy $h\nu_1 + h\nu_2$ exceeds the ionization threshold of the atom. Therefore, two-photon ionization of the atom is possible in principle. We do not consider here the rare case when ν_1 coincides with the frequency for the transition ν_{12}, when two-step resonance ionization of the atom is possible [9]. We are interested in the more realistic situation when the frequency offset is $\Delta\nu = |\nu_1 - \nu_2| \gg \delta\nu_1$. In this case, RETPI is possible and has a fairly high probability due to the presence of an intermediate resonance [9] without the real excitation of level 2 (Fig. 1a). The probability of this process (in s^{-1}) is determined by the expression [13]

$$W_{1i}^{(2)} = \frac{\lambda_{21}^2}{32\pi^3}\frac{g_2}{g_1}\frac{A_{21}}{(\Delta\nu)^2}\sigma_{2i}I_1I_2, \qquad (1)$$

where A_{21} and λ_{21} are the Einstein coefficient and wavelength for the transition 1–2, g_1 and g_2 are the degeneracies of levels 1 and 2, σ_{2i} is the cross section for photoionization from the excited state at frequency ν_2, and the offset is expressed in Hz. To get some idea of the magnitude of $W_{1i}^{(2)}$, we will consider a simple numerical example. Let the transition 1–2 correspond to Ly α HI ($\lambda_{21} = 1215$ Å), with $A_{21} \simeq$

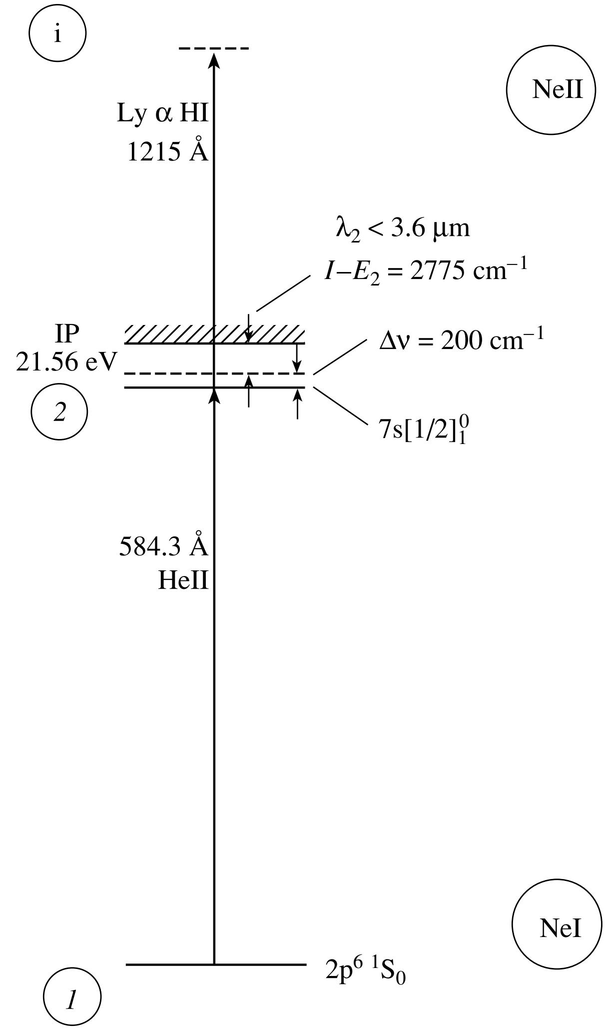

Fig. 2. RETPI scheme for NeI → NeII.

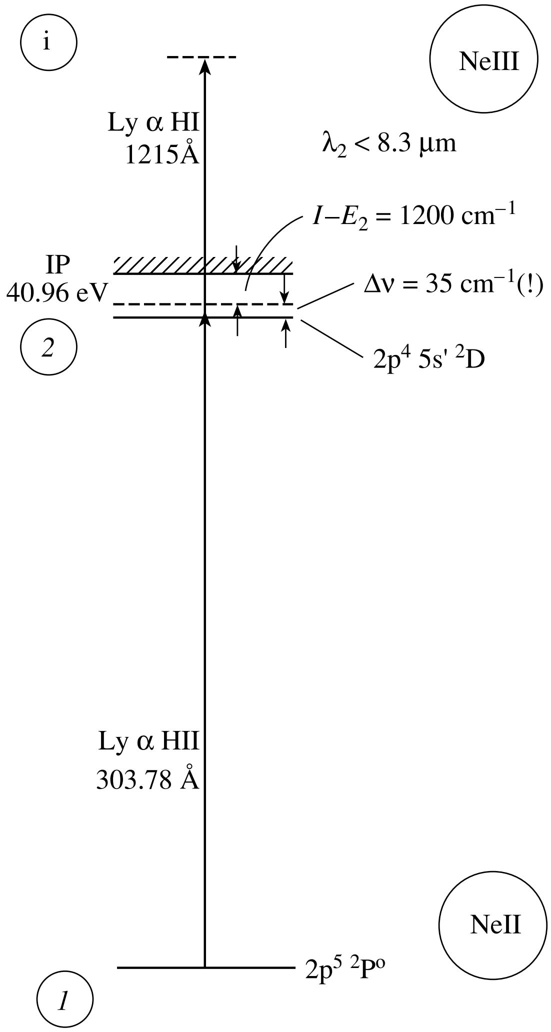

Fig. 3. RETPI scheme for NeII → NeIII.

10^9 s^{-1} and the cross section for photoionization of the excited state $\sigma_{2i} \simeq 10^{-17}$ cm^2. Let the spectral lines have the same wavelength λ_{21}, spectral widths $\delta\nu_1 = \delta\nu_2 \simeq 300$ cm^{-1} (10^{13} Hz), and effective spectral temperatures $T_{eff} \simeq 15\,000$ K. The intensities $I_{1,2}$ (photons/cm^2 s) of the spectral lines are then determined by the expression

$$I_{1,2} = \frac{8\pi}{\lambda^2}\frac{\delta\nu_{1,2}}{\left[\exp\left(\frac{h\nu_{1,2}}{kT_{eff}}\right) - 1\right]} \tag{2}$$

and are equal to $I_1 = I_2 = 6.5 \times 10^{20}$ photons/cm^2 s. If the frequency offset for λ_1 relative to a resonance transition for an atom (ion) subject to RETPI is $\Delta\nu \simeq 1000$ cm^{-1} (3×10^{13} Hz), $W_{1i}^{(2)} \simeq 6 \times 10^{-7}$ s^{-1}. This is quite substantial for a rarified astrophysical plasma, for which the electron-excitation and recombination rates can be comparable to or even lower than this value. It stands to reason that we must bear in mind the quadratic dependence of $W_{1i}^{(2)}$ on the frequency offset from the intermediate resonance $\Delta\nu$ and the intensity of the radiation. Expression (1) for the probability of RETPI of an atomic particle per unit time can be written in the form

$$W_{1i}^{(2)} = \beta^{(2)} I_1 I_2, \tag{3}$$

where the coefficient $\beta^{(2)}$ (in cm^4 s) is

$$\beta^{(2)} \simeq \frac{\lambda_{12}^2}{32\pi^3}\frac{g_2}{g_1}\frac{A_{21}}{(\Delta\nu)^2}\sigma_{2i}. \tag{4}$$

Expressions (1) and (2) for $W_{1i}^{(2)}$ are presented for the case when the line width $\delta\nu_1$ at frequency ν_1 satisfies the condition $\delta\nu_1 \ll \Delta\nu$ and the photoionization cross section σ_{2i} varies only slightly within the width of the line at ν_2, as is shown in Fig. 1a.

The cross sections for two-photon absorption (in cm^2) at the frequencies ν_1 and ν_2 are given by

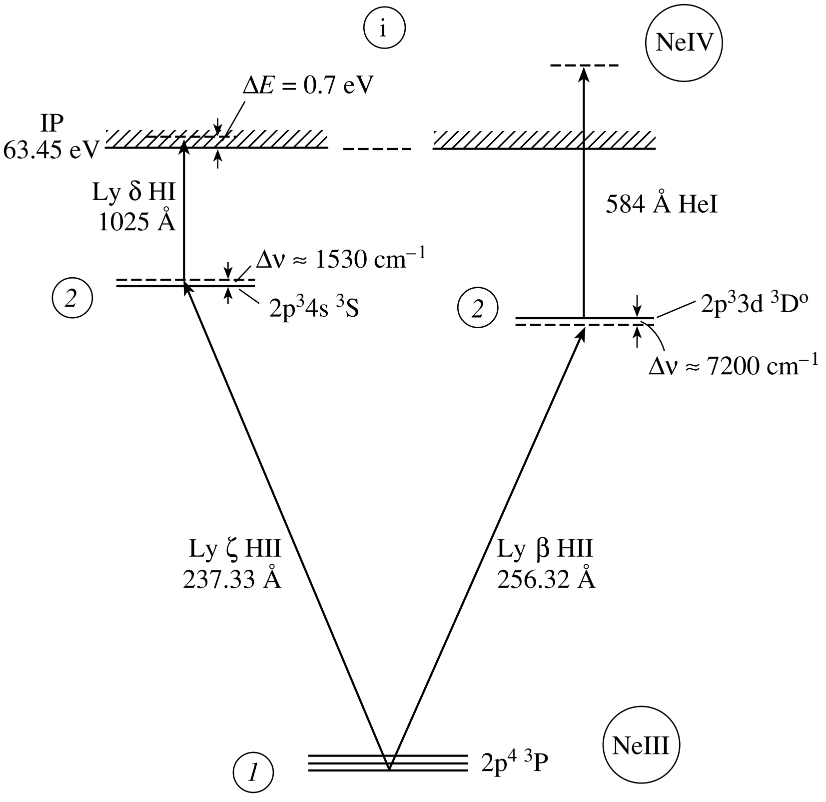

Fig. 4. RETPI scheme for NeIII → NeIV.

the expressions

$$\sigma_1^{(2)} = \beta^{(2)} I_2 \tag{5a}$$

and

$$\sigma_2^{(2)} = \beta^{(2)} I_1. \tag{5b}$$

Accordingly, the coefficients for two-photon absorption per unit length are given by the expressions

$$\chi_1^{(2)} = \sigma_1^{(2)} N_0 = \beta^{(2)} I_2 N_0 \tag{6a}$$

and

$$\chi_2^{(2)} = \sigma_2^{(2)} N_0 = \beta^{(2)} I_1 N_0, \tag{6b}$$

where N_0 is the density of two-photon-absorbing particles (in cm^{-3}). The numbers of absorbed photons n_1 and n_2 per unit time per unit volume at frequencies ν_1 and ν_2 are the same and are given by the expression

$$n_1 = n_2 = \chi_1^{(2)} I_1 = \chi_2^{(2)} I_2 = \beta^{(2)} I_1 I_2 N_0 = W_{1i}^{(2)} N_0. \tag{7}$$

For example, if the probability $W_{1i}^{(2)} \simeq 10^{-5}$–$10^{-7}$ s^{-1} and the density of two-photon-absorbing particles is $N_0 \simeq 10^3$ cm^{-3}, the coefficients for the two-photon absorption are much smaller than 10^{-20} cm^{-1}.

3. SCHEMES FOR SUCCESSIVE RETPI FOR Ne AND Ar

Analysis of the permitted photon transitions for neutral Ne and Ar atoms and their ions indicates the possibility of RETPI under the action of appropriate lines or pairs of lines of HI, HeI, and HeII in transitions to the ground state in the EUV; these lines usually have large optical depths, intensities, and line widths. Using the Grotrian diagrams for neon and argon [14] and original data for NeII [15], NeIII [16, 17], NeIV [18], ArI and ArII [19], ArIII [20], and ArIV [21], we selected among the large number of quasi-resonance coincidences those having the closest resonances with some permitted photon transition for Ne or Ar atoms or ions, as was done in [13].

Figures 2–5 present the RETPI schemes for Ne ions up to NeV selected in this way. There is no suitable resonance with EUV spectral lines of HeII for NeV. Thus, NeV lies at the end of the successive-RETPI chain: NeI → NeII → NeIII → NeIV → NeV. In all cases, the offset from the intermediate resonance does not exceed 1500 cm^{-1}. In the RETPI reactions NeII → NeIII and NeIV → NeV, the offset $\Delta\nu$ is very small, and we expect a shift in the ionization equilibrium toward NeIII and NeV relative to the densities of NeII and NeIV. In addition, virtually excited NeI and NeII have very low photoionization

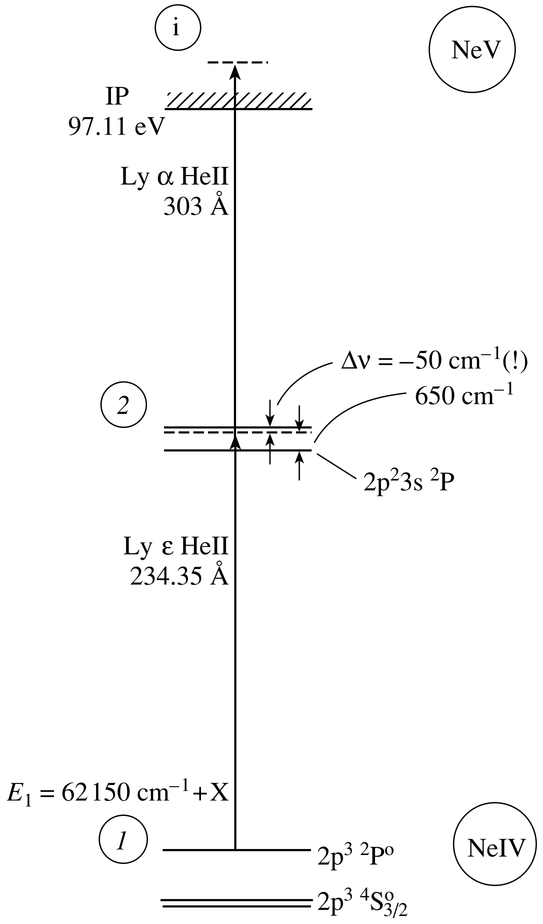

Fig. 5. RETPI scheme for NeIV → NeV.

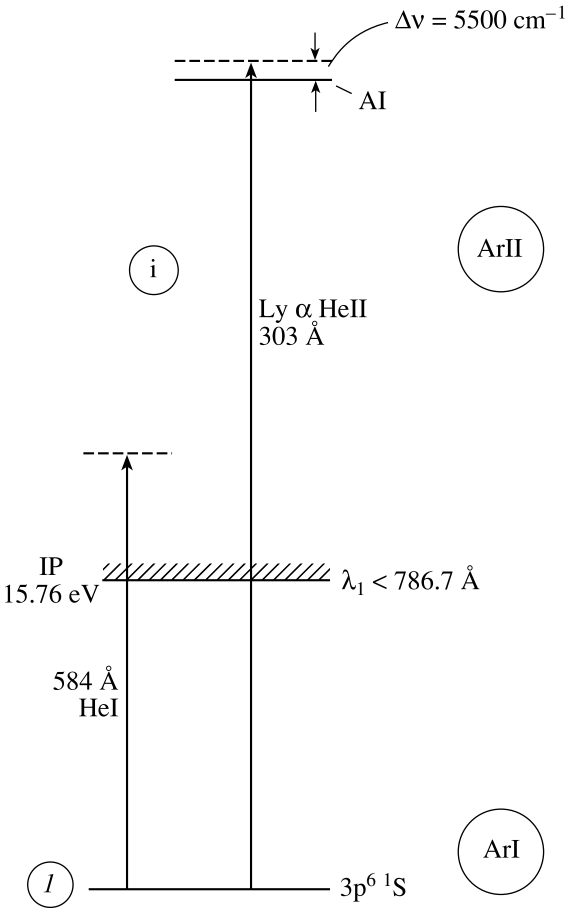

Fig. 6. RETPI scheme for ArI → ArII (AI is an autoionization state).

energies, and nearly any radiation can participate in the second RETPI stage: both radiation from within the plasma and weaker radiation, from the central star, for example. In the case of NeIV, RETPI is possible only from a low-lying excited level (see the scheme in Fig. 1b) whose position is not known precisely. In this case, the participation of electron collisions is required to excite this low-lying level, since recombinational population of the level is not possible in the absence of NeIV. This should limit the rate of formation of NeV in a plasma with a low electron density; on the other hand, the formation of NeV via RETPI requires intense optically thick Ly α and Ly ε lines of HeII, which can be radiated in a plasma with a high density of HeII and, consequently, of photoelectrons.

There are more possibilities for Ar compared to Ne. First, the photoionization of ArI can be realized via the absorption of a single EUV photon radiated by the central star, which gives rise to the photoconversion of HeI/HeII, as well as the Ly α 303 Å recombination line of HeII (Fig. 6). However, there are quite a few possibilities for RETPI of ArII, shown in Fig. 7, both with the participation of high lines of the Ly HI series (Fig. 7a) with a comparatively small offset $\Delta\nu = 180$ cm^{-1} and with the participation of the 515.6 Å, 522.2 Å, and 584.3 Å EUV lines of HeI (Figs. 7b–7d). Especially efficient is the scheme with the participation of the intense 584.3 Å line, for which the offset is very small ($\Delta\nu \simeq 40$ cm^{-1}, which can be comparable to the Doppler width of the HeI line). ArIV can be formed in two ways (Fig. 8). First, the intense 303 Å HeII line can photoionize ArIII with one photon whose energy slightly exceeds the ionization threshold. Second, RETPI can occur from a low-lying $3p^4\ ^1D$ excited state that is populated by electron collisions (the case of Fig. 1b). This is also applicable to RETPI of ArIV from low-lying excited states with small offsets $\Delta\nu$ (Fig. 9). Finally, there is a very favorable situation for the RETPI reaction ArV→ArVI (Fig. 10), which has a very small offset ($\Delta\nu = 50$ cm^{-1}). This offset is comparable to the Doppler width of the 522 Å HeI line, which is in-

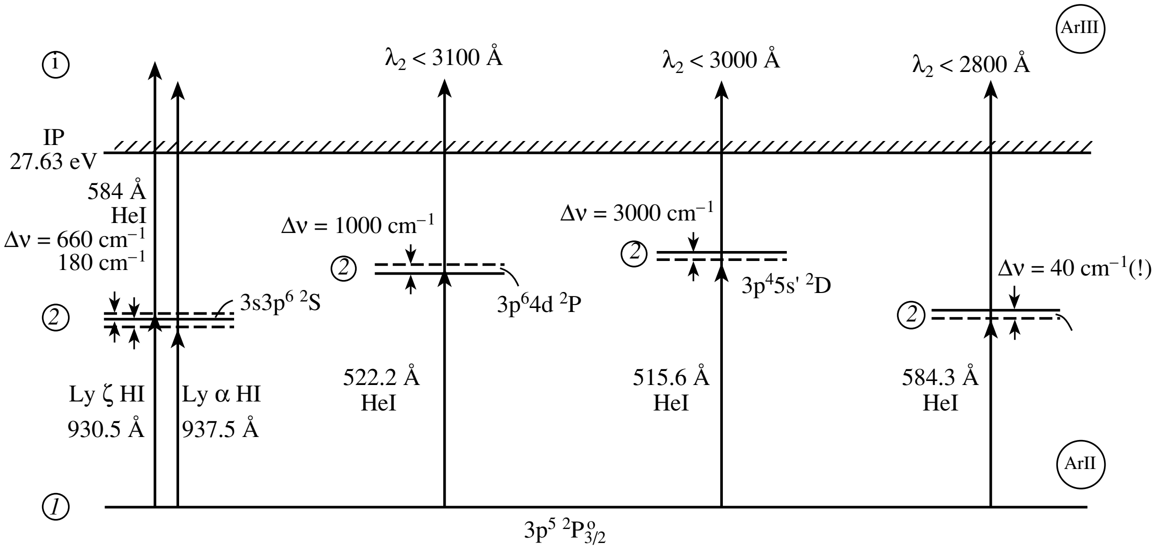

Fig. 7. Possible RETPI schemes for ArII → ArIII.

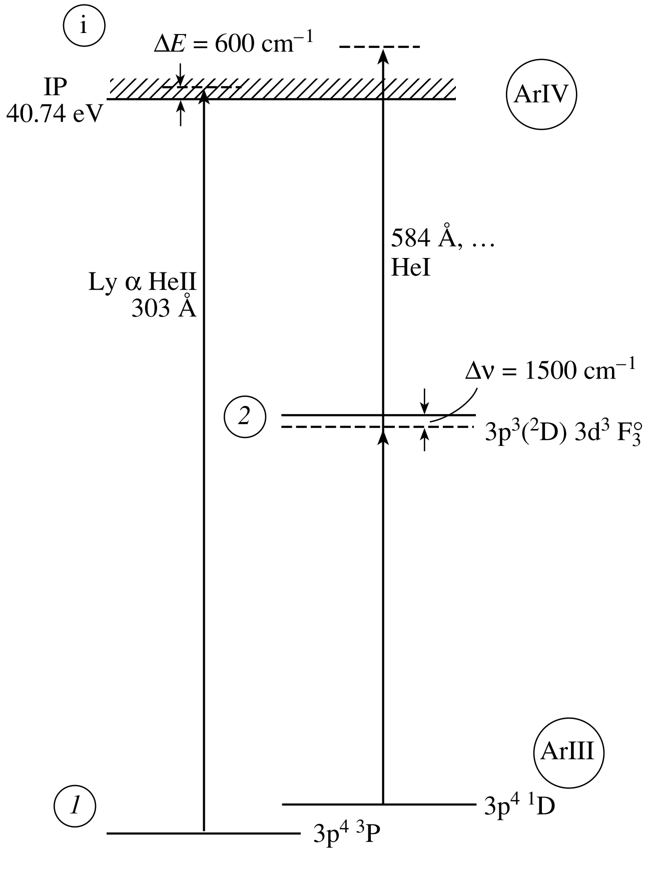

Fig. 8. RETPI process for ArIII → ArIV initiated from a low-lying excited state.

creased by Doppler diffusion of the radiation during resonance scattering [6]. Thus, in the case of Ar, the chain of successive RETPI reactions can continue right up to ArVI.

All these schemes are summarized in the table, which presents the chains of successive RETPI reactions for the atoms and ions considered under the action of radiation in one or two spectral lines with

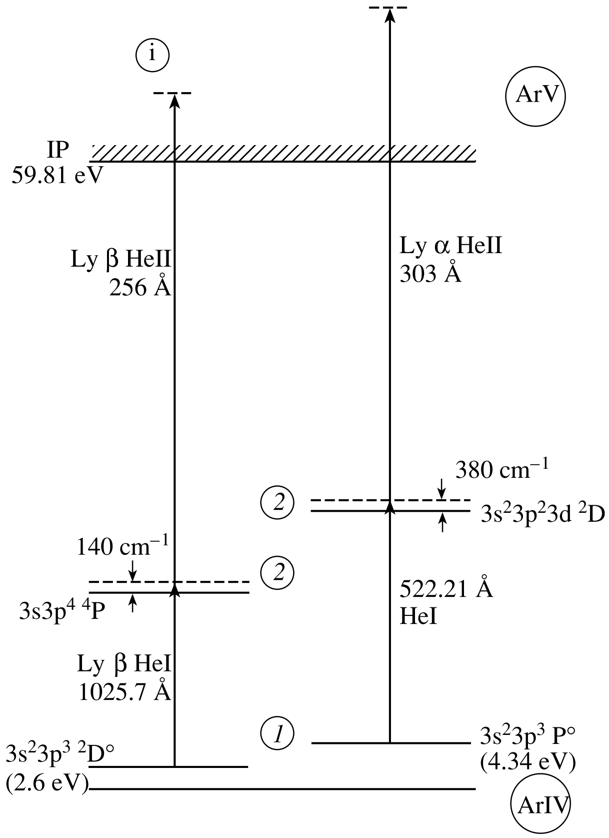

Fig. 9. RETPI process for ArIV → ArV initiated from a low-lying excited state.

progressively increasing photon energies: HI + HeI, HI + HeII, HeI + HeII, and HeII + HeII. The resulting set of successive-RETPI schemes for Ar strongly resembles that for Ne, although it includes other combinations of intense EUV spectral lines.

4. CONCLUSIONS

First and foremost, we conclude that the elementary RETPI processes we have considered should be taken into account in ionization-balance calculations for specific spectral lines, especially for radiation-rich regions. We expect some nonmonotonicity in the appearance of ions of certain multiplicities due to the existence of favorable near coincidences between the frequencies of intense exciting lines and of absorption lines of the atoms and ions. The resulting nonmonotonicity in the appearance of successive ions can lead to deviations from standard models if electron temperatures are estimated without including the effects of RETPI. The same is true in connection with estimates of the densities of elements based on emission lines that arise via the recombination of ions whose formation rate is enhanced due to RETPI of ions of some multiplicity. In contrast to electron-collisional ionization, the probability of this process displays a nonmonotonic dependence even on the effective temperature of the radiation, since $W_{1i}^{(2)}$ is sensitive to the offset $\Delta\nu$, which has various values for various ions.

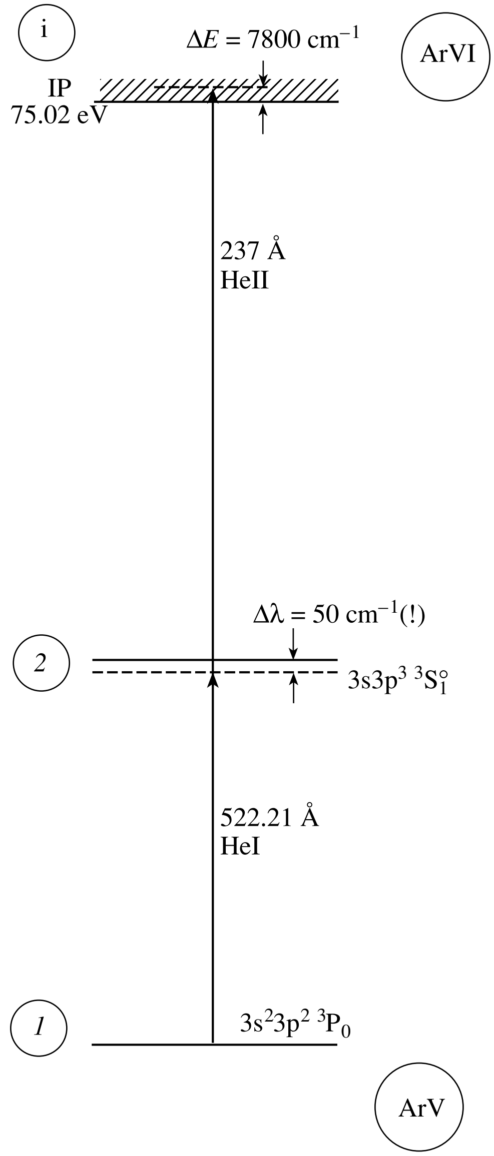

Fig. 10. RETPI scheme for ArV → ArVI with a very small frequency offset $\Delta\nu$.

Finally, we note that, strictly speaking, RETPI is a purely collisionless photon process only when the RETPI process is initiated from the ground state (Fig. 1a). However, in some of the schemes considered, the RETPI is initiated from a low-lying excited level with an energy less than a few eV (Fig. 1b). In this case, some links in the RETPI chain rely on collisions. However, it is unlikely that these links will become a bottleneck for the chain, since the cross sections for the electronic excitation of the low-lying levels are much greater than the cross sections for the electronic ionization of the corresponding ions in the

Chains of successive-RETPI schemes for Ne and Ar based on HI, HeI, and HeII lines in the far VUV

Element	Pairs of photoionizing HI, HeI, and HeII lines			
	HI + HeI	HI + HeII	HeI + HeII	HeII + HeII
Ne	NeI → NeII (21.56 eV)	NeII → NeIII (40.96 eV)	NeIII → NeIV (63.45 eV)	NeIV→NeV (97.11 eV)
	584 Å + 1215 Å	303 Å + 1215 Å	256 Å + 584 Å	234 Å + 303 Å
		NeIII → NeIV (63.45 eV)		
		237 Å + 1025 Å		
Ar	ArI → ArII (15.76 eV)	ArI → ArII (15.76 eV)	ArIII → ArIV (40.74 eV)	
	584 Å	303 Å	584 Å + 584 Å	
			303 Å	
	ArII → ArIII (27.63 eV)	ArIV → ArV (59.81 eV)	ArIV → ArV (59.81 eV)	
	930 Å + 584 Å	1025 Å + 256 Å	522 Å + 303 Å	
	584 Å + 1215 Å		ArV → ArVI (75.02 eV)	
	522 Å + 1215 Å		522 Å + 237 Å	
	515 Å + 1215 Å			

collision-dependent chain. Nonetheless, this remains a subject for a specialized analysis of specific models for ionization balance in radiation-rich astrophysical plasmas.

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REFERENCES

1. K. Davidson and R. M. Humphreys, Ann. Rev. Astron. Astrophys. **35**, 1 (1997).
2. T. Gull, private communication.
3. S. Johansson and V. S. Letokhov, Astron. Astrophys. **378**, 266 (2001).
4. V. V. Klimov, S. Johansson, and V. S. Letokhov, Astron. Astrophys. **385**, 313 (2002).
5. S. R. Pottasch, *Planetary Nebulae* (Reidel, Dordrecht, 1984).
6. D. E. Osterbrock, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (Univ. Sci. Books, Sausalito, Ca., 1989).
7. I. Robson, *Active Galactic Nuclei* (Wiley, Chichester, 1986).
8. A. V. Filippenko, Astrophys. J. **289**, 475 (1985).
9. V. S. Letokhov, *Laser Photoionization Spectroscopy* (Nauka, Moscow, 1987; Academic, Orlando, 1987).
10. N. B. Delone, *Interaction of Laser Radiation with Matter* (Nauka, Moscow, 1989) [in Russian].
11. S. Johansson and V. S. Letokhov, Science **291**, 625 (2001).
12. S. Johansson and V. S. Letokhov, Pis'ma Zh. Éksp. Teor. Fiz. **73**, 135 (2001) [JETP Lett. **73**, 118 (2001)].
13. S. Johansson and V. S. Letokhov, Astron. Astrophys. **375**, 319 (2001); Astron. Astrophys. **395**, 345 (2002).
14. S. Bashkin and J. O. Stoner, Jr., *Atomic Energy Levels and Grotrrian Diagrams* (North-Holland, Amsterdam, 1975), Vol. 1.
15. W. Persson, Phys. Scripta **3**, 133 (1971).
16. W. Persson, C.-G. Wahlström, L. Jönsson, and H. O. DiRocco, Phys. Rev. A **43**, 4791 (1991).
17. A. E. Livingston, R. Buttner, A. S. Zacarias, *et al.*, J. Opt. Soc. Am. B **14**, 522 (1997).
18. A. E. Kramida, T. Bastin, E. Bimont, *et al.*, Eur. Phys. J. D **7**, 525 (1999).
19. G. Norlin, Phys. Scripta **8**, 249 (1973).
20. J. E. Hansen and W. Persson, J. Phys. B **20**, 693 (1987).
21. F. Bredice, M. Gallardo, and J. G. Reyna Almandos, Phys. Scripta **51**, 446 (1995).

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