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Multiple two-photon resonance-enhanced ionization of elements in natural conditions: Nebulae in the vicinity of hot stars

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The possibility is considered of two-photon ionization of atomic particles with the atom (ion) level quantum being in quasi-resonance with an intense noncoherent monochromatic VUV light in natural conditions, for example, inside planetary nebulae in the vicinity of bright stars. The collisionless resonance-enhanced photoionization mechanism considered may give rise to multiply-charged ions as a result of successive (multiple) resonance-enhanced ionization of the photoions produced in a rarefied media with very low rate of the recombination.

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Although two-photon absorption was predicted by Göppert-Mayer [1] as far back as 1931, its experimental observation occurred only 30 years later [2] following the invention of laser sources of intense coherent light that led to the discovery of numerous nonlinear optical effects. Almost all of them use not only the high intensity of laser light, but also its coherence that makes it possible to accumulate nonlinear effects, specifically to generate optical harmonics [3] etc. in conditions of phase matching. Two-photon absorption, however, requires no light coherence, but substantially increases in conditions where quasi-resonance exists with some intermediate quantum level. This allows such an effect to become manifest in the case of two-photon ionization, provided that the ions produced accumulate. It is precisely this condition that can be satisfied in the rarefied medium of gas nebulae in space, where the recombination rate of the ions produced is extremely low ($10^{-5} - 10^{-8}\,\mathrm{s}^{-1}$) and where an intense VUV radiation exists at the same time on resonance transitions in hydrogen and helium.

Planetary nebulae are known borrowed energy from the star(s) immersed within them. A specific feature of planetary nebulae is the huge optical thickness in the spectral lines of transitions to the ground or metastable states. Because of this, the photons resulting from the recombination of the photoions HII (or HeII), which are being constantly produced under the effect of the ionizing radiation of the stars, repeatedly undergo resonance scattering before they leave the nebular media and thus become observable. This diffusive confinement (or trapping) effect is accompanied by the broadening of the emission line spectrum and an increase of the radiation intensity inside the nebula, and it is limited either by the decay of the photons as a result of absorption or by their escape from the spectral line because of the Doppler frequency redistribution upon their scattering by moving resonant particles [4]. These effects are most important where the optical thickness $\tau_0 \gtrsim (\Delta\omega_{\mathrm{Dopp}}/2\Gamma)^2$, where $\Delta\omega_{\mathrm{Dopp}}$ and 2Γ are the Doppler and radiative spectral line widths, respectively, because in that case the trapping effect of the Lorentzian wings of the radiative spectral contour becomes substantial. As a result, the intensity P of the trapped spectral lines reaches its maximum, i.e., the black-body radiation intensity at the corresponding wavelength λ, and can be described in terms of the effective temperature T_{eff} [4]:

$$I(\lambda, T) = \frac{8\pi}{\lambda^2}\frac{\delta\nu}{h\nu/(e^{kT_{\mathrm{eff}}}-1)}\ [\mathrm{photons/cm^2\cdot s}], \qquad (1)$$

where $\delta\nu$ is the spectral line width [in Hz]. For example, for Ly_αIII ($\lambda = 1215\,\text{Å}$) at $T_{\mathrm{eff}} = 15\cdot 10^3\,\mathrm{K}$ and $\delta\nu \cong 250\,\mathrm{cm}^{-1}$, the intensity $I \cong 6\cdot 10^{20}\,\mathrm{photons/cm^2\cdot s}$, which corresponds to $10^3\,\mathrm{W/cm^2}$ of CW VUV radiation, a figure as yet unattainable, the present-day laser technology status being what it is. So high a radiation intensity at a comparatively small occupation number of the photon quantum state $\langle n\rangle \cong 5\cdot 10^{-4}$ is explained by the large number of free space states within the limits of a solid angle of 4π steradians and the large spectral width $\delta\nu$.

The high intensities of the noncoherent but relatively monochromatic radiation (as compared with black-body radiation) originating inside nebulae are quite sufficient to give rise to such nonlinear effects without

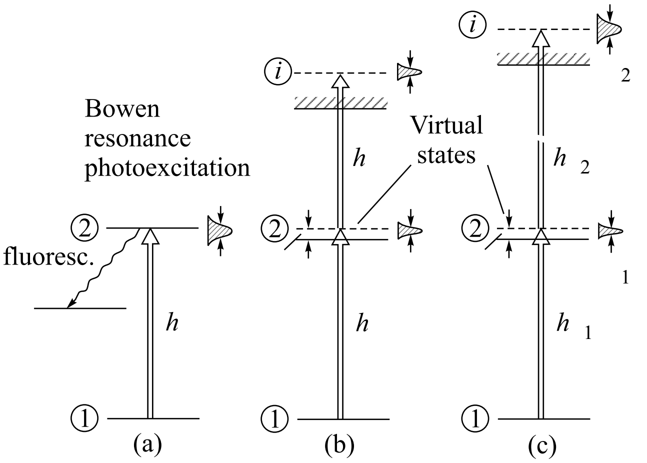

Fig.1. (a) Resonance fluorescence excitation by the Bowen mechanism and various schemes of (b) one-color and (c) two-color resonance-enhanced two-photon ionization

requirement of spatial coherence of the radiation, or the corresponding phase matching. The relative monochromaticity of the trapped radiation is especially favorable to the nonlinear effects sensitive to resonance with the radiation frequency. The accidental resonance effect was already successfully used by Bowen [5] to explain the abnormally bright OIII lines as resulting from their photoselective excitation by the intense 303-Å line of Ly_αHeII. However, such a one-photon resonance excitation requires that the atomic transition should be in exact resonance with the photon frequency, since the energy difference cannot be transferred to some third partner in the very rarefied nebular media (Fig.1a). This mechanism proves effective where the transfer radiation broadening can provide for the necessary resonance with the absorption line. The situation with resonance-enhanced two-photon transition to the ionization continuum (Fig.1b) is more favorable. In that case, the energy difference $h\Delta\nu$ may be much greater than $h\delta\nu$, as it is offset by the change of the kinetic energy of electrons upon their bound–free transitions through intermediate virtual states to the ionization continuum. When the frequency detuning $\Delta\nu$ is much greater than $\delta\nu$, the two-photon rate (in s^{-1}) is expressed as

$$W_{ph}^{(2)} \cong (2\pi)^{-3}\frac{g_2\lambda^2\sigma_{2i}}{g_1(\Delta\nu)^2}A_{21}I^2, \qquad (2)$$

where σ_{2i} is the cross section for photoionization from the real excited state *2* at a wavelength of λ, g_i is the statistical weight of i-th level, A_{21} is the Einstein coefficient for the *1–2* transiton, $\Delta\nu \gg \delta\nu$ is the detuning of the radiation frequency with respect to the exact resonance frequency (in Hz), and the intensity I of the isotropic radiation within the limits of the spectral width $\delta\nu$ is defined by expression (1). If the energy of photons of the same frequency $h\nu$ is not sufficient to photoionize the excited state, the second step of the two-photon process can quite well be effected by photons of higher energies associated with other trapped lines, such as HeI and HeII (Fig.1c). In that case, the two-color two-photon process will be effected by the bichromatic isotropic radiation of two trapped spectral lines at frequencies ν_i and with spectral widths $\delta\nu_i$, intensities I_i defined by expression (1), and effective temperatures T_{eff}. The rate of the two-color two-photon process is described as before by expression (2) wherein the product I_1I_2 is substituted by I^2.

For a typical case of Ly_αHI at $\sigma_{2\iota} \cong 10^{-17}\,\text{cm}^2$ and $A_{21} \cong 10^9\,\text{s}^{-1}$ and a typical spectral width of $\delta\nu \cong 300\,\text{cm}^{-1}$ and $\Delta\nu \cong 1000\,\text{cm}^{-1}$, the rate $W_{ph}^{(2)}$ at $T_{\text{eff}} \cong 15\cdot10^3\,\text{K}$ reaches $10^{-7}\,\text{s}^{-1}$. This value is very small for laboratory experiments [6], but is quite substantial under nebular conditions wherein the recombination rate W_{rec} is very low. At $W_{ph}^{(2)} > W_{\text{rec}}$, there takes place the accumulation of photoions of the next ionization degrees. As an illustration, Fig.2 presents a chain of successive (multiple) two-photon resonance-enhanced ionization schemes for carbon atoms up to multicharged ions CV exposed to intense lines of HI, HeI, and HeII. Similar multiple ionization schemes are also valid for NI→NV, OI→OV, NeI→NeV, and ArI→Ar VI, which will be discussed in an individual publication in a specialized journal.

In addition, $W_{ph}^{(2)}$ can perceptibly exceed the collisional electron ionization rate W_e, and this will intensify the corresponding recombination lines that are frequently interpreted within the framework of the electron ionization mechanism as being the result of an anomalous abundance of the element.

We would like to emphasize in conclusion that two-photon ionization is a purely photonic mechanism requiring no collisions. For this reason, it is especially effective in conditions of space with low electron concentrations, whose extent is great enough to form strong optically thick emission spectral lines of HI, HeI, and HeII. The manifestations of the above mechanism in the emission spectra of nebulae will be discussed in detail in a special astrophysical journal. In this paper, we have restricted ourselves to the consideration of the manifestation of the *nonlinear optical effect in natural conditions*. It should be noted that the possibility of occurrence of nonlinear optical effects under astrophysical conditions, specifically in stellar

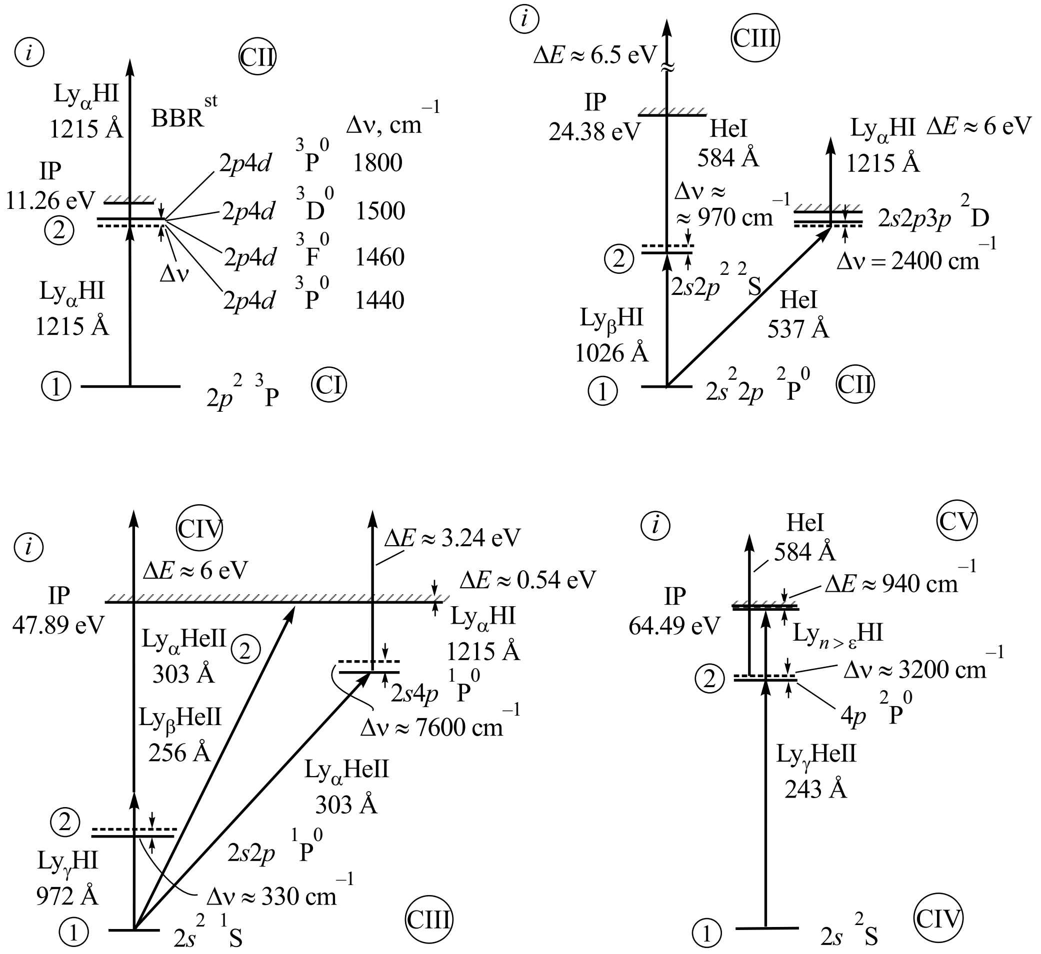

Fig.2. Schemes of the successive (multiple) resonance-enhanced two-photon ionization of carbon atoms and ions up to CV by intense lines of HI, HeI, and HeII

atmospheres, was generally discussed by Vavilov [7] as far back as 1950.

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