Diffusion ionization of Rydberg atoms due to black-body radiation

B. P. Kaulakis
Institute of Physics, Academy of Sciences of the Lithuanian SSR

(Submitted 1 February 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 6, 300–302 (25 March 1988)

Black-body radiation is found to cause a diffusion ionization of Rydberg atoms even at room temperature. The probability for the ionization of these atoms is determined and the conditions under which this process occurs are found.

It was only recently established that the ubiquitous black-body radiation plays an important role in the spectroscopy of Rydberg atoms even at room temperature.[1,2] Black-body radiation causes shifts in the energy of atomic levels,[2] induces transitions between atomic states,[2] causes photoionization of Rydberg atoms,[3] and affects the population of highly excited states in the recombination of ions.[4,5] We will show that black-body radiation also causes diffusive ionization of Rydberg atoms and ions. Under certain conditions, the principal condition among which is the collision-induced mixing of levels in l, the diffusion process resulting from black-body radiation is the basic mechanism for the ionization of Rydberg atoms.

Let us consider a production of Rydberg atoms or ions at a steady rate γ with an energy $\epsilon_0 = Z^2 2n_0^2$ (Z is the core charge) in a Planckian field with a temperature T. The function $f(\epsilon)$ for the distribution of electrons in the energy space ϵ of Rydberg atoms is given by the balance equation

$$\int_0^{\epsilon_t} (f(\epsilon') K_{\epsilon',\epsilon} - f(\epsilon) K_{\epsilon,\epsilon'}) d\epsilon' - f(\epsilon)[w_q(\epsilon) + w_i(\epsilon)] + \gamma\delta(\epsilon - \epsilon_0) = 0. \quad (1)$$

Here $K_{\epsilon,\epsilon'}$ and w_i are respectively the rate of the $\epsilon \to \epsilon'$ transition and the rate of direct ionization of Rydberg atoms as a result of black-body radiation, and w_q is the rate of radiation quenching of Rydberg atoms to lower states with $\epsilon > \epsilon_t \approx (ZT)^{2/3}/2$ [the states with $\epsilon > \epsilon_t$ do not participate in the ionization, since the rate of their spontaneous quenching is greater than the total rate of the induced transitions, $w_q(\epsilon) > w_b(\epsilon) = \Sigma_{n'} K_{\epsilon,n'}$. According to the results of Refs. 2 and 4–6, we have

$$K_{\epsilon,\epsilon'} = W_{\epsilon,\epsilon'} e^{(\epsilon'-\epsilon)/T} \Big/ \left(e^{(\epsilon'-\epsilon)/T} - 1\right), \quad W_{\epsilon,\epsilon'} = 2^{5/2} A_0 \epsilon^{5/2} / Z^5 (\epsilon' - \epsilon),$$

$$\epsilon' > \epsilon, \quad w_q = \tau^{-1} \epsilon^{5/2}, \quad \tau^{-1} = 4\sqrt{2} A_0 Z^{-5} \ln(\epsilon_g / \epsilon_t),$$

$$w_i = 4\sqrt{2} A_0 Z^{-5} T e^{-\epsilon/T} \epsilon^{3/2} \Phi(\epsilon/T), \quad w_b = (2\pi^2 A_0 / 3Z^4) T\epsilon,$$

where $W_{\epsilon,\epsilon'}$ is the probability for a spontaneous transition $\epsilon \to \epsilon'$ in the Kramers approximation, $A_0 = 8\alpha^3 Z^4 / 3\sqrt{3}\pi$, α is the fine-structure constant, ϵ_g is the ground-state energy, and $\Phi(x)$ is a slowly varying function $[\Phi(x)\to 1$ as $(x)\to 0$ and $x\to\infty$; $\Phi_{\min}\approx 0.78$ with $x_m\approx 1.5$ (Ref. 5)]. The inequalities $w_i(\epsilon)\ll w_q(\epsilon)\ll w_b(\epsilon)$ are satisfied over a broad energy range $0.2T\ll\epsilon\ll\epsilon_t$. This means that the electron redistribution in the energy space of Rydberg atoms and the ionization of Rydberg atoms can be taken into account in the diffusion approximation.[7,8] We derive from Eq. (1) in the usual way[7,8] the Fokker-Planck equation which can be written, by analogy with Refs. 9 and 10, in the form

$$\frac{d^2\varphi}{d\epsilon^2}+\frac{1}{T}\frac{d\varphi}{d\epsilon}-\frac{1}{\kappa T}\varphi=-\frac{\gamma}{\kappa}e^{-\epsilon/T}\delta(\epsilon-\epsilon_0). \quad (2)$$

Here $\varphi(\epsilon)=f(\epsilon)/f_0(\epsilon)$, and $f_0(\epsilon)=\epsilon^{-5/2}e^{\epsilon/T}$ is the equilibrium distribution. We used the expression for electron diffusion in the energy space of Rydberg atoms

$$B(\epsilon)=\frac{1}{2}\int K_{\epsilon,\epsilon'}(\epsilon'-\epsilon)^2 d\epsilon'=\kappa\epsilon^{5/2},\quad \kappa=2\sqrt{2}\pi^2 A_0 T^2/3Z^5.$$

By solving Eq. (2) with the boundary condition $\varphi(0)=0$ corresponding to the ionization process we obtain the expression for the ionization probability

$$P_i=e^{-\epsilon_0/\epsilon_p},\qquad \epsilon_p=2T\Big/\left(1+\sqrt{(24/\pi^2)\ln(\epsilon_g/\epsilon_t)+1}\right). \quad (3)$$

The probability for the ionization of Rydberg atoms by thermal radiation thus depends exponentially on the initial electron binding energy and on the radiation temperature (Fig. 1).

The collision-induced ionization of Rydberg atoms of cesium in an intrinsic gas was studied by Herrmann *et al.*[11] They found that the ionization probability depends

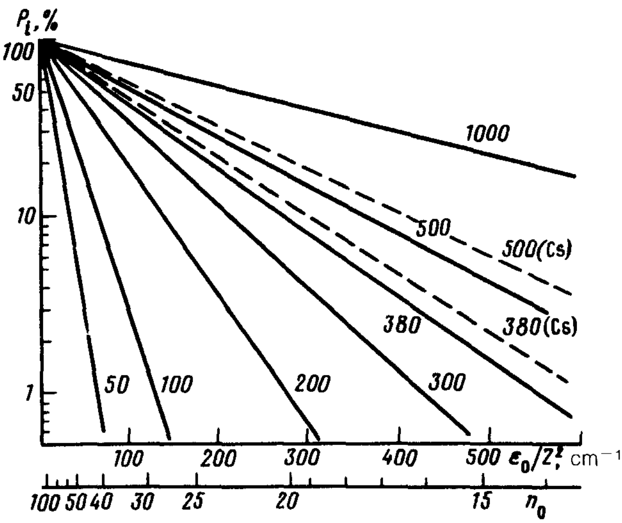

FIG. 1. Ionization probability P_i versus the binding energy ϵ_0 of an electron of the Rydberg atom or ion at various temperatures T of the Planck field. Solid curves—Hydrogenlike atom; dashed curves—cesium atom. The labels on the curves denote T/Z^2 K.

exponentially on the excitation energy ϵ_0 of Rydberg atoms. For ground-state cesium-atom densities $N_g \gtrsim 2\times 10^{13}$ cm^{-3} the observed phenomenon can be explained in terms of the diffusion mechanism for the collision-induced ionization.[10] In the limit $N_g \to 0$ an ionization probability of the type in (3) with $\epsilon_p \approx (137 \pm 3)$ cm^{-1} was obtained at $T = 380$ K by Herrmann *et al.*[11] According to (3), we find $\epsilon_p \approx 0.5T = 133$ cm^{-1} ($\epsilon_g = 3.14\times 10^4$ cm^{-1}, $\epsilon_t = 1.24\times 10^3$ cm^{-1}, and $Z = 1$). We see that the observed phenomenon can be explained in terms of the diffusion ionization resulting from thermal radiation.

The electron diffusion due to the black-body radiation can occur in the energy space of Rydberg atoms if the filling of the levels in l is mixed in a time corresponding to the lifetime of Rydberg atoms $\tau_{nl} \approx 3(l + 1/2)^2 n^3/2\alpha^3$. As a result of collision with atoms and molecules, the cross sections for the mixing of states with different l are large (on the order of the geometric cross section of Rydberg atoms at $n \leqslant 20$ and reach a value of 10^{-11} cm^2 at $n \geqslant 20$–30).[2] Consequently, the states with different l mix as a result of collisions at the densities $N_g \gtrsim 10^{10} - 10^{11}$ cm^{-3}. Other mechanisms of l mixing are also possible: collisions with electrons and ions, collisions with the electric field, and so forth. On the other hand, the collision-induced ionization can compete with the ionization due to black-body radiation only at densities $N_g \gtrsim 10^{13} - 10^{14}$ cm^{-3}. Accordingly, there is a broad range of conditions under which the process which we have studied is the principal mechanism for the ionization of Rydberg atoms and ions.

I wish to thank I. L. Beĭgman and L. P. Presnyakov for useful discussions.

[1]T. F. Gallagher and W. E. Cooke, Phys. Rev. Lett. **42**, 83 (1979).
[2]Rydberg States of Atoms and Molecules, Mir, Moscow, 1985, p. 496.
[3]W. P. Spencer *et al.*, Phys. Rev. **A26**, 1490 (1982); C. F. Burkhardt *et al.*, Phys. Rev. **A34**, 80 (1986).
[4]A. Burges and H. P. Summers, Mon. Not. R. Astr. Soc. **174**, 345 (1976).
[5]I. L. Beĭgman and R. A. Syunyaev, Preprint FIAN, No. 163, 1978.
[6]L. A. Vaĭnshteĭn, I. I. Sobel'man, and E. A. Yukov, Excitation of Atoms and Spectral Line Broadening, Nauka, Moscow, 1979, p. 319.
[7]E. M. Lifshitz and L. P. Pitaevskiĭ, Physical Kinetics, Pergamon Press, Oxford (1981).
[8]K. V. Gardiner, Stochastic Methods in Natural Sciences, Russ. transl. Mir, Moscow, 1986, p. 528.
[9]B. P. Kaulakis, A. R. Chizhyunas, and V. I. Švedas, Lithuanian Phys. J. **24**, 48 (1984).
[10]B. Kaulakys and V. Švedas, J. Phys. **B20**, L565 (1987).
[11]P. P. Herrmann *et al.*, J. Phys. **B19**, 1675 (1986).

Translated by S. J. Amoretty