Long-lived Stark states detected at a positive energy

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(Submitted 9 October 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **44**, No. 10, 457–459 (25 November 1986)

Stark states have been detected at a positive energy in a numerical calculation. The energy-level width of these states is less than the spacing between the levels. The existence of such states accounts for the resonant structure of the spectrum of photoionization in an electric field at energies higher than the ionization threshold.

According to the classical model of atomic ionization in a uniform electric field, the threshold field vanishes at zero-point energy, so that there can be no bound states at a positive energy E. The available results of quantum-mechanical calculations carried out for negative energy also rule out any conclusions that can be drawn regarding the long-lived states at $E>0$. The observation of resonances at $E>0$ in the cross section of photoionization in an electric field initially in rubidium[1] and later in a hydrogen atom[2,3] was therefore surprising to some extent.[4] In all experiments the resonant structure was observed only in the case of π polarization of laser light, i.e., when the electric field of the light wave was parallel to the vector of the uniform field. In the case of perpendicular polarization, (the σ polarization), no resonances were observed for positive energy. The second peculiarity of the cross section for photoionization at $E>0$ is the increase in the resonance width, in the distance between resonances, and in the modulation depth as a result of the increase in the electric field strength. This phenomenon was explained in several ways, some attempting to establish a connection between the resonances in the photoionization spectrum and the existence of relatively long-lived states at a positive energy[1,5] and some rejecting this connection.[6]

A numerical calculation of highly excited, nearly steady states of the hydrogen atom in a uniform electric field can uniquely resolve the controversy regarding the causes of the resonances in the photoionization spectrum at $E>0$ and qualitatively explain all the peculiarities of this phenomenon. The numerical methods which use the Breit-Wigner parametrization to determine the energy E and the level width Γ are effective enough at $|E| \gg \Gamma$ (Ref. 7). They do not allow, however, to trace the transition from negative energies to positive energies, since they lead to an unacceptably large error near $E=0$, even when the value of Γ is relatively small. We have therefore used a method of numerically calculating complex energy eigenvalues which makes use of the "radiation condition," i.e., which takes advantage of the absence of a converging component in the asymptotic expression for the wave function at infinity.[8]

The results of a numerical calculation for two values of the field strength F used experimentally in Ref. 2 are presented in Table I. The values of the energy E and of the level widths Γ are given in atomic units. The states are given by the parabolic quantum numbers, n_1 and n_2, and by the magnetic quantum number m ($n_1+n_2+m+1=n$).

ABLE I .

n, n_1, n_2, m	$F = 6.5$ kV/cm		$F = 8.0$ kV/cm	
	$E \times 10^4$	$\Gamma \times 10^4$	$E \times 10^4$	$\Gamma \times 10^4$
24, 23, 0, 0	0.11915	0.27521	1.9494	0.52426
25, 23, 1, 0,	0.27481	1.0868	2.0395	1.6812
25, 23, 0, 1	0.82980	0.74844	2.6980	1.1876
25, 24, 0, 0	1.4329	0.41753	3.3825	0.63808
26, 24, 1, 0	1.5228	1.3658	3.4327	1.9547
26, 24, 0, 1	2.0872	0.96356	4.0898	1.3689
26, 25, 0, 0	2.6872	0.52149	4.7640	0.71933

The calculation results show that for the most long-lived states with a given n, i.e., for states with $n_2 = m = 0$, the width of the energy levels is markedly narrower than the spacing between them. These states are populated most effectively by a π-polarized light ($\Delta m = 0$) in the transitions from the states with $n_1 - n_2 = \max$, $m = 0$. A π-polarization-induced photoionization from these states should therefore give rise to clearly defined resonances whose positions at $E > 0$ are determined by the energy of the nearly steady states with $n_2 = m = 0$. Since the width of the levels with $n_2 = 1$ and $m = 0$ for the values listed in Table I is greater than the spacing between them, the levels with $n_2 \gtrsim 1$ should overlap each other and should not appreciably affect the position of the resonances in the photoionization cross section. The absence of a resonant structure in the σ polarization ($\Delta m = 1$) stems, on the one hand, from the fact that the levels of the most long-lived states with $m = 1$ (the states with $n_2 = 0$, $m = 1$) are, at $E > 0$, nearly twice as wide as the corresponding levels with $n_2 = m = 0$. On the other hand, in the case of σ polarization of light, the dipole matrix

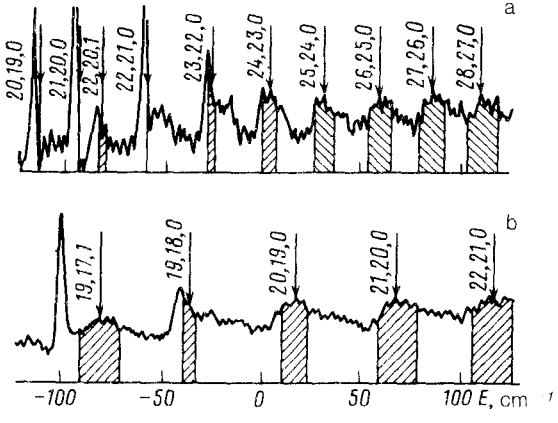

FIG. 1. Spectrum of the photoionization of a hydrogen atom in an electric field F. a) $F = 6.5$ kV/cm; b) $F = 14.4$ kV/cm. The arrows indicate the energies of the Stark states n, n_1, and n_2 ($m = 0$) obtained in the numerical calculation. The width of the hatched bars corresponds to the width of these levels.

elements for the transitions to such "extreme" relatively long-lived states are small, while the states with $n_1 \approx n_2$, whose width of the energy levels at $E > 0$ is much greater than the spacing between them, are populated most effectively.

The results of a numerical calculation of E and Γ for the long-lived Stark states are plotted in Fig. 1 in the experimental spectrum of hydrogen photoionization. This spectrum was recorded near the ionization threshold in the laser-induced π polarization.[2] We see that at $E > 0$ the positions of the experimental peaks coincide with the energy of the quasisteady states with $n_2 = m = 0$. As the strength of the electric field is increased, lower-lying levels with a lower value of n fall into the energy region near $E = 0$ which is studied experimentally. As can be seen from the results presented in Table I and in Fig. 1, the spacing between the levels increases faster than their width. As a result, the modulation depth in the photoionization spectrum may increase with increasing field.

In conclusion, we should mention that the notion of the existence of "nonoverlapping" Stark states at a positive energy may also be helpful in the quest of a more thorough understanding of other physical processes such as the excitonic photoabsorption in semiconductors.

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Translated by S. J. Amoretty