Experimental observation of a photoresonance of electrons localized above the surface of solid hydrogen

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The $1 \to 2$ and $1 \to 3$ photoresonance transitions have been observed in the spectrum of electrons localized above the surface of solid hydrogen. The transition frequencies in the spectrum are observed to depend on the pressure of the gaseous phase of hydrogen. This dependence can be attributed to a "quantum refraction." In the limit of a zero density of hydrogen molecules in the gas, the frequency of the $1 \to 2$ transition is 3.2 ± 0.1 THz.

The states of electrons localized above the surface of liquid helium have been studied quite thoroughly.[1] In the simplest model, the potential of the interaction of an electron with a surface is determined by electrostatic image forces and by the external clamping field E_z:

$$U(z) = e^2(1-\epsilon)/4z(1+\epsilon) - eE_z z \equiv - Qe^2/z - eE_z z \quad \text{at} \quad z>0,$$

$$U(z) = U_0 \quad \text{at} \quad z \leqslant 0,$$

where ϵ is the dielectric constant of the liquid helium, and the z axis is directed along the normal from the surface. The solution of the Schrödinger equation with such a potential leads in the limit $U_0 \to \infty$ to the following electron energy spectrum:

$$W_n = - Q^2 me^4/2\hbar n^2 - eE_z \langle z_n \rangle + P_{xy}^2/2m.$$

The last term in this expression corresponds to the free motion of the electron along the surface, and $\langle z_n \rangle = 3n^2\hbar^2/2me^2Q$ is the average distance from the electron to the surface in energy level n.

Similar electron states have been observed above the surfaces of insulators other than helium.[2] However, there has been no direct observation of a discrete nature of the electron spectrum for any insulator other than helium. The spectrum of electrons above the surface of solid hydrogen is particularly interesting because of Khaĭkin's suggestion of the possible existence of large-radius negative hydrogen ions.[3]

We have been able to observe a resonant optical absorption corresponding to $1 \to 2$ and $1 \to 3$ transitions in the spectrum of electrons localized above the surface of solid hydrogen. The spectroscopy was carried out at the wavelengths 78, 84 and 108 μm of a water-vapor laser.[4] The electron spectrum is changed by varying the field E_z, which clamps the electrons to the surface.

The hydrogen crystal is grown between two electrodes, 30 mm in diameter, oriented horizontally, and positioned 2.3 mm apart. The surface of the crystal lies roughly halfway between these electrodes. The upper electrode is a grid transparent to the

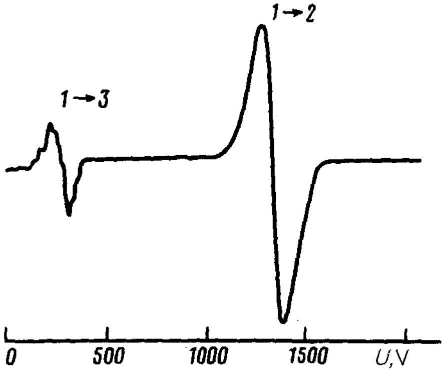

FIG. 1. Recording of the photoresonance signal at the wavelength 84 μm as the potential of the lower electrode is scanned. The 1→2 and 1→3 resonance transition can be seen. The hydrogen vapor pressure is 40 torr. The sensitivity of the measurements in the recording of the 1→3 transition was 2.5 times higher than that for the 1→2 transition.

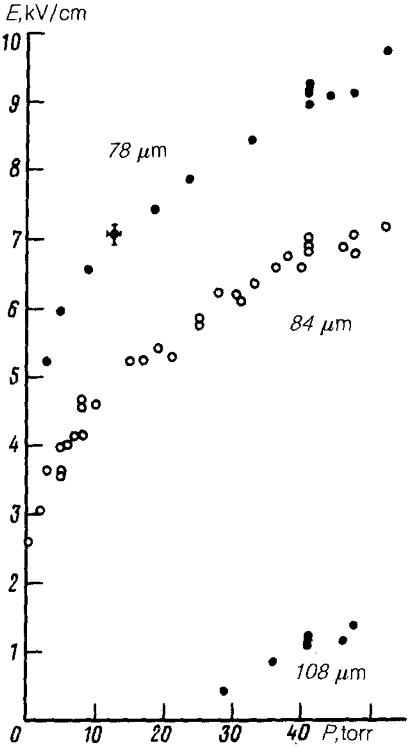

FIG. 2. Dependence of the field E_z at resonance on the hydrogen vapor pressure in measurements at the three laser wavelengths. The upper family of points corresponds to measurements at the wavelengths 78 μm; the family in the middle corresponds to 84 μm; and the lower family corresponds to 108 μm.

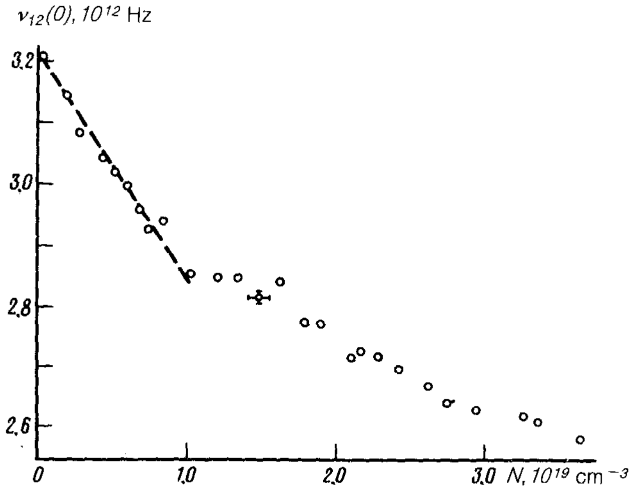

FIG. 3. Frequency of the 1→2 transition in a zero clamping field versus the density of hydrogen molecules in the gas phase.

laser radiation. The radiation passes through the windows of the optical cryostat to the surface of the hydrogen crystal, above which electrons are localized. After this radiation is reflected from the surface, it is detected by a photodetector.

In order to achieve a high relative sensitivity ($\sim 0.01\%$) in the measurements of the optical absorption by the electrons, we measure a quantity proportional to the derivative of the absorption signal at the frequency of a slight modulation of the clamping field. Figure 1 shows a recording from one of the experiments. While recording the photoresonance signal, we also measured the charge density at the surface of the hydrogen. Measurements of the potential of the lower electrode at resonance for various charge densities yielded the thickness of the crystal and the values of the field E_z at resonance.

The results show that the electron energy levels depend strongly on the pressure of the gaseous phase of the hydrogen. Figure 2 shows the measured dependence of the field E_z at resonance on the hydrogen vapor pressure at the three laser wavelengths. This behavior can be attributed to a "quantum refraction,"[5,6] which has not previously been observed in electron systems of this sort.

Figure 3 shows the dependence of the 1→2 transition frequency on the density (N) of hydrogen molecules in the gas phase, normalized to a zero clamping field. The initial linear region here correpsonds to densities at which the conditions $\langle z_1\rangle \ll N^{-1/3} \ll \langle z_2\rangle$ hold. As Fermi has shown,[5] the transition frequency increases by an amount $\hbar aN/m$, where a is the scattering length for the s-wave scattering of an electron by the hydrogen molecule. Our data yield $a = -3.1 \pm 0.4$ Å.

In the limit of a zero density of hydrogen molecules in the gas, the frequency of the 1→2 transition is found to be 3.2 ± 0.1 THz, or 32% higher than the value calculated from the simple model in the limit $U_0 \rightarrow \infty$.

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