Quantum refraction in gaseous H_2, D_2, Ne, and He for electrons levitating above the surface of crystalline hydrogen, deuterium, and neon

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(Submitted 12 April 1987)
Zh. Eksp. Teor. Fiz. **94**, 307–317 (January 1988)

The photoresonance 1 → 2 transition for electrons floating in a gas above the surface of a dielectric is investigated. It is demonstrated that the quantum-refraction theory can be used to explain the dependence of the transition frequency on the gas pressure. The results of the experiment confirm the negative value previously obtained by the authors [Sov. Phys. JETP **65**, 194 (1987)] for the scattering length of an electron by a hydrogen molecule.

INTRODUCTION

We have previously[1,2] reported the first observation of resonance absorption of light, for 1 → 2 and 1 → 3 transitions in the spectrum of electrons levitating above the surface of solid hydrogen. The water-vapor spectroscopy was carried out at wavelengths ~79, 84, and 108 μm. The electron spectrum was changed by varying the electric field $\mathscr{E}$ pressing the electrons to the surface. The experimental setup and the measurement procedure are described in detail in Ref. 2. The properties of similar electron systems are described in Ref. 3.

The essential result of Ref. 2 is observation of a dependence of the transition frequencies in the electron spectrum on the hydrogen vapor pressure. This dependence can be attributed to quantum refraction[4] if the length for scattering of an electron by a hydrogen molecule is taken to be $L = -1.4$ Å, which differs in magnitude and sign from the generally accepted $+0.672$ Å.[5] The difference in sign is fundamental, for were it confirmed it would lead to far-reaching consequences. In fact, a negative scattering length would mean that the dependence of the $e \to H_2$ scattering length on energy has a Ramsauer minimum and in the limit of zero collision energy the electron is effectively drawn to the hydrogen molecule.

Analysis of the available literature sources (see, e.g., Refs. 5 and 6) has shown that the generally accepted L was obtained by extrapolating high-temperature (compared with the energy of the molecule's rotational quantum) experimental and calculated data, and cannot in our opinion be regarded as absolutely reliable.

To cast light on the subject, we have performed additional experiments whose results are reported in the succeeding section of this article. We have first verified experimentally that the results of Ref. 2 are independent, within the limits of measurement accuracy, to the ratio of ortho- and para-hydrogen as monitored by the vapor pressure at the triple point. Next, all the measurements described in Ref. 2 were repeated for electrons levitating above solid deuterium and neon surfaces. Furthermore, we measured the shift of the resonance frequency ν_{12} for electrons levitating over solid hydrogen and deuterium following injection of helium gas into the system. The data obtained for deuterium, recalculated in the framework of a model assumed by us from very simple scaling considerations, agree well with the results of the experiments with hydrogen and allow us to state that the lengths for electron scattering by hydrogen and deuterium molecules are equal within the limits of experimental error. The lengths for electron scattering by neon and helium atoms, determined from experiment by the same procedure, agreed within measurement accuracy with the generally accepted values. This favors the negative lengths we obtained for scattering of electrons by hydrogen and deuterium molecules. Finally, the measurement dependences of the photoresonance linewidth on the gas density provide additional information that confirms the model.

ENERGY LEVELS FOR AN ELECTRON IN A GAS ABOVE A DIELECTRIC SURFACE

The potential energy of an electron in a gas above the surface of a solid dielectric can be expressed in the form

$$\varphi = U(z) + e\mathscr{E}z + \sum_{\zeta} u(\bar{r} - \bar{R}_{\zeta}), \tag{1}$$

where the z axis is perpendicular to the surface and $\bar{r}-\bar{R}_{\zeta}$ is the coordinate of the ζth gas molecule relative to the electron.

The first and predominant term of (1) describes, at $z > 0$, the electrostatic attraction of the electron to the dielectric; at distances large compared with the dielectric crystal-lattice period it has the form of a Coulomb potential. At $z < 0$ the term $U(z)$ represents a barrier preventing the electron from penetrating into the dielectric. As the simplest approximation for φ one can assume

$$\varphi^0 = U^0(z) = -\frac{Qe^2}{z} \equiv \frac{\varepsilon - \varepsilon_1}{4\varepsilon_1(\varepsilon + \varepsilon_1)} \frac{e^2}{z} \quad \text{for } z > 0, \qquad \varphi^0 = \infty \quad \text{for } z \leqslant 0, \tag{2}$$

where e is the elementary charge, ε the dielectric constant of the dielectric, and ε_1 the dielectric constant of the gas surrounding the electron. In the experiment, when the gas-molecule density is $n < 10^{20}$ cm^{-3}, we put $\varepsilon_1 = 1$ and disregard (with an error < 1%) the dielectric contribution of the gas to the energy of the electronic states. It is necessry at the same time to take into account the temperature correction to ε, necessitated by the thermal expansion of the dielectric. Figure 1 shows the relative changes of the molar volumes v of hydrogen, deuterium or neon in the solid phase as function of their saturated-vapor density.[8,9] From the Clausius-Masotti relation we have $\Delta Q/Q = -\Delta v/v$. It is known that solution of the Schrödinger equation with a potential φ^0 yields the following values for the energy levels:

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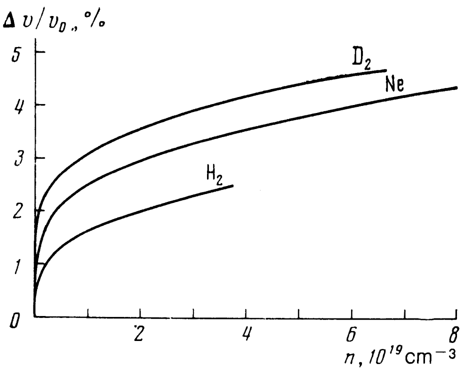

FIG. 1. Relative change of the molar volume v of solid hydrogen, neon, or deuterium vs the density of the corresponding equilibrium gas phase.

$$E_i^0 = -\frac{Q^2e^2}{2a_0 i^2} + \frac{p_\parallel^2}{2m}, \quad i=1,2,3,\ldots, \tag{3}$$

where $a_0 = \hbar^2/me^2 = 0.529$ Å is the Bohr radius, and the second term corresponds to free motion of the electron along the surface. In the same approximation, the average distance of the electron from the surface is

$$\langle z_i^0\rangle = \frac{3}{2}\frac{a_0}{Q} i^2. \tag{4}$$

The second term in (1) takes into account the external (needed in the experiment) clamping electric field $\mathscr{E}$ perpendicular to the surface. In first-order perturbation theory this field adds an increment $e\,\mathscr{E}\langle z_i^0\rangle$ to the energy of the ith level. Such a calculation was not always sufficient under the conditons of our experiment. In the reduction of the experimental results we therefore solved the Schrödinger equation with the potential $\varphi^0 + e\mathscr{E}z$ numerically.

The third term in (1) describes the quantum-refraction effect for an electron in a gas, and is expressed in terms of the Fermi pseudopotenial:

$$u(\bar{r}-\bar{R}_\zeta) = 2\pi a_0 e^2 L\delta(\bar{r}-\bar{R}_\zeta), \tag{5}$$

in which L is the electron-molecule scattering length, equal to the real part of the s-scattering amplitude taken with a minus sign. It was assumed here that the fields of the neighboring gas atoms do not overlap and that the volume per gas molecule is $n^{-1} \gg |L|^3$, which is certainly correct in our case. The solution of the Schrödinger equation, with allowance for the potential (5) summed over all the gas molecules, introduces into the electron-state energy, after functional averaging, a correction independent of the level number and proportional to the gas density:

$$E_F = 2\pi a_0 L e^2 n. \tag{6}$$

For such an averaging to be legitimate it is necessary, as pointed out by Fermi,[10] that a cube with side equal to the de Broglie wavelength contain many gas atoms. For our experiment, in which the effective velocity of an electron executing quantum oscillations in the ground or first-excited state exceeds by an order of magnitude its average thermal velocity, this condition can be written in the form

$$\langle z_i\rangle^3 \gg n^{-1}. \tag{7}$$

Since the correction (6) is the same for all the levels, it should not be manifested when spectroscopic transitions are observed. Nonetheless, recognizing that $\langle z_2^0\rangle = 4\langle z_1^0\rangle$, there is a possible gas-density interval in which condition (7) is not valid for the ground state, but remains in force for the excited state of the electron. The ensuing resonance-transition dependence on the gas density was observed for the first time for highly excited (Rydberg) atoms.

As a result, when the resonance frequency ν_{12} of the transition is determined as a function of the field $\mathscr{E}$ and of the gas density n, the variables are separated and

$$\nu_{12}(\mathscr{E}, n) = \frac{E_2(\mathscr{E}) - E_1(\mathscr{E})}{2\pi\hbar} + \frac{a_0 L e^2}{\hbar} n. \tag{8}$$

SPECTROSCOPY OF ELECTRON SYSTEM ABOVE THE SURFACE OF SOLID DEUTERIUM OR NEON

The measurement procedure is described in detail in Ref. 2. The method of growing solid deuterium and neon samples is similar to that for crystalline hydrogen. After crystallization from the liquid phase, the sample temperature was stabilized near the triple point for about an hour and a half. The triple-point parameters are listed for reference in Table I.

The charge was produced above the deuterium surface in the usual manner: a confining potential of ~1–1.5 kV was applied to the lower electrode of the experimental chamber, and a tungsten thermal emitter was pulsed once to produce electrons on the sample surface. The deuterium crystal with the free electrons levitated above its surface could be slowly

TABLE I.

	H_2	D_2	Ne	Note
P_0, Torr	54.0	128.5	324	Parameters in triple point
T_0, K	14.0	18.7	24.6	
Q_0	$3.13\cdot10^{-2}$	$3.48\cdot10^{-2}$	$2.43\cdot10^{-2}$	
$\langle z_1^0\rangle$, Å	25.3	22.8	32.7	Calculated values ($T = T_0$)
$\langle z_2^0\rangle$, Å	101.3	91.3	130.6	
$\langle z_2^0\rangle-\langle z_1^0\rangle$, Å	76.0	68.5	98.0	
ν_{12}^0 (0, 0), THz	2.43	2.99	1.46	
$\langle z_2\rangle-\langle z_1\rangle$, Å	71±2 *	61±2	90±3	Experimental values
ν_{12} (0, 0), THz	3.08±0.07	4.01±0.07	2.18±0.05	
L, Å	−1.4±0.2	−1.4±0.2	+0.1±0.04	
L^0, Å	+0.67	–	+0.13	Published data[5,7]

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*Numerical calculation including corrections quadratic in $\mathscr{E}$.

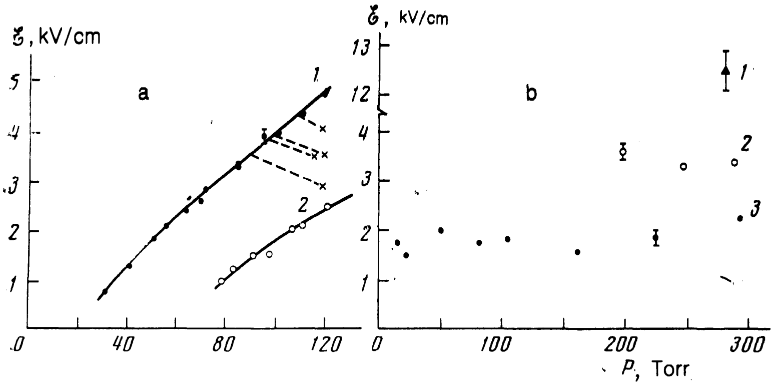

FIG. 2. Clamping field $\mathscr{E}$ vs the pressure of deuterium (a) and neon (b) gas under conditions of photoresonance of electrons levitated above the surface of solid deuterium or neon, for different wavelengths of the probing H_2O laser: a) $\lambda = 79\,\mu$m (1) and $84\,\mu$m (2); b) $\lambda = 84\,\mu$m (1), 108 μm (2), and 119 μm (3). The crosses mark the experimental points following additional injection of helium gas into the system (see the text).

cooled or heated without significantly changing the free charge.

We were unable to produce a layer of free electrons above a solid-neon surface by this method. Owing to the large mass and small cross section of the neon atoms, the electrons from the emitters had no time to become thermalized along their path to the surface, on which they produced a bound charge. It turned out however, that at low gas pressure and at a high potential of the lower electrode it was possible to ignite a gas discharge on the edges of the chamber near the peripheral section of the neon surface; free electrons appeared then on the surface. In contrast to deuterium and hydrogen, the free-electron lifetime on the neon surface was short (1–2 min), but sufficient for the measurement. Just as in the preceding experiments, the presence of a bound charge on the surface was monitored by the plot of the signal from the electron rf mobility sensor. Experimetns in which a bound charge was produced were disregarded.

We measured, for different values of the gas phase, the intensity of the clamping field $\mathscr{E}$, on which the frequency $\nu_{12}(\mathscr{E}, n)$ of the photoresonance coincided with one of the H_2O-laser emission frequencies. The measurement results for deuterium and neon are shown in Fig. 2. Just as in the experiments with hydrogen, the derivative $d\nu_{12}/d\mathscr{E}$, and hence also the difference

$$\langle z_2\rangle - \langle z_1\rangle = \frac{2\pi\hbar}{e}\frac{d\nu_{12}}{d\mathscr{E}},$$

turned out to be independent of pressure. This confirms the insensitivity of the Fermi increment to a change of the surface potential $U(z) + e\mathscr{E}z$ and makes it possible to determine from the experimental data the function $\nu_{12}(0, n)$ referred to $\mathscr{E} = 0$.

A plot of $\nu_{12}(0, n)$ for deuterium is shown in Fig. 3, where the results of measurements performed in a system of electrons above solid hydrogen are shown for comparison. The ratio of the scales of the figure was chosen from simple similarity considerations within the framework of the model chosen by us. Indeed, the range of variation of the gas density n in the experiment was such that, in accordance with condition (7), an electron in the excited state receives an increment (6) to the energy as a result of the quantum-refraction effect. For an electron in the ground state, however, this effect comes into play only for large n. It is natural to assume that the frequency shift of the ith level can be expressed in the entire range of variation of n with the aid of a certain function $f_i(\langle z\rangle)n^{1/3})$ equal to unity if condition (7) is met and describing effectively the "turning-off" of the quantum-refraction effect when n is decreased. Recognizing further the proportionality of the corresponding experimental and calculated values for deuterium and hydrogen

$$(\langle z^D\rangle - \langle z_1^D\rangle)/(\langle z_2^H\rangle - \langle z_1^H\rangle) \approx \langle z_i^D\rangle/\langle z_i^H\rangle = Q^H/Q^D = \gamma,$$

we can express the correction introduced by the quantum refraction into the photoresonance frequency in the form

$$\Delta\nu_{12}^D(0, n) = \frac{\hbar L^D n}{m}[f_2(\langle z_2^D\rangle n^{1/3}) - f_1(\langle z_1^D\rangle n^{1/3})]$$
$$= \frac{L^D}{L^H}\gamma^{-3}\Delta\nu_{12}^H(\gamma^3 n). \qquad (9)$$

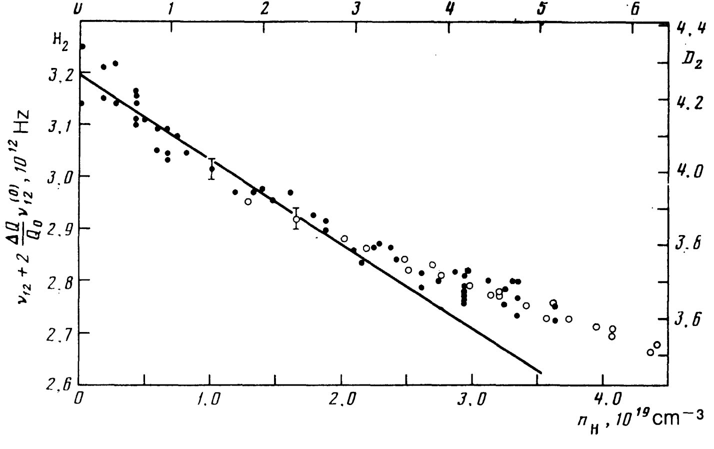

FIG. 3. Photoresonance frequency shift for electrons levitated above the surface of a solid phase, as a function of the gas-phase density for hydrogen (●, left-hand and lower scales) and deuterium (○, right-hand and upper scales).

The plots of $\nu_{12}(0, n)$ for hydrogen and deuterium should thus be similar if both the frequency scale and the density scale for deuterium are multiplied by γ^3. It is seen from Fig. 3 that the plots of $\nu_{12}(n, 0)$ for hydrogen and deuterium are parallel in the investigated density range, thereby confirming the expected equality of the length for scattering of an electron by a molecule of these isotopes, and offering evidence in favor of the model employed.

In an experiment with electrons levitated above the surface of solid neon (see Fig. 3) we were unable to observe, within the limits of the measurement error, a dependence of the photoresonance frequency on the neon-vapor pressure. This fact agrees well with the smallness of the known value of the length of scattering of an electron by a neon atom: $L = +0.13$ Å (Ref. 7).

The experimentally determined values of $\langle z_2\rangle - \langle z_1\rangle$, $\nu_{12}(0,0)$, and L for hydrogen, deuterium, and neon are listed in the table. For comparison we present also the values for $\langle z_2^0\rangle - \langle z_1^0\rangle$ and $\nu_{12}^0(0, 0)$ calculated in the approximation of the simplest potential (2). The difference between the experimental and calculated results is due to the idealization of the employed potential U^0 and can be used to refine its value. The quantum-refraction effect of interest to us, however, does not require in first approximation knowledge of the exact form of the near-surface potential, and the only significant parameter of the electron system, which determines the degree of inclusion of the effect, is the quantity $\langle z_i\rangle$.

PHOTORESONANCE LINEWIDTH AND ELECTRON MOBILITY

An independent source of information on the value of the scattering cross section of an electron by vapor molecules are the measured photoresonance-transition linewidths and the measured two-dimensional rf mobility of the electrons above the surface of the dielectric. Recall that in the limit of zero collision velocity the cross section for electron scattering by a molecule is given in terms of the corresponding linewidth by the equation

$$\sigma=4\pi L^2. \tag{10}$$

Figure 4 shows the results of our measurements of the linewidth of the 1→2 transition in electron systems above the surfaces of hydrogen, deuterium, and neon, as functions of the density of the corresponding gas phase. The ordinate is the distance, recalculated into frequency, between the extrema of the resonance-line derivatives and multiplied by $3^{1/2}$; this corresponds to the linewidth $\delta\nu_{12}$ at half-maximum in terms of its Lorentz profile. When the gas phase freezes, the photoresonance linewidth is practically the same in all three systems and is determined apparently by the inhomogeneity of the electric field in the experimental chamber.

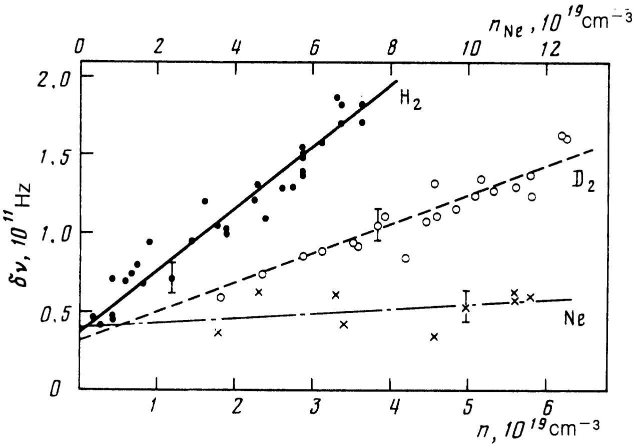

FIG. 4. Photoresonance linewidth vs the density of the equilibrium gas phase for electrons above the surfaces of solid hydrogen, deuterium, and neon (the neon density is given on the upper scale).

Good agreement between theory and experiment was demonstrated in Ref. 11, where the dependence of $\delta\nu_{12}$ on n in the electronic system above the surface of liquid helium served as the example. The expression obtained there for the gas component of the 1→2 transition photoresonance linewidth is

$$\delta\nu_{12}=\frac{\hbar\sigma n}{4m}\int_0^\infty dz[\psi_1{}^4+\psi_2{}^4-\psi_1{}^2\psi_2{}^2]. \tag{11}$$

Using the wave functions ψ_i obtained for the first two states from the Schrödinger equation with potential (2), we get

$$\delta\nu_{12}=0.118e^2Q\sigma n/\hbar. \tag{12}$$

Within the measurement accuracy, we observed no dependence of $\delta\nu_{12}$ on the vapor pressure in the electron system above a neon surface, in good agreement with the smallness of the cross section for electron scattering by a neon atom. An unexpected result was the difference, by almost a factor of two, between the slopes of the $\delta\nu_{12}(n)$ plots for hydrogen and deuterium. If Eq. (12) is used and $(\sigma/4\pi)^{1/2}$ is calculated, the results for hydrogen and deuterium are 2.0 ± 0.2 and 2.3 ± 0.2 Å, respectively. We have attempted to refine the form of the electron wave functions by taking into account the finite character of the potential barrier on the surface of the dielectric, and the need for effective cutoff of the Coulomb image potential at distances close to the surface. In a wide range of fit parameters, the integral in Eq. (11) is determined with good accuracy by the value of the frequency $\nu_{12}(0, 0)$. Using for the latter the experimentally obtained values, we have for $(\sigma/4\pi)^{1/2}$ the following corrected values: 1.8 ± 0.2 Å for hydrogen and 1.2 ± 0.1 Å for deuterium. A possible cause of this difference may be the strong energy dependence of the cross section for electron scattering by hydrogen and deuterium on account of the Ramsauer minimum. In fact, $\delta\nu_{12}(n)$ for hydrogen and deuterium were measured near the triple-point temperatures of these substances, which differ approximately by a factor 1.3. In deuterium, at higher temperature, the scattering cross section is smaller than in hydrogen, and this is natural if the Ramsauer minimum for these gases is located at > 2 meV. Recall that for a Ramsauer minimum to exist the electron-molecule scattering length must be negative.

The cross section for electron scattering by a molecule can be estimated also from the two-dimensional rf mobility μ of electrons levitated above the dielectric surface. We note in this connection Refs. 12 and 13, in which electron mobility above a solid-hydrogen surface was measured in a wide temperature range, and it was shown in particular that in the temperature interval 10–14 K of interest to us the value of μ is determined only by collisions between electrons and vapor molecules.

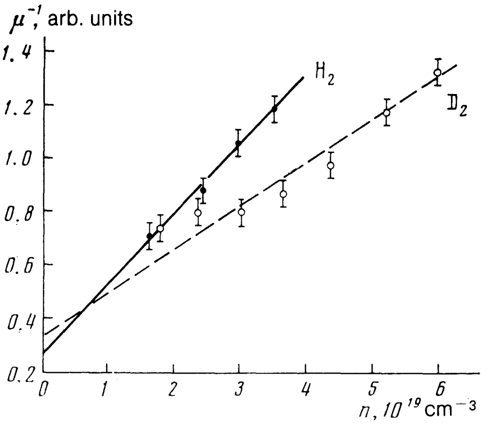

FIG. 5. Two-dimensional mobility μ of electrons levitated above the surface of solid hydrogen or deuterium, as function of the density of the equilibrium gas phase.

Recognizing that the greater part of the electrons are in the ground state, and using the potential (2) to determine the wave function of this state, we can write[3]

$$\mu=\frac{e}{\pi\hbar\sigma n}\left(\int\limits_0^\infty dz\,\psi_1^4\right)^{-1}=\frac{8ea_0}{3\pi\hbar\sigma nQ}. \tag{13}$$

Using the data from Ref. 12 for μ measured near the triple point, we obtain for $(\sigma/4\pi)^{1/2}$ from (13) the estimate ~0.9 Å. A similar estimate based on the experimental data of a later paper[14] gives 1.1 Å. These values are close enough to our photoresonance linewidth measurements.

The rf sensor[2] used by us to monitor the state of the election system enabled us to measure the electron mobility above the surfaces of solid hydrogen and deuterium by a procedure similar to that described in Ref. 13. The slope of the plot of the sensor signal against the potential of the lower electrode of the experimental chamber is proportional (on the initial linear section of the plot) to μ. We did not carry out an absolute calibration of the instrument. The results are shown in Fig. 5. To separate the dependence on the gas-phase density, the ordinate is proportional to μ^{-1}. We note right away that, compared with measurement of the photoresonance linewidth, which is more closely related to the location of the investigated surface section, the measurement of μ is more approximate. In the latter measurement, in fact, it is necessary to ensure good surface and homogeneity of the clamping field over the entire interface area, and account must also be taken of uneven thickness of the solid phase in the chamber. It can be noted nonetheless that the ratio of the values of $(\sigma/4\pi)^{1/2}$ obtained for hydrogen and deuterium turns out to be of the same order as the one calculated from the photoresonance linewidth.

PHOTORESONANCE PHASE SHIFT BY HELIUM GAS

If the model assumed by us is correct, the appearance of helium gas above the surface of the dielectric should cause a frequency shift in a direction opposite to the one observed by us when the hydrogen and deuterium pressures are increased. The electron-helium atom scattering length ($L = +0.63$ Å, Ref. 7) is well known and large enough for a quantitative check on the theory.

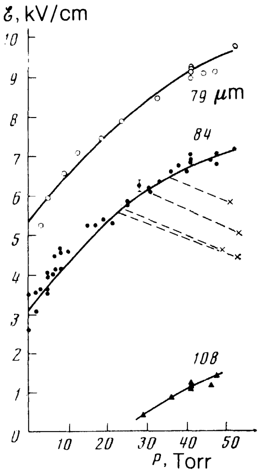

FIG. 6. Clamping field $\mathscr{E}$ vs the pressure of hydrogen gas under condition of photoresonance of electrons levitated above a solid hydrogen surface using H_2O-laser emission. The crosses denote experimental points obtained after injecting additional helium gas into the system (see the text).

We measured the frequency shift of the 1→2 resonance transition for electrons above surfaces of solid hydrogen and deuterium, with helium gas injected into the experimental chamber. The experimental procedure was the following. The solid hydrogen or deuterium sample was cooled to a vapor pressure on the order of several Torr and its temperature was stabilized. Helium was next admitted up to a specified pressure substantially higher than the intrinsic hydrogen or deuterium vapor in the chamber. The sample was next slowly heated and melted, and the dust brought in by the helium was removed from the surface (by sinking). After a secondary crystallization the sample was slowly cooled to the working temperature and the usual measurements made.

The measurement results are shown in Figs. 2a and 6, and the experimental points for photoresonance in the presence of helium are designated by crosses. Dashed straight lines connect these points with the resonance values of the clamping field in the absence of helium at the same partial pressure of hydrogen or deuterium, and reveal thus the contribution of the helium itself to the effect.

Figure 7 shows the frequency shift $\Delta\nu_{12}$ of the 1→2 transition as a function of the helium-atom density. The straight line in the figure corresponds to the dependence ex-

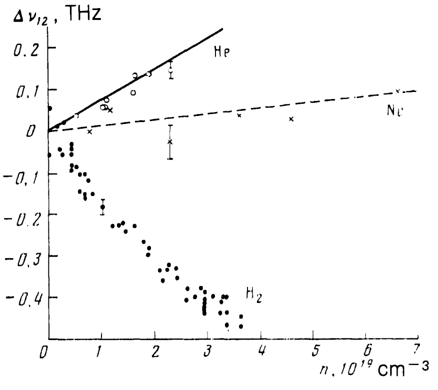

FIG. 7. Experimental and calculated dependences of the electron photoresonance frequency shift on the densities of gaseous helium, neon, and hydrogen.

pected from Eq. (8) and calculated using the known electron-helium atom scattering length. The agreement between the experimental and calculated data can be regarded as good.

Note that we have performed the experiment at temperatures high enough to prevent formation of adsorbed helium on the surface. Such a layer can be shown to cause the opposite effect—lowering of the photoresonance frequency. In our case the effect is not observed and the $\Delta\nu_{12}(n)$ plots obtained in experiments with hydrogen and deuterium at different temperatures have the same slopes. Adsorption of helium on the surface of solid hydrogen, as shown by experiment,[14] sets in only at temperatures lower than 5 K.

For comparison, Fig. 7 shows also $\Delta\nu_{12}(n)$ plots for electrons above neon and hydrogen surfaces, as functions of the density of their vapor molecules. The dashed line is the calculated relation for neon, determined from the known electron-neon atom scattering. All the experimental data shown in Figs. 3 and 7 are corrected for the temperature dependence of the dielectric constant of the solid phase (no such correction was taken into account in Ref. 1).

The transition frequencies for electrons levitated above liquid He^4 and He^3 surfaces were measured in Refs. 15 and 16, but observation of a dependence of the transition frequencies on the helium vapor pressure is not reported there. This is not surprising. According to the discussion above, a frequency shift can be observed only in a certain range of the gas-phase density n, in which the quantum-refraction effect is "turned on" only for one of the quantum levels participating in the transition. For He^4 it is known that $\langle z_1^0 \rangle = 114$ Å (Ref. 3), and for the transition 1 → 2, using the condition (7) for each of the levels, we obtain $1.1\cdot 10^{16}\ \mathrm{cm}^{-2} \lesssim n \lesssim 6.7\cdot 10^{17}\ \mathrm{cm}^{-3}$, a condition satisfied in the temperature interval 0.7–0.9 K. Thus, the density range in which quantum refraction can be observed in helium is smaller by two orders than in the case of solid hydrogen. In accordance with (7) and (8), the maximum photon resonance shift in He^4 is thus not larger than 5 GHz. A similar estimate for He^3 ($\langle z_1{}^0 \rangle = 150$ Å) yields 2 GHz. These values are quite small and their observation calls for a special experiment.

CONCLUSION

The aggregate of the experimental results attests to a negative length for scattering of an electron by hydrogen and deuterium molecules. Hydrogen and deuterium in the solid and liquid phases are thus new examples of dielectrics having on their surface a positive barrier to electrons, whereas the length for scattering of an electron by an individual molecule is negative. Up to now, the only such example was solid argon, for which $V_0 = -0.2 \pm 0.02$ eV in the liquid state, whereas, $L = -0.90$ Å (Ref. 7).

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Translated by J. G. Adashko