Electron States above the Surfaces of Solid Cryodielectrics for Quantum-Computing.

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Most of the experimental and theoretical work on two-dimensional electron states above dielectric surfaces with $\varepsilon - 1 \ll 0$ has been done for the case of liquid helium[1]. In the simplest model, the interaction potential for an electron near the surface of such a dielectric depends on the electrostatic image force, and on the external electric field E, which is normal to the surface and is necessary to collect a sufficient number of electrons near the surface:

$$\Phi = \begin{cases} \dfrac{e^2(\varepsilon-1)}{4z(\varepsilon+1)} + eEz = -\dfrac{Qe^2}{z} + eEz, & z>0; \\ \\ V_0, & z<0; \end{cases} \tag{1}$$

the z axis is normal to the surface, and V_0 is the surface potential barrier. If $V_0 \to \infty$ one obtains the electron energy spectrum:

$$\mathcal{E}_n = -\frac{Q^2 m e^4}{2\hbar^2 n^2} + eE\langle n|z|n\rangle + \frac{p^2}{2m}, \qquad n = 1, 2, 3 \ldots \tag{2}$$

The first term in this expression gives the exact solution for E=0. The second term is the first-order correction for a non-zero confining field, where the average distance of electrons from the surface in the n-th energy level is

$\langle n|z|n\rangle = 3n^2\hbar^2/(2me^2Q)$. This correction provides an extremely convenient way of fine-tuning the energy spectrum with electric signals. The last term is specific for 2D in-plane motion; for in-plain confined electron it should be replaced with the proper in-plain quantum-state energy.

In 1999 Platzman and Dykman[2] have introduced an idea that electrons, trapped in vacuum in the image states on the surface of a micrometer-thick liquid-helium film, is a very promising system for a physical implementation of quantum computer. They proposed to use patterned electrodes to adjust separately fields E acting on each electron and, hence, to control its resonant-transition frequency, $f_{1,2} = (\mathcal{E}_1 - \mathcal{E}_2)/\hbar$. The ground $|1\rangle$ and the first $|2\rangle$ excited states of each electron can represent two orthogonal states of a qubit, which can be controlled using an external microwave-driving field, E_{RF}. External electric signals applied to the patterned electrodes could also control an interaction between two or three adjacent electrons to form corresponding quantum gates. The 'clock rate' of such a system corresponds to Rabi-oscillation frequency, $\Omega_{1,2} = eE_{\mathsf{RF}}\langle 1|z|2\rangle/\hbar$, and a so-called π-pulse ($\pi/\Omega_{1,2}$) of microwave irradiation will change the qubit's state in the most efficient way.

Levitating electrons are virtually isolated from the outside world as compared with electrons in solid-state devices. This is a great advantage because the relevant wave function decoherence time is the most important parameter, which severely limits the electron-based quantum computer implementations. Acceptable value of the decoherence/clock-time ratio should be on the order of 10^4–10^5 and is defined by error-correcting algorithms[4]. For the case of liquid-He substrate, levitating electrons are mainly disturbed by capillary waves (*i.e.* ripplons) and phonons. From the estimates made in Ref. [2] it follows, that temperatures around 0.01K are necessary to reduce decoherence time up to 10^{-5} s. Later, the same authors remade their calculations[3] and showed, that the relaxation rate of an in-plain confined electron can be 10 times slower then that of free electrons. With the clock rate of 1GHz this gives a decoherence/clock time ratio of 10^5 that is an acceptable value. Unfortunately, there were no direct experiments to prove these optimistic estimates yet.

The Platzman&Dykman idea[2] of quantum computing with electrons floating on liquid helium attracted attention of experimentalists[5, 6, 7]. It was argued[5], that the minimal requirements[4] for the physical implementation of quantum computation with levitating electrons could, in principle, be realized, but serious fundamental investigations are needed.

The liquid helium is not the only substrate suitable for the levitating-electrons qubit implementation. Previously, we proposed to use cryo-crystals (hydrogen isotopes or neon) instead[8]. Our choice seems to have the important practical advantages, in spite of evident difficulties to grow high-quality atomically-flat surfaces of solid hydrogen or solid neon.

- *Tolerance for mechanical vibrations.* In the Platzman&Dykman scheme all the important parameters depend exponentially on the helium depth. The similar systems with solid substrates will be more tolerable.
- *An order of magnitude higher resonant energies.* The resonance transitions for electrons on cryo-crystals are in the THz-region that corresponds to $\approx 10\,\mathrm{meV}$ or $100\,\mathrm{K}$ in energy units.
- *Higher operational temperatures.* Strong coupling of electrons with liquid-helium capillary waves (ripplons) is the main source of the wave function decoherence in the case of helium, which forces experimenters to work at temperatures $<$0.01K and, hence, at very poor heat removal conditions. In the case of cryo-crystals, the operational temperature may be of the order of 1K or even higher. Our optimism is based on the theoretical results derived by Levinson[9], where the relevant decoherence times for

hydrogen and neon at a temperature of 1K were estimated as 150ns and 4ms respectively.

Having in mind the same 1 GHz clock rates as in Ref. [2], we can conclude, that Ne is the better choice then He. As for the hydrogen isotopes, their corresponding numbers are not that poor either, to rule them out completely. Taking into account the resonance-transition frequencies $\sim 3\,\mathrm{THz}$ common for all the systems, the choosing of 100 GHz clock rates gives a decoherence/clock-time ratio of 10^{-4}, which is acceptable. Besides, the in-plain movement of confined electron has a discrete set of levels in contrast to the in-plain free electron continuum states, that makes electron-phonon relaxation less effective. That is why one should hope, that the decoherence time for in-plain confined electrons above hydrogen or neon will be considerably longer then that estimated in Ref. [9] with the free electron model.

The most appropriate method to study the quantum states of levitating electrons is the active microwave resonant-transition spectroscopy. The same technique will be necessary to control the levitating-electron states for future quantum gate operation. For electrons above liquid-He, the microwave spectroscopy measurements were done for in-plain free electrons[10, 11, 12, 13, 14] but not for in-plain confined ones that are of the main interest in the qubit projects.

The electron states above solid cryodielectrics have their resonant frequencies in the terahertz region. Using the CW-operating water vapor laser[16] we performed the unique spectroscopic measurements of surface electrons with hydrogen, deuterium, and neon used as a substrate[15]. At that time, however, only the results for in-plain free electron system were of interest. Some results on photoresonance linewidth for electrons above solid H_2, D_2 and Ne are reproduced on Fig.1. The linewidth dependence on collisions with gas molecules is seen clearly. The residual linewidth at $n \to 0$ is a measure of the crystal surface quality.

At the Fig. 2 we show the example of photoresonanse spectroscopy in both (in-plain-free and in-plain confined) regimes for electrons, levitating above solid hydrogen[8]. The experiment started at point (1) at which electrons were deposited on the surface with a thermo-emitter. At this point the in-plain RF-absorption is high; the electrons are in-plain free and dissipate RF-power effectively. Then, we start to vary the bottom electrode potential, moving along the way designated by arrows. The points (1), (2), (4), and (6) outline the region of the maximum achievable electron densities, $n_{max}(E) = E/(4\pi e)$. That is why the path (1), (2), (4), and (6) is irreversible (the electrons escaped from the surface when E was reduced). On the contrary, on the way from (2)

to (3), or from (4) to (5) the n is constant and one can move between these points in a reversible manner. On the way from (6) to (5) the electron density was low and electrons became more and more in-plain confined at large E. Under these conditions the RF-dissipation tends to zero, but we were still able to observe the photoresonance signal, which was somewhat irregular but had about the same intensity.

At the moment we are working with the new experimental cell with patterned electrodes, which is designed for preparation of the in-plain-confined electron systems. In order to pose the problem in a more simple way we interconnect electrodes by sets of thousands in several groups, which may be regarded as a primitive 'aggregated-qubit' prototype'. To demonstrate the one- and two-qubit operations with this prototype, the resonant far-infrared radiation of the water-vapor laser[16] will be used.

References

[1] V.S. Edelman, *Sov.Phys.Usp.* **23**, 227 (1980).

[2] P.M. Platzman and M.I. Dykman, *Science* **284**, 1967 (1999); M.I. Dykman and P.M. Platzman, *Fortschritte der Physik* **48**, 1095 (2000).

[3] M.I. Dykman, P.M. Platzman, and P. Seddighrad, *Phys.Rev.B* **67**, 155402 (2003).

[4] D. P. DiVincenzo, Computation, *arXiv: quant-ph*/0002077 (2000).

[5] M.J. Lea, P.G. Frayne , and Y. Mukharsky, *Fortsch. der Physik* **48**, 1109 (2000).

[6] G. Papageorgiou, Y. Mukharsky, K. Harrabi, P. Glasson, P. Fozooni, P.G. Frayne, E. Collin, M.J. Lea, *Physica E* **18**, 179, (2003).

[7] J.M. Goodkind and S. Pilla, *Quantum Inf. Comput.* **1**, 108 (2001); A.J. Dahm, J.M. Goodkind, I. Karakurt, and S. Pilla, *J. Low Temp. Phys.* **126**, 709 (2002); A.J. Dahm, J.A. Heilman, I. Karakurt, and T.J. Peshek, *Physica E* **18**, 169 (2003).

[8] I.I. Smolyaninov and V.V. Zavyalov, *arXiv:cond-mat*/0009360 (2000).

[9] I.B. Levinson, *Soviet physics: JETP* **68**, 395 (1989).

[10] C.C. Grimes, T.R. Brown, M.L. Burns, and C.L. Zipfel , *Phys. Rev. B* **13**, 140 (1976).

[11] D. K. Lambert and P. L. Richards, *Phys. Rev. B*, **23**, 3282 (1981).

[12] E. Collin, W. Bailey, P.Fozooni, P.G. Frayne, P. Glasson, K. Harrabi, M.J. Lee, and G. Papageorgiou, *Phys.Rev.Lett.* **89**, 245301 (2002).

[13] V.S. Edelman, *Zh. Eksp. Teor. Fiz.* **77**, 673 (1979) [*Sov.Phys. JETP* **50**, 338 (1979)].

[14] A.P. Volodin and V.S. Edelman, *Zh. Eksp. Teor. Fiz.***81**, 368 (1981) [*Sov. Phys. JETP* **54**, 198 (1981)].

[15] V.V. Zavyalov and I.I. Smolyaninov, *Sov. Phys. JETP Lett.* **44**, 182 (1986); V.V. Zavyalov and I.I. Smolyaninov, *Zh. Eksp. Teor. Fiz.* **92**, 339 (1987) [*Sov. Phys. JETP* **65**, 194 (1987) V.V. Zavyalov and I.I. Smolyaninov, *Zh. Eksp. Teor. Fiz.* **94**, 307 (1988) [*Sov. Phys. JETP* **67**, 171 (1988).

[16] V.V. Zavyalov and G. D. Bogomolov, *Instruments and Experimental Tech.* **25**, 708 (1982).

Some physical characteristics of the described systems.

	^{4}He, T=0.01 K (liquid)	H_2, T=1 K (solid)	Ne, T=1 K (solid)
Dielectric constant, ε	1.054	1.29	1.24
Q-factor for the dielectric,	0.007	0.024	0.031
Ground-state levitation distance, nm	11	2.5	3.3
Resonant frequency, for E=0, THz	0.126 Ref. [10]	3.1 Ref. [15]	2.2 Ref. [15]
Low voltage Stark tuning rate, GHz·cm/V	0.8 Ref. [10]	0.17 Ref. [15]	0.22 Ref. [15]
Estimated decoherence time for in-plain free electrons, s	10^{-5} Ref. [2]	10^{-7} Ref. [9]	$4{\cdot}10^{-3}$ Ref. [9]
Triple point temperature, K	—	14.0	24.6
Triple point pressure, Torr	—	54	324

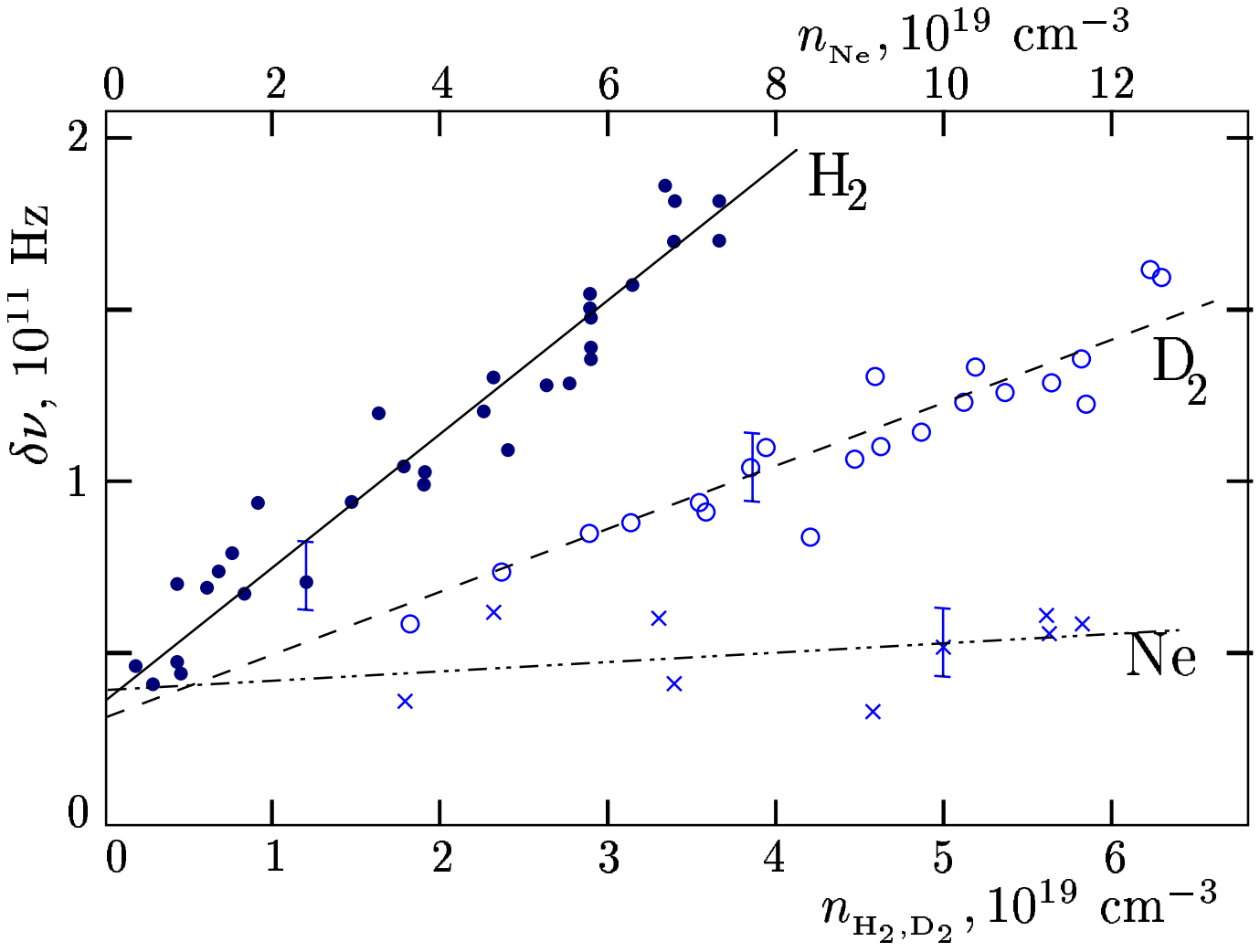

Fig. 1

Photo-resonance linewidth versus vapor density for electrons above solid H_2, D_2, and Ne (the Ne density is shown separately on the upper scale).

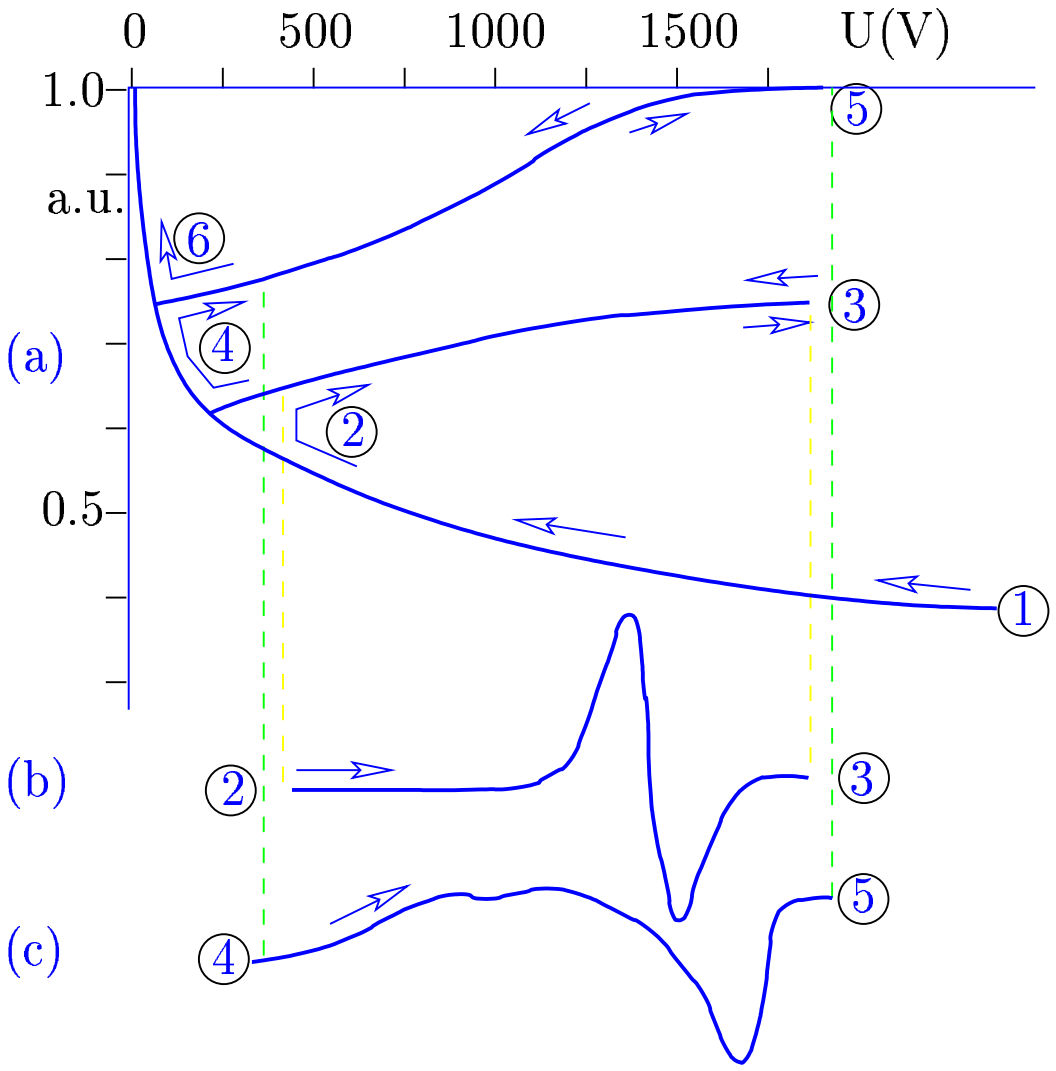

Fig. 2

(a) Radio-frequency in-plain absorption of electrons on top of a 1 mm thick hydrogen crystal measured as a function of the bottom electrode potential.

(b,c) Photoresonance for out-of plain 1→2 transitions detected in the electron layer on the way (2–3) (b), and (4–5) (c). Optical signal is proportional to the derivative of the optical absorption at $\lambda = 84.3\mu$ m.