

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

V.V. Zavyalov*, I.I. Smolyaninov**,
E.A. Zotova*, A.S. Borodin*, S.G. Bogomolov*

*P.L. Kapitza Institute for Physical Problems Kosygina 2, Moscow, Russia;

**Electrical and Computer Engineering Department, University of Maryland,
College Park, MD 20742

Electrons levitating above the surface of liquid He are known to be the promising two-level quantum ensemble, which could become one of the leading contenders for a scalable quantum-computer implementation. Unfortunately, the need to operate at milli-Kelvin temperatures presents a major obstacle and adds to the complexity of the electrons-on-helium based quantum computer design. Previously, we proposed to use the similar electron system based on electrons levitating above solid hydrogen (or, better, neon) cryocrystals as alternative to the liquid-He substrate. Such substitution could help to avoid capillary-wave and high-vapor-pressure problems, and may shift the operation temperatures into the 1-4K range. Now, we present more thorough discussion of the problem and outline some relevant experiments.

PACS numbers: 73.20.-r, 73.21.Fg, 67.

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 helium¹. 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:

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

the z axis is normal to the surface, and V_0 is the surface potential barrier.

If $V_0 \rightarrow \infty$ one obtains the electron energy spectrum:

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

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-plane confined electron it should be replaced with the proper in-plane quantum-state energy.

In 1999 Platzman and Dykman² have introduced the idea that electrons, trapped in vacuum in the image states on the surface of a μm -thick liquid helium film, are 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 excited $|2\rangle$ 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, $\Omega_{1,2} = eE_{\text{RF}}\langle 1|z|2\rangle/\hbar$, 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 values of the decoherence/clock-time ratio should be on the order of 10^4 – 10^5 and are defined by error-correcting algorithms⁴. For the case of liquid-He substrate, levitating electrons are mainly disturbed by capillary waves (*i.e.* riplons) and phonons. From the estimates made in Ref. 2 it follows, that temperatures around 0.01K are necessary to extend the decoherence time up to 10^{-5} s. These estimates were made for in-plane free electrons. For in-plane confined electrons the decoherence time should be greater, because the discrete set of levels (in contrast to the in-plane free electron continuum states) makes electron-riplon relaxation less effective. Indeed, the same authors remade later their calculations³ and showed, that the relaxation rate of an in-plane confined electron can be 10 times slower than that of a free one. 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.

Table 1. Some physical characteristics of the described systems.

	⁴ He, (0.01K)	H ₂ , (1K)	Ne, (1K)
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-plane free electrons, s	10^{-5} [Ref. 2]	10^{-7} [Ref. 9]	$4 \cdot 10^{-3}$ [Ref. 9]

The Platzman&Dykman idea² of quantum computing with electrons floating on liquid helium attracted attention of experimentalists⁵⁻⁷. It was argued⁵, that the minimal requirements⁴ 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) instead⁸. Our choice seems to have 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 He-substrate thickness and, hence, are extremely sensitive to liquid-surface waves. The similar systems with solid substrates will be more stable.
- *An order of magnitude higher resonant energies.* The resonance transitions for electrons on cryo-crystals are in the THz-region that corresponds to ≈ 10 meV or 100 K in energy units.
- *Higher operational temperatures.* Strong coupling of electrons with liquid-helium capillary waves (ripples) is the main source of the wave function decoherence in the case of helium, which forces experimenters to work at temperatures < 0.01 K and, hence, at very poor heat removal conditions. In the case of cryo-crystals, the operational temperature may be of the order of 1 K or even higher. Our optimism is based on the theoretical results derived by Levinson⁹, where the relevant decoherence times for hydrogen and neon at a temperature of 1 K were estimated as 150 ns and 4 ms respectively.

Having in mind the same 1 GHz clock rates as in Ref. 2, we can conclude, that Ne is the better choice than He. As for the hydrogen isotopes, their

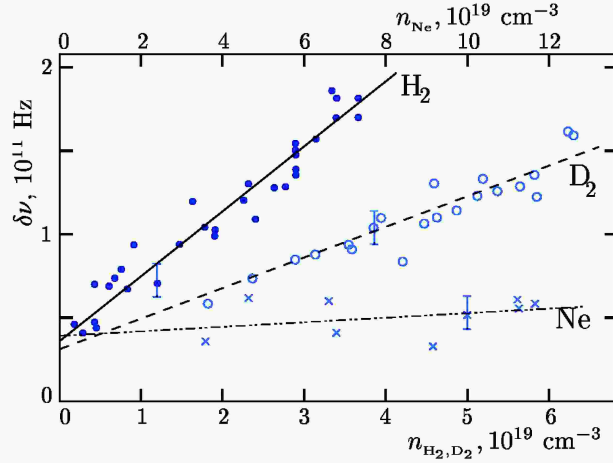


Fig. 1. Photo-resonance linewidth versus vapor density for electrons above solid H₂, D₂, and Ne (the Ne density is shown separately on the upper scale).

corresponding numbers are not that poor either, to rule them out completely. Taking into account the resonance-transition frequencies ~ 3 THz, the choosing of 100 GHz clock rates gives a decoherence/clock-time ratio of 10^{-4} , which is acceptable. And again, the discreteness of in-plane movement of confined electrons makes electron-phonon relaxation less effective. That is why one should hope, that the decoherence time for in-plane confined electrons above hydrogen or neon will be considerably longer than 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-plane free electrons^{10–14} but not for in-plane 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 laser¹⁶ we performed the unique spectroscopic measurements of surface electrons with hydrogen, deuterium, and neon used as a substrate¹⁵. At that time, however, only the results for in-plane free electron system were of interest. Some results on photoresonance linewidth for electrons above solid H₂, D₂ and Ne are reproduced on Fig.1. The linewidth dependence on collisions with gas molecules is seen clearly. The residual linewidth at $n \rightarrow 0$ is a measure of the crystal surface quality and confinement field (E) inhomogeneity.

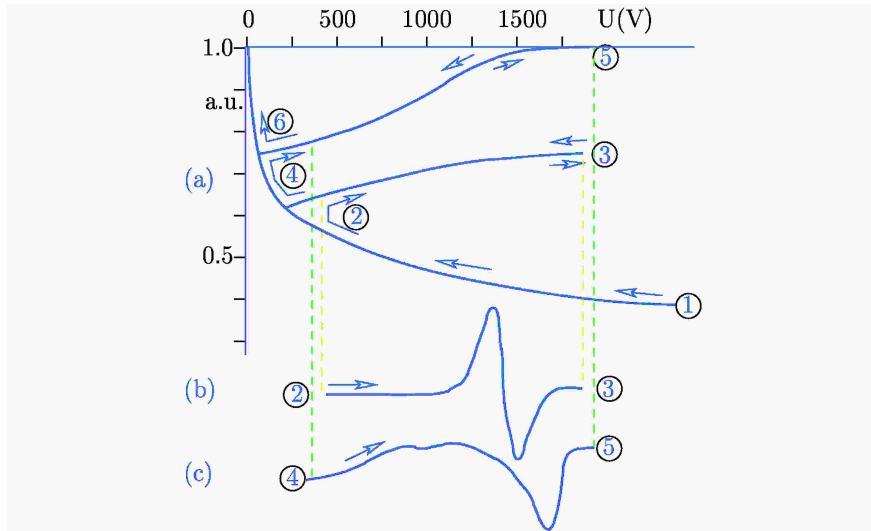


Fig. 2. **(a)** Radio-frequency in-plane absorption of electrons on top of a 1 mm thick hydrogen crystal measured as a function of the bottom electrode potential. **(b,c)** Photoresonance for out-of plane 1→2 transitions detected in the electron layer on the way (2→3) (b), and (4→5) (c). Optical signal is proportional to the derivative of the optical absorption at $\lambda = 84.3\mu\text{m}$.

At the Fig. 2 we show the example of photoresonance spectroscopy in both (in-plane-free and in-plane confined) regimes for electrons, levitating above solid hydrogen⁸. The experiment started at point (1) at which electrons were deposited on the surface with a thermo-emitter. At this point the in-plane RF-absorption is high; the electrons are in-plane 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-plane 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-plane-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 laser¹⁶ will be used.

ACKNOWLEDGMENTS

This research is supported by the CRDF grant RP1-2332-MO-01.

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).