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Proposed ripplon induced weak localization of electrons over liquid helium

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Ripplon induced weak localization is proposed for electrons on a liquid helium surface. Ripplon scattering is quasi-elastic, the ripplons are quasi-static relative to the electron velocity, and the relative change in occupation number of the ripplon state in a scattering event is small. Conditions for the observation of ripplon induced weak localization are calculated.

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Electrons bound to a liquid helium surface form an ideal two-dimensional system. Electron motion along the surface in a weak perpendicular field, $E_\perp$, is metallic with scattering occurring only from ripplons at temperatures below 0.5 K. The formation of a ripplonic polaron, consisting of an electron self-trapped in a dimple in the helium surface, is predicted [1] to occur in the presence of a sufficiently strong perpendicular field. A recent claim has been made for the observation of this state [2].

Localization effects for electrons on helium films have been discussed only in terms of this ripplonic polaron. We present an alternate route to localization of electrons on helium films. Our suggestion is that electrons are weakly localized, and possibly strongly localized on a short time scale, by quasi-elastic ripplon scattering. When temporal strong localization occurs, a dimple or a precursor will form beneath the electron even if the polaronic state is not bound. We propose that as the holding field is increased to enhance electron-ripplon scattering, the system will traverse the regimes, weak localization to strong localization to the bound polaron state.

Weak localization

Weak localization is the term applied to the coherent backscattering of electrons by elastic scattering from a random set of potentials. It is a precursor to strong localization. Excellent reviews on this topic exist [3–5]. Consider a set of fixed random potentials. Electrons can backscatter by traversing a circuit of scatterers in clockwise (forward) or counter-clockwise (time reversed) directions. A diagram is shown in Fig. 1,*a*. In zero magnetic field with only elastic scattering the difference in phase shift along the two paths, $\Delta\varphi$, vanishes. The amplitudes for forward, A_f, and time-reversed, A_r, paths are additive. The probability of returning to the origin is

$$P = \left|A_f + A_r\right|^2 = \left|A[1 + \cos(\Delta\varphi)]\right|^2 = |A|^2 \qquad (1)$$

compared to $2|A|^2$ for scattering in other directions. This enhancement of back scattering leads to an increase in resistivity. In a magnetic field the additional phase shift $[(e/\hbar)\int \mathbf{A}\, d\mathbf{l}]$ differs for the two paths and coherence is destroyed at fields $\sim \Phi_0/l^2$. Here Φ_0 is a flux quantum and l is the elastic mean free path. This leads to a negative magnetoresistance at low fields.

Weak localization by ripplons

We argue that weak localization should occur from ripplon scattering. Ripplon scattering differs from scattering from fixed random potentials in the following ways.

1) Scattering is quasi-elastic. The dominant electron-ripplon scattering events involve the absorption or emission of ripplons with wave vectors, q, $\sim$ the thermal wave vector of the electron, k_T. For 1 K electrons the energy of ripplons which dominate the scattering is $\hbar\omega_q \sim 10^{-2}$ K. Thus, the change in the electron wave vector, k, in a single scattering event is < 1 %. The total phase change

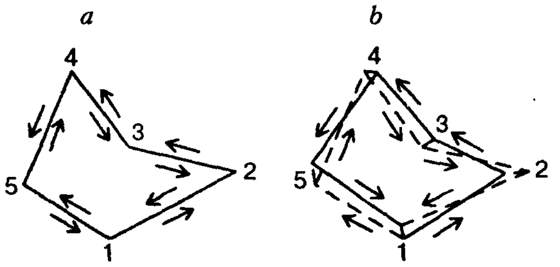

Fig. 1. Diagram illustrating forward and reversed paths: fixed scatterers (*a*); quasi-static scatterers(*b*).

$\sim 5\,kl$ for $l \sim 100$ nm is ~ 20 rad, and $\Delta\varphi$ is ~ 0.2 rad.

2) Ripplons are quasi-static in the reference frame of the electrons. The velocity of ripplons with $q = k_T$ is $\sim 3{\cdot}10^{-3}$ of the electron velocity. The positions at which scattering occurs on the two paths are nearly the same. This is illustrated in Fig. 1,*b*. The total change in phase is nearly unaffected by the motion of slow ripplons.

3) The percentage change in the occupation number of ripplons in a scattering event involving the absorption or emission of a ripplon of one quantum is small. The occupation number is $\sim T/\hbar\omega_q \sim 100$ at 1 K. Electrons on the forward and time-reversed paths scatter from ripplons of the same amplitude to within 1 %.

We conclude that the total phase change for electrons which traverse the two paths is nearly the same, and the loss in coherence for back scattering is very small. The reader may be inclined to make an analogy with phonon scattering which dephases the electrons in other two-dimensional systems. This analogy is incorrect. Phonon scattering occurs at energies $\hbar\omega \sim \hbar s k_F \sim 1$ K, where s is the sound velocity and k_F is $\sim 10^8$ m^{-1}. Electron-phonon scattering is not quasi-elastic, and the occupation number is $\sim$ unity. Thus, a phonon of one quantum absorbed on one path will not exist for the time-reversed path. A good analogy of ripplon induced weak localization is weak localization by quasi-elastic scattering from helium atoms which has been observed in [6,7].

Strong localization by ripplons

Electron localization by ripplons or substrate scattering is complicated by the formation of a dimple under the electron. This dimple forms if an electron is temporarily localized even though no bound polaron state exists. The dimple impedes the motion of the electron. Nevertheless, we examine the possibility of strong localization by ripplons.

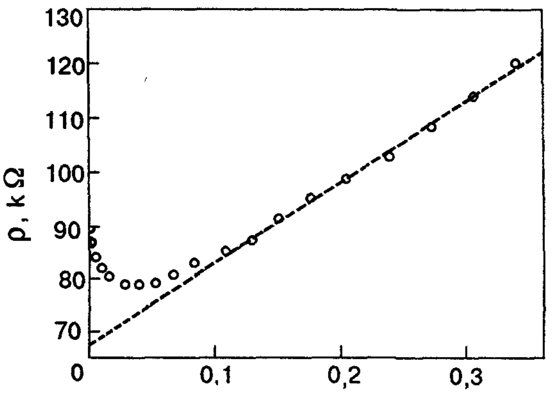

Fig. 2. Resistivity vs. B^2; $n = 6 \cdot 10^{13}$ m^{-2}, $T = 1.3$ K.

Strong localization occurs for short elastic mean free paths. The amplitude of the electronic wave function from successive scatterings will add constructively in some region of space where the electron becomes localized, and destructive interference will occur in other regions of space. The wave function decays as $\exp(-r/\xi)$, where $\xi > l$ is the localization length. In fixed random potentials, conduction occurs via variable-range tunneling from one localized state to another with the absorption or emission of a thermal excitation [8]. There is interference between different tunneling paths. A magnetic field suppresses destructive interference along critical links in the hopping network. This results in a giant negative magnetoresistance [9].

The situation is much more complicated for the case of electrons on helium. Consider a mean free path of 50 nm. The change in k for each scattering is $\sim \pm 1$ %. The change in φ is ~ 1 rad after ~ 100 scattering events which occurs in about 1 ns. Also, ripplons move a distance $\sim l/10$ in ~ 1 ns. Thus, a localized state can survive for at most 1 ns. This is also the time for a dimple of size $\sim l$ to form under the electron. We propose that in the absence of bound polarons, electrons will be relocalized at another site in a time ~ 1 ns or will tunnel to another site in a shorter time. The mobility, given by the Einstein relation and a diffusion constant $D \sim l^2/\tau$ ($\tau \sim 1$ ns), is $\sim 10^{-1}$ m^2/V·s.

Possibility of experimental realization

We estimate the mean free path required to insure $\cos(\Delta\varphi) > 0.7$ is $l < 400$ nm. This requires $E_\perp \sim$ 250 kV/m, although a small negative magnetoresistance may be observed at lower fields. All other sources of scattering are absent on a bulk surface, and weak localization effects can be ascribed to ripplons. However, the charged bulk surface is unstable at this value of field, and weak localization may best be observed on helium films. In this case scattering from substrate roughness may interfere. A low density of electrons is required to insure that localization is not a result of electron-electron interactions. The advantage of using electrons on a helium surface to study the transition from weak to strong localization is that the electron mean free path can be varied, in situ, by changing the holding field. Further, the electron-electron interaction can be altered by changing the density.

We have some data that support our suggestion. In Fig. 2 we show the resistivity versus B^2 for electrons on a a ~ 30 nm thick helium film. At low fields there is a large negative magnetoresistance, more characteristic of strong localization. At higher fields the resistivity fits the Drude formula, $\rho \sim [1 + (\mu B)^2]$. The mobility, μ , is 1.5 $m^2/V{\cdot}s$, $l \sim 50$ nm, and $E_\perp \sim 600$ kV/m. The field at which the minimum occurs is consistent with this value of l. Scattering from substrate imperfections may occur here, but the theoretical ripplon scattering rate accounts for ~ 40 % of the total scattering. We argue that since every other scattering event involves ripplons, localization effects could not be observed if ripplon scattering dephased the electronic wave function.

Localization of electrons on a helium surface is an example of classical weak localization. This has been studied both theoretically [10,11] and experimentally [6,7,12] in other systems. A search for ripplon induced localization is underway.

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1. V. B. Shikin, *Sov. Phys. JETP* **33**, 387 (1971). See also references in F. M. Peeters, *Physics of the Two-Dimensional Electron Gas*, J. T. Devreese and M. Peeters (eds.), Plenum Press, N.Y. , G. E. Marques and N. Studart, *Phys. Rev.* **B39**, 4133 (1989).
2. O. Tress, Yu. P. Monarkha, F. C. Penning, H. Bluyssen, and P. Wyder, *Phys. Rev. Lett.* **77**, 2511 (1996).
3. G. Bergmann, *Phys. Rep.* **107**, 1 (1984).
4. P. A. Lee and T. V. Ramakrishnan, *Rev. Mod. Phys.* **57**, 287 (1985).
5. S. Chakravarty and A. Schnid, *Phys. Rep.* **140**, 193 (1986).
6. P. W. Adams and M. A. Paalanen, *Phys. Rev.* **B39**, 4733 (1989).
7. A. M. L. Hanssen, R. W. van der Heijden, A. T. A. M. de Waele, and H. M. Gijsman, *Surf. Sci.* **229**, 365 (1990).
8. A. L. Efros and B. I. Shklovskii, *Electronic Properties of Doped Semiconductors*, Springer-Verlag, New York (1984).
9. V. I. Nguyen, B. Z. Spivak, and B. I. Shklovskii, *Sov. Phys. JETP.* **62**, 1021 (1985).
10. V. V. Afonin, Yu. M. Galperin, and V. L. Gurevich, *Sov. Phys. JETP* **61**, 1130 (1985); V. V. Afonin, Yu. M. Galperin, V. L. Gurevich, and A. Schmid, *Phys. Rev.* **A36**, 5729 (1987).
11. M. J. Stephen, *Phys. Rev.* **B36**, 5663 (1987).
12. P. W. Adams and M. A. Paalanen, *Phys. Rev. Lett.* **58**, 2106 (1987).