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Configurational dephasing in a weak-localization experiment

P. W. Adams
Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803

M. A. Paalanen
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

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We have determined the dephasing time for the two-dimensional electron gas on the surface of a H_2 crystal from low-field magnetoresistance measurements. We find that a moderate amount of helium gas above the H_2 surface causes large increases in resistivity, but unexpectedly small negative magnetoresistance effects. We attribute this to a suppression of weak localization as a result of the dephasing effect of the thermal motion of helium atoms normal to the H_2 surface.

Electrons on the surface of solid hydrogen form a nondegenerate two-dimensional electron gas (2D EG) whose mobility, μ, and density, n_0, can be varied over a wide range.[1] In practice one can rather simply determine these two quantities by applying a perpendicular magnetic field, B, and then measuring the classical Drude resistivity, $\sigma_{xx}^{-1}=\sigma_0^{-1}[1+(\mu B)^2]$ where $\sigma_0=n_0e\mu=e^2n_0\tau_0/m_{\rm el}$, n_0 is the areal electron density and τ_0 is the elastic scattering time. In the present paper we describe measurements of the low-field magnetoresistance ($\mu B\ll 1$) in which τ_0 is dominated by the electron scattering from helium gas atoms. In particular we are interested in the weak localization of the electrons and their dephasing scattering due to the motion of the He atoms.

In the presence of disorder, in this case the random density fluctuations of the helium gas, the Boltzmann conductivity σ_0 has a small negative correction term arising from weak localization effects[2,3]

$$\sigma=\sigma_0-\frac{T_F}{T}\frac{e^2}{2\pi^2\hbar}\ln(\tau_\phi/\tau_0)\,, \tag{1}$$

where $T_F=\pi\hbar^2n_0/m_{\rm el}k_B$ is the Fermi temperature and τ_ϕ is the electron dephasing time. This correction term can be pictured as a coherent backscattering of electrons resulting from the interference between the electron wave and its time reversed counterpart.[4] The interference is destroyed if the phase of the electron wave is disturbed by inelastic scattering, motion of the scatterers or by perpendicular magnetic field.

The low-field magnetoresistance (MR) due to weak-localization effects can be used to determine the dephasing time τ_ϕ.[5,6] The negative MR for a nondegenerate Boltzmann gas is governed by the following theoretical formula (first order in $\hbar/E\tau_0$)[7-9]

$$\sigma_{xx}=\frac{T_F}{T}\frac{e^2}{\pi\hbar^2}\frac{1}{k_BT}\int_{E_c^0}^{\infty}e^{-E/k_BT}\frac{1}{1+(\mu B)^2}\times\left[E\tau_0-\frac{\hbar}{2\pi}\phi_l(E,B)\right]dE\,, \tag{2}$$

where $E_c^0=(\hbar/2\pi\tau_0)\ln(\tau_\phi/\tau_0)$ is the strong localization threshold,[3,10] B is the perpendicular magnetic field, the $[1+(\mu B)^2]^{-1}$ factor takes into account the high-field Drude behavior, and the function $\phi_l(E,B)$ is defined as an integral[9]

$$\phi_l(E,B)=\int_{\tau_0/\tau_\phi}^{\infty}\frac{(B/B_c)e^{-x^l}}{2\sinh(Bx/2B_c)}dx\,. \tag{3}$$

In Eq. (3) the characteristic field $B_c=\hbar/4eD(E)\tau_\phi$ and the exponent l depends on the details of the dephasing mechanism. Equations (2) and (3) are a more general form of our earlier expression for the negative magnetoresistance.[3,8]

In general we can distinguish three types of dephasing mechanisms with different l values and expressions for the dephasing time τ_ϕ.[8,11,12] The most common case is the dephasing due to inelastic scattering. When the electron energy loss in a single inelastic collision is large, i.e., $\Delta E\tau_0>\hbar$, then $\tau_\phi=\tau_{\rm in}$ (inelastic scattering time) and $l=1$. However for e-He scattering $\Delta E\approx\sqrt{m_{\rm el}/M_{\rm He}}E$ is small and one expects for this quasielastic case that the thermal motion of the He scattering centers is the dominant dephasing mechanism. If a He atom moves a substantial fraction of an electron wavelength, $\lambda_{\rm el}$, during the time τ_ϕ, then the coherence of the backscattering will be suppressed. If one assumes that the helium motion is ballistic on length scales of the order of $\lambda_{\rm el}$ then $l=3$ and the dephasing time $\tau_\phi=(6\tau_0\tau_\lambda^2)^{1/3}$ where $\tau_\lambda=\lambda_{\rm el}/v_{\rm He}$ and $v_{\rm He}$ is the helium thermal velocity. If on the other hand the helium motion is diffusive with diffusivity $D_{\rm He}$ then $l=2$ and $\tau_\phi=(4\tau_0\tau_\lambda)^{1/2}$, where $\tau_\lambda=\lambda_{\rm el}^2/2D_{\rm He}$. In addition to the above cases where the He atoms were considered to move in the 2D plane of the electrons, they also can disappear into the third dimension perpendicular to the H_2 surface. This disappearance of the scattering centers is unique to our system and also breaks the coherence of the backscattering. Therefore, there are two relevant length scales $\lambda_{\rm el}$ for our 2D EG. The first is the thermal wavelength $\lambda_T=\hbar/(2m_{\rm el}k_BT)^{1/2}$ which is about 10 nm at 4.2 K and the second is the extent of the electron wave function above the H_2 surface $\langle z\rangle\cong 1.7$ nm. Clearly since $\langle z\rangle\ll\lambda_T$ at 4.2 K the perpendicular motion of He will be the dominant dephasing mechanism with the value of $l=2$

and with the dephasing time $\tau_\phi=(2\tau_\perp\tau_0)^{1/2}$ where $\tau_\perp=\langle z\rangle/v_{He}\cong 20$ ps.[13]

Shown in Fig. 1 is the magnetoresistance of the 2D EG in He gas with density $n_g=5.4\times10^{20}$ cm^{-3}. The electron mobility is totally limited by the gas atom scattering, because $\mu=2.5$ m^2/Vs on bare H_2 surface at $n_g=0$. Note the negative magnetoresistance at low fields and the positive B^2 dependence at higher fields. We believe the low-field behavior represents the negative MR of weak localization effects and the nearly high-field tail is the Drude resistivity. The field dependence of Fig. 1 is quantitatively very similar to what we have previously observed on bare disordered H_2 surfaces[3] with one exception, namely the mobilities at which one begins to see a negative magnetoresistance is roughly a factor of 5 lower than observed in surface scattering data. This difference does not appear to be entirely attributable to a larger dephasing rate in helium gas atom scattering. The measured values of τ_ϕ/τ_0 at gas densities $n_g>10^{20}$ cm^{-3} are only about 75% lower than surface scattering values of τ_ϕ/τ_0 at comparable mobilities. It seems likely that the lower mobility in helium is a consequence of a small hydrodynamic mass enhancement of the electrons resulting from correlated motion between the electrons and surrounding helium atoms.

We have also shown in Fig. 1 the best fits of Eqs. (2) and (3) for our data for both $l=1$ and 3 cases. In both fits we have treated μ, τ_ϕ/τ_0, and E_c as variable parameters and their values for the best fits are shown in the Figure. First, we notice that these parameters are practically independent of the selected l value. Second the cutoff energy $E_c\simeq 20$ K is considerably larger than the expected strong localization threshold $E_c^0=(\hbar/2\pi\tau_0)\ln(\tau_\phi/\tau_0)=4$ K. We believe that Eq. (2), which is only a first-order term of the perturbation expansion overestimates the magnetoresistance near the localization threshold E_c^0 and as a result $\ln(\tau_\phi/\tau_0)$ is underestimated and in addition E_c, the lower limit of the integration, is pushed upwards in the fitting procedure. As a third observation the $l=1$ fit is better than the $l=3$ fit. We have not calculated the $l=2$ curve but expect it to be between $l=1$ and $l=3$ fits and also somewhat worse than $l=1$ fit. However, we would like to point out that the differences between different l fits are not conclusive due to the first-order nature of Eq. (2).

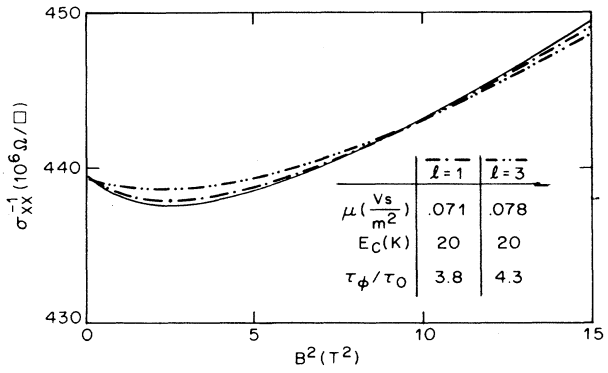

FIG. 1. Magnetoresistance of the 2D EG at $n_g=5.4\times10^{20}$ cm^{-3} and $T=4.2$ K. The scatter in the data is of the order of the linewidth (5×10^{-4}). In Eq. (2) μ, τ_ϕ/τ_0, and E_c are varied for the best fits, ···· line is for $l=1$ and –··– for the $l=3$ case.

The measured values of the dephasing time τ_ϕ/τ_0 are somewhat smaller than expected from the above theoretical estimates. The biggest contribution to the dephasing time should come from the perpendicular motion of the He atoms yielding $\tau_\phi/\tau_0=(2\times10^{-19}n_g\ \text{cm}^3)^{1/2}$, if we use Saitoh's[14] expression for the gas atom scattering time τ_0. This formula predicts correctly the observed density threshold of $n_g>10^{19}$ cm^2 for the appearance of the negative magnetoresistance but a larger than observed value of ~4 for τ_ϕ/τ_0 at the density $n_g=5.4\times10^{20}$ cm^3 of Fig. 1. We also notice that for this dephasing process $l=2$ is expected to give a better fit than the $l=1$ value contrary to the results in Fig. 1.[13] We again attribute these small quantitative discrepancies to the fact that Eq. (2) is only the lowest order term given by the perturbation theory where $\hbar/E\tau_0$ is the expansion parameter and higher order terms are important close to the strong localization threshold $\hbar/E\tau_0\approx1$. However we are quite convinced that the measured short dephasing times cannot be explained by inelastic scattering which is estimated to be nearly 2 orders of magnitude weaker than the observed dephasing values.

We can also determine the dephasing time τ_ϕ from the zero magnetic-field conductivity as shown in Ref. 10. Us-

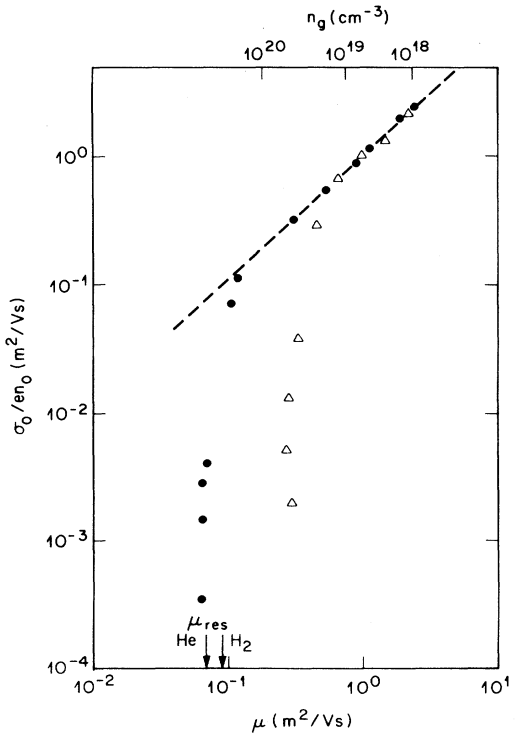

FIG. 2. The conductivity normalized by the initial electron density as a function of mobility at $T=4.2$ K. ●: helium gas scattering, △: surface scattering at $n_g=0$. The arrows point to the residual mobility $\mu_{res}=e\hbar\ln(\tau_\phi/\tau_0)/2\pi m_{el}k_BT$, which is estimated using previously determined magnetoresistance values of $\tau_\phi/\tau_0=3.8$ and 5.7 for He and H_2, respectively.

ing Eqs. (2) and (3) one can show that at $B=0$ the conductivity starts to decrease exponentially, $\propto \exp(-E_c^0/k_BT)$ when the mobility falls below

$$\mu_{\rm res}=\frac{e\hbar \ln(\tau_\phi/\tau_0)}{2\pi m_{\rm el}k_BT}. \quad (4)$$

In Fig. 2 we have plotted for both He and H_2 the normalized conductivity σ/n_0e versus mobility $\mu\simeq e\tau_0/m_{\rm el}$ which is determined from the high-field magnetoresistance. Note that $\sigma/en_0\simeq\mu$ at high mobilities but begins to deviate from classical behavior at sufficiently small μ. This point of departure represents a measure of $\ln(\tau_\phi/\tau_0)$ as given by Eq. (4). The value of $\ln(\tau_\phi/\tau_0)$ obtained from the He magnetoresistance data is about a factor of 2 smaller than the value obtained from Eq. (4) as shown by the arrow in Fig. 2. Similarly Fig. 2 gives for H_2 about three times larger $\ln(\tau_\phi/\tau_0)$ than the previously obtained magnetoresistance value.[3] This is consistent with our earlier observation that the magnetoresistance fits underestimate the values of $\ln(\tau_\phi/\tau_0)$. We also notice from Fig. 2 that the residual mobility is substantially lower in the He gas than on the bare H_2 surface which as discussed earlier may represent a small hydrodynamic mass enhancement ($m_{\rm el}^*\leq 5m_{\rm el}$) of the electrons.

In summary, we have investigated the 2D magnetotransport of electrons in helium gas. We observe essentially classical transport as a result of the strong dephasing effect of the helium's thermal motion and this is, to our knowledge, the first observation of configurational dephasing.

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