Microwave-Resonance-Induced Resistivity: Evidence of Ultrahot Surface-State Electrons on Liquid ^{3}He

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(Received 29 November 2006; published 7 June 2007)

Measurements of the dc resistivity of surface-state electrons on liquid helium exposed to microwave radiation are reported. It is shown that the resonant microwave excitation of surface-state electrons is accompanied by a strong increase in their resistivity, which is opposite to the result expected from the previously used two-level model. We show that even a very small fraction of electrons excited to the first excited state and decaying back due to vapor-atom scattering strongly heat the electron system, causing a population of higher subbands. The calculated resistivity change is in good agreement with the observed data.

DOI: 10.1103/PhysRevLett.98.235302 PACS numbers: 67.90.+z, 73.20.−r, 73.25.+i, 78.70.Gq

External electrons attracted to liquid helium by a weak image force form a series of two-dimensional subbands near its surface [1,2]. For the vertical motion (z direction), the energy spectrum of electrons Δ_l is similar to the spectrum of a hydrogen atom (the Rydberg states), $\Delta_l = -\Delta/l^2$ (here $l = 1, 2, \ldots$ is the subband index). The binding energy $\Delta = me^4(\epsilon - 1)^2/32\hbar^2(\epsilon + 1)^2$, where m is the electron mass, e is the elementary charge, $\hbar$ is the Planck constant, and ϵ is the dielectric constant of liquid helium. For liquid ^{4}He, $\Delta \simeq 7.6$ K; for liquid ^{3}He, $\Delta \simeq 4.2$ K. Along the surface (xy direction) the electron motion is free except for the scattering from He vapor atoms or surface capillary waves (ripplons). The subband energy can be shifted by an electric field $E_\perp$ perpendicular to the surface, which allows the tuning of the resonant frequency for intersubband microwave (MW) absorption.

The Rydberg states of surface-state electrons (SSE) on liquid helium were observed and extensively studied more than two decades ago [3,4]. The recent interest in the MW resonance absorption in this system has been generated by the theoretical suggestion [5] that electrons in the two lowest Rydberg states could be used as electronic qubits controlled by the MW field. In an experiment on SSE on liquid ^{4}He [6] MW absorption saturation was observed and attributed to the quantum saturation of the fractional occupancy of the excited state n_2 approaching that of the ground state n_1 ($n_1, n_2 \to 1/2$). To interpret the data, a simple two-level model was used, assuming that the distribution function for the in-plane motion energy, $\varepsilon_k = \hbar^2k^2/2m$, is not affected by excitation, where $\hbar\mathbf{k}$ is the 2D momentum.

The excess occupancy of the higher subbands may affect the dc resistivity of SSE. Therefore, it is interesting to use linear dc resistivity measurement as a probe for occupancy saturation. Such measurements were demonstrated already in 1981 [7]. The theory of SSE conductivity limited by vapor atoms [8], applied to the simple two-level model with equal level occupancies, predicts a decrease in SSE resistivity by no less than 10%.

In this Letter, we report the results of SSE resistivity measurements carried out simultaneously with resonant MW absorption for different radiation powers. Even at low powers (long before the saturation), we observe a strong *increase* in SSE resistivity induced by MW radiation. This is opposite to the expected behavior of the simple two-level model. To interpret the data, we extend the SSE conductivity theory [8] to an arbitrary distribution n_l in the lth subband, and propose a theory that takes into account the coupling between the vertical excitation of SSE and their in-plane motion caused by vapor-atom scattering [9]. Our analysis indicates that even an extremely low excitation $n_2 \sim 10^{-3}$ substantially increases the electron temperature T_e causing an electron population of higher subbands. Remarkably, the quantum saturation $n_1 \to n_2$ is reached by ultrahot electrons ($T_e/T \simeq 50$). The calculated resistivity increase is in good agreement with the observed data.

The experiment was carried out for SSE on liquid ^{3}He at temperatures near $T = 0.5$ K, where electron relaxation is mostly determined by collisions with helium vapor atoms. The mobility is about 50 m^2/V s [10], which corresponds to the momentum relaxation rate $\nu_0 \approx 3.5 \times 10^9$ s^{-1}. This is the same scattering regime in which the experiment of Ref. [6] was performed. The helium surface was placed midway between two parallel disk electrodes. SSEs were forced toward the surface by a vertical electric field $E_\perp$ created by a positive voltage applied to the bottom electrode. The top electrode consisted of two concentric-ring gold-plated copper electrodes used to measure the change in electron resistivity by a capacitive-coupling method [11]. An ac input signal of 1 MHz was applied to the inner electrode, while the output signal was detected at the outer electrode. Resistivity was obtained by the phase shift of the output signal. A MW radiation of 130 GHz was passed through the region between the electrodes to excite electrons from the ground subband ($l = 1$) to the first excited subband ($l = 2$). The energy difference between these two subbands was tuned to the resonance with the MW field by varying the voltage applied to the bottom electrode.

To observe the resistivity change induced by MW excitation, $E_\perp$ was slowly swept around the resonance while the in-phase and quadrature components of the output signal were recorded. In Fig. 1, we show a typical set of resistivity data. Different curves correspond to different input MW powers measured at the entrance to the cryostat, as indicated in the caption. Resistivity reaches its maximum at a certain $E_\perp$. This value corresponds to the resonant electron excitation from the ground subband to the first excited subband. In the experiment, we also measured the absorption of MW power as a function of $E_\perp$ using an InSb bolometer [12]. It was found to reach the maximum at the same value of $E_\perp$ as that of the resistivity signal. The vertical shift of the curves at high input power is attributed to the heating of the copper experimental cell by the microwaves, which leads to a small increase in liquid temperature. This increase was estimated from the known temperature dependence of resistivity, which is about 0.01 K at the highest input power.

In contrast with the results of Ref. [7] obtained at lower T (0.35 K), no resistance decrease was observed at any input powers in our experiment. We think that at $T = 0.35$ K, electron transport [7] was affected by ripplon scattering, which could change the sign of the observed effect. For the data shown in Fig. 1, resistivity increases to about 60% of its initial value at the highest input power. At low power, the peak amplitude of the resistivity curves increases rapidly with power. At high power, it increases more slowly and the line becomes broader.

The physics of the observed effect can be understood by considering the two-level model if we take into account the

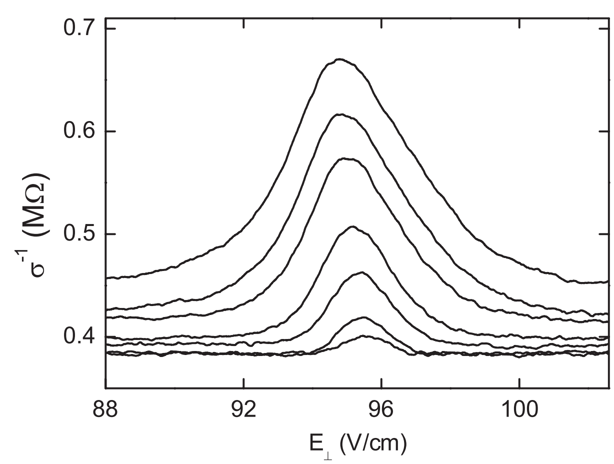

FIG. 1. SSE resistivity σ^{-1} vs $E_\perp$. The data are obtained at $T = 0.5$ K and electron density $n_e = 1.9 \times 10^7$ cm^{-2}. The curves correspond (from bottom to top) to input MW powers of 20, 40, 95, 190, 400, 670, and 1085 μW.

coupling between the vertical excitation and the in-plane motion of electrons induced by scattering. An excited electron absorbs the energy quantum $\hbar\omega_0 = \Delta_2 - \Delta_1 \equiv \Delta_{21}$ from a MW field, which is about 6 K for a typical $E_\perp \sim 100$ V/cm. The electron decay back to the ground subband caused by collisions with vapor atoms hardly changes the electron energy because of the small mass ratio $m/M \sim 10^{-4}$, where M is the atomic mass of ^{3}He. Thus, the absorbed energy is transferred to the kinetic energy of the electron motion along the surface. Then, electron-electron collisions, which have a very high rate in this system, quickly redistribute the energy obtained from the field, forming an equilibrium distribution with the effective electron temperature $T_e > T$.

An improvement in the rate equation for fractional occupancies of the simple two-level model employed previously [6] can be made by taking into account the fact that T_e is different from the ambient temperature T:

$$r(n_1 - n_2) = \frac{1}{\tau}(n_2 - e^{-\Delta_{21}/T_e} n_1), \tag{1}$$

where r is the stimulated absorption (emission) rate, and τ is the lifetime of the excited level due to scattering by vapor atoms. The absorption rate has the usual resonant form [6], $r = \Omega^2\gamma/2(\delta^2 + \gamma^2)$, where $\delta = \omega - \omega_0$, γ is the linewidth [13], and Ω is the Rabi frequency. The Rabi frequency is given by $\hbar\Omega = eE_0\langle 1|z|2\rangle$, where E_0 is the MW field and $e\langle 1|z|2\rangle$ is the transition dipole moment. In the framework of the two-level model, τ^{-1} does not depend on T_e, and, for $E_\perp \sim 100$ V/cm, it is about 1/5 of the momentum relaxation rate of ground-subband electrons ν_0 [8]. At $T = 0.5$ K, we have $\tau \simeq 1.4 \times 10^{-9}$ s. According to Eq. (1), the relative occupancy

$$\eta \equiv \frac{n_2}{n_1} = \frac{r\tau + e^{-\Delta_{21}/T_e}}{r\tau + 1} \tag{2}$$

saturates ($\eta \to 1$) for high powers $r\tau \gg 1$ and is equal to the usual Boltzmann factor if $r\tau \to 0$.

Electron temperature is obtained by balancing the power taken from the field $\hbar\omega_0 r(n_1 - n_2)$ and the power transferred to vapor atoms $(T_e - T)\tilde{\nu}(T_e)$, where $\tilde{\nu}$ is the energy relaxation rate. Using Eq. (1), the energy balance equation can be written as

$$(T_e - T)\tau\tilde{\nu}(T_e) = \Delta_{21} n_1(\eta - e^{-\Delta_{21}/T_e}). \tag{3}$$

T_e differs from T when the relative occupancy η is larger than the Boltzmann factor $e^{-\Delta_{21}/T_e}$, which is shown to be always the case in Eq. (2) with $r\tau > 0$.

Important conclusions can be deduced by simple estimation. The energy relaxation rate $\tilde{\nu}$ is much lower than the momentum relaxation rate ν_0 because $m/M \ll 1$. Under the present experimental conditions, $\nu_0/\tilde{\nu} \approx 3.2 \times 10^2$ [8] and $\tau\tilde{\nu} \sim 10^{-2}$. Therefore, Eqs. (2) and (3) indicate that substantial heating $T_e - T \sim T$ occurs even at a very small excitation ($r\tau \ll 1$), $r\tau \sim \eta - e^{-\Delta_{21}/T_e} \sim (T/n_1\Delta_{21})\tau\tilde{\nu} \sim 10^{-3}$. It is clear that, for the saturation condition ($r\tau > 1$, $\eta \to 1$), the SSE should be extremely overheated, and the population of higher subbands cannot be ignored.

For an arbitrary distribution n_l, the energy relaxation rate can be written as [14]

$$\tilde{\nu} = \frac{m}{M}\nu_0 \sum_{l,l'} n_{l'} e^{\Delta_{l'l}/T_e} e^{-(|\Delta_{l'l}|+\Delta_{l'l})/2T_e} \left[\frac{(2T_e + |\Delta_{l'l}|)B_{11}}{T_e B_{l'l}} + \frac{\hbar^2 B_{11}}{2mT_e C_{l'l}} \right], \quad (4)$$

where $\Delta_{l'l} = \Delta_{l'} - \Delta_l$, and the matrix elements $B_{l'l}$ and $C_{l'l}$ are defined in Ref. [8]. For the Boltzmann distribution $n_{l'} \propto e^{-\Delta_{l'}/T_e}$, the energy relaxation given by Eq. (4) obviously coincides with the result of Ref. [8].

The present two-level model can even be solved analytically. The ratio $\tilde{\nu}/n_1$ is a linear function of η. Therefore, for a given T_e, Eq. (3) can be reduced to a simple linear equation for the excitation parameter $r\tau$. Its solution gives the relationship between T_e and $r\tau$. The dependence $T_e(r\tau)$ is obtained by simply inverting the established relationship between T_e and $r\tau$. The solution of the two-level model is shown in Fig. 2 for $T = 0.5$ K and $\Delta_{21} = 6.24$ K. As expected, even at very low excitation rates, $r\tau > 5 \times 10^{-4}$, SSEs are significantly heated, making the thermal excitation factor $e^{-\Delta_{21}/T_e}$ predominant in the relative occupancy: $\eta(T_e) \gg \eta(T) \simeq r\tau$. This also means that one cannot reach the quantum saturation condition $r\tau > 1$ without extreme overheating of the SSE and the two-level model breaking down.

The conclusion that is drawn from Fig. 2 qualitatively agrees with our conductivity data because, for hot SSE in the vapor-atom scattering regime, electron resistivity increases with T_e [8]. At high T_e, the probability of intersubband electron scattering by vapor atoms increases, and the electron scattering rate increases with the population of the higher subbands.

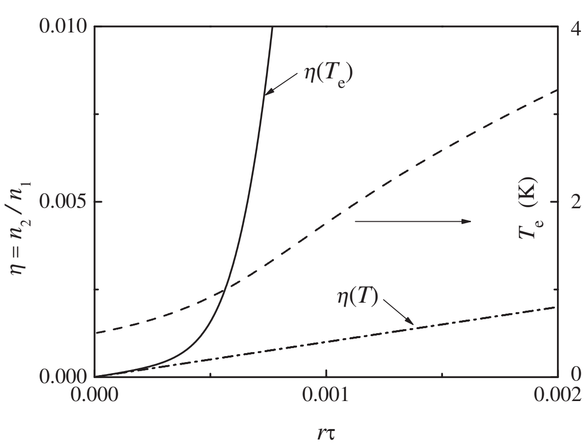

FIG. 2. Relative occupancy of excited level $\eta = n_2/n_1$ versus excitation rate $r\tau$ (solid line). The electron temperature T_e is indicated on the right axis (dashed line).

To incorporate highly excited subbands in our treatment, we assume that, for $l > 2$, electrons are distributed in accordance with the usual Boltzmann form $n_l \propto e^{-\Delta_l/T_e}$, whereas n_1 and n_2 are obtained from the rate equations including MW excitation and scattering between different subbands. According to Fig. 2, this treatment is valid in the excitation range $5 \times 10^{-4} < r\tau \lesssim 0.1$, which corresponds to our experimental conditions. It will also be approximately valid for the saturation condition $r\tau \gtrsim 1$, because in this case most SSEs populate high levels with $l \gg 1$. This statement has been verified by the numerical solution of about 200 rate equations for SSE levels [14].

For the all-level theory, electron temperature was calculated under the resonance condition ($\omega = \omega_0$), when the Rabi frequency Ω equals $\sqrt{2r\gamma}$. $T_e(\Omega)$ is shown in Fig. 3 as a solid line. The sharp increase in electron temperature up to 2 K is in accordance with the result obtained for the two-level model (Fig. 2). When SSEs start populating higher subbands, the increase in $T_e(\Omega)$ becomes slower. At even higher powers, the dependence $T_e(\Omega)$ saturates, which corresponds to $r\tau > 1$. For the two-level model, the highest electron temperature is about 105 K. The all-level theory reduces maximum T_e to about 27 K.

The momentum relaxation rate ν can be found using the results obtained for hot SSE [8] and extended for a non-Boltzmann distribution n_l. In contrast with the simple two-level model [6], even the two-level model with heating results in a resistivity increase with Ω due to electron scattering to the excited level, as shown in Fig. 4 by a dashed line. For the all-level theory (solid line), $\nu(\Omega)$ increases much more strongly. At much higher Ω, it saturates in agreement with Fig. 3.

The comparison of resistivity peak amplitude between the theory and the experiment is given in Fig. 5. The experimental points are plotted as a function of the input power P, whereas the calculated line is plotted as a func-

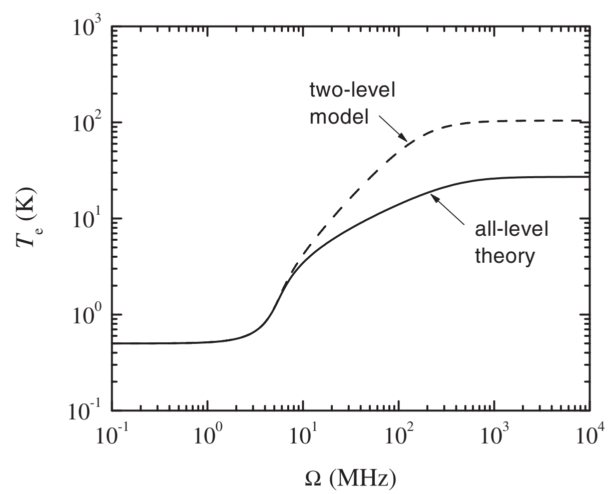

FIG. 3. Electron temperature T_e versus Rabi frequency calculated for $E_\perp = 95.33$ V/cm and $T = 0.5$ K: two-level model (dashed line) and all-level theory (solid line).

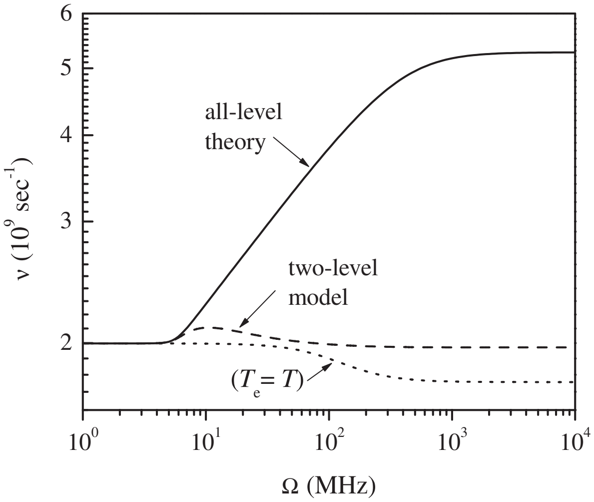

FIG. 4. Momentum relaxation rate versus Rabi frequency: simple two-level model with $T_e = T$ (dotted line), the two-level model with heating (dashed line), and all-level theory (solid line).

tion of Ω^2. Because the proportionality coefficient between Ω and $\sqrt{P}$ is not known in our experiment, the data and theoretical curve are fitted by changing the range of the top axis. The proportionality coefficient a between Ω and $\sqrt{P}$ obtained by fitting is found to be about 1.26×10^3 MHz/$\sqrt{\mathrm{W}}$. Then, Ω is estimated to be about 40 MHz at the highest input power for the data shown in Fig. 5. The values of the MW power in the cell and Ω can also be roughly estimated from the magnitude of the MW absorption signal measured using the InSb bolometer [12]. We found that this estimate of Ω is consistent with that obtained from Fig. 5. According to Fig. 3, for such Ω, the

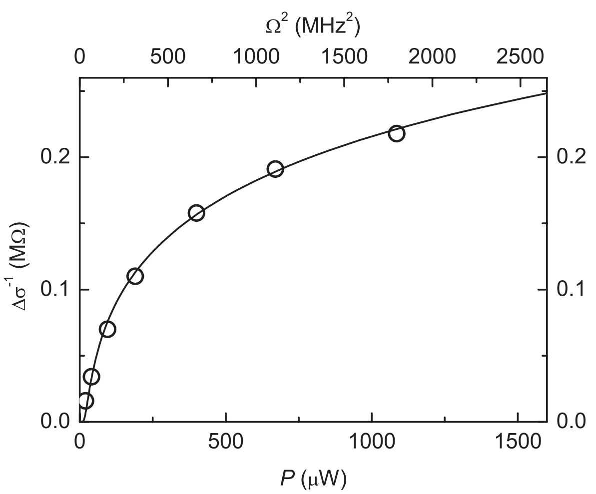

FIG. 5. Peak amplitude of resistivity curves shown in Fig. 1 versus input MW power P indicated on bottom axis (circles), and theoretical calculations of $\Delta\sigma^{-1}$ vs Ω^2 indicated on top axis (solid line).

electron temperature should be about 9 K. Therefore, SSE are extremely overheated long before the quantum saturation condition $r\tau > 1$ is reached.

In conclusion, our conductivity measurement provides interesting information about the state of the electron system in the presence of resonant MW radiation. We have observed a strong increase in the resistivity of SSE on liquid ^{3}He induced by the MW resonance absorption at very low excitation rates, $r\tau \ll 1$. This observation is explained by the theoretical approach, which incorporates overheating of the electron system caused by the interplay between the MW excitation and the electron scattering by vapor atoms. The results obtained here indicate that heating is a very important factor for the adequate analysis of the MW absorption experiment. To protect qubit operation from the heating effect, a proper detuning of the in-plane excited levels of qubits from the first excited Rydberg level should be incorporated.

We thank H. Mukuda and A. Fukuda. We are grateful to Mark Dykman for helpful discussion. This work is partly supported by a Grant-in-Aid for Scientific Research from Monka-sho, and JSPS. D. K. thanks the Japan Society for the Promotion of Science.

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