Microwave saturation and the Rabi frequency of the Rydberg states of electrons on helium

E.Collin, W.Bailey P.Fozooni P.G.Frayne, P.Glasson, K.Harrabi M.J.Lea and G.Papageorgiou

Department of Physics, Royal Holloway, University of London, Egham, Surrey TW20 0EX, England.

Abstract

We present measurements of the resonant microwave excitation of the Rydberg energy levels of surface state electrons on superfluid helium. The temperature dependent linewidth $\gamma(T)$ agrees well with theoretical predictions and is very small below 300 mK. Absorption saturation and power broadening were observed as the fraction of electrons in the first excited state was increased to 0.49, close to the thermal excitation limit of 0.5. The Rabi frequency was determined as a function of microwave power. The experiments show that the conditions are met for the use of these states in an electronic qubit.

Key words: Electrons on helium; Quantum computing; Microwave excitation

It has been suggested that surface state electrons on liquid helium could be used as quantum bits, or qubits[1]. Electrons are attacted by an image charge in the liquid surface. The states would be the ground (quantum number $i = 1$) and first excited ($i = 2$) Rydberg states[2][3][4] of electrons in this potential well, coupled by coherent resonant microwaves. We present new measurements of the resonant interaction of millimetric microwaves with electrons on superfluid ^{4}He.

Power from a Gunn diode oscillator [5] was passed through a doubler and transmitted down overmoded waveguide, through thermal filters, into an experimental cell in a dilution refrigerator at temperatures to below 100 mK. The electrons were held on the surface of liquid helium between capacitor plates. The microwaves were polarised vertically by a grid on the cavity input port and propagated horizontally. Power transmitted through the cell was detected by a low temperature InSb Putley bolometer [6]. The vertical holding field E_z could be swept by varying the voltage across the capacitor plates. The absorption linewidth was measured using sine or square wave modulation of E_z at 5 kHz.

The experimental resonant frequency f_{12}, from current and previous work, versus the vertical electric pressing field E_z, is shown in Fig.1. The strong Stark effect can be used to tune the resonance though the frequency of the applied microwaves. The results are in good agreement with numerical calculations of the eigenstates in the trapping potential.

The absorption line was close to the expected Lorentzian shape [7], as shown in Fig.2, though at low temperatures it is convoluted with inhomogeneous broadening. A key parameter for qubit performance is the linewidth γ of the resonance. The temperature-dependent linewidth $\gamma(T)$ (HWHM) is shown in Fig.3, at a frequency of 189.6 GHz, after subtraction of the inhomogeneous linewidth γ_0. Above 1 K, scattering from ^{4}He vapor atoms dominates and is proportional to the vapor pressure, while below 1 K, the scattering is from surface waves (ripplons). The theory by Ando shown by the solid line [8] gives

$$\gamma(T) = AT + BN_{gas} \quad (1)$$

[1] E-mail: m.lea@rhul.ac.uk

where the first term is due to ripplon scattering and $N_{gas} \propto T^{3/2} \exp(-7.17/T)$ is the number density of ^{4}He vapor atoms. The coefficients A and B depend on the holding field E_z. Both inelastic and elastic collisions contribute to the linewidth. Inelastic collisions

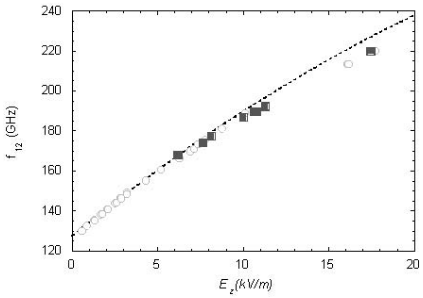

Fig. 1. The resonant absorption frequency for electrons on helium. Squares are our results whereas circles are from [2]. The spacing between the holding electrodes in our cell is 2.1 mm. The dashed line is a calculation from [2].

produce decay of the excited state with a lifetime $\tau = 1/(2 \times 2\pi\gamma_{inel})$ (the radiative lifetime is estimated to be very long, ~ 0.1 s, in this system) while elastic collisions produce fluctuations in the energy levels and hence a linewidth $\gamma_{\rm el}$ (and also decoherence). The total Lorentzian half-width $\gamma = \gamma_{\rm inel} + \gamma_{\rm el}$. The new experimental measurements are in good agreement with previous data above 1.2 K [2] and lie close to the theoretical values shown by the solid line. Experimentally, at low powers, the linewidth is independent of the microwave power. As the power increases, the absorption line broadens and the absorption saturates,

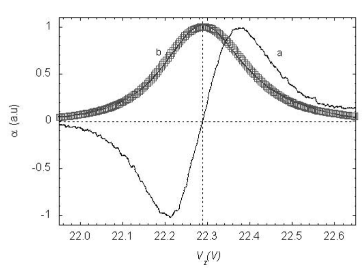

Fig. 2. Absorption line at 1.1 K using low microwave powers at 189.6 GHz. (a)The derivative signal and (b) the numerically integrated line with a Lorentzian fit to the data.

due to the finite occupancy of the excited state. As the microwave power increases, stimulated absorption and emission is balanced by the decay rate $1/\tau$ from the excited state. The thermal equilibrium value for the excited fraction $n_2 = R\tau/(1 + 2R\tau)$ at resonance, where R is the resonant excitation rate, with a limit of $n_2 = 0.5$. Absorption saturation and power broadening were observed experimentally. An excitation fraction of 0.49 of the electrons in the first excited state was generated, close to the limit. The Rabi frequency at maximum power was estimated to be about 500 MHz. These Rydberg states have very high Q-factors, at least

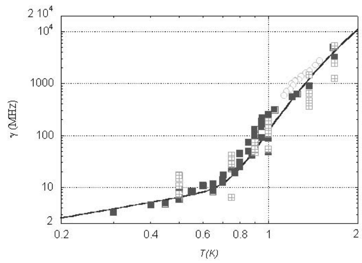

Fig. 3. The temperature dependent half-width γ at low powers (189.6 GHz). The squares are our results, while the circles are from [2]. The black line is the calculation by Ando [7].

on bulk helium. Below 0.3 K, the ratio of $f_{12}/(2\gamma)$ is very high and should be over 2×10^5 below 100 mK. Excitation levels close to the thermal equilibrium maximum can be readily achieved. The experiments show that the conditions are met for the use of these states as electronic qubits, though many challenges remain in implementing this system [9]. Further results and analysis will be presented elsewhere. We thank M.I.Dykman, P.M.Platzman and J.Single-ton for discussions and F.Greenough, A.K.Betts and others for technical support. The work was supported by the EPSRC, the EU, INTAS and Royal Holloway, University of London.

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