Temperature dependent energy levels of electrons on liquid helium

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SUPPLEMENTAL MATERIAL

This Supplemental Material describes the technical details of the microwave equipment and cell used in these experiments, including the microwave source, the waveguide and components, the microwave cell and the InSb, or Putley, detector.

I. Microwave source

The microwave system used is shown in Fig. 1. Microwave power was generated by a Gunn diode oscillator [1] (82.5 – 97.5GHz, minimum output 30 mW) and passed through a doubler (5 mW maximum output from 165 to 195 GHz) and transmitted down overmoded waveguide, through thermal filters, into the experimental cell mounted on a dilution refrigerator. The frequency of the Gunn oscillator was phase-locked to a 10 MHz quartz crystal resonator. Higher frequencies, up to 260 GHz, were obtained from a Carcinotron source. The most detailed experiments were done at a frequency of 189.6 GHz.

II. Microwave cell

The cell is shown schematically in Fig. 1 in the main text. The electrons were held between two circular upper and lower capacitor plates, radius 28 mm, with an electrode separation of h = 2.075 mm. These were fabricated on microwave micro-circuit board with polished OFHC copper, plated with a 1 μm flash of gold. The lower electrode had a central disc of radius 22 mm, and an outer annular ring with 4 equal segments, separated by a 0.5 mm gap of dielectric as shown in Fig 4 in the main text. The electrodes were mounted on copper plates in the cell which acted as a guard.

The free electrons were produced by thermionic emission from a pulsed filament in the upper cell.

The electron magnetoconductivity was measured using a Corbino geometry to obtain the electron density and mobility. The central electrode was driven with a 10 kHz ac signal which was detected on the lower outer ring electrodes via capacitive coupling to the electrons. The currents to the four electrode segments were balanced to level the cell with the electrons in place. The electron density profile was calculated to be constant out to a radius of about 27 mm, depending on the potentials.

The two electrodes form a microwave pillbox cavity. When the frequency is swept, various resonant modes are excited. For a maximum electric field E_z on the electrons, we require

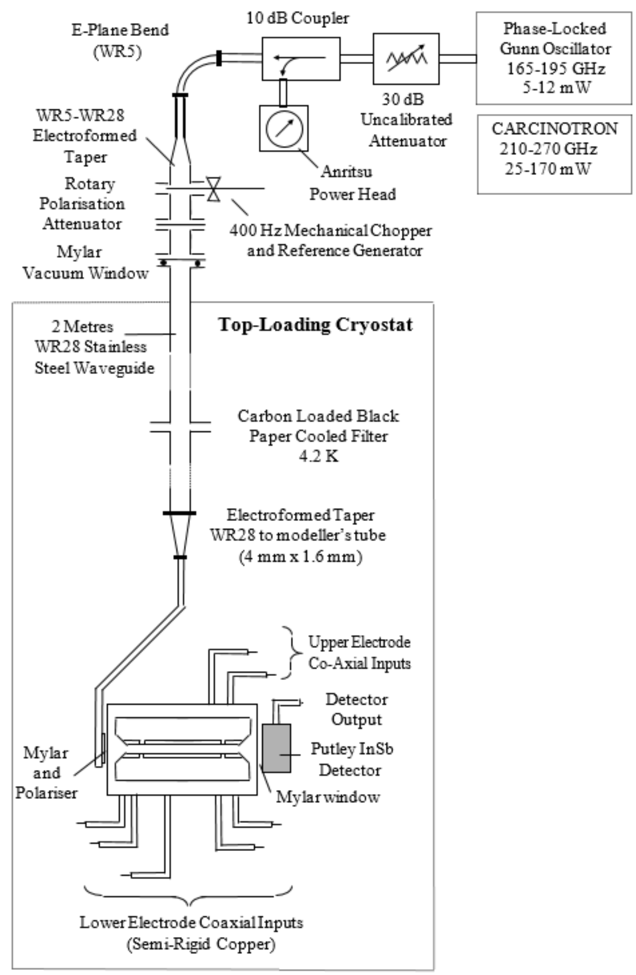

FIG. 1. The microwave system used.

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a TM_{mnp} microwave mode with $p = 2$, where the mode numbers refer to the azimuthal, radial and axial directions. The mode number p is the number of standing half-wavelengths along the z-axis. For this mode the z-axis component of the microwave field is maximum in the middle of the cell where the electrons are distributed. For our cell, the low frequency cut-off for these modes would be 150 GHz. Experiments on a test cell clearly showed these volume-mode resonances and the onset of the $p = 2$ modes. Above the cut-off frequency, the cell is overmoded with a wide range of m and n resonances, and was tuned to maximise the signal output. Once tuned, it was very stable. The microwave intensity may have nodes and anti-nodes across the electron sheet, with a typical node spacing of about 1 mm, much smaller than the sheet diameter.

The input and output microwave ports were vacuum-sealed using Mylar windows and indium O-rings. The microwaves were polarized vertically by a horizontal wire grid (20 lines/mm) on the input port and propagated horizontally through the cell to the output port, which was coupled to an InSb hot-electron, or Putley [2], bolometer [3] in a carefully designed reflective housing. The detector element was thermally isolated by a thin (0.5 mm) PTFE gasket. A d.c. bias current I, up to 50 μA, was passed through the detector from a voltage source, using a current-limiting resistance of 10^5 Ω. The resistance $R(P)$ of the detector element was both temperature and power dependent, where the power P dissipated comes from the Joule heating $P = I^2R(P)$ and from the absorbed microwave power. The resistance at low power increased from 5 kΩ at 4.2 K to 26.5 kΩ at 0.9 K and to 160 kΩ at 0.5 K. The voltage sensitivity $S = -\, \mathrm{d}V/\mathrm{d}P = -\, I\, \mathrm{d}R(P)/\mathrm{d}P$ of the detector was calculated by measuring $R(P)$ as a function of bias current. The detector sensitivity was a maximum for a bias voltage of about 300 mV, corresponding to a bias current of 20 μA. The voltage output from the detector was amplified by a factor of 100 using a preamplifier. The overall maximum sensitivity, measured at the preamplifier output, is about 2.4 V/μW at 0.9 K, compared to a specified sensitivity of 0.6 V/μW at 4.2 K. The sensitivity increased further at lower temperatures, depending on the bias current, which had to be reduced at lower temperatures to reduce Joule heating. The noise-equivalent power (NEP) of the Putley detector was typically 0.5 pW/√Hz with a preamplifier input noise of 1.1 nV/√Hz.

The microwave power output of the oscillator was measured at room temperature with an Anritsu Power Meter ML83A. The power passing through the cell was measured with the Putley detector. The microwaves were modulated using several techniques and the modulation was measured with a lock-in amplifier following the preamplifier. With no electrons on the helium, a mechanical 6-bladed chopper was installed in the waveguide at room temperature. A photodiode was used to monitor the rotation of the chopper and to synchronize the lock-in amplifier (at about 330 Hz). The output from the Putley detector for the chopped microwaves was used (i) to monitor the microwave frequency dependent transmission through the cell and (ii) to measure the microwave input power during the absorption experiments before the helium was charged. The linearity of the Putley detector was carefully checked at all operating temperatures and was accurately linear up to an output voltage greater than 1000 mV, corresponding to some 400 nW absorbed in the InSb element. The transmission loss from the source through to the detector was typically in the range −23 to −40 dB.

[1] Radiometer Physics Gmbh.

[2] E. H. Putley, Appl. Opt. **4**, 649 (1965).

[3] QMC Instruments Ltd.