Towards Paul trapping of single electron bubbles in liquid helium

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Synopsis Single electron bubbles (SEBs) in liquid ^{4}He place an electron spin in a defect-free, nuclear-spin-free host. We present a strongly overdamped surface-electrode Paul trap for SEBs whose trap depth is limited by vortex-ring nucleation, with an operating window at 0.7 K (20–25 V, 0.5 MHz) and a DC-transport and acoustic-cavitation scheme to test confinement.

Solid-state spin qubits are limited by defects, interfaces and magnetic impurities in their host. Electrons floating on liquid helium [1] or solid neon [2] avoid bulk defects but remain bound to a surface. In bulk liquid ^{4}He, an excess electron is repelled by Pauli exclusion and self-traps inside a cavity of radius ≈ 1.9 nm set by zero-point energy, surface tension and pressure. While this single electron bubble (SEB) places the electron spin in a defect-free, nuclear-spin-free liquid, spatially confining the bubble within the bulk liquid remains a central challenge.

To achieve this, we have built a surface-electrode point Paul trap [3] for SEBs (figure 1(a)). A grounded central disk (radius 0.5 mm) concentric with a radio-frequency (RF) ring electrode (outer radius 3.5 mm) forms an on-axis RF electric-field null ≈ 1 mm above the electrode surface.

In liquid ^{4}He at 0.7 K, thermal roton and phonon scattering strongly damps the SEB motion. Its mobility [4] and hydrodynamic mass $m^* \approx 243\, m_{\mathrm{He}}$ give a momentum-relaxation time $\tau \approx 55$ ns, corresponding to $\Omega\tau \approx 0.17$ at $\Omega/2\pi = 0.5$ MHz. In this overdamped regime, the micromotion is supressed and phase-lagged, reducing the pseudopotential depth $\Psi = e^2E^2/[4m^*(\Omega^2 + \tau^{-2})]$ (for RF field amplitude E) by a factor of ≈ 35 compared to vacuum [5]. Here $\Psi = m^* v_1^2/4$ equals the mean micromotion kinetic energy for velocity amplitude v_1. Because an SEB moving faster than $v_c \approx 20\ \mathrm{m\,s^{-1}}$ nucleates and attaches to a quantized vortex ring [6], the trap depth cannot exceed $\Psi_{\max} = m^* v_c^2/4 \approx k_B \times 11.7$ K for any trap geometry or drive frequency. Electrostatic field calculations and driven Langevin simulations place the 0.7 K operating window at $V_{\mathrm{rf}} \approx 20$–25 V, giving a well depth of ≈ 7–10 K while keeping $v_1 < v_c$ (figure 1(b)).

We inject SEBs from a ^{63}Ni β-source and detect them by acoustic cavitation [7], using the negative-pressure swing of a focused ultrasound pulse to expand an SEB past its tensile stability limit to an optically detectable size. Because the trap sits above the acoustic focus, a DC-electrode sequence controls the SEB density during loading and then guides trapped bubbles from the RF null into the focus. Comparing cavitation counts with the trap switched on and off provides a direct test of confinement. The experiment is currently underway.

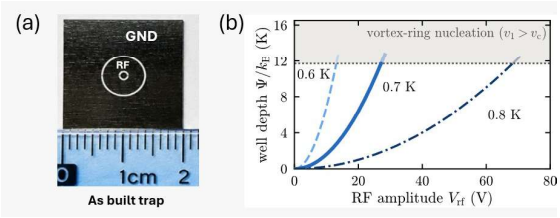

Figure 1. (a) As-built trap. (b) Well depth vs RF amplitude at 0.5 MHz with the vortex-ring nucleation ceiling ($v_1 > v_c$).

References

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