The Surface of Liquid Helium - an Unusual Substrate for Unusual Coulomb Systems

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1 Introduction

The study of basic physical problems has always benefited from a choice of systems which are as simple as possible. In atomic physics such a system is apparently the hydrogen atom. I would like to discuss in this lecture an example in the field of condensed matter physics, which in its simplicity, but moreover also with respect to some of its particular features bears some resemblance with the hydrogen atom. The topic are electrons, trapped at the surface of liquid helium [1].

Imagine an electron, supplied by a suitable source in the vapor space above the helium surface, which is pulled towards the liquid by an externally applied weak electric field. Close to the surface the potential for the electron, given by the image charge resulting from the polarization of the liquid, is

\[ V(z) = \frac{e^2(\varepsilon - 1)}{4\varepsilon z(\varepsilon + 1)} \]

where \( z \) and \( \varepsilon \) are the distance from the surface and the dielectric constant of helium, respectively. For \( z < 0 \), i.e. inside the liquid, the potential is about \(+ 1 \text{ eV}\). The electron is therefore trapped above the surface in a potential well, acting perpendicular to the surface, whereas parallel to the surface it is (nearly) free to move.

The potential well given by Eq. (1) is in its \( z \)-dependence identical to the radial dependence of the hydrogen potential. Hence we obtain similar energy levels for such a surface state electron (SSE) on helium as for the hydrogen atom, yet with a pre-factor which is four orders of magnitude smaller, because the image charge is only a small fraction of the elementary charge. The ground state, for example, instead of being 13.6 eV is only 1 meV below the vacuum level. The corresponding effective "Bohr radius", describing the average distance of the electron from the surface, is 76 Å, large compared to the interatomic spacing of the helium surface, so that this "substrate" appears essentially smooth for the electron\(^1\). Experimentally, the existence of

\(^1\) apart from quantized surface waves (ripplons) from which the electrons can be scattered as discussed below
Fig. 1. Experimental trace showing the absorption derivative due to surface state electrons on liquid helium versus voltage across the experimental cell. The incident microwave frequency was 160 GHz and the temperature 1.2 K. The linear Stark effect was utilized to tune the splitting between bound electronic surface states to resonance with the incident radiation. The $1\leftrightarrow2$ and $1\leftrightarrow3$ transitions are analogous to the Lyman-$\alpha$ and -$\beta$ transitions of hydrogen. (From Ref. [2]).

the hydrogen-like energy levels of SSE was confirmed by Grimes and Brown using a spectroscopic measurement in the microwave regime [2]. (See Fig. 1).

If we put more than one electron into the surface potential well, we have to consider the Coulomb interaction among the charges, and also the Fermi nature of the electrons. The latter aspect, however, will only become important if the thermal de Broglie wavelength $\lambda_{th}$ is comparable to or larger than the interparticle distance $r$. For $\lambda_{th} \leq r$ the electrons are expected to behave classically in their motion parallel to the surface. Since most of the experiments to be discussed here were carried out in the temperature range around 1 K, corresponding to $\lambda_{th} \approx 10^{-3}$ Å, the electrons can be treated as a classical 2-dimensional Coulomb system up to densities of $10^{10}$ e/cm$^2$.

2 Some Basic Experiments with Surface State Electrons

In a way, the electron sheet on liquid helium represents the most simplified and abstract realization of a physisorbed film on an inert substrate. It turns out, nevertheless, that in spite of this simplicity it provides a rich variety of physical phenomena:

i) As already indicated the electrons are essentially free to move in directions parallel to the surface. Scattering by ripplons and, at temperatures above $\sim 1$ K, by atoms in the gas phase limits the mobility. In addition