Electron tunnelling through a quantifiable barrier of variable width.

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Abstract. This is the first study of electron tunnelling through a quantifiable barrier of adjustable width. We find quantitative agreement between the measured and calculated tunnelling probability with no adjustable constants. The tunnel barrier is a thin film of ³He on Cs, which it wets. We excite photoelectrons which have to tunnel through the barrier to escape. The image potential must be included in calculating the barrier and hence the tunnelling current. This has been a debatable point until now. We confirm that an electron has a potential of 1.0 eV in liquid ³He for short times before a bubble forms. We show that the thickness of the ³He is given by thermodynamics for films of thickness at least down to 3 monolayers.

1. Introduction
In this paper we show that a thin film of liquid ³He makes an ideal tunnelling barrier for electrons. As the geometry and potentials are independently measured we can calculate the tunnel current without any adjustable constants and compare it with measurements. As tunnelling is a fast process, the electron spends little time in the material of the barrier, so the instantaneous potential is relevant. This is important when the barrier is liquid helium, as an electron bubble can form over a long time period but does not form in the fast tunnelling process.

Another important contribution to the potential barrier is the interaction energy of the tunnelling electron with the nearby metal electrodes. This is the image potential and has often been omitted from analyses of tunnelling currents because there has not been a clear demonstration that it is essential; although it is essential for the energies of absorbates [1]. We show that the image potential has a very large effect on the value of the tunnelling current and it must be included in any quantitative consideration of tunnelling.

2. Experimental Method
The tunnelling electrons are photo-emitted from a thin cesium film which is evaporated in-situ at $T \leq 80$ K, onto a gold plated Dove prism. The anode, a thick gold film is mounted parallel to the photocathode and ~20 mm above it, and held at a potential of typically 100 V with respect to the photocathode; this potential is much greater than the contact potential between the Cs
and Au which is \( \sim 3 \) V. The photocathode is illuminated with monochromatic light from an Acton Research ARC 275 monochromator, which enters the cell through four windows of BK7 glass. The photocurrent is measured with a Keithley 617 electrometer.

The brass cell is inside of a Janis \(^4\)He bath cryostat, and is completely immersed in liquid helium at 1.3 K. The pressure in the cell is measured through a 1 cm diameter tube. A quantity of \(^3\)He is added slowly at \( \sim 4 \times 10^{-7} \) mol s\(^{-1}\). After which equilibrium is reached in 15 to 30 minutes. The photocurrent is measured as the wavelength of the light is swept from 350 nm to 850 nm and back at a speed of 100 nm/min, which is well below the response time of the electrometer. This is repeated for a series of pressures up to the saturated vapour pressure. The maximum current is typically \( 10^3 \) pA at a wavelength \( \sim 530 \) nm, and the signal to noise ratio at this current is \( \sim 10^4 \). We checked that the power of the incident light is not sufficient to locally heat the substrate and thus change the thickness of the adsorbed film. The film of liquid helium on the anode does not impede electron collection by the anode, under steady state conditions.

![Figure 1](image.png)

**Figure 1.** The measured photocurrent in pA, with a vacuum and with liquid \(^3\)He films, is shown as a function of photon energy. The film thicknesses calculated from Eq. (5) are 0, 8.7, 10.2, 12.3, and 14 Å. Also shown are the calculated currents (solid lines) from the model using Eq. (4) with \( \alpha = 20 \) for \( d = 8, 11.5, 15 \) and 17.5 Å, i.e. film thicknesses 6.1, 9.6, 13.1 and 15.6 Å.

![Figure 2](image.png)

**Figure 2.** The electron potential energy is shown as a function of distance \( d \) from the Cs surface, Eq. (2). The potential is the sum of the image potential and the potential of an electron in liquid \(^3\)He. For times so short that a bubble cannot form, this is 1.0 eV. The film is shown extending to \( d = 15 \) Å. The tunnel barrier is shown hatched. \( z_0 = 1.9 \) Å.

3. Results and Analysis

The measured values of the photocurrent as a function of photon energy are shown in figure 1. The top curve is the photocurrent in a vacuum, and shows the current starting when the photon energy equals the work function. The lower curves correspond to increasing \(^3\)He pressures. The photocurrent decreases rapidly with increasing pressure. It can be clearly seen that the increasing thickness of the \(^3\)He film, which creates the tunnel barrier, increasingly attenuates the current from low energy photons, as lower energy electrons have a lower probability of tunnelling.

The photocurrent is determined by scattering in the gas and tunnelling through any liquid \(^3\)He film on the cesium. The effect of the gas is twofold; electrons are scattered back into the photocathode very soon after they are emitted and they are scattered on their path to the anode.
which reduces their mobility. The photocurrent $i$, relative to the vacuum photocurrent $i_0$, is given by [2]

$$\frac{i_0}{i} - 1 = \frac{\sqrt{KE_1 KE_2}}{2\lambda e\Xi} = \alpha \text{ where } KE_1 = 0.6(\epsilon_p - \phi_w) \text{ and } KE_2 = \frac{2e\Xi\lambda}{\sqrt{2\sqrt{6\pi}f}}$$  

(1)

where $KE_1$ and $KE_2$ are the kinetic energies of the electrons near to and far from the photocathode, respectively; $\lambda$ is the electron mean free path in the atom gas, $f$ is the fraction of energy lost in each collision, $f = 2m_e/m_a$ where $m_a$ is the mass of the $^3\text{He}$ atom, $m_e$ is the mass of the electron, $\Xi$ is the electric field, $\epsilon_p$ is the photon energy and $\phi_w$ is the workfunction. In our experiments the pressure, $p$, is low and $\lambda = k_BT/p\sigma$ is long, and the electrons are not thermalised by scattering with the gas [2, 3]. The parameter $\sigma$ is the low energy electron-atom collision scattering cross section, $\sigma = 4.99 \text{ Å}^2$ [4]. As the gas pressure is increased $\lambda$ decreases and the current decreases too. The electric field is high enough that the electron, far from the photocathode, loses its memory of its injected energy and its kinetic energy is due to the drift velocity in the electric field.

We now consider the tunnel barrier created by the $^3\text{He}$ film. An electron in liquid helium has a potential energy of $\phi_{\text{He}} \sim 1 \text{ eV}$ [5]. This is the potential before the electron has had sufficient time to create a bubble and so lower its energy. This time is of the order of $d_0/s$, where $d_0$ is the bubble diameter, 34 Å and $s = 238 \text{ m/s}$ the velocity of sound in liquid helium, $d_0/s \sim 1.4 \times 10^{-11} \text{ s}$. A typical tunnelling time is $(m_e/(2V_0 - E))^{1/2}d$ [6], so the time to go $d = 20 \text{ Å}$ is $\sim 10^{-15} \text{ s}$. Thus the tunnelling electrons do not even begin to create bubbles.

An electron, in the vacuum outside the Cs, will have a potential energy due to its image charge, so the total potential energy of an electron on a film of liquid helium on Cs is

$$V(z) = -\frac{e}{16\pi\epsilon_0 z} + \phi_{\text{He}}$$  

(2)

Here $z$ is the distance of the electron from the surface of the Cs. The $1/z$ potential cannot be correct for energies below the Fermi energy in the Cs, as electrons in the Cs could otherwise lower their energy by moving into the $1/z$ potential well. We cut off the $1/z$ potential at $z_0$ where $z_0$ is given by $e/16\pi\epsilon_0 z_0 = \phi_w$, hence $z_0 = 1.9 \text{ Å}$ for $\phi_w = 1.9 \text{ eV}$. The helium atoms cannot approach the Cs surface closer than $z_0$ due to electron repulsion between the electrons on the He atom and the conduction electrons. This is important when we discuss the film thickness later. The potential is shown in figure 2. The shaded area is the tunnel barrier due to a helium film.

The tunnelling probability $p_t$ is calculated in the WKB approximation:

$$p_t(\epsilon, d) = \exp (-2 \int_{z_1}^d k \, dz) \text{ where } k \text{ is given by } \frac{\hbar^2 k^2}{2m_e} = (V(z) - \epsilon) \text{ for } 0 < \epsilon < V(z)$$  

(3)

The energy of the electron $\epsilon$ is relative to the vacuum energy which is taken as zero. The end of the film is at $z = d$. We have approximated the prefactor to 1 in equation (3).

We now combine this escape probability with the back scattering of the gas, Eq. (1), [3]

$$\frac{i}{i_0} = \frac{t}{1 + \alpha t}$$  

(4)

where $t$ is the average tunnelling probability over the range of electron energies 0 to $\epsilon_p - \phi_w$.

We calculate the current as a function of $\epsilon_p$, when there is a tunnel barrier, from the measured vacuum current. We use $i_0/i - 1 = 20$ for all $\epsilon_p$ when there is tunnelling. The measured and
calculated currents, as a function of photon energy, are shown in figure 1. There is generally good agreement. The energy of the peak of the thinnest film is not shifted much from the vacuum current. This is because the tunnelling with \( t \sim 0.2 \) only has a small effect on the current as \( t/(1 + \alpha t) \) is not very different to \( 1/(1 + \alpha) \) for this value of \( t \). For thicker films, \( \alpha t \) in equation (4) is smaller, as \( t \) decreases rapidly with film thickness for the lower energy electrons, and this causes the peak to shift to higher energies. The top of the barrier for \( d = 15 \text{ Å} \) is 0.8 eV, so for photons with energy \( \epsilon_p > 2.7 \text{ eV} \), the photocurrent becomes weakly dependent on the photon energy as electrons increasingly go over the top of the barrier, as clearly seen in figure 1.

The film thicknesses \( d \) can be calculated from \( \Delta \mu \):

\[
\Delta \mu = -\Delta C_3/d^3 = k_B T \ln(p/p_0)
\]  

(5)

This equation is only expected to apply to liquid films of several monolayers.

The \(^3\text{He}\) film thickness from the tunnelling measurements is found by fitting the measured and calculated current as a function of photon energy, as shown in figure 1. This gives a value for \( d \). The film thickness is then \( d - z_0 \). As \( z_0 = 1.9 \text{ Å} \), the three film thicknesses from tunnelling are 6.1, 9.6 and 13.1 Å, and from the chemical potential, using \( \Delta C_3 = 700 \text{ KÅ}^{-1} \), we calculate 8.7, 10.2 and 12.3 Å. Thus, for the second and third thicknesses, the agreement is better than 10%. For the thinnest film, the thickness is poorly determined by the tunnelling, as the current is mainly determined by the gas. The cautious conclusion is that equation (5) applies at least down to 3 monolayers of helium.

4. Conclusions

We have shown that liquid \(^3\text{He}\) on Cs is an electron tunneling system which has a tunnel barrier with adjustable width, so that the effect of the width of the barrier can be studied while everything else is kept constant. The behaviour can be explained without any adjustable constants. The system has other attributes, the Cs surface is very clean, the barrier is pure liquid \(^3\text{He}\) which gives a very well defined tunnel barrier, the geometry is planar and well defined so the measurements can be analysed, at larger film thicknesses we have an independent measure of the barrier thickness because the film thickness is set by thermodynamics, and we directly measure the work function of the Cs.

The image potential substantially reduces the thickness of the barrier for the thin films we have measured. For example for \( d = 15 \text{ Å} \) and 2.2 eV photons, with the image potential \( t = 1.33 \times 10^{-3} \) and without it \( t = 9.61 \times 10^{-7} \). The values of \( t/(1 + 20t) \) are \( 1.29 \times 10^{-3} \) and \( 9.61 \times 10^{-7} \), respectively. So the current would be orders of magnitude lower without the image potential, and we could not explain our results without it. As we have an independent measurement of the thickness of the film which creates the barrier, which is not the case for most barriers, we have the strong result that the image potential must be included in the calculation of the tunnel barrier.

Several important conclusions can be drawn. They are, 1. the image potential must be included in the potential barrier as it makes a very large effect, 2. the thickness of the thin film of liquid \(^3\text{He}\) is given by its chemical potential from thick films down to thin films of at least 3 monolayers, 3. confirmation that the electron potential of an electron in liquid \(^3\text{He}\) is 1.0 eV.

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