Scanning Tunnelling Microscopy

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Introduction

Scanning tunnelling microscopy is the practice of imaging at the atomic scale. An image of the scanned object is formed when the sharp tip of the microscope is brought close to the surface and a voltage is applied. This potential results in electrons tunneling through the vacuum that separates the tip and object. Certain conditions are necessary for this phenomenon to occur which will be further discussed in this report, among other aspects of quantum mechanics that allow for scanning tunnelling microscopy.

Discussion

Scanning tunnelling microscopy is predicated on the quantum mechanical phenomenon knows as tunnelling. This non classical scenario exists when a particle of quantized energy E approaches a barrier with potential (often denoted as) V_0 where $E < V_0$. The particle is capable of tunnelling through the potential barrier with a probability[1]

$$P = \frac{|F|^2}{|A|^2} = \frac{16E(V_0 - E)}{V_0^2} e^{-2\kappa b}$$

where F and A are the amplitudes of the transmitted and incoming particles' wave, respectively. The width of the barrier is b and the κ factor considers the height of the barrier. The amplitude of the particle decreases as it tunnels through the barrier, and so, $F < A$. With the framework of quantum tunnelling established, we can now explore how this has been applied to microscopy.

The barrier in the case of microscopy is a region of space, on the order of a few angstroms, between the microscope tip and the surface of the object[2]. As the needle tip is moved along the surface with a certain voltage applied, the current caused by the transfer of electrons by way of tunnelling is used to determine the changes in distance between tip and sample[3]. This tunnelling current I can be written as the following proportionality

$$I \propto e^{\frac{-2z}{\lambda}}$$

where z is the barrier length and λ is known as the tunnelling depth, how far the particle's wave function extends into the barrier[4]. To understand the effect of λ, the energy levels of the system must be explored first. The height of the barrier is determined by the work function, ϕ, of the two metals; the minimal work necessary to remove an electron from the solid to a point in the vacuum. The electrons in the metal are modelled as particles in a finite well with quantized energy levels with every energy state filled up to a single work function below the energy of a free electron. This maximum level is known as the Fermi level, E_F [4]. The induced voltage results in the Fermi levels of the two metals to be unequal, allowing for the electrons from the higher energy state to tunnel to the lower state[5]. The λ term can now be defined as[4]

$$\lambda = \frac{\hbar}{\sqrt{2m\phi}}$$

where m is the mass of the particle and $\hbar$ is the reduced Planck's constant.

The sole purpose that scanning tunnelling microscopy is predicated upon is the exclusive quantum mechanical phenomenon of tunnelling. Classically, a particle with a certain energy cannot overcome a barrier with a higher (potential) energy, like a ball rolling towards a hill. As such, there is no classical equivalent to tunnelling microscopy. The probabilistic nature of quantum particles defined by their wave functions allows for a realm of physical possibilities that cannot be described classically[6]. The definite state of classical systems prevents any possibility of a particle travelling through a barrier. Such a particle must have enough energy to overcome the barrier.

Scanning tunnelling microscopy has allowed us to develop an understanding of the atomic scale by providing an imaging technique that is not confined by classical laws. Gaining insight at this subatomic scale allows for researchers to better understand various material properties. Understanding friction and surface chemical reactions become much easier with the level of detail that this method provides[7]. Additionally, as IBM showed using 35 Xenon atoms to draw their logo, lithography is in the realm of possible applications of tunnelling microscopy[8].

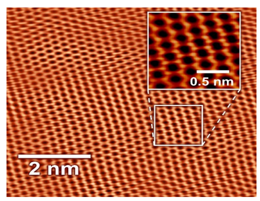

Figure 1: STM image of graphite displaying the nanostructure of the material[9]

The ability of a scanning tunnelling microscope to effectively operate at extreme temperatures is another valued aspect. Cooling the microscope to temperatures below 4 K allows for the study of superconductive materials. Operating at temperatures well over 900 K shows the effects of diffusion on the surfaces of various metals[10]. The spatial precision that the microscopy provides is also an effective way of fabricating nanostructures. The ability to create atomic structures has allowed for scientists to make a current amplifier out of a C_{60} molecule, for instance[11]. Despite the high spatial precision of the microscope, the time aspect remains an issue. The imaging and atomic manipulation processes are both time consuming, on the order of seconds, which limits their functionality and widespread usability[12].

Conclusion

The idea of taking images at the atomic scale is a profound one, and the quantum mechanical phenomenon of tunnelling permits just that. Applying a voltage between the microscope tip and object surface, the tunnelling electrons induce a current that is used to detect the structure of the metal surface. This method carries various applications that are not possible in the classical sense such as the manufacturing of nanostructures and examining of material properties at the smallest possible scale. Continuing research in this field is focused on improving the effectiveness of these applications in order to fully exploit the capabilities of quantum mechanics.

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