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Aspects of Photon Emission from Metallic Surfaces in the Scanning Tunneling Microscope

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The first observation of photon emission from the tip–surface region of a scanning tunneling microscope in 1988 [1 to 3] stimulated several fundamental experiments into the nature of inelastic tunneling, energy dissipation, and tip–surface interactions. In addition to conventional (elastic) tunnel current related phenomena such as topography, I–U spectroscopy, and barrier height measurements, photon emission can be simultaneously studied. Their respective analogues are photon mapping, isochromat spectroscopy, and intensity–distance measurements. Furthermore, investigation of the spectral distributions of emitted photons can be readily performed using a simple optical spectrometer equipped with an optical multichannel analyser [4].

The interaction of electrons with a metallic surface is known to give rise to the excitation of surface plasmon modes of well defined energies. Light emission increases in intensity with electron energy and, at the energies involved in tunneling, conventional considerations would predict that emission is essentially negligible on flat surfaces. Fluorescence spectra obtained at elevated tip voltages ($U_t \gtrsim 100$ V) have been assigned to transition radiation and emission from surface plasmons for noble-metal surfaces in accord with conventional electron bombardment studies.

However, in the tunneling regime ($U_t \lesssim 5$ V) and in the proximity field emission regime ($U_t \lesssim 40$ V), the discovery of red-shifted emission with enhanced photon intensities (quantum efficiency $\approx 10^{-4}$ photons/electron for W tips on Ag [3]) on noble-metal surfaces showed that the physics underlying photon emission in the STM was strikingly different. Furthermore intense photon emission was also detected from transition-metal surfaces [5, 6].

This enhanced emission has recently been explained in terms of the radiative decay of tip-induced localized plasmons that actually couple to tunneling electrons primarily via inelastic tunneling [6, 7]. Several theoretical [8 to 10] and experimental results supporting such mechanisms are outlined below: Firstly, a lack of a significant bias dependence in fluorescence yield and spectral distribution support a resonant process. Next, model calculations, of the experimental results [8 to 10], agree well with fluorescence spectra measured for transition-metal tips. Furthermore, experimental photon intensities also show an encouraging similarity lending persuasive support to our interpretation.

It is also significant that higher intensities and new spectral features found using noble-metal tips, and the angular distribution of the photon intensity also fit well in the framework outlined above. Enhanced photon emission is not only confined to the tunnel

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regime. Field emission resonances are also detected in isochromat spectra and signal a clear indication of inelastic tunneling at energies of up to 50 eV [2, 7, 11].

It should be noted that the final density of states, which lie at an energy $h\nu$ below the Fermi energy of the emitter, strongly affects the photon intensity. This intensity depends also on the tip–sample distance.

The above concepts have been applied in interpreting photon maps that exhibit clear contrasts depending on surface material and geometry. Contrasts on a length scale of ≈ 20 nm, which are attributed to variations in the probabilities for excitation and radiative decay of plasmons have been used to demonstrate that tip-induced plasmons are localized below the tip apex [5]. Two mechanisms have been invoked to explain modification of the excitation probability on an atomic scale: firstly the junction geometry modifies the field enhancement of the tip-induced plasmons and their coupling to tunneling electrons. In addition, the existence of a second contrast mechanism has been shown using bias-dependent photon maps. This mechanism has tentatively been assigned to variations in the local density of states below the Fermi energy. Hence, photon maps contain information about the local chemical composition of the surface.

The enhancement of electromagnetic fields in surface microstructures can significantly modify physical properties of systems. One startling example is the surface enhanced Raman scattering (SERS) effect. Proposals that the pore structure of coldly condensed Ag films facilitates SERS activity previously received much attention [12] as well as additional considerations of local charge transfer processes [13]. Although early work lent support to the presence of microstructural features on the appropriate scale from interpretation of STM micrographs [14] observation of electromagnetic enhancement in the cavity between Ag tip and Ag surface provides a controlled means to investigate the geometric dependence

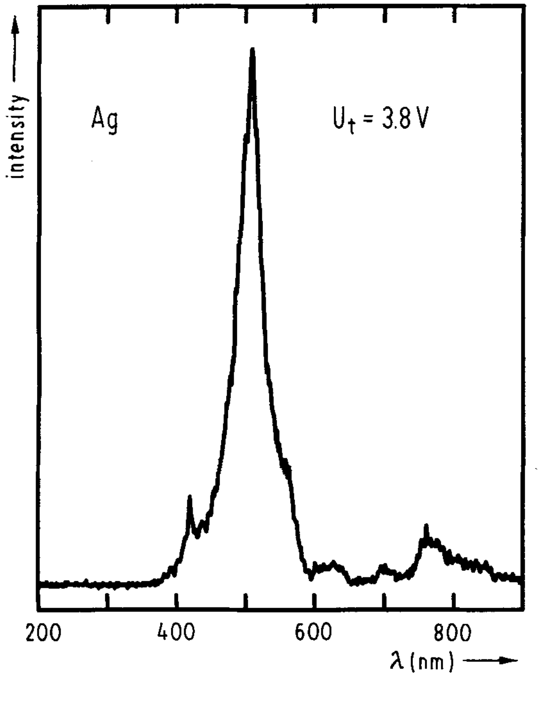

Fig. 1. Fluorescence spectrum from an Ag surface excited by tunneling electrons from an Ag-coated W tip. The FWHM of the emission feature is ≈ 0.2 eV

of this effect using photon emission. Fig. 1 shows a particularly interesting example of how well defined such resonances can occasionally be. The spectrum was obtained for an Ag-coated tip operating on an Ag surface. The emission feature at ≈ 2.5 eV has a FWHM of only 0.2 eV and an the emission intensity corresponds to an estimated photon yield of $\approx 10^{-4}$ photons/tunnel electron.

The phenomena of photon emission with metals may be of potential use as a single photon source. Due to their fermion character and Coulomb repulsion, electrons are expected to traverse the tunneling barrier one at a time at the currents used in our experiments. Selecting photons close to the quantum cut-off energy should ensure that only a single photon of that energy is emitted. To date only approximations to single photon sources have been experimentally realized [15] and several detailed tests are required to confirm the single photon nature of emission from the STM.

In conclusion, photon emission from STM provides a unique tool to explore inelastic pathways of tunneling electrons through the barrier region. In a more general sense the technique can provide chemical information as well as give a deeper insight into the role of electromagnetic coupling between the tip and surface.

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