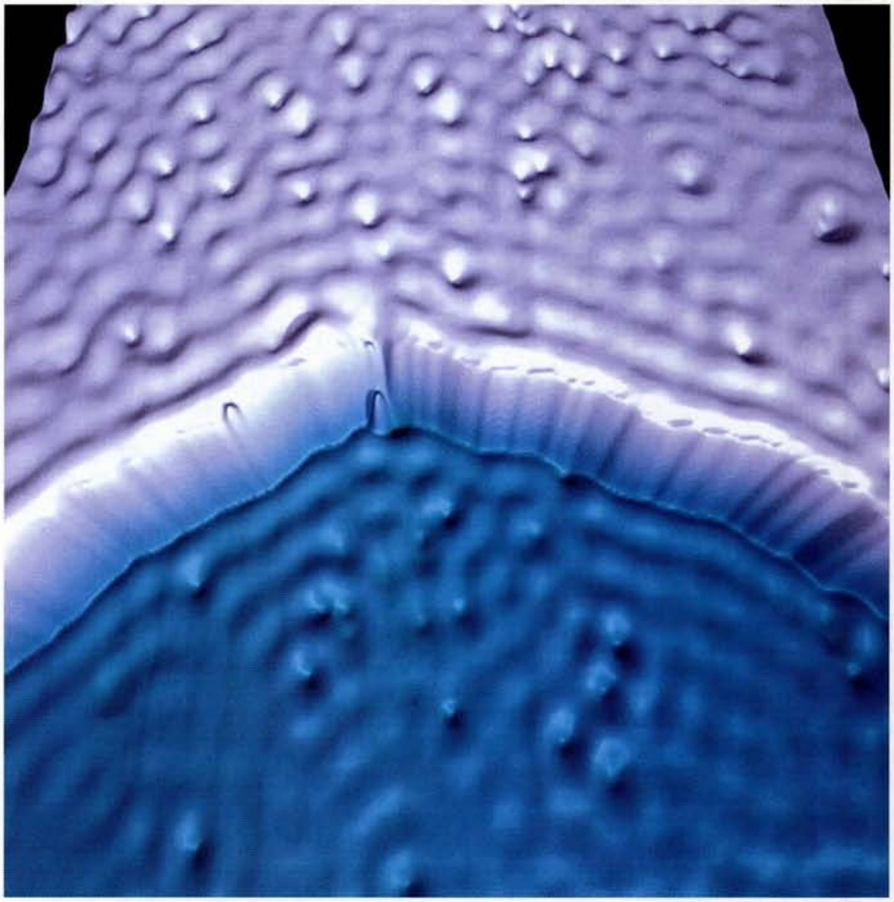
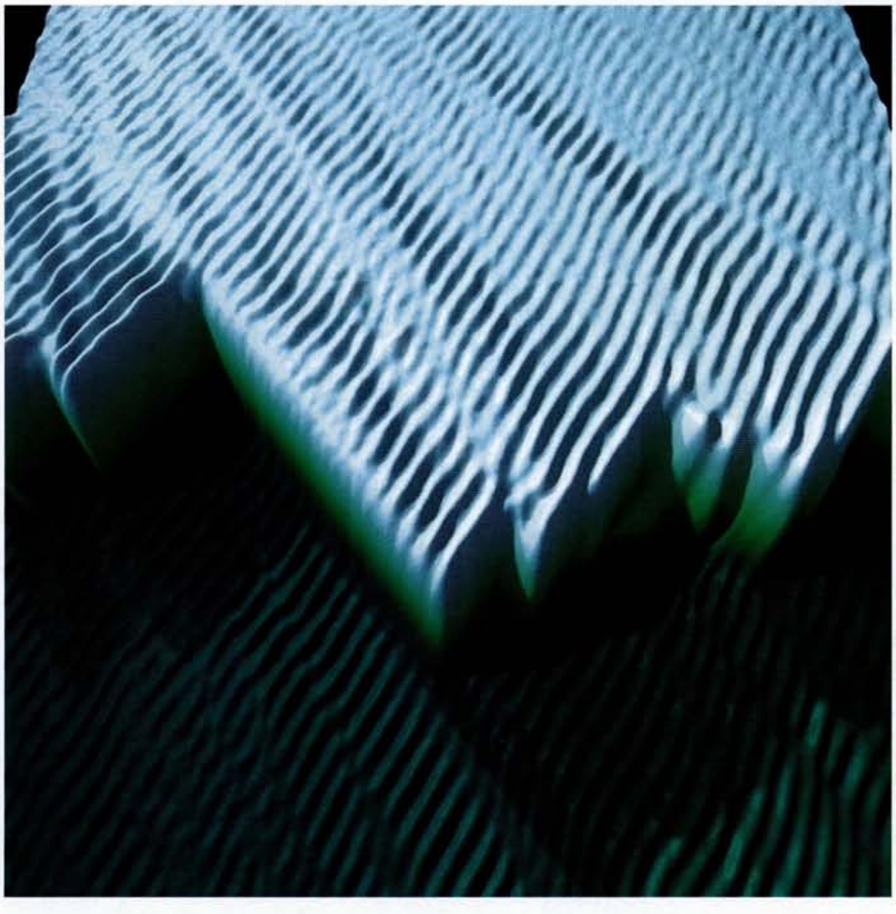
Fig 1





These days we no longer need to imagine quantum mechanics, we can see it with our own eyes

Fig 3

Looking at electronic wave functions on metal surfaces

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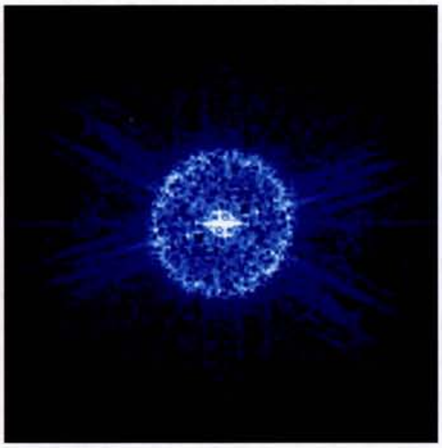

Fig 2

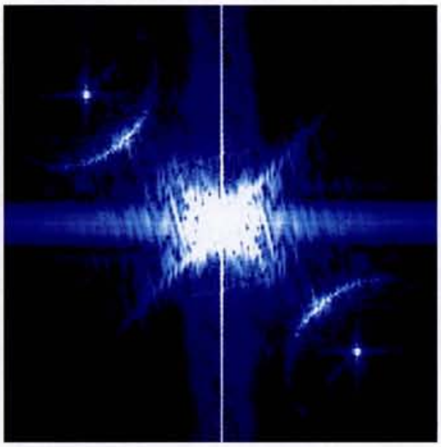

Fig 4

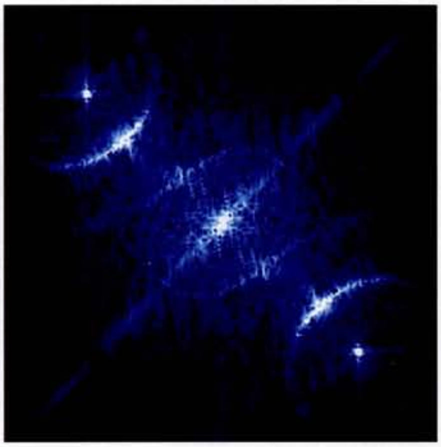

Fig 5

The wave function ψ completely describes the motion of a particle (or an ensemble of particles), but unfortunately is not directly observable in an experiment. There are, however, different ways to obtain experimental evidence for the wave-like nature of a particle state. Perhaps the most straightforward way to do that is based on the phenomenon of interference. If two beams of coherent light cross each other, a periodic variation of the light intensity is observed in the crossing zone. Such a standing wave pattern is a fingerprint of the photonic wave functions. It is an important peculiarity of quantum mechanics that interference phenomena are not restricted to the situation where two different waves cross – a particle wave can also interfere with itself. This phenomenon occurs, for example, when a particle is scattered by an obstacle. In the vicinity of the obstacle the incoming and the scattered parts of the particle wave interfere and create a standing wave pattern of the probability density. This means that when we look for the particle we are more likely to find it on the wave crests than in the troughs of the interference pattern. Because every particle wave interferes with itself the same scattering experiment can also be performed with many independent particles (in this case the interference pattern represents a particle

The project described here is not only a beautiful example of the visual side to physics, it is also a beautiful example of international cooperation. The first use of the idea—to apply a Fourier transform to STM pictures to see electron waves instead of just the surface atoms—came out of a collaboration between Plummer, Sprunger and the Aarhus group headed by Besenbacher. Hofman, who had been working at Tennessee, took Be(1010) samples to Berlin where the images shown in this pictorial were taken. All of the participants are now preparing a paper on the use of a Fourier transform to map the Fermi contour at metal surfaces. (TC)

density wave). When the particles carry 'charge' (this could be just electric charge, spin, magnetic moment or any other quantity which is a constant for every particle) the particle density wave in the vicinity of the obstacle transforms to an analogous wave-like perturbation of the charge density. This is exactly the quantity which is accessible to an experiment. Here it is shown how charge density oscillations can be observed on metal surfaces.

Some electrons on certain metal surfaces are allowed to move in directions parallel to the surface but they are forbidden to plunge into the bulk of the metal. These so-called surface state electrons can be thought of as a two-dimensional gas of particles. The motion of this 2D electron gas is hindered by the different kinds of obstacles which are found on surfaces such as step edges, dislocations, point defects or adsorbates. According to what has been explained above, scattering at these obstacles induces a wave-like perturbation of the surface state charge density. The shape of this charge density oscillation was theoretically predicted by Friedel almost forty years ago for the case of a charged impurity in a gas of free electrons – see Friedel, *Nuovo Cimento (Suppl.)* 7, 287 (1958). But it took quite a long time until Friedel oscillations could be imagined in an experiment. In 1993, two research groups at IBM Almaden and IBM Yorktown Heights found wave-like patterns on the (111) surfaces of copper and gold – see *Nature* 363, 524 (1993), and *Phys. Rev. Lett.* 71, 1071 (1993). Both groups used a scanning tunnelling microscope (STM) to image the surface charge density with high lateral resolution. An example of what charge density oscillations on (111) noble metal surfaces look like is shown in *fig* 1. We have recorded this image of a silver (111) surface with an STM which operates at temperatures down to 4 K. It is clearly visible in *fig* 1 that wave trains emanate from the two differently oriented step edges and from the point-like depressions on the terraces. The circular wavelets which appear near point impurities indicate that the electrons on Ag (111) can hit the impurities from all directions, they are free as far as their motion parallel to the surface is concerned. By calculating a two-dimensional Fourier transform the wavelengths which are contained in *fig* 1 can be analyzed in more detail. Such a Fourier image is shown in *fig* 2. It displays a sharp circular feature in the center. The radius of the circle amounts to two times the Fermi wave-vector of the surface state. The Fourier image shows a replica of the surface Brillouin zone with the Fermi contour of the surface state. The circular Fermi contour which we find here clearly evidences the free character of electrons; for a given energy their momentum does not depend on the propagation direction.

These findings have shown how one can look at wave functions on metal surfaces and explore the details of their shape by taking advantage of interference phenomena

To find free electrons on a metal surface is rather the exception than the rule because the periodic lattice potential usually constrains the electronic motion. Indeed one can investigate the interaction between electrons and lattice potential by determining how the electronic momentum depends on energy and propagation direction. Such experiments are usually performed with angle-resolved photoemission, but in principle this information could also be extracted from the charge density oscillations which are observable with the STM. All STM experiments so far have, however, focused on the special case where surface state electrons exhibit the properties of free particles. To explore how the deviation from free particle motion is reflected in the charge density oscillations we have investigated the $(10\bar{1}0)$ surface of beryllium – see *Phys. Rev. Lett.* 79, 265 (1997) and *Europhys. Lett.* 39, 67 (1997). The isotropic Be(0001) surface had already been investigated by groups in Aarhus and Tennessee – see *Science* 275, 1764 (1997). On Be$(10\bar{1}0)$ the surface state electrons can be considered a model system for a non-free two-dimensional electron gas. We have found that the Friedel oscillations on Be$(10\bar{1}0)$ are highly anisotropic. This is illustrated in *fig* 3, an STM image which displays two terraces separated by a zig-zag shaped step edge. The image has been Fourier-filtered to separate the charge density oscillations from the topographic corrugation due to the crystal lattice. One immediately sees in *fig* 3 that the step edges running from top right to bottom left give rise to pronounced wave trains while the remaining step edges induce almost no waves. *Figure* 4 shows the Fourier image of the raw data which were used to prepare *fig* 3. We recognize two peaks at a position corresponding to the lattice periodicity and two semi-elliptic lines around the lattice peaks. These lines represent the Fermi contour of the surface state on Be$(10\bar{1}0)$, that is, the distance from the center of the image to a point on the semi-ellipses equals two times the wave vector of a surface state electron. The offset of the semi-ellipses with respect to the center of the Fourier image indicates that the electronic motion is constrained by the crystal potential.

To investigate the shape of the Friedel oscillations on Be$(10\bar{1}0)$ in detail, we have processed the raw data which were used for *fig* 3 so as to remove the contribution of the step edge in the Fourier image. As a result of this processing step a new ellipse becomes visible in the Fourier image (*fig* 5). The additional ellipse has the same curvature as the brighter semi-elliptic lines, and with respect to them it is shifted by a distance which equals the lattice period. This finding indicates that the Friedel oscillations on Be$(10\bar{1}0)$ contain multiple wavelengths, and that the wavelengths of the individual spectral components differ by inverse lattice vectors. As explained in more detail in *Europhysics Letters,* such a multiperiodic wave pattern reveals the non-free character of the surface state electrons. Non-free electrons in metal crystals are usually described by Bloch functions. Bloch functions are composed of a plane wave and a sum of terms with lattice periodicity. If we take a Bloch function and let it interfere with itself we find that the interference pattern contains multiple wave vectors which differ by inverse lattice vectors. Thus, *fig* 5 shows that the Friedel oscillations which were observed on Be$(10\bar{1}0)$ are an interference pattern of Bloch electrons. By comparing the spectral weight in the centered ellipse with the stronger semi-ellipses it is even possible to determine the difference of the electronic wave functions from plane waves. In conclusion, these findings on Be$(10\bar{1}0)$ have shown how one can take a look at wave functions on metal surfaces and explore the details of their shape by taking advantage of interference phenomena.

Text by Beat Briner