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LETTER TO THE EDITOR

On the corpuscle–wave transition of electrons in mesoscopic systems†

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Abstract. The electron phase coherence length ξ determines the size regime where a three-dimensional (3D) confinement becomes an electron resonator. ξ may become as large as some μm in mesoscopic metal and semiconductor crystals if inelastic scattering is strongly suppressed. Depending on the confinement size, electrons exhibit either more wave or more corpuscular character. This was recently observed in isolated metal particles as well as in silicon inversion-layer nanostructures. The experimental results favour Einstein's arguments against those of Bohr in the famous dispute as to whether such a wave-corpuscle transition is sharp or not.

An important dispute between Bohr and Einstein concerned the question whether wave and corpuscle properties of energy and matter are mutually exclusive in a single experiment or not. Wave properties are coupled with the appearance of interference phenomena. Historically, this field was mainly covered by optical investigations which were greatly facilitated with the invention of lasers. A recent discussion on the wave-corpuscle duality of photons by Mittelstaedt *et al* [1] favours Einstein's latter hypothesis. Now isolated sub-μm ('mesoscopic') metal crystals were found to allow straightforward studies of electron waves as well. Here the role of the mirror in optical experiments is performed by the crystal surface. We report on experiments which evidence the transition of corpuscle-wave properties for electrons [2–4].

In wave mechanics, one describes itinerant electrons as wavepackets whose spread and shape depend on the phase relation between the partial waves. A wavepacket maintains its phase coherence over some characteristic distance ξ until its energy changes via inelastic scattering. This suggests to relate ξ to the Thouless diffusion length ξ_0 [4] which is

$$\xi_0 = v_F(\tau_E \tau_M/3)^{1/2} \tag{1}$$

for a degenerate electron gas in three dimensions with v_F the Fermi velocity, τ_E the energy relaxation time, and τ_M the momentum relaxation time.

The inelastic scattering time τ_E, usually larger than τ_M by several orders of magnitude, is governed by collisions between electrons and low-frequency phonons as follows from the conservation of energy and momentum:

$$\hbar^2(k+q)^2/2m = (\hbar k)^2/2m \pm \hbar v q \tag{2}$$

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where $\hbar$ is Planck's constant, m is the electron mass, k and q are the electron and phonon wavevectors, respectively, and v is the long-wavelength velocity of sound. Solving equation (2) for q we obtain

$$q = \mp 2k \cos \Phi \pm 2mv/\hbar \qquad (3)$$

where Φ is the angle between k and q.

Equation (3) demonstrates that:

(i) elastic scattering (first term) is dominant and most effective for small Φ

(ii) inelastic scattering (second term) requires long-wavelength phonons just with momenta of $2mv$ only [5].

Owing to the mismatch between the high electron velocity near the Fermi surface, $v_F \approx 10^6$ m s^{-1} and the small velocity of sound $v \approx 10^3$ m s^{-1}, inelastic scattering is much less effective than elastic scattering and $\tau_E \gg \tau_M$ holds at any temperature. The occupation probability of the phonons relevant for inelastic scattering depends strongly on temperature. At room temperature, τ_E lies between 10^{-13} and 10^{-10} s and is larger by about four orders of magnitude if zero temperature is approached [4].

In the range of reduced inelastic scattering at low temperatures, the phase coherence length of electrons was indeed found to become as large as a few μm in 1D and 2D systems [6, 7]. A quantum size behaviour was also discovered quite recently in isolated mesoscopic metal crystals. In these 3D confinements, also called quantum dots or zero-dimensional conductors, the quasistatic conductivity was found to decrease proportionally with the crystal volume [2-4]. The particles undergo a size-induced metal-insulator transition (SIMIT) in the mesoscopic size regime. Surprisingly, however, the SIMIT is observed even at room temperature where thermal energies are significantly larger than the mean level spacings. For bulk metals, ξ should be of the order of 10 nm at room temperature, a value prohibiting the observation of electron phase coherence effects in systems larger than 10 nm, in contrast to the experimental findings. The puzzle was solved by realising that the very phonons in charge of inelastic scattering are missing in mesoscopic crystals [4, 8]. From equation (3), one obtains $\hbar/2mv \approx$ 100 nm for their wavelength. The description of phonons as elastic disturbances travelling at a velocity v through the lattice implies that their wavelength is considerably shorter than the crystal diameter. Otherwise the system becomes a phonon resonator allowing standing waves only, in analogy to the above quantum dot, i.e. an electron resonator. As a figure of merit, considerably more than ten phonon wavelengths should match the lateral size of the crystal. Thus the phonons propagating in a sub-μm crystal have wavelengths shorter than those required for inelastic scattering. In consequence, the probability for inelastic processes is essentially reduced and τ_E as well as ξ become correspondingly larger [4]. Here one encounters the seemingly paradoxical situation that the absence of inelastic scattering in mesoscopic particles, normally expected to enhance their conductivity, converts them into electron resonators and gives rise to the SIMIT. In order to probe quantum size effects, the wave nature of electrons must not be significantly affected by the probe [7]. The contactless quasistatic conductivity measurements of the metal particles are doubtlessly the least invasive method used so far [2, 3].

The inelastic phonons (equation (3)) play an important role in the localisation of the electron waves. Compared with the above-mentioned studies carried out with 1D and 2D confinements at very low temperatures [6, 7], 3D sub-μm confinements give straightforward evidence for the wave character of electrons due to the phonon deficiency.

The transition from the classical corpuscle behaviour (size-independent resistivity) to wave character (size-dependent resistivity) has in fact been detected for metal crystals whose diameters varied between ~10 nm and some μm. The resistivity ρ as a function of diameter x is presented in figure 1. The data were deduced from the quasistatic electrical conductivity dependent on crystal size [2, 3]. The figure also shows the amplitude of resistance fluctuations as a function of probe spacing of silicon inversion-layer nanostructures (right-hand scale) [7]. Both sets of experimental data reveal a transition from the bulk into the quantum regime. The bulk conductivity is described by the corpuscle behaviour of electrons, whereas the quantum conductivity is governed by the wave properties. In agreement with theorcrical predictions [2, 3, 7] the quantum resistivity of the 3D confinements is characterised by the proportionality $\rho \sim x^{-3}$, whereas the resistance fluctuation δR in the inversion layers becomes independent of size. However, a first-principle decision whether the transition is sharp or smooth (dotted regime in the figure) fails owing to the following fundamental physical reasons. In any confinement, the electrons experience random scattering potentials (e.g., at the surface or at lattice defects) and interact with statistical phonon excitations not allowing a sharp onset of inelastic phonons. In addition, an ensemble with mesoscopic particles having identical sizes, shapes and numbers of defects is physically not realisable. All these effects tend to deteriorate the quality of an electron resonator and correspondingly mix the wave and corpuscular properties of electron ensembles in a fairly broad transition regime. Our analysis of the experimental results available so far is in favour

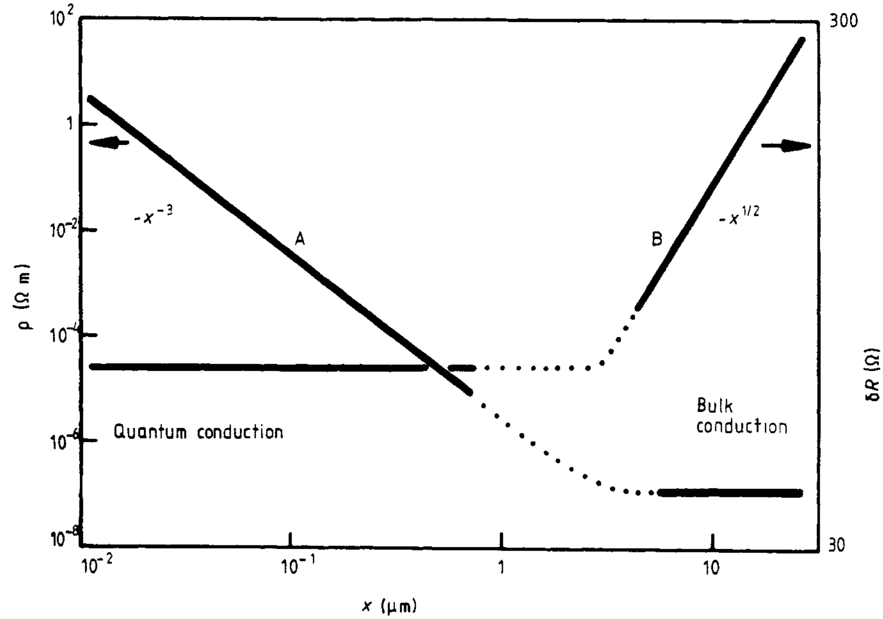

Figure 1. Resistivity ρ (left-hand scale) of isolated mesoscopic metal crystals at 300 K plotted against crystal size x (curve A) (note the log-log scalings). In the μm (dotted) regime a transition from quantum to bulk conduction takes place. Correspondingly, the nature of the electrons changes from wave to corpuscular character. For comparison, the amplitude of resistance fluctuations δR (right-hand scale) in silicon inversion-layer nanostructures at 0.4 K is also plotted against probe spacing x (curve B) (after [7]). The latter experiments indicate a transition from quantum to bulk behaviour in the same size regime as the mesoscopic metal crystals.

of Einstein's ideas. The possible coexistence of corpuscle and wave nature in the transition from bulk to quantum conduction is favoured by principally unsharp experimental conditions.

Evidence for unsharp duality was not sought until very recently in a photon split-beam experiment [1]. In the split-beam experiment, the photons delivering the information on their state of duality are annihilated by the detection process. In contrast, probing the state of duality of electrons in mesoscopic systems by an electromagnetic field does not remove electrons from the investigated ensemble nor does it influence their properties significantly. Mesoscopic metal particles seem to represent an important system to probe and 'shift' (by changing size and inelastic phonon interaction) the duality of electrons.

In conclusion, the SIMIT presents the key for the conditions under which the electron wavepackets experience a size confinement [3]. Dimensionality and size of electron confinements define the requirements allowing us to observe electron interference effects. In wires and thin films, the electron phase coherence length is known to become as large as some μm only at low temperatures [6 ,7]. In these systems, one or two spatial dimensions usually remain large compared to ξ. If all the three dimensions are reduced, a confinement of electrons may initiate a large value of ξ and lead to the SIMIT which in turn limits any further miniaturisation of modern microdevices (VLSI) [4, 9]. In this case, isolated mesoscopic crystals are quantum dots both for electrons and phonons. In mesoscopic systems it is possible for the first time to observe and even manipulate the electron nature with the confinement size.

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