KONDO PHYSICS

What the noise is all about

Shot noise measurements in carbon nanotube quantum dots show many-body effects related to exotic Kondo models with both spin and orbital angular momentum, paving the way for studies on a rich class of strongly correlated transport phenomena.

Reinhold Egger

Probably the best known and most widely studied many-body phenomenon in condensed-matter physics is the Kondo effect. Dating back to the 1960s, it was first invoked by Jun Kondo[1] as the origin of the counterintuitive low-temperature resistivity minimum observed in certain magnetic alloys. Kondo explained this particular feature in terms of the exchange interaction between the spin of conduction electrons and that of magnetic impurity atoms, but the mechanism has since proved exceedingly important in a wide range of interacting many-body problems in condensed matter physics. During the past decade in particular, the Kondo effect has received increased attention[2] as rapid developments in nanotechnology have allowed the controlled manipulation and characterization of 'artificial' magnetic impurities — quantum dots containing just a single unpaired spin — that are exchange-coupled to conduction electrons in connecting leads. More importantly, these new systems allow for the exploration of non-trivial and otherwise inaccessible extensions of Kondo's original model, which was governed by the standard symmetry group SU(2) associated with the electron's spin.

The work reported by Thomas Delattre and colleagues on page 208 of this issue[3] looks at shot noise measurements in carbon nanotube quantum dots (Fig. 1a). In contrast to 'traditional' Kondo systems, carbon nanotube dots possess an additional doubly degenerate orbital degree of freedom. When this 'pseudospin' is combined with the true spin, the resulting 'superspin' may show a Kondo effect with symmetry group SU(4). Shot noise provides valuable information beyond the reach of conventional conductance measurements, and the results reveal characteristic many-body effects that differ from the predictions of SU(2) models because of the orbital pseudospin[3].

In quantum-dot-based systems with only spin degeneracy, the Kondo effect arises from the entanglement of the dot's spin with that of the conduction electrons in the leads (Fig. 1b). At low temperatures compared with the so-called Kondo temperature, a many-body resonance pinned to the Fermi level is formed, which then carries a resonant current (Fig. 1b). In ultra-small solid-state or molecular electronic devices, this effect is ubiquitously seen in Coulomb blockade spectroscopy, and the many-body nature of the SU(2) Kondo effect has been studied in great detail[2].

When further quantum numbers are relevant, more complex situations can arise. This happens in carbon nanotubes where an additional doubly degenerate orbital degree of freedom arises because of clockwise and anticlockwise motion around the circumference of the nanotube (Fig. 1a). Recent experiments in such systems have suggested that one can realize a peculiar spin–orbital Kondo effect with symmetry group SU(4) (Fig. 1c) as well as a purely orbital SU(2) Kondo effect[4]. Similar results have also been reported for semiconductor dots[5].

However, conventional linear conductance measurements alone cannot reliably distinguish between SU(4) and SU(2) Kondo effects[6]. Shot noise, on the other hand, is a versatile tool that can elucidate the difference

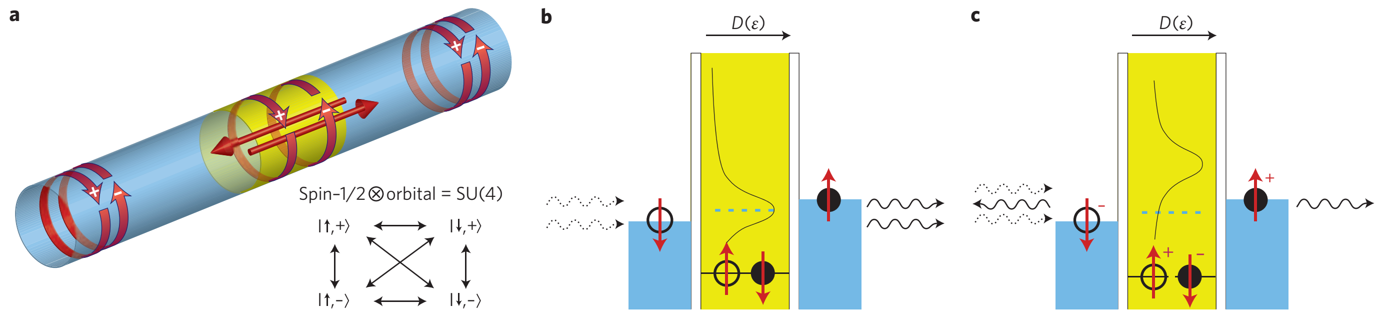

Figure 1 | Spin and orbital Kondo effects in carbon nanotubes. **a**, Schematic diagram of a carbon nanotube dot system with degenerate spin and orbital degrees of freedom. The orbital effects arise because of clockwise and anticlockwise motion around the circumference of the nanotube. If the spin and orbital degrees of freedom are conserved during dot-to-lead tunnelling, the SU(4) Kondo effect can take place (a diagram of the possible spin-flip transitions is depicted under the nanotube illustration). **b**, The spin-flip co-tunnelling process in the SU(2) Kondo effect (only a single orbital state is present). A many-body resonance, the 'Kondo peak', is formed in the density of states, $D(\varepsilon)$, at the Fermi level (dashed line). Empty (filled) circles represent the configuration before (after) the tunnelling event. Incoming electron wavepackets (dotted wavy arrows) are fully transmitted (solid arrows) acquiring a $\pi/2$ scattering phase. **c**, Virtual spin-flip processes in the SU(4) Kondo effect. Both spin and orbital degrees of freedom are now degenerate and the Kondo peak is asymmetric with respect to the Fermi level. Half of the incoming particles are backscattered, and outgoing waves acquire a scattering phase of $\pi/4$.

between the two cases. In contrast to average current measurements, shot noise probes current fluctuations, which can yield valuable information on the microscopic mechanisms involved in the charge transport. When transport is dominated by weak backscattering events, the shot noise is simply determined by the product of the average backscattered current and the effective charge, e^*, of the relevant backscattered particles. This has previously allowed measurements of the fractional charge $e^* = e/3$ — here e is the fundamental electron charge — of quasi-particles in the fractional quantum Hall state at filling factor 1/3.

Although it contains rich information on the transport characteristics of a system, experimental and theoretical investigations of shot noise are challenging. Experimentally, this is because low-frequency current noise is often dominated by extrinsic $1/f$ noise. Few experimental studies on Kondo dots are available so far, one recent example[7] being the experimental evidence for reduced shot noise with $e^* = 5e/3$, the universal effective charge expected at very low temperatures for the SU(2) case. In turn, theoretical treatments of shot noise necessarily have to be conducted in non-equilibrium settings, which is the reason that they are more difficult to perform than linear conductance calculations. In fact, just a few reliable theoretical methods — each covering only restricted parameter regimes — are available at present. For the SU(4) Kondo dot, Fermi liquid theory[8,9] predicts enhanced shot noise with universal charge $e^* = 0.3e$. Shot noise therefore offers a 'smoking gun' to distinguish between different types of Kondo effect.

Although the experiments reported by Delattre *et al.* have not yet reached the ultimate low-energy limit described by Fermi liquid theory, they represent an important advance in condensed matter physics. Their work is the first to report a clear and significant shot noise enhancement compared with the non-interacting case. This is a distinct signature of the SU(4) Kondo effect, distinguishing it from the SU(2) case, for which a shot noise reduction is expected instead. In fact, Delattre *et al.* show that their results are well described by a temperature-dependent self-consistent mean-field approach, but only when SU(4) is taken as the relevant symmetry group. This breakthrough establishes shot noise as a leading approach in identifying subtle many-body effects, as was the case a decade ago for fractional quantum Hall systems.

These results point to a wide class of exotic Kondo problems that are now coming into experimental reach. The combination of spin and orbital degrees of freedom, possibly with additional degenerate lead channels, gives rise to a plethora of interesting new many-body problems. Such situations can be realised in nanodevices even out of equilibrium and are also likely to yield non-Fermi liquid behaviour. More progress on the Kondo story can be expected in the near future, and the work by Delattre and colleagues[3] is an important step in the right direction. ❐

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DARK MATTER

Many birds, one stone

A new theory for dark matter has the power to explain several experimental results simultaneously, even those seemingly at odds with each other.

Dan Hooper

An increasingly compelling body of evidence, accumulated over the past months and years, signals that the Milky Way contains a surprising number of highly energetic electrons and positrons. In particular, the satellite-based experiment PAMELA has measured[1] the positron fraction — the ratio of the number of positrons to the number of electrons plus positrons — in the cosmic-ray spectrum to be climbing rapidly above energies of 10 GeV. The balloon-based ATIC has also observed[2] an intriguing feature in the cosmic-ray electron (plus positron) spectrum, between about 300 and 800 GeV. Together, these observations seem to imply the presence of a relatively nearby source (or sources) of electrons and positrons at gigaelectronvolt to teraelectronvolt energies. Furthermore, the observation by WMAP[3,4] of anomalous emission from the inner region of our Galaxy suggests that energetic electrons and/or positrons are highly abundant there as well.

Although the origin of these particles remains unknown, an exciting possibility is that they may be the product of the annihilation of dark-matter particles in the halo of the Milky Way. But efforts to explain these signals using dark matter face a number of challenges. First, the spectrum of electrons and positrons generated by dark matter is generally too soft unless the annihilations proceed mostly to leptons (the particle family that includes electrons and positrons, and muons and taus) rather than to quarks, gauge bosons and so on. On a similar note, many dark-matter candidates are predicted to produce more cosmic-ray antiprotons than are observed if the annihilation rate is normalized to the electron and positron signals registered by PAMELA and ATIC. Once again, this seems to favour annihilations that proceed largely to electrons, muons or taus. Finally, to produce these signals, the dark matter must annihilate at a rate hundreds or thousands of times higher than would be naively predicted for a thermal relic.

Writing in *Physical Review D*, Nima Arkani-Hamed and colleagues propose[5] a model for dark matter that solves each of these problems, and a couple of others to boot. The basic idea is this: in