HIGH-TEMPERATURE SUPERCONDUCTIVITY

Testing Fermi-liquid models

G.A. Sawatzky

IN trying to identify the mechanism responsible for the behaviour of high-temperature (high-T_c) superconductors, it is important to obtain a useful description of the electrons in the materials, above and below the transition temperature, especially near the characteristic energy or 'Fermi level'. Several groups[1-3] have reported high-resolution angle-resolved photoelectron spectroscopy (ARPES) data purporting to indicate 'Fermi-liquid' type behaviour — that is, the effective charge carriers move independently. It is worth taking a closer look at these data and at what the technique can really show.

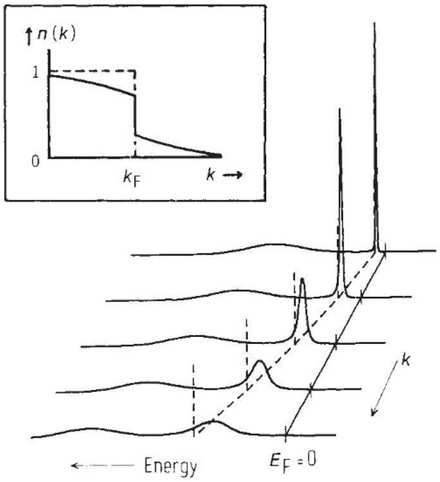

FIG. 1 In angle-resolved photoelectron spectroscopy (ARPES), both energy and momentum conservation must be considered: the emitted electron, excited by a photon of fixed energy, necessarily has momentum opposite to that of the electrons remaining in the sample. This restricts the experiment to exciting only a narrow set of energy states. Changing the angle at which electrons are detected, changes the resonance energy. Broken lines, spectra for a one-electron Fermi liquid; solid line, an interacting-electron system describable as a Fermi liquid. Inset, occupation of momentum states for one-electron system (broken line) and real system (solid line) showing the discontinuous jump at the Fermi momentum.

The ARPES technique is used to measure the probability that the material in its ground state of, say, N electrons can be raised by a monochromatic photon into a final state of N–1 electrons and a free electron, which is detected. From this one can determine the character of the valence band in which the N or N–1 electrons are found and which is responsible for the electronic properties of the material. If the photon energy is sufficiently high, the free electron departs from the material without interacting with the other electrons and the simplifying 'sudden' approximation can be used to relate the electron spectrum to the states of the material.

In the most simple model of electron behaviour, the one-electron model, each electron in the valence band is assumed to move independently. A primary characteristic of such a 'Fermi liquid' of electrons is that all possible electronic states below the Fermi level and corresponding Fermi momentum are filled and all those above are empty (Fig. 1, inset). The ARPES spectrum for such a one-electron system would consist of a single peak the energy of which varies with the detection angle (related to the electron wavelength or momentum) and which vanishes when pushed above the Fermi level, which corresponds to a well defined momentum in the solid (Fig. 1).

In real materials, there are interactions between the electrons, of the electrons with the lattice vibrations (phonons) and, in magnetic systems such as (perhaps) the high-T_c superconductors, of electrons with 'magnons'. For the Fermi-liquid description still to apply[4], it is not possible to discuss simple electrons. Instead, it is necessary to define new quasiparticles corresponding to the electrons 'dressed' with a distortion of their surroundings due to the various interactions.

With the correct description, one finds that all states below the Fermi level are occupied by quasiparticles, all those above are empty. The lifetime of the quasiparticle at the Fermi level must be infinite, which leaves its imprint on the ARPES spectrum as a peak at the Fermi energy with no width (Fig. 1). For the description to be useful, the properties of the quasiparticles must change smoothly with small changes of energy around the Fermi level. This implies that the width of the spectral peak changes smoothly, say as the square of the difference, for departures from the Fermi energy (Fig. 1).

The ARPES spectrum of the quasiparticle Fermi liquid is particularly interesting (Fig. 1). There is a small additional angle-dependent shift of the peak energy related to the fact that the quasiparticle's mass is greater than that of the simple electron. The energy-dependent broadening yields the particle's lifetime. The structure that arises at higher energy is significant as it is related to the interactions that give the quasiparticle its character (Fig. 2): the sudden removal of an electron from its dressing leaves the remaining system in various higher states corresponding to excitations of phonons (lattice vibrations), plasmons (current vortices), magnons (spin states) and so on. The number and distribution of these reveals what the dressing was made of. Because the excitations detract from the intensity of the lowest-energy peak, the integrated intensity of the latter is a second indicator of the quasiparticle mass.

Thus, to demonstrate that the high-T_c superconductors can be described in terms of a Fermi liquid (at least, above their transition temperature) it is necessary to show that the ARPES spectrum includes a sharp peak corresponding to the quasiparticle, well separated from a broad, incoherent continuum corresponding to the broadened excitations. The width of the quasiparticle peak, and its derivative with respect to energy, should tend to zero as the detection angle is changed to tune the peak to the Fermi level and corresponding momentum. And the peak should vanish for energies above the Fermi level. Of course, finite temperature and finite energy resolution weaken the precision of these criteria.

The published spectra do display an angle-dependent feature ('peak' seems too strong a description). The extent to which it moves with changing angle is about a tenth of that predicted by theory,

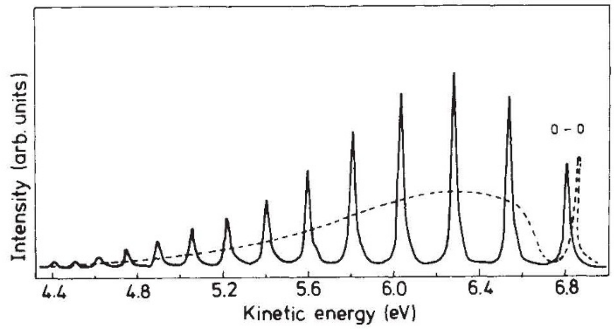

FIG. 2 Schematic photoelectron spectrum of gaseous hydrogen[5] (photon energy, 21.2 eV). Insofar as the vibrational progression of peaks is due to the bonding character of the H_2 1*s* electrons, the equilibrium bond length is dependent on the degree of occupation of that level. The electrons are dressed by interatomic displacements. The intensities are given by Franck–Condon factors, the molecular equivalent of the sudden approximation. The ARPES spectrum of solid hydrogen, developed from the molecular spectrum, will be angle dependent, but for some angle will resemble the broken line. The fundamental transition (0–0) becomes the solid-state quasiparticle peak. The phonon excitations develop into a broad, incoherent quasicontinuum. For a Fermi liquid, the two features should be clearly distinguishable. The relative intensity of the 0–0 peak, can be related to the quasiparticle mass: for a well defined quasiparticle, electron and dressing move coherently.

which would seem to indicate that about 90 per cent of the spectral intensity should be found in the incoherent continuum and that the effective mass is ten times that of the electron. Indeed, each group finds a very large 'background' to the spectrum. But in none of the spectra is there a clear separation of the peak from the background. In fact, the feature's structure typically is rather broad and strongly asymmetric, the shape changing as rapidly with changing angle as does the feature's maximum, if not more rapidly. Furthermore, the point at which the Fermi level is crossed is not all that clear.

These observations indicate a system in which the electrons are highly dressed and in which interactions between quasiparticles have an important effect, in particular on the asymmetric spectral structure. Nevertheless, the observation of a Fermi level (a sharp energy cut-off) does indicate that we are dealing with Fermi-type particles (dressed electrons). Theories based on Bose-type particles, such as electron pairs bound by magnetic or lattice interactions, would be hard pressed to account for this fact. A gap of 30 meV appears in the ARPES spectrum as the superconductor is cooled through its transition temperature, corresponding to the gap predicted in the 'BCS' theory of conventional superconductivity.

Despite all this, the data do not persuade me that it will be fruitful to concentrate on Fermi-liquid theories for describing the normal state or the transition to the superconducting state of the oxide superconductors. Even higher resolution is required to show whether well defined quasiparticles dominate the spectrum within 30 meV of the Fermi level. If they do, one can turn to Fermi-liquid models. But if it becomes clear that the incoherent part of the spectrum extends within this range of the Fermi level or if the coherent peak fails to behave properly, theorists will have to look to other models. □

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NEUROETHOLOGY

Deceptively simple behaviour

Jennifer Altman

INVERTEBRATES and lower vertebrates supply neurobiologists with many excellent opportunities for studying the relationship between nervous systems and behaviour. The choice of these animals for research has rested on two assumptions: that they have relatively simple nervous systems, and that their behaviours are stereotyped — that is, a particular response is always carried out in the same way. The first assumption has seemed increasingly shaky in the past few years, as what were thought of as simple linear circuits are now recognized as complex distributed networks. The picture that emerged from two recent meetings* means that the second assumption must also be called into question — the behaviour of lower animals has variability and flexibility very like that seen in higher vertebrates.

Here are a few of the many examples on offer. Careful examination of the development of various forms of simple learning in the gill-withdrawal reflex in juveniles of the sea-slug *Aplysia* is forcing a revision of ideas about the organization of the learning processes in the adult (T. Carew, Yale University). Gill withdrawal is a simple protective response that has been used for many years to study the cellular basis of synaptic plasticity[1]. If the siphon is touched repeatedly, the response wanes or habituates but a novel stimulus at another site produces dishabituation — the full response returns. A third form of learning is sensitization; the response increases when a noxious stimulus, such as an electrical shock to the animal's tail, is given before the reflex habituates.

As dishabituation and sensitization both involve a facilitation of the response, they have generally been thought of as different manifestations of the same process; most studies have thus been carried out on dishabituation because it is easier to control. But Carew and colleagues have found striking differences between the two processes; for example, during development dishabituation appears about 60 days before sensitization. Looking carefully again at adult *Aplysia*, they have found that here too dishabituation and sensitization can be separated. The processes are differentially sensitive to stimulus strength and occur at distinctly different times after stimulation[2].

This separation has also led Carew's group to re-examine the cellular basis of the learning processes. They conclude that, in addition to the much-studied monosynaptic connection between the sensory and motor neurons, a polysynaptic pathway of as yet unidentified interneurons seems to be necessary to explain all the forms of plasticity seen in the reflex. So *Aplysia* begins to come into line with higher animals, where learning takes place not just in reflex circuits but also in pathways parallel to them.

Rapid escape manoeuvres, such as the evasive running of cockroaches and crickets, have long been thought to epitomize stereotyped responses. More detailed examination of the behaviour in cockroaches has, however, revealed considerable variability in the direction (R. Ritzmann, Case Western Reserve University, Cleveland) and the duration (H. Gras *et al.*, Universität Göttingen) of the run. In cockroaches, the behaviour can be divided into an initial turn away from the stimulus, lasting about 60 milliseconds, followed by a run in a random direction that takes the animal out of danger. The cockroach is responding to wind currents — of the sort that would be generated by a predator approaching from behind — that are detected by appendages on the abdomen. Evasive running is suppressed in female crickets during mating, when the male also comes from behind (F. Huber, Max-Planck Institut, Seewiesen). Presumably the species is saved from extinction by changes in the coupling between neurons in the evasion pathway, possibly brought about by alterations in the concentration of a sex hormone.

The problem of adapting the output of a circuit to the demands of the moment has been much studied in the stomatogastric system — the small group of neurons that controls stomach movements in lobsters and crabs[3]. Recently, Heinzel and Selverston[4] provided behavioural evidence that neuromodulatory chemicals can alter the interactions between neurons and thus change the output of a network. They observed the movements of the teeth in the lobster's stomach as they injected the pentapeptide proctolin into the animal; when proctolin is present, the movements of the teeth change from grinding to chewing[5].

In the stomatogastric system, the organization of the networks that control the four parts of the stomach are now known to be influenced by at least ten neuromodulatory transmitters, which work either by changing intrinsic membrane properties or by varying the strengths of synaptic coupling (E. Marder, Brandeis University; see the recent News and Views article by Selverston[6]). An important problem for the future is how the complex effects of so many neuromodulators are coordinated to prevent networks becoming over-modulated to the point where they cease to function (Marder).

Another outstanding question, now

* *Second International Congress of Neuroethology* (ICN), West Berlin, 10–16 September 1989; satellite symposium *Motor Control in Arthropods*, 18–21 September, Tutzing, West Germany. The proceedings of the second ICN are published as *Neural Mechanisms of Behavior* (Thieme, Stuttgart).