QUANTUM CHROMODYNAMICS

Lifestyles of the small and simple

Ultracold atoms in optical lattices are already used to simulate complex solid-state phenomena. But could the same platform also give us a better grasp of how quarks group together?

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Quarks find other quarks — with different flavours and colours — attractive. They can choose either to form tight nuclear families, so-called baryons, or to pair up weakly with a large number of mates, in a phenomenon known as colour superconductivity. Theoretically, we expect the former behaviour to occur at low density, as in ordinary matter, and the latter at high density, as might be reached under enormous pressure inside neutron stars. Ákos Rapp and colleagues propose a terrestrial analogue, with cold atoms standing in for quarks, that should be much more accessible to experimental exploration (Phys. Rev. Lett. 98, 160405; 2007).

When two different kinds of fermions experience an attractive interaction, there are two basic ways they can express it. They can pair tightly with specific partners, forming bosonic molecules, which will occur if the attraction between pairs is very strong. Alternatively, they can orchestrate their behaviour collectively, as described by the famous wave function of Bardeen, Cooper and Schrieffer (BCS), to share their attraction among many partners. Such collective organization leads to ‘super’ behaviour: superconductivity for charged pairs, or superfluidity for neutral partners. In superfluids all the dancers move together coherently, so that the partner-swaps keep synchronized. ‘Free love’ is an option for the BCS state when attraction between individual pairs is weak.

The mathematical descriptions of these alternatives — molecular versus collective — seem, at first sight, very different. Physically, however, the two kinds of behaviour can be related continuously. First, the bosonic molecules can form Bose–Einstein condensates (BECs). In the condensed state, molecules too display super behaviour. Superfluidity based on bosons is familiar from the classic case of helium-4.

Microscopically, as well, the difference can be straddled. Imagine starting from a very strong attraction, and tuning it down. As the attraction weakens, molecules bind more loosely. They grow, and eventually they begin to overlap. Then, in a generalization of ordinary chemical bonding, they can begin to share partners. As the attraction weakens further, their state converges ever more closely toward BCS.

Recently the BEC–BCS transition has been explored in a number of beautiful experiments using ultracold atoms. A continuous ‘crossover’ between the two extremes is observed, with no sharp phase transition. So far, the experiments explore relatively simple situations, featuring homogeneous gases and just two kinds of fermions. Rapp et al., motivated in part by quantum chromodynamics, look forward to more complex arrangements. They predict that richer behaviour will emerge, featuring a true phase transition.

Specifically, they propose to create a lattice of preferred locations for atoms, using lasers to set up an effective potential. This sort of thing has become almost routine recently. They are looking ahead to experiments that load three types of fermionic atoms into the trap. They focus on the situation when there is complete symmetry among the different types, and mutual attraction between them.

Call the three different types A, B and C. When mutual attraction is strong, it is expected that bound units ABC will occupy lattice sites (Fig. 1a). If the lattice potential supports just one bound state, further accumulation will be disfavoured by Fermi statistics. The resulting triples resemble an assembly of baryons. When mutual attraction is weak, some form of BCS pairing is expected to occur.

Figure 1 Cold fermionic atoms in an optical lattice might behave similarly to quarks. Three atoms with different internal quantum numbers (represented here by different colours) can, depending on the strength of the interactions between them, form either a, bound units of ‘trions’ or b, some form of Cooper pairs. The pairs can be extended and overlapping, and partner-swapping is common.
Plasma heating with millimetre waves

The need for an intense source of coherent, millimetre-wavelength radiation to heat a fusion plasma and control its instabilities represents a significant challenge in the development of the ITER experimental fusion reactor. This challenge may now have been met.

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Reaching and maintaining the temperatures and densities needed to ignite and sustain thermonuclear reactions in a magnetically confined plasma requires a multi-stranded approach to plasma heating. In addition to the principal mechanism of ohmic heating — which relies on the large electrical currents generated inductively in a tokamak plasma’s core — a variety of auxiliary methods for heating a plasma have been suggested, from irradiating it with neutral high-energy particle beams to exposing it to high-power radio waves at frequencies matched to the collective normal modes of the plasma. The use of millimetre radio waves at the highest normal mode frequency has the added potential to very locally deposit energy and eventually control instabilities of a fusion plasma as well as heating it. But to do so requires the development of a millimetre-radio-wave source of unprecedented output power and performance. On page 411 of this issue, Sakamoto and colleagues report a significant scientific and technological achievement in the development of just such a source, known as a gyrotron, that is capable of producing more than a megawatt of continuous, coherent, millimetre-wave radiation. The device meets all the demands made of it for use in ITER, the international experimental tokamak reactor currently under construction in the south of France, and paves the way for the development of similar sources for future fusion power plants.

The collective normal mode of a magnetized plasma that the authors’ device is designed to couple into is the electron cyclotron resonant mode. The frequency of this mode is directly proportional to the local magnetic field, B, applied to a plasma, and for non-relativistic electrons is given by \( f_{\text{ecl}} = 2B \) GHz. Because the magnetic field within a tokamak plasma changes so much from its core to its edge, this dependence means that with an excitation source that emits in a very narrow-frequency band, electron cyclotron heating (ECH) of the plasma can be performed in an extremely localized manner. Moreover, depending on the launching configuration (the precise manner in which the radio waves are injected into the plasma), this mechanism provides a non-inductive means for generating currents within a plasma — an approach known as electron cyclotron current drive (ECCD). Multi-megawatt ECH and ECCD systems composed of many megawatt-range gyrotrons exist on several of today’s toroidal magnetic fusion devices. Operating at the shortest natural resonant wavelength, ECH offers the best localization properties of all millimetre-radio-wave heating methods; an additional advantage is that electron cyclotron waves propagate seamlessly from free space to the plasma with no regions of evanescence, which significantly simplifies the launching system. For the ITER tokamak, whose toroidal magnetic field will be 5.3 T at the plasma centre, this frequency is in the range of 130–200 GHz depending on the local position inside the plasma. To fulfil the scientific goals of ITER, a total electron cyclotron power of 20 MW at 170 GHz will need to be injected continuously into the plasma.

Electron cyclotron waves not only provide a useful means of heating an ITER-scale fusion plasma, but are expected to play a key role in controlling deleterious instabilities — known as neoclassical tearing modes (NTM) — that can arise in these plasmas. These modes cause localized perturbations in the confining magnetic field that compromise its ability to confine a plasma, which degrades the characteristics of the plasma and can even extinguish it completely. When an NTM instability arises, the size of the perturbation it causes can be minimized (or potentially eliminated)