Shear Zone, Zanskar Himalaya and validated it from micro-textural data. Based on ^{207}Pb–^{206}Pb ages of detrital zircons from meta-sedimentary rocks from the eastern and western Dharwar blocks, M. Bidyananda (PRL) reported those zircons to be older than the Early Proterozoic, and that the crust-forming cycle took place in both the blocks during the Archaean Period. S. B. H. Kumar (Bangalore University) proposed a two-stage evolutionary model of the Eastern Dharwar craton as follows: (1) 2700 Ma back plume induced volcanism forming oceanic plateaus eventually accreted to protocontinent; (2) 2600–2550 Ma back subduction-induced partial melting of oceanic slab, giving rise to calc alkaline rocks over early formed protocontinent. S. Gupta (NGRI) reported 42–51 km anomalously thick crust below the mid-Archaean segment of the western Dharwar craton indicative of Archaean crustal shortening. Secondly, prominent low S-wave velocity zone in the mid-crust in the south Indian granulite terrain was interpreted as due to the possible entrapment of fluids during metamorphism, 2.6 Ga back. From his study on foreland basin development in compressional tectonic domain, G. K. Agarwal (University of Lucknow) narrated the relationship between basal friction coefficient and thrust and wedge geometry, and also simulated intermontane basins from a combination of basal detachment sheets. On the basis of samples collected during summer and winter seasons from northwestern India, S. Yadav (JNU) pointed out that the sources of aerosols in that region are the Thar desert and the certain litho-units of the Himalaya. He also suggested the ongoing desertification of Thar area due to natural removal of its dust particles. S. Gupta (University of Calcutta) presented palynostratigraphic studies from Sarda and Gandak wells, classified Tertiary succession of the Ganga Basin into 10 palynostratigraphic zones and specified age of litho-units using respective index taxa. J. Sanwal (Kumaon University) presented multi-proxy studies from Dulam area of Kumaun Himalaya, and based on the discovery of vertebrate fossils Mus and Golunda amongst other microfossils, four palaeocommunities were proposed; stable carbon isotope analysis of organic matter led to climatic zonation *vis-à-vis* ascertaining climatic changes through time (31 to 22 ka BP). P. K. Singh (BHU) discussed ultra-high temperature metamorphism from sapphirine–spinel–quartz bearing granulites from G. Madugula area of Eastern Ghats and reported isobaric cooling and isothermal decompression subsequent to peak metamorphism, and based on the P–T path. He correlated M_1 metamorphism of the study area with the Granvillan event. On the basis of structural analysis from Dudatoli–Almora Crystalline of the Kumaun Himalaya, N. R. Tripathy (BHU) concluded that the Rf/j method was the best strain analysis technique, and that the study area had undergone three generations of deformation and folding events. From the studies on the tectonic evolution of the Chiplakot Crystalline Belt (CCB) of the Kumaun Himalaya, Y. Kumar (Kurukshetra University) presented his microtextural and fission track data and concluded that the middle of the CCB had undergone maximum shear strain, and that the hanging wall side of the CCB had undergone faster exhumation than its footwall. Award for best presentation was given to G. K. Agarwal and the second best award went to S. Yadav. The Young Scientist Presentation was encapsulated in an abstract volume containing all the eleven abstracts.

Soumyajit Mukherjee, Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee 247 667, India.
e-mail: msoumyajit@yahoo.com

RESEARCH NEWS

Condensation of bound pairs of fermionic atoms

R. Srinivasan and Andal Narayanan

The probability of occupancy of single-particle quantum states in a collection of indistinguishable non-interacting particles is dependent on the total spin quantum number of the individual particles.

A dilute collection of atoms called fermions obey Fermi–Dirac statistics, if the total spin quantum number of electrons, protons and neutrons of the individual atoms is a half-integer (measured in units of Planck constant). In this statistics, all energy levels up to a maximum energy $E_F = k_B T_F$ are filled with one atom in each level and all the energy levels above E_F are empty at zero kelvin temperature. E_F is called the Fermi energy and T_F the Fermi temperature. At zero Kelvin, the fermionic atoms are said to be in a fully degenerate state. At finite temperatures for which $K_B T \ll E_F$, a narrow range of energy levels above E_F get occupied. If we can cool a cloud of fermionic atoms close to T_F, we can study the behaviour of a weakly interacting cloud of nearly degenerate fermionic atoms.

Alternatively, a dilute collection of atoms called bosons obey Bose–Einstein statistics, if the spin quantum number is an integer. They will exhibit the phenomenon of Bose–Einstein condensation (BEC) when cooled below a transition temperature T_c which is proportional to $n^{2/3}$, n being the number density of atoms, In BEC, a finite fraction of all the atoms occupies the lowest available energy state of the system. This fraction becomes nearly equal to one at zero kelvin.

For a dilute collection of alkali atoms which have a single electron in their outermost shell, the angular momentum quantum number $J = 1/2$. The nucleus has an angular momentum quantum number I which depends on the isotopic composition of the nucleus. For example, for ^{85}Rb, $I = 5/2$, while for ^{87}Rb, $I = 3/2$. Similarly, for ^{6}Li, $I = 1$ and for ^{40}K, $I = 4$.

The energy levels will be labelled by the $\mathbf{F} = \mathbf{J} + \mathbf{I}$ quantum number. In a low-density vapour, at a pressure of 10^{-11} mbar the only interaction between these atoms arises from head-on collisions between two atoms which is characterized by the so-called *s*-wave scattering length. This interaction is weak and it can be both repulsive ($a > 0$) and attractive ($a < 0$) in nature.

Both ^{85}Rb and ^{87}Rb are bosons, and they exhibit the phenomenon of BEC when cooled below the transition temperature T_c. However, to achieve a stable condensate with a large number of atoms, the interaction between atoms has to be repulsive ($a > 0$). Since ^{87}Rb has $a > 0$, it was the first alkali atom to be Bose-condensed[1] when cooled below a transition temperature of 150 nK. Stable BECs of other alkali elements like ^{23}Na have also been achieved and their properties studied[2].

Alternatively, ^{6}Li and ^{40}K are fermions and they obey Fermi–Dirac statistics. For ^{6}Li, T_F is a few microkelvin at a pressure of 10^{-11} mbar. Both ^{6}Li and ^{40}K have been recently cooled to temperatures below T_F and their properties studied.

Cooling of the fermion gas of atoms to T_F and below

From room temperature, both fermionic and bosonic alkali atoms can be cooled to a few microkelvin, through resonant interaction with photons close to the absorption wavelength of the atom. Laser cooling and trapping of atoms in a magneto-optical trap have been described earlier[3,4]. With laser cooling, one can achieve a cloud of alkali atoms with a density of about 10^{11} atoms/cm^3 and a temperature of the order of a few tens to a few hundreds microkelvin. To cool the atoms to still lower temperatures, one resorts to forced evaporative cooling. The atoms which are in a MOT are loaded either in a magnetic trap (MT) by switching-off the cooling beams or in an optical trap (OT) which is produced by focusing a far-off resonant, high-intensity laser beam at the centre of the MOT. In the case of magnetic trapping, atoms in a weak-field-seeking Zeeman level $|F, m_F\rangle$ only are trapped. In an OT, atoms in all Zeeman sub-levels of the ground hyperfine level will be trapped. By increasing the magnetic field in an MT or by achieving tight focusing of trapping laser beam in an OT, one can achieve a high density of atoms (about 10^{13}/cm^3) in the cloud. In the case of an MT, one uses a RF frequency tuned between adjacent Zeeman levels of the atom in the magnetic field, to achieve evaporative cooling. By starting with a RF frequency corresponding to the value of the magnetic field at the edge of the cloud and progressively lowering the frequency as a function of time, atoms with high kinetic energy are assisted to go from a trapped state to an untrapped state and leave the trap. In the case of the OT the intensity of the far-off resonant trapping beam is gradually reduced to lower the depth of the trapping potential, facilitating atoms with kinetic energy larger than the potential well-depth to leave the trap. The remaining atoms suffer elastic collisions to achieve a Maxwellian distribution of velocities at a lower temperature. The temperature decreases progressively as more and more of the atoms leave the trap.

With such a technique, if the temperature reaches a value below the condensation temperature for bosonic atoms, then this results in BEC. The density in the condensate is about 10^{14}/cm^3 and the number of atoms is about 10^6.

There is a problem in achieving elastic collisions between atoms in the same hyperfine ground state $|F, m_F\rangle$, if the atom is a fermion. As already mentioned, the predominant interaction at these low densities is *s*-wave in character. However, the Pauli exclusion principle forbids two atoms in the same hyperfine level to be present at the same point for *s*-wave scattering to result. So there will be no elastic collisions for the atoms to rethermalize themselves to a lower temperature, after the atoms of high kinetic energy have left the trap. Thus the low temperature achievable in magnetically trapped, single, hyperfine state fermions is limited.

Several schemes have been proposed to overcome this problem. In the first scheme, one has a mixture of bosonic and fermionic atoms in the trap. The fermionic atoms can suffer *s*-wave collisions with the bosonic atoms. One can cool the bosonic atoms by evaporative cooling and, through boson–fermion collision reduce the temperature of the fermions. This is known as sympathetic cooling.

The other technique is to trap atoms belonging to two different hyperfine sub-levels of the ground state. For example the two hyperfine sub-levels ($|F, m_F\rangle$) $|9/2, 9/2\rangle$ and $|9/2, 7/2\rangle$ of the ^{40}K atoms are weak-field-seeking and can be trapped in equal numbers in an MT. One can then use a microwave frequency corresponding to the transition from $F = 9/2$ to $F' = 7/2$ hyperfine levels of the ground state to induce a transition from $|9/2, 9/2\rangle$ to $|7/2, 7/2\rangle$ and $|9/2, 7/2\rangle$ to $|7/2, 7/2\rangle$ levels. In a magnetic field B, the frequencies of the two transitions will differ slightly due to the Zeeman shift of the two ground hyperfine sub-levels, as shown in Figure 1. It will be possible to evaporate equal fractions of the atoms in the two hyperfine states $|9/2, 7/2\rangle$ and $|9/2, 9/2\rangle$ by such a process. Since there is no prohibition on the atoms in the two different ground sub-levels from suffering *s*-wave collisions, one can achieve evaporative cooling. Such a technique has been used with ^{40}K by DeMarco and Jin[5] to achieve a temperature of ground $0.5T_F$. T_F was 0.6 μK for a total number of 10^6 atoms in an MT with a geometric mean frequency of $2p \times 71.5$ Hz. (See ref. 5 for further details.)

The above technique will not work for ^{6}Li, as the ground hyperfine levels are $|1/2, 1/2\rangle$ and $|1/2, -1/2\rangle$. One of them can be trapped in an MT, but not both. So one should use an OT in which atoms in both hyperfine states can be trapped in equal proportions. This should be an incoherent mixture of the two states in the trap. Evaporative cooling is achieved by reducing the intensity of the far-off resonant trapping beam leading to forced evaporation of atoms of high kinetic energy. Efficient cooling can be achieved, as demonstrated by Granade *et al.*[6]. ^{6}Li atoms could be cooled in an OT to 0.5 T_F with 3×10^5 atoms in one of the hyperfine states remaining in the trap.

Whatever be the technique used to achieve evaporative cooling, one is not able to achieve a temperature lower than about 0.13 T_F. The sharp drop in the efficiency of evaporative cooling as the temperature is reduced below T_F arises from two effects. First, at absolute zero a Fermi gas exerts a pressure. It is this pressure which prevents the gravitational collapse of a white dwarf. As the temperature goes below T_F, this pressure opposes a decrease in size of the cloud. So the density of the atoms in the cloud decreases as the cloud cools and more and more atoms leave the trap. In a bosonic cloud, the size of the cloud decreases as the atoms leave and so a high density of atoms is maintained as the cloud cools. The rate of elastic collisions decreases as

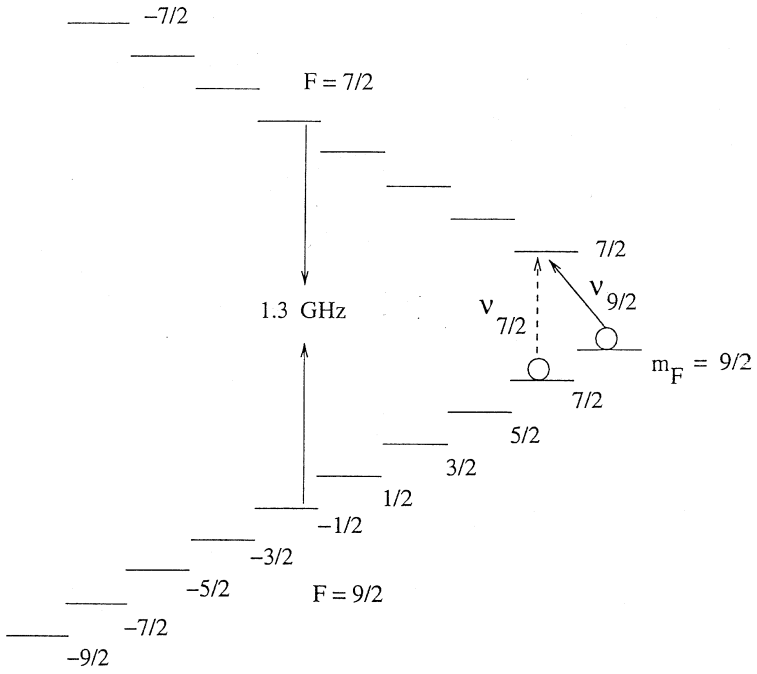

Figure 1. Zeeman sub-levels of the hyperfine structure of ^{40}K ground states, $F = 9/2$ and $F = 7/2$ (reprinted with permission from ref. 5 (2003) *AAAS*).

the density in the fermion cloud falls. Secondly, below T_F the occupancy of low-lying energy levels increases reducing the phase space available for elastic collisions. Both these effects are responsible for the reduction in the efficiency of evaporative cooling below T_F.

BCS pairing and weakly bound dimers in a fermion cloud

Nearly degenerate fermionic atoms with weak attractive interaction ($a < 0$), exhibit an interesting pairing mechanism. Atoms hovering close to the Fermi sea, pair in momentum and spin states. In real space these atoms can be at distances of about two orders of magnitude larger than the size of the atom. As a result, macroscopic number of atoms have correlated momenta and the Fermi sea is said to become unstable towards pairing of fermions. The net spin quantum number of a fermionic pair is an integer and hence this pair acquires the characteristic of a boson in certain aspects.

The bosonic character of a fermionic pair can be well understood at T_F. At this temperature, and paired fermions (also called as Copper pairs) undergo a transition towards a single state referred to as the condensation of Bardeen, Cooper and Schreifer (BCS) pairs. This condensation of the BCS pairs is the microscopic origin of superconductivity as elucidated by the BCS theory. This is also the mechanism responsible for the superfluid behaviour of ^{3}He.

The binding energy of the Copper pair (which is twice the superconducting energy gap Δ) increases as the superconducting transition temperature T_c increases. If we plot the scaled transition temperature T_c/T_F against the scaled binding energy $2\Delta/k_BT_F$, one gets a continuous curve for all the superconductors (normal and high T_c) (see Figure 2). For normal superconductors, T_c/T_F is of the order of 10^{-5} to 10^{-4}, while for high T_c superconductors and superfluid liquid ^{3}He, it is in the range 10^{-2}. Thus in order to realize conventional and high T_c superconducting behaviour in a dilute collection of ultracold fermionic atoms in the form of BCS pairing and superfluidity, it is necessary that (a) the scattering length is negative, i.e. the interaction is attractive, and (b) the temperature is lowered considerably below T_F. For example, in ^{6}Li at magnetic fields below 500 G, the scattering length is negative. It varies between 0 and –300 a_0 (a_0 is the Bohr radius) for a magnetic field varying between 0 and 300 G. For small values of scattering length, one would expect a superfluid behaviour at temperatures much below what have been achieved so far. One should increase the negative scattering length to much higher values, if one should hope to see BCS pairing in these alkali atoms.

It is well known that if we have bosonic atoms they will form a BEC below a temperature T_c. This condensate also exhibits superfluidity as in the case of ^{4}He. If we are to plot a scaled transition temperature of these atoms vs a scaled binding energy as we did for fermions, taking for T_F the Fermi temperature of the ion cores, and the ionization energy of the atom for the binding energy 2Δ, the points lie on a curve as depicted[7] in Figure 2. The BCS-paired superfluids and the Bose-condensate superfluids appear to fall on a continuous curve! Furthermore, Holland *et al.* have proved that if one could form weakly bound dimer pairs of the alkali atoms with a large and tunable scattering parameter, the pairs will Bose-condense at temperatures close to T_F and such Bose condensation will appear in the region marked with a cross in Figure 2. Such a regime where $T_c/T_F = 1$, is traditionally referred to as the high temperature superconducting regime.

As we had mentioned earlier, a stable BEC of bosons can be achieved for $a > 0$. As we just mentioned BCS pairing and condensation happen for fermions with $a < 0$. We also saw that the transition between the BCS and BEC regime is a continuous one. The experimental verification of this cross-over from the BCS to the BEC regime has been one of the Holy Grail's of physics, as this will help us study how interactions modify one of the fundamental aspects of the particle, namely its bosonic or fermionic nature. It will also throw much light on the nature of high temperature superconductivity.

The procedure which people adopted to achieve this goal has the following essential steps.

(a) Start with a cold dilute collection of fermionic atoms with $a < 0$.
(b) Lower the temperature and look for BCS pairing and superfluidity.
(c) Change the scattering length to positive $a > 0$.
(d) Make bound pairs of fermionic atoms (dimers with integer spin value).
(e) Look for BEC condensation.

In order to achieve any of the above, it is first necessary to have a large *s*-wave

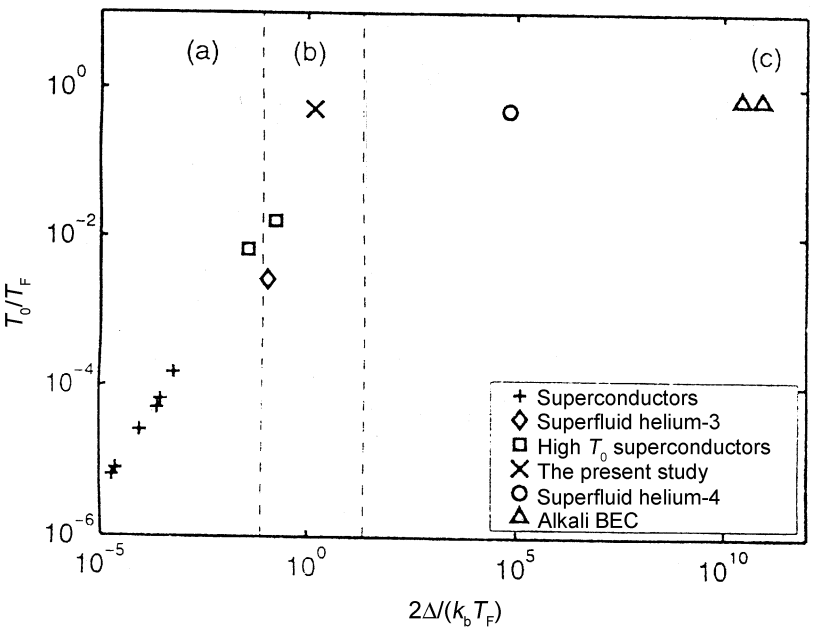

Figure 2. Plot of normalized transition temperature against the binding energy for superfluids. Region (a) corresponds to BCS pairing in superconductors and superfluid ^{3}He. In region (c) are the Bose condensates of super-fluid ^{4}He and Bose-condensed alkali atoms. For region (b) the binding energy is the ionization energy and T_F is the Fermi temperature of ion cores (from ref. 7).

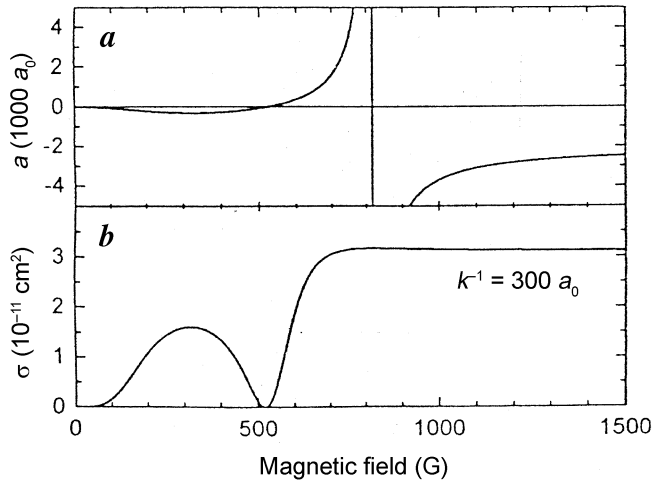

Figure 3. ***a***, Model curve approximating theoretical calculations of *s*-wave scattering length for ^{6}Li atoms in the two lowest spin states against the magnetic field. ***b***, Corresponding behaviour of scattering cross-section (from ref. 8).

scattering parameter '*a*', whose sign can be changed from positive to negative. Both of these were achieved with a technique called Feshbach resonance.

Feshbach resonance

When the energy of a bound state of an inter-atomic potential is equal to the sum of the kinetic energies of the colliding pair of atoms, then these atoms undergo a transition from a free state to a bound state. This results in resonance scattering and a change in the magnitude and sign of *a* is thus achieved.

Assuming a non-zero kinetic energy, this process is possible only when the threshold potential energy of the bound state is higher than that of the kinetic energies of the colliding atoms. This is achieved in ultra-cold gaseous alkali atoms with small kinetic energies.

Also, because of the existence of the hyperfine states (*F* levels) in these atoms which generally have different spin labels, we can tune a desired bound state into resonance using Zeeman shift by applying an external magnetic field. Also, if the kinetic energies of the colliding atoms are small, then atoms starting in the ground state hyperfine levels will not get scattered into the excited state and the Feshbach resonance effect will be stable and well-resolved.

Let us consider ^{6}Li in the ground hyperfine state $F = 1/2$. A theoretical calculation of the scattering length as a function of the magnetic field follows the curve[8] shown in Figure 3. From Figure 3 we see that the scattering length of ^{6}Li atom is zero at zero value of the magnetic field. This implies that if we trap ^{6}Li atoms in the ground hyperfine states $|1/2, 1/2\rangle$ and $|1/2, -1/2\rangle$ in an OT and try to cool them evaporatively, there will be no cooling as the elastic collision cross-section is zero. It is necessary to apply a magnetic field to produce a non-zero scattering length. At 300 G, the scattering length is –300 a_0. The interaction is attractive and produces enough elastic collision rate for efficient evaporative cooling. This was how evaporative cooling of ^{6}Li was achieved in an OT[6].

As the magnetic field is increased further, the scattering length reverses its sign between 500 and 550 G. So elastic scattering again goes to zero at a magnetic field corresponding to sign reversal. Actually, there is a narrow Feshbach resonance around this point that is not shown in Figure 3. If we produce a trap with a depth $U/k_BT = h$, slightly greater than unity (for example, $h = 2$), then the atoms with kinetic energy greater than hk_BT will leave the trap. This is called free evaporation. Keeping h fixed, the fraction of atoms remaining in the OT, after a fixed holding time in the trap, is measured as a function of the applied magnetic field. This gives the fraction of atoms lost due to elastic collisions during the holding time. If the scattering length goes to zero at a magnetic field B_0, the evaporation loss must be a minimum and the atoms remaining in the trap should be maximum at this value of the magnetic field. This was verified by Joachim *et al.*[8].

If the field is increased beyond the value B_0, the positive scattering length

increases to very large values near about 850 G. It reverses sign, becomes attractive and decreases in magnitude as the magnetic field is increased further. It reaches a steady value of –2200 a_0 at a magnetic field of 1.5 kG. This Feshbach resonance has a large width and has been used to alter the magnitude and sign of the scattering length in ^{6}Li.

Feshbach resonance thus provides a handle for varying the magnitude and sign of the interatomic interaction.

Search for BCS pairing

To search for BCS pairing at temperatures which have been attainable in ^{6}Li, it is necessary to work with a magnetic field slightly larger than 850 G, at which Feshbach resonance occurs in this atom species. This will make the scattering length (a) large in magnitude and negative in sign.

O'Hara *et al.*[9] cooled about 10^5 atoms of ^{6}Li to a temperature much below T_F in an OT, with an applied magnetic field of 910 G. The atoms are released from the trap and absorption images are taken at intervals of 200 μs as the atoms expand. It is found that the aspect ratio of the absorption image changes with time, indicating a highly anisotropic expansion of the atoms. This expansion was fitted both to a collisionless superfluid hydrodynamic theory and a collisional normal fluid hydrodynamic theory. There is discrepancy with the collisional normal hydrodynamic calculations at the longest evaporation times. This suggests that a paired BCS superfluid state has been formed. However, evidence for the BCS superfluid state is not direct.

Preparation of long-lived dimers of fermions in large numbers

The other possibility is to form weakly bound dimers of fermionic atoms and bosonic atoms and Bose-condensing the dimers. However, to form a stable Bose-condensate of the dimers, the interaction between the dimers should be repulsive ($a > 0$).

When the magnetic field is ramped down across a Feshbach resonance, changing the sign of the scattering length from negative to positive, dimers of the atoms are expected to be formed as the magnetic field crosses the resonance value. The binding energy of the molecule will increase continuously as the magnetic field decreases in value from B_r. That such dimers are formed was earlier shown in the case of Bosonic atoms ^{23}Na in the Bose–Einsten condensate by Wynar *et al.*[10]. However, these dimers are formed in a highly excited vibrational state. They can make a transition to a low-lying vibrational state. The energy released in such a transition often exceeds the trap depth and will make the dimers leave the trap. Their lifetime in the trap is small (milliseconds) and is much less than the inverse of the elastic collision rate. So they are not in thermal equilibrium with the condensate atoms.

If one wants the dimer molecules made of fermionic atoms to show Bose condensation, the following conditions should be achieved: (a) the dimers must form in sufficiently large numbers so that the Bose-condensation temperature of the dimers is higher than the temperature achieved with the fermion atoms, and (b) the lifetime of the weakly bound dimers must be long compared to the elastic collision time, so that the dimers achieve thermal equilibrium with the atomic cloud.

Regal *et al.*[11] investigated the formation of dimers in a fermion cloud of ^{40}K atoms by ramping down the magnetic field from 227.81 G at the rate of 40 μsG^{-1} across the Feshbach resonance field of 224.21 G. The ^{40}K atoms were cooled first in an MT and later in an OT to a temperature of 150 nK. The number of atoms present in the trap, after reaching a final value of the magnetic field, was measured by absorption imaging in a resonant probe beam after expansion from the OT. Figure 4 shows this number as a function of the final value of the magnetic field. One sees a sharp drop in the number of free ^{40}K atoms as the Feshbach resonance field is crossed. This decrease indicates the formation of dimer molecules. They also verified that if the field was first decreased and then increased back to the original value, the atoms reverted back to the original value indicating the break-up of the dimers to give back the free atoms. Using the photo-dissociation technique they measured the binding energy of the dimer as a function of magnetic field and showed that the binding energy increases as the magnetic field decreases below its value B_r at resonance. The most interesting observation was that nearly 50% of the atoms are converted into dimers for the above-mentioned ramping rate of the magnetic field and the number density of dimer molecules was large enough for the Bose-condensation temperature to be three times as large as the temperature of the ^{40}K atoms in the trap.

Strecker *et al.*[12] prepared dimers of ^{6}Li molecules by cooling the atoms in an OT to a final temperature of the order of 0.1 T_F and then sweeping the magnetic field across the narrow Feshbach resonance at 543.25 G. They confirmed the formation of a large fraction of the atoms into dimers. The important observation of these workers is that the lifetime of the dimers so produced is of the order of a second, much higher than the inverse of the elastic collision rate.

Compared to the dimers of bosonic atoms, dimers of fermionic atoms have a longer lifetime, longer than the inverse of the elastic scattering rate. This behaviour arises from the fact that the transition from the highly excited vibrational state to a low-lying vibrational state is suppressed in dimers of fermionic atoms. The long lifetime of fermionic atoms in comparison to the inverse of the elastic collision rate, implies that these dimers reach thermal equilibrium with the atoms and so have the same temperature as the atoms. If about 10^5 dimers can be formed at a density of about 10^{13} cm^3, the Bose condensation temperature of the cloud of dimers can be higher than the tempera-

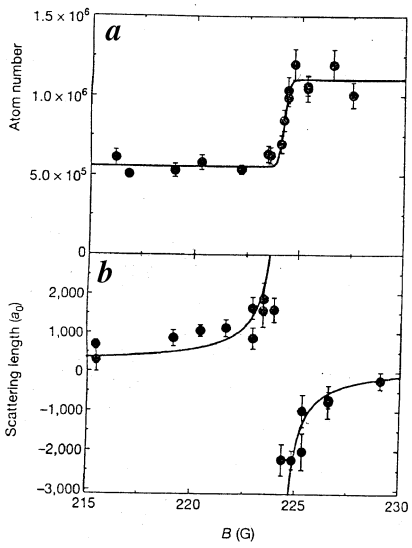

Figure 4. ***a***, Atom loss as the magnetic field is ramped across Feshbach resonance in ^{40}K (Reprinted with permission from ref. 11 *Nature*). ***b***, Previous measurement of Feshbach resonance.

ture of the bath. So one can obtain stable, Bose-condensed dimers even at temperatures of the order of 0.2 T_F.

That a large fraction of atoms form dimers can be explained as follows. The reaction we have to consider will be the exothermic three-body collisions resulting in the production of dimers, and the endothermic collisions between an atom and a dimer resulting in the dissociation of the dimer. The binding energy of the dimer can be made larger than a microkelvin by choosing the magnetic field. In such a case, as the system is cooled the equilibrium will be shifted in favour of a mixture of atoms and a large number of dimers.

Bose condensation of dimers of fermionic atoms ^{6}Li and ^{40}K

It is now possible to produce about 10^5 and 10^6 dimers of fermionic atoms of ^{6}Li and ^{40}K in thermal equilibrium with the atomic bath. If these dimers are produced at temperatures below the condensation temperature, one may hope to see BEC of these dimers.

BEC in dimers of ^{6}Li has been realized by Jochim *et al.*[13] and Zwierlin *et al.*[14]. Jochim *et al.*[13] produced the dimers of ^{6}Li by evaporatively cooling an incoherent mixture of ^{6}Li atoms in the ground hyperfine sub-levels $|1/2, 1/2\rangle$ and $|1/2, -1/2\rangle$ in an OT and sweeping the field across the broad Feshbach Resonance around 850 G. Taking the polarizability of the dimer to be twice the polarizability of the atom, the depth of the potential well seen by the dimer will be twice the depth of the well seen by the atom. However, since the mass of the dimer is also twice the atomic mass, the trap frequencies will be the same. Keeping the magnetic field on either side of the Feshbach resonance, evaporative cooling is done by lowering the power of the trapping laser beam. As the power is reduced, the trap depth decreases. The atoms cool by evaporative cooling and the number of atoms left in the trap will follow the law $N/N_0 = (I/I_0)^a$, where N_0 and I^0 are the initial number of atoms and initial intensity of the laser beam respectively. a is approximately 0.25. At the value of the initial intensity I_0, the temperature of the atoms is about one-tenth the trap depth and the rate of elastic collisions is about 10^4/s. At a value of $p = I/I_0 = 0.05$, the temperature of the trap reaches the Fermi temperature of the atoms, which is proportional to $N^{1/3}$. As the laser intensity is reduced further, the trap depth which is proportional to p, decreases faster than the Fermi energy which is proportional to $p^{1/3}$. There is a threshold value of p at which E_F is equal to the trap depth and the trap is filled to its rim. A further decrease in p will cause the trap depth to become smaller than E_F, resulting in spilling of the atoms. Therefore, below this threshold value of p, there will be a rapid decrease in the number of atoms in the trap.

After evaporatively cooling the atoms by reducing the laser intensity to a final p value, the number of atoms in the trap is measured as follows. The laser power is rapidly turned on to its full value. This will heat up the atoms and dissociate any dimers which are formed. To ensure that all the dimers are dissociated, the magnetic field also was ramped up across the Feshbach resonance. Figure 5 shows the total number of atoms in the trap as a function of the final p value for two different values of the magnetic field B, i.e. 1176 and 764 G. The scattering length is $-3500\ a_0$ at the former value of the magnetic field, while it is $+3500\ a_0$ at the latter value. No dimers are expected to be formed in the former case. From Figure 5 one sees that the number of atoms in the trap decreases sharply for p, less than 2×10^{-3}. This is the threshold value of p at which the trap depth is equal to the Fermi energy. When p is less than the threshold value and when $B = 764$ G, a much larger number of atoms are trapped than when $B = 1176$ G. One can theoretically calculate the number of available states in the trap for a given trap depth and hence the number of atoms in the trap. This is the straight line plotted in Figure 5 with uncertainties lying within the range indicated by dashed lines. One can explain the larger number of atoms trapped below threshold for $B = 764$ G by the formation of the dimers. The number of dimers formed can be calculated from the difference between the closed and open circles at a given value of p. One sees almost all the atoms form dimers at an optimum value of the magnetic field (inset, Figure 5). Since the lifetime of the dimers in the trap is much larger than the inverse elastic collision rate, the temperature of the dimers must be the same as the temperature of the atoms, which has been estimated to be less than 0.2 T_F. The calculated condensation temperature for the dimers is significantly more than this temperature, indicating that the dimers should be in the Bose-condensed state. This was verified by measuring the frequency of the collective excitation mode. The frequency of the collective excitation mode of the Bose condensate of dimers in the Thomas–Fermi approximation was in excellent agreement with the measured value.

Zwierlin *et al.*[14] started with 3.5×10^7 atoms of ^{6}Li in an OT and cooled them by evaporative cooling in a steady magnetic field of 770 G to different low temperatures. The magnetic field was ramped quickly to 925 G to dissociate any molecules that might have been formed before switching-off the field. The atoms were allowed to expand ballistically for differ-

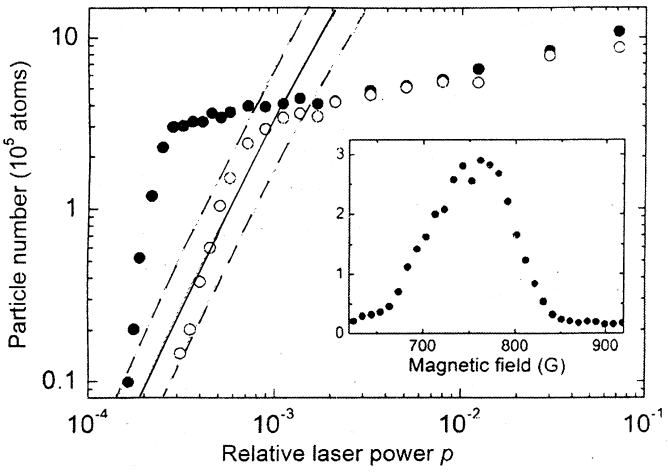

Figure 5. Number of trapped particles as a function of $p = (I/I_0)$, relative intensity of the laser on both sides of Feshbach resonance. Open circles are for $B = 1176$ G and $a = -3500\ a_0$. Closed circles are for $B = 764$ G and $a = +3500\ a_0$. (Inset) Optimum magnetic field for production of dimers (Reprinted with permission from ref. 13 (2003) *AAAS*).

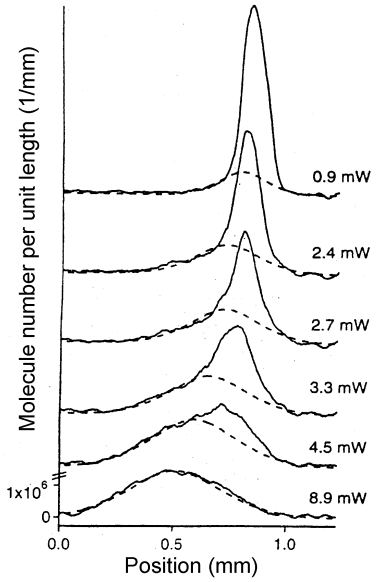

Figure 6. Radically averaged profiles through absorption images of ballistically expanded, dissociated dimers of ^{6}Li at different final laser powers. Note the development of a bimodal distribution as the power is reduced (from ref. 14).

ent times from 1 to 30 ms before absorption imaging. The density distribution of atoms in the image could be fitted to a Gaussian distribution at high temperatures, at large final values of the laser power used in the OT. As the final laser power is reduced, the atoms reach lower temperatures by evaporative cooling. At lower values of the final laser power, a bimodal distribution is observed, as seen in Figure 6. This is clear evidence for the condensate. The onset of BEC was observed at 600 nK, with 1.4×10^6 dimers in the trap. From the integrated area one can evaluate the condensate fraction which increased from 0 to 75% as the temperature was decreased from 600 nK to lower values.

Greiner *et al.*[15] have produced a condensate of dimers of ^{40}K. They started with an incoherent mixture of ^{40}K atoms in the ground hyperfine sub-levels $|9/2, -9/2\rangle$ and $|9/2, -7/2\rangle$ in an OT and cooled the atoms to a temperature of $\approx 0.1\ T_F$ by forced evaporative cooling. At this value of the temperature, the magnetic field was slowly ramped down from 202.78 to 201.54 or 201.67 in 7 ms. The Feshbach resonance is located at 202.1 G. The difference from the procedure used by Regal *et al.*[11] was in the slower ramp rate used in this work. This ramp rate was slow compared to the elastic collision rate and the radial trap frequency. The field sweep is adiabatic and resulted in the production of dimers which had a lifetime of about 100 ms in the trap. This lifetime is much larger than the inverse elastic collision rate and so the molecules reach thermal equilibrium with the atoms in the trap.

The velocity distribution of the molecules was measured first by dissociating the molecules with a rf pulse. The dimer dissociates into one atom in the state $m_F = -5/2$ and the other atom in the state $m_F = -9/2$. The unbound atoms are in the state $m_F = -7/2$. Using state-selective absorption imaging, the velocity distribution of the atoms in the –5/2 state is measured. Theory shows that the scattering length for molecule–atom interaction is 1.2 *a* and the molecule–molecule interaction is 0.6 *a*, where *a* is the *s*-wave scattering length of atom–atom interaction. More than 150,000 molecules are formed in the trap. Each molecule experiences a large interaction energy in the mean field approximation because of the large enhancement of the scattering length '*a*' near the Feshbach resonance. When the atoms are released, this will cause a rapid expansion in the radial direction along which trapping frequency is large. The measured momentum distribution will be different from the original momentum distribution in the cloud. To overcome this, the magnetic field is rapidly moved down further by 4 G in 10 μs before the rf pulse is applied to dissociate the dimers and the OT is switched-off for time-of-flight imaging. This rapid ramping of the magnetic field reduces the interaction strength considerably. But it also results in a loss of 50% of the molecules.

The time-of-flight images clearly show the development of a bimodal distribution below about 250 nK. From the area under the central peak of the distribution one can estimate the condensate fraction as a function of temperature, as the temperature is reduced below T_c.

By adjusting the final value of the magnetic field after the rapid sweep, one can adjust the interaction energy of the molecule. One can measure the interaction energy as a function of the final scattering length. It is found that the interaction energy varies linearly with the scattering length '*a*' and extrapolates to zero as *a* tends to zero. This is expected from the proportionality of the molecule–molecule and molecule–atom interaction strength to the atom–atom scattering length '*a*'.

Conclusion

In this study the cooling of a cloud of fermions to a temperature below its Fermi temperature and the attainment of Bose condensation in weakly bound dimers of fermions are described. We may expect an extensive study of the properties of the molecular condensates as a function of the binding energy. New physics will come out if one goes from one side to the other of the Feshbach resonance, changing the sign of the scattering length. One will go from molecular condensation to a BCS-like pairing. The behaviour of fermions in this crossover regime will be rich in new physics.

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The authors are in the Raman Research Institute, C. V. Raman Avenue, Sadashivanagar, Bangalore 560 080, India
**For correspondence.*
e-mail: andal@rri.res.in