

BOSE–EINSTEIN CONDENSATES

Spins mixed up

An atomic Bose–Einstein condensate represents a highly correlated, coherent state of matter. Experiments now reveal that the collective matter-wave properties extend to include coherent dynamics of the spin degrees of freedom.

NICHOLAS BIGELOW

is in the Department of Physics and Astronomy, University of Rochester, Bausch and Lomb Hall 206, Rochester, New York 14627, USA.

e-mail: nbigel@le.rochester.edu

The existence of atomic spin and the magnetic properties of a bulk sample of atoms are intimately linked. In the familiar picture, the constituent atoms that make up a solid lump of matter collectively form — depending on the nature of the inter-atomic exchange interactions — a magnetic state governed by thermodynamic variables such as temperature. For example, in iron the interactions are ferromagnetic and below a characteristic temperature (the Curie temperature) the sample can display permanent magnetism as in the case of a simple bar magnet. The situation is far less obvious if the atomic system is a dilute gas of neutral atoms with a density comparable to the ones found in the upper reaches of the atmosphere. On page 111 of this issue, Chang and colleagues¹ describe recent experiments that elucidate the collective spin behaviour of just such a gas. In their case, the system under investigation has a further, most remarkable property: it is also a Bose–Einstein condensate (BEC).

Quantum fluids with spin degrees of freedom have a long history that includes complex systems such as superfluid helium-3 and *p*-wave superconductors. When the quantum fluid is a trapped atomic BEC, the condensate is an equally intricate object. At the most fundamental level, a BEC is a state in which a macroscopic number of identical particles occupy the same quantum ground-state of a system. In most textbook introductions to BEC, the particles are assumed to be non-interacting. When the particles are atoms, however, interactions do occur, in the form of collisions. As a gas of atoms is cooled, these collisions have a vital randomizing effect that maintains thermal equilibrium and allows cooling to a point where the BEC forms. As the BEC emerges, one might guess that the randomness of collisions would suppress a build up of correlations. But, these interactions in fact drive the build-up of the coherent many-particle wavefunction, and endow the condensate with many of its marvellous properties.

A BEC of spin-1 atoms — the simplest non-trivial case involving bosons — has three components,

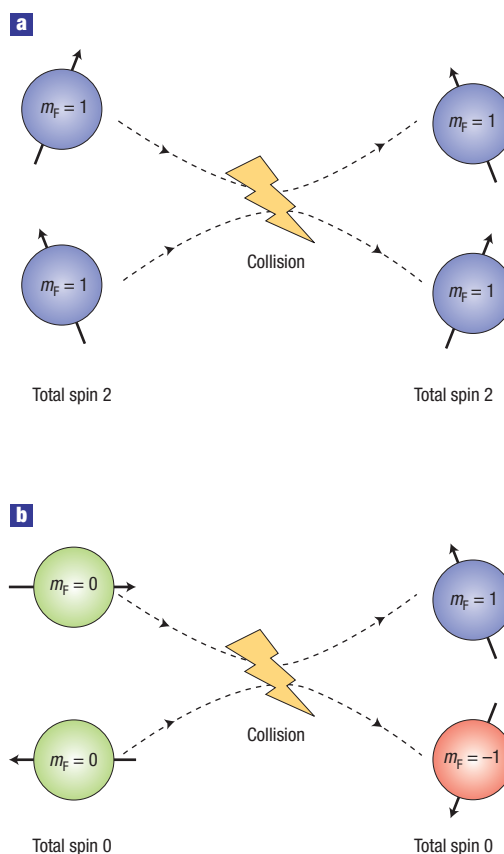


Figure 1 Atoms on a collision course. When two spin-1 atoms collide, their spin orientations matter. **a**, Two spin ‘up’ atoms must retain their state in order to conserve angular momentum. **b**, In contrast, if the two atoms are, for example, both in the state $m_F = 0$, then the collision can involve a change of the spin-state of each atom while conserving total angular momentum.

corresponding to the possible spin projections (with the quantum number m_F having a value of -1 , 0 or $+1$). This is one example of a multicomponent ‘spinor’ BEC^{2,3}. At first glance, a stable multicomponent condensate might seem simple enough. Collisions will serve the same sort of role as in the one-component condensate. They can maintain coherence within each component and will mediate equilibrium between the coupled single-component condensates. The nature of atomic collisions, however, changes drastically when the atoms have finite spin, and so does the nature of the resulting BEC. Consider two colliding spin-1 atoms in an atom trap (Fig. 1). If the atoms are both spin ‘up’ ($m_F = +1$), then during the collision, by conservation of angular momentum,

they must remain in that state (Fig. 1a). By contrast, if two atoms come together in a constellation that yields zero net spin of the pair (either both have $m_F = 0$ or one is +1 and the other -1), then the collision can involve a change of spin-state of each atom while conserving total angular momentum (Fig. 1b). Notice that unlike the spins of a bar magnet, the strict conservation in the atomic gas arises because the atoms are isolated in a trap and because binary collisions dominate. The overall effect on the BEC is that collisions can coherently interconvert the population between the individual BEC components in a process known as spin-mixing^{4,5}.

In the earlier experiments on spinor condensates^{6–8}, the ground-state structure of the condensate was directly probed, and results included observation of population evolution of the individual BEC spin components. Further experiments showed that the spin components could also self-organize into spatially structured states resembling spin domains. However, the coherence of the process was not at all clear. Simply put, earlier experiments did not discriminate between a pure-state ensemble, that is, a condensate in which the individual atoms are each in a coherent superposition of spin states, and a mixed state ensemble, in which the atoms are individually only in one of the spin states^{9–11}.

Chang *et al.* have addressed the problem in a clever way. First they prepared a spin condensate of rubidium atoms in the $m_F = -1$ state. Then, using microwave excitation techniques familiar to NMR, they set the populations in each of the three m_F components to chosen values. Subsequently, they allowed the BEC to evolve both in the presence and absence of magnetic fields and followed the population dynamics. By carefully choosing the

parameters, they were able to observe repeated population oscillations between the different components with well-defined phases. To interpret the results they used an elegant reformulation of previous mean-field theories^{2–5} based on the language of the Josephson effect.

Reaching far beyond prior work, the group also investigated the use of time-dependent magnetic fields to control the coherent evolution of the condensate^{12,13}, thus engineering the sample into a final spin-state of their choosing. What is particularly exciting about this example of coherent control is that one day it may provide a handle on eclectic topological excitations such as skyrmions^{14,15}, particle-like spin vortices that can exhibit unexpected fractional statistics, linking their tiny little BEC to physics as far reaching as the fractional quantum Hall effect and colour confinement in quantum chromodynamics.

REFERENCES

1. Chang, M.-S., Qin, Q., Zhang, W., You, L. & Chapman M. S. *Nature Phys.* **1**, 111–116 (2005).
2. Ho, T.-L. *Phys. Rev. Lett.* **81**, 742–745 (1998).
3. Ohmi, T. & Machida, K. *J. Phys. Soc. Jpn* **67**, 1822–1825 (1998).
4. Law, C. K., Pu, H. & Bigelow, N. P. *Phys. Rev. Lett.* **81**, 5257–5261 (1998).
5. Pu, H., Law, C. K., Raghavan, S., Eberly, J. H. & Bigelow, N. P. *Phys. Rev. A* **60**, 1463–1470 (1999).
6. Stenger, J. *et al. Nature* **396**, 345–348 (1998).
7. Stamper-Kurn, D. M. *et al. Phys. Rev. Lett.* **80**, 2027–2030 (1998).
8. Hall, D. S., Matthews, M. R., Ensher, J. R., Wieman, C. E. & Cornell E. A. *Phys. Rev. Lett.* **81**, 1539–1542 (1998).
9. Schmaljohann, H., Erhard, M., Kronjäger, J., Sengstock, K. & Bongs, K. *Appl. Phys. B* **79**, 1001–1007 (2004).
10. Kronjäger, J. *et al.* Preprint at <<http://arxiv.org/abs/cond-mat/0509083>> (2005).
11. Higbe, J. M. *et al. Phys. Rev. Lett.* **88**, 180403 (2002).
12. Pu, H., Raghavan, S. & Bigelow, N. P. *Phys. Rev. A* **61**, 023602 (1999).
13. Pu, H., Raghavan, S. & Bigelow, N. P. *Phys. Rev. A* **63**, 063603 (2001).
14. Mueller, E. J. & Ho T.-L. *Phys. Rev. Lett.* **88**, 180403 (2002).
15. Kasamatsu, K., Tsubota, M. & Ueda, M. *Phys. Rev. Lett.* **93**, 250406 (2004).