QUANTUM MANY-BODY PHYSICS

Confinement in a quantum magnet

It is well established that protons and neutrons are bound states of quarks. Now magnetic excitations in systems of coupled spin chains are observed to consist of fractional constituent particles as well.

Martin Greiter

The elementary excitations of a state of matter consisting of a large collection of interacting particles can be very different from those of the original particles. In the most interesting examples, the particles effectively decompose into smaller constituent particles, which only carry a fraction of their quantum numbers. When these constituents are free, such as the quasiparticle excitations in quantum Hall states, detecting them is straightforward in principle. But if they are 'confined' in the sense that they can only exist as bound states with each other, as it might be the case in spin liquids hypothesized to describe high-temperature superconductors, observing them is more difficult. Writing in *Nature Physics*, Lake and colleagues report the first observation of a crossover between confined and de-confined spinon excitations by varying the energy scale in inelastic neutron scattering experiments on a quantum magnet[1]. To borrow jargon from particle physics, they observed 'asymptotically free' spinons with spin-1/2 at high energy transfers and bound states of spinons with spin-1 at lower energies. Or put more simply, they have observed confinement in a condensed-matter system.

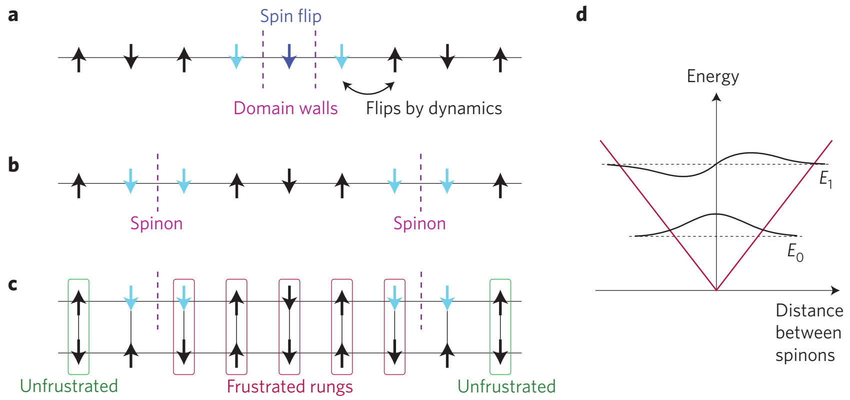

Figure 1 | Spinon confinement in coupled spin chains. **a**, A spin-flip (dark blue) in a spin chain creates two domain walls or parallel spin on neighbouring sites. **b**, These two domain walls or spinons (light blue) propagate independently and each carry spin-1/2, because the spin-flip carries spin-1. **c**, When two spin chains are coupled to form a spin ladder, all the rungs in between the two spinons are frustrated, which generates a linear confinement potential between them. **d**, The energy gaps for triplet and singlet excitations in the ladder correspond to the ground state (E_0) and first-excited-state (E_1) energies of the oscillator describing the relative motion of the spinons. The model illustrated in **a**–**c** is simplistic, as the long-range order present here is not present in the true ground states, and the true spinons are not domain walls, but excitations of spin-1/2 in an otherwise featureless spin liquid.

The classic example of confinement among constituent particles is in the context of quantum chromodynamics[2] (QCD). Quantum chromodynamics assumes that hadrons such as protons, neutrons and pions are composed of quarks, which, among other quantum numbers, carry fractional charge and are held together by non-Abelian gauge-field interactions (or equivalently, by the interchange of virtual particles called gluons). This interaction couples to an SU(3) quantum number known as colour, which takes notional values of 'red', 'blue' or 'green'. Unlike most forces, the force mediated by the gluons does not decrease with increasing distance, which confines the quarks into bound states with no net colour, or technically speaking, SU(3) colour singlets. Depending on which quarks one combines to form these singlets, one obtains protons, neutrons, and so on. All the hadrons are comparatively heavy, as a lot of energy is stored in the internal field configuration in which the quarks wiggle around each other vigorously but cannot escape. A property called asymptotic freedom implies that the quarks interact only weakly if probed at sufficiently high energies, which makes them visible in high-energy experiments.

In certain condensed-matter systems, similar constituent particles appear as collective excitations of strongly correlated many-body states. The classic examples are the fractionally charged quasiparticles of quantized Hall states[3] and the spinons that carry the spin but not the charge of an electron, and constitute the elementary excitations of one-dimensional antiferromagnetic spin chains[4]. In both these examples, the constituent particles are free (that is, not confined), which makes it possible to probe them directly. There are other instances, however, where theoretical models suggest that the constituent particles are confined, as the quarks in QCD are. It has been a long-standing problem to observe them experimentally in these systems, as most probes just detect the bound states without revealing the internal structure.

The emergence of fractionally quantized excitations (spinons) in antiferromagnetic chains is illustrated in Fig. 1. Reversing a single spin in such a chain is known as a spin-flip, which carries spin-1 and creates two antiferromagnetic domain walls separating two parallel spins on each side of the spin that was reversed. These walls can propagate outward freely, which decomposes the spin-flip into two spinons, each carrying spin-1/2 (Fig. 1b).

In an isolated chain, spinons are free. Confinement among spinons results if two antiferromagnetic spin chains[5–7] are coupled (Fig. 1c). If one creates two spinons at some distance along the chains, the spins on the rungs between the spinons become ferromagnetically aligned, which costs energy as the interaction across the rungs favours them to align antiferromagnetically. The associated cost in energy is therefore proportional to the number of these rungs, and the potential between spinons therefore increases linearly with distance.

The most direct way to observe the spinons is through inelastic neutron scattering, which measures the energy absorption spectrum for spin-flips at various wavevectors. If the spin-flip were to create only one particle, one would observe a resonance with a well-defined energy. As it decays into two smaller constituent particles — the spinons — there is a continuum of ways to distribute the total momentum of the spin-flip among the spinons. This yields a continuous absorption spectrum, and is exactly what Lake and colleagues observe when probing their system at high energies.

The energy gap associated with the confinement can now be understood as the quantum mechanical zero-point energy of the constant-force oscillator describing the relative motion of the two spinons[7] (Fig. 1d). The first excited state of this oscillator is also important, as the wavefunction describing it is antisymmetric under spinon interchange, whereas the ground state is symmetric. The wavefunction in spin-space is therefore similarly symmetric (that is, a spin triplet) for the ground state and antisymmetric (that is, a spin singlet) for the first excited state.

The energy gap for magnetic excitations in a system of antiferromagnetically coupled spin chains (a spin ladder) is long established[5]. But beyond theoretical models[6,7], it is not at all clear how one can establish, even as a matter of principle, that we are really looking at confined spinons. Lake *et al.* accomplish this by studying a system in an effectively quantum critical regime: they compare the measured intensity of the magnetic absorption spectrum to universal predictions of a conformal field theory, the SU(2) level k Wess–Zumino–Novikov–Witten model[8] with $k = 2S$, where S is the spin. This enables Lake *et al.* to establish that the spin of the critical low-energy excitations is effectively $S = 1$ in the energy window between 10 and 32 meV, and $S = 1/2$ above a crossover regime extending up to roughly 70 meV. In other words, they observe how asymptotically free spinons at high energies evolve into excitations with spin $S = 1$ as they lower the energy, and thereby show that the $S = 1$ triplon excitations are bound states of confined spinons each with $S = 1/2$.

The implications of these observations go beyond demonstrating a condensed-matter analogy of a phenomenon familiar from high-energy physics. In my view, the most tantalizing implication is the perspective it might give us on high-temperature superconductivity in the cuprates[9]. These materials consist of weakly coupled CuO layers, which are responsible for the anomalous properties and are for most purposes adequately described by two-dimensional antiferromagnets doped with mobile holes. We may view the planes as infinite arrays of strongly coupled spin chains, as compared to the weakly coupled pairs of chains investigated by Lake *et al.* Many of the key properties, including the superconductivity and anomalous properties of the so-called pseudo-gap phase, could be understood rather plausibly if the holes were in fact spinon–holon bound states held together by a strong confinement force. If Lake and colleagues could confirm this picture at a level similar to the results reported for spinon confinement in coupled chains, it would provide a huge step towards solving high-temperature superconductivity. ❐

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SCIENCE EDUCATION

Lessons to be learned

How do you create an inquisitive mind? Simply accumulating knowledge isn't good enough, suggest Lei Bao and colleagues (*Am. J. Phys.* **77,** 1118–1123; 2009). Specifically, the teaching and learning of 'content knowledge' in physics at middle- and high-school level seems to have little effect on the students' developing ability for scientific reasoning. The findings are based on data collected from more than 3,000 incoming first-year science and engineering university students in China and the USA, all of whom had enrolled in introductory physics courses.


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The students' knowledge and their scientific-reasoning ability was assessed via three standardized tests: the 'force concept inventory', used to measure basic knowledge of mechanics, and the 'brief electricity and magnetism assessment', to evaluate content knowledge; and a protocol known as Lawson's classroom test of scientific reasoning, to assess their reasoning skills. The results of these tests might be surprising: the Chinese students had a clear edge when it came to solving physics problems, but this did not translate into better scientific-reasoning ability — here their scores matched those of US students.

Bao *et al.* presented some key results in an earlier publication (*Science* **323,** 586–587; 2009), but now they offer more detail and context, serving not least to highlight the differences in physics education between the USA and China. The curriculum in the USA is fairly flexible and can vary substantially based on individual choice, whereas education in China comprises five years of physics courses for every secondary-school student.

But there are also differences when it comes to those who teach. In many US states there is a lack of well-qualified science teachers, and they often teach several science courses. In contrast, in China there are hundreds of 'normal universities' dedicated to producing qualified secondary-school teachers. Teachers in China also tend to specialize more: "Except in schools in some under-developed areas, it is not common for a chemistry teacher to teach a physics course or vice versa", say Bao *et al.*

It seems, then, that knowing facts does not, in itself, lead to good reasoning skills. As both are needed for success in research, aspects of science teaching might need to be reconsidered. Bao *et al.* judge that their data support the developing trend in education towards building up knowledge and skills from experience, rather than from bare facts alone.

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