The elementary excitations of a state of matter consisting of large collection of interacting particles can be very different from 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, as in fractionally quantised Hall states, it is conceptually clear how to observe them. But what if they are confined, as it might be the case in spin liquids hypothesised to describe high $T_c$ superconductors?

The classic example of confinement among constituent particles is given by the theory of the strong interactions in particle physics, also known as quantum chromodynamics\(^1\) (QCD). The theory assumes that hadrons, which most prominently include protons, neutrons, and pions, consist of several smaller particles called quarks, which among other quantum numbers carry fractional charge and are held together through a non-Abelian gauge field interactions, or equivalently, through the interchange of virtual particles called gluons. This interaction couples to an SU(3) quantum number, which is called colour and can take the nominal values “red”, “blue” or “green”. Unlike weak, electromagnetic, and gravitational 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 where the quarks wiggle around each other vigorously but cannot escape. This theory has not led to quantitative advances in nuclear physics, as contemporary methods do not allow us to evaluate systems consisting of significant numbers of strongly interacting quarks, but has still been confirmed experimentally, due to a property called “asymptotic freedom”. This property 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 most established examples are the fractionally charged quasiparticles in quantised Hall states\(^2\) and spinons—that is, particles with the spin of an electron but without the charge, in models of antiferromagnetically interacting spins (\(i.e.,\) neighbouring spins like to point in opposite directions) on a one-dimensional lattice\(^3\) (\(i.e.,\) spin chains). In both these examples, the constituent particles are “free”, \(i.e.,\) deconfined, which greatly eased the task of observing and hence establishing them. 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 outstanding problem to observe them experimentally in these systems, as most probes just detect the bound states without revealing the internal structure. On page XXX of this issue, Lake and colleagues\(^4\) report the first observation of a crossover between confined and deconfined spinon excitations through variation of the energy scale they employ in inelastic neutron scattering experiments on a quantum magnet. To borrow jargon from particles physics, they observed
“asymptotically free” spinons with spin $1/2$ at high energy transfers and bound states of them with spin $1$ at lower energies. Or put more simply, they have observed confinement in a condensed matter system.

To see how they accomplished this, a little bit of background is helpful. Let us begin with the fractional quantisation of charge in the Laughlin state\(^2\) describing the quantised Hall fluid at Landau level (LL) filling fraction $1/3$. There are three times as many states in the lowest LL as there are electrons. Analyticity properties require that the many body wave function has as many zeros in each particle coordinate as there are states, that is, three times as many as there are electrons. The Fermi statistics of the electrons requires that one of the zeros for a given electron coordinate coincides with each of the positions of the other electrons. The distinguishing feature of the Laughlin state is that all the remaining zeros are also attached to the electrons, such that each coordinate coincides three zeros. A true hole in the liquid is consequently given by three zeros without an electron attached. These three zeros will repel each other, and each of them will form a “quasihole”. As the hole had an effective charge $+e$ (where $-e$ is the electron charge), each quasihole will have charge $+e/3$. This charge has been observed in resonant tunnelling experiments\(^5\).

The mechanism for fractional quantisation of spin in antiferromagnetic spin chains\(^3\) is actually similar, except that the electrons are now replaced by spin-flips, which carry spin one. We view the spin-up-flips as “particles” in a background where all the spins point down. Since the antiferromagnetic interaction favours neighbouring spin to anti-align, it induces an effective repul-
sion between the spin-flips, which takes the role of the Coulomb repulsion between the electrons in the quantum Hall liquid. The emergence of fractionally quantised excitations, “spinons” with one half of the spin of a spin flip, is illustrated in Figure 1. In analogy to the creation of the hole in the quantum Hall fluid, we remove a spin-up-flip or create a spin-down-flip by turning an up spin into a down spin in Figure 1a. This creates two domain walls (i.e., parallel spins) on each side of the spin we flipped, which propagate independently, as shown in Figure 1b. As the spin-flip carried spin one, each of the domain walls or spinons will carry spin 1/2.

The most direct way to observe the spinons is through inelastic neutron scattering, which in essence measures the energy absorption spectrum for spin flips at various wave vectors. 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.

Confinement among spinons results if one couples two antiferromagnetic spin chains⁶,⁷, as illustrated in Figure 1c. If one creates two domain walls or spinons at some distance along the chains, the spins on the rungs between the spinons become ferromagnetically aligned (i.e., they point in the same direction), which costs energy as the interaction across the rungs favours them to align antiferromagnetically. The associated cost in energy is hence proportional to the number of these rungs, and the force between the spinons does not decrease with the distance.
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\(^8\). The first excited state of this oscillator is also important, as the wave function describing it is antisymmetric under spinon interchange while the ground state is symmetric. The wave function in spin space is therefore likewise symmetric (\textit{i.e.}, a spin triplet) for the ground state and antisymmetric (\textit{i.e.}, a spin singlet) for the first excited state.

The energy gap for magnetic excitations in antiferromagnetic ladder systems (\textit{i.e.}, coupled spin chains) is long established\(^6\). But beyond theoretical models\(^7,8\), 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 and her colleagues succeed through an ingenious combination of two factors. First, the material they probe is effectively critical at the relevant energies, which implies that the lowest energy excitations are gapless. Second, by comparing the measured intensity of the magnetic absorption spectrum around what would be the magnetic ordering wave vector if the system were ordered to universal predictions of a conformal field theory, the so-called SU(2) level \(k = 2S\) Wess-Zumino-Novikov-Witten model\(^9\), they are able to extract the spin of the now effectively gapless excitations as they vary the energy at which they measure the magnetic absorption spectrum. This enables them 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 with \(S = 1/2\) each.
Let me conclude with a personal view why this experiment is important. One of the main problems in contemporary condensed matter physics, if not physics in general, is the problem of high $T_c$ superconductivity in the cuprates$^{10}$. The materials consist of weakly coupled CuO layers, which are responsible for the anomalous properties and 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 the anomalous properties of the so-called 'pseudo-gap' phase, could be understood very plausibly if the holes where in fact spinon-holon bound states held together by a strong confinement force. If Lake and her 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 $T_c$.

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Figure Captions

Figure 1 | **Spinon confinement in coupled spin chains.** a, A spin flip in a spin chain results into two domain walls or parallel spin on neighbouring sites. b, These two domain walls or spinons propagate independently and carry spin 1/2 each, since the spin flip carried spin one. c, When two spin chains are coupled to form spin ladder, all the rungs in between the two spinons are frustrated, which yields a linear confinement potential between them. d, The energy gaps for triplet and singlet excitations in the ladder correspond to the ground state and first excited state energies of the oscillator describing the relative motion of the spinons. The illustration in (a)-(c) is somewhat 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.