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. ❐

Martin Greiter is at the Institut für Theorie der Kondensierten Materie, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany.
e-mail:greiter@tkm.uni-karlsruhe.de

References

1. Lake, B. *et al. Nature Phys.* **6,** 50–55 (2010).
2. Greiner, W. & Schafer, A. *Quantum Chromodynamics* (Springer, 1994).
3. Laughlin, R. B. *Phys. Rev. Lett.* **50,** 1395–1398 (1983).
4. Giamarchi, T. *Quantum Physics in One Dimension* (Oxford Univ. Press, 2004).
5. Dagotto, E. & Rice, T. M. *Science* **271,** 618–623 (1996).
6. Shelton, D. G., Nersesyan, A. A. & Tsvelik, A. M. *Phys. Rev. B* **53,** 8521–8532 (1996).
7. Greiter, M. *Phys. Rev. B* **66,** 054505 (2002).
8. Witten, E. *Commun. Math. Phys.* **92,** 455–472 (1984).
9. Zaanen, J. *et al. Nature Phys.* **2,** 138–143 (2006).

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.

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.

© ISTOCKPHOTO / BO1982

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.

ANDREAS TRABESINGER