Spinons, Solitons, and Breathers in Spin-1/2 Chains

No matter how strong the nearest neighbor antiferromagnetic interactions, quantum fluctuations prevent static long-range order within an infinite line of spin-1/2 quantum moments. What at first blush appears to be the simplest possible antiferromagnet, thus turns out to be a unique correlated spin liquid [1]. The structures of two materials with this extraordinary brand of dynamic magnetism are illustrated above Figs. 2 and 3. Figs. 2(a) and 3(a) show *zero field* inelastic neutron scattering data from these materials as a function of energy transfer, $\hbar\omega$, and wave vector transfer, q. For conventional magnets such data feature a sharp sinusoidal ridge through the q-ω plane, which is evidence for coherent spin wave excitations. While a ridge is also visible in the present data, its energy width greatly exceeds the experimental resolution. The implication is that neutrons cannot create coherent excitations in spin-1/2 chains. This is a surprise given that mobile domain walls called spinons are known to be well-defined excited states carrying heat and momentum over macroscopic distances. The paradox is resolved by recognizing that a spinon is actually just half of a spin flip (see Fig. 1 (a)-(c)). Two spinons are needed to scatter a neutron, and the broadened spectrum reflects the range of energies for spinon pairs that can carry the linear momentum delivered by the neutron.

Spinons also lead to remarkable properties in a *non-zero* magnetic field. While a classical antiferromagnet develops magnetization through uniform canting of otherwise antiferromagnetic spins, the magnetization of a spin-1/2 chain is carried by a finite density of spinon like defects. The average distance between these magnetized defects defines a characteristic field dependent length scale which is manifest in the neutron scattering data as a q-shift in the longitudinal part of the zero field sinusoidal ridge of scattering. The result is a set of overlapping gapless continua. Predicted more than 20 years ago, the effect found its first experimental realization this year at the NCNR [2]. The data shown in Fig 2(b) were acquired under the same conditions as Fig. 2(a) though with the spin chain in a magnetized state induced by an external field. There is no complete theory for these data but it was recently shown that much of the spectral weight can be associated with the two-particle continuum of the high field version of spinons called psinons [4]. Comparison of the data in Fig. 2(b) to this theory however reveals that there is spectral weight close to $q = \pi$ that cannot be accounted for by psinons [2]. Theoretical work is now

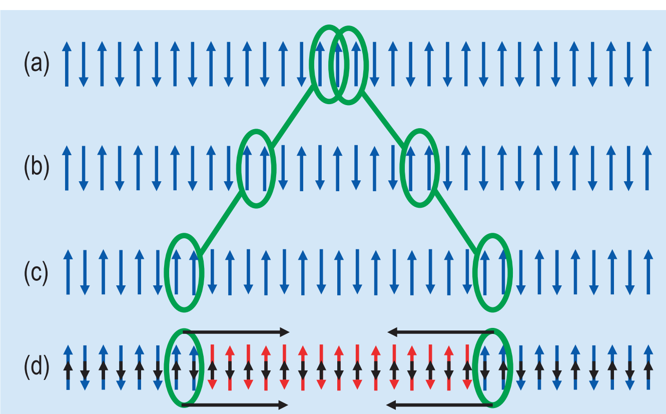

Fig. 1. Qualitative illustration of spinons in a spin-1/2 chain. (a) Shows a spin-flip excitation in an otherwise ordered segment of a spin chain. In the subsequent two frames the spin-flip is spatially separated into domain wall boundaries illustrating spinons that each carry half a spin flip. Separation of the walls costs no energy. (d) shows the situation when a staggered field (small black arrows) breaks the symmetry between even and odd sites of the lattice. Spinons now attract each other (separation costs energy) and can be expected to form bound states. Note that in a real spin-1/2 chain spinons are dynamic quantum degrees of freedom with a finite spatial extent.

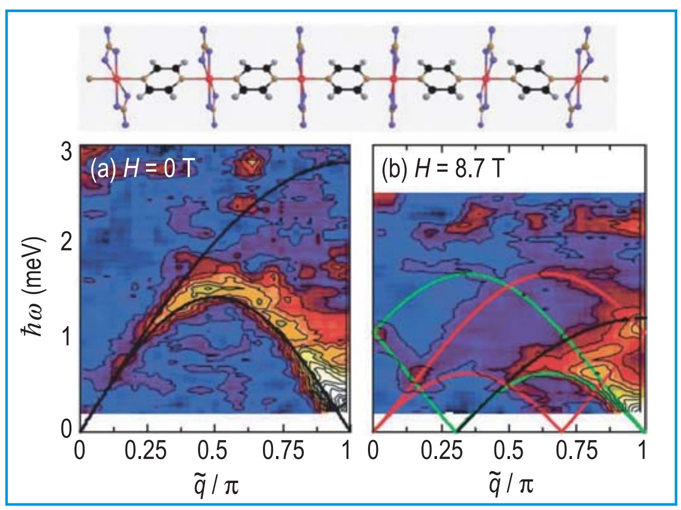

Fig. 2. False color image of SPINS neutron scattering data [2] from $Cu(C_4H_4N_2)(NO_3)_2$ (CuPzN) in zero and high field. Spin-1/2 copper atoms shown in red form uniform chains. The experiment provides evidence for a two-particle continuum from spin-1/2 particles with a field dependent chemical potential. The solid lines show boundaries for various types of continua determined through Bethe Ansatz and exact diagonalization.

under way to determine the nature of the corresponding excitations.

Static long-range order in the antiferromagnetic spin chain implies breaking the symmetry between odd and even sites of the lattice. As noted above, this does not occur spontaneously in a spin-1/2 chain but an applied field that alternates from site to site does break the symmetry and can therefore be expected to have a pronounced effect on both static and dynamic properties. Surprisingly, a staggered field is not hard to achieve. When even and odd sites along the spin chain have differently oriented atomic coordination environments, application of a uniform field induces an accompanying staggered field.

The molecular magnet $CuCl_2 \cdot 2$(dimethylsulfoxide) (CDC) has alternating coordination environments and Fig. 3(b) shows the dramatic effects on the neutron scattering spectrum in a field [3]. The zero field two spinon continuum coalesces into resolution limited modes with different energy gaps at $q = \pi$ and at the incommensurate wave vector. The staggered field breaks the domain symmetry (Fig. 1(d)), favoring antiferromagnetic domains that are aligned with the applied staggered field. If the domain between two spinons is out of phase with the staggered field the spinons attract each other. The strength of interaction grows with spinon separation resulting in asymptotically bound spinons. Because they consist of spinon pairs, these bound states can be created directly through neutron scattering.

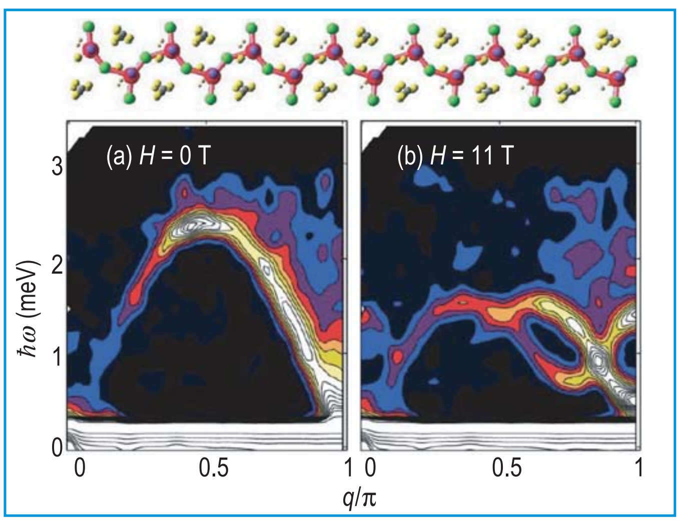

Fig. 3. False color image of DCS neutron scattering data [3] from $CuCl_2 \cdot 2$(dimethylsulfoxide) (CDC) in zero field and in a field of 11 Tesla. Spin-1/2 copper atoms shown in red form spin chains with alternating orientation of the coordinating environment, causing an effective staggered field in registry with the lattice in conjunction with the uniform field. The staggered field causes formation of soliton and breathers from spinons as evidenced by resolution limited modes with a finite energy gap.

Following the initial discovery of a field induced gap in a spin-1/2 chain at the NCNR [5], Affleck and Oshikawa showed that the relevant low energy field theory describing bound spinons is the quantum sine-Gordon model [6]. It can be shown that the excited states at the incommensurate wave vector in the spin-1/2 chain are topological excitations called solitons, while those at $q = \pi$ are soliton bound states called breathers. Identifying the lowest energy excitation at the incommensurate wave vector with a soliton, the quantum sine-Gordon model perfectly accounts for the energy of the two lower excitations at $q = \pi$ as being the corresponding breathers. The agreement between the observed excitation energies and the predictions of the quantum sine-Gordon model persists throughout the field range that we have accessed, which corroborates the identification of both excitations [3]. There is also detailed agreement between the experimental data and bound state structure factor calculations [7].

Despite its apparent simplicity, the spin-1/2 chain features a potpourri of complex many body physics that can be probed in exquisite detail using neutron spectroscopy. These experiments spur theoretical progress towards understanding strongly correlated electron systems and exemplify the close connection that is possible between theory and experiment in low dimensional quantum magnets.

References

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C. Broholm[1,2], **Y. Chen**[3], **M. Kenzelmann**[1,2], **C. P. Landee**[4], **K. Lefmann**[5], **Y. Qiu**[2,6], **D. H. Reich**[1], **C. Rischel**[7], **M. B. Stone**[8], **and M. M. Turnbull**[4]

[1] Johns Hopkins University, Baltimore, MD 21218

[2] NIST Center for Neutron Research
National Institute of Standards and Technology, Gaithersburg, MD 20899-8562

[3] Los Alamos National Laboratory, Los Alamos, NM 87545

[4] Clark University, Worcester, MA 01610

[5] Risø National Laboratory, DK-4000 Roskilde, Denmark

[6] University of Maryland, College Park, MD 20742

[7] Niels Bohr Institute, University of Copenhagen
DK-2100, Copenhagen, Denmark

[8] Pennsylvania State University
University Park, PA 16802