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Direct Observation of Magnon Fractionalization in the Quantum Spin Ladder

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We measure by inelastic neutron scattering the spin excitation spectra as a function of applied magnetic field in the quantum spin-ladder material (C5H12N)2CuBr4. Discrete magnon modes at low fields in the quantum disordered phase and at high fields in the saturated phase contrast sharply with a spinon continuum at intermediate fields characteristic of the Luttinger-liquid phase. By tuning the magnetic field, we drive the fractionalization of magnons into spinons and, in this deconfined regime, observe both commensurate and incommensurate continuua.

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Gapped quantum antiferromagnets (AFs) offer some of the most exotic states of electronic matter ever to be observed, and as such have been the enduring focus of intense theoretical and experimental interest. In an applied magnetic field, the threefold degeneracy of the triplet excitations is lifted and the triplet gap $\Delta$ is closed at a critical field $B_c = \Delta / g_\mu_B$. The properties of the states beyond this quantum critical point (QCP) depend strongly on system dimensionality [1], and in one dimension (1D), where long-range order is forbidden, the field-induced phase is expected to be a spin Luttinger liquid (LL). In this state, spin-flip excitations fractionalize into spinons, elementary excitations for momentum transfers along the ladder [Qh, Fig. 1(b)]. The dispersion in the perpendicular directions $E_f = 3.5$ meV or $E_f = 4.7$ meV. Cryomagnets were used for vertical fields up to 14.8 T $|b|/|b|/|b|$ axis.

INS data in the QD phase, $B < B_c$, are summarized in Fig. 1. Here we focus on the 1D ladder dispersion: sharp (resolution-limited) peaks arise from a dispersive triplet excitation for momentum transfers along the ladder [Qh, Fig. 1(b)]. The dispersion in the perpendicular directions $E_f = 3.5$ meV or $E_f = 4.7$ meV. Cryomagnets were used for vertical fields up to 14.8 T $|b|/|b|/|b|$ axis.

Previous attempts to observe the essential physics of the field-induced LL phase in quasi-1D magnets such as the candidate Haldane material NDMAP [2], effective $S = 1$ chain IPACuCl3, [3] and possible spin-ladder system CuHCl [4] have generally encountered problems due to additional terms in the spin Hamiltonian. These include single-ion anisotropy, Dzyaloshinskii-Moriya interactions, and especially interchain couplings. While a spinon continuum has been measured in the gapless chain materials Cu-benzoate [5], CuPzN [6], and KCuF 3 [7], the spin-ladder compound piperidinium copper bromide [(C5H12N)2CuBr4] [8,9] offers the first opportunity to induce LL physics in a gapped system by an applied magnetic field. A number of thermodynamic measurements, specifically of thermal expansion [10], specific heat [11], and magnetocaloric effect [11,12], as well as by nuclear magnetic resonance [13], are consistent with predictions for an ideal ladder. By INS the rung and leg exchange parameters, Jl and Jh, as well as additional terms in the spin Hamiltonian, are determined directly.

High-quality single crystals of (C5D12N)2CuBr4 were grown from solution, and up to 10 were coaligned to obtain samples with masses of approximately 2.5 g. INS experiments were performed on the spectrometers IN14 (ILL, Grenoble), FLEX (HMI, Berlin), and TASP (SINQ, Villigen), using a focusing monochromator/analyzer and a Be filter between sample and analyzer (fixed final energies $E_f = 3.5$ meV or $E_f = 4.7$ meV). Cryomagnets were used for vertical fields up to 14.8 T $|b|/|b|/|b|$ axis.

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High-quality single crystals of (C5D12N)2CuBr4 were grown from solution, and up to 10 were coaligned to obtain samples with masses of approximately 2.5 g. INS experiments were performed on the spectrometers IN14 (ILL, Grenoble), FLEX (HMI, Berlin), and TASP (SINQ, Villigen), using a focusing monochromator/analyzer and a Be filter between sample and analyzer (fixed final energies $E_f = 3.5$ meV or $E_f = 4.7$ meV). Cryomagnets were used for vertical fields up to 14.8 T $|b|/|b|/|b|$ axis.

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High-quality single crystals of (C5D12N)2CuBr4 were grown from solution, and up to 10 were coaligned to obtain samples with masses of approximately 2.5 g. INS experiments were performed on the spectrometers IN14 (ILL, Grenoble), FLEX (HMI, Berlin), and TASP (SINQ, Villigen), using a focusing monochromator/analyzer and a Be filter between sample and analyzer (fixed final energies $E_f = 3.5$ meV or $E_f = 4.7$ meV). Cryomagnets were used for vertical fields up to 14.8 T $|b|/|b|/|b|$ axis.
[\(Q_k\) and \(Q_l\), Figs. 1(a) and 1(c)] is shown to demonstrate the excellent one-dimensionality of the system. In fact, we have found a systematic variation of order 30 \(\mu\text{eV}\) in the effective ladder bandwidth [14], and subtract this interladder contribution to obtain the intrinsic parameters \(J_r\) and \(J_l\). Figures 1(d) and 1(e) show the INS intensity at \(Q = \frac{1}{2} 1.500\) (the band minimum), demonstrating a Zeeman splitting into three triplet components at finite field; Gaussian fits yield the energies shown in Fig. 1(f).

The spectrum changes dramatically above \(B_c\): we find a continuum of excitations extending over much of the Brillouin zone and up to energies of 0.8 meV. We consider first a field corresponding to half magnetic saturation (\(m = 0.5\), Fig. 2), where the ladder is equivalent to a gapless spin chain in zero field (below). Here the continuous spectrum of spinon excitations [15] is bounded by \(\epsilon_f(Q_h) = \hbar \omega(Q_h)\) and \(\epsilon_u(Q_h) = 2\hbar \omega(Q_h)\), where \(\hbar \omega(Q_h) = \alpha J \sin(2\pi Q_h)\) [16] with \(\alpha\) a quantum renormalization factor which is determined exactly from the system geometry and interaction parameters. In Fig. 2(a), it is clear that the commensurate \(m = 0.5\) spectrum is well described by such a shape. Its continuum nature is illustrated strikingly in high-statistics measurements taken at \(B = 10.1\) T; both constant-\(E\) [Figs. 2(b) and 2(d)] and constant-\(Q\) [Fig. 2(c)] scans show broad regions of continuous intensity, the latter extending from 0.15 meV (lower measurement limit) to 0.8 meV. We stress two important points. First, these data are taken well inside the LL regime, at a temperature significantly below the LL crossover, \(T_{\text{LL}}\) [11], but above the boundary to 3D order induced by...
FIG. 3 (color online). Incommensurate excitations in the LL phase. (a),(b) Spinon continua calculated for an $S = 1/2$ XXZ chain with anisotropy $\delta = 0.5$ (see text) at $m = 0.25, 0.75$ (a) and $m = 0.5$ (b), data shown also in Fig. 2(a) convolved with instrumental resolution; dashed white lines represent INS scans at $E = 0.2$ and $0.4$ meV. (c)–(f) Constant-$E$ scans (trajectories as in Fig. 2(b) inset) for $B = 7.9$ and $12.3$ T. (g) Constant-$Q$ scans at the ZB for two chosen magnetizations $m$ between 0 and 0.5. (h) Summary of data for ZB excitation energy as a function of $m$. Red lines are predictions based on the XXZ chain: solid from panel (a) and dashed (shown for comparison) from panel (b).

The measured triplets dispersion is dominated by the ladder terms: we obtain $J_r = 12.8(1)$ K and $J_l = 3.2(1)$ K [black line in Fig. 1(b)]. From the fits to the linear Zeeman splitting [solid lines in Fig. 1(f)], the $g$ factor for this orientation is $g = 2.17(3)$, while $B_c = 6.8(1)$ T. The two approaches agree perfectly, and are consistent with values of $g$ and $B_c$ determined by other techniques.

Theoretically, the excitations of a field-polarized ladder are gapped spin waves with dispersion relation $\epsilon(Q_h) = g\mu_B(B - B_c) + J_l[1 + \cos(2\pi Q_h)]$ [18]. A mean-field treatment is exact here because all quantum fluctuations are quenched. The red lines in Figs. 4(b) and 4(c) are fitted using this expression: when the small 3D coupling term is removed, we obtain $J_r = 13.1(1)$ K, $J_l = 3.3(1)$ K, and $B_c = 13.6(1)$ T. The fit to the ZB energy in Fig. 4(a) yields $B_c = 13.6(2)$ T.

The LL continuum arises from the fractionalization of spin-flip excitations ($\Delta S^z = 1$) into two elementary and deconfined $S = 1/2$ objects. Indeed, in a unified description of the full phase diagram, the magnon excitations in the QD and FM phases are bound states of these spinons, and the QCP at $B_c$ may be regarded as a field-driven spinon binding-unbinding or confinement-deconfinement transi-
tion. The theoretical description for a ladder in the strong-coupling limit may be obtained by a mapping to the $S = 1/2$ XXZ chain with anisotropy $\delta = 1/2$ [19]. The low-energy sector of the ladder [i.e., the lowest Zeeman-split branch in Fig. 1(f)] is governed by

$$\mathcal{H}_{XXZ} = \sum_i J_i (\hat{S}^x_i \hat{S}^x_{i+1} + \hat{S}^y_i \hat{S}^y_{i+1} + \delta \hat{S}^z_i \hat{S}^z_{i+1}) - b_{\text{eff}} \hat{S}_i^z,$$

(1)

where the effective field $b_{\text{eff}} = 2b_z B - (B_x + B_y)/2$ is such that $-b_z \leq b_{\text{eff}} \leq b_z$, with $b_z = \frac{1}{2} J_l$ the saturation field for the XXZ chain. This effective model has spinon excitations in whose dispersion $J = J_1$ and $\alpha = 1.299$ [16], whence the bounds $e_l(Q_h)$ and $e_u(Q_h)$ shown as solid lines in Fig. 2(a).

Because $\hat{S}_i$ in Eq. (1) is a composite of the two physical spins on each ladder rung, the total INS cross section contains a rung structure factor modulating the contributions from longitudinal and transverse spin correlations [14]. All data in the LL phase were measured on the maxima of the transverse structure factor (insets in Fig. 2), where the longitudinal contributions are zero.

We have calculated the transverse spin correlation function for all values of $m$ following Ref. [20], and in Figs. 3(a) and 3(b) present the results for $m = 0.25, 0.75$, and 0.5. In the XXZ-chain model, the spectral intensities are symmetric in $m$ about $m = 0.5$. Data taken at $B = 10.1$ T correspond to $m = 0.48(2)$, while fields $B = 7.9$ and 12.3 T correspond, respectively, to $m = 0.24(2)$ and 0.72(2). The theoretical intensities were convolved with the 4D instrumental resolution to obtain the global fit shown as red lines in Figs. 2(b)–2(d) and 3(c)–3(f), while the red lines in Figs. 3(g) and 3(h) are obtained directly. The shaded bands indicate the error bars in the experimental determination of a single constant of proportionality valid for all fields, energies, and wave vectors. Their width combines the statistics of all our scans with uncertainties in the exact magnetization values at the chosen fields and in the convolution procedure. The agreement is quantitatively excellent. We note, in particular, that only the smallest asymmetries between $m < 0.5$ and $m > 0.5$ may be discerned in the data [comparing Fig. 3(c) with 3(e) and Fig. 3(d) with 3(f)], and that the energy dependence of the intensity is described exactly [Fig. 2(c)].

Measurements in the QD and FM phases provide two independent and complementary determinations of $J_x$ and $J_l$. While the values of $B_x$ and $B_y$ deduced from these are marginally smaller than from thermodynamic studies, the latter were performed mostly on undeuterated samples and in different orientations. By exploiting the $Q$ specificity of INS, we have accounted for a 3% effect from interladder coupling [14]. We then find that the intrinsic ladder leg parameters in the two regimes are identical within their errors, but the rung parameters are not: this apparent magnetostriction effect is of order 1%–2%. That such a phenomenon may occur is not surprising in a structurally “soft” material of this nature [10]. In fact this discrepancy is the sum of all additional contributions, including any other magnetoelastic terms or complex spin interactions. Our magnon dispersion analysis therefore quantifies the statement that $(C_5H_{12}N)_2CuBr_4$ is an excellent spin-ladder system.

A key property of the LL spectrum is the presence of a zero-energy mode at an incommensurate wave vector $0 < Q_{\text{min}} < 1/2$ which changes systematically with field [21]. However, the spectral weight at $Q_{\text{min}}$ vanishes as $E \to 0$ [Fig. 3(a)], precluding a direct measurement of the incommensurability. Instead we have presented indirect confirmation of the theoretical prediction in the form of the field-tuned finite-$E$ spectra and the ZB energy [Figs. 2 and 3]. The question of the evolution of spectral weight in the LL is of particular interest in the context of the commensurate 3D ordered phase which emerges at sufficiently low temperature [12,13]. At intermediate energies, we return to the question of the symmetry of the measured spectra about
m = 0.5: physical effects arising due to departures from strict strong coupling, and from the higher triplet branches, are expected to cause some asymmetry in intensities, but these are clearly extremely small for energies \( 0.5J_f < E < 2.5J_l \). At high energies, it remains to address, both experimentally and theoretically, the nature of the higher spinon continua expected from the upper two triplet branches.

In summary, we have performed a comprehensive INS investigation of the magnetic excitation spectrum in \((C_5H_{12}N)_2CuBr_4\), a spin-ladder compound whose energy scales are perfectly suited to systematic studies in laboratory fields. We observe the presence of a broad continuum of spinon excitations in the intermediate, Luttinger-liquid (LL) phase, which is starkly different from the discrete (magnon) excitations measured below the critical field (QD phase) and above saturation (FM phase). From the QD and FM results, we extract the ladder parameters with unprecedented accuracy, demonstrating directly that even the sum of all other effects beyond the “nearly ideal” Hamiltonian of weakly coupled ladders falls below the 2% level. The spinon continuum proves the occurrence of field-induced fractionalization into elementary \( S = 1/2 \) entities as the system enters the LL regime. An excellent, fully quantitative description of the incommensurate continua measured at all fields is obtained from an effective chain model for a ladder with the coupling ratio \( J_r/J_l \approx 4 \) of \((C_5H_{12}N)_2CuBr_4\).

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