Magnon damping in spin-ladders

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A knowledge of quasi-particle lifetimes and dispersion relations is crucial to an understanding of the ground-state properties of solids since these excitations govern the low-temperature behavior of strongly correlated systems. Here, we report on the determination of the low-temperature lifetime of spin wave excitations (magnons) in a quasi-one dimensional Haldane-gaped quantum spin ladder IPA-CuCl$_3$ by means of high energy resolution neutron resonant spin echo spectroscopy. Using this novel inelastic neutron technique, we have found two magnon modes at the antiferromagnetic zone centre separated by Δω = 50 μeV zero field splitting, exhibiting a line width of Γ_1 = 5 μeV and Γ_2 = 15 μeV respectively. These narrow magnon line widths cannot be measured by other commonly used inelastic neutron scattering techniques such as triple-axes spectrometers (TAS) since their resolution is limited to the meV range by beam intensity.

Long lifetime at low temperatures

One-dimensional physics is unique due to unavoidable collisions among counter-propagating particles, regardless of their mutual interaction strength. In gapped quantum spin liquids, such as Haldane spin chains, the quasiparticles (magnons) persist in the limit T → 0 K, since mutual collisions are rare due to their exponentially small density. Interactions become important at elevated temperatures as a consequence of the increased density of the thermally excited magnons. This results in a reduction of magnon lifetimes and a thermally induced blue-shift of their energies.

An other remarkable feature of one dimensional gaped spin chains is that, when the T = 0 K energy gap is used as the temperature scale, all experimental curves are identical to within system-dependent, but temperature-independent, scaling factors of the order of unity. This quasi-universal scaling behavior is the consequence of the shared one-dimensional topology of the spin chains. In the framework of the non-linear σ model (NLσM) [1], this quasi universality can be understood by combining all exchange interactions relevant for a particular material into one effective antiferromagnetic coupling constant J_{eff}, which will determine the low temperature behavior of the systems. According to NLσM, the zero temperature gap $\Delta_0 = 0.41\ J_{eff}$ and the temperature dependence of the magnon line width is described by the equation,

$$\Gamma(T) = 3\sqrt{\frac{\Delta_0 k_b T}{2\pi v^2}}\exp\left(-\frac{\Delta_0}{k_b T}\right) \qquad (1)$$

where v is the magnon velocity. According to this formula, an exponentially small magnon linewidth or, equivalently, an exponentially long magnon lifetime is expected at low temperatures. This prediction was partially confirmed by earlier inelastic neutron scattering experiments [2], since the magnon line width of IPA-CuCl$_3$ at temperatures lower than T = 10 K was below experimental resolution limits. Due to the narrow magnon line width of IPA-CuCl$_3$, it is an ideal system to test the low-temperature predictions of NLσM by TRISP, the neutron resonant spin echo spectrometer at the FRM II.

Oscillating decay

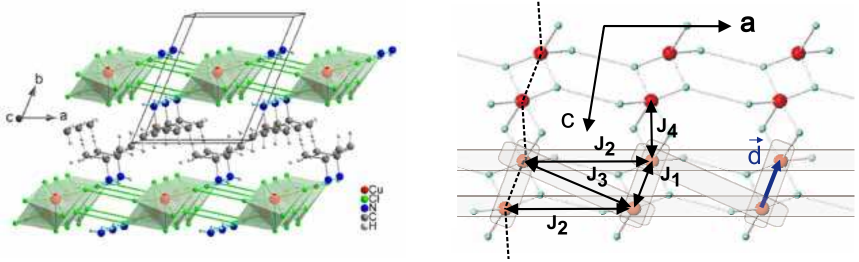

Figure 1: a) Crystal structure of IPA-CuCl$_3$. Magnetic CuCl$_3$ and nonmagnetic polymeric IPA layers alternate along the b crystallographic direction. b) Single magnetic CuCl$_3$ plane viewed from the top. Characteristic spin-ladder running along a is showed in gray.

IPA-CuCl$_3$ crystallizes in a triclinic space group P1. The key features of the structure are shown in figure 1a. IPA forms layers in a-c plane preventing magnetic interactions along the b direction. The magnetic properties of IPA-CuCl$_3$ described by a single magnetic CuCl$_3$ layer in the a-c plane are shown in figure 1b. Cu^{2+} ions that carry S = ½ spins, form ladders that run along the crystallographic a axis, as described in detail in [3]. Exchange interactions along the ladder legs (J_1 and J_2 in fig. 1b) are antiferromagnetic. Pairs of spins on each ladder rung are correlated ferromagnetically due to the dominating J_1 coupling. So, IPA-CuCl$_3$ is an archetypical composite Haldane spin-chain with a gap-energy Δ_0 = 1.17 meV at the aniferromanetic zone center (0.5,0,0) at T = 0.5 K. By measuring the neutron polarization as a function of spin echo time τ_{SE}, we determined the Fourier transform of the scattering function of our sample. We found an oscillating decay (fig. 2) which is characteristic of a small separation of two magnon modes. Fitting the data with a fourier transform of two Lorentzian functions (green line in fig. 2), each describing a single magnon excitation, we have determined the splitting Δω = 47 μeV and the line widths Γ_1 = 5 μeV and Γ_2 = 15 μeV. The relative weight of the two magnon modes is 2:1, from which we infer that the broader mode corresponds to $S^z = \pm 1$ triplets, while the narrower band is a $S^z = 0$ triplet mode and the origin of the splitting is a single-ion anisotropy.

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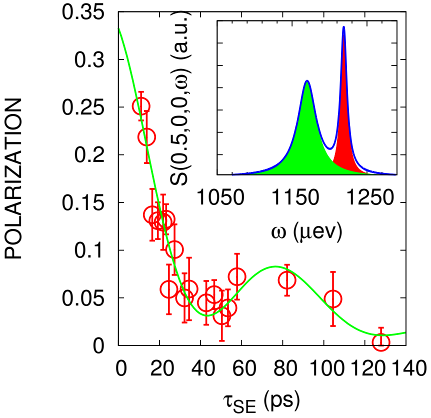

Figure 2: Neutron polarization (P) as a function of spin echo time (τ_{SE}) measured at T = 0.5 K at the antiferromagnetic zone centre (0.5,0,0). The blue line is a fit assuming two magnon modes separated by a small zero field splitting. The inset shows the resulting neutron spectral function determined from the fit.

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