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Neutron study of fracton excitations in percolating antiferromagnets

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H.Ikeda (a), M.Takahashi (b), J.A.Fernandez-Baca (c), R.M.Nicklow(c)

(d)

(a) National Laboratory for High Energy Physics, Tsukuba 305, Japan

(b) Institute of Applied Physics, Tsukuba University, Tsukuba 305, Japan

(c) Oak Ridge National Laboratory, Oak Ridge, TN37831, USA

(e)

We report the results of an inelastic neutron scattering experiment on nearly-percolating Heisenberg antiferromagnets ($\text{RbMn}_c\text{Mg}_{1-c}\text{F}_3$), in which the Mn concentrations ($c=0.31, 0.34$ and 0.39) are very close to the percolation threshold ($c_p=0.312$). A broad peak superimposed on Ising-cluster excitations was observed throughout the Brillouin zone. The intensity of a broad peak increased on approaching the percolation threshold. The origin of this broad peak is attributed to the excitation of fractons in a percolating network.

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Fractals, Magnetic excitations, Neutron scattering - excitations,

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H.Ikeda

National Laboratory for High Energy Physics, Oho 1-1, Tsukuba
305, Japan

Fax: +81-298-64-3202

e-mail: hikeda@kekvox.kek.jp

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In recent years, considerable attention has been directed towards the dynamical properties of highly ramified percolating networks that exhibit a fractal geometry [1,2]. A random site-diluted Heisenberg antiferromagnet is an ideal system for probing the existence of these excitations. In such a system and at concentrations close to, but just above, the percolation threshold there should be a crossover from long-wavelength spin-wave excitations to short-wavelength fracton excitations. The origin of this crossover is the fact that the fractal geometry is realized only at length scales shorter than the geometrical correlation length (ξ_G) [3]. The geometrical correlation length of this system is defined as $\xi_G = (c - c_p)^{-\nu_G} a_0$ ($\nu_G = 0.88$ for a 3D system, and a_0 is the atomic spacing) and its corresponding wave vector is $q_c = \xi_G^{-1}$. Magnetic excitations in diluted magnetic systems have been extensively studied using neutron inelastic scattering techniques [4], and in order to look for fracton excitations neutron scattering studies have been performed on a three-dimensional (3D) diluted near-Heisenberg antiferromagnet ($\text{Mn}_{0.5}\text{Zn}_{0.5}\text{F}_2$) [5].

Recently, a renewed experimental effort has been initiated to characterize the fractal component of the dynamics in the diluted magnetic systems. For this, it was important to distinguish fracton excitations from other localized excitations, such as Ising cluster excitations.

We have recently performed an experiment aimed to give the first quantitative measurement of fracton excitations in the near-percolating Heisenberg systems [6]. For that experiment we chose a diluted pure-Heisenberg antiferromagnet ($\text{RbMn}_{0.39}\text{Mg}_{0.61}\text{F}_3$), in which the Mn concentration (0.39) is very close to the percolation threshold ($c_p = 0.312$). The corresponding cross-over wave vector is $q_c = \xi_G^{-1} = 0.024$ reciprocal lattice units (rlu). The excitations with wave vectors smaller than q_c are expected to be spin waves, while the excitations with wave vectors larger than q_c are expected to be

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fractons. Since q_c in that system is very small, the fracton region is observable in the standard momentum resolution of neutrons. The energy spectra obtained at several wave vectors from $q=0$ to $0.375(\text{ZB})$ rlu reveal that the observed line shapes are not smooth, but have some small structure, originating from the Ising cluster excitations, throughout the Brillouin zone. Also, over the entire Brillouin zone the energy spectrum of the additional contribution shows a very broad, smooth shape. The energy width of this spectrum is much broader than the energy resolution. As the wave vector increases, the intensity of the scattered neutrons decreases rapidly. We analysed the line shape of the magnetic response of an additional magnetic contribution obtained at 4.5 K. From a physical point of view, a damped harmonic oscillator (DHO) would be the most reasonable model to fit these excitations. We therefore fitted the broad excitation data to the functional form $\chi''(q,E) = A \Gamma(q)E/((E^2 - E_p(q)^2)^2 + (\Gamma(q)E)^2)$, where A is a constant. It should be noted that since the value of $\Gamma(q)$ is much larger than $E_p(q)$, the excitations are strongly over-damped over the entire Brillouin zone. From this as well as other experimental results, we concluded that the over-damped intensities are from fracton excitations.

Very recently, we extended our experiments in order to look at the concentration dependence of these excitations together with the temperature variation of the excitation spectra. Our experiment was performed on single crystal samples (about 1 cc in volume) of $\text{RbMn}_c\text{Mg}_{1-c}\text{F}_3$ ($c=0.31$ and 0.34). $c=0.31$ is a percolation concentration and therefore the 31% sample orders at $T=0$ K. The 34% sample orders at 8 ± 1 K with the same magnetic configuration as in the pure system. The inelastic scattering measurements were performed on a triple-axis spectrometer installed at the HFIR reactor at the Oak Ridge National Laboratory (ORNL). The crystal was oriented with its $[0\ 1\ -1]$ axis

vertical. The magnetic excitations were measured for wave vectors along the $[0\ 1\ 1]$ direction from the $(1/2\ 1/2\ 1/2)$ zone center ($q=0$), to the zone boundary ($q=0.375$ rlu).

The concentration dependence of the energy spectra at $q=0.2$ is depicted in Fig.1. The intensities were normalized to the incoherent scattering intensities centered at $E=0$. As is shown, the intensity from the broad magnetic response increases with approaching T_N . This feature is also seen in other q -values measured. On approaching c_p , the crossover wave vector (q_c) of the sample decreases, and hence a large fraction of the infinite cluster, characterized by a length scale shorter than q_c^{-1} ($=\xi_G$), is fractal. This means that the fracton contribution to the scattered intensity has a largest intensity in the $c=0.31$ sample. The observed energy spectra as a function of concentration are consistent with this fractal picture; this confirms again our conclusion of the observation of fractons.

Another evidence for fractons is seen in the temperature variation of $\chi''(q, E)$ at wave vectors larger than q_c . In Fig.2, the energy spectra at $q=0.2$ rlu in $\text{RbMn}_{0.31}\text{Mg}_{0.69}\text{F}_3$ obtained from $T=5$ K to 150 K are shown. At $T=40$ K, peaks from Ising-cluster excitations almost disappear due to the much more enhanced thermal fluctuations of the molecular fields than at $T=5$ K. On the other hand, the over-damped component is predominant at this temperature, and the line shape is broaden compared to that measured at $T=5$ K. In this figure we observe the remarkable fact that the over-damped component can survive even at $T=150$ K ($\gg T_N (=0\text{K})$), and the peak energy slightly shifts towards higher energies with increasing T . These are completely different from the traditional spin-wave excitations in the Heisenberg system. The increase in the peak energy could be related to the localized nature of fractons, and thus the

excitation energy (oscillating frequency) could be increased by obtaining the thermal energy.

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Fig. 1 Concentration dependence of $(\chi''(q,E))$ in $\text{RbMn}_c\text{Mg}_{1-c}\text{F}_3$ ($c=0.31, 0.34$ and 0.39) at $T=5\text{K}$. Intensities were normalized to the elastic incoherent scattering intensities.

Fig. 2 Temperature variation of $(\chi''(q,E))$ in $\text{RbMn}_{0.39}\text{Mg}_{0.61}\text{F}_3$ at $q=0.2$ as a function of energy transfer observed at $T=4.5\text{ K}$ (open circles), 9 K (closed circles), 19 K (open triangles), 40 K (closed triangles), 60 K (crosses) and 100 K (open squares). The vertical bars represent error bars.

Fig. 1

Fig. 2

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