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Frustrated magnet Li$_2$ZrCuO$_4$ - paramagnetism meets paraelectricity

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Abstract. By measuring $^7$Li nuclear magnetic resonance, Cu$^{2+}$ electron spin resonance and a complex dielectric constant in the frustrated spin-1/2 chain compound γ-Li$_2$ZrCuO$_4$ we find that the electric sublattice of mobile Li$^+$ ions orders glass-like at $T_g$ $\sim$ 100 K. This yields the emergence of non-equivalent spin sites in the spin-1/2 CuO$_2$ chains. We suggest that such a remarkable interplay between electrical and spin degrees of freedom may influence the properties of the spiral spin state in Li$_2$ZrCuO$_4$ which develops in this material at low temperatures.

1. Introduction

Search for new functional materials with cross-coupling between electrical and magnetic degrees of freedom constitutes an active research field in condensed matter physics and material science. Such coupling can be achieved, e.g., in artificial nanostructures that combine a material with a large piezoelectric constant and a material with a large magnetostriction. In this work we present an example of an intrinsic single-phase system where the magnetic sublattice meets the electrically active one. This is a frustrated quantum spin-1/2 chain cuprate Li$_2$CuZrO$_4$ with a possible spiral spin structure whose peculiar low-temperature magnetic properties have been recently discussed in terms of the proximity to a quantum critical point$^1$.

2. Materials and methods

The orthorhombic crystal structure of Li$_2$CuZrO$_4$ (space group Cccm) is composed of chains formed by edge-shared "flattened out" CuO$_4$ tetrahedra running along the c-axis. The CuO$_2$ strongly frustrated spin-1/2 chains in Li$_2$CuZrO$_4$ form planes similar to LiCu$_2$O$_2$ that are stacked along the b-axis. Li$_2$CuZrO$_4$ orders magnetically at $\sim$ 6 K$^1$. The lithium ions in Li$_2$CuZrO$_4$ occupy two different types of positions: 4$b$ (Li$^0$) with occupancy about 100 % and 8$l$ (Li$I$) with occupancy 50 % (fig 1.). X-ray and neutron diffraction data$^2$ reveals two contiguous crystallographic 8$l$ positions for the Li$I$ ion between which it can hop.

Below we report the results of $^7$Li NMR, Cu$^{2+}$ ESR, and dielectric measurements for the powder sample of Li$_2$CuZrO$_4$ which was oriented in magnetic field along a-axe and fixed in the epoxy (for the chemical synthesis, see Ref. 2). The $^7$Li (I = 3/2) NMR spectra of Li$_2$CuZrO$_4$ samples were measured at a frequency of 38 MHz in the temperature range 6 - 300 K in magnetic field parallel to the Cu-planes by point-by-point sweeping of magnetic field. The quadrupole splitting which is estimated to be of the order of 0.05 MHz$^{-1}$ ($\approx$0.003T in our experiment) is unresolved in spectrum of our oriented powder samples and line shape can be described by a single Gaussian profile. The frequency dependent dielectric measurements were performed with the pressed powder pellet of Li$_2$CuZrO$_4$ in the temperature range 4 – 300 K. Finally, we have also performed a temperature dependent high field electron spin resonance (HF-ESR) measurement at a frequency of $\sim$ 350 GHz with the home-made spectrometer (for technical details, see Ref. 4)
Fig. 1. Fragment of slightly idealized Li$_2$CuZrO$_4$ structure with the super-transferred Cu-O-Li$_{III}$ bonds. Arrows point to the oxygen ion displacements in a real structure.

3. Results and discussion

We start with the $^7$Li NMR measurements which proved to be a very instructive tool to study both the Li ion mobility and the magnetic ordering in the cuprates. Well inside the paramagnetic state ($T > 150$K) the $^7$Li NMR response of Li$_2$CuZrO$_4$ (Fig. 2) seemingly presents a single line, however, the lineshape and the $T_2^{-1}$ nuclear relaxation rate analysis reveals a hardly resolved superposition of two Lorentzian lines with a full width of 0.01 T, which may be ascribed to the response of two lithium species with mobile Li$_I$ ions and immobile Li$_{III}$ ions, respectively. Lowering the temperature allows for a clear separation of two NMR signals. Below a characteristic temperature $T_g \sim 100$ K we observe two well separated lines with a different temperature behavior. The critical growth of the relaxation parameters (not shown) near magnetic phase transition temperature 5.5K and the temperature dependence of linewidth of the high-field (right) line allows us to assign it to the NMR response of the Li$_{III}$ ions nuclei. Strong and unusual temperature dependent shift of the low-field (left) line position from 2.315T at 100K to 2.28T at 6K and inhomogeneous broadening of the left line (Fig. 3) clearly associated with the NMR response of mobile Li$_I$ ions.

Fig. 2. The $^7$Li NMR spectrum of the oriented Li$_2$CuZrO$_4$ sample with the resonance frequency of 38.0MHz at several temperatures

One should note that the temperature dependence of the Li NMR linewidth for immobile Li$_{III}$ ions (high-field right line) shows up a rather conventional low-temperature rise that can be ascribed to the development of the critical spin fluctuations by the approach of the spin ordering. Assuming roughly the same spin fluctuation contribution for the both NMR signals we can single out the additional contribution to the inhomogeneous broadening of the left line. The difference between the magnitudes of two linewidths (shown by dashed line in fig.3) reflects the temperature dependence of the
additional contribution to the width of the left line. This additional broadening can be concerned with a slowing down of Li_1 motion between two equivalent half-occupied positions when the temperature decreases. The onset temperature for the motional narrowing of the NMR line with a temperature growth is usually correlated with the glass transition temperature T_g (in our case T_g ≈ 100K) that can be hence associated with a glass-like ordering of the Li_1 sublattice in Li_2CuZrO_4.

Fig. 3. Temperature dependence of the NMR linewidth for low- and high-field NMR lines. Dashed line shows the difference between the values of two linewidths reflecting an additional contribution to the inhomogeneous broadening of the left line.

Further evidence of a glass-like structural ordering can be provided by dielectric measurements. As it was expected from the NMR data, the temperature dependence of a dielectric constant shown in Fig. 4 reveals a frequency-dependent behavior (both real ε’ and imaginary ε’’ parts) at temperatures around T_g ~ 100 K which is typical for a glass-like transition. Interestingly, our dielectric measurements point to some intriguing high- and low-temperature features. The high-temperature rise of the real part of the dielectric constant evidences most likely a contribution of Li_1 to ionic conductivity. The low-temperature features of ε’ could be due to a possible coupling of the glass-like Li_1 system to the quantum critical behavior that develops in the CuO_2 spin-1/2 chains at low temperatures

Fig. 4. Temperature dependence of real (ε’) and imaginary (ε’’) parts of a dielectric constant for a pressed sample of Li_2CuZrO_4.

In fact, indications of the influence of the electric Li_1 sublattice on the subsystem of Cu spins have been found in the high-field ESR experiment that we performed at a field of ~ 12 T. Upon cooling the
sample below $T_g \sim$ 100K the otherwise single-line high temperature ESR spectrum begins to split into two lines (not shown). This suggests a temperature driven development of two nonequivalent Cu sites with slightly different g-factors. Since the split Li position is situated close to the Cu site (Fig. 1) the positively (1+) charged mobile Li obviously contributes to the crystal field potential acting on the orbital states of the Cu ion and thus to the orbital part of the g-factor. Hence the occurrence of two ESR lines suggests a particular freezing pattern of the electrical Li sublattice below $T_g$, that may intervene with the low temperature quantum magnetism of the CuO$_2$ spin chains.

5. Conclusion

We have measured $^7$Li NMR, Cu$^{2+}$ ESR, and dielectric constants of a frustrated quantum spin-1/2 chain cuprate Li$_2$CuZrO$_4$. The examination of the temperature behavior of the $^7$Li NMR line shape together with dielectric constant measurements evidences the glass-like structural ordering of the mobile Li ion electrical sublattice at $T_g \sim$ 100 K. The interplay between the subsystem of mobile Li ions and the spin subsystem is suggested by an observation of a local Cu$^{2+}$ site nonequivalence by ESR at temperatures below $T_g$.

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