# Magnetic properties of $CuCr_2Se_4$-single crystals doped with niobium

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$CuCr_2Se_4$ belongs to the group of chalcogenide spinels with a general formula $CuCr_2X_4$ (where X = S, Se, Te). They all exhibit metallic conductivity and ferromagnetic properties with high Curie temperatures: $T_C$ = 380 K [1,2], 420 K [1,3] and 326 K [4] for sulphur, selenium, and tellurium compounds, respectively. The metallic conductivity and the ferromagnetic properties are attributed to mixed valence state of chromium ions [5]. All these compounds crystallize in a normal spinel structure, space group *Fd*3*m* with copper ions located in one eight of the tetrahedral interstices and chromium in half of octahedral ones.

Single crystals of the $Cu[Cr_{2-x}Nb_x]Se_4$ spinel admixed with Nb ions ($x$ = 0.2, 0.4, 0.6) were grown from the mixture of the binary selenides CuSe and $Nb_2Se_3$ using a chemical vapour transport method with the anhydrous chromium chloride as a transporting agent. As the starting materials for the syntheses of the selenides were used high-purity elements: copper, niobium and selenium, all with the stated purities better than 99.99%.

The static dc magnetic susceptibilities were measured in two different cooling modes. In the zero-field cooled (ZFC) mode, the sample was first cooled down in the absence of an external magnetic field and then investigated while heating in a given magnetic field of $H_{dc}$ = 100 Oe. The field-cooled (FC) mode usually followed ZFC run when the same magnetic field was set on at high temperatures and measurements were performed with decreasing temperature. For both modes, the cooling process always started from the paramagnetic state. Dynamic ac magnetic susceptibility including its higher harmonics was measured at an internal oscillating magnetic field of $H_{ac}$ = 1 Oe with an internal frequency of $f$ = 120 Hz. Magnetization and magnetic susceptibility were measured with the use of Quantum Design Physical Properties Measurement System (QD-PPMS) in the temperature range 10–400 K and at magnetic field up to 70 kOe.

The single crystals of $Cu[Cr_{2-x}Nb_x]Se_4$ ($x$ = 0.2, 0.4, 0.6) are ferromagnets with the Curie temperature changing from 337 K for $x$ = 0.2, *via* 356 K for $x$ = 0.4 to 358 K for $x$ = 0.6 and the Curie-Weiss temperature changing from 347 K for $x$ = 0.2, *via* 360 K for $x$ = 0.4 to 363 K for $x$ = 0.6. This means that substituting niobium in place of chromium strongly reduces the ferromagnetic interactions of both long- and short-range compared to the $CuCr_2Se_4$ matrix. Saturation magnetization slightly shifts towards higher magnetic fields, as niobium content increases.

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