

Article

Magnetization of Magnetically Inhomogeneous $\text{Sr}_2\text{FeMoO}_{6-\delta}$ Nanoparticles

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1. Synthesis of Nanosized Strontium Ferromolybdate Particles

The citrate-gel technique was used for the synthesis of $\text{Sr}_2\text{FeMoO}_{6-\delta}$ (SFMO) nanoparticles using ultra-high purity $\text{Sr}(\text{NO}_3)_2$, $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}$ and citric acid monohydrate $\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O}$ as initial reagents. Synthesis details are described in [1]. Figure S1 shows a flowchart of the manufacturing procedure.

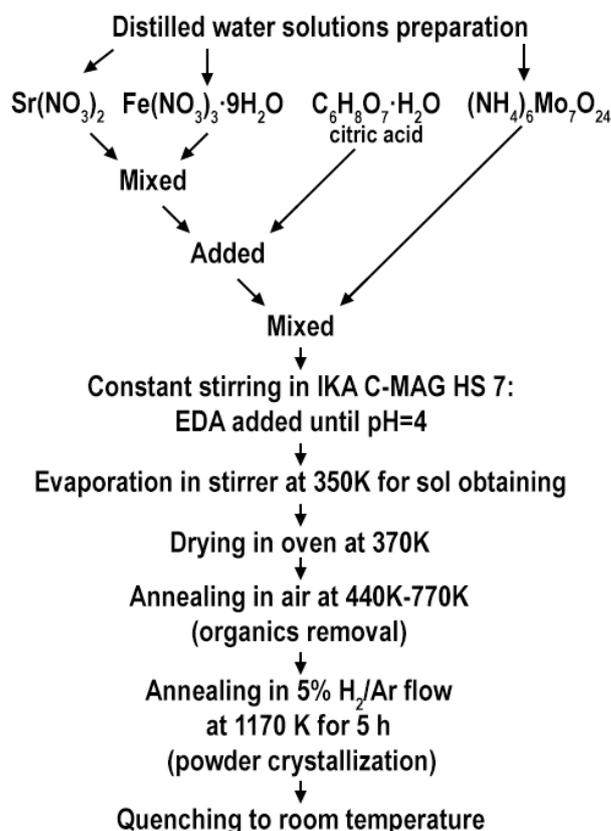


Figure S1. Flowchart of the fabrication of magnetically inhomogeneous $\text{Sr}_2\text{FeMoO}_{6-\delta}$ nanoparticles by the citrate-gel technique [1].

2. X-ray Diffraction

Experimental X-ray diffractograms were obtained at room temperature in a DRON-3 X-ray diffractometer (Bourestnik, Saint Petersburg, Russia) using the $\text{CuK}\alpha$ radiation at a scanning rate of 60 deg/h. Crystalline structure and the degree of superstructural ordering of the iron and molybdenum cations were evaluated by means of the ICSD-PDF2 database (Release 2000) and Rietveld refinement [3], a non-linear least-square fitting of the whole diffraction pattern to a crystal structure model. Figure S2 illustrated a typical XRD pattern.

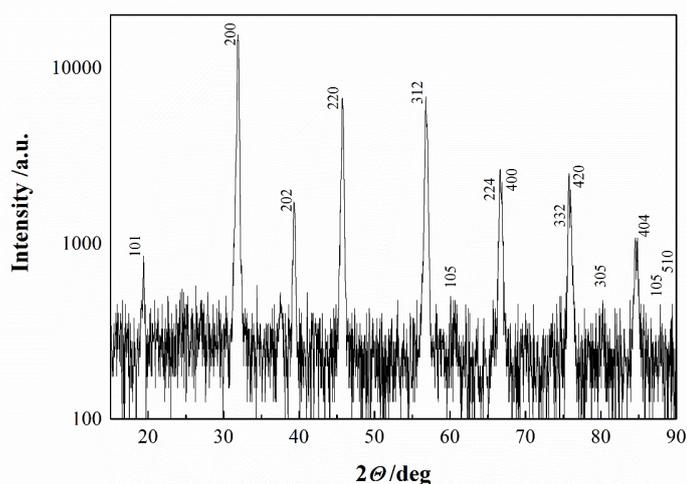


Figure S2. X-ray diffraction pattern of the fabricated Sr₂FeMoO_{6-δ} nanoparticles.

Rietveld refinement was carried out by applying the PowderCell software package [4]. The weighted residual of least-square refinement amounted to $R_{wp} = 0.152$, the expected (best possible R_{wp}) residual to $R_{exp} = 0.138$ and the goodness of fit to $GOF = (R_{wp}/R_{exp})^2 = 1.21$. The degree of superstructural ordering (P) was calculated by the formula $P = (2 \cdot SOF_{Fe} - 1) \cdot 100\%$ [5], where SOF is the site occupancy factor of Fe ions refined by the Rietveld method. Figure S3 illustrates the result of Rietveld refinement of the (101) superstructural XRD peak in comparison to the ideal structure from the ICSD-PDF2 database (Release 2000).

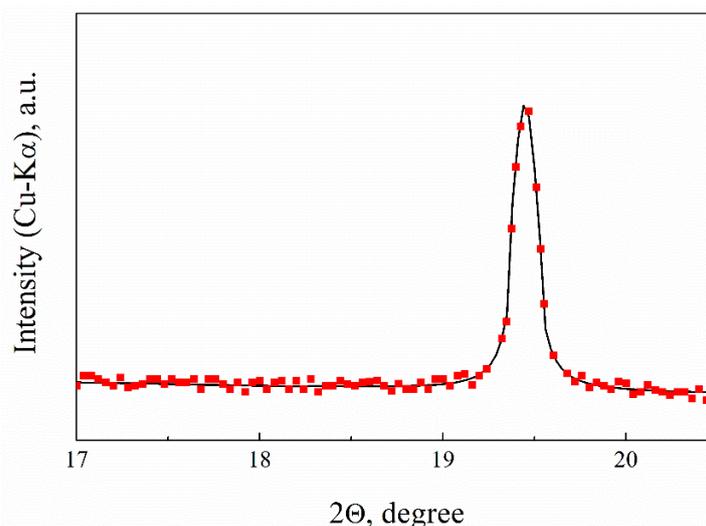


Figure S3. Comparison of the superstructural (101) XRD peak of Sr₂FeMoO_{6-δ} with $P = 88\%$ (red squares) with the ideal structure with $P = 100\%$ (black solid line).

3. Resonance Field versus Reduced Temperature

Figure S4 represents the resonance field B_r versus reduced temperature $\vartheta = (1 - T/T_c)$ with T_c the Curie temperature. The slope of this curve amounts to $dB_r/d\vartheta = -1.825$ T.

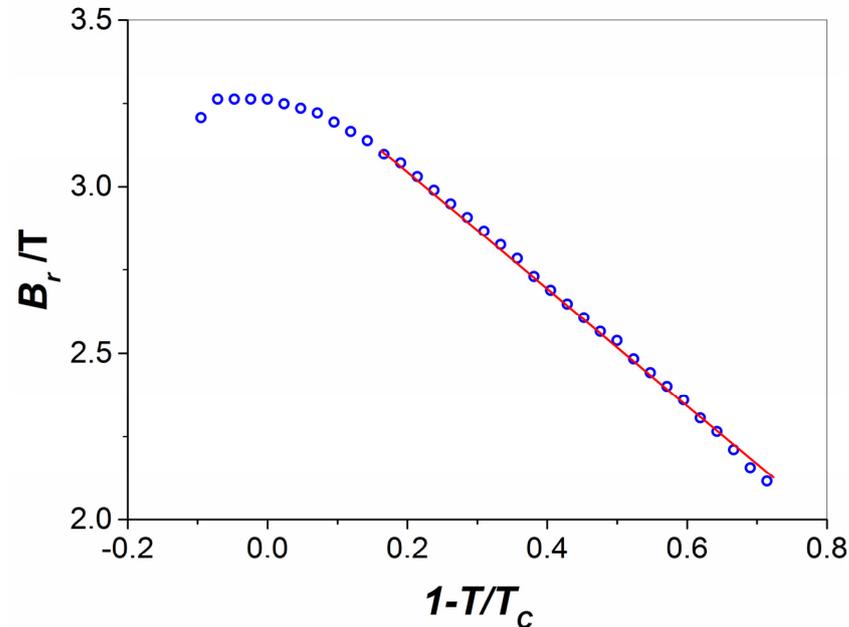


Figure S4. Resonance field B_r versus reduced temperature $\vartheta = (1 - T/T_c)$. The linear part of the curve is marked by a red line.

4. Field Dependence of the Magnetization

Figure S5 depicts the field dependence of the magnetization of the SFMO nanoparticles measured at 5 K using a “Liquid Helium Free High Field Measurement System” vibrating sample magnetometer (Cryogenic Ltd., UK).

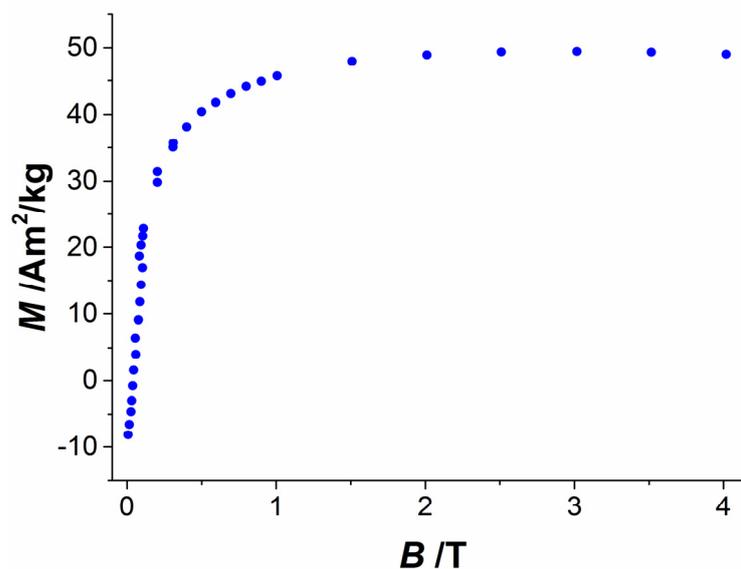


Figure S5. Field dependence of the magnetization of the SFMO nanoparticles measured at 5 K.

References

- Suchanek, G.; Kalanda, N.; Artsiukh, E.; Yarmolich, M.; Sobolev, N.A. Tunneling conduction mechanisms in strontium ferromolybdate ceramics with strontium molybdate dielectric intergrain barriers. *J. Alloys Comp.* **2020**, *860*, 158526. <https://doi.org/10.1016/j.jallcom.2020.158526>.

2. Yarmolich, M.; Kalanda, N.; Demyanov, S.; Fedotova, J.; Bayev, V.; Sobolev, N.A. Charge ordering and magnetic properties in nanosized Sr₂FeMoO_{6-δ} powders. *Phys. Status Solidi B* **2016**, *253*, 2160–2166. <https://doi.org/10.1002/pssb.201600527>.
3. Rietveld, H.M. A profile refinement method for nuclear and magnetic structures. *J. Appl. Cryst.* **1969**, *2*, 65–71. <https://doi.org/10.1107/S0021889869006558>.
4. Nolze, G. PowderCell: a mixture between crystal structure visualizer, simulation and refinement tool. *POWDER DIFFRACTION: Proceedings of the II International School on Powder Diffraction*. Kolkata, India, 20-23 January 2002; Sen Gupta, S.P., Chatterjee, P., Eds.; Allied Publishers Limited: Delhi, India, 2002; pp.146–155.
5. Huang, Y.H.; Karppinen, M.; Yamauchi, H.; Goodenough, J.B. Systematic studies on effects of cationic ordering on structural and magnetic properties in Sr₂FeMoO₆. *Phys. Rev. B* **2006**, *73*, 104408. <https://doi.org/10.1103/PhysRevB.73.104408>.