

# Symmetry Analysis of the Toroidal Moment in Magnetoelectric Crystalline Materials

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In ferroic materials, the direction of the net electric polarization, magnetization, or strain is dictated by its symmetry. The electric dipole moments, magnetic moments, and strain will only spontaneously align if the thermodynamic conditions induce a crystallographic transition to a phase which permits them. These transitions are then characterized by which symmetry elements are no longer present across the transition.

A fourth type of ferroic order has been theorized, in which the induced magnetic structure would permit a net toroidal moment. In a toroidized material, pairs of anti-aligned spins permit terms in the magnetoelectric susceptibility tensor which correspond to a toroidal moment perpendicular to the ring of spins. The candidate material  $\text{LiCoPO}_4$  ( $Pnma'$ ) has received particular attention recently, since it fulfills key requirements of ferrotoroidicity.[1] We have been interested in other structural analogs as well. The magnetic symmetry of both  $\text{LiFePO}_4$  ( $Pnma'$ ) and  $\text{LiNiPO}_4$  ( $Pnm'a$ ) also permits a toroidal moment, while it is not permitted in  $\text{LiMnPO}_4$  ( $Pn'm'a'$ ).

In the previous year at this conference, I presented the results of neutron diffraction experiments studying the evolution of the magnetic ordering in the series  $\text{LiMn}_x\text{Co}_{1-x}\text{PO}_4$  and its end members. The results were that all members studied in the solid solution series gave the same magnetic ordering as  $\text{LiCoPO}_4$ , similar to our results for the  $\text{LiMn}_x\text{Fe}_{1-x}\text{PO}_4$  series. The purpose of this presentation is to present the full symmetry analysis of the magnetic structures in olivine materials to clarify which symmetry elements are required to permit a toroidal moment. This will be compared to the magnetic symmetry observed in other candidates, to clarify why toroidal moments are only predicted in a subset of antiferromagnetic materials. [2]

References:

- (1) Zimmerman, A. *et al. Nature Comm.* **2014**, 5, 4796.
- (2) Gnewuch, S. and E. Rodriguez. *J. Solid State Chem.* **2018**, 271, 175-190.