Journal of Materials Science and Nanomaterials

Mohapatra and Singh, J Mater Sci Nanomater 2017, 2:1

Commentary **Open Access**

Spin Frustrated Multiferroics: A New Way to Technology

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Received date: November 30, 2017; **Accepted date:** December 07, 2017; **Published date:** December 22, 2017

Introduction

Over the past few decades, the most versatile branch of physics named the "condensed matter physics" has been a hot topic of research in the scientific community. It explores widely the microscopic and macroscopic properties of matter. Here, the most interesting and fundamental aspect is the interaction between the electrons in solids which results in to a numerous applications. From this point of view, the fabrication of the 'ultimate memory devices' has been in ever-increasing demand owing to its robust, dense, fast, non-volatile and less energy expensive features. This objectives can be achieved by using various multiferroic and magnetoelectric materials; thus paving way for electric-field control of magnetization and vice-versa. Among several magnetoelectric materials, spin frustrated multiferroics are most versatile due to its magnetic field control of dielectric/ferroelectic properties. In fact, this can solely be achieved by the interplay and coexistence of several order parameters such as spin, charge, lattice and orbital degrees of freedom [1,2].

Multiferroics (MF) are defined as the class of multifunctional materials possessing two or more ferroic orders (viz. ferroelectric, ferromagnetism, ferroelasticity and ferrotoroidicity) simultaneously within the same system and at the same time. In particular, the coupling between magnetic and electric order parameters is often termed as the 'magnetoelectric (ME) coupling'. In spite of remarkable technological applications, the natural occurrence of the ME multiferroic materials are rare owing to its mutual exclusive characteristic property. Based on the microscopic sources of magnetism and ferroelectricity, multiferroics (MF) are broadly classified in two classes: type-I MF and type-II MF. In Type-I MF, the magnetism and ferroelectricity originates from different independent sources, as a result produces weak ME coupling. Usually, in type-I MF materials, ferroelectric transition (TFE) temperature appears at much elevated temperature than the magnetic transition (TN) temperature. Also, spontaneous polarization is often large which is of the order 10-100 $\mu C/cm^2$. On the other hand in type-II MF, the ferroelectricity is driven by magnetic order. However, the polarization in type-II MF is much smaller (~ 10^{-2} $\mu C/cm^2$). The coupling of various ferroic order parameters in multiferroic materials enhances its viability for large scale technological applications such as: magnetic field sensors, microwave resonators, etc. [1-3].

Most of the type-II MF show a unique behaviour termed as 'magnetic frustration' which originates in selected lattice systems owing to the lattice geometry where it is impossible to minimize all interactions at the same time. In principle, the frustrated systems give rise to a large degeneracy in the ground state and there is no long-range magnetic ordering. Mathematically, one can understand it by considering two spins where the Hamiltonian is expressed as,

$$H = -2J\vec{S}_i \cdot \vec{S}_j$$

Where for J<0 the ground state corresponds to all nearest neighbour (NN) pairs being antiparallel (antiferromagnetic) while for J>0, the ground state corresponds to all parallel spins (ferromagnetic) [4-8]. The simplest example of geometrically frustrated systems is the 2D triangular lattice/equilateral triangle where only two of the three spins is satisfied being antiparallel to each other. Now, the third spin cannot align antiparallel due to conflicting preferences among each other from its neighbouring spins. Other examples of spin frustrated magnetic systems are spins at the corner of a tetrahedron, the corner shared triangular lattice, shown in Figures 1a-1c).

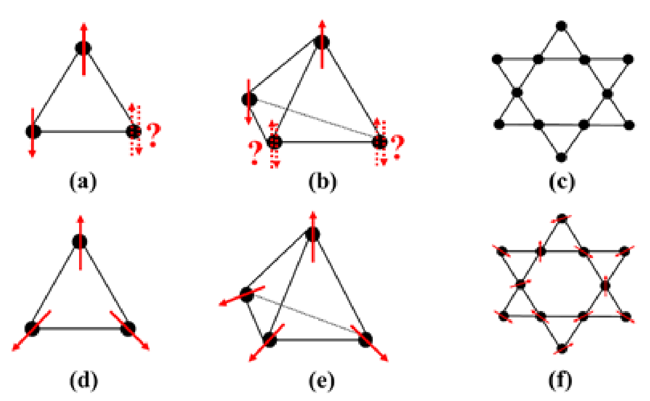

Figure 1: Examples of few spin frustrated magnetic lattices.

Usually, magnetic frustration can be lifted from the spin frustrated systems by cooling the material down to a certain finite temperature. Consequence of which is the emergence of long range magnetic ordered state at low temperature takes place indicating some kind of compromised spin configurations shown in Figures 1d-1f. As a result of this non-collinear spin configuration, degeneracy is introduced in to the system. In order to measure the degree of frustration, an empirical formula is expressed as,

$$f = -\theta_{CW} / T_N$$

Where θ_{CW} is the Curie-Weiss constant which is calculated by fitting the inverse-susceptibility ($1/\chi$) versus temperature plot and T_N is known as the antiferromagnetic (AFM) transition temperature or the Nèel temperature.

$Bi_2Fe_4O_9$ (BFO) belongs to the category of materials which shows a unique kind of pentagon spin frustration [9-15]. BFO found to exhibit orthorhombic crystal structure (space group 'Pbam') with lattice constant a=7.905 Å, b=8.428 Å, c=6.005 Å and α=β=γ=90°. Over the past few decades, BFO has gathered a considerable attention of the researchers and also extensively studied for its numerous practical applications such as gas sensors, catalytic, magnetic, electronic and temperature dependent behaviour. The past few decades has seen a tremendous growth in the study of BFO subjected to various physical properties such as structural, magnetic, photo-to-current response, photo-luminescence, photocatalytic and photo electrochemical response. Further, investigation on BFO took a steep rise owing to the evidence of substantial ME coupling near to room temperature [5]. Magnetic measurements has previously confirmed it to be an antiferromagnetic material with magnetic transition or Nèel temperature (T_N) around 260 K. To further assist the TN at 260 K, Mössbauer study was also carried out, thus supporting the same. A pronounced anomaly in the temperature dependent dielectric measurements near the vicinity of magnetic transition temperature both in case of polycrystalline and single crystals of BFO establishes the fact of strong coupling between the dielectric and magnetic order parameters. This eventually proved multiferroicity in BFO near room temperature suggesting it to be a potential material for creating new fundamental devices in the field of information technology, magnetic field sensors, actuators, magnetic memory devices, spintronics devices etc.

Acknowledgement

AKS acknowledges the Board of Research in Nuclear Science (BRNS), Mumbai (Sanction No. 2012/37P/40/BRNS/2145), UGC-DAE-CSR Mumbai (Sanction No. CRS-M-187, 225) and Department of Science and Technology (DST), New Delhi (Sanction No. SR/FTP/PS-187/2011) for funding. SRM is thankful to CSIR, India for a SRF fellowship and financial assistance.

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