SKYRMION CRYSTAL FROM RKKY INTERACTION MEDIATED BY 2D ELECTRON GAS

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We consider a C_6 invariant lattice of magnetic moments coupled via a Kondo exchange J with a 2D electron gas (2DEG) [1]. The effective Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction between the moments stabilizes a magnetic skyrmion crystal in the presence of magnetic field and easy-axis anisotropy (see Fig. 1). An attractive aspect of this mechanism is that the magnitude of the magnetic ordering wave vectors, $\boldsymbol{Q}_{\boldsymbol{\nu}}$ ($\nu = 1,2,3$), is dictated by the Fermi wave number k_F : $|\boldsymbol{Q}| = 2k_F$. Consequently, the topological contribution to the Hall conductivity of the 2DEG becomes of the order of the quantized value, e^2/h, when J is comparable to the Fermi energy ε_F .

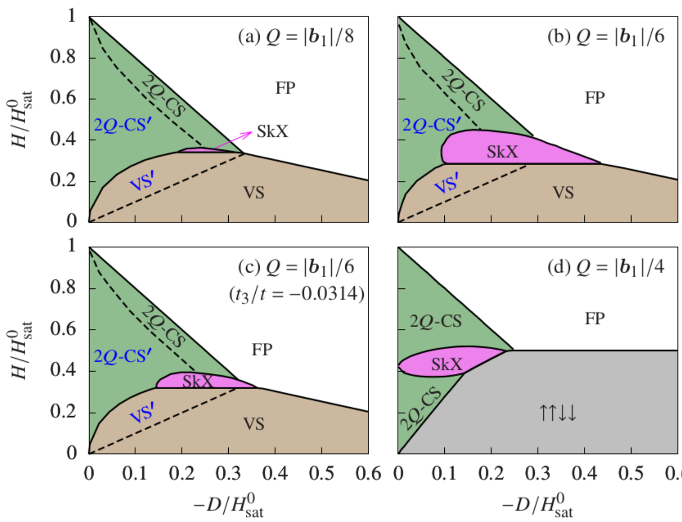

Fig. 1: Phase diagrams of the TL single RKKY model with easy-axis single ion anisotropy in a magnetic field.

[1] https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.207201

NOVEL MATERIALS WITH MAGNETIC SKYRMIONS AND THEIR THREE-DIMENSIONAL DYNAMICS

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Magnetic skyrmion, i.e., a topologically stable swirling spin configuration, has recently attracted attention as a particle-like object potentially suitable for the design of high-density information bits. Previous observations of skyrmions have mostly focused on noncentrosymmetric systems, where Dzyaloshinskii-Moriya interaction plays an important role [1,2]. On the other hand, recent theoretical studies suggest that skyrmions can be stabilized even in centrosymmetric systems by considering different microscopic mechanisms. For example, geometrical frustration of short-range exchange interactions on triangular lattice is predicted to stabilize a hexagonal lattice of skyrmions [3]. Another potential mechanism is the RKKY and four-spin interactions mediated by itinerant electrons, which is expected to favor a skyrmion lattice state for highly-symmetric (such as hexagonal or tetragonal) crystal lattice systems [4].

In this talk, I overview the recent experimental discovery of skyrmions in centrosymmetric systems [5-9]. In particular, we focus on the case of centrosymmetric tetragonal magnet $GdRu_2Si_2$, where the square lattice of skyrmions with extremely small diameter (1.9 nm, i.e. the smallest value ever reported for single-component bulk materials) has been observed [8,9]. Our results demonstrate that skyrmions can be stabilized even without geometrically frustrated lattice nor inversion symmetry breaking, and suggest that rare-earth intermetallics with highly-symmetric crystal lattice may ubiquitously host nanometric skyrmions of exotic origins.

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EMERGENT ELECTROMAGNETISM IN SPIRAL MAGNETS

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Emergent electromagnetism in non-collinear magnets has attracted recent intensive interest. Skyrmion is a representative example, where the non-coplanar spin structure gives the emergent magnetic field associated with the scalar spin chirality, i.e., the solid angle subtended by the spins. Spiral magnet with non-collinear but co-planar spin configuration, is characterized by the vector spin chirality, which is time-reversal even, and is not directly related to the Hall effect.

Here I discuss the emergent electromagnetic phenomena, i.e., Berry phase effects, of the conduction electrons coupled to the spiral spin structure. It includes the emergent inductance [1], [2], and transverse conductivity due to the combined effect of spin orbit interaction and exchange field.

These works have been done in collaboration with Daichi Kurebayashi, Tomoyuki Yokouchi, Fumitaka Kagawa, Max Hirschberger, Yoshichika Otani, and Yoshinori Tokura.

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STABILIZATION OF ZERO-FIELD SKYRMIONS IN FERROMAGNETIC AND SYNTHETIC ANTIFERROMAGNETIC SYSTEMS

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In this study, we show that inserting a bias layer in the ferromagnetic multilayer stack, and utilizing interlayer electronic coupling between this bias layer and the ferromagnetic skyrmion multilayer, we successfully demonstrate the stabilization of sub 100 nm skyrmions at room temperature. We then show that room-temperature antiferromagnetic skyrmions can be stabilized in synthetic antiferromagnet (SAF) systems. To this aim, we elaborate a material system in which perpendicular magnetic anisotropy, antiferromagnetic coupling and chiral order can be adjusted concurrently. Utilizing the same bias layer, we demonstrate by Magnetic Force Microscopy [1] and by spin NV relaxometry [2] that the spin-spiral state obtained in a SAF system with vanishing perpendicular anisotropy can be turned into isolated antiferromagnetic skyrmions stable at zero field. These experimental results are completed with model-based estimations of their size and stability, showing that room-temperature stable antiferromagnetic skyrmions below 10 nm in radius can be anticipated in further optimized SAF systems [6]. Antiferromagnetic skyrmions in SAF systems may thus solve major issues associated to ferromagnetic skyrmions for low-power spintronic devices.

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BEYOND HEISENBERG SOLIDS: FROM MULTI-SPIN INTERACTIONS TO NOVEL CHIRAL PARTICLES

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It became customary to study the stability, lifetime, dynamics, thermodynamics and transport properties of localized nanoscale magnetization particles such as skyrmionics by classical spin-lattice models with pairwise Heisenberg-type exchange interactions. The mapping of fermionic many-body systems onto a classical Heisenberg model is a nontrivial thing and by far not unique. In this presentation I motivate beyond Heisenberg multi-spin interactions [1]. I give examples, where these interactions play a decisive role [2]. I focus on MnGe in the B20-phase, which exhibits a three-dimensional spin-texture. We introduce a novel class of magnetic exchange interactions [3] – the topological-chiral interactions (TCI) rooted in the so-called topological orbital moment, which manifests as a result of finite scalar spin chirality in non-coplanar magnets. The long-wave length limit of the interactions relates to the highly acclaimed Faddeev model demonstrating that the interaction is an origin of 3D magnetization textures all the way down to hopfions.

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FRACTIONAL ANTIFERROMAGNETIC SKYRMION LATTICE IN $MnSc_2S_4$

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By combining neutron scattering neutron experiments with extensive Monto Carlo simulations we identify a fractional antiferromagnetic skyrmion lattice stabilized in the $MnSc_2S_4$ spinel [1]. The triple-q phase is stabilized by perturbing the J_1-J_2-J_3 Hamiltonian by anisotropic couplings and single-ion anisotropy. This scenario is realised in $MnSc_2S_4$ owing to its enormous ground-state degeneracy [2].

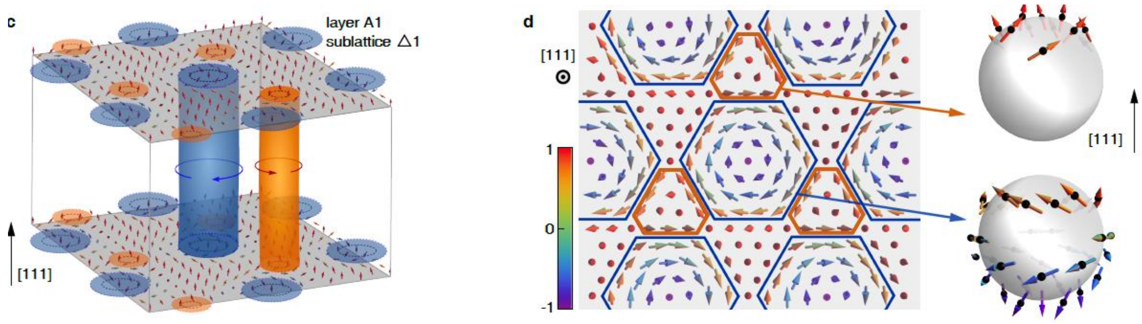

Figure. Left: The Mn^{2+} triangular lattice layers along the [111] direction can be divided into three sublattices which form cylinders of fractional skyrmions. Right: Spin texture of one triangular sublattice. The fractional skyrmions with opposite winding directions are described in the two spheres shown on the right.

Our work demonstrates that the theoretically proposed antiferromagnetic skyrmions can be stabilized in real materials.

[1] https://doi.org/10.1038/s41586-020-2716-8

[2] DOI: 10.1038/NPHYS391

TOPOLOGICAL MAGNETIC PHASE IN THE CANDIDATE WEYL SEMIMETAL CeAlGe

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In topological materials science, the aim is to find pronounced phenomena rooted in the concepts of topology in new materials, and harness them for novel and robust functions. Promising materials classes include magnetic materials hosting nanoscale magnetic skyrmions, or Dirac and Weyl semimetals, which are hallmarked by topological invariants in real- or reciprocal spaces, respectively. With recent attention focused on magnetic topological materials, here we consider the question if novel functionalities may be found in systems with electronic *and* magnetic structures that are both topologically nontrivial, and where they coexist and may be coupled. In this context, I will present our recent experimental work on the polar tetragonal magnet CeAlGe [1]. This system was predicted recently to be an easy-plane ferromagnetic type-II Weyl semimetal, yet the magnetic and electrical properties were little-explored. From magnetometry, neutron scattering and electrical transport measurements, we find CeAlGe to be a host of nanoscale and incommensurately-modulated multi-***k*** magnetic phases. For an intermediate field along the polar **c**-axis, one of the incommensurate phases generates a topological Hall effect, and we propose it to be generated by a novel magnetic structure containing anti-meron pairs [Fig. 1]. We discuss the implication for the existence of such magnetic phases in Weyl semimetals and the possibilities for new functionalities.

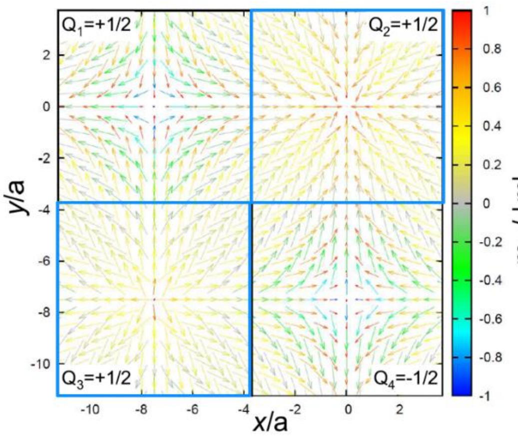

Fig. 1: View along the polar **c**-axis of the proposed topological magnetic structure in CeAlGe. Blue squares indicate merons of opposite helicity.

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MAGNETIC SKYRMIONS FOR UNCONVENTIONAL COMPUTING AND REVEALING LATENT INFORMATION

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Novel computational paradigms in combination with proper hardware solutions are required to overcome the limitations of our state-of-the-art computer technology [1-3]. In this talk, I will address the potential of topologically stabilized magnetic whirls – so-called skyrmions – for two unconventional computing schemes – reservoir computing and stochastic computing. Reservoir computing is a computational scheme that allows to drastically simplify spatial-temporal recognition tasks. We have shown that random skyrmion fabrics provide a suitable physical implementation of the reservoir [4,5] and allow to classify patterns via their complex resistance responses either by tracing the signal over time or by a single spatially resolved measurement [6]. Stochastic computing allows to speed up a calculation while trading for numerical precision. Information is encoded in terms of bit-streams as a probability. A key requirement and simultaneously a challenge are that the incoming bitstreams are uncorrelated. The Brownian motion of magnetic skyrmions allows creating a device that reshuffles the bit-streams [7,8]. In any type of hardware-based computation, some sort of readout of the system is needed. While often a significant effort is made in enhancing the resolution of an experimental technique to obtain further insight into the sample and its physical properties, an advantageous data analysis has the potential to provide a deeper insight into given data set [9].

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