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Phys. Rev. B 93, 220408 — Published 27 June 2016

DOI: 10.1103/PhysRevB.93.220408
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We report neutron scattering experiments which reveal a large spin gap in the magnetic excitation spectrum of weakly-monoclinic double perovskite Sr$_2$ScOsO$_6$. The spin gap is demonstrative of appreciable spin-orbit-induced anisotropy, despite nominally orbitally-quenched 5$d^3$ Os$^{5+}$ ions. The system is successfully modeled including nearest neighbor interactions in a Heisenberg Hamiltonian with exchange anisotropy. We find that the presence of the spin-orbit-induced anisotropy is essential for the realization of the type I antiferromagnetic ground state. This demonstrates that physics beyond the LS or JJ coupling limits plays an active role in determining the collective properties of 4$d^3$ and 5$d^3$ systems, and that theoretical treatments must include spin-orbit coupling.

PACS numbers: 71.70.Ej, 71.70.Gm, 78.70.Nx

The role of spin-orbit coupling (SOC) in 4$d$ and 5$d$ transition metal oxides is relatively poorly understood outside of the LS and JJ coupling limits. The need to understand the intermediate regime is typified by the diverse range of properties found in double perovskites (DPs) containing 4$d$ and 5$d$ ions, including high-temperature half-magnetic ferrimagnetism [1, 2], structurally selective magnetic states [3–5], complex geometric frustration [6–11], and Mott insulating states [12–14]. Whilst the complex array of ground states has generated a great deal of interest, the interaction mechanisms controlling them remain undetermined.

For DPs hosting 4$d^3$ or 5$d^3$ ions, the role of SOC is particularly unclear. There exists dispute between different theories describing SOC and its influence on the interactions [10, 14–20]. To first order, 5$d^3$ ions in an octahedral environment are expected to be orbitally quenched, Fig. 1(a) [9, 17], yet there is mounting evidence that SOC has considerable influence [6, 11, 21–23]. This has been demonstrated by the presence of ∼2–18 meV gaps in the magnetic excitation spectra of Ba$_2$YRuO$_6$, La$_2$NaRuO$_6$ and Ba$_2$YOsO$_6$ [9, 11, 21]. Such large gaps, on the same energy scale as the $T_N$s, implies a departure from an orbital singlet, and raises the question of how SOC manifests in the collective properties.

Beyond a fundamental interest in the influence of SOC, it is vital to determine the sign and strength of exchange interactions between 5$d$ ions in order to understand the magnetism of many DPs, including the exceptionally high $T_C = 725$ K seen in Sr$_2$CrOsO$_6$ [24, 25]. Investigations of Sr$_2$CrOsO$_6$ and related materials show that exchange interactions between Os$^{5+}$ ions cannot be neglected [3, 14, 18–20, 23, 26]. However, the strong coupling between Cr$^{3+}$ and Os$^{4+}$ ions makes it difficult to measure the strength of the Os-Os coupling. Additionally, there is a lack of agreement regarding the mechanism that stabilizes type I antiferromagnetic (AFM) order on the face-centered-cubic (FCC) lattice of B$'$ ions in $A_2B'B'O_6$ DPs, where $B$ is diamagnetic, and B$'$ is either Ru$^{5+}$ (4$d^3$) or Os$^{5+}$ (5$d^3$) [10, 11]. Most attempts to determine the exchange interactions in these systems have been limited to theoretical models not directly related to measurements, with conflicting results [10, 14, 27–29]. Therefore, to understand the underlying behavior, it is desirable to obtain the interactions experimentally.

To access Os$^{5+}$ ion interactions experimentally, we in-
vestigate \( \text{Sr}_2\text{ScOsO}_6 \). It is the single-magnetic-ion analogue of \( \text{Sr}_2\text{CrOsO}_6 \), therefore all magnetic interactions result solely from the frustrated quasi-FCC Os\(^{5+}\) lattice. Despite this, \( \text{Sr}_2\text{ScOsO}_6 \) hosts a remarkably high \( T_N \) (92 K) for a single-magnetic-ion DP \([23, 31, 32]\). It is therefore a model system for investigating the role of the Os\(^{5+}\) 5\(d^3\) magnetic interactions in a high transition temperature material.

We present the inelastic neutron scattering (INS) spectrum of \( \text{Sr}_2\text{ScOsO}_6 \), and find a large spin gap below \( T_N \). A Heisenberg Hamiltonian with anisotropic exchange terms is considered. We find that over a large parameter space, the solution which best describes the data is one with the isotropic nearest-neighbor (NN) term \( J_1 = -4.4 \text{ meV} \), and negligible next-nearest-neighbor (NNN) interactions. The success of the model reveals that anisotropy is essential to selection of the type I AFM ground state. This suggests that SOC within the 5\(d^3\) manifold, along with strong Os-O hybridization, promotes a high \( T_N \) in this otherwise frustrated material. Therefore, it is NN interactions combined with SOC-induced anisotropy that are key to the collective behavior realized in \( \text{Sr}_2\text{ScOsO}_6 \), and related 4\(d^3\) and 5\(d^3\) systems. This demonstrates that SOC must be included in theoretical treatments of these materials.

A 16.5 g polycrystalline sample of \( \text{Sr}_2\text{ScOsO}_6 \) was used for INS experiments on SEQUOIA at the Spallation Neutron Source at Oak Ridge National Laboratory \([33]\), see Supplemental Material (SM) \([34]\) for full details. The structural and magnetic properties of the same sample were reported in Ref. \([23]\), finding space group \( P2_1/n \) with \( a = 5.6398(2) \text{ Å}, b = 5.6373(2) \text{ Å}, c = 7.9884(3) \text{ Å} \) and \( \beta = 90.219(2)^\circ \) at 5 K, and \( T_N = 92 \text{ K} \).

Measured INS spectra are shown in Fig. 2. There is a pronounced change in the spectrum at low neutron momentum transfer (\( Q \)) upon crossing \( T_N \). This behavior is reminiscent of the observed gap development below \( T_N \) in other single magnetic ion 4\(d^3\) and 5\(d^3\) DPs \([9, 11, 21]\). The higher \( Q \) scattering, which changes only in intensity with temperature, is identified as phonon scattering.

The detailed \((Q,E)\)-space structure and temperature dependence of the scattering is presented in Fig. 3. Figure 3(a) demonstrates that intensity is distributed to higher energies at low temperatures, as expected from a gap opening. The peak of the scattering intensity at 6 K is at \( \eta = 19(2) \text{ meV} \). This compares to previous observations, which have been used as a magnitude estimate for the gap, of \( \eta = 18(2) \text{ meV} \) in \( \text{Ba}_2\text{YOsO}_6 \) (\( T_N = 69 \text{ K} \)), \( \eta \approx 5 \text{ meV} \) in \( \text{Ba}_2\text{YRuO}_6 \) (\( T_N = 36 \text{ K} \)) and \( \eta \approx 2.75 \text{ meV} \) in \( \text{La}_2\text{NaRuO}_6 \) (\( T_N = 15 \text{ K} \)) \([9, 11, 21]\). This generally supports a picture of gap energy scale varying with \( T_N \). Figure 3(c) presents data that has been corrected for the Bose thermal population factor, \( 1 - \exp(-E/k_B T) \)^\(-1\). The sharp drop in intensity at low \( E \) below \( T_N \) demonstrates the opening of the gap.

Constant-\( E \) cuts averaged from 5 to 9 meV show scattering centered around AFM ordering wavevector \( |Q_{(001)}| \approx 0.8 \text{ Å}^{-1} \), Fig. 3(d), with some asymmetry in the lineshape resulting from \( |Q_{(100)}/(010)| \approx 1.1 \text{ Å}^{-1} \) fluctuations. To track the relative strength of the fluctuations we extract the dynamic susceptibility, \( \chi''(T) \), for fixed range \( 5 < E < 9 \text{ meV} \) and \( 0.5 < Q < 1.2 \text{ Å}^{-1} \) via
the same method as Ref. [11] (see also SM [34]). The opening of a gap below \( T_N \) is again indicated, Fig. 3(b), by the reduction in \( \chi''(T) \) evaluated at low-energy.

We investigate a model Heisenberg Hamiltonian with anisotropic exchange terms. The results we present here include only NN terms, \( J_1 \), (see Fig. 1(b)) because the NNN terms, \( J_2 \), are dramatically suppressed (estimated as \( J_2 \leq 0.01J_1 \) in Ref. [10]), as discussed below. We tested this assumption by seeking solutions over a wide range of parameter space with \( J_2 \neq 0 \), see SM [34], but found that \( J_2 = 0 \) provided the best description of the experimental INS data.

The model is parametrized with an isotropic term, \( J_1 \), which is decoupled from the physical origin of the spin gap, and an exchange anisotropy term, \( K_1 \), to account for the gap. Unlike isotropic exchange terms, anisotropic exchange terms only couple to a particular component of spin, e.g. \( S_x \). \( x \) represents the direction of spin alignment. We assume that the exchange interactions are unaffected by the weak monoclinic distortion, justified by two considerations: first, the distortion is much smaller than found in \( d^3 \) systems in which the distortion is reported to affect the physical properties of \( d^3 \) systems [6, 34, 35]. Secondly, the properties of the closely related cubic compound \( Ba_2YO_8O_6 \) are remarkably similar to \( Sr_2ScOsO_6 \) [11]. The Hamiltonian is therefore

\[
\mathcal{H} = -\sum_{\text{NN}} J_1^{\alpha\beta} S_{i\alpha} S_{j\beta} = -\sum_{\text{NN}} (J_1 S_i \cdot S_j + K_1 S_{ix} S_{jx}).
\]

\( J_1 \) and \( K_1 \) are defined such that positive values are ferromagnetic (FM) and negative values are AFM. The exchange parameters scale inversely with spin, with positive values for magnetic (FM) and negative values are AFM. The exchange interactions are unaffected by the weak monoclinic distortion, justified by two considerations: first, the distortion is much smaller than found in \( d^3 \) systems in which the distortion is reported to affect the physical properties of \( d^3 \) systems [6, 34, 35]. Secondly, the properties of the closely related cubic compound \( Ba_2YO_8O_6 \) are remarkably similar to \( Sr_2ScOsO_6 \) [11]. The Hamiltonian is therefore

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\]

\( J_1 \) and \( K_1 \) are determined from neutron diffraction [23] [36]. We use the bottom and top of the spin wave band, \( \Delta = 12 \) meV and \( \Gamma = 40 \) meV, respectively, as conditions to determine the parameters \( J_1 \) and \( K_1 \). \( \Delta \) was determined by inspection of the 6K data in Fig. 3(c), in which the increasing intensity begins to saturate at \( E \approx 12 \) meV. \( \Gamma \) was determined by inspection of broad constant-\( Q \) cuts from the \( E_i = 120 \) meV data (see SM Fig. S2 [34]), designed to capture all magnetic scattering up to high energies, in which 6K and 115K cuts converge at 40 meV. An additional constraint for the local stability of the ground state, depicted in Fig. 1(b), is that the spin-wave frequencies are real throughout the magnetic Brillouin zone. Utilizing this model, we find the solution \( J_1 = -4.4 \) meV and \( K_1 = -3.8 \) meV. This gives a mean-field transition temperature of 181 K, two times greater than the measured \( T_N \). This is reasonable, as calculated mean-field temperatures are generally expected to exceed measured values [37], and the Curie-Weiss constant for this compound, \( \Theta = -677 \) K [23], is also far greater than \( T_N = 92 \) K.

The simulated powder-averaged INS cross section \( S(Q, E) \) for \( J_1 = -4.4 \) meV and \( K_1 = -3.8 \) meV is compared to the low-temperature data in Fig. 4, and we find good agreement. An overview is provided by colormaps in Fig. 4(a) and (b), and a more detailed comparison is given by constant-energy cuts in Fig. 4(c). Note that this solution is equivalent to a single-ion anisotropy model with \( J_1 = -4.4 \) meV and \( D = 7.5 \) meV.

Although SOC has been noted as the origin of the spin gap in 5d DPs [11, 21], the underlying mechanism by which it acts to produce the gap remains an open question. In general, the possible mechanisms in a three-dimensional system are Dzyaloshinský-Moriya (DM) interactions, single-ion anisotropy, and exchange anisotropy, all of which are induced by SOC. There are two observations which favor dismissal of the DM interaction as the origin of the gap: (i) the highly symmetric cubic or close-to-cubic crystal structures in which the gap has been observed (space group \( Fm\bar{3}m \) has inversion symmetry at the Os site, \( P2_1/n \) does not) and (ii) the type I collinear AFM structure common to several DPs including \( Sr_2ScOsO_6 \) – two perpendicular DM interactions would be required to produce a gap, but would favor a non-collinear spin state.

We also expect that single-ion anisotropy is negligible, because it is dramatically suppressed for the orbitally suppressed \( d^3 \) configuration, and the 3.6 eV \( t_{2g} \) to \( e_g \) splitting in \( Sr_2ScOsO_6 \) [30] means that the excited spin states lie at very low energy.
state perturbations are minimal [39]. This is supported by the experimental observation that no gap emerges in La$_2$NaOsO$_6$ which only displays short-range order, whereas a gap is observed in long-ranged-ordered sister-compound La$_2$NaRuO$_6$ [21]. A single-ion term, being a local effect, would not be sensitive to short- versus long-range order, and would emerge in the short-range ordered state. Therefore, exchange anisotropy is the most-likely explanation for the gap in 4$d^3$ and 5$d^3$ DPs. Independent of the gap’s origin, the determination that $J_1 \approx -4.4$ meV and $J_2$ is negligibly small, has significant consequences.

There is dispute in the literature over the strength of long-range interactions in 4$d^3$ DPs, and the origin of type I AFM order in 4$d$ and 5$d$ single-magnetic-ion DPs. Competition between type I and type III order results in frustration on the (quasi-)FCC lattice of Os/Ru ions. Theoretical studies found that type I order can be stabilized either by a FM $J_2$ in an isotropic (i.e. $K_1 = 0$) Heisenberg Hamiltonian, or by some form of anisotropy [10]. Nilsen et al. [22] attempted to extract the interactions in Ba$_2$YRuO$_6$ via Reverse Monte Carlo (RMC) analysis of diffuse neutron scattering, and found large interactions beyond NN, with $|J_2| \approx \frac{1}{2}|J_1|$. However, by use of an isotropic Heisenberg Hamiltonian, their analysis implicitly assumed significant long-range interactions to stabilize the correct ground state, and, as they point out, could not distinguish from an anisotropy-based model. We have found that, in-fact, an NN-only exchange model with significant SOC-induced anisotropy provides the best description of the INS spectrum for Sr$_2$ScOsO$_6$.

Our result can be rationalized based on the superexchange pathways present, illustrated in Fig. 1(c). The NN Os-O-O-Os superexchange pathway is anticipated to be strongly AFM due to the half-filled Os$^{5+}$ $t_{2g}$ levels [40, 41]. Direct $t_{2g}$-$t_{2g}$ overlap is also an AFM NN contribution. The NNN pathway, however, relies on overlap with empty Sc$^{3+}$ $t_{2g}$ orbitals, and was estimated as $J_2 \leq 0.01J_1$ in Ref. [10], consistent with our result.

This analysis is, however, at odds with attempts to model the exchange interactions in 3$d^5$-5$d^3$ DPs, including Sr$_2$CrOsO$_6$, using density functional theory [18, 27–29]. Studies estimated $|J_2|$ in the range 1.9–24 meV (for $s = 0.8$ meV), but did not consider the anisotropy terms (single-ion or exchange anisotropy) reported here, despite mentioning the likely frustration of Os$^{5+}$ ions. Therefore, much like the modeling of Ba$_2$YRuO$_6$ via RMC, the longer-range interactions may have been implicitly forced to have large values. This is particularly relevant in Sr$_2$CrOsO$_6$, in which both magnetic ions have d$^3$ configuration, therefore unlike (Ca,Sr)$_2$FeOsO$_4$ no occupied e$_g$ orbital pathways contribute to longer-range interactions [4, 42]. Anisotropy could therefore have a major influence in Sr$_2$CrOsO$_6$, and further calculations including anisotropy terms would be illuminating. Similar calculations for Sr$_2$ScOsO$_6$ will be directly constrained by the size of the observed gap and by $J_1 \approx -4.4$ meV, independent of the gap’s origin.

As anisotropy is essential in stabilizing the AFM order in Sr$_2$ScOsO$_6$, it should also be relevant in type I Ba$_2$YOsO$_6$, Ba$_2$YRuO$_6$ and Sr$_2$YRuO$_6$ [7, 11, 43, 44]. Diffraction experiments found no structural distortion (Ba$_2$YOsO$_6$ and Ba$_2$YRuO$_6$), or a small monoclinic distortion (Sr$_2$YRuO$_6$), therefore the same interaction pathways as for Sr$_2$ScOsO$_6$ are applicable. Although exchange/single-ion anisotropies are formally absent (to 2nd order) in a cubic system [39], the type I order should coincide with a distortion via magneto-elastic coupling in Ba$_2$YOsO$_6$ and Ba$_2$YRuO$_6$. Although this structural distortion, if present, is outside the range of detection of present diffraction experiments, it would allow anisotropy to enter the Hamiltonian. Anisotropy has been directly observed via spin-gaps in both these materials [9, 11]. We therefore propose that in all these systems, SOC is essential in determining the magnetic ground state.

Amongst these materials, Sr$_2$ScOsO$_6$ boasts the highest $T_N$. As has previously been noted, large Os-O hybridization is an important factor in heightened $T_N$s [18, 23]. Our results suggest that, by promoting selection of a particular ground state and relieving frustration, Os$^{5+}$ SOC also acts to enhance $T_N$ in Sr$_2$ScOsO$_6$. This notion is supported by the trend in gap size with $T_N$ across the measured compounds, and by the observation that 3$d$ transition metal DPs have lower $T_N$s and usually favor a different, Type II, ground state [45].

It is also informative to compare Sr$_2$ScOsO$_6$ to the equivalent 5$d^2$ systems Sr$_2$MgOs$^3$O$_6$ [32] and Sr$_2$ScReO$_6$ [46, 47]. We expect 5$d^2$ ions to have a smaller magnetic moment [48], and reduced Os-O-Os AFM superexchange as the $t_{2g}$ levels are not half-filled. This results in a lower AFM energy scale, but unquenched SOC, which will promote a high $T_N$ compared to that AFM energy scale if the SOC promotion of $T_N$ is correct. Both these expectations are met - compared to Sr$_2$ScOsO$_6$ these compounds have lower inherent energy scales as indicated by their Curie Weiss constants, but have $T_N$s of 105 K and 75 K, comparable to that of Sr$_2$ScOsO$_6$. Therefore SOC has an important role in high-$T_N$ DPs beyond the 5$d^3$ case.

In conclusion, by modeling the magnetic excitation spectrum of archetypal system Sr$_2$ScOsO$_6$, we have extracted the exchange parameters resulting from Os$^{5+}$ ion interactions. The presence of a large spin gap demonstrates that SOC is significant, i.e. the 5$d^3$ ions deviate from the nominal orbital singlet expected from LS coupling. We find that only NN interactions are significant, and as a consequence, SOC-induced anisotropy governs the magnetic state in this otherwise frustrated system, and assists in promoting a high $T_N$. This demonstrates that the interplay of NN interactions with anisotropy should be considered for the collective properties of high-$T_C$ 5$d^3$ systems, particularly Sr$_2$CrOsO$_6$. 
The authors gratefully acknowledge M. B. Stone, S. E. Nagler and B. D. Gaulin for useful discussions. The research at Oak Ridge National Laboratory’s Spallation Neutron Source was supported by the Scientific User Facilities Division, Office of Basic Energy Sciences, U.S. Department of Energy (DOE). Support for a portion of this research was provided by the Center for Emergent Materials an NSF Materials Research Science and Engineering Center (DMR-1420451). Research by RF sponsored by the DOE, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division.

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