Valence Bond Glass on an fcc Lattice in the Double Perovskite Ba$_2$YMoO$_6$ \\
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We report on the unconventional magnetism in the cubic $B$-site ordered double perovskite Ba$_2$YMoO$_6$, using ac and dc magnetic susceptibility, heat capacity and muon spin rotation. No magnetic order is observed down to 2 K while the Weiss temperature is $\sim -160$ K. This is ascribed to the geometric frustration in the lattice of edge-sharing tetrahedra with orbitally degenerate Mo$^{5+}$ $s = 1/2$ spins. Our experimental results point to a gradual freezing of the spins into a disordered pattern of spin singlets, quenching the orbital degeneracy while leaving the global cubic symmetry unaffected, and providing a rare example of a valence bond glass.

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Magnetic insulators with lattices in which antiferromagnetic (AF) bonds are geometrically frustrated have been studied widely in the pursuit of exotic quantum ground states such as spin liquid [1,2]. Such nonclassical ground states have mainly been sought in low dimensional structures such as the triangular lattice system $\kappa$-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$ [3] and the kagome antiferromagnet herbertsmithite [4]. Materials with a geometrically frustrated face centered cubic (fcc) lattice have in this respect received much less attention. The 12 near-neighbor magnetic bonds $J_1$ between the [000] and [$1\over{2}$ $1\over{2}$ 0] spins on the fcc lattice form a network of edge-sharing tetrahedra (Fig. 1). When these bonds are AF ($J_1 > 0$) the magnetism is geometrically frustrated, giving rise to a large (but not macroscopically large [5]) as for the kagome lattice) ground-state manifold of spin configurations unrelated by symmetry. Further neighbor interactions ($J_2$) along the 6 [100] vectors lift this degeneracy only partially; $J_2 < 0$ (along the 6 [100] vectors) leads to type I order, weak AF exchange ($0 < J_2 < 2J_1$) to type III order and stronger AF exchange $J_2 > 2J_1$ to type II order. Thermal or quantum fluctuations and quenched disorder have been shown to result in a bias for respectively collinear and anticolinear states within these degenerate ground-state manifolds [6–8], an entropic selection effect termed “order from disorder” [9]. This is in agreement with experiments on well-known compounds of rocksalt structure such as MnO [10,11], Cd$_{1-x}$Mn$_x$Te [12], and NiO, MnSe [10]. Classical type I, II or III order has also been confirmed for $s = 1/2$ [13–15] although less is known about the physics at the boundaries between the classical phases. In this Letter we describe the unconventional magnetism in the compound Ba$_2$YMoO$_6$, providing experimental evidence that an exotic valence bond glass (VBG) [16,17] state can stabilize at the boundary between the known classical phases on the fcc lattice. Such a disordered state has been predicted to be possible even in the absence of structural disorder, as an example of a nonequilibrium quantum ground state [16].

The $B$-site ordered double perovskites are of general stoichiometry $A_2B'B'O_6$ where the $A$ site typically hosts alkaline-earths and lanthanides and the $B'$ sites can host 3$d$, 4$d$, and 5$d$ transition metal (TM) ions. Depending on the combination of $B$ and $B'$ site ions, electronic phases from strongly correlated metals via half-metals [18] and semiconductors [19,20] to Mott insulating can be realized. Mott insulating 4$d$ and 5$d$ TM compounds are rare. The occurrence of this insulating phase in the double perovskites is due to the large distance between the TM ions, of the order of 5 to 6 Å. Examples of Mott insulators are Ba$_2$LaRuO$_6$ and Ca$_2$LaRuO$_6$ [21], respectively, type III and type I antiferromagnets. Sr$_2$CaReO$_6$ [22] and Sr$_2$MgReO$_6$ [23] (the Re$^{6+}$ has $s = 1/2$) have spin-glass ground states, consistent with a negligible $J_2$ along the pathway Re-O-B'O-Re. There is a large group of Mo$^{5+}$ compounds Ba$_2$LnMoO$_6$ with Ln = Nd, Sm, Eu, Gd, Dy, Er, Yb and Y [24]. The Mo$^{4+}$ has a singly-occupied 4$d$ $t_{2g}$ level with $s = 1/2$. Because of the strong spin-orbit coupling in 4$d$ TM ions in a cubic crystal field this is expected to lead to a $j = 3/2$ triplet [25,26]. Only the larger lanthanide compounds

FIG. 1. Four MoO$_6$ octahedra (shaded grey) and Y ions (large spheres) in the cubic unit cell of Ba$_2$YMoO$_6$ (left). The Mo$^{5+}$ ions form a lattice of edge-sharing tetrahedra (right). The cubic lattice constant is 8.389 Å.
(Ln = Nd, Sm and Eu) have Néel order (Type I, implying \( J_2 < 0 \)) coinciding with a weak Jahn-Teller distortion [24,27,28], while the exchange interaction is of the order of 100 K [24]. The other compounds were found to be paramagnetic and with cubic symmetry at all temperatures. \( \text{Ba}_2\text{YMoO}_6 \) is the simplest of these compounds because the \( \text{Y}^{3+} \) ion does not carry a magnetic moment. The magnetic exchange is mainly via the 90° \( \text{B}^\prime-\text{O}-\text{O}-\text{B}^\prime \) π – π bonds [21,24], giving rise to 12 near-neighbor AF \( J_1 \) bonds for each spin, across the edges of the tetrahedra (Fig. 1).

Polycrystalline \( \text{Ba}_2\text{YMoO}_6 \) was prepared by the solid state reaction of stoichiometric oxides of \( \text{Y}_2\text{O}_3, \text{MoO}_3 \) and \( \text{BaCO}_3 \) powders of at least 99.99% purity. These were ground, die-pressed into a pellet and heated under flowing 5% \( \text{H}_2/\text{N}_2 \). The final synthesis temperature was 1200–1250°C with three intermediate regrinding steps to ensure phase homogeneity. It was found that a first heating step of ~2 hr at 900°C in air and thorough homogenization helps to prevent the formation of \( \text{BaMoO}_4 \) and \( \text{Y}_2\text{O}_3 \) impurities. Phase purity was confirmed by laboratory x-ray powder diffraction. In a related paper [29] neutron powder diffraction shows a frequency dependent maximum between 26 and 70 K. Remarkably, the maximum gradually gets sharper as the frequency increases, instead of weaker as expected for a spin-glass transition. The agreement between the dc susceptibility and \( \chi' \) below 20 K is a strong indication that the Curie term can be ascribed to the weakly-coupled spins.

The heat capacity associated with the single \( \text{Mo}^{5+} \) 4d electron in \( \text{Ba}_2\text{YMoO}_6 \) (as shown in Fig. 4) was obtained from comparison with the heat capacity of the diamagnetic analogue \( \text{Ba}_2\text{YNbO}_6 \). The heat capacity from phonons of \( \text{Ba}_2\text{YMoO}_6 \) is expected to be lower than for \( \text{Ba}_2\text{YNbO}_6 \) by a factor 0.991 due to the mass difference between the Mo and Nb nuclei. However, this is small compared to the experimental error in the sample mass which is known with
The magnetic properties of Ba$_2$YMn$_2$O$_6$ are very different to those of the related compound Sr$_2$MgReO$_6$ [23], where a first order transition to a conventional spin-glass state is observed. That the crossover in Ba$_2$YMn$_2$O$_6$ is not a conventional spin-glass transition is also clear from the unusual frequency dependence of the ac susceptibility. The gradual freezing and crossover region around 50 K are consistent with a pseudogap predicted for the VBG [17]. This gap, which corresponds to a spin-singlet dimerization energy scale, is filled by levels corresponding to emergent weakly-coupled spins which give rise to a diverging susceptibility as the temperature is decreased. In close agreement with Ref. [17] the observed low-temperature susceptibility follows a power law $\chi \propto (T - T_\text{c})^{-\gamma}$ with $\gamma = 1$. As noted earlier, this contribution from effectively weakly-coupled spins cannot be related one-to-one to any structural disorder but arises as a cooperative effect, due to the amorphous arrangement of spin singlets. The heat capacity does not become zero at the lowest temperature measured which is consistent with a small residual entropy and an ungapped spectrum as expected for the VBG.

The classical ground-state energy is highest when $J_2 = 2J_1$, at the crossover between type III ($J_2 < 2J_1$) and type II magnetism (the energy per spin is $-J_1/2 + J_2/4$ for $J_2 < 2J_1$). One possibility is that around this crossover a spin-singlet state is energetically favored. A complete explanation of why spin singlets stabilize will in the
present case also involve the orbital degrees of freedom; it is the valence-bond formation rather than a Jahn-Teller effect that fixes the orbital orientation. This could be accompanied by local structural distortions which do not lead to experimentally observable [24,29] structural changes because the valence bonds do not form a regular pattern within the crystal. As first observed by Goodenough and Battle [21], the band width is an important factor in understanding the magnetism in double perovskites with 4d and 5d transition metal ions. Because Ba$_2$YMoO$_6$ is a relatively wide-band insulator it could also be that the stability of a spin-singlet state can be understood in terms of the $t-J$ model [31].

In conclusion, the $B$-site ordered double perovskite Ba$_2$YMoO$_6$ has Mo$^{5+}$ ions with a singly-occupied degenerate $t_{2g}$ orbital in a cubic crystal field and with $s = 1/2$. These moments are located on an fcc lattice and coupled antiferromagnetically, with a Weiss temperature of $-160$ K. At high temperature the single-ionic $j = 3/2$ moments are strongly reduced by quantum fluctuations, consistent with the formation of stable spin-singlet dimers at low temperatures. Remarkably, the dimerization pattern appears to be disordered, giving rise to emergent effectively unpaired spins with a diverging susceptibility as the temperature is reduced, in agreement with theoretical predictions of a VBG [17]. It is proposed that the stabilization of spin singlets is a result of the fine-tuning of the ratio $J_2/J_1$ to the boundary between the classical type II and type III phases. Clearly the present results provide a strong motivation for further theoretical explorations of the phase diagram of the fcc antiferromagnet and of the interplay between spin and orbital degrees of freedom in 4d and 5d transition metal compounds. This is the first observation of a VBG in a quantum magnet. Further experimental studies are needed to understand the relationship between the structural and magnetic disorder in this class of materials.

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*Note added.*—After submission of this Letter a paper on Ba$_2$YMoO$_6$ by Aharen et al. [32] has appeared. Their conclusions are broadly in agreement with our observations.

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[30] The data thus obtained gives a lower limit to the heat capacity associated with the singly-occupied $4d$ $t_{2g}$ level, which is sufficient for the present purpose.
