Magnetic Excitations and Electronic Interactions in Sr$_2$CuTeO$_6$: A Spin-1/2 Square Lattice Heisenberg Antiferromagnet

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Sr$_2$CuTeO$_6$ presents an opportunity for exploring low-dimensional magnetism on a square lattice of $S = 1/2$ Cu$^{2+}$ ions. We employ ab initio multireference configuration interaction calculations to unravel the Cu$^{2+}$ electronic structure and to evaluate exchange interactions in Sr$_2$CuTeO$_6$. The latter results are validated by inelastic neutron scattering using linear spin-wave theory and series-expansion corrections for quantum effects to extract true coupling parameters. Using this methodology, which is quite general, we demonstrate that Sr$_2$CuTeO$_6$ is an almost ideal realization of a nearest-neighbor Heisenberg antiferromagnet but with relatively weak coupling of 7.18(5) meV.

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Mott insulators are a subject of intense interest due to the observation of many different quantum phenomena [1,2]. In low-dimensional systems, frustration and quantum fluctuations can destroy long-range magnetic order giving rise to quantum paramagnetic phases such as valence-bond solids with broken lattice symmetry or spin liquids, where symmetry is conserved but with possible new collective behaviors involving emergent gauge fields and fractional excitations [3–5]. The spin-1/2 frustrated square lattice with nearest-neighbor (NN) $J_1$ and next-nearest neighbor $J_2$ exchange interactions is one of the simplest models for valence-bond solids and spin liquids [4,6]. Yet, despite the many theoretical efforts, experimental realizations of the $J_1$-$J_2$ model have been rather scarce. The double perovskite oxides are particularly interesting as magnetic interactions can be tuned by changing structure, stoichiometry, and cation order [7,8]. In the search for a quantum magnet with weak exchange energies, Sr$_2$CuTeO$_6$ has been proposed [9,10].

The tetragonal crystal structure of the double perovskite Sr$_2$CuTeO$_6$ [11] consists of corner sharing CuO$_6$ and TeO$_6$ octahedra that are rotated in a staggered fashion about the c axis; see Figs. 1(a) and 1(b). The CuO$_6$ octahedra are elongated along the c axis, effectively resulting in the ground state of a Cu$^{2+}$ (3$d^9$) ion having a hole in the in-plane $d_{x^2-y^2}$ orbital, where z is along the c axis. This could eventually result in quasi-2D magnetism in Sr$_2$CuTeO$_6$ with dominant intraplane exchange interactions. In the basal ab plane, the exchange that couples the Cu$^{2+}$ ions is the super-superexchange interaction mediated through the bridging TeO$_6$ octahedra as shown in Fig. 1(b), which is expected to reduce the coupling strength in Sr$_2$CuTeO$_6$.

Magnetic susceptibility and heat capacity measurements on Sr$_2$CuTeO$_6$ indicate a quasi-2D magnetic behavior, suggesting that it is a realization of the square-lattice $J_1$-$J_2$ model [10]. More recently, neutron diffraction measurements on Sr$_2$CuTeO$_6$ have shown it to order in a Néel antiferromagnetic (AFM) structure below $T_N = 29$ K with moments in the ab plane [12]; see Fig. 1(a). The ordered moment at 1.5 K was found to be reduced to $0.69(6)\mu_B$ from the classical value of $1\mu_B$ [12], indicating a renormalization by quantum fluctuations [13,14]. These observations demand further investigation into the magnetic ground state and excitations that elucidate the role of quantum effects in Sr$_2$CuTeO$_6$.

In this Letter, we show that Sr$_2$CuTeO$_6$ is an almost ideal realization of a two-dimensional square lattice Heisenberg antiferromagnet. This is achieved by a novel ab initio configuration interaction calculation of relevant exchange interactions, which are reaffirmed by modeling the inelastic magnetic spectrum using spin-wave theory and correcting the exchange interactions by series expansion.
Let us first consider the electronic interactions in Sr$_2$CuTeO$_6$. For a Cu$^{2+}$ ($3d^9$) ion in O$_6$ octahedral ligand cage, the degenerate 3$d$ levels are split into low-energy $t_{2g}$ and high-energy $e_g$ manifolds with a hole in the latter. In the tetragonally elongated CuO$_6$ octahedra in Sr$_2$CuTeO$_6$, the degeneracy of $t_{2g}$ and $e_g$ is further reduced into states with $e'_g$, $b_{2g}$ ($t_{2g}$), and $b_{1g}$, $a_{1g}$ ($e_g$) symmetry as shown in Fig. 1(c). The ground state wave function composition of Cu$^{2+}$ in Sr$_2$CuTeO$_6$ and the $d$-level excited state energies and corresponding wave functions are summarized in Table I. These are obtained from calculations at complete-active-space self-consistent-field (CASSCF) and multireference configuration-interaction (MRCI) levels of the many-body wave function theory [15], on embedded cluster of atoms containing a single reference CuO$_6$ octahedron and the surrounding six TeO$_6$ octahedra; see Supplemental Material [16] for computational details. In contrast to correlated calculations based on density functional theory in conjunction with dynamical mean field theory (DFT + DMFT), our calculations are parameter free and accurately describe correlations within the cluster of atoms in a systematic manner. An active space of nine electrons in five 3$d$ orbitals of the Cu$^{2+}$ ion was considered at the CASSCF level to capture the correlations among the 3$d$ electrons. In the subsequent correlated calculation, on top of the CASSCF wave function all single and double (MR-SDCI) excitations were allowed from the Cu 3$s$, 3$p$, 3$d$, and O 2$p$ orbitals of the reference CuO$_6$ octahedron into virtual orbital space to account for correlations involving those electrons [40,41]. All calculations were done using the MOLPRO quantum chemistry package [42].

From Table I it is evident that, at the CASSCF level, the ground state hole orbital predominantly has $d_{x^2−y^2}$ character with a small $d_{z^2}$ component. This admixture is due to the staggered rotation of CuO$_6$ and TeO$_6$ octahedra. Note that the wave function obtained in the MR-SDCI calculation also contains nonzero weights from those configurations involving single and double excitations into O 2$p$ orbitals. The MR-SDCI calculations predict the lowest crystal field excitation ($a_{1g}$ to $b_{1g}$) to be nearly degenerate at 0.86 eV, an accidental degeneracy very specific to Sr$_2$CuTeO$_6$. The highest $d$-level excitation is at 1.01 eV; see Fig. 1(c). It is interesting to note that the on-site $d$-$d$ excitations in Sr$_2$CuTeO$_6$ occur at rather low energies in comparison with 1D or 2D layered cuprates [40,41,43]. The presence of highly charged Te$^{6+}$ ions around the CuO$_6$ octahedron effectively decrease the effect of the ligand field on the Cu 3$d$ orbitals [16], a phenomenon observed in layered perovskite compound Sr$_2$IrO$_4$ [44].

Having established the ground state hole orbital character and Cu$^{2+}$ on-site $d$-$d$ excitations in Sr$_2$CuTeO$_6$, we evaluate the exchange interactions shown in Fig. 1(a). The exchange couplings were derived from a set of three different MRCI calculations on three different embedded clusters. To estimate $J_1$, a cluster consisting of two active CuO$_6$ octahedral units and two bridging TeO$_6$ octahedra was considered, for $J_2$ and $J_3$, only one bridging TeO$_6$ octahedron was included in the active region [16].

The coupling constants were obtained by mapping the energies of the magnetic configurations of the two unpaired electrons in two Cu$^{2+}$ ions onto that of a two-spin Heisenberg Hamiltonian $H_{ij} = J_{ij} S_i \cdot S_j$. A CASSCF reference wave function with two electrons in the two Cu$^{2+}$ ground state $d_{x^2−y^2}$-type orbitals was first constructed for the singlet and triplet spin multiplicities [45], state averaged. In the MRCI calculations the electrons in the doubly occupied Cu 3$d$ orbitals and the Te 4$d$ and O 2$p$ orbitals of the bridging TeO$_6$ octahedron were correlated. We adopted a difference dedicated configuration interaction (MR-DDCI) scheme [46,47] recently implemented within MOLPRO, where a subset of the MR-SDCI determinant space [48] that excludes all the double excitations from the inactive orbitals to the virtuals, is used to construct the

<table>
<thead>
<tr>
<th>Symmetry of $d^9$ states</th>
<th>Relative E (eV)</th>
<th>CASSCF/MRCI wave function</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{1g}$</td>
<td>0.00/0.00</td>
<td>0.97($d_{x^2−y^2}$) + 0.24($d_{z^2}$)</td>
</tr>
<tr>
<td>$b_{2g}$</td>
<td>0.778/0.856</td>
<td>−0.24($d_{x^2−y^2}$) + 0.97($d_{z^2}$)</td>
</tr>
<tr>
<td>$b_{1g}$</td>
<td>0.796/0.863</td>
<td>1.0($d_{z^2}$)</td>
</tr>
<tr>
<td>$e'_g$</td>
<td>1.013/1.098</td>
<td>0.94($d_{x^2}$) − 0.34($d_{z^2}$)</td>
</tr>
<tr>
<td>$e'_g$</td>
<td>1.013/1.098</td>
<td>0.34($d_{x^2}$) + 0.94($d_{z^2}$)</td>
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FIG. 1. (a) and (b) Crystallographic and magnetic structure of Sr$_2$CuTeO$_6$. The Cu$^{2+}$ ions order magnetically into an arrangement indicated by the red arrows. The different exchange couplings are shown by arrows connecting two Cu$^{2+}$ ions. (c) Energy level diagram of $d$ states in octahedral (O$_6$) symmetry, for a tetragonally elongated octahedron and for the Cu$^{2+}$ ion in Sr$_2$CuTeO$_6$ whose Cu-O bond lengths are labeled.

TABLE I. Relative energies of the Cu$^{2+}$ ion $d$-level excitations in Sr$_2$CuTeO$_6$ (in hole representation). The composition of wave functions at the CASSCF level is also provided. Only the five 3$d$ orbitals of the Cu$^{2+}$ ion were included in the CASSCF active space. At MRCI level, the wave function would also contain contributions from the other correlated orbitals (see text).
The experimental in-plane couplings were obtained from fits to INS using SWT and corrected by SE; see text. Values are given in meV.

<table>
<thead>
<tr>
<th>J</th>
<th>CASSCF</th>
<th>MR-DDCI</th>
<th>Experiment</th>
</tr>
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<tbody>
<tr>
<td>J₁</td>
<td>2.320</td>
<td>7.386</td>
<td>7.18(5)</td>
</tr>
<tr>
<td>J₂</td>
<td>0.006</td>
<td>0.051</td>
<td>0.21(6)</td>
</tr>
<tr>
<td>J₆</td>
<td>0.000</td>
<td>0.003</td>
<td>0.04</td>
</tr>
</tbody>
</table>

many-body wave function. This approach has resulted in exchange couplings for several quasi-2D and quasi-1D cuprates that are in excellent agreement with experimental estimates, e.g., see Ref. [49].

In Table II the Heisenberg couplings derived at the CASSCF and MR-DDCI level with Davidson corrections for size-consistency errors [50] are listed. We see that all the interactions are AFM. At the fully correlated MR-DDCI level of calculation we obtain the in-plane exchange coupling J₁ to be the largest at 7.39 meV. At the CASSCF level where the Anderson type of exchange is accounted for, i.e., related to intersite d-d excitations of the dₓ²−y²−dₓ²−y² type [51,52], only 30% of the J₁ exchange is obtained. The MR-DDCI treatment, which now includes excitations of the kind t₂gₓ²−t₂gₓ², etc., and O 2p to Cu 3d charge-transfer virtual states as well, enhances J₁. Our calculations estimate a second neighbor in-plane coupling J₂ = 0.007J₁ and the coupling along the c axis to be practically zero; see Table II.

Although it may perhaps be expected that the dominant superexchange comes from bridging Te 4d orbitals—the path Cu²⁺−O²⁻−Te⁰⁺−O²⁻−Cu²⁺, we find that the Te outermost occupied 4d orbitals are corelike at ≈50 eV below the valence Cu 3d and the oxygen 2p orbitals, and, hence, a negligible contribution to the magnetic exchange. A MR-DDCI calculation that does not take into account the virtual hopping through the Te d states results in J₁ = 7.79 meV. Thus, we conclude that the dominant superexchange path is Cu²⁺−O²⁻−O²⁻−Cu²⁺ along the two bridging TeOₓ octahedra; see Ref. [16]. Interestingly, we find that the superexchange involving virtual hoppings from the doubly occupied Cu 3d orbitals of t₂g symmetry and the dₓ² of e₉ symmetry, 0.86–1.1 eV lower than the dₓ²−y² orbitals (see Table I), contribute almost half to the exchange coupling—a calculation without the doubly occupied Cu d orbitals in the inactive space result in a J₁ of 4.51 meV.

Next, we turn to inelastic powder neutron scattering (INS) measurements to determine experimentally the nature of magnetic interactions. The experiments were performed at Paul Scherrer Institute, using the spectrometer FOCUS (not shown), and Institut Laue-Langevin on the thermal time-of-flight spectrometer IN4 [53].

The data were collected on a sealed Al envelope containing 24.1 g of Sr₂CuTeO₆ powder at temperatures of 2, 60, and 120 K with incident neutron energy of 25.2 meV and Fermi chopper at 250 Hz. The raw data were corrected for detector efficiency, time-independent background, attenuation, and normalized to a vanadium calibration following standard procedures using LAMP and Mslice software packages [54].

The spin-spin correlations between Cu ions can be probed using INS as a function of momentum and energy transfer (Q, ℏω), where the former is defined as Q = |aα + bβ + cγ| in terms of reciprocal lattice vectors. The magnetic neutron scattering cross section is directly related to the imaginary part of the dynamical susceptibility χ''(Q, ℏω). At sufficiently high temperatures above Tₐ, the magnetic excitations are generally heavily damped and uncorrelated [55]. In the case of Sr₂CuTeO₆, some magnetic correlations persist even at 60 K (≈2Tₐ), indicative of the low dimensionality of the system, see Ref. [16]. On warming to 120 K, the magnetic signal can no longer be observed and we subtract this data from the 2 K measurements to reveal a purely magnetic contribution to the signal.

In Fig. 2 we present the measured and calculated magnetic spectra. Figure 2(a) shows the inelastic powder χ''(Q, ℏω) spectrum mapped over momentum and energy transfer. We observe dispersive modes originating from the magnetic Bragg peak positions around |Q| = 0.9 and 1.87 Å⁻¹, which correspond to (0.5,0,5,0) and (1.5,0,5,0). The dispersion is linear, which is consistent with AFM spin waves and remains gapless within the energy resolution of our measurements of 1.4 meV at the elastic line (FWHM).
The dominant feature in our spectrum is a strong, flat band around 15.4 meV, shown in Fig. 2(c). The intensity decreases with increasing |Q| as expected for magnetic scattering; see Fig. 2(d). For low-dimensional systems, powder averaging produces a van Hove-like maximum at the zone boundary. Therefore, we interpret the flat band as due to the zone boundaries and not to a dispersionless excitation. We observe that the signal at 15.4 meV has a FWHM of 1.7 meV, which is significantly larger than the 1.2 meV instrumental resolution at this energy transfer. This implies that there is dispersion along the zone boundary.

There are two potential sources of zone boundary dispersion. First, a finite J₂ leads to dispersion along the zone boundary. This effect can be captured by spin wave theory (SWT). Second, it has been well established that even the purely nearest neighbor (J₂ = 0) spin-1/2 Heisenberg antiferromagnet on a square lattice exhibits a quantum effect dispersion where E(π, 0) is lower than E(π/2, π/2). The latter effect cannot be captured by SWT but by several other theoretical approaches—series expansion (SE) [57,58], exact diagonalization [59], quantum Monte Carlo (QMC) methods [60,61], variational wave function (VA) [56], etc. In the presence of an AFM J₂ coupling, the quantum dispersion and the J₂ dispersion reinforce each other.

For calculating the powder-averaged neutron spectra, the classical (large-S) linear spin-wave (SWT) works best, owing to significantly faster computation time. Therefore, our approach is to fit the magnetic spectrum using SWT to extract effective J₁ and J₂ parameters and then to use SE to correct these values to obtain true J₁ and J₂ parameters. In doing so, we consider a Heisenberg Hamiltonian, \( \hat{\mathcal{H}} = \sum_{(ij)} S_i \cdot S_j + J_2 \sum_{(ij)} S_i \cdot S_j \). We neglect the very small c-axis coupling as obtained in our calculations; see Table II. The magnetic dispersion can be described as
\[
\hbar \omega = Z_c \sqrt{A^2 - B^2},
\]
where \( A = 2J_1 + J_2 (\cos(2\pi h - 2\pi k) + \cos(2\pi h + 2\pi k) - 2) \) and \( B = J_1 (\cos 2\pi h + \cos 2\pi k) \) [62].

To fit the data we calculate the imaginary part of the susceptibility, including an anisotropic Cu²⁺ form factor [63,64]. The resulting spectrum is shown in Fig. 2(b) which has been calculated using \( J_1 = 7.60(3) \) and \( J_2 = 0.60(3) \) meV. Comparing the spectra in Figs. 2(a) and 2(b), we find good agreement across the entire wave vector and energy transfer range. The SWT simulation is able to reproduce the strong flat mode around 15.4 meV and spin-waves emerging from the AFM positions. At larger |Q|, we find that the intensity is predicted to decrease more rapidly than observed; see Fig. 2(d). This could be an artifact of imperfect subtraction of the phonon spectrum, a small mixing of the dₓ₅₋₃ orbitals influencing the magnetic form factor or multiple scattering.

We now turn to the series-expansion method up to 6th order for J₁,J₂ to correct the exchange coupling parameters derived from SWT for the quantum effects [57,65]. Figure 3(a) shows the calculated single-magnon energies for the SE and SWT calculations for different relative strengths J₂/J₁ and J₁/J₂. We employ the convention where (π/2, π/2) and (π, 0) correspond to points \((h, k) = (1/2, 0)\) and \((1/4, 1/4)\) (and equivalent) in reciprocal space, respectively. The SE calculations show a zone-boundary dispersion of around 7% when second neighbor exchange is absent. Comparing this to SWT calculations, see Fig. 3(a), it is clear that a nonzero AFM J₂ parameter modifies this part of the dispersion in a similar manner.

From SWT fits, we find that J₂/J₁ = 0.079(3) which leads to a 9.3(5)% dispersion between (π/2, π/2) and (π, 0). However, in SE, the same dispersion is explained largely by quantum fluctuations, see Fig. 3(b), such that J₂/J₁ = 0.025(5), or J₂ = 0.21(6) meV. By correcting the SWT results by SE, we obtain a more realistic value of the ratio of the exchange coupling parameters. The zone boundary dispersion can be estimated by other theoretical approaches for J₂ = 0 [56,58–61]. In Fig. 3(a) we show that the same amount of dispersion as we observe can also be explained in the absence of J₂ interaction. Nonetheless, our experimental results place an upper limit on the size of J₂. We note that reducing J₂ must increase J₁ accordingly J₁ ≈ J₁(1 - J₂/J₁)/(1 - J₂/J₁), which results in J₁ ≈ 7.18(5) meV. For a quasi-2D system, Tₕ can be used to estimate the coupling Jₕ between layers using Jₕ[Tₕ(a bulk)]². We find the correlation length is \( \xi(T_N)/a \approx 10 \) from three-loop order given in Ref. [66]. This gives an out-of-plane coupling on the order of 0.04 meV. Comparing experimentally obtained exchange parameters with \textit{ab initio} calculations in Table II, we find remarkably good agreement. Indeed, this demonstrates the power of our approach in obtaining a complete description of the magnetic
interactions which has rather rarely been applied to strongly correlated electron systems.

We note that neutron scattering measurements have recently been performed on the related Sr$_2$CuWO$_6$ compound where the $J_3 \gg J_1$ leads to columnar antiferromagnetic order [67,68]. Exchange parameters have been estimated using calculations based on density functional theory corrected for Hubbard type interactions and are in reasonable agreement with experiments without corrections for quantum fluctuations [67,68]. It would be interesting to validate the proposed exchange interaction mechanisms in Sr$_2$CuWO$_6$ using more accurate many-body calculations similar to those adopted in this work.

In summary, we have characterized magnetic interactions in a new layered antiferromagnet Sr$_2$CuTeO$_6$ using detailed ab initio configuration interaction calculations and inelastic neutron scattering measurements. The calculations accurately predict the exchange interactions, and further determine the dominant exchange path, i.e., via Cu$^{2+}$-$O^2-$O$^2-$Cu$^{2+}$ and not via Te 4d orbitals, as previously suggested. By simulating the magnetic excitations using classical SWT corrected by SE, we show that NN exchange coupling is around 7.18(5) meV with very weak next-nearest interactions on the order of < 3% of $J_1$. The low-energy scale of interactions in Sr$_2$CuTeO$_6$ should make it an appealing system to study theoretically and experimentally as an almost ideal realization of a nearest-neighbor Heisenberg antiferromagnet. Moreover, our work brings to the fore a novel strategy for exploring Heisenberg antiferromagnets from ab initio calculations to simulations of magnetic spectra taking into account quantum effects.

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P. B. and V. M. K. contributed equally to this work.

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