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

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$\text{Sr}_2\text{CuTeO}_6$  presents an opportunity for exploring low-dimensional magnetism on a square lattice of  $S = 1/2$   $\text{Cu}^{2+}$  ions. We employ *ab initio* multireference configuration interaction calculations to unravel the  $\text{Cu}^{2+}$  electronic structure and to evaluate exchange interactions in  $\text{Sr}_2\text{CuTeO}_6$ . 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  $\text{Sr}_2\text{CuTeO}_6$  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,  $\text{Sr}_2\text{CuTeO}_6$  has been proposed [9,10].

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

Magnetic susceptibility and heat capacity measurements on  $\text{Sr}_2\text{CuTeO}_6$  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  $\text{Sr}_2\text{CuTeO}_6$  have shown it to order in a Néel antiferromagnetic (AFM) structure below  $T_N \approx 29$  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  $\text{Sr}_2\text{CuTeO}_6$ .

In this Letter, we show that  $\text{Sr}_2\text{CuTeO}_6$  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.

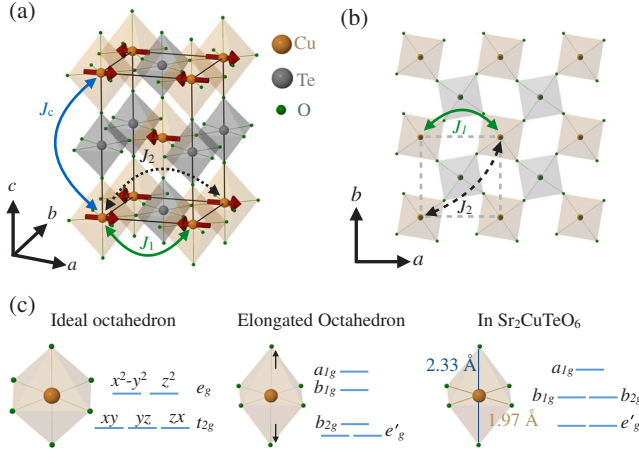


FIG. 1. (a) and (b) Crystallographic and magnetic structure of Sr<sub>2</sub>CuTeO<sub>6</sub>. The Cu<sup>2+</sup> ions order magnetically into an arrangement indicated by the red arrows. The different exchange couplings are shown by arrows connecting two Cu<sup>2+</sup> ions. (c) Energy level diagram of *d* states in octahedral (*O<sub>h</sub>*) symmetry, for a tetragonally elongated octahedron and for the Cu<sup>2+</sup> ion in Sr<sub>2</sub>CuTeO<sub>6</sub> whose Cu-O bond lengths are labeled.

Let us first consider the electronic interactions in Sr<sub>2</sub>CuTeO<sub>6</sub>. For a Cu<sup>2+</sup> (*3d<sup>9</sup>*) ion in O<sub>6</sub> octahedral ligand cage, the degenerate 3*d* levels are split into low-energy *t<sub>2g</sub>* and high-energy *e<sub>g</sub>* manifolds with a hole in the latter. In the tetragonally elongated CuO<sub>6</sub> octahedra in Sr<sub>2</sub>CuTeO<sub>6</sub>, the degeneracy of *t<sub>2g</sub>* and *e<sub>g</sub>* is further reduced into states with *e'<sub>g</sub>*, *b<sub>2g</sub>* (*t<sub>2g</sub>*), and *b<sub>1g</sub>*, *a<sub>1g</sub>* (*e<sub>g</sub>*) symmetry as shown in Fig. 1(c). The ground state wave function composition of Cu<sup>2+</sup> in Sr<sub>2</sub>CuTeO<sub>6</sub> 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<sub>6</sub> octahedron and the surrounding six TeO<sub>6</sub> 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<sup>2+</sup> 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<sub>6</sub> 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<sub>x<sup>2</sup>-y<sup>2</sup></sub>* character

TABLE I. Relative energies of the Cu<sup>2+</sup> ion *d*-level excitations in Sr<sub>2</sub>CuTeO<sub>6</sub> (in hole representation). The composition of wave functions at the CASSCF level is also provided. Only the five 3*d* orbitals of the Cu<sup>2+</sup> 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).

| Symmetry of <i>d<sup>9</sup></i> states | Relative E (eV)<br>CASSCF/MRCI | CASSCF wave function  |
|---|--------------------------------|---|
| <i>a<sub>1g</sub></i>                   | 0.00/0.00                      | 0.97  <i>d<sub>x<sup>2</sup>-y<sup>2</sup></sub></i> ⟩ + 0.24  <i>d<sub>xy</sub></i> ⟩  |
| <i>b<sub>2g</sub></i>                   | 0.778/0.856                    | -0.24  <i>d<sub>x<sup>2</sup>-y<sup>2</sup></sub></i> ⟩ + 0.97  <i>d<sub>xy</sub></i> ⟩ |
| <i>b<sub>1g</sub></i>                   | 0.796/0.863                    | 1.0  <i>d<sub>z<sup>2</sup></sub></i> ⟩   |
| <i>e'<sub>g</sub></i>                   | 1.013/1.098                    | 0.94  <i>d<sub>yz</sub></i> ⟩ - 0.34  <i>d<sub>zx</sub></i> ⟩                           |
|   | 1.013/1.098                    | 0.34  <i>d<sub>yz</sub></i> ⟩ + 0.94  <i>d<sub>zx</sub></i> ⟩                           |

with a small *d<sub>xy</sub>* component. This admixture is due to the staggered rotation of CuO<sub>6</sub> and TeO<sub>6</sub> 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<sub>1g</sub>*-*b<sub>1g</sub>* and *a<sub>1g</sub>*-*b<sub>2g</sub>*) to be nearly degenerate at 0.86 eV, an accidental degeneracy very specific to Sr<sub>2</sub>CuTeO<sub>6</sub>. 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<sub>2</sub>CuTeO<sub>6</sub> occur at rather low energies in comparison with 1D or 2D layered cuprates [40,41,43]. The presence of highly charged Te<sup>6+</sup> ions around the CuO<sub>6</sub> octahedron effectively decrease the effect of the ligand field on the Cu *d* orbitals [16], a phenomenon observed in layered perovskite compound Sr<sub>2</sub>IrO<sub>4</sub> [44].

Having established the ground state hole orbital character and Cu<sup>2+</sup> on-site *d-d* excitations in Sr<sub>2</sub>CuTeO<sub>6</sub>, 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<sub>1</sub>* a cluster consisting of two active CuO<sub>6</sub> octahedral units and two bridging TeO<sub>6</sub> octahedra was considered, for *J<sub>2</sub>* and *J<sub>c</sub>* only one bridging TeO<sub>6</sub> 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<sup>2+</sup> ions onto that of a two-spin Heisenberg Hamiltonian  $\mathcal{H}_{ij} = J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$ . A CASSCF reference wave function with two electrons in the two Cu<sup>2+</sup> ground state *d<sub>x<sup>2</sup>-y<sup>2</sup></sub>*-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<sub>6</sub> 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 II. Heisenberg exchange couplings derived from *ab initio* CASSCF/MR-DDCI data and experimentally for  $\text{Sr}_2\text{CuTeO}_6$ . The experimental in-plane couplings were obtained from fits to INS using SWT and corrected by SE; see text. Values are given in meV.

| $J$   | CASSCF | MR-DDCI | Experiment |
|-------|--------|---------|------------|
| $J_1$ | 2.320  | 7.386   | 7.18(5)    |
| $J_2$ | 0.006  | 0.051   | 0.21(6)    |
| $J_c$ | 0.000  | 0.003   | 0.04       |

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  $J_1$  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  $d_{x^2-y^2}^0-d_{x^2-y^2}^2$  type [51,52], only 30% of the  $J_1$  exchange is obtained. The MR-DDCI treatment, which now includes excitations of the kind  $t_{2g}^5 e_g^1 - t_{2g}^6 e_g^2$ , etc., and  $O\ 2p$  to  $\text{Cu}\ 3d$  charge-transfer virtual states as well, enhances  $J_1$ . Our calculations estimate a second neighbor in-plane coupling  $J_2 = 0.007J_1$  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  $\text{Cu}^{2+}-\text{O}^{2-}-\text{Te}^{6+}-\text{O}^{2-}-\text{Cu}^{2+}$ , we find that the Te outermost occupied  $4d$  orbitals are corelike at  $\approx 50$  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  $J_1 = 7.79$  meV. Thus, we conclude that the dominant superexchange path is  $\text{Cu}^{2+}-\text{O}^{2-}-\text{O}^{2-}-\text{Cu}^{2+}$  along the two bridging  $\text{TeO}_6$  octahedra; see Ref. [16]. Interestingly, we find that the superexchange involving virtual hoppings from the doubly occupied Cu  $3d$  orbitals of  $t_{2g}$  symmetry and the  $d_{z^2}$  of  $e_g$  symmetry, 0.86–1.1 eV lower than the  $d_{x^2-y^2}$  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  $J_1$  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  $\text{Sr}_2\text{CuTeO}_6$  powder at temperatures of 2, 60, and 120 K with incident neutron energy of

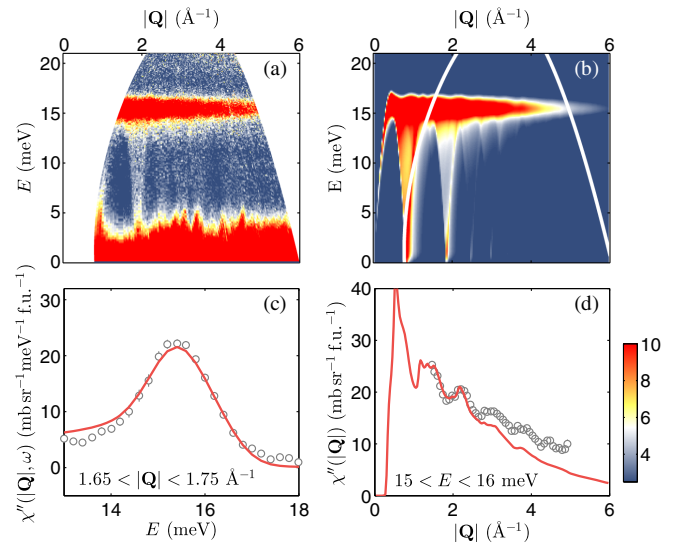


FIG. 2. (a) Dynamic susceptibility  $\chi''(|\mathbf{Q}|, E)$  map obtained by subtraction of 120 K from 2 K data. (b) Calculated powder average inelastic spectrum using  $\tilde{J}_1 = 7.60(3)$  and  $\tilde{J}_2 = 0.60(3)$  meV. The solid white lines show the detector edges. The SWT intensity is scaled to match the measured pattern in units of  $\text{mb sr}^{-1} \text{meV}^{-1} \text{f.u.}^{-1}$ . (c) A constant wave vector cut for  $|\mathbf{Q}| \approx 1.7 \text{ \AA}^{-1}$  through the dynamic susceptibility with a solid red line showing the calculated cut from SWT. (d)  $|\mathbf{Q}|$  dependence of the magnetic band around 15.4 meV and a comparison to SWT calculations.

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 ( $|\mathbf{Q}|, \hbar\omega$ ), where the former is defined as  $|\mathbf{Q}| = |\hbar\mathbf{a}^* + \hbar\mathbf{b}^* + \hbar\mathbf{c}^*|$  in terms of reciprocal lattice vectors. The magnetic neutron scattering cross section is directly related to the imaginary part of the dynamical susceptibility  $\chi''(|\mathbf{Q}|, \omega)$ . At sufficiently high temperatures above  $T_N$ , the magnetic excitations are generally heavily damped and uncorrelated [55]. In the case of  $\text{Sr}_2\text{CuTeO}_6$ , some magnetic correlations persist even at 60 K ( $\approx 2T_N$ ), 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  $\chi''(|\mathbf{Q}|, \omega)$  spectrum mapped over momentum and energy transfer. We observe dispersive modes originating from the magnetic Bragg peak positions around  $|\mathbf{Q}| = 0.9$  and  $1.87 \text{ \AA}^{-1}$ , 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  $|\mathbf{Q}|$  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  $J_2$  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 ( $J_2 = 0$ ) spin-1/2 Heisenberg antiferromagnet on a square lattice exhibits a quantum effect with two results: (i) at  $(\pi, 0)$  the sharp spin-wave peak develops a line shape extending towards higher energies—a quantum effect that has often been explained in terms of spinon deconfinement [56]; (ii) a 6%–8% zone boundary dispersion where  $E(\pi, 0)$  is lower than  $E(\pi/2, \pi/2)$ . 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  $J_2$  coupling, the quantum dispersion and the  $J_2$  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  $\tilde{J}_1$  and  $\tilde{J}_2$  parameters and then to use SE to correct these values to obtain true  $J_1$  and  $J_2$  parameters. In doing so, we consider a Heisenberg Hamiltonian,  $\mathcal{H} = \tilde{J}_1 \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + \tilde{J}_2 \sum_{\langle\langle ij \rangle\rangle} \mathbf{S}_i \cdot \mathbf{S}_j$ . 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  $A = 2\tilde{J}_1 + \tilde{J}_2 [\cos(2\pi h - 2\pi k) + \cos(2\pi h + 2\pi k) - 2]$  and  $B = \tilde{J}_1 (\cos 2\pi h + \cos 2\pi k)$  [62]. To fit the data we calculate the imaginary part of the dynamic susceptibility including an anisotropic  $\text{Cu}^{2+}$  magnetic form factor [63,64]. The resulting spectrum is shown in Fig. 2(b) which has been calculated using  $\tilde{J}_1 = 7.60(3)$  and  $\tilde{J}_2 = 0.60(3)$  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  $|\mathbf{Q}|$ , 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  $d_{xy}$  orbitals influencing the magnetic form factor or multiple scattering.

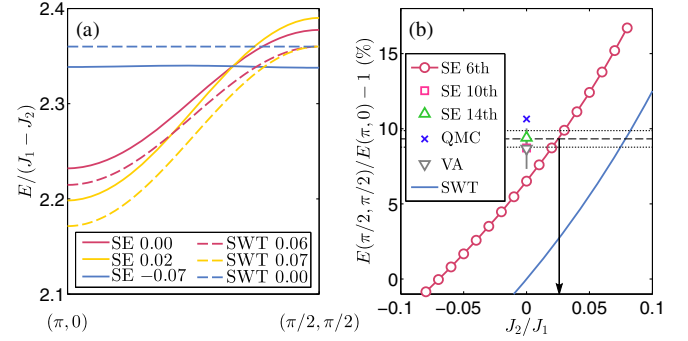


FIG. 3. (a) Dispersion between  $(\pi, 0)$  and  $(\pi/2, \pi/2)$  calculated using SE and SWT methods for  $J_1 = 1$  and  $J_2/J_1$  values given in the legend. (b) Calculated change of zone boundary energies at  $(\pi, 0)$  and  $(\pi/2, \pi/2)$  obtained from SE and SWT. The dashed horizontal line denotes the dispersion expected for the calculated ratio of  $\tilde{J}_2/\tilde{J}_1 = 0.078$  and the horizontal lines either side show the corresponding uncertainty of  $\pm 0.005$  in  $\tilde{J}_2/\tilde{J}_1$ .

We now turn to the series-expansion method up to 6th order for  $J_1$ - $J_2$  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  $J_2/J_1$  and  $\tilde{J}_2/\tilde{J}_1$ . We employ the convention where  $(\pi/2, \pi/2)$  and  $(\pi, 0)$  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  $\tilde{J}_2$  parameter modifies this part of the dispersion in a similar manner.

From SWT fits, we find that  $\tilde{J}_2/\tilde{J}_1 = 0.079(3)$  which leads to a 9.3(5)% dispersion between  $(\pi/2, \pi/2)$  and  $(\pi, 0)$ . However, in SE, the same dispersion is explained largely by quantum fluctuations, see Fig. 3(b), such that  $J_2/J_1 = 0.025(5)$ , or  $J_2 = 0.21(6)$  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  $J_2 = 0$  [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  $J_2$  interaction. Nonetheless, our experimental results place an upper limit on the size of  $J_2$ . We note that reducing  $J_2$  must increase  $J_1$  accordingly  $J_1 \approx \tilde{J}_1(1 - \tilde{J}_2/\tilde{J}_1)/(1 - J_2/J_1)$ , which results in  $J_1 \approx 7.18(5)$  meV. For a quasi-2D system,  $T_N$  can be used to estimate the coupling  $J_c$  between layers using  $T_N \approx J_c [\xi(T_N)/a]^2$ . 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 *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  $\text{Sr}_2\text{CuWO}_6$  compound where the  $J_2 \gg J_1$  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  $\text{Sr}_2\text{CuWO}_6$  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  $\text{Sr}_2\text{CuTeO}_6$  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  $\text{Cu}^{2+}-\text{O}^{2-}-\text{O}^{2-}-\text{Cu}^{2+}$  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  $\text{Sr}_2\text{CuTeO}_6$  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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[1] D. Khomskii, *Transition Metal Compounds* (Cambridge University Press, Cambridge, England, 2014).

- [2] W. Witczak-Krempa, G. Chen, Y. B. Kim, and L. Balents, *Annu. Rev. Condens. Matter Phys.* **5**, 57 (2014).
- [3] P. W. Anderson, *Mater. Res. Bull.* **8**, 153 (1973).
- [4] P. W. Anderson, *Science* **235**, 1196 (1987).
- [5] L. Balents, *Nature (London)* **464**, 199 (2010).
- [6] G. Shirane, Y. Endoh, R. J. Birgeneau, M. A. Kastner, Y. Hidaka, M. Oda, M. Suzuki, and T. Murakami, *Phys. Rev. Lett.* **59**, 1613 (1987).
- [7] G. King and P. M. Woodward, *J. Mater. Chem.* **20**, 5785 (2010).
- [8] S. Vasala and M. Karppinen, *Prog. Solid State Chem.* **43**, 1 (2015).
- [9] D. Iwanaga, Y. Inaguma, and M. Itoh, *J. Solid State Chem.* **147**, 291 (1999).
- [10] T. Koga, N. Kurita, and H. Tanaka, *J. Phys. Soc. Jpn.* **83**, 115001 (2014).
- [11] D. Reinen and H. Weitzel, *Z. Anorg. Allg. Chem.* **424**, 31 (1976).
- [12] T. Koga, N. Kurita, M. Avdeev, S. Danilkin, T. J. Sato, and H. Tanaka, *Phys. Rev. B* **93**, 054426 (2016).
- [13] J. D. Reger and A. P. Young, *Phys. Rev. B* **37**, 5978 (1988).
- [14] R. R. P. Singh, *Phys. Rev. B* **39**, 9760 (1989).
- [15] T. Helgaker, P. Jørgensen, and J. Olsen, *Molecular Electronic-Structure Theory* (Wiley, Chichester, 2000).
- [16] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.117.237203>, for additional information regarding the *ab initio* multi-reference configuration interaction calculations as well as magnetization and INS measurements, which includes Refs. [17–39].
- [17] M. Klintonberg, S. Derenzo, and M. Weber, *Comput. Phys. Commun.* **131**, 120 (2000).
- [18] R. Pou-Amerigo, M. Merchan, P.-O. Widmark, and B. Roos, *Theor. Chim. Acta* **92**, 149 (1995).
- [19] P.-O. Widmark, P.-A. Malmqvist, and B. O. Roos, *Theor. Chim. Acta* **77**, 291 (1990).
- [20] A. Bergner, M. Dolg, W. Kuechle, H. Stoll, and H. Preuss, *Mol. Phys.* **80**, 1431 (1993).
- [21] P.-O. W. K. Pierloot, B. Dumez, and B. O. Roos, *Theor. Chim. Acta* **90**, 87 (1995).
- [22] P. Fuentealba, L. von Szentpaly, H. Preuss, and H. Stoll, *J. Phys. B* **18**, 1287 (1985).
- [23] R. Broer, L. Hozoi, and W. C. Nieuwpoort, *Mol. Phys.* **101**, 233 (2003).
- [24] R. Maurice, A. M. Pradipto, C. de Graaf, and R. Broer, *Phys. Rev. B* **86**, 024411 (2012).
- [25] V. M. Katukuri, H. Stoll, J. van den Brink, and L. Hozoi, *Phys. Rev. B* **85**, 220402 (2012).
- [26] K. Peterson, D. Figgen, E. Goll, H. Stoll, and M. Dolg, *J. Chem. Phys.* **119**, 11113 (2003).
- [27] R. Dovesi, R. Orlando, A. Erba, C. M. Zicovich-Wilson, B. Civalieri, S. Casassa, L. Maschio, M. Ferrabone, M. De La Pierre, P. D’Arco, Y. Nol, M. Caus, M. Rrat, and B. Kirtman, *Int. J. Quantum Chem.* **114**, 1287 (2014).
- [28] G. Kresse and J. Furthmüller, *Phys. Rev. B* **54**, 11169 (1996).
- [29] Jmol: an open-source Java viewer for chemical structures in three dimensions, <http://www.jmol.org>.
- [30] K. Fink, R. Fink, and V. Staemmler, *Inorg. Chem.* **33**, 6219 (1994).
- [31] C. J. Calzado, S. Evangelisti, and D. Maynau, *J. Phys. Chem. A* **107**, 7581 (2003).

- [32] A. B. van Oosten, R. Broer, and W. C. Nieuwpoort, *Chem. Phys. Lett.* **257**, 207 (1996).
- [33] V. M. Katukuri, S. Nishimoto, V. Yushankhai, A. Stoyanova, H. Kandpal, S. K. Choi, R. Coldea, I. Rousochatzakis, L. Hozoi, and J. van den Brink, *New J. Phys.* **16**, 013056 (2014).
- [34] N. A. Bogdanov, V. M. Katukuri, H. Stoll, J. van den Brink, and L. Hozoi, *Phys. Rev. B* **85**, 235147 (2012).
- [35] V. M. Katukuri, V. Yushankhai, L. Siurakshina, J. van den Brink, L. Hozoi, and I. Rousochatzakis, *Phys. Rev. X* **4**, 021051 (2014).
- [36] J. Pipek and P. G. Mezey, *J. Chem. Phys.* **90**, 4916 (1989).
- [37] G. Kresse and D. Joubert, *Phys. Rev. B* **59**, 1758 (1999).
- [38] A. A. Mostofi, J. R. Yates, G. Pizzi, Y.-S. Lee, I. Souza, D. Vanderbilt, and N. Marzari, *Comput. Phys. Commun.* **185**, 2309 (2014).
- [39] H.-J. Schmidt, A. Lohmann, and J. Richter, *Phys. Rev. B* **84**, 104443 (2011).
- [40] L. Hozoi, L. Siurakshina, P. Fulde, and J. van den Brink, *Sci. Rep.* **1**, 65 (2011).
- [41] H.-Y. Huang, N. A. Bogdanov, L. Siurakshina, P. Fulde, J. van den Brink, and L. Hozoi, *Phys. Rev. B* **84**, 235125 (2011).
- [42] H. J. Werner, P. J. Knowles, G. Knizia, F. R. Manby, and M. Schütz, *Wiley Interdiscip. Rev. Comp. Mol. Sci.* **2**, 242 (2012).
- [43] M. M. Sala, V. Bisogni, C. Aruta, G. Balestrino, H. Berger, N. B. Brookes, G. M. de Luca, D. D. Castro, M. Grioni, M. Guarise, P. G. Medaglia, F. M. Granozio, M. Minola, P. Perna, M. Radovic, M. Salluzzo, T. Schmitt, K. J. Zhou, L. Braicovich, and G. Ghiringhelli, *New J. Phys.* **13**, 043026 (2011).
- [44] N. A. Bogdanov, V. M. Katukuri, J. Romhányi, V. Yushankhai, V. Kataev, B. Büchner, J. van den Brink, and L. Hozoi, *Nat. Commun.* **6**, 7306 (2015).
- [45] *Magnetic Interactions in Molecules and Solids*, edited by C. de Graaf and R. Broer (Springer International Publishing, New York, 2015), Chap. 2, p. 69.
- [46] J. Miralles, J.-P. Daudey, and R. Caballol, *Chem. Phys. Lett.* **198**, 555 (1992).
- [47] J. Miralles, O. Castell, R. Caballol, and J.-P. Malrieu, *Chem. Phys.* **172**, 33 (1993).
- [48] In MR-SDCI all configurations involving single and double excitations from the active and inactive orbitals to the virtual orbital space are considered in the wave function expansion.
- [49] D. Muñoz, F. Illas, and I. de P. R. Moreira, *Phys. Rev. Lett.* **84**, 1579 (2000); D. Muñoz, C. de Graaf, and F. Illas, *J. Comput. Chem.* **25**, 1234 (2004); A. M. Pradipto, R. Maurice, N. Guihéry, C. de Graaf, and R. Broer, *Phys. Rev. B* **85**, 014409 (2012); R. Maurice, A.-M. Pradipto, C. de Graaf, and R. Broer, *Phys. Rev. B* **86**, 024411 (2012).
- [50] R. J. Cave and E. R. Davidson, *J. Chem. Phys.* **89**, 6798 (1988).
- [51] P. W. Anderson, *Phys. Rev.* **79**, 350 (1950).
- [52] P. W. Anderson, *Phys. Rev.* **115**, 2 (1959).
- [53] G. Cicognani, H. Mutka, and F. Sacchetti, *Physica (Amsterdam)* **276–278B**, 83 (2000).
- [54] LAMP, the Large Array Manipulation Program, [http://www.ill.eu/data\\_treat/lamp/the-lamp-book](http://www.ill.eu/data_treat/lamp/the-lamp-book); R. Coldea, mslice: a data analysis program for time-of-flight neutron spectrometers, [http://mslice.isis.rl.ac.uk/Main\\_Page](http://mslice.isis.rl.ac.uk/Main_Page).
- [55] H. M. Rønnow, D. F. McMorrow, R. Coldea, A. Harrison, I. D. Youngson, T. G. Perring, G. Aeppli, O. Syljuåsen, K. Lefmann, and C. Rischel, *Phys. Rev. Lett.* **87**, 037202 (2001).
- [56] B. Dalla Piazza, M. Mourigal, N. B. Christensen, G. J. Nilsen, P. Tregenna-Piggott, T. G. Perring, M. Enderle, D. F. McMorrow, D. A. Ivanov, and H. M. Rønnow, *Nat. Phys.* **11**, 62 (2015).
- [57] R. R. P. Singh and M. P. Gelfand, *Phys. Rev. B* **52**, R15695 (1995).
- [58] W. Zheng, J. Oitmaa, and C. J. Hamer, *Phys. Rev. B* **71**, 184440 (2005).
- [59] G. Chen, H.-Q. Ding, and W. A. Goddard, *Phys. Rev. B* **46**, 2933 (1992).
- [60] O. F. Syljuåsen and H. M. Rønnow, *J. Phys. Condens. Matter* **12**, L405 (2000).
- [61] A. W. Sandvik and R. R. P. Singh, *Phys. Rev. Lett.* **86**, 528 (2001).
- [62] The first order quantum correction to SWT is to multiply the calculated dispersion by  $Z_c = 1.18$  [14]. In the presence of  $J_2$ ,  $Z_c$  becomes very weakly  $\mathbf{Q}$  dependent. However, for  $J_2 \ll J_1$  it is a good approximation to use a constant  $Z_c = 1.18$ .
- [63] P. J. Brown, *International Tables for Crystallography* (Kluwer Academic Publishers, Dordrecht, 2006), Vol. C, p. 454.
- [64] *Modern Techniques for Characterizing Magnetic Materials*, edited by Y. Zhu (Springer, Boston, MA, 2005), Chap., p. 3.
- [65] N. Tsyrlin, T. Pardini, R. R. P. Singh, F. Xiao, P. Link, A. Schneidewind, A. Hiess, C. P. Landee, M. M. Turnbull, and M. Kenzelmann, *Phys. Rev. Lett.* **102**, 197201 (2009).
- [66] P. Hasenfratz and F. Niedermayer, *Phys. Lett. B* **268**, 231 (1991).
- [67] H. C. Walker, O. Mustonen, S. Vasala, D. J. Voneshen, M. D. Le, D. T. Adroja, and M. Karppinen, *Phys. Rev. B* **94**, 064411 (2016).
- [68] O. J. Burrows, G. J. Nilsen, E. Suard, M. Telling, J. R. Stewart, and M. A. de Vries, arXiv:1602.04075.