Chemical pressure effects on magnetism in the quantum spin liquid candidates

Yb$_2$X$_2$O$_7$ ($X = $ Sn, Ti, Ge)

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The linear and nonlinear ac susceptibility measurements of Yb-pyrochlores, Yb$_2$X$_2$O$_7$ ($X = $ Sn, Ti, and Ge), show transitions with a ferromagnetic nature at 0.13 and 0.25 K for Yb$_2$Sn$_2$O$_7$ and Yb$_2$Ti$_2$O$_7$, respectively, and an antiferromagnetic ordering at 0.62 K for Yb$_2$Ge$_2$O$_7$. These systematical results (i) provided information about the nature of the unconventional magnetic ground state in Yb$_2$Ti$_2$O$_7$; (ii) realized a distinct antiferromagnetic ordering state in Yb$_2$Ge$_2$O$_7$; and (iii) demonstrated that the application of chemical pressure through the series of Yb-pyrochlores can efficiently perturb the fragile quantum spin fluctuations of the Yb$^{3+}$ ions and lead to very different magnetic ground states.

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The study of natural science has been increasingly focused on quantum phenomena. And the understanding of quantum phenomena is now at the forefront of modern condensed matter research. One celebrated example is quantum spin liquids (QSLs), in which a disordered, liquidlike spin state is led by quantum spin fluctuations. While the notion of QSL is now established in one-dimensional (1D) spin systems, realizing QSLs in dimensions greater than one has been a long-sought goal. Just recently, several materials with two-dimensional (2D) geometrically frustrated lattices, such as the triangular lattice and the kagome lattice, have been identified as QSLs (see references in [1]). It is urgent and of critical importance to understand the characteristic behavior of QSLs.

Therefore, as a potential three-dimensional (3D) QSL due to the effective $S = 1/2$ nature of the Yb$^{3+}$ cations, the pyrochlore Yb$_2$Ti$_2$O$_7$ has recently received a lot of attention [2–7]. Several neutron scattering measurements [5,8,9] show no evidence of long-range magnetic ordering for Yb$_2$Ti$_2$O$_7$ but a magnetic ordered phase with an emergent spin wave excitation with applied magnetic fields above 0.5 T [10,11]. Related theoretical studies proposed it to be a Coulombic quantum spin liquid [11,12] or a model exchange quantum spin ice [13]. On the other hand, the specific-heat data [14] and the report of weak Bragg peaks [15,16] suggest that Yb$_2$Ti$_2$O$_7$ is ferromagnetically ordered around 0.24 K, which has been related to the Higgs mechanism [16]. Ross et al. pointed out that one possibility for these discrepancies could be the 1–2% chemical disorder in single-crystal samples [17], in which the high-temperature melting process tends to enhance the Yb$^{3+}$ and Ti$^{4+}$ site disorder. Their studies revealed that generally the polycrystalline samples have better chemical stoichiometry than single crystals. For example, most studied polycrystalline samples shows a sharp anomaly in the specific heat around 0.2–0.26 K, and the single crystals usually show broad features in the specific heat with sample dependence. Recently, several $\mu$SR experiments even within polycrystalline samples yielded different results [18,19]. Therefore, despite all these intensive studies, the true nature of this unconventional magnetic ground state, or this transition around 0.26 K, in Yb$_2$Ti$_2$O$_7$ is still under debate. To clarify this controversy is of great interest and will help to better understand the QSL behavior in pyrochlores.

Moreover, how various perturbations affect this fragile QSL state has not been systematically studied. However, the studies on perturbation effects, such as the chemical pressure, are important since a thorough study of the neighborhood of Yb$_2$Ti$_2$O$_7$ in composition space should help to clarify the factors that influence the ground state. Recent studies [20–22] on Yb$_2$Sn$_2$O$_7$, with a larger lattice parameter than that of Yb$_2$Ti$_2$O$_7$, showed a ferromagnetic ordering below 0.11 K but with persistent spin dynamics down to 0.05 K, indicating it is approaching a quantum phase transition near the ferromagnetic ordered critical point. The comparison between the Sn and Ti samples already shows that the lattice parameter change or the application of chemical pressure on Yb-pyrochlores can perturb the the fragile magnetic ground state. To further probe this state, we have synthesized another pyrochlore, Yb$_2$Ge$_2$O$_7$, by using a high-temperature–high-pressure (HTHP) technique [23,24]. This sample has a smaller lattice parameter than that of Yb$_2$Ti$_2$O$_7$ due to the small ionic size of Ge$^{4+}$. The series of Yb$_2$X$_2$O$_7$ ($X = $ Sn, Ti, and Ge) then provide a unique opportunity to examine how the chemical pressure consistently affects their magnetic ground states.
Here, we use the linear and nonlinear ac susceptibility measurements on the Yb$_2$X$_2$O$_7$ series to study their magnetic ground states. Until now, the nonlinear ac susceptibility component has been largely neglected for exotic magnetism studies in pyrochlores, but we show that it can efficiently provide critical information for identifying the true character of various magnetic ground states.

Polycrystalline samples of Yb$_2$Ti$_2$O$_7$ and Yb$_2$Sn$_2$O$_7$ were made by standard solid state reactions. The ac susceptibility measurement is obtained using an ac-dc current calibrator (Valhalla Scientific, model 2700) and three lock-in amplifiers (Stanford Research, SR 830). The phases of the lock-in amplifiers are set to measure each harmonics signal, which is shifted from the oscillating magnetic field according to Eq. (2). The lock-in amplifiers are also set to read the linear component (first harmonic response) and the nonlinear components (second and third harmonic responses) with respect to the oscillating ac field frequency. The rms amplitude of the ac excitation field ($h_0$) varies from 0.43 to 4.3 Oe with frequency ($f$) ranging from 40 to 1000 Hz. The applied external dc magnetic field ($H_{dc}$) varies from 0 to 1000 Oe. The data were taken while warming up the sample from the base temperature with a rate of 7.6 mK/min with the zero-field-cooling process. The linear and nonlinear ac susceptibility values have been scaled by the ac field and ac frequency. The susceptibility values, therefore, can be compared for each individual sample of Yb$_2$B$_2$O$_7$.

The notations of the linear and nonlinear ac susceptibility terms are described as follows. Principally, the magnetization $m$ is expressed as

$$m = m_0 + \chi_0 h + \chi_1 h^2 + \chi_2 h^3 + \cdots. \quad (1)$$

Then in the ac susceptibility measurements, the induced voltage $E$ of the pick-up coil is given, applying the magnetic field $h = h_0 \sin \omega t$, as

$$E = A\left\{\chi_0 h_0 \cos \omega t + \chi_1 h_0^2 \sin 2\omega t - 3/4 \chi_2 h_0^3 \cos 3\omega t - 1/2 \chi_4 h_0^4 \sin 4\omega t + \cdots\right\} \quad (2)$$

with

$$
\chi_0 = \chi_0 + 3/4 \chi_2 h_0^2 + 5/8 \chi_4 h_0^4 + \cdots, \quad (3)$$

$$\chi_1 h_0 = \chi_1 h_0 + \chi_3 h_0^3 + 15/16 \chi_5 h_0^5 + \cdots, \quad (4)$$

$$3/4 \chi_2 h_0^3 = 3/4 \chi_2 h_0^3 + 15/16 \chi_4 h_0^4 + 63/64 \chi_6 h_0^6 + \cdots. \quad (5)$$

Here, $\chi_0$, $\chi_1$, $h_0$, and $3/4 \chi_2 h_0^2$ are the first harmonic, second harmonic, and third harmonic component [25] that we have measured during the experiments. Since the used ac field $h_0$ is small, the first harmonic component is similar to the linear ac susceptibility ($\chi_0 \approx \chi_0$). In the main text, we use $\chi_0'$ to denote the linear ac susceptibility, and $\chi_1' h_0$ and $3/4 \chi_2' h_0^2$ are the second harmonic and third harmonic component, respectively.

The ac susceptibility measured for Yb$_2$Ti$_2$O$_7$ is shown in Figs. 1 and 2. The characteristic behaviors are as follows: (i) both the real and imaginary parts of the linear ac susceptibility ($\chi_0'$ and $\chi_0''$, respectively) show a peak at $T_c = 0.25$ K with frequency $f = 40$ Hz, ac field $h_0 = 1.65$ Oe, and dc field $H_{dc} = 0$ Oe.
$H_{dc} = 0$ Oe. This result is consistent with the reported data and indicates a possible magnetic ordering at $T_C$ [15]. With increasing $f$, this peak becomes broader and shifts to lower temperatures [Figs. 1(a) and 1(b)]. (ii) $\chi''_0'$ is comparable to $\chi''_0$ in order of magnitude. (iii) This transition is very sensitive to the amplitude of $h_0$. As shown in Figs. 1(c) and 1(d), for both $\chi''_0$ and $\chi''_0'$, with increasing $h_0$, the magnitude of the peak increases strongly and the peak shifts to lower temperatures. It is noteworthy that $\chi''_0'$ is independent of $h_0$ above $T_C$ but depends on $h_0$ at and below $T_C$. (iv) With increasing $H_{dc}$, the peak becomes broader and shifts to higher temperatures. With $H_{dc} = 1000$ Oe, the peak is almost smeared out, as plotted in Fig. 2(a). (v) The second harmonic component $\chi''_0 h_0$ plotted in Fig. 2(b) appears just below $T_C$ (or vanishes above $T_C$) and shows an asymmetrical peak below $T_C$. (vi) The third harmonic component $3/4 \chi''_0 h_0$ plotted in Fig. 2(c) changes its sign from negative in the region above $T_C$ to positive in the region below $T_C$, when the temperature was lowered through $T_C$. Accordingly, the peak position of $\chi''_0'$, the vanish point of $\chi''_0 h_0$, and the inflection point of $3/4 \chi''_0 h_0^2$ are consistently located at $T_C$, as shown in Fig. 2(d).

The ac susceptibility measured for Yb$_2$Sn$_2$O$_7$ is shown in Fig. 3. Its linear ac susceptibility shows a similar peak to that of Yb$_2$Ti$_2$O$_7$, but at a lower temperature $T_C = 0.13$ K with $f = 47$ Hz, $h_0 = 1.4$ Oe, and $H_{dc} = 0$ Oe. The overall behavior of this transition for Yb$_2$Sn$_2$O$_7$, shown from the linear component under different frequency [Figs. 2(a) and 2(b)], different $h_0$ [Figs. 2(c) and 2(d)], different $H_{dc}$ (Fig. 1 from Ref. [19]), and the second and third harmonic components [Figs. 2(e) and 2(f), respectively], is similar to that of Yb$_2$Ti$_2$O$_7$. One noteworthy feature is that $\chi''_0'$ for Yb$_2$Sn$_2$O$_7$ [Fig. 2(c)] starts to show the dependence of $h_0$ below 0.4 K with increasing $h_0$, which is much higher than its $T_C$. This is different from that of Yb$_2$Ti$_2$O$_7$, in which $\chi''_0'$ is independent of $h_0$ above $T_C$.

The linear ac susceptibility measurements with a fixed ac field have been intensively used to study the short-range-ordered ground states for spin ices Dy$_2$Ti$_2$O$_7$ [26,27], Ho$_2$Ti$_2$O$_7$ [28,29], spin liquid Tb$_2$Ti$_2$O$_7$ [30,31], and related R$_2$Sn$_2$O$_7$ [29,32] pyrochlores. The limited ac susceptibility data reported on Yb$_2$Ti$_2$O$_7$ show a transition around 0.24 K [15]. It is difficult to tell the exact nature of this transition from this ac susceptibility data. On the other hand, the linear susceptibility ($\chi''_0$) measured with different $h_0$ and the nonlinear susceptibility (second harmonic $\chi''_0 h_0$ and third harmonic $3/4 \chi''_0 h_0^2$ components) resulting from hysteresis and nonlinearity of magnetization can provide critical information on the nature of magnetic phase transitions. The reported linear and nonlinear ac susceptibility studies on various magnetic materials have provided consistent evidence to identify the characteristics of different magnetic ground states [25,33–39]. For spin glasses [33,34], the $\chi''_0$ shows a symmetrical cusp at the spin-glass transition temperature ($T_{SG}$), which shifts to higher temperatures with increasing frequency. For ferromagnetic (FM) ordering, (i) $\chi''_0$, $\chi''_0 h_0$, and $3/4 \chi''_0 h_0^2$ all show an asymmetrical peak at the FM transition temperature ($T_C$) [33]. It is important to note that $\chi''_0 h_0$ can be observed only if a
system exhibits a spontaneous magnetization, due to the lack of inversion symmetry with respect to the applied ac field. Therefore, for a direct paramagnetic to spin-glass transition, only odd harmonics are expected, while for ferromagnets both even and odd harmonics should be present \[25,37–39\].

(ii) \(\chi^\prime_0\) is comparable in magnitude to \(\chi^\prime\). (iii) The peak of \(\chi^\prime_0\) is sensitive to \(h_0\). Normally, the peak becomes stronger and shifts to lower temperatures with increasing \(h_0\). This is due to the contribution of domain magnetization in the FM region. This is also why \(\chi^\prime_0\) is just dependent on \(h_0\) in the FM phase below \(T_C\) but shows independence of \(h_0\) in the paramagnetic phase above \(T_C\) \[25\]. (iv) \(T_C\) shifts to higher temperatures with increasing \(H_{dc}\), which is caused by superposition of an internal field and an externally applied field. (v) \(\chi^\prime h_0\) vanishes above \(T_C\) and \(3/4\chi^2 h_0^2\) diverges with negative sign in the paramagnetic region above \(T_C\). Both phenomena have been explained in the framework of molecular field theory considering the domain magnetization \[25,35\]. For antiferromagnetic (AFM) ordering, (i) the peak of \(\chi^\prime_0\) at \(T_N\) is independent of the frequency and amplitude of \(h_0\); (ii) \(\chi^\prime_0\) is much weaker in magnitude than \(\chi^\prime_0\); (iii) there is no signal for nonlinear ac susceptibility \[37\]; and (iv) \(T_N\) shifts to lower temperatures with increasing \(H_{dc}\).

The characteristic behaviors of the ac susceptibility shown in Figs. 1–3 then clearly suggest that the transitions at 0.13 K for Yb\(_2\)Sn\(_2\)O\(_7\) and 0.25 K for Yb\(_2\)Ti\(_2\)O\(_7\) are both of a ferromagnetic nature. Several other noteworthy features are

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**FIG. 3.** (Color online) All data were taken with \(H_{dc} = 0\) Oe for Yb\(_2\)Sn\(_2\)O\(_7\). Temperature dependencies of (a) \(\chi^\prime_0\) and (b) \(\chi^\prime_0\) measured with \(h_0 = 1.4\) Oe under different frequencies. Temperature dependencies of (c) \(\chi^\prime_0\), (d) \(\chi^\prime_0\), and (e) \(\chi^\prime h_0\) measured with \(f = 200\) Hz, \(H_{dc} = 0\) Oe under different \(h_0\) and (f) \(3/4\chi^2 h_0^2\) measured with \(f = 200\) Hz, \(h_0 = 2.6\) Oe, and \(H_{dc} = 0\) Oe.
FIG. 4. (Color online) All data in (a)–(d) were taken for Yb$_2$Ge$_2$O$_7$. (a) The powder x-ray diffraction pattern of as-prepared polycrystalline samples. (b) Temperature dependency of the reciprocal susceptibility. The symbols are experimental data and the solid line is the Curie-Weiss fit. Inset: the lattice parameter dependence of the Curie constant ($\theta_{\text{CW}}$) for Yb$_2$B$_2$O$_7$. Temperature dependency of $\chi'_{0}$ measured with (c) $H_{\text{dc}} = 0$ Oe under different $f$ and $h_0$ and (d) $f = 200$ Hz, $h_0 = 2.6$ Oe under different $H_{\text{dc}}$. (e) dc magnetic field dependence of the transition temperatures for Yb$_2$B$_2$O$_7$.

as follows: (i) there is a frequency dependence for $\chi''_{0}$ for Yb$_2$Ti$_2$O$_7$ between 0.4 and 0.27 K [Fig. 1(b)]. Meanwhile, the neutron scattering experiments of Yb$_2$Ti$_2$O$_7$ [9] show that three-dimensional spin correlations develop below 0.4 K and then cross over to quasi-two-dimensional magnetic correlations below 0.26 K. Therefore, the frequency dependence of $\chi''_{0}$ observed here in the same temperature regime could be related to these three-dimensional spin correlations. (ii) There is a small shoulder above the peak at $T_C$ for the low-frequency $\chi''_{0}$ and $\chi''_{0}$ for Yb$_2$Sn$_2$O$_7$ [Figs. 3(a) and 3(b)], which may indicate a two-step process or an inhomogeneous $T_C$. (iii) With increasing $h_0$, the $\chi''_{0}$ for Yb$_2$Sn$_2$O$_7$ starts to change below 0.4 K, which is higher than 0.13 K. This feature suggests that the ferromagnetic cluster, or the short-range FM ordering, already develops above $T_C$ for Yb$_2$Sn$_2$O$_7$. This result is consistent with the recent studies on Yb$_2$Sn$_2$O$_7$ [21,22], which showed a FM ordering, but with the short-range ordering entering below 2 K and persistent spin fluctuations down to 50 mK. (iv) With increasing $f$, both for Yb$_2$Sn$_2$O$_7$ and Yb$_2$Ti$_2$O$_7$, the linear ac susceptibility peak shifts to lower temperatures [Figs. 1(a) and 3(a)]. Normally, for a FM transition, its ac susceptibility peak either shows no frequency dependence or shifts slightly to higher temperatures with increasing $f$. Future studies will be required to determine...
whether this feature is intrinsic to quantum spin fluctuations or related to the recently proposed Coulombic ferromagnet [12], which is an exotic partially FM polarized phase.

The room-temperature powder x-ray diffraction pattern [Fig. 4(a)] confirms the cubic lattice for the pyrochlore Yb$_2$Ge$_2$O$_7$ prepared by the HTHP method. The obtained lattice parameter is 9.8257(5) Å, which is consistent with the reported value [40,41] and smaller than those of Yb$_2$Ti$_2$O$_7$ (α = 10.032 Å) and Yb$_2$Sn$_2$O$_7$ (α = 10.304 Å). The dc magnetic susceptibility [Fig. 4(b)] shows no magnetic ordering down to 1.8 K. The obtained Curie constant $\theta_{CW}$ is 0.9 K is larger than those of Yb$_2$Ti$_2$O$_7$ ($\theta_{CW} = 0.75$ K) and Yb$_2$Sn$_2$O$_7$ ($\theta_{CW} = 0.62$ K). Here all three $\theta_{CW}$ values are consistently obtained by fitting the dc susceptibility below 10 K, which is measured at 10 Oe with the zero-field-cooling process. A general trend [inset of Fig. 2(b)] is that with the increasing lattice parameter for Yb-pyrochlores, the $\theta_{CW}$ value decreases.

The characteristic behaviors of the ac susceptibility for Yb$_2$Ge$_2$O$_7$ are as follows: (i) the $\chi''$ shows a peak at $T_N = 0.62$ K. This feature is evident in the amplitude and frequency of ac field [Fig. 4(c)]; (ii) $\chi''$ exhibits a much weaker peak that $\chi_0''$ (not shown here); (iii) No signal for nonlinear susceptibility. (iv) With increasing $H_{dc}$, $T_N$ for Yb$_2$Ge$_2$O$_7$ shifts to lower temperatures [Fig. 4(d)], which is distinct from that of $T_C$ for Yb$_2$Ti$_2$O$_7$ and Yb$_2$Sn$_2$O$_7$. Figure 4(e) shows a comparison among the dc field dependence of $T_N$ and $T_C$ for Yb-pyrochlores. All of these features are significantly different from those of Yb$_2$Ti$_2$O$_7$ and Yb$_2$Sn$_2$O$_7$ with FM nature. Actually, they correspond to those characteristic behaviors of an AFM ordering with $T_N = 0.62$ K.

For Yb$_2$B$_2$O$_7$, with decreasing lattice parameter, the $\theta_{CW}$ remains positive and increases. This is expected since the smaller lattice should enhance the exchange interaction and lead to larger $\theta_{CW}$. The change of dipolar interaction here could be neglected due to the $1/r^3$ nature of the forces. Then, Yb$_2$Ge$_2$O$_7$ exhibits an AFM ordering at 0.62 K but with a positive $\theta_{CW} = 0.9$ K. One possible reason for this inconsistency is that for Yb$_2$B$_2$O$_7$, the $\theta_{CW}$ is determined by the details of the anisotropic exchange interactions. The theoretical studies on Yb$_2$Ti$_2$O$_7$ [11] have proposed that the value of $\theta_{CW}$ is a linear combination of various exchange interactions, which can be either positive or negative. The calculated sum leads to a positive $\theta_{CW}$ for Yb$_2$Ti$_2$O$_7$.

Another theoretical calculation from Thompson et al. gave different values of the exchange interactions for Yb$_2$Ti$_2$O$_7$, but the Curie constant is consistently positive [7]. For Yb-pyrochlores, the exchange interactions are largely affected by the local environment of the Yb$^{3+}$ ions. The large chemical pressure imposed on Yb$_2$Ge$_2$O$_7$ may significantly tune the local structure of Yb$^{3+}$ ions from that of Yb$_2$Ti$_2$O$_7$ and Yb$_2$Sn$_2$O$_7$, although its average structure still remains cubic, so as to lead to different exchange interactions. The signs and the values of these exchange interactions may result in AFM ordering but a positive sum for the $\theta_{CW}$. Future studies on the local structure of Yb$^{3+}$ ions for Yb$_2$Ge$_2$O$_7$ are needed to better understand the nature of its AFM ordering.

In summary, our ac susceptibility measurements, especially the largely neglected nonlinear ac susceptibility, successfully provided additional information to the magnetic ground states of Yb-pyrochlores, which are a transition at 0.13 K with FM nature and a short-range-ordering feature for Yb$_2$Sn$_2$O$_7$, a transition at 0.25 K with FM nature for our studied polycrystalline Yb$_2$Ti$_2$O$_7$, and an AFM ordering at 0.62 K for Yb$_2$Ge$_2$O$_7$. Through these systematical results, we (i) suggested the unconventional magnetic ground state in Yb$_2$Ti$_2$O$_7$ of FM nature; (ii) realized an AFM ground state in Yb$_2$Ge$_2$O$_7$, which provides a new playground for exotic magnetism in pyrochlores (since so far all the experimental and theoretical studies on QSLs in pyrochlores are obtained from the FM Yb-pyrochlores, future studies on this distinct AFM state will lead to broader or different insights); (iii) demonstrated that the chemical pressure can efficiently perturb the quantum spin fluctuations in Yb-pyrochlores. These findings will guide and inform a more comprehensive understanding of the QSL physics in pyrochlores.

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