Studies of Magnetic Order in $\text{Yb}_2\text{Ti}_2\text{O}_7$
# Studies of Magnetic Order in Yb$_2$Ti$_2$O$_7$

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|                                | Geetha Balakrishnan (University of Warwick)  |
| Muon spectroscopy              | Isao Watanabe (Advanced Meson Science Laboratory, Riken)  
|                                | Adrian Hillier (ISIS)  |
| Theory                         | Shigeki Onoda (Condensed Matter Theory Laboratory, RIKEN)  
|                                | Ying-Jer Kao (NTU – Taipei)  |
| Neutron scattering             | Yixi Su (JCNS – Julich)  |
| Magnetization                  | Elsa Lhotel (Institut Néel, Grenoble)  
|                                | Sean Giblin (Cardiff)  |
Pyrochlore titanates

$\text{Ho}_2\text{Ti}_2\text{O}_7$, $\text{Dy}_2\text{Ti}_2\text{O}_7$
Spin ice - Ising

$\text{Er}_2\text{Ti}_2\text{O}_7$
Quantum XY AFM
Order by disorder

$\text{Tb}_2\text{Ti}_2\text{O}_7$
(Quantum) spin liquid

$\text{Yb}_2\text{Ti}_2\text{O}_7$
Quantum spin ice

$\text{Gd}_2\text{Ti}_2\text{O}_7$ & $\text{Gd}_2\text{Sn}_2\text{O}_7$
Heisenberg AFM

Dy$_2$Ti$_2$O$_7$
Spin ice - Ising

Yb$_2$Ti$_2$O$_7$
Quantum spin ice?

Tb$_2$Ti$_2$O$_7$
(Quantum) spin liquid?

Yb\textsubscript{2}Ti\textsubscript{2}O\textsubscript{7} - a pyrochlore with long-range FM order

Yb\textsuperscript{3+} ions with an effective spin- $\frac{1}{2}$.

Magnetic susceptibility follows Curie-Weiss law with $\theta = +0.4$ K.

Heat capacity suggests Yb\textsubscript{2}Ti\textsubscript{2}O\textsubscript{7} orders (ferromagnetically) at 0.214 K.

Entropy of 0.671$R$ recovered by 6 K.

cf. Full $R\ln2$ entropy associated for effective spin- $\frac{1}{2}$ of 0.693$R$ – simple!

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No long-range order in polycrystalline Yb$_2$Ti$_2$O$_7$

Neutron diffraction, muon spin relaxation, and $^{170}$Yb Mössbauer.

First-order transition in spin-dynamics at 0.24 K.

**BUT**

No long-range order.

Neutron scattering suggests strong quasi-two-dimensional (2D) spin correlations at low T. Correlations give way to long-range order under the application of modest (0.5 T) magnetic fields along [110].

Transition at 240 mK involves a crossover from 2D correlated state to a short-ranged 3D correlated state.

Higgs transition in single-crystal Yb$_2$Ti$_2$O$_7$

Polarized neutron scattering shows diffuse [111]-rod scattering and pinch-point features develop on cooling.

These features are suddenly suppressed below $T_C \sim 0.21$ K where magnetic Bragg peaks and a full depolarization of the neutron spins are observed.

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CONCLUSION

Magnetic charges are carried by fractionalized bosonic quasi-particles, spinons, undergo a Bose-Einstein condensation through a first-order transition via the Higgs mechanism.

Higgs transition in single-crystal Yb$_2$Ti$_2$O$_7$

Thermal hysteresis.

Magnetic intensity on Bragg peaks.

First-order ferromagnetic transition.

Long-range FM order in single-crystal Yb$_2$Ti$_2$O$_7$

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Muon spectroscopy

100% spin polarised muon implanted into the sample.

Muon-spins precesses in local magnetic environment. Muons decay with half life of 2.2 $\mu$s giving

$$\mu^+ = e^+ + \nu_e + \nu_{\mu^+}$$

Decay positrons are counted and can be used to detect small internal magnetic fields of $\sim 0.01\mu_B$.


Muon Spin Relaxation ($\mu$SR)

Zero-field, (ZF) and longitudinal-field (LF) studies carried out using the MuSR spectrometer at ISIS-RAL.

Polycrystalline and single-crystal samples of Yb$_2$Ti$_2$O$_7$ mounted on silver plates.

$^3$He-$^4$He dilution fridge $0.04 \leq T \leq 5$ K.

Stray fields cancelled to level of 1 $\mu$T.

Asymmetry:

$$A(t) = \frac{[N_F(t) - \alpha N_B(t)]}{[N_F(t) + \alpha N_B(t)]}.$$
Zero-field $\mu$SR – powder sample

$A(t)$ normalized by $A(t = 0, T = 0.6 \text{ K})$.

**Powder**

At 0.5 K, exponential decay of $A(t)$ - indicates Yb spins are fluctuating, yielding a slow relaxation of the muon spins.

At 0.25 K, [slightly below $T_c$ determined from the $C(T)$], steep drop in $A(t < 0.5 \mu\text{s})$, followed by a slow relaxation.

Initial drop indicates muon spins are depolarized more quickly in the pulse duration of 70 ns.

Strong evidence Yb moments are static or quasi-static within $\mu$SR time window (10 ps to 1 $\mu$s).

Zero-field $\mu$SR – single crystal sample

**Single crystal**

At high $T$ (4.0, 0.4, and 0.3 K) relaxation of muon spins is slightly slower than in powder.

At $T = 0.25$ K, we again observe a rapid initial drop in the asymmetry followed by a slow relaxation.

Size of the initial decrease in asymmetry is reduced from that of the powder.

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Zero-field $\mu$SR - $A(t)$

$\mu$SR time spectra can be analysed using:

$$A(t) = A_1 \exp(-\lambda_1 t) + A_2 \exp(-\lambda_2 t).$$

Zero-field μSR - $A(t)$

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$$A(t) = A_1 \exp(-\lambda_1 t) + A_2 \exp(-\lambda_2 t).$$

$A_2(t = 0)$ is nearly $T$ independent at high $T$.

Below $\sim 0.3$ K, $A_2(t = 0)$ falls to an almost constant value of $\frac{1}{4}$ and $\frac{1}{2}$ its high-$T$ value for powder and single crystal respectively.

$\Rightarrow$ volume fraction of static or quasi-static moments is $\sim 80 - 100\%$.

Relaxation rate $\lambda_2$ same at $\sim 1$ K, reaching a maximum at $\sim 0.25$ K.

$\lambda_2$ for powder enhanced by a factor of 2, compared with single-crystal.

Peak in $\lambda_2$ indicates that the time scale of magnetic fluctuations increases and crosses $\mu$SR time window, (10 ps to 1 $\mu$s), around this $T$.

$\lambda_2$ decreases monotonically with increasing longitudinal field both well below and well above $T_C$.

At 0.7 K, $A(t)$ still shows a single slow exponential time decay even in a magnetic field of 0.25 T.

Some of the magnetic excitations lie in the $\mu$SR time window in this $T$ and field range.

Below $T_C$ (~0.1 K) $A(t)$ shifts upward with increasing field, with no crossing.

Shift accompanied by recovery in asymmetry.

Initial drop in asymmetry disappears at 0.25 T - approx. order of $T_C$.

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Shift accompanied by recovery in asymmetry.

Initial drop in asymmetry disappears at $0.25$ T - approx. order of $T_C$.

Muon spectroscopy $\Rightarrow$ static or quasi-static moments.

Full entropy from heat capacity $\Rightarrow$ long-range order.

Other μSR studies

No difference in $A(t)$ data between high $T$ (1 K) and base $T$ (16 mK) for single crystal or powder.

No long-range magnetic order.

BUT

Also no change in fluctuation rate.

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Powder sample.

\( A(t) \) data very similar to our own.

Appears non-exponential at short time and low-\( T \).

**BUT Conclusions:**

No long-range magnetic order.

First-order transition in spin fluctuation rate.

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Powder and single crystal samples.

Low-$T$, SQUID magnetometers.

Crushed powder with Cu paste.

$M/H$ vs $T$ for $H//[100]$ and $[110]$; $H = 5$ Oe.

At high $T$, Curie - Weiss law.

At low $T$, abrupt rise limited by the demagnetisation factor of the samples.

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**Ferromagnetic Order**

Ordered moment (along [100]) estimated from extrapolation to $H \to 0$.

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Magnetisation - first order transition

Strong relaxation.

Equilibrium is only reached after ~600 seconds.
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Small hysteresis indicates 1st-order transition.

Increase in \(M(T)\) appears below maximum in \(C(T)\).
Magnetisation - first order transition

Zero-field cooled, field-cooled magnetisation show irreversibility.

Domains in FM ordered state.

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Domains in FM ordered state.

ZFC-FC suppressed and transition broadened and shifted to higher $T$ in fields up to 500 Oe.

Hysteresis in $M(H)$ for powder;
\[ H_c \approx 10 \text{ Oe} @ 80 \text{ mK}. \]
\[ H_c \approx 5 \text{ Oe} @ 200 \text{ mK}. \]

Results qualitatively similar in single crystal.

AC susceptibility

$\chi'(T)$ sharp peak at transition (243 mK).

Peak in $\chi'(T)$ coincides with onset of signal in $\chi''(T)$.

No frequency dependence.

Small $T$ hysteresis in $\chi'$ and $\chi''$.

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Neutron scattering, μSR, heat capacity, and magnetisation data all show OUR SAMPLES of Yb₂Ti₂O₇ undergo a first-order transition to a ferromagnetic long-range ordered state.

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Sample characterisation is key - attention must be paid to all aspects of sample preparation, especially with a number of competing effects or adjacent ground states.


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<td>Tb$<em>2$(Ti$</em>{2-x}$Tb$<em>x$)O$</em>{7-x/2}$</td>
<td>T. Taniguchi et al., Phys. Rev. B 87, 060408 (2013).</td>
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Is the peak in heat capacity of Yb$_2$Ti$_2$O$_7$ a good indication of the onset of long-range order? If not - what does this peak signify?
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Thank you for your attention