Magentic-Field Induced Quantum Phase Transition and Critical Behavior in a Gapped Spin System TlCuCl$_3$

F. Yamada$^{a,*}$, T. Ono$^a$, M. Fujisawa$^a$, H. Tanaka$^a$, T. Sakakibara$^b$

$^a$Department of Physics, Tokyo Institute of Technology, Tokyo152-8551
$^b$Institute for Solid State Physics, The University of Tokyo, Kashiwa, Chiba 277-8581

Received 12 June 2005; revised 13 June 2005; accepted 14 June 2005

Abstract

Magnetization measurements were performed on TlCuCl$_3$ with gapped ground state. The critical density and the magnetic phase diagram were obtained. The interacting constant was obtained as $U/k_B = 313$ K. The experimental phase boundary for $T < 5$ K agrees perfectly with the magnon BEC theory based on the Hartree-Fock approximation with realistic dispersion relations and $U/k_B = 320$ K. The exponent $\phi$ obtained with all the data points for $T < 5$ K is $\phi = 1.99$, which is somewhat larger than theoretical exponent $\phi_{\text{BEC}} = 3/2$. However, it was found that the exponent converges at $\phi_{\text{BEC}} = 3/2$ with decreasing fitting window.

Keywords: TlCuCl$_3$; spin gap; field-induced magnetic ordering; magnon; Bose-Einstein condensation

1. Introduction

TlCuCl$_3$ is an $S = 1/2$ interacting dimer system, which has an excitation gap $\Delta = 7.5$ K [1]. In an external magnetic field, the gap closes and the system undergoes magnetic phase transition for $H > 5.4$ T. This phase transition is a magnetic quantum phase transition and is described as the Bose-Einstein condensation (BEC) of spin triplets called magnons or triplons [2]. The BEC theory based on the Hartree-Fock (HF) approximation with a parabolic isotropic dispersion relation $\hbar^2 k^2 / 2m$ gives the phase boundary described by the power law $(g/2)[H_N(T) - H_c] \propto T^\phi$ with exponent $\phi_{\text{BEC}} = 3/2$ [2], where $H_c = \Delta / g\mu_B$ is the gap field. A point given by $T = 0$ and $H = H_c$ on the temperature vs field diagram denotes the quantum critical point. In the previous study [3,4], it was shown that the experimental phase boundary is expressed by the power law with exponent $\phi = 2.0 \sim 2.2$. This exponent is somewhat larger than $\phi_{\text{BEC}} = 3/2$. Recently, the deviation of the exponent $\phi$ toward larger value from $\phi_{\text{BEC}} = 3/2$ was theoretically discussed [5,6,7]. Misguich and Oshikawa [7] extended the HF calculation by Nikuni et al. [2] by using a realistic dispersion relation and achieved remarkable quantitative agreement with the experimental phase diagram. They also calculated the critical density of triplons $n_{\text{cr}}(T)$ and estimated the interacting constant $U/k_B = 340$K. We carried out magnetization measurements on TlCuCl$_3$ to reevaluate $n_{\text{cr}}(T)$, $U$ and critical exponent $\phi$.

2. Experimental details

Single crystals of TlCuCl$_3$ were grown by the vertical Bridgman method. The details of preparation were reported in reference[3]. The magnetization measurements were performed using SQUID magnetometer (Quantum Design MPMS XL) in the temperature region $1.8K \leq T \leq 100K$ in magnetic fields of up to 7 T. The magnetic fields were applied parallel to the $b$-axis and [2, 0, 1] direction and perpendicular to the $(1, 0, \bar{2})$ plane. The magnetization measurements were also performed using Faraday Force Magnetometer [8] at Institute of Solid State Physics in the temperature region $30mK \leq T \leq 4 K$ in magnetic fields up to 8 T. The magnetic fields were applied perpendicular to the $(1, 0, \bar{2})$ plane.

3. Results and discussion

The critical density $n_{\text{cr}}$ of triprons corresponds to the absolute values of the magnetization at $T_N$ or $H_N$. Figure 1 shows the critical density $n_{\text{cr}}$ as a function of temperature.
2) coincide when the constant $H$ for the relation $(H/T)^{2}$ agrees well in the low temperature region for $T < 320$ K [7]. Both results agree perfectly for $T < 5$ K.

We analyze the phase boundary for the magnetic field perpendicular to the $(1, 0, \frac{1}{2})$ plane using the power law. In the present analysis, we set the lowest temperature at $T_{\text{min}} = 30$ mK and varying temperature range for fitting. Using all the data points, we obtained $\phi = 1.99$, which is somewhat larger than $\phi_{\text{BEC}} = 3/2$ derived by the triplon BEC theory based on the HF approximation [2] as obtained in the previous measurements $\phi = 2.0 \sim 2.2$ [3,4]. However, the critical exponent $\phi$ decreases with decreasing fitting window, and converges to $\phi_{\text{BEC}} = 3/2$, as predicted by Nohadani et al. [6]. For $T \leq 1.80$ K, we obtain $\phi = 1.52 \pm 0.06$, which is nearly equal to $\phi_{\text{BEC}} = 3/2$ derived from the triplon BEC theory [2].

4. Conclusion

We have presented the critical density of triplons and the magnetic phase diagram of TICuCl$_3$. The interacting constant was estimated as $U/k_B = 313$K. The phase boundary is expressed by the power law and agrees perfectly with the triplon BEC theory based on the HF approximation with realistic dispersion relations and $U/k_B = 320$ K [7]. The critical exponent $\phi$ decreases with decreasing fitting range. We obtained $\phi = 1.52 \pm 0.06$ for $T \leq 1.80$ K, which is nearly equal to $\phi_{\text{BEC}} = 3/2$ derived from the triplon BEC theory [2]. These results strongly support the BEC description of field-induced magnetic ordering in TICuCl$_3$.

5. Acknowledgements

This work was supported by The 21st Century COE Program at Tokyo Tech. "Nanometer-Scale Quantum Physics" both from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

[1] W. Shiramura, K. Takatsu, H. Tanaka, M. Takahashi, K. Kamishima, H. Mitamura and T. Goto J. Phys. Soc. Jpn. 66 (1997) p.1900
[2] T. Nikuni, M. Oshikawa, A. Oosawa, and H. Tanaka Phys. Rev. Lett. 84 (2000), p. 5868.
[3] A. Oosawa, M. Ishii and H. Tanaka J. Phys. : Condens. Matter 11 (1999) p.265
[4] A. Oosawa, H. Aruga Katori and H. Tanaka Phys. Rev. B 63 (2001) 134416
[5] N. Kawashima, J. Phys. Soc. Jpn. 79 (2004), p. 3219.
[6] O. Nohadani, S. Wessel, B. Normand, and S. Hass Phys. Rev. B 69 (2004), 220402(R).
[7] G. Misguich and M. Oshikawa J. Phys. Soc. Jpn. 73 (2004), p. 3429.
[8] T. Sakakibara, H. Mitamura, T. Tayama and H. Amitsuka Jpn. J. Appl. Phys. 33 (1994) p.5067