Single crystal growth and heat capacity measurements of triangular lattice $R_2Pt_6Ga_{15}$
(R=rare earth)

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Abstract. We have succeeded in synthesizing the single crystal of $R_2Pt_6Ga_{15}$ (R=La-Nd, Sm-Lu) with hexagonal Sc$_{0.67}$Fe$_2$Si$_5$-type structure using Ga self flux method. The crystal structure was confirmed by the powder X-ray method. The unit-cell volume $V$ of $R_2Pt_6Ga_{15}$ follows the lanthanide concentration except R = Ce, Eu and Yb, indicating that the valences of R = La, Pr, Nd, Sm, Gd-Tm, and Lu ion are trivalent, whereas those of R = Ce, Eu and Yb ion are deviate from trivalent. We have measured the specific heat $C(T)$ of $R_2Pt_6Ga_{15}$. It is found that the magnetic order takes place in $R_2Pt_6Ga_{15}$ (R=Pr, Nd, Sm-Tm). Moreover, the multiple phase transitions were observed in $R_2Pt_6Ga_{15}$ (R = Nd, Eu, Gd and Ho).

1. Introduction
In highly correlated f electron system, many anomalous physical properties have been discovered around the quantum critical point. Among the Yb member compounds, YbRh$_2$Si$_2$ [1], β-YbAlB$_4$ [2] and quasi-crystal Au$_{51}$Al$_{34}$Yb$_{15}$ [3] exhibit anomalous quantum critical behaviors which cannot be explained by the conventional Hertz-Millis-Moriya (HMM) theory [4, 5, 6]. In YbRh$_2$Si$_2$, the magnitude of magnetic frustration effect can be important role to take place these critical behaviors. In rare earth compound, the magnetic ground state is explained by the competition between the Kondo effect and the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction, so-called Doniach phase diagram [7]. The magnetic frustration effect can also suppress to the magnetic order such like the Kondo effect. The quantum critical behavior due to the magnetic frustration effect in Ce$_2$Pt$_2$Pb [8] with Shastry - Sutherland lattice and YbAgGe [9] with distorted kagome lattice have been observed. To search for the compound with the magnetic frustration is possible to discover the novel quantum phenomena.

The $R_2Pt_6X_{15}$ (R=rare earth, X = Al, Ga) system with hexagonal Sc$_{0.67}$Fe$_2$Si$_5$-type structure (space group P6$_3$/mmc) would be one of the suitable candidate to research the magnetic frustrate system. The R ions coordinate the triangular lattice layer and the nearest R-R distance is about 4.3 Å [10]. While, the distance between triangular-lattice layers is about 8.7 Å along c-axis, which is more than twice as long as the in-plane R ion distance, namely the magnetic R-ions in $R_2Pt_6Ga_{15}$ form a two-dimensional triangular-lattice. In $R_2Pt_6X_{15}$, $R_2Pt_6Al_{15}$ (R=Ce, Gd-Lu) [10, 11, 12, 13, 14, 15] and $R_2Pt_6Ga_{15}$ (R=La, Ce, Pr) [16, 17, 18] have ever been reported. The lattice parameters of $a$ and $c$ of Ce$_2$Pt$_6Ga_{15}$ are 4.326 and 16.522

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Å, respectively, whereas those of Yb$_2$Pt$_6$Al$_{15}$ are 4.266 and 16.361 Å, respectively. It is possible to synthesize R$_2$Pt$_6$X$_{15}$ (R = heavy rare earth). Therefore, we have searched for new R$_2$Pt$_6$Ga$_{15}$ compound and measured the specific heat of R$_2$Pt$_6$Ga$_{15}$.

| R$_2$Pt$_6$Ga$_{15}$ | La | Ce | Pr | Nd | Sm | Eu | Gd |
|---------------------|----|----|----|----|----|----|----|
| Figure 1. The photographs of single crystal R$_2$Pt$_6$Ga$_{15}$. |
| Tb | Dy | Ho | Er | Tm | Yb | Lu |

| R$_2$Pt$_6$Ga$_{15}$ | a (Å) | c (Å) | V (Å$^3$) |
|---------------------|-------|-------|-----------|
| Figure 2. The lattice constants a, c, and unit-cell volume V of hexagonal R$_2$Pt$_6$Ga$_{15}$. |

2. Experimental
The single crystals of R$_2$Pt$_6$Ga$_{15}$ (R=La-Nd, Sm-Lu) were grown in Ga-flux method. Rare earth, Pt and Ga materials were placed in an alumina crucible and sealed in an evacuated quartz tube.
The sealed tubes were heated to 1100 °C, soaked for 5 hours, then cooled down to 300 °C in 160 hours. The excess Ga was spun off in a centrifuge, and then washed out in distilled water. Figure 1 shows the photograph of obtained single crystal R$_2$Pt$_6$Ga$_{15}$. Typical sample size is from 2 to 5 mm.

The single phase of the hexagonal R$_2$Pt$_6$Ga$_{15}$ (R=La-Nd, Sm-Lu) structure was confirmed by the powder X-ray diffraction method. We obtained the lattice parameters of R$_2$Pt$_6$Ga$_{15}$ by Rietveld analysis. Figure 2 displays the lattice constants $a$, $c$, and unit-cell volume $V$ of R$_2$Pt$_6$Ga$_{15}$. $V$ monotonously shrinks from R= La to Lu except R = Ce, Eu and Yb, indicating that the R$_2$Pt$_6$Ga$_{15}$ system follows the well-known lanthanide concentration except R = Ce, Eu and Yb. The results indicate that the valences of R = La, Pr, Nd, Sm, Gd-Tm and Lu ion are likely to be trivalent, while those of R = Eu and Yb ion are close to divalent.

The specific heat $C(T)$ measurement from 300 to 2 K was carried out by the relaxation method using a commercial physical property measurement system (PPMS; Quantum Design).

3. Results and discussion

We have measured the $C(T)$ of R$_2$Pt$_6$Ga$_{15}$. Figure 3 shows the temperature dependence of $C(T)$ of R$_2$Pt$_6$Ga$_{15}$ (R=La-Nd, Sm-Lu) below 25 K. The $C(T)$ of La$_2$Pt$_6$Ga$_{15}$ and Ce$_2$Pt$_6$Ga$_{15}$ were taken from Yamashita et al [18]. There is no phase transition below 2 K for R$_2$Pt$_6$Ga$_{15}$ (R = La, Ce, Yb and Lu). The $C(T)$ of R$_2$Pt$_6$Ga$_{15}$ (R = La, Yb and Lu) follow $C(T) = \gamma T + \beta T^3$ expression in low temperature. The $\gamma$ of Yb$_2$Pt$_6$Ga$_{15}$ and Lu$_2$Pt$_6$Ga$_{15}$ are 25 and 19 mJ/mol K$^2$, respectively.
respectively, and those of $\beta$ are 2.17 and 1.87 mJ/mol K$^4$, respectively. The valence of Yb ion is near divalent. The result is consistent to the deviation from the lanthanide concentration for Yb$_2$Pt$_6$Ga$_{15}$. Unfortunately, Yb$_2$Pt$_6$Ga$_{15}$ does not exhibit quantum critical behavior, although we searched for the novel phenomena around quantum critical point in Yb$_2$Pt$_6$Ga$_{15}$.

It is found that there are anomalies of $C(T)$ due to the magnetic order in R$_2$Pt$_6$Ga$_{15}$ (R=Pr, Nd, Sm-Tm). Moreover, the multiple phase transitions were observed in R$_2$Pt$_6$Ga$_{15}$ (R = Nd, Eu, Gd and Ho). There is an anomaly in the magnetic susceptibility around the phase transition [19], indicating that the phase transitions are magnetic order. The magnetic order temperature $T_M$ corresponding to the middle point between the peak and the onset roughly follows the de Gennes scaling and $T_M$ in R$_2$Pt$_6$Ga$_{15}$ with R = light rare earth deviate from the de Gennes scaling, as shown in Fig. 4, where $g_J$ is the Lande g-factor and $J$ is the total angular momentum and we assumed that the valence of Eu ion is divalent. This result and the order of $T_M$ are similar to that of RCu$_2$Si$_2$ and RRhIn$_5$ with no geometrical frustration [20, 21]. The suppression of $T_M$ due to the magnetic frustration effect in R$_2$Pt$_6$Ga$_{15}$ (R=Pr, Nd, Sm-Tm) would be negligible small. However, whether the magnetic frustration effect is strong or not is dependent to the magnetic structure of R$_2$Pt$_6$Ga$_{15}$. If the magnetic structure of R$_2$Pt$_6$Ga$_{15}$ is XY-type, the magnetic frustration effect would be observed and the complex magnetic structure is possible. We are measuring the magnetic properties and intend to measure neutron diffraction of R$_2$Pt$_6$Ga$_{15}$.

![Figure 4](image-url)

**Figure 4.** The magnetic order temperature $T_M$ versus de-Gennes factor of R$_2$Pt$_6$Ga$_{15}$.

**Acknowledgments**

We thank Mr. Taki and Mr. Minamiguchi for technical support. This work was supported by a Grant-in-Aid for Scientific Research Young Scientists B (No 24740248) Grant-in-Aid for Scientific Research C (No 26400333) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society of the Promotion of Science (JSPS).

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