Physical properties and crystal chemistry of Ce₂Ga₁₂Pt

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Abstract

Single crystals of the new ternary compound Ce₂Ga₁₂Pt were prepared by the self-flux technique. The crystal structure with the space group P4/nbm was established from single crystal x-ray diffraction data and presents a derivative of the LaGa₆Ni₀.₆ prototype. Magnetic susceptibility measurements show Curie–Weiss behaviour due to local Ce³⁺ moments. At high temperatures, the magnetic anisotropy is dominated by the crystal-electric-field (CEF) effect with the easy axis along the crystallographic c direction. Ce₂Ga₁₂Pt undergoes two antiferromagnetic phase transitions at \( T_{N,1} = 7.3 \) K and \( T_{N,2} = 5.5 \) K and presents several metamagnetic transitions for the magnetic field along c. Specific-heat measurements prove the bulk nature of these magnetic transitions and reveal a doublet CEF ground state. The 4f contribution to the resistivity shows a broad maximum at \( T_{\text{max}} \approx 85 \) K due to Kondo scattering off the CEF ground state and excited levels.

(Some figures may appear in colour only in the online journal)

1. Introduction

The investigation of new cerium-based intermetallic compounds is a fascinating research area owing to the large variety in their physical ground states. Phenomena like valence fluctuations, heavy fermion behaviour, unconventional superconductivity and localized magnetism are frequently observed [1]. Recently, systems with reduced dimensionality or frustration have been attracting strong interest because these features lead to an enhancement of quantum fluctuations which often results in unusual, very interesting properties. In particular, an increase of the superconducting transition temperature when going from three-dimensional to more two-dimensional compounds was predicted [2] and indeed observed among different classes of unconventional superconductors with magnetic fluctuations, e.g., CeCoIn₅ [3] and the iron arsenides [4].

Ternary cerium compounds with gallium and 4d transition metals have so far only scarcely been investigated [5]. More detailed studies on the crystal structures and physical properties have been performed on compounds containing Ni, Co, Fe and Mn [6]. With Ni the existence of gallium-rich CeGa₆Ni₀.₆ [7], Ce₂Ga₁₀Ni [8], Ce₂Ga₁₇Ni₁₂ [9] and Ce₂Ga₁₅Ni₁₂ [10] has been shown, with different stacking patterns of atomic slabs along one crystallographic direction.

Only a few physical characterization studies on ternary gallides have been reported: CeGa₆Pd presents a broad antiferromagnetic (AFM) phase transition at \( T_N = 5.5 \) K with an enhanced Sommerfeld coefficient of the electronic specific heat [5]. It exhibits magnetic anisotropy and a pronounced metamagnetic transition when the field is applied along the c direction. The related compound Ce₂Ga₁₇Pd orders antiferromagnetically at \( T_N = 11 \) K and presents a similar metamagnetic transition. Further members of this compound family RE₂Ga₁₂TM with RE = La, Ce and TM = Ni, Cu have also been investigated [11, 12].

Here, we report on the physical and structural properties of a new, related compound Ce₂Ga₁₂Pt showing disorder in the gallium substructure. Detailed magnetic, transport and thermodynamic measurements on single crystals reveal local Ce³⁺ moments which undergo two successive AFM transitions at \( T_{N,1} = 7.3 \) K and \( T_{N,2} = 5.5 \) K.


Table 1. Data collection and structure refinement parameters for Ce$_2$Ga$_{12}$Pt.

| Parameter                          | Value               |
|-----------------------------------|---------------------|
| Space group                       | P4/nbm              |
| Z                                 | 2                   |
| $a$ (Å)$^a$                       | 6.1004(2)           |
| $c$ (Å)$^a$                       | 15.5961(7)          |
| Unit cell volume (Å$^3$)          | 580.41(1)           |
| Calculated density (g cm$^{-3}$)  | 7.420(1)            |
| Absorption coefficient (1 cm$^{-1}$) | 485.90              |
| Radiation and wavelength (Å)     | Mo Kα 0.710 73      |
| Diffractometer                    | Rigaku AFC7         |
| $2\theta_{\text{max}}$           | 64.73               |
| $N(hkl)$ measured                 | 5158                |
| $N(hkl)$ symmetrically independent| 566 (R$_{\text{int}}$ = 0.031) |
| $N(hkl)$ used for refinement ($I > 2\sigma(I)$) | 511                  |
| Mode refinement                   | $F(hkl)$            |
| Restrictions                      | $F(hkl) > 4\sigma(F)$ |
| Refined parameters                | 26                  |
| $R(F)$                            | 0.024               |

$^a$ The lattice parameters were obtained from x-ray powder diffraction data.

2. Experimental details

2.1. Single crystal growth

Single crystals of Ce$_2$Ga$_{12}$Pt were obtained by using a flux growth method. Ce ingots (Ames, 99%), Pt foil (Chempur, 99.95%) and Ga pieces (Chempur, 99.999%) were used in a 1:1.05:20 ratio. For preparation, the reaction mixture was put inside an Al$_2$O$_3$ crucible and sealed in a Ta tube with a sieve. The tube was enclosed in a quartz ampoule and kept at 1100 °C for 2 h. Subsequently, the melt was cooled down to 450 °C at a rate of 5 K h$^{-1}$; at this point the ampoule was immediately inverted and centrifuged. The plate-like single crystals were mechanically extracted from the sieve.

2.2. X-ray diffraction

Single crystal x-ray diffraction data were collected on a Rigaku AFC7 diffraction system (Mo Kα radiation, $\lambda = 0.71073$ Å). X-ray powder diffraction patterns of the powdered single crystals were performed on a Huber Imaging Plate Guinier Camera G670 using Cu Kα1 radiation ($\lambda = 1.54060$ Å). The unit cell parameters were refined by a least squares procedure using the peak positions extracted from powder patterns measured with LaB$_6$ as internal standard ($a = 4.15692$ Å). Indexing of the diffraction peaks in the powder diagrams was controlled by intensity calculations using the positional parameters of the refined crystal structures. All crystallographic calculations were performed with the program package WinCSD [13].

2.3. Physical property measurements

Magnetic measurements were performed in a commercial Quantum Design (QD) magnetic property measurement system (MPMS) with a 5 T magnet as well as in a QD VSM SQUID equipped with a 7 T magnet. The resistivity, $\rho(T)$, was determined down to 1.8 K using a standard ac four-probe geometry in a QD physical property measurement system (PPMS). The PPMS was also used to measure the specific heat, $C(T)$, with a heat-pulse relaxation technique.

3. Results and discussion

3.1. Crystal structure

Taking into account the lattice parameters (table 1) and the observed extinctions in the diffraction intensities ($hk0$ observed only with $h + k = 2n$, $0kl$ observed only with $k = 2n$) the centrosymmetric tetragonal space group P4/nbm was assumed, being in agreement with the crystal structure of the Sm$_2$Ga$_{12}$Ni type [14] also found for the palladium analogous compound Ce$_2$Ga$_{12}$Pd [5]. Refined of the crystal structure resulted in a low residual of $R(F) = 0.028$. Analysis of the displacement parameters at this stage revealed that the $B_{\text{eq}}$ value for the Ga4 position is twice as large as that for other Ga-occupied sites. Moreover, this position revealed a strong anisotropy of displacement ($B_{11} = B_{22} \gg B_{33}$). To clarify this issue, the difference density map at $z = 0.428$ was calculated without taking into account the Ga4 position (figure 1, 2).
Figure 2. Left: ordered models of the crystal structure of Ce$_2$Ga$_{12}$Pt based on the Ga4 (Sm$_2$Ga$_{12}$Ni type, top), Ga6 (Sm$_2$Ga$_{12}$Ni type, middle) and Ga5, Ga6, Ga7 positions (bottom). Right: hypothetical structure REGa$_6$ with cubic cavities in the Ga framework (top), atomic arrangement in the hexagallides of RE metals with the PuGa$_6$-type crystal structure (middle) and filled cubic voids in the crystal structure of La$_2$Ga$_{12}$Ni$_{12}$ (bottom).

Table 2. Atomic coordinates and displacement parameters for Ce$_2$Ga$_{12}$Pt.

| At. Wy. site | Occ. | x/a | y/b | z/c | $B_{eq}^a$ | $B_{11} = B_{22}$ | $B_{13}$ | $B_{12}$ | $B_{13} = -B_{23}$ |
|-------------|------|-----|-----|-----|-----------|-----------------|---------|---------|----------------|
| Ce 4h       | 1    | 3/4 | 1/4 | 0.24593(4) | 0.73(1) | 0.64(2) | 0.92(2) | -0.00(2) | 0         |
| Pt 2c       | 1    | 3/4 | 1/4 | 0    | 0.69(1) | 0.61(2) | 0.83(2) | 0         | 0         |
| Ga1 8m      | 1    | 0.5003(2) | -x | 0.08808(5) | 0.80(1) | 0.82(2) | 0.76(3) | 0.16(2) | 0.02(2) |
| Ga2 4g      | 1    | 1/4 | 1/4 | 0.18437(8) | 0.70(2) | 0.68(3) | 0.72(4) | 0         | 0         |
| Ga3 4g      | 1    | 1/4 | 1/4 | 0.34179(8) | 1.12(2) | 1.23(3) | 0.90(4) | 0         | 0         |
| Ga4 8m      | 0.56(1) | 0.5863(2) | x - 1/2 | 0.4299(2) | 0.96(6) | 0.8(1) | 1.32(9) | -0.4(1) | 0.2(1) |
| Ga5 8m      | 0.39(1) | 0.5451(3) | x - 1/2 | 0.4270(2) | 0.75(8) | 0.7(1) | 0.9(1) | -0.5(1) | 0.3(1) |
| Ga6 8m      | 0.025(3) | 0.952(5) | -x | 0.423(2) | 0.7(6)   |       |        |        |        |
| Ga7 2c      | 0.034(6) | 3/4 | 1/4 | 1/2 | 0.8(8)   |       |        |        |        |

$B_{eq} = 4/3[B_{11} (a^*)^2 a^2 + \cdots + 2 B_{23} (b^*) (c^*) bc \cos \alpha]$.  

bottom). Beside the non-spherical distribution around the Ga4 position, the map revealed additional maxima of density located symmetrically to the Ga4 position with respect to the diagonal mirror plane. Further calculation of the difference density revealed a next maximum at 1/4 1/4 1/2. In total, to describe the electron density in the region 0.4 < z < 0.6, four sites with different occupancies are necessary (figure 1, top; table 2) resulting in a reduction of the residual to $R(F) = 0.024$. Thereby, the atomic displacement parameters for all Ga positions are of the same order (table 2); only Ga3 shows slightly enlarged values. The latter feature can be understood by considering ordering models of the crystal structure of Ce$_2$Ga$_{12}$Pt. While the occupation of the Ga4, Ga5 and Ga6 positions by Ga is rather certain due to their places within the Ga network, the position Ga7 may also be occupied with platinum because of its rather cubic environment. Nevertheless the distances to the next neighbours of 2.79 Å are more in agreement with the Ga1–Ga2 distances (which are not affected by crystallographic disorder), being in the range 2.63–2.75 Å in this structure compared with the observed Pt–Ga distance of 2.56 Å. Thus, we assume the occupation of the Ga7 position by gallium. Finally, the total content of the unit cell Ce$_4$Ga$_{23.9(2)}$Pt$_2$ is well in agreement (within one e.s.d.) with the ideal composition Ce$_2$Ga$_{12}$Pt.

The observed partially occupied Ga site can be described using three different ordered models (figure 2, left). In models
I and II the position at 1/4 1/4 1/2 is empty. They both represent a structural motif of the Sm$_2$Ga$_{12}$Ni type, and are enantiomorphs considering the Ga4 and Ga6 sites, which are symmetrical with respect to the mirror plane running through the base diagonal parallel to [001]. Model III is necessary to understand the position Ga7 at 1/4 1/4 1/2. In this case the sites Ga5, Ga6 and Ga7 have to be used. Because of the low occupation of the Ga7 site, the positions of the neighbouring sites are difficult to establish among the overlapping maxima of the difference electron density, thus the probability of this atomic arrangement in Ce$_2$Ga$_{12}$Pt is much lower than those of both previous models. The enlarged displacement parameters for the Ga3 position are caused by the non-equivalent locations of Ga3 in the ordered models of Ce$_2$Ga$_{12}$Pt.

The genesis of the crystal structure of Ce$_2$Ga$_{12}$Pt and the observed crystallographic disorder may by understood starting with a hypothetical atomic arrangement with the composition RE$_2$Ga$_{12}$ containing segments of the BaAl$_4$-type structure (composition RE$_2$Ga$_4$, RE rare earth metal) separated by slabs of empty cubes formed by Ga atoms only (composition Ga$_4$). The total composition adds up to RE$_2$Ga$_{12}$. The Ga network in such an arrangement bears two types of cavity: the large one has 18 vertices and is occupied by the RE atoms and the small one has the shape of a slightly distorted cube and is empty (figure 2, top right). The empty cube formed by gallium atoms seems to be unstable, and in the real structure of the REGa$_4$ compounds (PuGa$_6$ type [15–17]) it is screwed towards a tetragonal antiprism (figure 2, middle right). This kind of local atomic arrangement of Ga is indeed observed in Ce$_2$Ga$_{12}$Pt and other representatives of the Sm$_2$Ga$_{12}$Ni type around $z = 0.5$. Another way to stabilize the cubic voids is to fill them up with an appropriate species. In this case, the local arrangement will be in agreement with the CsCl type of structure which is characteristic for the equiatomic compounds of transition metals (TM) with gallium and aluminum. Thus transition metals should also be suitable for fixing of the cubic environment also in multi-component structures. For the RE$_2$Ga$_{12}$TM$_x$ compounds it was first found as a substructure of La$_2$Ga$_{12}$Ni$_{1.2}$ (around $z = 0.0$ and 0.5, figure 2, bottom right) [7] and further for the representatives of Sm$_2$Ga$_{12}$Ni type (around $z = 0.0$) [5, 12].

The disorder in the region $0.4 < z < 0.6$ seems to be characteristic for the representatives of Sm$_2$Ga$_{12}$Ni type. The published values of the displacement parameters [5, 12] are very similar to those for Ce$_2$Ga$_{12}$Pt without accounting for the disorder.

3.2. Physical properties

We now turn to the physical characterization of a Ce$_2$Ga$_{12}$Pt single crystal. The inverse susceptibility shown in the inset of figure 3, with the magnetic field along and perpendicular to the $c$ direction, presents Curie–Weiss behaviour due to 4f-derived magnetic moments. A Curie–Weiss fit above 200 K yields an effective moment of $\mu_{eff} = 2.46 \mu_B$ for the magnetic field along $c$ and $\mu_{eff} = 2.41 \mu_B$ for the magnetic field perpendicular to $c$, close to that of the free Ce$^{3+}$ moment (2.54 $\mu_B$). The anisotropy at high temperatures is reflected in different Weiss temperatures, $\Theta_{Wc} = -20$ K and $\Theta_{Wb} = -50$ K, for the field parallel and perpendicular to $c$, respectively. These observations can be understood in terms of the crystal-electric-field (CEF) effect, which leads to a pronounced single-ion anisotropy with Ising-type behaviour, i.e., the magnetic easy direction is the $c$ axis of the tetragonal unit cell. However, on the basis of the present results, a complete determination of the CEF parameters cannot be given. This would need further experimental input.

In the main part of figure 3, we present the temperature dependence of the dc susceptibility, $\chi(T)$, at various magnetic fields. At $B = 1$ T (black curve), Ce$_2$Ga$_{12}$Pt undergoes two AFM transitions at $T_{N1} = 7.3$ K and $T_{N2} = 5.5$ K (see the arrows in figure 3). The AFM nature of these magnetic transitions is evident from the susceptibility, because in the paramagnetic phase $\chi(T)$ is nearly field independent and drops below $T_{N1}$. At $B = 1.8$ T (red curve), $T_{N2}$ is shifted to below 2 K, whereas $T_{N1}$ is only shifted slightly. For magnetic fields $B \geq 3.5$ T, no transition could be resolved above 2 K. The second transition at $T_{N2}$ is most likely due to spin reorientation, presumably also causing a change of the ordering vector, which is commonly observed in magnetic rare earth compounds.

The magnetic anisotropy of Ce$_2$Ga$_{12}$Pt is further apparent in the magnetization data at $T = 2$ K, presented in figure 4 and measured for magnetic fields along the $c$ direction (red symbols) and in the basal plane (black symbols), respectively. Below $B = 1$ T, the two curves nearly coincide, reflecting a rather isotropic AFM state. However, for $B \parallel c$ three metamagnetic transitions could be resolved at 1.4, 2.1 and 2.8 T, respectively. By contrast, for $B \perp c$ the magnetization increases almost linearly without any metamagnetic transition up to 5 T. The magnetic anisotropy at 5 T, $M_c/M_{ab} = 4.6$, is therefore much larger than at small fields. Presently, the precise origin of these metamagnetic transitions cannot be resolved and more microscopic probes such as, e.g., neutron
Diffraction, are necessary to unravel the change of the magnetic structure. The comparison with magnetization data in the literature on related compounds suggests that metamagnetic transitions along the c direction are rather common in this type of compound, as they have also been observed in Ce2Ga12Pd [5] and in Ce2Ga12Ni [11, 12]. Whereas in Ce2Ga12Pt the saturated moment along the c direction ($M_{S\perp c} = 1.15 \mu_B$/Ce) is comparable to that for Ce2Ga12Ni ($M_{S\perp c} = 1.2 \mu_B$/Ce), it is much smaller than that in Ce2Ga12Pd ($M_{S\perp c} = 1.75 \mu_B$/Ce).

The electrical resistivity measured within the basal plane plotted in the main panel of figure 5 shows a temperature dependence typical for intermetallic Ce compounds. Three different temperature regions can be identified: (i) above 150 K, the resistivity of the single crystal depends nearly linearly on temperature due to phonons as discussed below; (ii) below 150 K, there is a deviation from the linear behaviour, probably due to reduced spin-disorder scattering at the CEF levels which get depopulated upon cooling; (iii) the first AFM transition is clearly resolved as a distinct anomaly at $T_{N,1}$. However, at $T_{N,2}$ no further anomaly was observed (see the upper left inset of figure 5). The overall decrease results in a resistivity ratio, $\rho_{300 K}/\rho_0 = 14$, reflecting the good sample quality of our single crystal, much better than that of recently reported Ce2Ga12Ni single crystals, where $\rho_{300 K}/\rho_0 = 2.3$ [12]. However, the residual resistivity, $\rho_0 = 7.7 \mu\Omega$ cm, is still enhanced compared to other intermetallics, probably due to the structural disorder discussed above.

To analyse the 4f contribution to the resistivity in Ce2Ga12Pt we have synthesized a related nonmagnetic reference compound, La2Ga12Rh, because the synthesis of La2Ga12Pt was not successful. The structural details of La2Ga12Rh will be discussed in a forthcoming publication. The susceptibility of La2Ga12Rh presents weak Pauli paramagnetism without any magnetic or superconducting transition down to 2 K (not shown). In figure 5 we also present the resistivity of La2Ga12Rh with the absolute values plotted on the right hand scale. The temperature dependence is linear above 50 K, reflecting the phonon scattering of a nonmagnetic metal. The sample quality is not as good as for Ce2Ga12Pt, resulting in higher absolute values of the residual resistivity, $\rho_0 = 138 \mu\Omega$ cm, and a correspondingly low resistivity ratio, $\rho_{300 K}/\rho_0 = 2.54$. We now assume that the temperature dependence of the resistivity in Ce2Ga12Pt can be described as the sum of the residual resistivity, $\rho_0$, the phonon contribution, $\rho_{ph}(T)$, and the magnetic contribution, $\rho_{m}(T)$, i.e. $\rho(T) = \rho_0 + \rho_{ph}(T) + \rho_{m}(T)$. Accordingly, the resistivity of La2Ga12Rh is the sum of the residual resistivity and the phonon contribution only, $\rho_{ph}(T) = \rho_{ph}^0 + \rho_{ph}(T)$. In first approximation, $\rho_{ph}$ of Ce2Ga12Pt and La2Ga12Rh should be equal, as the Debye temperatures of Ce2Ga12Pt and La2Ga12Pd are rather similar (see below). Therefore, we get $\rho_{ph}(T) = \rho_{ph}^0 + \rho_{ph}(T)$ with $\rho_{ph} = \rho_{ph}^0 + \rho_{ph}(T)$. Accordingly, the resistivity of La2Ga12Rh is the sum of the residual resistivity and the phonon contribution only, $\rho_{ph}(T) = \rho_{ph}^0 + \rho_{ph}(T)$. In first approximation, $\rho_{ph}$ of Ce2Ga12Pt and La2Ga12Rh should be equal, as the Debye temperatures of Ce2Ga12Pt and La2Ga12Pd are rather similar (see below). Therefore, we get $\rho_{ph}(T) = \rho_{ph}^0 + \rho_{ph}(T)$ with $\rho_{ph} = \rho_{ph}^0 + \rho_{ph}(T)$. In first approximation, $\rho_{ph}$ of Ce2Ga12Pt and La2Ga12Rh should be equal, as the Debye temperatures of Ce2Ga12Pt and La2Ga12Pd are rather similar (see below). Therefore, we get $\rho_{ph}(T) = \rho_{ph}^0 + \rho_{ph}(T)$ with $\rho_{ph} = \rho_{ph}^0 + \rho_{ph}(T)$. In first approximation, $\rho_{ph}$ of Ce2Ga12Pt and La2Ga12Rh should be equal, as the Debye temperatures of Ce2Ga12Pt and La2Ga12Pd are rather similar (see below). Therefore, we get $\rho_{ph}(T) = \rho_{ph}^0 + \rho_{ph}(T)$ with $\rho_{ph} = \rho_{ph}^0 + \rho_{ph}(T)$.

In figure 6, we show the specific heat of the same single crystal on which the magnetic measurements (see figures 3 and 4) were performed. The 4f contribution to the specific heat, $C^{4f}(T)$, of Ce2Ga12Pt was obtained by subtracting the phonon contribution, which was estimated from the literature values of the nonmagnetic La2Ga12Pd [5], yielding $C^{4f}(T) = 4 m_J (K^{-2} \text{mol}^{-1}) \times T + 1.8 m_J (K^{-2} \text{mol}^{-1}) \times T^3$. The corresponding Debye temperature of La2Ga12Pd amounts to 200 K. Additionally, we have cross-checked the phonon contribution of Ce2Ga12Pt from a linear fit of $C(T)/T$ versus $T^2$ between 10 and 20 K, which gives a Debye temperature of 205 K, very similar to the one of La2Ga12Pd. The resulting 4f contribution to the specific heat of Ce2Ga12Pt presents a large double-peak anomaly at $T_{N,1,2}$, confirming the intrinsic nature of these two AFM transitions observed in $\chi(T)$. Below
Figure 6. The 4f increment to the specific heat of Ce$_2$Ga$_{12}$Pt, calculated by subtracting the phonon contribution estimated from the literature values for nonmagnetic La$_2$Ga$_{12}$Pd [5]. The two AFM transitions are marked by arrows.

$T_{N,2}$, $C_{4f}(T)$ follows a quadratic temperature dependence presumably due to two-dimensional AFM magnons, which is reasonable regarding the layered nature of the crystal structure. Extrapolating the quadratic temperature dependence to zero temperature, one finds a Sommerfeld coefficient of order $\gamma \sim 0.2$ J (K$^{-2}$ mol$^{-1}$ Ce$^{-1}$). The magnetic entropy gain per Ce atom, calculated by integrating $C_{4f}(T)/T$ over temperature, amounts to 1.2$R\ln 2$ at 8 K, which proves that the CEF ground state is a doublet, but indicates that the first excited level is not too far above the ground state (of order 10 to 20 K). In addition, the fact that the whole Zeeman entropy of this doublet ground state is released at the upper AFM phase transition implicates a Kondo temperature which does not exceed $T_{N,1}$.

4. Conclusions

We succeeded in growing single crystals of a new ternary compound, Ce$_2$Ga$_{12}$Pt, which presents an interesting tetragonal crystal structure with two-dimensional Ce planes embedded into a three-dimensional Ga–Pt framework showing, on top, crystallographic disorder. The magnetic anisotropy due to the CEF effect is revealed by magnetic susceptibility measurements and presents Ising-type behaviour with the easy magnetic axis along $c$. Ce$_2$Ga$_{12}$Pt orders antiferromagnetically at $T_{N,1} = 7.3$ K followed by a second AFM transition at $T_{N,2} = 5.5$ K, most probably due to spin reorientation of the 4f moments. Several metamagnetic transitions are observed when the field is applied along $c$, typical for this type of compounds. Specific-heat measurements prove the intrinsic nature of the magnetic transitions and reveal a doublet CEF ground state with a related Kondo temperature $T_K \lesssim T_{N,1}$. Resistivity measurements further support classification of Ce$_2$Ga$_{12}$Pt as a magnetically ordered Kondo lattice system in the weak-coupling regime of the Doniach phase diagram [18].

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