Deviation from the Kadowaki-Woods relation in Yb-based intermediate-valent systems

N. Tsujii\(^1\), K. Yoshimura\(^2\) and K. Kosuge\(^2\)

\(^1\)National Institute for Materials Science, Sengen1-2-1, Tsukuba, Ibaraki 305-0047, Japan
\(^2\)Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

Abstract. The \(T^2\) coefficient of electrical resistivity, \(A\), is compared with the electronic specific-heat coefficient, \(\gamma\), for a number of Yb-based compounds. It is revealed that many systems including YbCuAl, YbInCu\(_4\), YbAl\(_3\) and YbCu\(_5\) show \(A/\gamma^2\) values close to \(0.4 \times 10^{-6} \, \mu\Omega\text{cm}(\text{mol} \cdot \text{K}/\text{mJ})^2\), which is remarkably smaller than that known as the Kadowaki-Woods relation, \(A/\gamma^2 = 1.0 \times 10^{-5} \, \mu\Omega\text{cm}(\text{mol} \cdot \text{K}/\text{mJ})^2\). Empirically, the compounds with the smaller \(A/\gamma^2\) values appear to show weak intersite magnetic-correlation and/or to have almost fully-degenerated (\(J = 5/2\) or \(7/2\)) ground states.

PACS numbers: 71.27.+a, 75.30.Mb

Submitted to: J. Phys.: Condens. Matter

\(^\dagger\) To whom correspondence should be addressed (TSUJII.Naohito@nims.go.jp)
1. Introduction

The low-temperature properties of many U- and Ce-based intermetallic compounds are well described by Fermi-liquid state [1]. Here, the specific heat $C$ and the electrical resistivity $\rho$ as a function of temperature $T$ vary as $C \propto \gamma T$ and $\rho \propto AT^2$, where $\gamma$ and $A$ are constant. The coefficients $\gamma$ and $A$ are related to the electron effective mass $m^*$ as $\gamma \propto m^*$ and $A \propto (m^*)^2$, respectively. The ratio $A/\gamma^2$ therefore does not depend on $m^*$.

In fact, Kadowaki and Woods showed that many U- and Ce-based compounds show a universal relation, $A/\gamma^2 = 1.0 \times 10^{-5} \mu\Omega\text{cm (mol·K/mJ)}^2$ [2]. Furthermore, this relation has proved to be applicable to $d$-electron systems with large $\gamma$, for example, A15-type intermetallics like $\text{V}_3\text{Si}$ [3], nearly-ferromagnetic itinerant-electron systems like $\text{YCo}_2$ [4], and metallic oxides close to metal-insulator transition like $\text{V}_2\text{O}_3$ under high pressure [3] and $\text{LiV}_2\text{O}_4$ [5]. These observations demonstrate that the Fermi-liquid state is a general feature for a wide range of correlated-electron systems.

Large $\gamma$ has also been reported in a number of Yb-based intermetallics [6]. One can naturally expects that the Kadowaki-Woods relation, $A/\gamma^2 = 1.0 \times 10^{-5} \mu\Omega\text{cm (mol·K/mJ)}^2$, also holds for these Yb compounds. In several Yb-based compounds, however, the $A/\gamma^2$ values have been reported to be remarkably smaller than that of the Kadowaki-Woods relation. For $\text{YbCu}_4\text{Ag}$ [7, 8] and $\text{YbCu}_{5-x}\text{Ag}_x$ [9, 10], the $A/\gamma^2$ values are $0.1-0.6 \times 10^{-6} \mu\Omega\text{cm(mol·K/mJ)}^2$, nearly two orders of magnitude smaller than that for the Kadowaki-Woods relation. It is also reported that the $A/\gamma^2$ for $\text{YbCu}_{4.5}$ [11, 12] and $\text{YbNi}_2\text{Ge}_2$ [13] is close to this value. In addition, this value well coincides with the ratio for the transition metals such as Re, Os, Ni, and so on [3, 14].

This deviation of $A/\gamma^2$ value from the Kadowaki-Woods relation can pose quite an interesting subject to the Fermi-liquid theory, if it is a general phenomena for a class of materials. However, there have been no systematic studies on the $A/\gamma^2$ values for Yb-based compounds. We have therefore investigated the $A/\gamma^2$ relation in several Yb-based compounds. We have measured the electrical resistivity of the Yb-based compounds, $\text{YbAl}_2$, $\text{YbInAu}_2$, $\text{YbInCu}_4$, and $\text{YbCuAl}$. These systems are typical examples of Yb-based intermediate-valent or heavy-fermion compounds. We also have examined the $A/\gamma^2$ values for several other compounds using the values reported in literature.

2. Experimental

Polycrystalline samples of $\text{YbAl}_2$ and $\text{YbCuAl}$ have been prepared by argon arc melting and subsequent annealing. To compensate the loss of Yb due to evaporation, slightly additional amount of Yb was used in synthesis. Polycrystalline sample of $\text{YbInAu}_2$ was prepared by melting the elements in a BN crucible placed in an evacuated silica tube, and slow cooling. For $\text{YbInCu}_4$, a single crystal sample was prepared by an In-Cu flux technique [15]. Powder x-ray diffraction shows that single phased samples were obtained for all the compounds. Electrical resistivity was measured by a standard dc four probe technique in the temperature range between 4.2 and 300 K.
3. Results

Figure 1 shows the electrical resistivity $\rho$ as a function of temperature $T$. The residual resistivity $\rho_0$ of these samples are almost the same as or smaller than those reported in the literature [11, 15, 16, 17, 18, 19]. $\rho$ of YbInCu$_4$ decreases abruptly at 40 K due to the valence transition of Yb [15]. The sharp transition indicates that our crystal is well ordered [20]. YbCuAl shows relatively rapid decrease below approximately 20 K. This temperature roughly corresponds to the characteristic temperature $T^*$, below which the coherence between Kondo singlets develops and the system enters the Fermi liquid regime [21]. For YbInAu$_2$, $T^*$ is of the order of 70 K. For YbAl$_2$, $\rho$ does not show a distinct temperature dependence up to 300 K. This indicates that $T^*$ of YbAl$_2$ is above the room temperature.

In Fig. 2, $\rho - \rho_0$ are plotted as a function of $T^2$. For YbCuAl, YbInAu$_2$, and YbAl$_2$, $\rho - \rho_0$ is described by the $T^2$ power law at low temperatures, indicating the evolution of Fermi-liquid state. For YbInCu$_4$, $\rho - \rho_0$ deviates from the $T^2$ dependence above 20 K, and the data up to 30 K are well fitted with the correction of $T^5$ dependence, as is shown in Fig. 2 (b). This suggests that the conventional electron-phonon scattering is important in YbInCu$_4$.

The values of the $T^2$ coefficient $A$ have been obtained by fitting the data at low temperatures, and are listed in table 1. In these $A$ values, errors of the order of 20% can exist due to the inaccuracy in estimating the sample dimension. For YbAl$_2$ and YbInCu$_4$, however, the error in $A$ can be much larger because of the small value of $A$ and the presence of the $T^5$ term.

The $A$ values are plotted against $\gamma$ on the Kadowaki-Woods plot [2, 3, 4], as is shown in Fig. 3. We also plot $A$ and $\gamma$ values of several systems reported in literatures. The values of $A$ and $\gamma$ are listed in table 1.

In Fig. 3, one can see that the Kadowaki-Woods relation, $A/\gamma^2 = 1.0\times10^{-5} \mu\Omega\text{cm(mol-K/mJ)}^2$, is almost preserved for YbNi$_2$B$_2$C, YbRh$_2$Si$_2$, Yb$_2$Co$_3$Ga$_9$, CeNi, and YbInAu$_2$. On the other hand, it is apparent that several systems show a significant deviation from the relation. In particular, there appears to exist another ‘universal’ relation; $A/\gamma^2 \approx 0.4 \times 10^{-6} \mu\Omega\text{cm (mol-K/mJ)}^2$, for YbCu$_{5-x}$Ag$_x$, YbCu$_{4.5}$, YbCuAl, YbNi$_2$Ge$_2$, YbAl$_3$, YbInCu$_4$, YbCu$_4$Al, CeNi$_9$Si$_4$ and CeSn$_3$. Extrapolation of this line well coincides with the $A/\gamma^2$ value for the transition metals such as Pd or Re [14]. As for YbAl$_2$ and YbCu$_2$Si$_2$, the $A/\gamma^2$ ratio appears to be situated between the two lines.

4. Discussion

We have shown in the preceding section that many Yb-based and several Ce-based compounds show nearly two times smaller values of $A/\gamma^2$ than that for the Kadowaki-Woods relation. In this section, we discuss on the possible origin of the deviation from the Kadowaki-Woods relation.

At first, it must be remarked that the $A$ value depends not only on $T_K$ but also on
many factors, including anisotropy, carrier concentration, Fermi-surface topology, band structures, and site disorder. In particular, the effect of site disorder may be important as is pointed by several authors, since the effect can suppress $A$ through the Kondo-hole effect \[^{11, 12, 13}\]. Here, the site disorder gives the additional resistivity: $\rho_{\text{disorder}} = \rho_0 - BT^2$ \[^{19}\], which results in the reduced $T^2$ coefficient of $A - B$. However, although this mechanism may be important in some systems, it is unlikely that the Kondo-hole effect can explain all the small $A/\gamma^2$ values, especially almost universal value, $A/\gamma^2 = 0.4 \times 10^{-6} \mu\Omega\text{cm(mol·K/mJ)}^2$. Kondo-hole effect should result in a random distribution of the $A/\gamma^2$ values. Moreover, the additional term, $\rho_{\text{disorder}} = \rho_0 - BT^2$, has been observed in only limited systems, such as YbInAu\(_2\) under high pressures \[^{11}\]. Thus, we believe that the Kondo-hole effect is not the crucial origin for most of the small $A/\gamma^2$ values. As for the other effect such as carrier concentration or band structures, although these effect must be taken into consideration, it is unlikely that these effect can explain the smaller ‘universal’ relation.

We next consider this phenomenon relating with the three mechanisms: (i) single-body band effect, (ii) intersite magnetic correlation, and (iii) the ground state degeneracy.

4.1. Single-body band effect

Miyake \textit{et al.} have considered theoretically the effect of many-body correlations in heavy-fermion systems, where conduction electrons have a strong frequency-dependence in its self energy. They have suggested that the many-body effect can enhance the $A/\gamma^2$ value by about 25 times larger than the case of single-body band, and this would explain the 25 times different $A/\gamma^2$ between the transition metals and the heavy-fermion systems \[^{3}\].

Similar argument may be applicable for YbAl\(_2\), of which $\gamma$ is relatively small. In this compound, the many-body and the single-body effects can be comparable, which may reduce the $A/\gamma^2$ to the same order as that in transition metals. On the other hand, for YbCuAl, YbCu\(_4\)Ag, YbCu\(_5\) or CeNi\(_9\)Si\(_4\), these systems exhibit much larger $\gamma$ (100-600 mJ/molK\(^2\)) than those of transition metals. This indicates that DOS of the conduction band is enhanced through the many-body effect, i.e., the Kondo-lattice formation.

Even in YbAl\(_3\), for which the $\gamma$ value (45 mJ/mol-K\(^2\)) may not be so large, the de-Haas van Alphen effect measurements have revealed that the Fermi surface of YbAl\(_3\) is strongly renormalized due to many-body effect of the localized 4\(f\) moment and the conduction electrons \[^{60}\]. We therefore suppose that the single-body band effect is not dominating for these systems.

4.2. Intersite magnetic correlation

As is pointed in ref. \[^{2}\], many U-based compounds on the Kadowaki-Woods line exhibit strong intersite magnetic-correlation, including magnetic ordering in UPt, UGa\(_3\) and
A/γ² relation in Yb-based systems

UIn₃, and distinct spin-fluctuations in UAl₂ and UPt₃. Magnetic correlation due to the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction is also considered to be important for those Ce- and Yb-based compounds such as CeAl₃ [61, 62], CeCu₂Si₂ [63], CeB₆ [64], CeCu₆, CeRu₂Si₂ [66], YbRh₂Si₂ [69, 50], and so on. For d-electron systems such as LiV₂O₄ [48], YCo₂ [56] and (Y,Sc)Mn₂ [58], the presence of strong magnetic correlation has been demonstrated by neutron scattering or NMR. It is notable that these compounds include both nearly-ferromagnetic (UAl₂ [65], YCo₂ [56] etc.) and nearly-antiferromagnetic systems (CeCu₆ [46], CeCu₂Si₂ [63] etc.).

On the other hand, for the systems with the smaller A/γ² value, magnetic correlation does not appear to be important. Physical properties are well explained using a single-impurity model in YbCu₅ [10, 66], YbCu₅−ₓAgₓ [9, 22] [23], YbCu₄Ag [24] [25], YbCuAl [27], CeNi₉Si₄ [29] and CeSn₃ [35]. Single-impurity character is also demonstrated by neutron scattering experiments for YbCuAl [28] and YbInCu₄ [37]. Therefore in these compounds, intersite magnetic correlation can be neglected. For YbCu₄₅, magnetic ordering is not observed even at 235 kbar down to 50 mK [26], suggesting the weak RKKY interaction.

This remarkable contrast in the strength of magnetic interactions implies that there exist qualitatively different scattering mechanisms in the electrical resistivity. For the case with strong magnetic interactions, A and γ are enhanced both by the large density of state (DOS) at the Fermi energy (E_F) and by the strong spin-fluctuations. In contrast, for the single impurity-like case, the large A is solely attributed to the DOS at E_F. One may hence consider that this difference is the possible origin of the two ‘universal’ A/γ² relations.

However, this tendency is inconsistent with the theoretical calculations based on the spin fluctuation theory [67, 68]. Takimoto et al. have shown that the value of A/γ² is almost constant from the pure Kondo regime (single-impurity limit) to almost magnetically instability limit. The value of A/γ² they estimated is close to the Kadowaki-Woods relation [67]. Similar result is also reported by Continentino, who have shown that the A/γ² value is independent of the distance from magnetic instability [68].

It should also be noted that there exist some exceptions of the above tendency. In CePd₃, intersite magnetic correlation is considered to be of minor importance [55]. For YbInAu₂ or Nb₃Sn, no evidence of strong magnetic-correlation is reported. However, A/γ² values in these systems are close to the Kadowaki-Woods relation. On the other hand, Pd and Pt show the small A/γ² value, though they are well-known examples of nearly-ferromagnetic metals [38]. Therefore, these findings may not justify the above scenario, in which strong intersite magnetic-correlation enhances A/γ² values.

4.3. Ground state degeneracy

One may notice that most of the systems with the smaller A/γ² values in Fig. 3 are classified as the intermediate-valent compounds, where crystal-field splitting, Δ_CF, is of minor importance, and the full degeneracy N for Yb³⁺ or Ce³⁺ ion is almost
preserved [69]. In fact, physical properties of YbCu$_4$Ag, YbCuAl, CeSn$_3$ and CeNi$_9$Si$_4$ are explained by the impurity model for $N = 8$ (Yb$^{3+}$) or $N = 6$ (Ce$^{3+}$), as is noted in the preceding subsection. For YbAl$_3$ and YbAl$_2$, Shimizu et al. have suggested by the $^{171}$Yb-NMR that the $N = 8$ ground state is well conserved in these compounds [34]. Even in YbCu$_5$, which exhibits a large $\gamma = 550$ mJ/mol·K$^2$, $\Delta_{\text{CF}}$ is considered to be comparable with the Kondo temperature $T_K$, and the low temperature properties are characterized by $N = 4$ [22, 23].

On the contrary, the systems such as CeCu$_6$, CeAl$_3$ and CeCu$_2$Si$_2$ are considered to be affected by the crystal-field effect, which reduce the ground state degeneracy down to $N = 2$ [69].

The difference in $N$ is related to the magnitude of the magnetic moment which participate in the Fermi-liquid formation. It can therefore affect on the $A/\gamma^2$ values. We note that the difference between $N \geq 4$ and $N \leq 3$ states can be crucial. Theoretical calculation predicts that the DOS has a peak situated above $E_F$ for the case of $N \geq 4$, whereas the peak is positioned just at $E_F$ for $N \leq 3$ [70]. Similarly, magnetic excitation spectra also show inelastic structure for large $N$ [71, 72]. Hence, we suppose that in those Yb- and Ce-based intermediate-valent systems, their largely-degenerated states ($N \geq 4$) develop the excitation spectra with qualitatively different shape from that in those heavy-fermion systems with small $N$ ($\leq 3$), resulting in the significant difference in the $A/\gamma^2$ values. There have been no theories for the $N$ dependence of $A/\gamma^2$ value as far as we know. Theoretical investigation for the relation between $N$ and $A/\gamma^2$ is desired [73].

However, some exceptions for this understanding should be noted. For Yb$_2$Co$_3$Ga$_9$ [40], the full degeneracy for Yb$^{3+}$ is considered to be preserved, though they exhibit the same order of $A/\gamma^2$ as that for the Kadowaki-Woods relation. In addition, it is unclear whether all the U-based compounds on the Kadowaki-Woods line can be understood in terms of $N \leq 3$ ground states. In these U-compounds, the enhanced low-energy excitations due to intersite magnetic correlation may also be responsible.

We also note that CePd$_3$ is again exceptional. This compound is a typical intermediate-valent compound. The full degeneracy $N = 6$ is considered to be preserved, and the intersite magnetic correlation is also of minor importance [55]. Nevertheless, this compound show the same order of $A/\gamma^2$ value as that of heavy-fermion compounds. However, it should be remarked that the carrier concentration of CePd$_3$ is unusually small ($\sim 0.3$ per unit cell) [74], and hence this compound would be close to Kondo-insulators. This situation cannot allow us to make a naive comparison for CePd$_3$.

Finally, an important suggestion is given experimentally from the electrical resistivity measurement under pressures. Knebel et al. [13] have examined the $AT_{\text{max}}^2$ of YbNi$_2$Ge$_2$ under pressure, where $T_{\text{max}}$ is the maximum temperature of the resistivity adhering to a $T^2$ power-law, and should be proportional to $\gamma^{-1}$. The value of $AT_{\text{max}}^2$ is therefore a measure of $A/\gamma^2$. They have found that $AT_{\text{max}}^2$ increases by a factor about 25 times under high pressures. Similar variation of $AT_{\text{max}}^2$ under pressure has also been reported for
These phenomena are most likely related to either of the change of the intersite magnetic correlation or that of the ground state degeneracy. Hence, performing similar experiments on much more systems may eventually reveal the underlying origin of the two 'universal' $A/\gamma^2$ relations.

In addition, the effect of disorder must be carefully taken into consideration. If the disorder makes little effect on the host-material properties, its effect on the resistivity would be described by the Kondo-hole effect, which reduces $A$. On the contrary, in most of systems, disorder is considered to affect the whole range of electrical properties in the Kondo-lattice formation. It would reduce the characteristic temperature $T^*$, which results in the enhanced $A$ values. This may be the case in YbInAu$_2$, where site disorder easily occur because of its crystal structure. Therefore, the $A/\gamma^2$ values in several systems may not be intrinsic. Experimental works using high quality samples are particularly important.

5. Summary

We have measured the electrical resistivity and have examined the $A/\gamma^2$ values of YbAl$_2$, YbInAu$_2$, YbInCu$_4$ and YbCuAl. We have also plotted $A$ vs. $\gamma$ for several systems reported in literature. The result reveals that the $A/\gamma^2$ values are not unique among materials, but varies in the range of $0.4 \times 10^{-6} - 1.0 \times 10^{-5} \mu\Omega\text{cm}(\text{mol-K/mJ})^2$. In particular, it has been found that there exists another 'universal' relation; $A/\gamma^2 = 0.4 \times 10^{-6} \mu\Omega\text{cm}(\text{mol-K/mJ})^2$, for a number of systems including YbCuAl, YbAl$_3$, YbInCu$_4$, YbCu$_4$Al as well as YbCu$_5$, YbCu$_{4.5}$, YbCu$_{4.5}$Ag, YbNi$_2$Ge$_2$, CeNi$_9$Si$_4$ and CeSn$_3$. This value of $A/\gamma^2$ is about 25 times smaller than that known in the Kadowaki-Woods relation; $A/\gamma^2 = 1.0 \times 10^{-5} \mu\Omega\text{cm}(\text{mol-K/mJ})^2$.

To explain this deviation, several possible mechanisms have been discussed. The Kondo-hole effect or the single-body-band effect may be applicable for some systems. However, these two mechanisms cannot explain the almost 'universal' nature of the smaller $A/\gamma^2$ values. Thus, we have considered the tendency of these compounds empirically, and have focused on the intersite magnetic correlation and the ground state degeneracy.

As for the former, we have pointed that most of the systems with the smaller $A/\gamma^2$ value exhibit single-impurity like behavior. This suggests that the intersite magnetic interactions are negligible in these systems. In contrast, many systems on the Kadowaki-Woods line are known to show strong magnetic correlation. This tendency is valid for many compounds plotted in Fig. 3. However, this interpretation is inconsistent with the theoretical results based on the spin-fluctuation theory.

As for the latter, it has been found that the ground state degeneracy $N$ differs largely between the systems with the smaller $A/\gamma^2$ and those on the Kadowaki-Woods line. Almost all the systems with the smaller $A/\gamma^2$ values (except for $d$-electron systems) show largely degenerated ground state; i.e., $N \geq 4$. On the other hand, those on the Kadowaki-Woods line are considered to have $N \leq 3$ state due to the crystal-field
splitting. Since this difference can affect on the magnitude of the magnetic moment as
well as the shape of the excitation spectra, the $A/\gamma^2$ values may also vary depending on
$N$.

For both the cases, i.e., the intersite magnetic correlation and the ground state
degeneracy, our interpretations are only empirical. Hence, theoretical confirmations are
strongly desired.

Acknowledgments

Authors gratefully acknowledge T Takimoto, S Kambe, K Miyake, J M Lawrence, G
Hilscher, H Kitazawa and H Suzuki for valuable discussion and suggestions.

References

[1] Stewart G R 1984 Rev. Mod. Phys. 56 755
[2] Kadowaki K and Woods S B 1986 Solid State Commun. 58 507
[3] Miyake K, Matsuura T, Varma C M 1989 Solid State Commun. 71 1149
[4] Gratz E, Hilscher G, Michor H, Markosyan A, Talik E, Czjzek G and Mexner W 1996 Czechoslovak
J. Phys. 46 Suppl. S4, 2031
[5] Urano C, Nohara N, Kondo S, Sakai F, Takagi H, Shiraki T and Okubo T 2000 Phys. Rev. Lett. 85 1052
[6] Fisk Z and Maple M B 1992 J. Alloys Compd. 183 303
[7] Graf T, Lawrence J M, Hundley M F, Thompson J D, Lacerda A, Haanappel E, Torikachvili M
S, Fisk Z and Canfield P C 1995 Phys. Rev. B 51 15053
[8] Graf T, Movshovich R, Thompson J D, Fisk Z and Canfield P C 1995 Phys. Rev. B 52 3099
[9] Tsujii N, He J, Yoshimura K, Kosuge K, Michor H, Kreiner K and Hilscher G 1997 Phys. Rev. B 55 1032
[10] Tsujii N, He J, Amita F, Yoshimura K, Kosuge K, Michor H, Hilscher G and Goto T 1997, Phys.
Rev. B 56 8103
[11] K. Alami-Yadri, H. Wilhelm, D. Jaccard, Solid State Commun. 108, 279 (1998).
[12] Alami-Yadri K, Wilhelm H and Jaccard D 1998 Eur. Phys. J. B 6 5
[13] Knebel G, Braithwaite D, Lapertot G, Canfield P C and Flouquet J 2001 J. Phys.: Condens.
Matter 13 10935
[14] Rice M J 1968, Phys. Rev. Lett. 20 1439
[15] Sarrao J L, Immer C D, Benton C L, Fisk Z, Lawrence J M, Mandrus D and Thompson J D 1996
Phys. Rev. B 54 12207
[16] Mignot J M and Wittig J 1986 in Physics of Solids under High Pressure, edited by Schilling J S
and Shelton R N, North-Holland, p.311.
[17] Cattaneo E 1986 Z. Phys. B Cond. Matt. 64 317
[18] van Daal H J, van Aken P B, Buschow K H J 1974 Phys. Lett. 49A 246
[19] Havinga E E, Buschow K H J and van Daal H J 1973 Solid State Commun. 13 621
[20] Lawrence J M, Kwei G H, Sarrao J L, Fisk Z, Mandrus D and Thompson J D 1996 Phys. Rev. B 54 6011
[21] Lavanga M 1985 J. Magn. Magn. Mater. 47-48 360
[22] Michor H, Kreiner K, Tsujii N, Yoshimura K, Kosuge K and Hilscher G 2002 Physica B 319 277
[23] Hauser R, Kreiner K, Bauer E, Michor H, Hilscher G, Rotter M, Müller H, Tsujii N, Yoshimura
K and Kosuge K 1999 Physica B 259-261 136
[24] Rossel C, Yang K N, Maple M B, Fisk Z, Zirngiebl E and Thompson J D 1987 Phys. Rev. B 35 1914
A/\gamma^2 \text{ relation in Yb-based systems}

[25] Besnus M J, Haen P, Hamdaoui N, Herr A and Meyer A 1990 Physica B 163 571
[26] Link P, Alami-Yadri K, Jaccard D, Sierra J and Walker E 1995 Physica B 206-207 361
[27] Hewson A C, Newns D M, Rasul J W and Read N 1985 J. Mag. Mag. Mater. 47-48 354
[28] Murani A P, Mattens W C M, de Boer F R and Lander G H 1985 Phys. Rev. B 31 52
[29] Michor H, Bauer E, El-Hagary M, Dusek C, Rogl P and Hilscher G, in Proceedings of the 29th International Conference on Low-Temperature Physics, to be published in Physica B
[30] Bud'ko S L, Islam Z, Wiener T A, Fisher I R, Lacerda A H and Canfield P C 1999 J. Mag. Mag. Mater. 205 53
[31] Bauer E, Hauser R, Keller L, Fischer P, Trovarelli O, Sereni G, Rieger J J and Stewart G R 1997 Phys. Rev. B 56 711
[32] Bauer E, Galatanu A, Naber L, Galli M, Marabelli F, Seuring C, Heusler K, Scheidt E-W, Schreiner T and Stewart G R 2000 Physica B 281-282 319
[33] Ebihara T, Uji S, Terakura C, Terashima T, Yamamoto E, Haga Y, Inada Y and Onuki Y 2000 Physica B 281-282 754
[34] Shimizu T, Takigawa M, Yasuoka H and Wernick J H 1985 J. Mag. Mag. Mater. 52 187
[35] Schlottmann P 1985 J. Appl. Phys. 57 3155
[36] Pillmayr N, Bauer E and Yoshimura K 1992 J. Mag. Mag. Mater. 104-107 639
[37] Lawrence J M, Shapiro S M, Sarrao J L and Fisk Z 1997 Phys. Rev. B 55 14467
[38] Takigawa M and Yasuoka H 1982 J. Phys. Soc. Jpn. 51 787
[39] Dhar S K, Mitra C, Manfrinetti P, Palenzona A and Bonville P 1999 Physica B 259-261 150
[40] Dhar S K, Mitra C, Bonville P, Rams M, Krölas K, Godart C, Alleno E, Suzuki N, Miyake K, Watanabe N, Onuki Y, Manfrinetti P and Palenzona A 2001 Phys. Rev. B 64 094423
[41] Thompson J D, Borges H A, Fisk Z, Horn S, Parks R D and Welles G L 1987 in Theoretical and Experimental Aspects of Valence Fluctuations and Heavy Fermions, edited by Gupta L C and Malik S K (Plenum Press, New York, 1987), p. 151
[42] Oomi G and Mori N 1994 J. Alloys Compd. 207-208 275
[43] Sereni J G, Beaurepaire E and Kappler J P 1993 Phys. Rev. B 48 3747
[44] Clementiev E S, Mignot J-M, Alekseev P A, Lazukov V N, Nefedova E V, Sadikov I P, Braden M, Kahn R and Lapertot G 2000 Phys. Rev. B 61 6189
[45] Besnus M J, Kappler J P, Ravet M F, Meyer A, Lahionel R, Pierre J, Siaud E, Nieva G and Sereni J 1986 J. Less-Common Metals 120 101
[46] Rossat-Mignod J, Regnault L P, Jacoud J L, Vettier C, Lejay P, Flouquet J, Walker E, Jaccard D and Amato A 1988 J. Mag. Mag. Mater. 76-77 376
[47] Koike Y, Metoki N, Kimura N, Yamamoto E, Haga Y, Onuki Y and Maezawa K 1999 Physica B 259-261 602
[48] Lee S H, Qiu Y, Broholm C, Ueda Y and Rush J J 2001 Phys. Rev. Lett. 86 5554
[49] Trovarelli O, Geibel C, Mederle S, Langhammer C, Grosche F M, Gegenwart P, Lang M, Sparm G and Steglich F 2000 Phys. Rev. Lett. 85 626
[50] Gegenwart P, Custers J, Geibel C, Neumaier K, Tayama T, Tenya K, Trovarelli O and Steglich F 2002 Phys. Rev. Lett. 89 056402
[51] Ishida K et al., Phys. Rev. Lett., to be published.
[52] Yatskar A, Budraa N K, Beyermann W P, Canfield P C and Bud’ko S L 1996 Phys. Rev. B 54 3772
[53] Kambe S, Flouquet J, Haen P and Lejay P 1996 J. Low Temp. Phys. 102 477
[54] Ikeda S-I, Maeno Y, Nakatsuji S, Kosaka M and Uwatoko Y 2000 Phys. Rev. B 62 R6089
[55] Murani A P, Raphel R, Bowden Z A and Eccleston R S 1993 Phys. Rev. B 53 8188
[56] Yoshimura M, Kekata M, Takahashi Y and Yasuoka H 1988 Phys. Rev. B 37 3593
[57] Wada H and Shiga M 1991 Butsuri(in Japanese) 46 483
[58] Ballou R, Lelevre-Berna E and Foak B 1996 Phys. Rev. Lett. 76 2125
[59] Lawrence J M, Thompson J D and Chen Y Y 1985 Phys. Rev. Lett. 54 2537
[60] Ebihara T, Inada Y, Murakawa M, Uji S, Terakura C, Terashima T, Yamamoto E, Haga Y, Onuki...
$A/\gamma^2$ relation in Yb-based systems

Y and Harima H 2000 J. Phys. Soc. Jpn. 69 895
[61] Barth S, Ott H R, Gygax F N, Hitti B, Lippelt E, Schenck A, Baines C, van den Brandt B, Konter T and Mango S 1987 Phys. Rev. Lett. 59 2991
[62] Nakamura H, Kitaoka Y, Asayama K and Flouquet J 1988 J. Phys. Soc. Jpn. 57 2644
[63] Ishida K, Kawasaki Y, Tabuchi K, Kashima K, Kitaoka Y, Asayama K, Geibel C and Steglich F 1999 Physica B 259-261 678
[64] Sato N, Sumiyama A, Kunii S, Nagano H and Kasuya T 1985 J. Phys. Soc. Jpn. 54 1923
[65] Takagi S, Homma T, Yoshida T, Komatsubara T and Kasuya T 1991 J. Phys. Soc. Jpn. 60 1097
[66] Tsuji N, Yoshimura K and Kosuge K 1999 Phys. Rev. B 59 11813
[67] Takimoto T and Moriya T 1996 Solid State Commun. 99 457
[68] Continentino M A 2000 Eur. Phys. J. B 13 31
[69] Brandt N B and Moshchalkov B B 1984 Adv. Phys. 33 373
[70] Rajan V T 1983 Phys. Rev. Lett. 51 308
[71] Kuramoto Y and Müller-Hartmann E 1985 J. Mag. Mag. Mater. 52 122
[72] Cox D L, Bickers N E and Wilkins J W 1985 J. Appl. Phys. 57 3166
[73] Lawrence J M has tentatively suggested that $A/\gamma^2$ can be a decreasing function of $N$ (private communication), if we assume that $A = \rho^{\text{unit}}/T_K^2$, where $\rho^{\text{unit}}$ is the unitarity limit described as $\rho^{\text{unit}} \propto N\sin^2(\pi/N)$, and that $\gamma = (N - 1)\pi k_B/6T_K$.[70]
[74] Webb B C, Sievers A J and Mihalisin T 1986 Phys. Rev. Lett. 57 1951
[75] Jaccard D, Wilhelm H, Alami-Yadri K and Vargoz E 1999 Physica B 259-261 1
| Compounds          | A   | γ    | $A/\gamma^2$ | Magnetic correlation | Ground state degeneracy |
|-------------------|-----|------|--------------|----------------------|------------------------|
| YbCu$_5$         | 0.15| 550  | 0.05         | w                    | 4                      |
| YbCu$_{1.5}$Ag$_{0.5}$ | 0.064| 380  | 0.04         | w                    | 6                      |
| YbAgCu$_4$       | 0.023| 210  | 0.05         | w                    | 8                      |
| YbCu$_{1.5}$ Al  | 0.1 | 600  | 0.03         | w                    | 8                      |
| YbCuAl           | 0.068*| 260  | 0.1          | w                    | 27, 28                 |
| CeNi$_9$Si$_4$   | 0.017| 156  | 0.07         | w                    | 6                      |
| YbNi$_2$Ge$_2$   | 0.0078| 136  | 0.04         |                       |                        |
| YbCu$_2$Al       | 0.0025| 50-100| 0.03-0.1    |                       |                        |
| YbAl$_3$         | 5×10^{-4} | 45  | 0.06         | w                    | 31                     |
| CeSn$_3$         | ~0.03|      |              | w                    | 6                      |
| YbInCu$_4$       | 6×10^{-4} | 50  | 0.03         | w                    | 37                     |
| YbAl$_2$         | 4×10^{-4} | 17  | 0.14         | w                    | 31, 34                 |
| CeNi$_9$         | 0.013| 60   | 0.36         | m                    | 8                      |
| YbInAu$_2$       | 0.0070*| 40  | 0.44         |                       |                        |
| CeCu$_6$         | ~1.0 |      |              | s                    | 46                     |
| UPt$_3$          | ~1.0 |      |              | s                    | 47                     |
| LiV$_2$O$_4$     | 2.0 | 200  | 5            | s                    | 48                     |
| YbRh$_2$Si$_2$   | 22 | 1700 | 0.8          | s                    | 2                     |
| YbRh$_2$Si$_2$   | 1.0 | 300  | 1.1          | s                    | 51                     |
| YbNi$_2$B$_2$C   | 1.2 | 530  | 0.43         | m                    | 2, 3                   |
| CeRu$_2$Si$_2$   | 0.62| 350  | 0.51         | s                    | 16                     |
| Sr$_3$Ru$_2$O$_7$| 0.075| 110  | 0.6          | s                    | 3                      |
| CePd$_3$         | 2.5 |      |              | w                    | 55                     |
| V$_2$O$_3$       | 4  |      |              | s                    | 3                      |
| YCo$_2$          |      |      |              | s                    | 56                     |
| (Y,Sc)Mn$_3$     | 0.2 | 80   | 3.1          | s                    | 58                     |

(* this work)

Table 1. List of the $T^2$ coefficient of electrical resistivity $A$ and the $T$-linear specific heat coefficient $\gamma$. The units of $A$, $\gamma$, and $A/\gamma^2$ are $\mu\Omega$cm/K$^2$, mJ/mol·K$^2$, and $10^{-5}\mu\Omega$cm(mol·K/mJ)$^2$, respectively. Here 'mol' means magnetic-ion mol. The values of $A$ given in this work are marked by asterisk. The character w, m, and s indicates that the magnetic correlation is weak, mediate, and strong, respectively.
Figure 1. Electrical resistivity $\rho$ of YbAl$_2$, YbInAu$_2$, YbCuAl polycrystals and flux-grown YbInCu$_4$ single crystal as a function of temperature $T$.

Figure 2. Electrical resistivity with the residual resistivity subtracted, $\rho - \rho_0$, as a function of the square of temperature, $T^2$. The dotted lines in (b) indicate the $T^2$ power law. The solid line for YbInCu$_4$ is the result of fitting by the sum of $T^2$ and $T^5$ terms.
$A/\gamma^2$ relation in Yb-based systems

$A / \gamma^2 = 1.0 \times 10^{-5}$

$A / \gamma^2 = 0.4 \times 10^{-6}$

Figure 3. Plot of the $T^2$ coefficient of electrical resistivity $A$ vs. the $T$-linear specific heat coefficient $\gamma$. Solid and dotted lines represent $A/\gamma^2 = 1.0 \times 10^{-5}$ and $0.4 \times 10^{-6}$ $\mu\Omega\text{cm(mol·K/mJ)}^2$, respectively. Data for Yb compounds are represented by black-filled symbols. Black-filled circles (●) indicate the data of the present work. Gray-filled symbols represent Ce- and U-based compounds. $d$-electron based systems are indicated by open symbols. For references, see table 1.