Pressure-induced quantum instability in highly correlated electron systems

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Summary:

The temperature dependent electrical resisitivities of three Kondo compounds $CeAl_3$, $CeRh_2Si_2$ and $Y_{0.8}U_{0.2}Pd_3$ have been measured at high pressure up to 3 GPa. It is found that the heavy Fermion state is collapsed at high pressure and the Grüneisen parameters decrease with increasing pressure showing a crossover in the electronic state from a heavy Fermion state to an intermediate valence state. In the 5f compound $Y_{0.8}U_{0.2}Pd_3$, the non Fermi liquid properties are found to suppress at high pressure and the Fermi liquid behavior is recovered above 4-5 GPa. We also report the effect of pressure on the tunnel magntoresistance in Co-Al-O granular film and the quantum phase transition in the magnetic multilayers under high pressure. The tunnel magnetoresistance is found to be enhanced by applying pressure, which is explained by considering higher order tunneling effect.

1.Introduction

There have been a lot of investigations about the electronic and magnetic properties of concentrated Kondo (CK) compounds containing Ce or U because these compounds give an important information for studying the role of strong electron correlations in the metallic systems(Stewart,1984, p. 755, Brandt,1984, p.373). The CK compounds show several anomalous properties, such as a huge value of linear term coefficient γ in the electronic specific heat, a large T^2-term in the electrical resistivity $\rho(T)$ at low temperatures, a log T -term in the $\rho(T)$ at high temperatures and so forth.

It is well known that the electronic states of CK compounds are strongly dependent on the change in pressure or volume and magnetic field since these are electronically unstable (Thompson, 1994, p. 383). The electronic states of the systems are characterized by the so-called Kondo temperature T_K. The fact mentioned above indicates the large change in the magnitude of T_K by an application of pressure. Usually the heavy fermion (HF) system having a low T_K of the order of several degree Kelvin has a large Grüneisen parameter Γ of the order of 100 (Kagayama and Oomi,1996, p.42). T_K of HF compounds increases rapidly with increasing pressure to show a crossover into a new electronic state (Mignot,1982, p. 203), which is called the intermediate valence (IV) state having relatively small Γ (Flouquet, 1982, p. 2127). We have reported such pressure-induced crossover for several Ce compounds (Kagayama, 1991,p.7690, Kagayama and Oomi, 1993, p.155, Kagayama *et al.*, 1994, p.3927).

On the other hand, in the materials showing Kondo properties, some physical quantities such as electrical resistivity, specific heat, magnetic susceptibility etc., show large deviations from the normal Fermi liquid (FL) behaviors. These phenomena have been called as non Fermi liquid (NFL) properties, which is related to the instability of quantum electronic state or quantum phase transition (QPT). In order to get a deep insight in the study of electronic structure of CK compounds, it is worthwhile to extend our investigation at high pressure to other highly correlated electron systems having different T_K values and other materials including d electrons.

In the present work, we will describe some examples of high pressure works mainly for the following materials, $CeAl_3$, $CeRh_2Si_2$, $Y_{0.8}U_{0.2}Pd_3$, Co-Al-O and Fe/Cr magnetic multilayers (MML). The results are discussed briefly on the basis of pressure-induced electronic crossover by using the Grüneisen parameters, quantum phase transition and tunneling effect.

2.Experimental

The details of high pressure apparatus in which we can change three external forces (*T, P, H*) simultaneously were described elsewhere (Honda *et al.*, 2002, p. 11501). The range of *T, P* and *H* are $1.3 < T < 350$K, $0 < P < 3$ GPa (in hydrostatic pressure) and $0 < H < 9$T, respectively.

3.Results

3.1 Heavy Fermions including 4f-electrons

(1) $CeAl_3$

This material is a prototype of heavy Fermion, in which a large value of γ and a extremely large value of T^2-term in the electrical resistivity have been found (Andres et.al.,1975, p. 1779). These properties are affected significantly by applying pressure. At high pressure, this compound shows a crossover in the electronic state from HF to IV state.

The temperature dependence of the electrical resistivity $\rho(T)$ of $CeAl_3$ at various pressures up to 8 GPa and $\rho(T)$ of $LaAl_3$ at ambient pressure are shown in Fig.1 (Kagayama and Oomi,1996, p. 42). The $\rho(T)$ of $LaAl_3$ is similar to the ordinary non-magnetic metal; it varies linearly with temperature above 100 K without any anomaly. While, at ambient pressure, $\rho(T)$ of $CeAl_3$ increases logarithmically with decreasing temperature until it reaches a maximum at 35 K and has a shoulder near 6 K. This behavior is due to the Kondo scattering on a thermally populated level split by crystalline electric field (Cornut and Coqblin,1972, p. 4541). With increasing pressure, the peak and shoulder are merged into one peak, which is shifted towards higher temperatures. The $\rho(T)$ at 8 GPa becomes similar to that of $LaAl_3$. This result is interpreted as a pressure-induced crossover in the electronic state of $CeAl_3$ from low-T_K HF state to high-T_K IV state associated with an increase in the hybridization between conduction and 4f electrons.

In order to get the temperature-dependent 4f magnetic contribution $\rho_{mag}(T)$, the $\rho(T)$ of $LaAl_3$ is assumed to be pressure independent phonon part of $CeAl_3$ and subtracted from the $\rho(T)$ data of $CeAl_3$ at various pressures, $\rho_{mag}(T) = \rho(CeAl_3) - \rho(LaAl_3)$. Figure 2 illustrates the $\rho_{mag}(T)$ as a function of $\log T$. The maximum temperature T_{max} in the $\rho_{mag}(T)$ is shown in Fig. 3. T_{max} is found to increase with increasing pressure. Since T_{max} is roughly proportional to the T_K, the pressure dependence of T_K may be inferred from the result in Fig. 3. On the other hand the logarithmic dependence of ρ_{mag} on the temperature is observed in the wide range above T_{max}. The negative slope becomes steeper at higher pressure reflecting the strong Kondo scattering with large enhancement of T_K at high pressures.

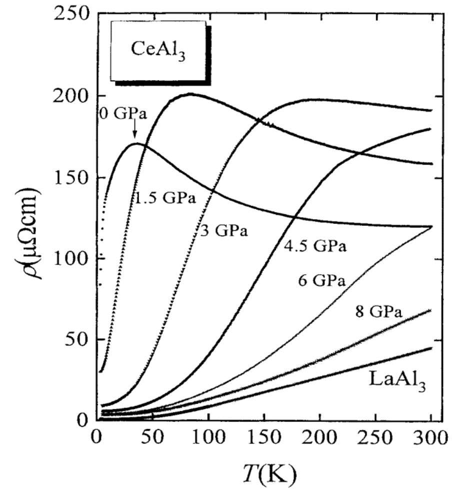

Fig. 1. The electrical resistivity $\rho(T)$ of $CeAl_3$ under high pressure as a function of temperature. $\rho(T)$ of $LaAl_3$ at ambient pressure is also shown for comparison.

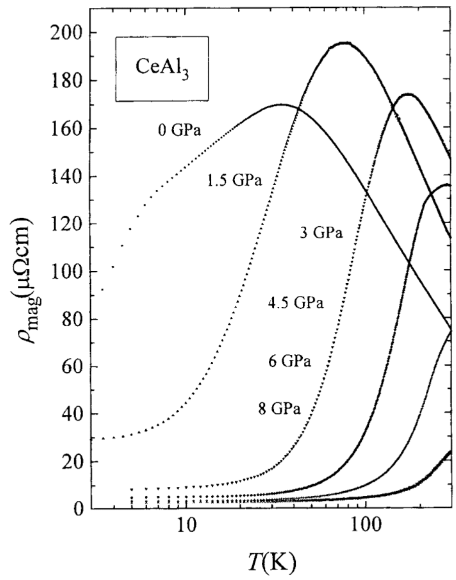

Fig. 2. The magnetic part of electrical resistivity, ρ_{mag}, as a function of $\log T$ at various pressures.

In order to examine the T^2-dependence in the $\rho_{max}(T)$ at low temperature, ρ_{max} is plotted as a function of T^2 for $CeAl_3$ in Fig. 4 up to 17 K for $P \leq 1.5$ GPa and to 80 K for $P \geq 3$ GPa. Above 0.8 GPa the T^2-dependence is clearly observed in the temperature range of the present work as shown by straight line. As pressure increases, the slope decreases and the temperature range showing T^2-dependence becomes wider.

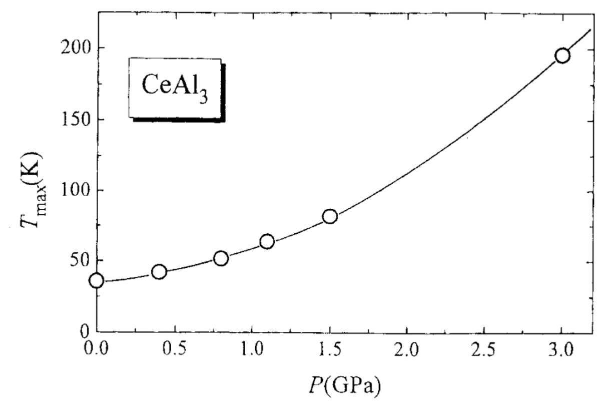

Fig. 3. The pressure dependence of the temperature T_{max} at which ρ_{mag} has a maximum.

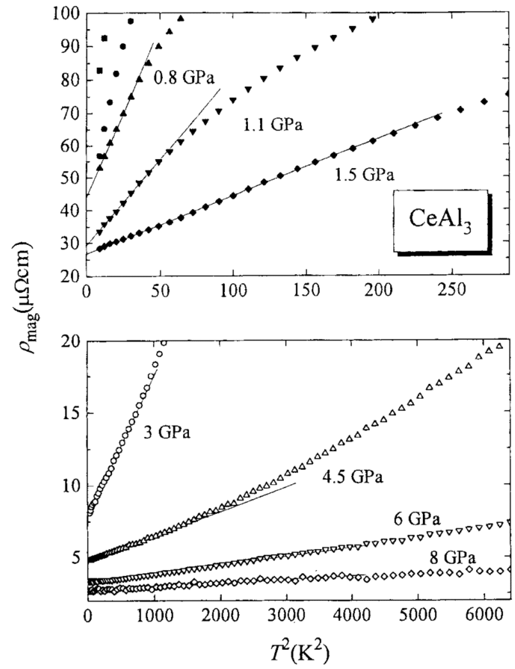

Fig. 4. ρ_{mag} of $CeAl_3$ as a function of T^2.

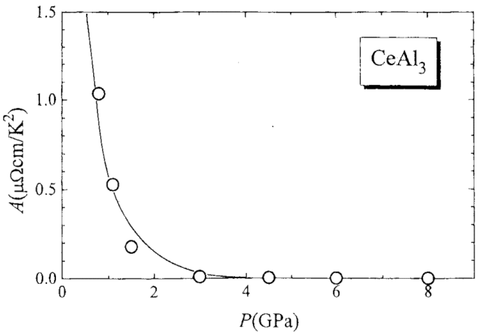

Fig. 5. The coefficient A of T^2-term as a function of pressure.

The coefficient A of T^2-term is shown in Fig. 5 as a function of pressure. The value of A is reduced to 3 orders magnitude smaller than that at ambient pressure, which was reported previously to be 35 $\mu\Omega$cm/K^2 (Andres *et al.*, 1975, p. 1779). The rapid decrease in the magnitude of A is explained by the enhancement of T_K by applying pressure, which is consistent with the increase in T_{max}, because the coefficient A is inversely proportional to T_K^2.

(2) $CeRh_2Si_2$

Fig. 6 shows the electrical resistivity $\rho(T)$ for *a*-axis as a function of temperature below 40 K under high pressures(Ohashi *et al.*,2003, p. 114428). At ambient pressure, the resistivity shows a sudden decrease near 35 K (=T_{N1}). Moreover, the resistivity shows a small anomaly at 24 K (=T_{N2}). The anomalies at T_{N1} and T_{N2} correspond to the magnetic phase transitions which were mentioned before. The anomaly near T_{N1} becomes less prominent with increasing pressure, corresponding to the pressure-induced decrease of the sublattice magnetization (Kawarazaki *et al.*,2000, p. 4167). T_{N1} decreases with increasing pressure and disappears above 1.0 GPa (~ P_{C1}). T_{N2} also decreases with increasing pressure and disappears above 0.58 GPa (~ P_{C2}). At 0.4 GPa, on the other hand, it is found that $\rho(T)$ shows the minimum T_{N2}~ 14.5 K along *a*-and *c*-axis. Furthermore, the hysteresis is found near T_{N2} along *a*-axis, indicating that this transition is first order. Although no hysteresis is observed at ambient pressure, the results of quasielastic neutron scattering indicates that this transition is first order at ambient pressure (Graf *et al.*,1998 p. 7442, Severing *et al.*,1989, p. 4164).

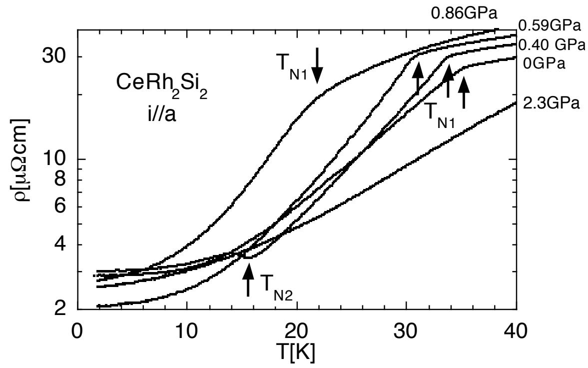

Fig. 6. Temperature dependence of the electrical resistivity of $CeRh_2Si_2$ along the *a*-and *c*-axis.

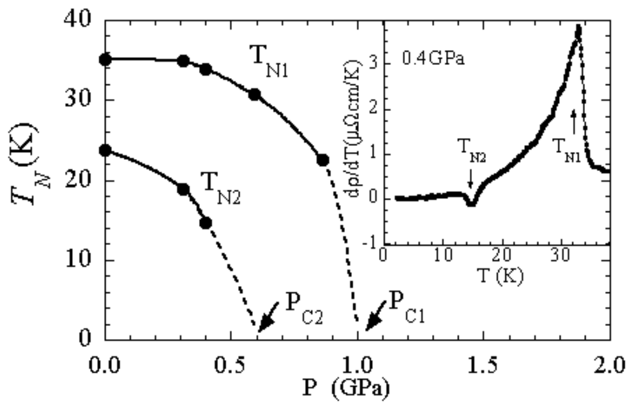

Fig. 7. Pressure dependence of the critical temperatures T_{N1} and T_{N2} of $CeRh_2Si_2$. Broken lines are extrapolations. An example of the dρ/dT at 0.4 GPa is shown in the inset.

Fig. 8 shows ρ(T) in a wide temperature range under high pressures up to 8 GPa. No anomaly was detected in the ρ(T) above 1.5 GPa since magnetic orderings were suppressed completely. Instead of that, the shoulder is found near 80 K (T_m) in the ρ(T) curve at 1.5 GPa ,which shifts rapidly to higher temperature with increasing pressure. Since this shoulder is related to Kondo or spin fluctuation temperature (~ T_K), the result implies that T_K increases with increasing pressure.

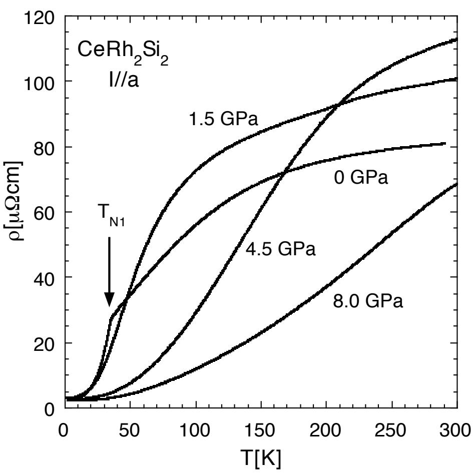

Fig. 8 Temperature dependence of the electrical resistivity of $CeRh_2Si_2$ along the *a*-axis up to 8 GPa.

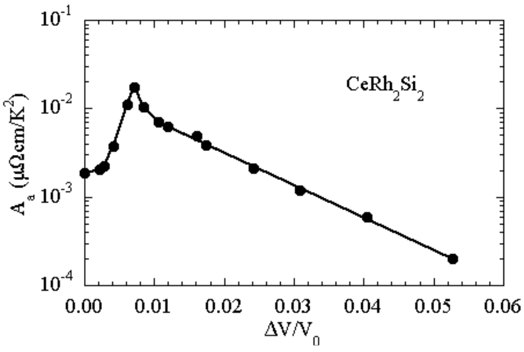

Fig. 9 A_a as a function of fractional change in volume, $\Delta V/V_0$.

In the low temperature range, T^2 dependence is observed in the $\rho(T)$ curves above 1.5 GPa. The coefficients of the T^2-term are plotted in Fig. 9 as a function of fractional change of volume, $\Delta V/V_0$, where V_0 is the volume at ambient pressure.

3.2 Instability of non Fermi liquid state at high pressure in $Y_{0.8}U_{0.2}$ Pd_3

This material has been well known as a typical example of NFL (Seaman *et al.,* 1991, p. 2882, Andraka and Tsvelik., 1991, p. 2886). The effect of pressure has been investigated by many authors mainly below 2 GPa (Chau *et al.*,1997, p. 600). Recently we found that this NFL state is unstable and the FL state is recovered at high pressure above several GPa (Oomi *et al.*, 2004, p. 3385). We suggest that this transition is a kind of QPT induced by high pressure.

Figure 10 shows *ρ(T)* of $Y_{0.8}U_{0.2}Pd_3$at high pressure along with that for YPd_3.It is seen that ρ(T) at 5.8 GPa is very different from those below 2GPa, particularly at low temperature below 100 K. At ambient pressure, the *ρ(T)* curve shows a linear temperature dependence below ca. 50 K. The coefficient of the linear term decreases with increasing pressure. The large difference in the *ρ(T)* curve suggests a crossover from NFL state to other electronic phase. We will discuss about the new electronic state at high pressure in section 4.

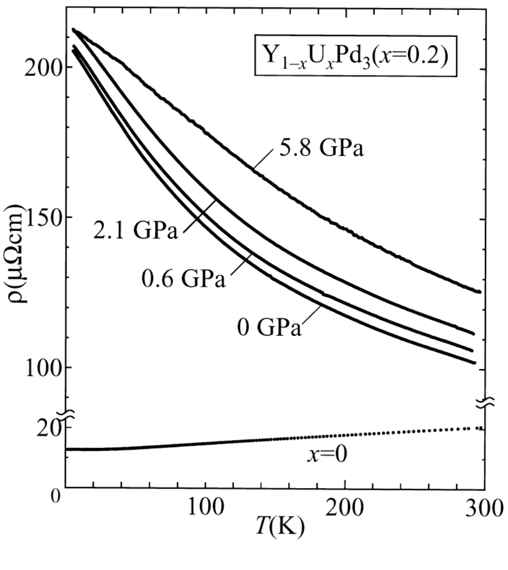

Fig. 10. *ρ(T)* as a function of *T* for $Y_{0.8}U_{0.2}Pd_3$ at high pressure including *ρ(T)* for YPd_3 as a reference.

3.3 Giant and tunnel magnetoresistances in nanoscale magnets under high pressure

(1)Effect of pressure on the tunneling conduction in Co-Al-O granular materials

A Co-Al-O granular film is a typical example of granular materials exhibiting tunnel magnetoresistance (TMR), which has a structure that Co granules (2-3 nm) are embedded in an insulating Al-oxide. The conductance of granular system is dominated by tunneling between Co granules across the insulating Al-oxide (Mitani *et al.* ,1998, p. 2779). In this transport, the charging energy of Co granules and the distance between them have been well known to be crucially important. Therefore, significant pressure effect on TMR of Co-Al-O granular films is expected. Figure 11 shows the MR ratio, $\Delta\rho(H)/\rho_{max}$ at 4.2 K as a function of magnetic field H(T) under high pressure (Kaji *et al.*,2003, p.055429). $\Delta\rho(H)/\rho_{max}$ is defined as $\Delta\rho/\rho_{max} = [\rho(H)- \rho_{max}] / \rho_{max}$, where ρ_{max} is the maximum resistivity around 50 mT. As pressure increases, the MR ratio increases from 13.5 % at ambient pressure to about 16 % at 3.1 GPa. The result indicates that the TMR is enhanced by applying pressure. Figure 12 shows the MR ratio at T = 4.2 K as a function of pressure P(GPa). The value of TMR increases by about 2 % by applying 3.1 GPa. TMR in granular system at low temperature has been explained well by the higher-order tunneling model (Takahashi and Maekawa, 1998, p. 1758). According to this theory, the magnitude of TMR in granular systems is described as

$$\Delta\rho / \rho_{\max} = 1 - (1 + m^2 P^2)^{-(n^*+1)} \cong (n^* + 1) m^2 P^2,$$

where $m = M/M_s$ is the magnetization normalized to the saturation magnetization M_s and P is spin polarization. $n^* = (\langle E_c\rangle/8\kappa'\langle s\rangle k_B T)^{1/2}$, where <s> is a mean distance between granules and $\langle E_c\rangle$ is charging energy of granules with average size, $\kappa'/\kappa \approx 1 + (1/4\kappa\langle s\rangle) \ln [(\gamma/\pi)^2 + (\langle E_c\rangle/2\pi k_B T)^2]$ and g is constant. κ is the decay factor of tunnel probability. n^* reflects the higher-order tunneling. The pressure affects mainly on <s>, so that κ' probably decreases with decreasing <s>. Taking the relation $n^* \propto (1/\kappa'\langle s\rangle)^{1/2}$ into account, n^* is expected to increases with increasing pressure. Using this relation, we calculated the TMR under high pressure(Kaji *et al.*,2003, p. 054429). The estimated values are shown in Fig. 12 by a dashed line. The result shows an increase in TMR with increasing pressure, which is qualitatively in agreement with the present experimental result. The quantitative difference is probably due to the rough approximation in the simplified model. The present result indicates that the pressure enhanced TMR is qualitatively explained on the basis of the higher-order tunneling theory.

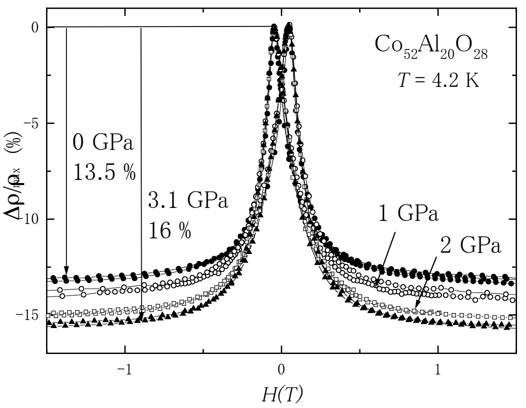

Fig. 11. MR curves measured at 4.2 K under high pressure.

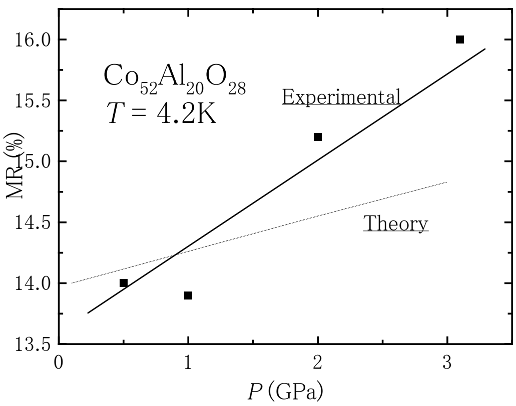

Fig. 12. Pressure dependence of the MR ratio. The dashed line shows the result of calculation.

(2) Quantum phase transition in Fe/Cr magnetic multilayers

The QPT has been reported for wide range of materials mainly for the alloys and intermetallic compounds including Ce or U magnetic elements as was mentioned in section1. But recently some examples have been found in materials including 3d transition magnetic elements such as Pd-Ni or magnetic multilayers (MML) (Nicklas *et al.*,1999, p. 4268, Aliev *et al.*,1998, p. 5884). Aliev *et al.* reported that the Fe/Cr MML shows a non Fermi liquid properties in the temperature dependence of $\rho(T)$ at magnetic fields. He pointed out that the $\rho(T,H)$ curve shows T-linear temperature dependence near the saturation magnetic field H_s, above which the resisitivity shows a saturation. Here we report the temperature dependent electrical resisitivity of $[Fe(20A)/Cr(10A)]_{20}$(hereafter abbreviated as Fe/Cr(10)) MML at high pressure.

In order to examine the temperature dependence of ρ of Fe/Cr(10), we made an attempt to fit the observed $\rho(T)$ to the following equation, $\rho(T)= \rho_0+AT^n$, where ρ_0, A and n are the constants. Figure 13 shows the values *of* $(\delta\rho(0K)- \delta\rho(T))$ at H= 0 T and 1.15 T as a function of T in the logarithmic scale, where $\delta\rho(T,H)$ is defined as $\rho(T,H)- \rho(T,H =2\ T)$. The value of H_s is around 1.10 T. From this plot it is found that $\rho(T)$ of Fe/Cr(10) is described by the power law. The values of n are obtained to be n= 2.3 and 1.1 at H= 0 and 1.15 T, respectively. This fact indicates that the power of T is nearly 1 around H_s and nearly 2 at H=0. We obtained the values of n in the range, 0< H< 1.15 T, in the same way and the result is shown in Fig. 14.The value of n at ambient pressure is almost constant below 0.5 T but it begins to decrease with increasing H above 0.5 T. Near H_s, the value of n is nearly 1 or smaller than *i*. This result is in agreement with the results obtained by Aliev *et. al*. (Aliev *et al.*,1998, p. 5884). This fact implies that the MML of Fe/Cr (10) shows a quantum phase transition near H_s.

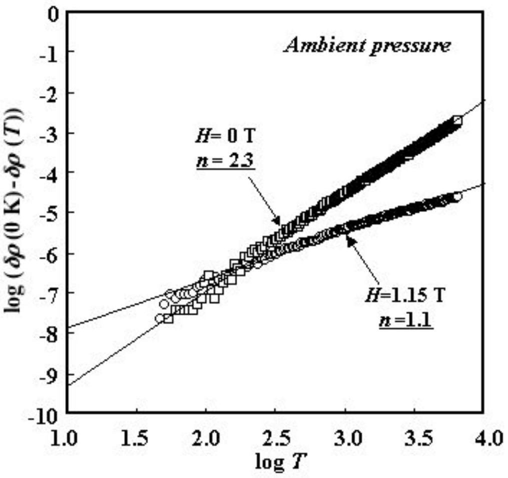

Fig. 13. log(δρ(0K)-δρ(T)) vs. log T of H=1.15 T and H=0 at ambient pressure.

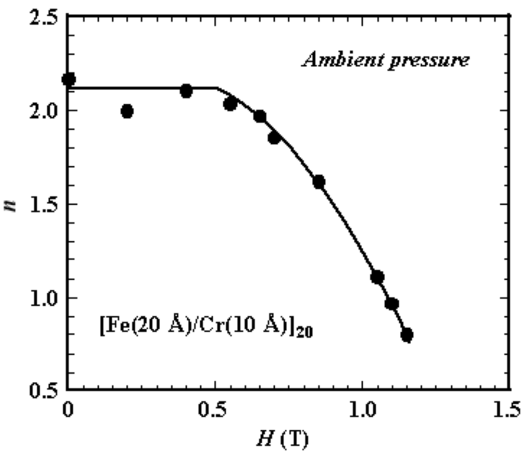

Fig.14. n vs. H at ambient pressure.

It is well established that H_s is dominated by pressure, in which H_s of Fe/Cr(10) increases with increasing pressure (G. Oomi *et al.,*1997). This fact indicates that the quantum phase transition in Fe/Cr MML depends significantly on the application of pressure. In the present work we examined the effect of pressure on the quantum phenomena in the Fe/Cr(10). Figure 15 shows the log-log plot of $(\delta\rho(0K)-\delta\rho(T))$ versus T for both P= 0.1 and 2.5 GPa. It is found that n at ambient pressure is 2.3 but 1.8 at 2.5 GPa, i.e., the magnitude of power n at H= 0 decreases with increasing pressure below H_s. These results indicate that the quantum phase transition is dominated by not only H_s but also by P.

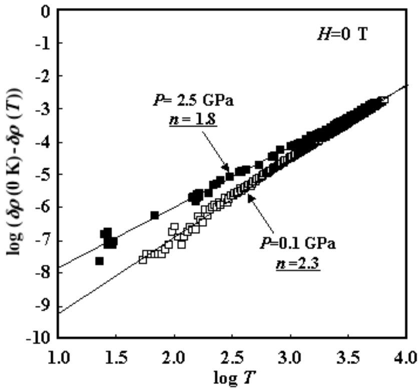

Fig.15. log(δρ(0K)-δρ(T)) vs. log T of P= 2.5 GPa and P= 0.1 GPa at H= 0.

4.Discussion

4.1 Pressure-induced crossover in heavy Fermion materials -the analysis by using Grüneisen parameters-

In order to discuss the volume dependence of T_K in detail, we analyzed the present result as follows (Yoshimori and Kasai, 1983 p. 475, Kagayama and Oomi, 1995, p. 1227, Kagayama and Oomi, 1996, p. 42). The Grüneisen parameter of T_K is defined as,

$$\Gamma \equiv -\frac{\partial \ln T_K}{\partial \ln V} \quad . \qquad (1)$$

Since the coefficient A of T^2-term is inversely proportional to $T_K{}^2$, i.e., $A \propto 1/T_K{}^2$, we have,

$$\Gamma = \frac{1}{2}\frac{\partial \ln A}{\partial \ln V} \quad . \qquad (2)$$

Equation(2) can be rewritten as follows,

$$\frac{1}{2}\ln\left[\frac{A(P)}{A(0)}\right] = \Gamma \ln\left(\frac{V}{V_0}\right). \qquad (3)$$

In Fig. 16, we plot the relative change of A against that of volume for $CeAl_3$ in logarithmic scale (Kagayama and Oomi, 1995, p. 1227), in which the pressure is included as an implicit variable. The slope in Fig.16 corresponds to the magnitude of Γ. From tangent at the origin of this plot, the value of Γ is estimated to be 97 at ambient pressure, which is extremely large because the Γ–values of normal metals and alloys are of the order of 1-10. As is seen in Fig. 16, the Γ is dependent on the volume change or pressure. The slope (Γ) becomes smaller as the change in volume is larger (higher pressure). Since the system shows a crossover from low-T_K to high-T_K state induced by pressure, it is expected that Γ decreases at high pressure. This result agrees with the fact that the values of Γ for IV materials having large T_K are smaller than those of low-T_K HF materials (Sawamura *et al.*,1997, p. 106).

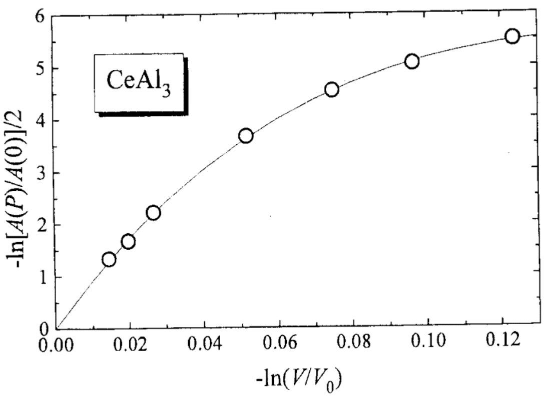

Fig. 16. A(P)/A(0) as a function of relative volume V/V_0 for $CeAl_3$ in logarithmic scale.

From the results for $CeRh_2Si_2$ shown in Figs. 8 and 9, Γ at ambient pressure is estimated to be 42, which is extremely large and comparable with those of heavy Fermion compounds 59 and 65 for $CeInCu_2$ and $CeCu_6$, respectively(Kagayama, and Oomi,1993, p. 155).

4.2 Collapse of non Fermi liquid state under high pressure.

In this subsection, we will consider briefly about the new electronic state of $Y_{0.8}U_{0.2}Pd_3$ at 5.8 GPa, which was shown in Fig. 10. To compare the electronic state at 5.8 GPa with that at ambient pressure, the $\rho_{mag}(T)$ curves are illustrated in Fig.17 together with that for $Y_{0.95}UP_{0.05}d_3$, which shows typical Fermi liquid behavior, i.e., the T^2 dependence in $\rho_{mag}(T)$ is observed. It is easily seen that the overall behavior of $\rho_{mag}(T)$ at 5.8 GPa is similar to that for $Y_{0.95}U_{0.05}Pd_3$. This fact implies that the electronic state of $Y_{0.8}U_{0.2}Pd_3$ at 5.8 GPa is considered as a normal FL.

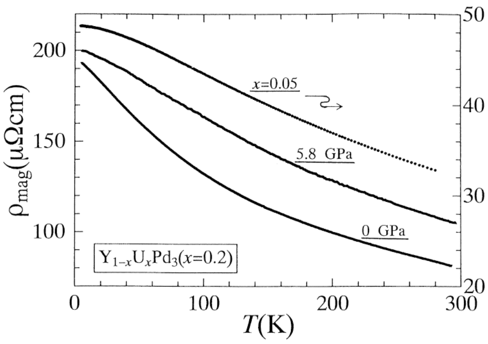

Fig.17 The temperature dependence of ρ_{mag} for x= 0.2 at 0 and 5.8 GPa and for x = 0.05 for comparison, in the chemical formula, of $Y_{1-x}U_xPd_3$.

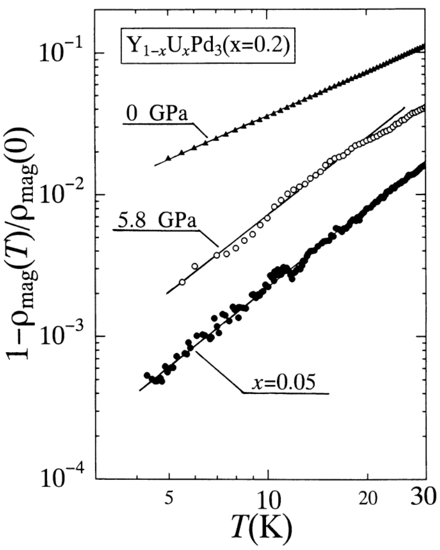

Fig.18 The normalized electrical resistivity, $\rho_{mag}(T)/\rho_{mag}(0)$, as a function of temperature T, for $Y_{0.8}U_{0.2}Pd_3$.

In order to confirm this consideration more clearly, the normalized resistivity, 1-$\rho_{mag}(T)/\rho_{mag}(0)$, is plotted in Fig.18 as a function of temperature in the logarithmic scale below 30 K. It is found that $\rho_{mag}(T)$ of $Y_{0.8}U_{0.2}Pd_3$ below 30 K changes its temperature dependence from the T-linear dependence (n=1.0) at ambient pressure to T^2 dependence (n= 1.9) below about 17 K at 5.8 GPa. It is also observed that $\rho_{mag}(T)$ of $Y_{0.8}U_{0.2}Pd_3$ at 5.8 GPa is parallel to that of $Y_{0.95}U_{0.05}Pd_3$, which is also a direct evidence of FL behavior.

Thus the electronic state of $Y_{0.8}U_{0.2}Pd_3$ at 5.8 GPa is confirmed to be in the normal FL state. In other words, the present results indicate that the NFL state of $Y_{0.8}U_{0.2}Pd_3$ at ambient pressure becomes unstable at high pressure and the FL state recovers above 4-5 GPa.

5.Conclusion

In the present work, we obtained the following results,

1) The heavy Fermion state of $CeAl_3$ becomes unstable at high pressure to show a crossover from low T_K to high T_K intermediate valence state,
2) The Grüneisen parameter of T_K of $CeAl_3$, 97, is extremely large, but it decreases with increasing pressure.
3) The antiferromagnetism of $CeRh_2Si_2$ disappears around 1 GPa, above which the heavy Fermion state is stabilized with a large Grüneisen parameter of 47.
4) $Y_{0.8}U_{0.2}Pd_3$ shows a pressure-induced crossover from the non Fermi liquid state to Fermi liquid state.
5) The tunnel magnetoresistance of Co-Al-O is enhanced by applying pressure, which is explained by assuming the higher order tunneling theory.
6) A quantum phase transition is observed in Fe/Cr magnetic multilayers, in which the power in the temperature dependence is suppressed by pressure.

References

ALIEV, F. G., MOSHCHALCOV, V. V., BRUYNSERAEDE, Y., Quantum Phase Transition in Fe/Cr multilayers tuned by a magnetic field, 1998, *Physical Review Letters*., **81** 5884-5887.

ANDRAKA B., TSVELIK, A. M., 1991, Observation of non-Fermi-liquid behavior in $U_{0.2}Y_{0.8}Pd_3$, *Physical Review Letters*, **67** 2886-2889.

ANDRES, K., GRAEBNER, J. E., Ott, H. R., 1975, 4*f*-virtual-bound-state formation in $CeAl_3$ at low temperatures, *Physical Review Letters*. **35** 1779-1782.

BRANDT, N. B., MOSHCHALKOV, V. V., 1984, Concentrated Kondo systems, Adv. in Phys. **33** 373-467.

CHAU, R., HAN, S. H., MAPLE, M. B., LÖHNEYSEN, H. V., ARONSON, M. C., 1997, Pressure-dependent electrical resistivity in $UCu_{5-x}Pd_x$, Physica B, **230-232**, 600-602.

CORNUT, B., COQBLIN, B., 1972, Influence of crystalline field on Kondo effect of alloys and compounds with cerium impurities, Phys. Rev. B **5** 4541-4561.

FLOUQUET, J., LASJAUNIAS, J. C., PEYRARD, J., RIBAULT M., R, 1982, Low-Temperature Properties of $CeAl_3$, J. Appl. Phys. **53** 2127-2130.

GRAF, T., HUNDLEY, M. F., MODLER, R., MOVSHOVICH, M., MADRUS, D., FISHER, R. A. PHILLIPS N. E., 1998, Magnetic phase transition in $CeRh_2Si_2$: specific heat, susceptibility, and resistance studies, Phys. Rev. B **57** 7442-7445.

HONDA, F., KAJI, S., MINAMITAKE, I., OHASHI, M., OOMI, G., ETO, T., KAGAYAMA, T., 2002, High pressure apparatus for the measurement of thermal and transport properties at multi-extreme conditions, J. Phys.: Condens. Matter **14** 11501-11505.

KAGAYAMA, T., OOMI, G., TAKAHASHI, H., MÔRI, N., ŌNUKI, Y., KOMATSUBARA, T.,

1991, Pressure-Induced Valence Instability of the Heavy-fermion Compound $CeInCu_2$, Phys. Rev. B **44** 7690-7693.
KAGAYAMA, T., OOMI, G., 1993, Collapse of the heavy fermion state under high pressure, transport and thermal properties of f-electron systems ed. G. Oomi, H. Fujii and T. Fujita (Plenum, New York) p.155-164.
KAGAYAMA, T., OOMI, G., ITO, E., ŌNUKI, Y., KOMATSUBARA, T., 1994, Volume Dependent Grüneisen Parameter in the Heavy Fermion Compound $CeInCu_2$, J. Phys. Soc. Jpn. **63** 3927-3930.
KAGAYAMA, T., OOMI, G., 1995, X-ray diffraction study of the heavy fermion compound $CeAl_3$ at high pressure, J. Magn. Magn. Mater. **140-144** 1227-1228.
KAGAYAMA, T., 1995, Dr. thesis (Kumamoto Univ.) (in Japanese).
KAGAYAMA, T., OOMI, G., 1996, Effect of pressure and magnetic field on the electrical resistivity of cerium kondo compounds, J. Phys. Soc. Jpn. **65** Suppl. B 42-48.
KAGAYAMA, T., unpublished.
KAJI, S., OOMI, G., MITANI, S., TAKAHASHI, S., TAKANASHI, K., MAEKAWA, S., 2003, Pressure enhanced tunnel magnetoresistance in Co-Al-O granular films. *Physical Review B*, **68**, 054429 (5 pages).
KAWARAZAKI, S., SATO, M., MIYAKO, Y., CHIGUSA, N., WATANABE, K., METOKI, N., KOIKE, Y., NISHI, M., 2000, Ground-state magnetic structure of $CeRh_2Si_2$ and the response to hydrostatic pressure as studied by neutron diffraction, Phys. Rev. B **61** 4167-4173.
MIGNOT, J. M., WITTING, J., 1982, Very-high-pressure resistivity of $CeIn_3$ and YbCuAl, Valence Instabilities, ed. P. Wachter and H. Boppart (North-Holland) p. 203-206.
MITANI, S., TAKAHASHI, S., TAKANASHI, K., YAKUSHIJI, K., MAEKAWA, S., FUJIMORI, H., 1998, Enhanced Magnetoresistance in Insulating Granular Systems: Evidence for Higher-Order Tunneling. *Physical Review Letters*, **81**, 2799-2802.
NICKLAS, M., BRANDO, M., KNEBEL, G., TRINKL, W., LOIDL, A., 1999, Non-Fermi-liquid behavior at a ferromagnetic quantum critical point in Ni_xPd_{1-x}, *Physical Review Letters*, **82**, 4268-4281.
OHASHI, M., OOMI, G., KOIWAI, S., HEDO, M., UWATOKO, Y., 2003, Fermi-liquid instability of $CeRh_2Si_2$ near a pressure-induced quantum phase transition, Phys. Rev. B **68** 144428 (7 pages).
OOMI, G., 2004, High pressure studies of anomalous electronic states of $Y_{1-x}U_xPd_3$, *J. Phys.:Condens. Matter,* **16**, 3385-3400.
SAWAMURA, T., KAGAYAMA, T., OOMI, G., 1997, Kondo state of mixed-valent compound $CePd_3$ under high pressure, Physica B, **239**, 106-108
SEAMAN, C. L., MAPLE, M. B., LEE, B. W., GHAMATY, S., TORIKACHVILI, M. S., KANG, J. S., LIU, L. Z., ALLEN, J. W., COX, D. L., 1991, Evidence for non-Fermi liquid behavior in the Kondo alloy $Y_{1-x}U_xPd_3$, *Physical Review Letters*, **67** 2882-2885.
SEVERING, A., HOLLAND-MORITZ, E., FRICK, B., 1989, Spin dynamics of CeX_2Si_2 (X=Au, Pd, Rh, Ru) , Phys. Rev. B **39**, 4164-4174.
STEWART, G. R., 1984, Heavy-fermion systems, Rev. Mod. Phys. **56**,755-787.
TAKAHASHI, S., MAEKAWA, S., 1998, Effect of Coulomb Blockade on Magnetoresistance in Ferromagnetic Tunnel Junctions. *Physical Review Letters*, **80**, 1758-1761.
THOMPSON, J. D., LAWRENCE, J. M., 1994, High pressure studies - physical properties of anomalous Ce, Yb and U compounds, Handbook on the Physics and Chemistry of Rare Earths ed. K. A.Gschneidner, Jr. et.al. (Elsevior, Amsterdam) Vol.19, p.383.
YOSHIMORI, A., KASAI, H., 1983, J. Magn Magn. Mater. **31-34,** 475-476.