Reply to comment by T. Terashima et al. on “Quantum criticality and nodal superconductivity in the FeAs-based superconductor KFe$_2$As$_2$”

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(Dated: May 21, 2010)

PACS numbers: 74.70.Xa, 74.20.Rp, 74.25.fc, 74.40.Kb

In our recent Letter,$^1$ we report the demonstration of a field-induced antiferromagnetic quantum critical point (QCP) and nodal superconductivity in KFe$_2$As$_2$. The evidences for a QCP include non-Fermi-liquid $\rho(T) \sim T^{1.5}$ at the upper critical field $H_{c2} = 5$ T and the development of a Fermi liquid state with $\rho(T) \sim T^2$ when further increasing the field. The coefficient $A$ of the $T^2$ term also tends to diverge towards $H_{c2} = 5$ T.

Terashima et al.$^2$ point out that our $H_{c2}$(onset) = 5 T, determined from the onset of the resistive transition, is much higher than their $H_{c2} = 1.25$ T, determined from the midpoint of the resistive transition. They attribute this large difference in $H_{c2}$ to the broad resistive transition of our sample, which indicates inhomogeneity in the sample. Therefore, they doubt if the $\rho(T) \sim T^{1.5}$ behavior of resistivity at $H_{c2}$(onset) = 5 T relates to quantum criticality. Their recent de Haas-van Alphen (dHvA) results$^3$ also do not support our proposed QCP at $H_{c2}$(onset) = 5 T in KFe$_2$As$_2$.

Recently, we have measured another KFe$_2$As$_2$ single crystal (S2). As seen in Fig. 1(a), the 10-90% transition width of S2 is 0.32 K, much smaller than 1.35 K of previous reported sample (S1) in Ref. [1]. This suggests that S2 is more homogeneous than S1. The sample S2 also has lower residual resistivity $\rho_0 = 1.49 \, \mu\Omega$ cm, and higher residual resistivity ratio (RRR) $\rho(290 \, K)/\rho(3 \, T) = 265$. In Fig. 1(b), $\rho(T)$ of S2 manifests $T^{1.5}$ dependence from $T_c$(onset) up to 11 K in zero field. From Fig. 1(c), $H_{c2}$(onset) = 3 T is obtained for S2, where $\rho(T) \sim T^{1.5}$ persists down to 50 mK. When further increasing the field, the $\rho(T) \sim T^2$ Fermi-liquid behavior is observed at lowest temperature for S2.

Since $H_{c2}$(onset) of S2 is significantly smaller than that of S1, we realize that the non-Fermi-liquid behavior of $\rho(T)$ at $H_{c2}$(onset) does not determine a QCP at $H_{c2}$(onset) for KFe$_2$As$_2$. In fact, for CeCoIn$_5$, while specific heat data demonstrated a QCP at the bulk $H_{c2} = 5$ T, non-Fermi-liquid $\rho(T) \sim T$ down to lowest temperature was found at higher field $H = 6$ T$^4$. We attribute this misfit to the inhomogeneity of the sample. At the QCP $H_{c2} = 5$ T, while the bulk of the CeCoIn$_5$ sample obeys $\rho(T) \sim T$, the rest of the sample still shows resistive transition, thus one can not observe $\rho(T) \sim T$ at the QCP. With increasing field, at $H = 6$ T, the bulk of the sample slightly develops $\rho(T) \sim T^2$ behavior, which balances the remaining resistive drop of the rest part of the sample, and gives an accidental $\rho(T) \sim T$ behavior. Only for extremely homogeneous sample with nearly zero resistive transition width, one may not notice this misfit since $H_{c2}$(onset) is almost equal to the bulk $H_{c2}$. We believe that this is also the case for KFe$_2$As$_2$, and the QCP, if exists, may locate at the bulk $H_{c2}$ as in CeCoIn$_5$.

Since the bulk of KFe$_2$As$_2$ have developed Fermi liquid state at $H = 5$ T, it is not surprising that dHvA oscillations were observed in a field range near 5 T$^3$. For our high-quality sample S2, we also find that the coefficient $A (= 0.0649, 0.0533$, and $0.0508 \, \mu\Omega \, cm/K^2$ for 5, 8, and 12 T, respectively) shows a slower field dependence than that of sample S1. This is consistent with the near constant effective mass $m^*$ in the field range $7 < H < 17.65$ T$^3$, which is far away from the QCP (if exists) near the bulk $H_{c2} \approx 1.25$ T.

In summary, we agree with Terashima et al.$^2$ that $H_{c2}$(onset) = 5 T is not a QCP for KFe$_2$As$_2$. The non-Fermi-liquid $\rho(T) \sim T^{1.5}$ at $H_{c2}$(onset) and the development of a Fermi liquid state with $\rho(T) \sim T^2$ when further increasing the field only suggest a QCP at the bulk $H_{c2}$. Bulk measurements, such as specific heat, are needed to confirm this field-induced QCP at $H_{c2}$ in KFe$_2$As$_2$.

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FIG. 1: (Color online). (a) Low-temperature resistivity of KFe$_2$As$_2$ single crystals S1 and S2 in zero magnetic field. (b) The same data in (a) plotted as $\rho$ vs $T^{1.5}$. The solid lines are fits to $\rho = \rho_0 + AT^{1.5}$. (c) $\rho$ vs $T^{1.5}$ for sample S2 in $H = 2, 3, 4, 5,$ and $8$ T (data sets are offset for clarity). The solid line is a fit of the $H = 3$ T data between 50 mK and 4 K. The dash lines are guides to the eye for the deviation from the $T^{1.5}$ dependence.