Band-Selective Modification of the Magnetic Fluctuations in Sr$_2$RuO$_4$: Study of Substitution Effects

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We report a study of magnetic, thermal, and transport properties of La$^{3+}$ substituted Sr$_2$RuO$_4$, performed in order to investigate the effects of additional electron doping in this correlated metal. A gradual enhancement of the electronic part of specific heat and a more drastic increase of the static magnetic susceptibility were observed in Sr$_{2-x}$La$_x$RuO$_4$ with increasing $y$. Furthermore, the quasi-two-dimensional Fermi-liquid behavior seen in pure Sr$_2$RuO$_4$ breaks down near the critical concentration $y_c \sim 0.20$. Combined with a realistic tight-binding model with rigid-band shift of Fermi level, the enhancement of the density of states can be ascribed to the elevation of the Fermi energy toward a van Hove singularity of the thermodynamically dominant $\gamma$ Fermi-surface sheet. On approaching the van Hove singularity, the effective nesting-vecor of the non-Fermi-liquid behavior to two-dimensional ferromagnetic fluctuations with short range correlations at the van Hove singularity. The observed behavior is in sharp contrast to that of Ti$^{4+}$ substitution in Sr$_2$RuO$_4$ which enhances antiferromagnetic fluctuations and subsequently induces incommensurate magnetic ordering associated with the nesting between the other Fermi-surface sheets ($\alpha$ and $\beta$). We thus establish that substitution of appropriate chemical dopants can band-selectively modify the spin-fluctuation spectrum in the spin-triplet superconductor Sr$_2$RuO$_4$.

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I. INTRODUCTION

Since the discovery of the superconductivity in the layered perovskite Sr$_2$RuO$_4$ \cite{1}, the material has been the subject of intense research \cite{2} for the following reasons. First, the superconductivity (with transition temperature $T_c = 1.5$ K) is of unconventional pairing symmetry, most probably spin triplet \cite{2}. Second, a highly conductive metallic state with mean free path $\ell > 1 \mu$m can be achieved, reflecting the well hybridized Ru 4$d$ and O 2$p$ character of the conduction bands in the stoichiometric material. This made it possible to clarify the detailed electronic structure by means of de Haas-van Alphen (dHvA) experiments \cite{2} \cite{4} \cite{5} and angle-resolved photoemission-spectra (ARPES) with \cite{6} results that are in qualitative agreement with band structure calculations \cite{7} \cite{8}: the Fermi surface consists of one hole sheet ($\alpha$) and two electron sheets ($\beta$ and $\gamma$). The $\alpha$ and $\beta$ bands are formed by the Ru $d_{yz}$ and $d_{xz}$ orbits, while the $\gamma$ band has $d_{xy}$ orbital character. On the basis of the cylindrical Fermi-surface topography, normal-state properties are described quantitatively within the framework of a quasi-two-dimensional Fermi-liquid \cite{7} \cite{8}.

For a strongly correlated, unconventional superconductor like Sr$_2$RuO$_4$, knowledge of the relationship between the superconductivity and the magnetic fluctuations is of fundamental importance in order to clarify the pairing mechanism. This is strikingly exemplified by a number of $f$-electron systems and in the high-$T_c$ cuprates, where the superconductivity emerges near regions of magnetic instability \cite{10} \cite{11} \cite{12}. In those cases, the magnetic instability point is reached by driving the magnetic ordering temperature to zero by tuning parameters such as pressure and carrier doping by chemical substitution \cite{13}. Also, non-Fermi-liquid normal state behavior is often observed in the vicinity of the quantum critical points.

Spin fluctuations are thought to act as the “magnetic glue” responsible for the superconducting pairing in many of these cases, including, as theoretically suggested, Sr$_2$RuO$_4$ \cite{14}. Experimentally, a more direct signature of spin fluctuations can be found in inelastic neutron scattering measurements. In Sr$_2$RuO$_4$, recent experiments revealed a weak, broadened structure around...
van Hove Singularity (vHS) of the Fermi energy is located 49 meV below a van Hove singularity (vHS) of the γ band. Note that the Fermi-energy is located 49 meV below a van Hove singularity (vHS) of the γ band. When the Fermi energy crosses the Fermi-surface changes from an electron pocket (left inset) to a hole pocket (right inset) when the Fermi energy crosses the van Hove singularity at additional electron doping level of \( y_c \sim 0.23/\text{f.u.} \).

Although substitution studies involve the introduction of disorder, they have the significant advantage of being “clean”, i.e. of not introducing disorder, but in the range of parameters used so far on \( \text{Sr}_2\text{RuO}_4 \), no magnetic instabilities have been discovered.

Attempts have been made to probe the proximity to magnetic quantum critical points by applying strong magnetic field \([18]\) or hydrostatic pressure \([19]\). These attempts of the necessity of higher temperature and therefore an introduction of additional electrons to the metallic bands at the Fermi energy. Also, structural distortions are minimized because of the similar ionic radii between \( \text{Sr}^{2+} \) and \( \text{La}^{3+} \). La substitution therefore provides a gentle way to study the effect of changing carrier concentration in the correlated metal and unconventional superconductor \( \text{Sr}_2\text{RuO}_4 \). We achieved electron doping up to \( y = 0.27 \), where the tight-binding calculation places the Fermi energy of the material well beyond the vHS. The main contribution of the enhancement of the DOS is confirmed to be due to the approach towards the vHS of the γ band. At the same time, the nesting wave vector of the γ band is shrinking towards \( q \sim 0 \) at the vHS, further enhancing the low-\( q \) susceptibility. We observe non-Fermi-liquid behavior around the “critical” doping level of \( y_c \sim 0.20 \) and attribute it to two-dimensional ferromagnetic fluctuations with short range correlations. The evolution of the ferromagnetic fluctuations with electron doping is in sharp contrast to the enhancement of the antiferromagnetic fluctuations induced by Ti substitution \([21, 22]\).

Throughout this paper, we stress that substitution of appropriate dopants into \( \text{Sr}_2\text{RuO}_4 \) can band-selectively modify the magnetic fluctuation spectrum.

II. EXPERIMENTAL

Single crystals of \( \text{Sr}_{2-x}\text{La}_x\text{RuO}_4 \) with \( y \) up to 0.27 were grown by a floating-zone method in an infrared image furnace (NEC Machinery, model SC-E15HD). Although it was difficult to grow crystals with increasing \( y \) because of the necessity of higher temperature and therefore an unstable molten zone during crystal growth, we finally succeeded in obtaining large crystals with typical size of \( 4 \text{ mm} \times 3 \text{ mm} \times 0.2 \text{ mm} \).

The La concentrations of the crystals were analyzed by electron-probe microanalysis (EPMA). Up to \( y = 0.14 \), the La substitutes well for Sr. On the other hand, we found that the analyzed La concentration \( y_{th} \) deviates from the nominal La concentration \( y_n \) for \( y_{th} > 0.14 \): the \( y_{th} \) varies roughly as \( y_{th} \sim 0.3y_n + 0.12 \). We confirmed tetragonal crystal symmetry for all \( \text{Sr}_{2-x}\text{La}_x\text{RuO}_4 \) crystals used in this study at room temperature from X-ray measurement. The lattice parameter along the in-plane (a axis) increases by \( \sim 0.5\% \) and that perpendicular to the plane (c axis) decreases by \( \sim 0.4\% \) continuously with \( y \) up to \( y = 0.27 \). The crystal symmetry and the change of lattice parameter by La doping are consistent with...
previous work on polycrystals.

Magnetic susceptibility measurements were performed using a commercial superconducting quantum interference device magnetometer down to 1.8 K (Quantum Design, MPMS-XL). The specific heat $C_P$ was measured by a thermal relaxation method from 0.5 K to 30 K (Quantum Design, model PPMS). The electrical resistivity was measured by standard four-probe dc and ac methods between 4.2 and 300 K and by an ac method between 0.3 and 5 K.

### III. RESULTS

#### A. Static magnetic susceptibility

Figure 2 shows the temperature dependence of the static magnetic susceptibility $\chi(T) = M/H$ of $\text{Sr}_{2-y}\text{La}_y\text{RuO}_4$ with $y$ up to 0.27 in an applied field of 1 T along (a) the basal $(ab)$ plane and (b) the $c$ axis. $T_M$ indicates the characteristic temperature at which $M/H$ shows a peak.

**Figure 2:** Temperature dependence of the magnetic susceptibility $\chi(T) = M/H$ of $\text{Sr}_{2-y}\text{La}_y\text{RuO}_4$ with $y$ up to 0.27 in an applied field of 1 T along (a) the basal $(ab)$ plane and (b) the $c$ axis. $T_M$ indicates the characteristic temperature at which $M/H$ shows a peak.

#### B. Specific heat

Figure 3 shows the temperature dependence of specific heat divided by temperature $C_P/T$ for $\text{Sr}_{2-y}\text{La}_y\text{RuO}_4$ up to $y = 0.27$ and down to $T = 0.5 K$. There is no sign of a phase transition, magnetic or otherwise, in line with the susceptibility results. The data for pure $\text{Sr}_2\text{RuO}_4$ ($y = 0$) were obtained by applying a magnetic field of 0.2 T along the $c$ axis in order to suppress the superconductivity ($T_c = 1.44$ K); the data for $\mu_0H = 0$ T essentially overlap with the data for 0.2 T for $T > 1.5$ K.

**Figure 3:** Temperature dependence of $C_P/T$ in $\text{Sr}_{2-y}\text{La}_y\text{RuO}_4$ up to $y = 0.27$. For pure $\text{Sr}_2\text{RuO}_4$ ($y = 0$) a magnetic field of 0.2 T was applied along the $c$ axis to suppress the superconductivity.
This result shows that out-of-plane La$^{3+}$ doping levels introduce less severe disorder within the conduction layers at the rate of $\sim 0.20$, as seen in Fig. 4(b). The residual resistivity $\rho_{c}$, defined by the extrapolation of the low temperature behavior ($d\rho_{c}/dT < 0$) at high temperature to metallic one ($d\rho_{c}/dT > 0$) at low temperature [34] moves monotonically to lower temperature with $y$ as seen in Ti-substituted Sr$_2$RuO$_4$ [23]. The residual resistivity $\rho_{c0}$ increases with doping with a slope $d\rho_{c0}/dy \sim 70 \text{ m}\Omega \text{ cm}/y$. At the same time, the resistivity anisotropy $\rho_{c}/\rho_{ab}$ at low temperatures remains around $2 \times 10^{3}$ for all dopant concentrations. Also, the temperature region over which a Fermi-liquid-like $T^2$ law is valid for $\rho_{c}$ is almost identical to that for $\rho_{ab}$. This result implies that the low-temperature transport mechanism along the $c$ axis is hardly affected by electron doping: the quasi-particles can propagate coherently between the RuO$_2$ layers at low temperatures.

### C. In- and out-of-plane resistivity

Figure 4(a) shows the in-plane resistivity $\rho_{ab}$ for various doping levels $y$, plotted against $T^2$. The residual resistivity $\rho_{ab0}$, defined by the extrapolation of the low temperature resistivity to $T = 0$ K, increases systematically with $y$ at the rate of $d\rho_{ab0}/dy \sim 40 \mu\Omega \text{ cm}$, that is, with a phase shift of impurity scattering $\delta_{0} \sim \pi/12$. The enhancement is much smaller than that seen in in-plane substituted Sr$_2$RuO$_4$ such as Sr$_2$Ru$_{1-x}$Ti$_x$O$_4$ and Sr$_2$Ru$_{1-x}$Ir$_x$O$_4$, where both Ti$^{3+}$ and Ir$^{4+}$ impurities act as unitary potential scatterers with $\delta_{0} \sim \pi/2$. This result shows that out-of-plane La$^{3+}$ substitution for Sr$^{2+}$ introduces less severe disorder within the conductive RuO$_2$ planes.

Another important result in Fig. 4(a) is the breakdown of the Fermi-liquid behavior around $y = 0.20$: the $T$-squared dependence $\rho_{ab} = AT^2 + \rho_{ab0}$ with $n = 2$, satisfied below about 30 K for pure Sr$_2$RuO$_4$ [9], starts to break down with $y$. This is displayed in Fig. 4(a) by the fact that the temperature range in which the $T$-squared fitting is valid shrinks with $y$ [31]. Also, the coefficient $A \times m_e^2/n_e$ gradually increases around $y \sim 0.20$, indicating the enhancement of the correlation among electrons by La doping. Here, $m_e$ and $n_e$ are the electron effective mass and carrier density, respectively. Our best fit for $y = 0.20$ is obtained with $n = 1.4 \pm 0.05$. As added in the inset of Fig. 4 the $T^1.4$ behavior is well satisfied between 0.3 and 10 K over more than one decade in temperature. It should be noted that such a deviation from Fermi-liquid behavior is not explained by an effect of disorder by La, because the $T$-squared behavior is recovered for $y = 0.27$ below $\sim 7$ K.

The temperature dependence of the resistivity along the $c$ axis, $\rho_{c}$, for various $y$ is presented in Figure 4(b). The crossover temperature from non-metallic behavior ($d\rho_{c}/dT < 0$) at high temperature to metallic one ($d\rho_{c}/dT > 0$) at low temperature [32] moves monotonically to lower temperature with $y$ as seen in Ti-substituted Sr$_2$RuO$_4$ [23]. The residual resistivity $\rho_{c0}$ increases with doping with a slope $d\rho_{c0}/dy \sim 70 \text{ m}\Omega \text{ cm}/y$. At the same time, the resistivity anisotropy $\rho_{c}/\rho_{ab}$ at low temperatures remains around $2 \times 10^{3}$ for all dopant concentrations. Also, the temperature region over which a Fermi-liquid-like $T^2$ law is valid for $\rho_{c}$ is almost identical to that for $\rho_{ab}$. This result implies that the low-temperature transport mechanism along the $c$ axis is hardly affected by electron doping: the quasi-particles can propagate coherently between the RuO$_2$ layers at low temperatures.

### D. Phase diagram of Sr$_{2-y}$La$_y$RuO$_4$

The phase diagram of Sr$_{2-y}$La$_y$RuO$_4$ is presented in Fig. 5 from (a) the in-plane resistivity and (b) the specific heat measurements. The substitution of La leads to the suppression of the characteristic temperature of the Fermi-liquid behavior [34] in addition to the suppression of $T_C$ around $y \sim 0.03$ as described in ref. [32]. Finally, for $y \sim 0.20$, we can see the breakdown of the Fermi-liquid behavior ($n = 1.4$) at low temperature. Also, the enhancement of $C_p/T$ at 0.5 K in Fig. 5(b) suggests deviation from Fermi-liquid behavior in the temperature dependence of $C_p/T$ (Fig. 3). This behavior may imply the presence of a quantum critical point, near $y = 0.20$, although no magnetically ordered state has been identified in this study. The critical concentration $y \sim 0.20$ is in good agreement with the prediction from tight-binding calculations, where $y_c$ is evaluated as 0.23 [6, 27].
IV. DISCUSSION

A. Enhancement of the density of states of the γ band by electron doping in Sr$_2$RuO$_4$

Let us first discuss the origin of the enhancement of the density of states by electron doping as seen in the specific heat in Fig. 4. In the band calculation based on a tight-binding model, whose parameters are determined by a fit to the experimentally-observed Fermi surfaces [3], the Fermi energy is located 49 meV below a vHS of the γ band as shown in Fig. 1, whereas such a singularity is not expected for the α and β bands [3, 8]. The Fermi energy coincides with the singularity at a doping level of an additional 0.23 electrons/f.u., if a rigid-band model is applicable to this system [3]. Very recently, we confirmed the rigid-band model to be valid with good quantitative agreement in Sr$_{2-y}$La$_y$RuO$_4$ up to $y=0.06$ in a comparison between quantum oscillation measurements (de Haas-van Alphen effect) and tight-binding calculations [32]. Here we find experimentally that the critical doping value appears to be 0.20 rather than 0.23 electrons/f.u. (Fig. 5). This indicates a very slight departure from the value appears to be 0.20 rather than 0.23 electrons/f.u. [32]. Here we find experimentally that the critical doping

B. Enhancement of the γ band magnetic susceptibility at $q \sim 0$ by electron doping in Sr$_2$RuO$_4$

On the basis of the rigid-band model described above, we now discuss the contributions from the γ band to the magnetic and thermal properties when additional electrons are doped into Sr$_2$RuO$_4$. Figure 6 shows the momentum dependence of the real part of the Lindhard susceptibility of Sr$_{2-y}$La$_y$RuO$_4$ up to $y=0.27$ based on the realistic tight-binding band-structure and a rigid-band shift. The contributions of the α, β bands (upper panel) and the γ band (lower panel) are presented separately, normalized to their values at $q=0$ and $y=0$. The inset shows the La concentration dependence of the static susceptibility ($q=0$) of the the α, β bands (open circles) and the γ band (closed circles), with the $y=0$ values indicating the relative contributions of (α, β) and γ to the bare density of states.

\[ \chi(q) = \sum_{\text{bands}} \rho_{\text{bands}}(q) \]

Here \( \rho_{\text{bands}}(q) \) is the density of states at momentum $q$ for each band. The expressions for $\rho_{\alpha\beta}(q)$ and $\rho_{\gamma}(q)$ are:

\[ \rho_{\alpha\beta}(q) = \rho_{\alpha}(q) + \rho_{\beta}(q) \]

\[ \rho_{\gamma}(q) = \rho_{\gamma}(q) \]

The sum is over the α, β, and γ bands, and $\rho_{\text{bands}}(q)$ is the density of states at momentum $q$ for each band. The susceptibility $\chi(q)$ is then defined as:

\[ \chi(q) = \sum_{\text{bands}} \rho_{\text{bands}}(q) \chi_{\text{bands}}(q) \]

where $\chi_{\text{bands}}(q)$ is the magnetic susceptibility for each band.
changes little apart from a small shift in \( Q^\gamma_{ic} \). This strongly suggests that it is the \( \gamma \) band that mostly affects the change in both the magnetic and thermal properties by electron doping. Especially, it is clearly found that the change in both the magnetic and thermal properties the inset of Fig. 6.

The peak in \( \chi^\gamma_0(q) \) at \( q = Q^\gamma_{ic} \sim (0.2\pi, 0.2\pi) \) as seen in pure Sr$_2$RuO$_4$ is explained by weak nesting of the two-dimensional \( \gamma \) bands at the nesting vector \( Q^\gamma_{ic} \), as illustrated in Figure 7(a). A corresponding structure has only recently been observed in inelastic neutron scattering measurement [15], where the experiments detect the imaginary part of the dynamical susceptibility.

The main effect of electron doping is that the nesting wave vector \( Q^\gamma_{ic} \) shifts to lower \( q \), while both \( \chi^\gamma_0(q = 0) \) and \( \chi^\gamma_0(Q^\gamma_{ic}) \) diverge. This divergence of \( \chi^\gamma_0 \) is logarithmic in \( (y-y_c) \), but one would expect the Stoner enhancement to lead to a much more dramatic increase in the renormalized susceptibility \( \chi^\gamma \). Finally, \( Q^\gamma_{ic} \) becomes zero at the van Hove singularity itself, at a critical electron concentration \( y_c = 0.23 \) (Figure 4(b)). Beyond the singularity \( (y > y_c) \), \( \chi^\gamma_0(q) \) at \( q \sim (\pi, \pi) \) (the X point) is dramatically suppressed, as seen for \( y = 0.25 \) and 0.27 in Figure 4(b). Here the Fermi energy is higher than the vHS, and as illustrated in the right inset of Figure 4 the Fermi surface of the \( \gamma \) band changes from an electron pocket to a hole one. As seen in Figure 4(c), the wave vector \( (\pi, \pi) \) then fails to connect the \( \gamma \) sheet with itself, leading to a substantial loss of susceptibility near the X point.

Using the above Lindhard calculation, although the Stoner factor is neglected in this calculation, we can qualitatively explain most of the evolution of the results of our our static susceptibility \( (q = 0) \) with La doping (Fig. 2). The marked increase of the observed susceptibility with La doping is explained in terms of the enhanced density of states at the Fermi level as the vHS is approached and \( Q^\gamma_{ic} \) shrinks to zero. We note again that the Lindhard susceptibility is always isotropic, in accordance with our experiment (Figure 2), since it essentially represents the Zeeman splitting in the metallic state. This holds despite the quasi-two-dimensionality of the electronic structure and spin-fluctuation spectrum. However, we note that there must also be another contribution to the susceptibility as well, because it is not easy to account in the above analysis either for the strength of the temperature dependence for \( y > 0.1 \) or for the behavior seen in at \( y = 0.27 \), for which an overall decrease of \( \chi \) is predicted.

C. Evolution of ferromagnetic fluctuations and their relation to the non-Fermi-liquid behavior

We now focus on the non-Fermi-liquid behavior around \( y \sim 0.20 \), where we observe a low-temperature upturn in the specific heat and a clear deviation from \( T^2 \) behavior in the resistivity. We have described in the previous section that we expect a strong enhancement of ferromagnetic fluctuations when the Fermi level crosses the vHS—evaluated at \( y_c = 0.23 \) in the rigid-band-shift model [4]—due to the enhanced DOS arising from the shift of the two-dimensional nesting-vector \( Q^\gamma_{ic} \) toward \( q = 0 \). The enhanced DOS is also expected to affect the specific heat coefficient \( C_P/T \).

The observed non-Fermi-liquid resistivity exponent of \( n = 1.4 \) for \( y = 0.20 \), as shown in the inset of Figure 4(a), is good agreement with the expectation of the self-consistent renormalization theory with \( n = 4/3 \) for two-dimensional ferromagnetic spin fluctuations [3]. The essential ingredient here is that the two-dimensional nesting-vector \( Q^\gamma_{ic} = 0 \). The situation is quite different in the Ti-substituted system Sr$_2$Ru$_{1-x}$Ti$_x$O$_4$, where at \( x_c = 0.025 \) the non-Fermi-liquid behavior is observed as well, but in that case with a linear \( (n = 1) \) resistivity power-law [21]. The origin of this behavior lies in the diverging antiferromagnetic fluctuations originating from the finite (incommensurate) nesting vector \( Q^\gamma_{ic} \) between the \( \alpha \) and \( \beta \) sheets [33].
Finally, let us discuss the absence of magnetic ordering in \( \text{Sr}_2-y\text{La}_y\text{RuO}_4 \) around \( y = y_c \) in our current study. Deviations from Fermi-liquid behavior are often observed around a quantum critical point in the vicinity of magnetic order [13]. Indeed, the expected divergence of the Lindhard susceptibility would strongly promote (ferro)magnetic ordering. In \( \text{Sr}_2-y\text{La}_y\text{RuO}_4 \) up to \( y = 0.27 \), however, we have seen no clear evidence for emergence of magnetic ordering, although the non-Fermi-liquid behavior is clearly observed around \( y \sim 0.20 \), indicating the immediate vicinity of the vHS. One possibility for the absence of the magnetic ordering seems to be that the magnetic correlation length is short as seen in the inelastic neutron scattering in pure \( \text{Sr}_2\text{RuO}_4 \) [12]; the magnetic excitations originating from the \( y \) band are widely spread around \( q \sim 0 \). The short range correlation reminds us of the case of the \( \text{Sr}_2\text{Ru}_1-x\text{Ti}_x\text{O}_4 \) with \( x = 0.09 \). Elastic neutron scattering measurements on this system revealed a clear SDW ordering below 25 K with the nesting vector \( \mathbf{Q}^{\beta}_{\text{el}} \). However, the correlation length at the ordered state is as short as \( \sim 5 \) nm [21] and no anomaly corresponding to the transition is observed in the specific heat [21]. The correlation length in \( \text{Sr}_2-y\text{La}_y\text{RuO}_4 \) has not been measured yet, although it will be important to see, in order to detect the evolution of the spin fluctuations at \( q \sim 0 \) by La doping.

**V. SUMMARY**

By minimizing the disorder level by substituting \( \text{La}^{3+} \) for \( \text{Sr}^{2+} \), we reported the effect of additional electron-doping in \( \text{Sr}_2\text{RuO}_4 \). The enhancement of the DOS by additional electrons is well explained by a rigid-band model based on the realistic tight-binding calculation. The result can be mainly ascribed to the approach of the Fermi energy towards a vHS of \( \gamma \) band, which is positioned at a doping level \( y_c \sim 0.20 \), 49 meV above the Fermi level in pristine \( \text{Sr}_2\text{RuO}_4 \). The enhancement of the magnetic susceptibility by electron doping toward the vHS can be viewed in terms of the shrinking of the nesting vector of the \( \gamma \) band from \( \mathbf{Q}^{\beta}_{\text{el}} \sim (0.2\pi, 0.2\pi, 0) \) at \( y = 0 \) to \( \mathbf{Q}^{\beta}_{\text{el}} \sim 0 \) at \( y \sim y_c \) on the basis of a calculation of the Lindhard susceptibility. The non-Fermi-liquid behavior around \( y \sim 0.20 \) is explained in terms of the two-dimensional ferromagnetic spin fluctuations with short range correlation. On the other hand, Ti substitution induces magnetic ordering associated with the nesting between other \( \alpha \) and \( \beta \) Fermi-surface sheets, so appropriate dopants can selectively enhance the spin fluctuations of different bands in \( \text{Sr}_2\text{RuO}_4 \). Thus, we stress that the layered ruthenate \( \text{Sr}_2\text{RuO}_4 \) is a prototype multi-band metal in which we can understand the physical properties with a surprising level of precision, given the correlated nature of the electronic state in this material.

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