Anisotropy in magnetic and transport properties of Fe$_{1-x}$Co$_x$Sb$_2$

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Anisotropic magnetic and electronic transport measurements were carried out on large single crystals of Fe$_{1-x}$Co$_x$Sb$_2$ ($0 \leq x \leq 1$). The semiconducting state of FeSb$_2$ evolves into metallic and weakly ferromagnetic by substitution of Fe with Co for $x < 0.5$. Further doping induces structural transformation from orthorhombic $P_{nnm}$ structure of FeSb$_2$ to monoclinic $P21/c$ structure of CoSb$_2$ where semiconducting and diamagnetic ground state is restored again. Large magnetoresistance and anisotropy in electronic transport were observed.

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I. INTRODUCTION

Previous attempts to explain the unusual magnetic and electronic properties of the narrow-gap semiconductor FeSi$^{1,2}$ were based on either the itinerant magnetism model, the Kondo description, the mixed valence model, or the two-band Hubbard model, and started with Jaccarino’s interpretation of an extreme narrow-band-energy-gap model.$^{3-6}$ From this work two different viewpoints have emerged. The first, proposed by Takahashi and Moriya,$^3$ takes FeSi as a nearly ferromagnetic semiconductor in an itinerant electron model. The second, as pointed out by Aeppli and Fisk,$^4$ takes FeSi as a transition metal version of the Kondo insulator with localized Fe moments. This viewpoint has the origin in the narrow gap/high density of states model that Jaccarino considered and then rejected. Experimental confirmation of that model was achieved by Mandrus et al$^{7}$ and Park et al.$^8$ Other analogous 3d model systems are highly desired in order to study this problem, particularly those of non-cubic and strongly anisotropic structures.

The magnetic properties of FeSb$_2$ strongly resemble those of FeSi.$^9,10$ Previous investigation of FeSb$_2$ has shown that the magnetism can be described by two effects: a thermally induced Pauli susceptibility and a low spin to high spin transition within the $t_{2g}$ multiplet of Fe ion in octahedral crystal field.

In order to show the possible Kondo insulator to heavy-fermion metal transition, we perturbed the FeSb$_2$ electronic system by electron doping. We report the anisotropy in magnetic and electronic transport properties of Fe$_{1-x}$Co$_x$Sb$_2$ as a function of Co content. The semiconducting ground state of FeSb$_2$ evolves into a metallic one by $x = 0.1$. Further Co substitution induces weak ferromagnetism for $0.2 \leq x < 0.5$. Beyond $x = 0.5$ there is a structural transformation from orthorhombic $P_{nnm}$ to the monoclinic $P21/c$ structure of CoSb$_2$ and the restoration of the anisotropic semiconducting ground state for $0.5 \leq x < 1$. The weak ferromagnetism and high temperature Curie-Weiss behavior is due to the small portion of localized Co ions. The large positive magnetoresistance arises in the Fe$_{1-x}$Co$_x$Sb$_2$ electronic system, particularly for $x$ values close to the metal - semiconductor crossover.

II. EXPERIMENTAL DETAILS

Single crystals were grown with the high temperature flux method.$^{11,12}$ Their structure and composition were determined by analyzing powder X-ray diffraction (XRD) spectra taken with Cu Kα radiation ($\lambda = 1.5418$ Å) using a Rigaku Miniflex X-ray machine. The lattice parameters were obtained by fitting the XRD spectra using the Rietica software.$^{13}$ A JEOL JSM-6500 SEM microprobe was used for verifying the Co concentration. Crystals were oriented using a Laue Camera and polished into rectangular bars along specific crystalline axes. Electrical contacts were made with Epotek H20E silver epoxy for a standard 4-wire resistance measurement. The dimensions of the samples were measured by a high precision optical microscope with 10 μm resolution. Magnetization, resistivity, and transverse magnetoresistance measurements were carried out in a Quantum Design MPMS-5 and a PPMS-9 varying the temperature from 1.8 K to 350 K and applying a magnetic field up to 90 kOe. Polycrystalline averages were calculated from $M/H \equiv \chi = 1/3 [\chi_a + \chi_b + \chi_c]$. Heat capacity data was collected in the PPMS-9 instrument using a relaxation technique.

III. RESULTS AND DISCUSSION

A. Crystal Structure

Fig. 1 shows the lattice constants and unit cell volume of Fe$_{1-x}$Co$_x$Sb$_2$ as a function of nominal Co content, as determined by powder X-ray diffraction. As can be seen from Fig. 1, the end member structures of Fe$_{1-x}$Co$_x$Sb$_2$ are orthorhombic $P_{nnm}$ and monoclinic $P21/c$ for FeSb$_2$ and CoSb$_2$, respectively. Both $\hat{a}$ and $\hat{b}$ axes show a smooth linear decrease with increasing $x$ for $0 \leq x < 0.5$. In contrast, the axis expands with increasing $x$ in the same doping range. At $x = 0.5$, the axis
a gradual increase of the monoclinic angle $\beta$ with increasing $x$. We observe a smooth evolution of $a$, $b$, and $c$ lattice parameters, with increasing $x$, indicating a structural phase transition to lower symmetry of the unit cell.

In the monoclinic region, for $0.5 \leq x < 1$, the unit cell volume refers to that of a pseudo-marcasite cell. This cell is related to the true unit cell of CoSb$_2$ (specified by $\overline{a}'$, $\overline{b}'$, $\overline{c}'$, and $\beta'$) by vectorial equations of the following form: $\overline{a}' = (\overline{a} - \overline{c})/2$, $\overline{b}' = \overline{b}$ and $\overline{c}' = (\overline{a} + \overline{c})/2$. In this doping regime as well, we observe a smooth evolution of $a$, $b$, and $c$ lattice parameters with increasing $x$. The evolution is concurrent with a gradual increase of the monoclinic angle $\beta'$, from 90.1° to 90.4° (Fig. 1(Inset)). This linear dependence on Co concentration, conforming to Vegard’s law, demonstrates that Co successfully substitutes for Fe in the entire doping range. In addition, energy dispersive SEM for several nominal $x=0.25$ samples showed that the uncertainty in Co concentration among samples grown from different batches was $\Delta x = 0.04$.

The anisotropy in the evolution of lattice parameters with Co content for $0 \leq x < 0.5$ is consistent with an increased occupancy of $d_{xy}$ orbitals, directed towards nearest neighbor Fe ions along axis of the crystal. Monoclinic distortion at $x = 0.5$ increases the axis and decreases the overlap of $d_{xy}$ orbitals. The reduced overlap results in an enlargement of the gap within the $t_{2g}$ multiplet and causes a change in electronic transport properties. The electronic system gradually evolves towards a semiconducting ground state of CoSb$_2$ with the increase of Co concentration from $0.5 \leq x < 1$.

Some data of the series were omitted for clarity: (a) magnetization of FeSb$_2$ along all three axes. (b) Magnetization along $a$ axis. Inset shows the $1/\chi$ and also the hysteresis loop of Fe$_{0.75}$Co$_{0.25}$Sb$_2$. (c) Magnetization along $b$ axis displays weak ferromagnetic transition at low temperatures for $0.2 \leq x \leq 0.45$. (d) $a$ axis magnetization resembles those of $b$ axis but shows no transitions at low temperatures.
TABLE I: Parameters of the fits to the polycrystalline average of $M/H$ data for $0 \leq x < 0.5$.  

| $x$ | $\Delta_\chi(K)$ | $W(K)$ | $p$ | $\chi_0(10^{-4} \text{emu/mol})$ | $\mu_{\text{eff}}(\mu_B)$ | $\Theta(K)$ | $\mu_{\text{eff}}/\Theta(\mu_B)$ | $T_c(K)$ | $P(10^{-4} \mu_B)$ |
|-----|------------------|--------|-----|-------------------------------|------------------------|-------------|-------------------------------|----------|------------------|
| 0   | 552              | 1.6    | 1.3 | 0.03                          | 0                      | 0           | 0                            | 0        | 0                |
| 0.05| 531              | 235    | 2.1 | 0.3                           | 0.41                   | -23         |                                |          |                  |
| 0.10| 511              | 471    | 2.5 | 1.6                           | 0.79                   | -71         |                                |          |                  |
| 0.20| 4.5              | 110    | 0.70 | 6.6                           | 1.49                   |            |                                |          |                  |
| 0.25| 3.3              | 104    | 0.99 | 6.0                           | 1.73                   |            |                                |          |                  |
| 0.30| 3.0              | 77     | 1.08 | 6.8                           | 1.87                   |            |                                |          |                  |
| 0.40| 1.5              | 17     | 1.35 | 7.3                           | 1.19                   |            |                                |          |                  |
| 0.45| 1.5              | 16     | 1.20 | 6.4                           | 0.75                   |            |                                |          |                  |

B. Magnetic Properties

For $x = 0$, the temperature dependence of the susceptibility is qualitatively the same for $H \parallel \hat{a}, \hat{b}$, and $\hat{c}$ as shown in Fig. 2(a). A diamagnetic to paramagnetic crossover at $T$ in the vicinity of 100 K occurs when a field is applied parallel to the $\hat{c}$ axis. This crossover is absent when fields are applied parallel to the $\hat{a}$ and $\hat{b}$ axes. Furthermore, for $H \parallel \hat{a}, \hat{b}$ below 100 K the susceptibility is temperature independent and can be described by a paramagnetic term $\chi_0 = \chi_0 = 2 \times 10^{-5} \text{emu/mol}$. These observations contradict previous measurements of FeSb$_2$, that reported a diamagnetic to paramagnetic crossover in the vicinity of 100 K for fields applied along all three axes. Our measurements were performed on large single crystal samples which eliminated the need for subtracting the background, which is often difficult to estimate with high certainty. Subtraction of the background was necessary in Ref. 9 due to very small mass of the FeSb$_2$ samples. Consequently, the intrinsic susceptibility of FeSb$_2$ determined on large single crystals, differs from Refs. 9 and 10 and is shown in Fig. 2(a).

In what follows, we explore to what extent different models can account for the observed paramagnetic moment and the temperature dependence of the susceptibility in Fe$_{1-x}$Co$_x$Sb$_2$. In the free-ion model the susceptibility $\chi$ is given by Jaccarino et al. as,

$$\chi_{FI} = N g^2 \mu_B^2 J(J+1) \left[ 2J+1 + \exp(\Delta_\chi/k_B T)/2 J + 1 + \exp(\Delta_\chi/k_B T) \right] + \chi_0.$$  

This model describes thermal excitations from low to high spin states, separated by a spin gap $\Delta_\chi$. Moreover in the simplest case, two spin states can be viewed as the $J = S = 0$ spin singlet and the $S = 1$ triplet state. Fitting the expression to the polycrystalline average of the magnetic susceptibility of FeSb$_2$ and setting $J = S$, we obtain $\chi_0 = 4.5 \times 10^{-6} \text{emu/mol}$, $\Delta_\chi = 527$ K and $S = 0.24$. The rather small value of $S$ implies that the free-ion model may not be the explanation for the thermally induced paramagnetism at high temperatures, or that a small portion of Fe spins in the S=0 low spin d$^4$ ground state(t$_{2g}$,S=0) takes part in the spin-state transition.

The magnetic susceptibility of FeSb$_2$ can also be described by the narrow-band-small-gap picture:

$$\chi_{NB} = \frac{2N \mu_B^2 p \exp(\Delta_\chi/T)(\exp(W/T) - 1)}{W(1 + \exp(\Delta_\chi/T))(1 + \exp((\Delta_\chi + W)/T))} + \chi_0$$

Here $\chi_{NB}$ is the Pauli susceptibility of an itinerant electron system with a density of states $N(E)$ consisting of two narrow bands of width $W$ separated by a gap $E_g \equiv \Delta_\chi$, so that the chemical potential is defined as $\mu = W + \Delta_\chi$. The density of states is given by $N(E) = N_p/W$, where $N$ denotes the number of unit cells and $p$ the number of states per unit cell. In this picture, $\chi_0$ is the temperature independent paramagnetic susceptibility. By fitting this model, we find the allowable values of parameters: $1.3 < p < 1.4$, $1.6K < W < 310K$, $850K < E_g < 1100K$. The result agrees with Ref.9 but differs in a positive Pauli term, $\chi_0 = 3 \times 10^{-6} - 4 \times 10^{-6} \text{emu/mol}$, instead of a diamagnetic term.

At high temperatures for $0 < x \leq 0.45$, the magnetic susceptibility along all three crystalline axes can be described by two terms: a thermally induced paramagnetic moment with progressively smaller gap $\Delta_\chi$, and a growing Curie-Weiss term, due to Co substitution:

$$\chi(T) = \chi_{CW} + \chi_{NB}$$

where

$$\chi_{CW} = \frac{N \mu_{\text{eff}}^2}{3k_B(T - \Theta)}$$

Results of fits for $0 \leq x < 0.5$ are shown in Table I. The gap $\Delta_\chi$ decreases with increasing doping as $x$ reaches 0.2. For $0.20 \leq x \leq 0.45$ the temperature dependence of the magnetic susceptibility above 180 K is characterized solely by the Curie-Weiss term and temperature independent Pauli term $\chi_0$.

The low temperature magnetic properties of Fe$_{1-x}$Co$_x$Sb$_2$ are anisotropic. For $H \parallel \hat{a}$ and $\hat{b}$, we observe a large increase of $M/H$ values, a signature of ferromagnetic transition. Consequently, hysteresis loops, shown in the inset to Fig. 2 (b), are observed for
FIG. 3: Normalized resistivity along all three axes as a function of temperature and different doping levels, $x$ denoted by different shapes and colors. $\text{Fe}_{1-x}\text{Co}_x\text{Sb}_2$ becomes metallic along all axes for $x > 0.05$. With increasing $x$, the metallic is lost in a crossover, where resistivity is nearly independent of temperature. Further increase of $T$ leads to metallic behavior again along $\hat{a}$ and $\hat{b}$. However, resistivity along $\hat{c}$ axis evolves gradually from metallic to semiconducting. Below 40 K for $x = 0$ and 0.05 samples the impurity tails up to 5 $\Omega\text{cm}$ are observed.

$0.2 \leq x \leq 0.45 (H||\hat{b})$, as well as for $x = 0.25 (H||\hat{a})$ at $T = 1.8K$. The saturation moments $P_z$ are listed in Table I. The Curie temperatures, determined by extrapolating the steepest slope of the $M/H$ curve to $M = 0$, vary from 5.9 to 7.2 K (Tab I.). This corresponds to the anomalies in the heat capacity measurements (Fig. 6). CoSb$_2$ is diamagnetic in the whole experimental temperature range. As Fe is in the nonmagnetic 3d$^4$ configuration, we assume that localized moment arises solely from the substituted Co atoms, and hence Curie-Weiss term.

To evaluate the high temperature moment per Co atom, we fit the polycrystalline average of the magnetic susceptibility for temperatures ranging from 180 to 350 K with the Curie-Weiss law. We find the moment of $\mu/\text{Co}$ to be $1 \pm 0.35 \mu_B$ for all the ferromagnetic $x$ (Tab. I). This suggests the existence of polarized moments of $\text{Co}^{2+}$ with low spin and quenched orbital momentum in the lattice. Therefore, we conclude that the weak ferromagnetism is due to the ordering of 0.2 % of $\text{Co}^{2+}$ moments. The fact that we were unable to detect any hysteresis loops above $T_c$ and the absence of any sample dependence among sample within one batch of crystals, as well as among crystals from different batches, argues against extrinsic sources of weak ferromagnetism in $\text{Fe}_{1-x}\text{Co}_x\text{Sb}_2$.

C. Electronic Transport

Whereas the electronic transport of FeSb$_2$ is strongly anisotropic, there is much less dependence on “direction” for $\text{Fe}_{1-x}\text{Co}_x\text{Sb}_2$. Figure 3 shows the normalized resistivity as a function of temperature along all three axes. Absolute values of the resistivity at $T = 350K$ for samples with doping up to $x = 0.4$ are listed in Tab. II. For $x = 0$ (FeSb$_2$), there is metallic behavior above 40 K along the $\hat{b}$ axis, and activated behavior below that temperature. On the other hand, FeSb$_2$ is semiconducting for current applied along $\hat{a}$ and $\hat{c}$ axes. With a small amount of doping ($x = 0.1$), the resistivity exhibits good
metallic behavior over the whole temperature range, and showing very small defect scattering ($\rho_0 \sim 10 \mu\Omega\text{cm}$) at 1.8 K, the lowest measured temperature.

For $0.1 < x < 0.4$ the electronic transport is metallic for current applied along all three principal crystalline axes. Metallicity induced by Co substitution is suppressed as the system evolves towards the region of the structural phase transition for $x \geq 0.5$, due to monoclinic distortion that causes doubling of the axis and the consequent reduction of the overlap of $d_{xy}$ orbitals. For $0.5 \leq x \leq 1$ ($P21/c$ structure) a small anisotropy appears again, but it has different character comparing it to $0 \leq x < 0.5$ ($Pnma$ structure). The structural change is likely one origin of that difference. More theoretical and experimental band structure work would be useful to shed light on the anisotropy of electronic transport of $\text{Fe}_{1-x}\text{Co}_x\text{Sb}_2$($0.5 \leq x \leq 1$).

For the semiconducting samples, we identify a regime of thermally activated resistivity above 40 K described by

$$\rho = \rho_0 e^{\Delta_\rho / k_B T}.$$  

Here $\Delta_\rho$ is the transport energy gap. The activation energy for the transport gap is obtained at temperatures above 40 K. The spin gaps are obtained from the narrowband-small-gap model of the polycrystalline magnetic susceptibility. For $x=0.05$ the average value of $\Delta_\rho$ from $\rho_a(T)$ and $\rho_c(T)$ is shown (they agree within measurement error $\sim 10\%$), since $\rho_0$ is metallic. For $0.5 \leq x < 1$ the value of $\Delta_\rho$ from $\rho_c$ is shown since $\rho_a$ and $\rho_b$ are metallic. Near structural phase transition, the value of $\Delta_\rho$ from $\rho_c$ is shown since $\rho_b$ and $\rho_c$ are metallic. A discrepancy between the spin and the transport gap values is evident. A possible difference between the gaps in charge and spin excitation channels has also been observed in pure FeSb$_2$ and as well as in FeSi.$^9$  

### Table II: Values of resistivity $\text{Fe}_{1-x}\text{Co}_x\text{Sb}_2$($0 \leq x \leq 0.4$) at 350 K.

| $x$  | $\rho_a$ ($\mu\Omega\text{cm}$) | $\rho_b$ ($\mu\Omega\text{cm}$) | $\rho_c$ ($\mu\Omega\text{cm}$) |
|------|-------------------------------|-------------------------------|-------------------------------|
| 0    | 0.79                          | 0.27                          | 0.63                          |
| 0.05 | 0.74                          | 0.23                          | 0.26                          |
| 0.1  | 0.39                          | 0.20                          | 0.24                          |
| 0.2  | 0.96                          | 0.59                          | 0.68                          |
| 0.3  | 1.38                          | 0.50                          | 0.69                          |
| 0.4  | 1.80                          | 1.04                          | 1.56                          |

In FeSb$_2$ application of a magnetic field induces a large anisotropic positive magnetoresistance for current applied along the highly conductive $b$ axis.$^9$ This effect is strongly enhanced in $\text{Fe}_{1-x}\text{Co}_x\text{Sb}_2$, particularly for highly metallic samples. As an example, in Fig. 6 the effect in $\text{Fe}_{0.9}\text{Co}_{0.1}\text{Sb}_2$ is shown. In addition, magnetoresistance for pure FeSb$_2$ is plotted for comparison. Whereas magnetic field has little effect on the semiconducting electronic transport along the $a$ and $c$ axes in FeSb$_2$, for the $b$ axis transport we observe up to two orders of magnitude of positive magnetoresistance at temperatures in the vicinity of the metal to semiconductor crossover temperature.

Away from the crossover temperature the effect diminishes, below 5 K and in the vicinity of room temperature the application of a magnetic field has no effect on the $b$ axis transport.

For $x = 0.1$, this strong effect is more isotropic and is observed for current applied along all three crystalline axes. However for $T || \hat{b}$, the effect is strongest. Below 10 K, the resistivity increases up to 2.5 orders of magnitude in an applied field of $H = 90$ kOe. The transverse magnetoresistance (MR), defined as

$$\text{MR} = \frac{\rho(90\text{kOe}) - \rho(0)}{\rho(0)},$$

reaches 36000\% at $T = 1.8$ K and $\sim 30\%$ at $T = 300$ K in 90kOe. This effect is comparable to the colossal magnetoresistance observed below room temperature in manganites. Furthermore, it is much higher at room temperature than in manganites. The origin of the magnetoresistance in FeSb$_2$(x=0) is most likely due to the large mobility (µ) of carriers. The mobile carriers in a magnetic field move in cyclotron orbits specified by $\omega_c\tau \sim \mu H > 1$. Therefore, a strong positive magnetoresistance effect is expected in even a moderate field.$^9$

Magnetic isotherms deviate from the quadratic relation for the ordinary metallic case, i.e. $\Delta \rho(H)/\rho_0 \propto H^2$ and there is a poor Kohler scaling for $\text{Fe}_{0.9}\text{Co}_{0.1}\text{Sb}_2$. The spin fluctuation mechanism proposed by Y. Takahashi and T. Moriya can be discarded based on the sign of the effect. Mainly because the spin fluctuation theory predicts negative magnetoresistance due to the thermally
suppressed spin fluctuation amplitude. In addition, the observed temperature dependence of magnetization does not contain $T^{3/2}$ and $T^{5/2}$ terms that arise from spin wave and spin wave - spin wave interactions.

D. Heat Capacity

The heat capacity $C_p/T$ as a function of $T^2$ below 10 K is shown in Fig. 6. We observe a weak but clear signature of a ferromagnetic transition in the vicinity of the $T_C$, as derived from magnetization measurements. By integrating $C_p/T$ over $T$ under this anomaly, the magnetic entropy contribution per Co is evaluated. For $x = 0.3$, we find $\Delta S = 0.35\% \, k_B \ln 2$, in good agreement with the results obtained from the magnetization measurement. The end members of the Fe$_{1-x}$Co$_x$Sb$_2$ series have negligible electronic specific heat $\gamma = 9.2 \times 10^{-3} \text{ mJ/mol K}^2$. This implies an negligible density of states at the Fermi level, i.e. an insulating state. The result agrees well with optical spectroscopy measurements that show a negligible Drude weight of $\sigma(\omega)$ at low frequencies.\textsuperscript{18}

The changes in $\gamma$ as a function of $x$ are correlated with the evolution of the magnetic properties, since the saturation moment dependence for samples in the ferromagnetic region reaches a maximum value for $x = 0.3$. Within the Kondo insulator framework, a metallic state with a large carrier mass enhancement is generated by a carrier induced closing of the hybridization gap. Consequently, the carrier mass enhancement leads to large $\gamma$ value due to a renormalized band structure. The $\gamma$ values observed in Fe$_{1-x}$Co$_x$Sb$_2$ are comparable to those in the ferromagnetic regime of FeSi$_{1-x}$Ge$_x$\textsuperscript{16} and FeSi$_{1-x}$Al$_x$, Fe$_{1-x}$Co$_x$Si as well.\textsuperscript{17,19} To estimate the carrier mass enhancement, we make the free-electron assumption. That is,

$$\gamma = \frac{\pi^2 k_B^2 N(E_F)}{3} = \frac{k_F^2 k_B m^*}{3\hbar^2}$$

with $k_F = (3\pi^2 n)^{1/3}$. The carrier density is denoted by $n$ and is estimated to be equal to the Co concentration assuming one itinerant electron per Co$^{2+}$. This model implies only a small enhancement of carrier mass and disagrees with the Kondo Insulator model. However, Hall constant measurements would be useful to determine the precise carrier density and so provide a definitive test for the applicability of the Kondo Insulator model. Furthermore, these measurements will help shed more light on the origin of the colossal magnetoresistance in this system.

IV. CONCLUSION

In summary, the Fe$_{1-x}$Co$_x$Sb$_2$ electronic system exhibits two consecutive metal to semiconductor crossovers. The first is caused by electron doping of the semiconducting ground state of FeSb$_2$ for $x = 0.1$. The second is induced by a structural change for doping levels in the vicinity of $x = 0.5$. The density of states at the Fermi level increases due to the increased Co concentration, as shown in the rise of the electronic specific heat. The weak ferromagnetism induced by the polarization of a small portion of Co$^{2+}$ ions arises in the metallic state for $0.2 \leq x < 0.5$. A colossal magnetoresistance as large as 36000% is observed in the vicinity of the first metal to semiconductor crossover. The overall properties of Fe$_{1-x}$Co$_x$Sb$_2$ can be understood in the narrow-band small-energy-gap framework where Co substitution gives rise to impurity states in the gap, metallicity, and Curie-Weiss behavior. This is further supported by the recent LDA+U calculation of Lukoyanov on FeSb$_2$, which indicates sharp peaks in the DOS at the edge of a small gap.\textsuperscript{20} Possible consequence of the presence of magnetic Fe or an unknown ferromagnetic impurity would imply that the value of the direct Coulomb repulsion parameter $U$ in ref. 20 does not exceed the critical value of $U_C = 2.6 \text{eV}$ for all values of $x$ in Fe$_{1-x}$Co$_x$Sb$_2$ and that the weak ferromagnetism is extrinsic.\textsuperscript{29}

![FIG. 6: $C_p/T$ as a function of $T^2$. Cusps correspond to ferromagnetic transition. Co doping gives rise to substantial increase in gamma.](image-url)
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