Coexistence of magnetism and superconductivity in $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$: A muon spin rotation and magnetization study

A. Shengelaya,¹ R. Khasanov,^{1,2} D. G. Eshchenko,¹ I. Felner,³ U. Asaf,³ I. M. Savić,⁴ H. Keller,¹ and K. A. Müller¹¹*Physik-Institut der Universität Zürich, CH-8057 Zürich, Switzerland*²*Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*³*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*⁴*Faculty of Physics, University of Belgrade, 11001 Belgrade, Serbia and Montenegro*

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We performed zero-field muon spin rotation (ZF- μ SR) and dc magnetization experiments in the ruthenate-cuprate $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$. It was found that this compound becomes weakly ferromagnetic at $T_m = 77.6$ K and superconducting below $T_c = 40$ K. ZF- μ SR experiments indicate that the magnetic order accounts for most of the sample volume and magnetism is not significantly affected in the superconducting state. The present investigation provides evidence for the coexistence of magnetism and superconductivity in $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$.

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I. INTRODUCTION

Recently, the hybrid ruthenocuprates $\text{RuSr}_2(\text{R}_{2-x}\text{Ce}_x)\text{Cu}_2\text{O}_{10}$ (Ru-1222) and $\text{RuSr}_2R\text{Cu}_2\text{O}_8$ (Ru-1212) ($R = \text{Sm}, \text{Eu}, \text{and Gd}$) have attracted much attention because of the coexistence of superconductivity and long-range magnetic order.^{1,2} These compounds have a layered structure with alternating CuO_2 and RuO_2 layers. It seems that superconductivity takes place in the CuO_2 layers like in the high- T_c cuprates, whereas magnetic order occurs in the RuO_2 planes. Till now most of the reports have focused on the Ru-1212 phase, where the magnetic transition is observed at $T_m = 133$ K and superconductivity sets in at $T_c = 35$ K.²⁻⁵ These experiments provide the evidence for the coexistence of superconductivity and magnetism in Ru-1212 compound. However, many important questions such as the nature of superconductivity, details of the magnetic order, and the mechanism of coexistence of superconductivity and magnetism still remain a matter of discussion.

In this paper we focus our attention on a Ru-1222 phase $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$, which is actually the first ruthenocuprate where the coexistence of superconductivity and magnetism was found.¹ Both Ru-1212 and Ru-1222 contain similar CuO_2 and RuO_2 planes. However, in Ru-1222 the R layer between CuO_2 planes is replaced by a fluorite-type ($\text{R}_{2-x}\text{Ce}_x\text{O}_2$; $R = \text{Gd}, \text{Eu}$) layer. This allows to vary the charge-carrier concentration in Ru-1222, in contrast to Ru-1212 which is a stoichiometric compound. Recently, a jump in the specific heat at T_c was observed in $\text{Gd}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$, confirming bulk superconductivity.^{6,7} However, no microscopic measurement of the magnetic state has been reported up to now and it remains to be demonstrated that magnetic order also has bulk character in order to infer the coexistence of magnetism and superconductivity in Ru-1222. In addition, the magnetic properties of Ru-1222 are more complicated than that of Ru-1212. Several magnetic transitions were found in magnetization measurements.¹ From the magnetization data alone it is practically impossible to determine the nature of these magnetic

transitions. To answer these questions we studied $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$ using zero-field muon spin rotation (ZF- μ SR). The μ SR technique is especially suitable for such a study since the positive muon is an extremely sensitive local probe to detect internal magnetic fields and their distribution. In addition, as a real-space probe, μ SR can determine the ordered volume fraction.

This paper is organized as follows. Sample preparation and principles of the μ SR technique are briefly described in Sec. II. In Sec. III we present dc magnetization, resistivity, and ZF- μ SR data and discuss the magnetic properties of $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$ based on the obtained data. In Sec. IV we summarize most important results and discuss a possible scenario for the coexistence of the magnetism and superconductivity in ruthenate-cuprates.

II. EXPERIMENTAL DETAILS

Ceramic samples with nominal composition $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$ were prepared by a solid-state reaction technique. Prescribed amounts of Eu_2O_3 , CeO_2 , SrCO_3 , Ru, and CuO were mixed and pressed into pellets and preheated at 1000 °C for about 1 day in the presence of flowing oxygen at atmospheric pressure. The product was cooled, reground, and sintered at 1050 °C for 72 h in a slightly pressurized oxygen atmosphere (~ 1.1 atm) and then cooled in a furnace to ambient temperature. Powder x-ray diffraction measurements confirmed the purity of the sample (97%) and provided the lattice parameters, $a = 3.846(1)$ Å and $c = 28.72(1)$ Å.

The dc magnetization data were obtained using a Quantum Design superconducting quantum interference device magnetometer. Resistivity measurements were performed with a standard four-probe dc technique on bar-shaped pieces cut out from the pellets. The contacts were made with silver paint. The μ SR experiments were performed on the beam line $\pi M3$ at the Paul Scherrer Institute (Switzerland) using positive low-momentum (29 MeV/c) “surface muons.” The essentially 100% spin-polarized muons are implanted into the bulk of the sample where they thermalize very rapidly

FIG. 1. Temperature dependence of the zero-field-cooled (ZFC) and field-cooled (FC) dc magnetization of $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$. Inset: resistivity data showing the superconducting transition.

($\sim 10^{-12}$ s) without any significant loss in their initial spin polarization. The muon decays with a mean lifetime of $\tau_{\mu^+} = 2.2 \mu\text{s}$ into a positron and two undetected neutrinos. Due to parity violation the decay positron is emitted preferentially along the muon spin direction, and by collecting several hundreds of thousands positrons the muon spin depolarization function is reconstructed which, in turn, reflects the spatial and temporal distribution of magnetic fields at the muon site. Because of its positive charge, the muon localizes at an interstitial lattice site and in the perovskite compounds forms a muoxyl bond with oxygen atoms.⁸ The whole ensemble of muons is randomly distributed throughout a layer of 100–200 μm thickness and therefore probes a representative part of the sample volume.

In ZF- μSR experiments the time evolution of the muon spin polarization is monitored with no external field applied, reflecting the interaction of the implanted muon spin with the local magnetic field at the muon site B_μ in the bulk of the sample (the earth's magnetic field was compensated to better than 10 μT). Each muon spin precesses in its local magnetic field B_μ with a precession frequency of $\nu_\mu = (\gamma_\mu/2\pi)B_\mu$, where $\gamma_\mu/2\pi = 135.5 \text{ MHz/T}$ is the gyromagnetic ratio of the positive muon. For a detailed description of the basic concepts of μSR and its application to study the magnetic properties of solids we refer to the literature.⁹

III. RESULTS AND DISCUSSION

A. dc magnetization

Figure 1 shows the temperature dependence of the zero-field cooled (ZFC) and the field-cooled (FC) magnetization for the $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$ sample. There is a strong increase of magnetization below $T_m \sim 90 \text{ K}$ with a large difference between ZFC and FC measurements, in agreement with a previous report.¹ A similar magnetic transition was also observed in Ru-1212 compound,¹⁰ which is consistent with canted antiferromagnetic order with a small ferromagnetic moment in accordance with a neutron-diffraction study.¹¹ Below $T_c \sim 40 \text{ K}$ the ZFC magnetization shows an additional decrease. This corresponds to the superconductivity onset

FIG. 2. Zero-field (ZF) μSR spectra of $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$ for three different temperatures. Solid lines represent fits using Eq. (1).

temperature determined from the resistivity measurements (see inset of Fig. 1). The superconducting transition is also reflected in FC magnetization as a small kink near 40 K, similar to a superconducting Meissner transition with a small volume fraction. Generally, this anomaly was found to be sample dependent and is strongly suppressed by an external magnetic field. A similar decrease of the FC magnetization in the superconducting state was previously reported for Ru-1212,¹² but not for Ru-1222.¹ The small volume of the Meissner fraction of the Ru-1222 samples, similar to Ru-1212, may raise the question concerning the impurity nature of superconductivity in these compounds.¹³ We note, however, that strong evidence for bulk superconductivity state in Ru-1222 comes from recent specific-heat measurements, where a sizable jump in the specific-heat coefficient γ was observed at T_c , comparable to underdoped high- T_c superconductors.^{6,7} Recent dc magnetization measurements on Ru-1212 samples provided evidence that a bulk Meissner state develops at low magnetic fields $H < 1 \text{ Oe}$ and temperatures much below T_c , which is sample dependent.¹² This peculiar behavior could be attributed to the spontaneous vortex phase. We will discuss this phase in more detail later.

In addition to a large increase of the magnetization below 90 K, there is a small peak in the ZFC data near 130 K (see Fig. 1). Moreover, there is a difference between ZFC and FC magnetization curves which extends up to $T_{irr} \sim 200 \text{ K}$. A similar behavior of magnetization was reported by other groups, and it seems to be an intrinsic property of Ru-1222.¹⁴ From the magnetization data alone it is very difficult to identify the nature of these magnetic anomalies. Therefore we performed ZF- μSR experiments to study the complex magnetic properties of Ru-1222 on a microscopic level.

B. Zero-field muon spin rotation

Figure 2 shows a representative ZF- μSR spectra for the $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$ sample at different temperatures. The clear oscillation observed in the time spectra at low temperatures implies that the muons sense a well-defined internal magnetic field. The μSR spectra were analyzed using the standard function⁹

FIG. 3. Fourier-transformed ZF- μ SR spectrum of $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$ at $T=5$ K. A double peak in the internal magnetic-field distribution is clearly seen. The solid line is a fit with a sum of two Gaussians represented by dashed lines.

$$A(t) = A_{\parallel} \exp(-\lambda t) + A_{\perp} \exp(-\Delta^2 t^2/2) \cos(\gamma_{\mu} B_{\mu} t + \Phi), \quad (1)$$

where $\gamma_{\mu}/2\pi = 135.538 \text{ MHz s}^{-1} \text{ T}^{-1}$ is the gyromagnetic ratio of the positive muon and B_{μ} the average static internal magnetic field at the muon site. In the absence of an external magnetic field, B_{μ} is determined by the local magnetic order parameter, i.e., the staggered magnetization. The two components are due to muons with B_{μ} parallel or transverse to the muon spin polarization. The corresponding relaxation rates are λ (longitudinal) and Δ (transverse).

We observed that a fit to Eq. (1) below 90 K with a single B_{μ} resulted in a very poor agreement with the spectra. In case of an incommensurate magnetic order the cosine function in Eq. (1) can change to a Bessel function.¹⁵ However, the Bessel function did not improve the fit either. We found that two different local magnetic fields B_{μ_1} and B_{μ_2} satisfactorily fit the spectra below 90 K. This was further confirmed by a Fourier transformation of the time spectra, where two peaks in the magnetic-field distribution were observed (see Fig. 3). It is seen from Fig. 2 that the oscillations are present also above 90 K but with a much smaller amplitude. This indicates that some magnetic order still exists above this temperature.

In Fig. 4(a) the internal magnetic fields B_{μ} are shown as functions of temperature. The solid lines are fits to the phenomenological power-law temperature dependence $B_{\mu}(T) = B_{\mu}(0)(1 - T/T_m)^n$. The obtained parameters are summarized in Table I. One can see that there are two oscillating signals which correspond to the large magnetic fields at the muon sites $B_{\mu}^{\text{HF1}}(0) = 74(10) \text{ mT}$ and $B_{\mu}^{\text{HF2}}(0) = 59(1) \text{ mT}$ with transition temperatures $T_{m1} \approx 200 \text{ K}$ and $T_{m2} \approx 95 \text{ K}$, respectively. We call them high-field (HF1 and HF2) signals. In addition, there is one oscillating signal with much lower field $B_{\mu}^{\text{LF}}(0) = 12.5(1) \text{ mT}$ below $T_{m3} = 77.6 \text{ K}$, which we call low-field (LF) signal.

The present results provide evidence of a magnetically ordered state in $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$. Moreover, it is clear that the magnetic order persists almost unchanged in the superconducting state since there is no anomaly of the

FIG. 4. (a) Temperature dependence of the different internal magnetic fields B_{μ} (HF1, HF2, LF) in $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$. The solid lines represent fitted curves to the power law $B_{\mu}(T) = B_{\mu}(0) \times (1 - T/T_m)^n$. (b) Temperature dependence of the volume fraction V_{μ} of the muon sites that experience an internal magnetic field. The lines are guides for the eye.

ZF- μ SR signal below the superconducting transition temperature $T_c = 40 \text{ K}$. Now the important question arises whether this magnetic order has a bulk character or occurs only in a small part of the sample. It is possible to extract the volume fraction of the magnetically ordered phase from the amplitude of the oscillating component of the ZF- μ SR spectra. In a magnetically ordered polycrystalline sample with randomly oriented grains in zero external field, the internal magnetic field is parallel (perpendicular) to the muon spin direction with a probability 1/3 (2/3). For a homogeneous magnetically ordered sample, one therefore expects that 2/3 of the amplitude of the ZF- μ SR signal exhibits an oscillatory behavior (transverse component) $A_{\perp}/(A_{\perp} + A_{\parallel}) = 2/3$, while 1/3 of the signal is nonoscillating (longitudinal component) and only slowly damped.

On the other hand, if the sample contains nonmagnetic regions, the amplitude of the oscillating signal will be ac-

TABLE I. T_m , $B_{\mu}(0)$, and n derived by fitting the measured values of $B_{\mu}(T)$ to the power law $B_{\mu}(T) = B_{\mu}(0)(1 - T/T_m)^n$ (see text).

μ SR signal	T_m (K)	$B_{\mu}(0)$ (mT)	n
HF1	200(10)	74(10)	0.6(1)
HF2	95(7)	59(1)	0.34(6)
LF	77.6(1)	12.5(1)	0.31(1)

cordingly reduced. For a polycrystalline sample where only a V_{or} portion of the total volume V_{to} orders, $A_{\perp}/(A_{\perp}+A_{\parallel}) = \frac{2}{3}V_{or}/V_{to} < \frac{2}{3}$. We determined the amplitude of the total initial muon spin polarization $P(t=0)$ from transverse-field measurements at $T=300$ K where the samples were non-magnetic. The volume fraction V_{μ} of muon sites that experience the internal magnetic field was determined as $V_{\mu} = V_{or}/V_{to}$. Figure 4(b) shows the temperature dependence of the volume fraction V_{μ} of muon sites that experience the internal magnetic field. One can see that the oscillating signal HF1 appears below 200 K and its asymmetry is practically constant down to 90 K. From the amplitude of this oscillatory component we deduce that only about 15(5)% of the sample is magnetically ordered in the temperature range 90–200 K. Below 90 K two new oscillatory signals HF2 and LF with much higher amplitudes appear in the μ SR spectra. From the total amplitude of the oscillating components we deduce that about 95(5)% of the sample volume is magnetically ordered below 90 K. It means that practically all sample volume is magnetically ordered above $T_c=40$ K. Moreover, Fig. 4 shows that the magnetic order persists almost unchanged in the superconducting state. One can ask what happens to the HF1 signal below 90 K. The amplitude of the HF1 signal is only 15(5)% which is in the limit of the μ SR sensitivity. It becomes very difficult to resolve this small component below 90 K where much stronger oscillating signals appear in the μ SR spectra. The situation is further complicated by the fact that the HF1 and HF2 signals have close frequencies. Therefore one cannot follow the HF1 signal below 90 K.

The presence of the two oscillating components (HF2 and LF) in EuRu-1222 at low temperatures is in contrast to Ru-1212 where only a single muon spin precession signal was observed.² Our μ SR signals correspond to two very different internal magnetic fields $B_{\mu}(0)=59(1)$ and 12.5(1) mT, respectively. The ratio of the two muon signal amplitudes $A_{HF2}/A_{LF} \approx 2$ and is practically temperature independent. One should note that $B_{\mu}^{HF2}(0)=59(1)$ mT is close to $B_{\mu}(0)=72(1)$ mT observed in Ru-1212 sample by μ SR,² but $B_{\mu}^{LF}(0)$ is much smaller. The two oscillating signals are most probably due to two different muon stopping sites in the Ru-1222 structure. Both Ru-1212 and Ru-1222 contain similar CuO_2 and RuO_2 planes. However, Ru-1222 contains in addition a fluorite type ($\text{R}_{2-x}\text{Ce}_x\text{O}_2$; $\text{R}=\text{Gd}, \text{Eu}$) layer between the CuO_2 planes. It is possible that the second muon stopping site is close to the $\text{R}_{2-x}\text{Ce}_x\text{O}_2$ layer. At this site muons will be far away from magnetically ordered RuO_2 planes, feeling a much reduced internal magnetic field in agreement with the experiment. In the case of two muon stopping sites we would expect the two oscillating signals having the same transition temperature. The fit showed that the HF2 signal has a transition temperature of 95 K which is higher than 78 K for the LF signal. However, one should note that the transition temperature of 95 K is obtained from the fit without having experimental points close to this temperature. The reason for this is that below 90 K the HF1 and HF2 signals overlap, and it is very difficult to separate them unambiguously especially because their oscillation frequen-

cies are close to each other as we already mentioned before. We think that the transition temperature of 95 K for the HF2 signal is artificially enhanced due to the interference with the HF1 signal and the intrinsic magnetic transition is lower and close to 77.6 K obtained from the temperature dependence of the LF signal.

We ascribed two oscillating components (HF2 and LF) to two muon stopping sites within the same magnetic phase. However, based on the obtained μ SR data we cannot exclude that the LF and HF2 signals extrapolate to different transition temperatures. Especially, it is open whether the HF2 signal does not indicate a first-order transition at 78 K. As this may be the LF and HF2 signals can belong to two different magnetic regions. Such a scenario was recently proposed in Ru-1222 based on the magnetization measurements.¹⁶ It is clear that Ru-1222 shows more complex magnetic behavior than Ru-1212, which requires further studies in particular with neutron diffraction.

C. Magnetic transitions in $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$ as revealed by μ SR

As one can see from Fig. 1, the magnetization behavior of $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$ can be divided basically into two regions, going from high to low temperatures. First, below $T_{irr} \approx 200$ K the irreversibility appears between the ZFC and FC data. Below $T_m \approx 90$ K there is an additional sharp increase of the magnetization and very strong irreversibility between the ZFC and FC branches. This behavior is typical for Ru-1222 and it was proposed that at T_{irr} the Ru spins order antiferromagnetically and below T_m weak ferromagnetism arises due to the canting of the Ru moments.¹ This scenario was supported by Mössbauer spectroscopy measurements which revealed magnetic hyperfine splitting in Ru-1222 samples below T_{irr} , indicating magnetic order.¹

Our μ SR results indeed confirm the presence of magnetic order below 200 K. However, they show that magnetism takes place only in a small portion ($\sim 15\%$) of the sample. Therefore there is no bulk magnetic order in Ru-1222 in the temperature range $T_m < T < T_{irr}$. It is important to point out that this magnetic order is not due to impurities. X-ray diffraction showed that our samples are single phase and any impurity content must be below 5%. This excludes impurity phases as a reason of magnetism below T_{irr} . Recently, formation of magnetic clusters (nanodomains) in Ru-1222 below T_{irr} was proposed from the magnetization measurements.¹⁶ The partial magnetic order below 200 K observed in our μ SR experiments is rather consistent with the existence of such magnetic clusters in the temperature range $T_m < T < T_{irr}$. However, the amplitude of the oscillating muon signal is fairly temperature independent in this temperature region [see Fig. 4(b)]. This shows that the magnetic nanodomains, if existing, do not behave as typical superparamagnetic particles. Note that for the superparamagnetic clusters the magnetic volume fraction is temperature dependent.

It is instructive to compare the magnetic transition temperatures obtained by ZF- μ SR with the magnetization data presented in Fig. 1. It is seen that the magnetic transition

observed with μ SR below ~ 200 K corresponds to T_{irr} in the magnetization data where small irreversibility between ZFC and FC starts to appear. Below ~ 90 K the magnetization strongly increases and a very large irreversibility between the ZFC and FC branches is observed. This corresponds to the sharp increase of the magnetic volume fraction observed by μ SR. Finally, a well resolved internal magnetic field appears at $T_m = 77.6$ K, which approximately corresponds to the temperature T_p where the ZFC magnetization has a peak. Below T_p the ZFC magnetization decreases. We note that the small peak observed in the ZFC magnetization near ~ 130 K (see Fig. 1) is not reflected in the μ SR data, suggesting that the magnetism related with this anomaly does not have a bulk character.

IV. SUMMARY AND CONCLUSIONS

In summary, we performed resistivity, dc magnetization, and ZF- μ SR experiments in the $\text{Eu}_{1.4}\text{Ce}_{0.6}\text{RuSr}_2\text{Cu}_2\text{O}_{10}$ ruthenocuprate. ZF- μ SR showed that 15(5)% of the sample volume orders magnetically below ~ 200 K. This corresponds to the onset of irreversibility in the magnetization data at T_{irr} where a difference between ZFC and FC branches appears. The observed partial magnetic order below T_{irr} is consistent with the existence of small magnetic regions in Ru-1222 which was inferred from the recent detailed magnetization measurements.¹⁶ With decreasing temperature there is a bulk magnetic transition at $T_m = 77.6$ K, and the magnetic phase accounts for the whole sample volume. Below $T_c = 40$ K the sample becomes superconducting and magnetic order persists unchanged in the superconducting state.

Taking into account the specific-heat measurements of Ru-1222, demonstrating bulk superconductivity,^{6,7} and the present results, we conclude that in Ru-1222 magnetism coexists with bulk superconductivity. Such a coexistence implies that the magnetism is related to the RuO_2 layers which are very weakly coupled to the superconducting CuO_2 planes. Generally, one may conclude that despite some structural differences between the Ru-1222 and Ru-1212 ruthenate-cuprates, they have similar physical properties. The most remarkable one is the microscopic coexistence of superconductivity and weak ferromagnetism. Such a coexistence is very surprising in view of the antagonistic nature of

superconductivity (SC) and ferromagnetism (FM). Many years ago it was proposed theoretically that exotic phases with coexistence of superconductivity and magnetism may occur in FM superconductors.^{17,18} In particular, it is possible that the spontaneous FM moments give rise to the so-called spontaneous vortex phase (SVP), so that the ferromagnetism coexists with the superconductivity. This can happen because the self-energy of a vortex becomes negative under an appropriate condition in the FM superconductor, and thus the vortices would be induced without applying an external magnetic field. A necessary condition for the SVP state was given by $H_{c1}^0 < M_{FM} < H_{c2}^0$, where H_{c1}^0 and H_{c2}^0 are the first and second critical fields for a nonmagnetic superconductor and M_{FM} is the average spontaneous FM magnetization. One can see that M_{FM} plays a role of the external magnetic field. In the SVP the sample is in the mixed state, even at zero applied magnetic field, and the Meissner state is absent. The Meissner state is possible only below the temperature where M_{FM} becomes smaller than H_{c1}^0 . Such a behavior would be consistent with the magnetization measurements in Ru-1212 and Ru-1222 compounds.^{12,19}

One can see that SVP explains the microscopic coexistence of SC and FM in ruthenate-cuprates as well as their peculiar SC properties. Now the question arises whether the SVP indeed exists in these compounds. Estimations showed that in ruthenate-cuprates H_{c1}^0 and M_{FM} are comparable, so that the formation of the SVP state is possible.¹⁹ Recently, using magneto-optical imaging it was demonstrated that in Ru-1222 magnetic flux is present below T_c in zero applied magnetic field,²⁰ but disappears above T_c . If confirmed, this would be the first direct observation of SVP. Up to now nearly all studies have been performed on polycrystalline ruthenate-cuprates. The availability of single crystalline and epitaxial thin-film samples would be important to further explore the peculiar superconducting and magnetic properties of these fascinating materials. In particular, it would be very interesting to perform small-angle neutron-scattering experiments to study SVP in the ruthenate-cuprates.

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