Unique interplay between superconducting and ferromagnetic orders in $EuRbFe_4As_4$

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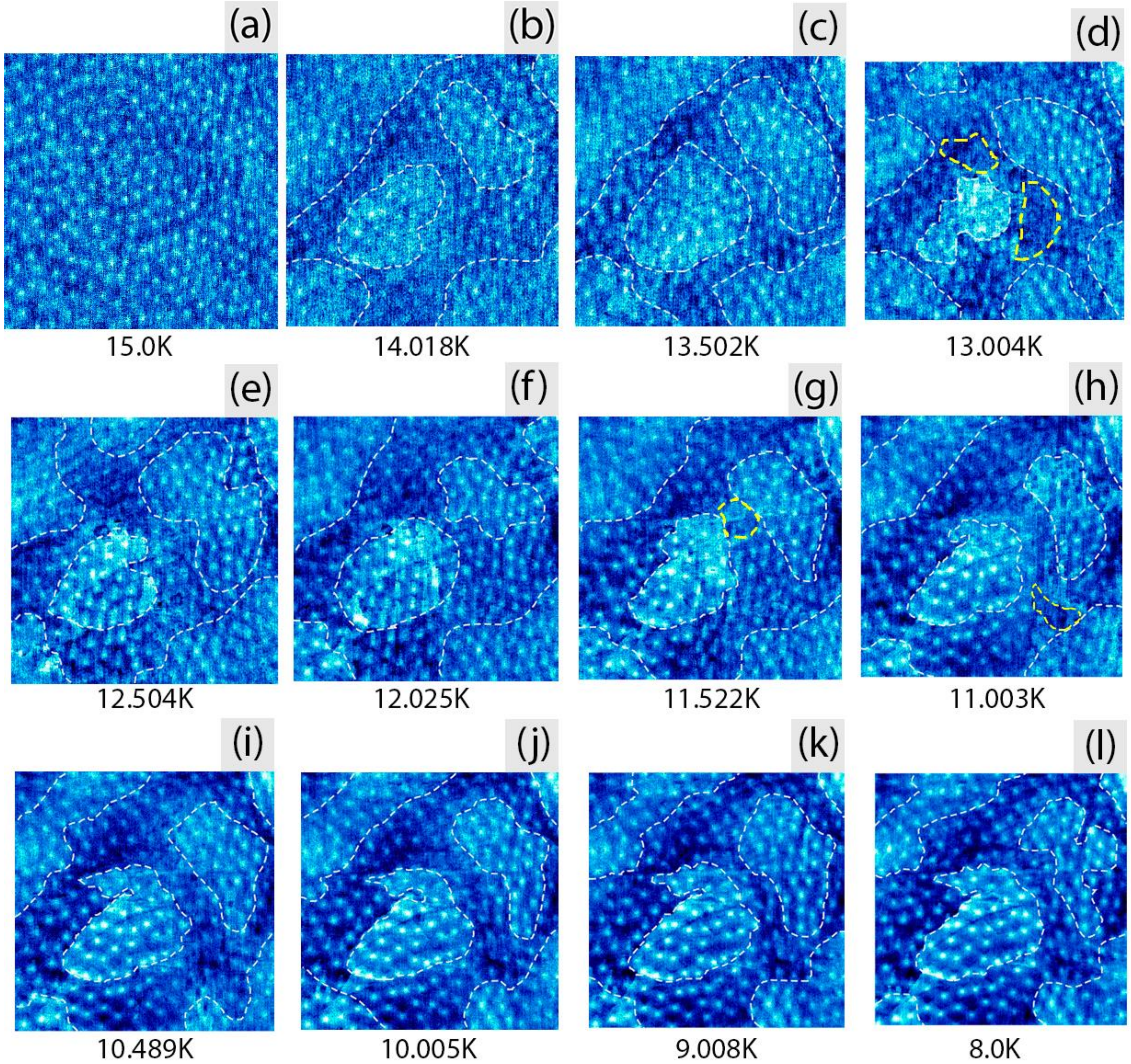

Figure 1: MFM images of magnetic response and superconducting structure on the (001) surface of $RbEuFe_4As_4$ single crystal in the constant field H = 30 Oe. The scanning surface area decreases from 12.4x12.4 μm^2 to 11.3x11.3 μm^2 by decreasing of temperature.

For the set of experimental results we analyzed vortex lattices : designed a vortex lattice, built distribution histograms of the distance between vortices and distribution histograms of the angles between straight lines connecting centers of vortices at 21 different temperatures from 20 K to 5 K, built temperature dependencies of typical distances between vortices, angles and concentration. In the fig. 2(a) we can observe a small reduction of typical angles value, it reflects changes in the number and position of vortices. In the fig. 2(b) we see the sharp increase of the distance between vortices at the temperature range from 10K to 14K. In the fig. 2(c) we observe the abrupt decrease of the vortex concentration at the temperature range from 10K to 14K, it corresponds to the increase of distance between vortices.

In the fig. 1(a) we see vortex lattice without any features. In the fig. 1(b) we can notice black point, as we suppose, it is an antivortex. Dark colors reflect areas, where the force, acting on cantilever above the surface, has an opposite sign in comparison with light spots corresponding to the vortices. In each fig. 3(b-l) we can see areas of antivortices, which appear between vortices, moving apart them slightly, but in general not changing the pattern of vortices. We can observe that antivortices are not distributed uniformly, but make up areas with a distinct dark contrast, against light areas in which there are no antivortices. The light and dark areas form the domains that we have separated with white outlines. Also we notice in the fig. 3(d) and 3(g) some areas (inside yellow outlines) without vortices and antivortices, probably they have annihilated. And we see the result of it on the curve of the temperature dependence of the vortex concentration: dramatic reduction of the concentration at the temperature range from 10 K to 14 K.

Introduction

New members of the iron-pnictide family, the so-called 1144-compounds, attract interest recently because the alternating layers of alkaline A and alkaline-earth B cations produce two different kinds of As sites. These materials can be viewed as the intergrowth of A-122 and B-122 iron-pnictides and they are naturally hole doped. The parent compounds are superconducting with transition temperatures Tc around 35 K, higher than most of the 122-materials; no spin-density-wave order has been observed. Among all possible candidates, Eu-based 1144-systems are even more intriguing, since the Eu-sublattice orders ferromagnetically below a critical temperature $T_N \approx 15$ K [1, 2], similar to the 122-counterpart $EuFe_2As_2$. Ferromagnetic order deep inside the superconducting state is very rare, in general; hence the "ferromagnetic superconductor" $EuRbFe_4As_4$ might pave the way towards realization of a "superconducting ferromagnet". However, the exact nature of the Eu magnetic order and its effect on superconductivity is unresolved because single crystals have been synthesized only recently.

Our experiments

Notable set of experiments was done in a constant field in the FC regime at a going down temperature from 20 K to 6 K. Figure 1 shows a series of experimental results in the constant field 30 Oe at temperature range from 15 K to 8 K. Fig. 1(a) illustrates vortex structures typical for the temperature range above the Curie temperature and below the superconducting transition temperature, disappeared after heating above T_{SC}. Thus, the observed sign-alternating contrast can be attributed to the vortex lattice. Fig. 1(b-l) show the distribution of the same Abrikosov vortices and the magnetic response at the temperature range below T_{Curie}. The observed contrast (light spots) corresponds to Abrikosov vortices with the magnetic flux density $\Phi_0/a^2 \sim 33$ Oe.

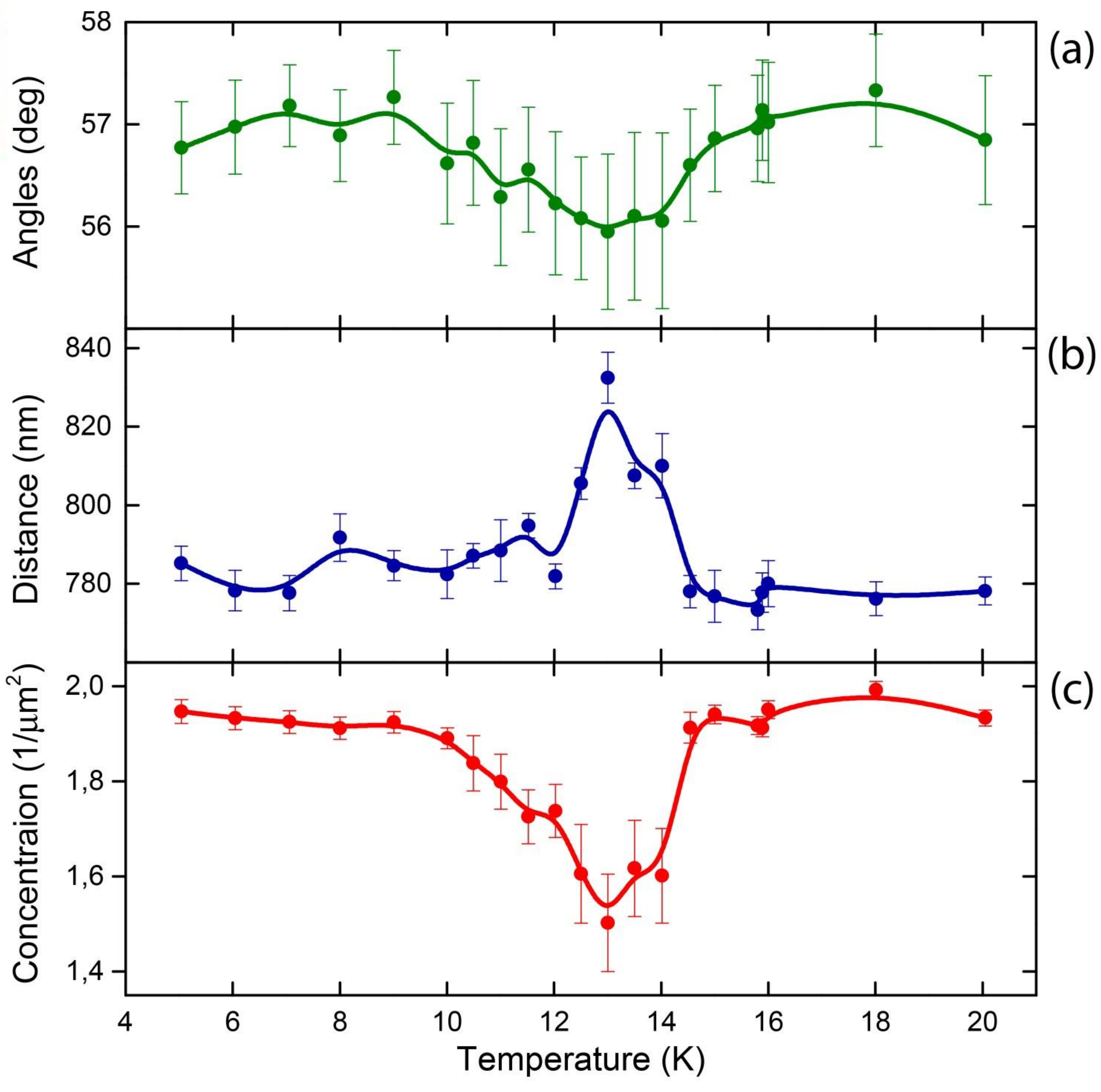

Figure 2: (a) Temperature dependence of the angles between straight lines connecting centers of vortices; (b) temperature dependence of the distance between vortices; (c) temperature dependence of the vortex concentration.

Conclusions

From our investigations on single crystals, we conclude that $RbEuFe_4As_4$ is a ferromagnetic multiband superconductor, in which superconductivity overcomes the ab-plane oriented ferromagnetic order of the Eu^{2+} ions. A detailed analysis of MFM data demonstrates that the ferromagnetic order does influences the vortex lattice, albeit weakly. Near T_N the integrated vortex density is reduced as demonstrated in fig. 2(c). On a local scale, the vortex distribution becomes inhomogeneous: domains with unchanged vortex density coexist with regions where the density becomes significantly higher or lower. This indicates that below T_N the vortex lattice is affected by ferromagnetism, but the intensity of the additional field remains rather low, as it is not able to alter the vortex lattice significantly. The weak coupling of ferromagnetism and superconductivity may imply the existence of a rather weak exchange fields between the Eu- and Fe-sublattices, where such effects have been discussed previously for the Eu-122 systems with Eu-bands located far away from the Fermi energy [3].

Acknowledgements and References

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