Observation of the FFLO-like nodal planes in the Au layer of Nb/Au/Fe trilayers by neutron reflectivity measurements

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From the study of Nb/Au/Fe and Nb/Au/Co trilayers,[1, 2)] it was suggested that the superconducting order parameter Δ shows an FFLO-like oscillation with a period of Λ~2.1 nm in the Au layer probably due to the existence of strong spin-orbit coupling. In order to observe the oscillation in Δ, we carried out neutron reflectivity measurements on a trilayer of Nb(28.8nm)/Au(10.4nm)/Fe(12.6nm) with a cap of Au(4.4nm). For a review on the FFLO (or LOFF) states, please see ref. 3.

The Nb layer shows superconductivity below T_c~8.0 K, whereas the Fe layer is ferromagnetic. Below T_c, the Au layer is supposed to be in a superconducting state due to a proximity effect of the Nb layer. For the observation of possible FFLO-like nodal planes, where paramagnetic moments will appear when a magnetic field is applied perpendicular to the planes,[4)] neutron reflectivity measurements were performed for $0.07<Q<6$ nm^{-1} at BL17 (Sharaku) in J-PARC/MLF. Measurements were first carried out at [10 K, 0 kOe], and then the sample was cooled to 2.3 K under zero magnetic field ($|H|$<0.1 Oe) to achieve a superconducting state. Measurements were carried out in sequence as shown in Fig. 1: [2.3 K, 0 kOe]→[2.3 K, 2 kOe]→[10 K, 2 kOe]. The data were obtained under four different conditions: (N, H=0) a normal state without field, (S, H=0) a superconducting state without field, (S, H≠0) a superconducting state with an applied field, and (N, H≠0) a normal state with an applied field.

The reflectivity obtained as a function of Q was in excellent agreement with previous results (Project No. 2012B0139). In the present experiment, we were particularly interested in the reflectivity at high Q's. To improve the S/N ratio, the signal was accumulated for a larger number of counts than in the previous measurements.

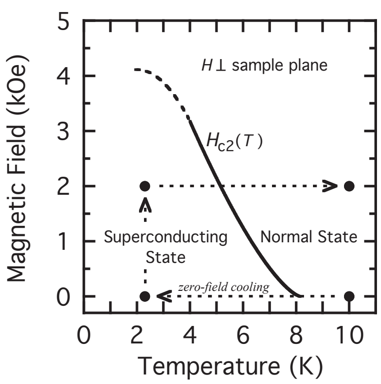

Fig. 1. Conditions for the measurements.

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In order to clearly show the changes in reflectivity when measurement conditions were changed, the reflectivity ratios $\log(R_1/R_2)$ were plotted as a function of Q in Fig. 2: [R(2.3 K, 2 kOe)/R(2.3 K, 0 kOe)], [R(2.3 K, 2 kOe)/R(10 K, 2 kOe)], [R(2.3 K, 0 kOe)/R(10 K, 0 kOe)], and [R(10 K, 2 kOe)/R(10 K, 0 kOe)] for (1) (S, H≠0)←(S, H=0), (2) (S, H≠0)←(N, H≠0), (3) (S, H=0)←(N, H=0), and (4) (N, H≠0)←(N, H=0), respectively. The base lines are shifted arbitrarily for clarity of comparison. The variations in $\log(R_1/R_2)$ are qualitatively the same as those obtained in the previous measurements.

At high Q's in Fig. 2, regular and periodic peaks are observed particularly for (1) and (2) with an interval of 0.4 nm^{-1} (shown as broken lines). This interval corresponds to a period of 15.7 nm in real space. Low-noise data acquired in this experiment allow for the resolution of these peaks. At present, the origin of the 15.7 nm period is not clear. The thickness of the Fe layer is 12.6 nm, and we can observe a peak at 0.5 nm^{-1} that corresponds to a thickness of 12.57 nm, reflecting a magnetic change in the Fe layer. For more elaborate analysis, we have to carry out reflectivity simulation based on an appropriate multilayer model, including magnetic components not only in Fe but also in Au. The intense peak at 3.2 nm^{-1} for (1) and (2), however, may prove the existence of the FFLO-like nodal planes in the Au layer.

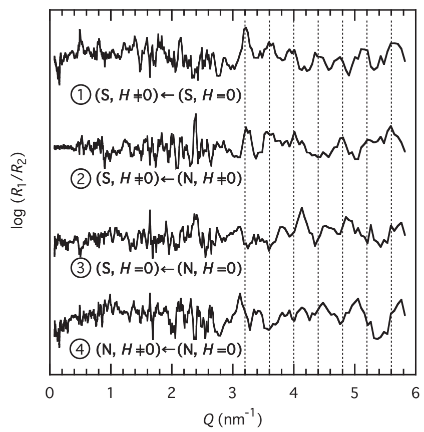

Fig. 2. Changes in neutron reflectivity.

References

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