Nb/rare-earth bilayers: RKKY systems in proximity to an *s*-wave superconductor

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We have been studying the superconducting proximity effects in Nb/rare-earth (RE) bilayers, where RE indicates Gd, Tb, Dy, or Ho (the first four heavy RE elements in the periodic table). The RKKY interaction is common mechanism responsible for the magnetic structures in the RE elements. The Nb/RE bilayers can thus be regarded as RKKY systems in proximity to an *s*-wave superconductor (Nb). Recent theoretical studies showed that a new class of superconducting systems based on RKKY interactions exhibits topological superconductivity and hosts Majorana fermions. This result may unexpectedly shed light on the understanding of the superconducting proximity effects in Nb/RE bilayers.

The details of the sample preparation have been reported in the previous APR. The superconducting transition temperature T_c of each sample was measured, and we performed a periodicity analysis on the $T_c(t_{RE})$ data using a quantitative fast Fourier transform (FFT) method, where t_{RE} is the thickness of the RE layer. In Fig. 1, the vertical bars indicate the periods of the oscillation components in $T_c(t_{RE})$. With the exception of the longest period (~3.5 nm) for Gd, two types of variations are confirmed in the element dependence of the period. Here, we refer to the longer periods (more than 1 nm) as λ_L and the shorter ones (about 1 nm) as λ_S. The spin modulation period intrinsic to Ho, λ_{spin}^{Ho}(=3.4 nm; closed circle: ref. 1), is located within a broad distribution of λ_L for Ho. We identify a linear change in λ_L (shown as a broken line) from Gd to Dy. The line is extrapolated to Ho, giving an extrapolated value of 2.45 nm. The distribution of λ_L for Ho can be explained by the two unresolved peaks at 3.4 and 2.45 nm.

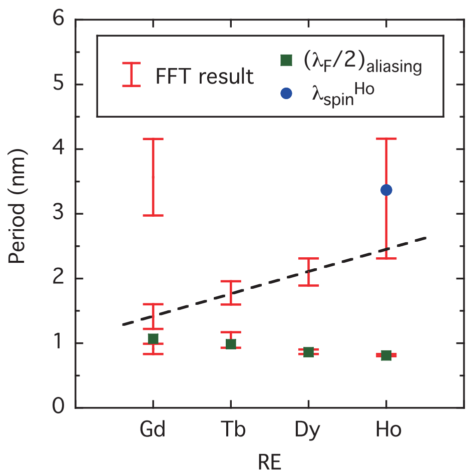

Fig. 1. Summary of the FFT analysis: periods of the oscillation components in $T_c(t_{RE})$ for Gd, Tb, Dy, and Ho. The closed circle (λ_{spin}^{Ho}) shows literature data.[1)]

According to the picture of the RKKY interaction between conduction electrons and 4*f* moments, the exchange energy E_{ex} at 0 K scales linearly with the 4*f* spin moment *S*, where *S*=7, 6, 5, and 4 μ_B for Gd, Tb, Dy, and Ho, respectively. The spatial period of the FFLO-like oscillation, λ_{FFLO}, in the REs therefore increases from Gd to Ho, as long as $\lambda_{FFLO}=\pi\hbar v_F/2E_{ex}$ holds and the Fermi velocity v_F is almost unchanged for the REs. The broken line actually suggests that λ_L increases as $S(\propto E_{ex})$ decreases. Further, the values of λ_L for Ho and Gd are consistent with the literature data for λ_{FFLO}.[1, 2)] We infer that the broken line indicates the element dependence of λ_{FFLO}.

The Fermi wavelength λ_F of each RE was calculated from λ_{FFLO} (the broken line) and the experimental values of E_{ex} for the Δ_2 valence states[3)] by using the above equation and $v_F=2\pi\hbar/m_e\lambda_F$ (m_e: electron mass). Note that there is little experimental data of v_F and λ_F for REs to date. Our calculations show that v_F=1.25, 1.46, 1.33, and 1.36 ($\times10^6$ m/s) for Gd, Tb, Dy, and Ho, respectively. These values are close to those predicted by the nearly free-electron model. The closed squares in Fig. 1 show the calculated results of $(\lambda_F/2)_{aliasing}$, i.e., the $\lambda_F/2$ aliased by discrete-thickness (Δt_{RE}=0.4 nm) sampling. We recognize that the values of $(\lambda_F/2)_{aliasing}$ reproduce λ_S values very well. Naively, therefore, λ_S reflects the formation of quantum well states in the RE layer, as observed in the superconducting Pb film.[4)]

The above discussion is simple, but provides a reasonable explanation for the two oscillation components λ_L and λ_S regardless of the RE. When we recall the intricate Fermi surface (FS) of RE as well as of Nb, however, the basis for the free-electron-like aspect is not obvious. The Fermi wave vector mismatch between two materials, in general, has a large influence on the proximity effect, and the FS which contributes to the proximity effect is mainly determined by the smaller one among the two materials.[5)] In our case, it would be difficult to extract a spherical-like FS from the intricate FSs of RE and Nb. We also have to explain the use of the bare electron mass instead of the effective mass for m_e, since the mass enhancement of the conduction electrons due to electron-phonon interaction has been calculated for bulk RE metals.[6)] This issue deserves further consideration.

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References

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