Proximity effect as a probe of electronic correlations and exchange field in F/S nanostructures

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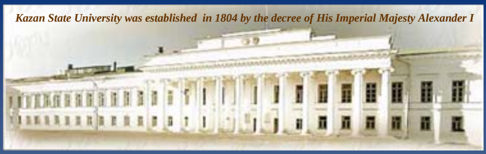


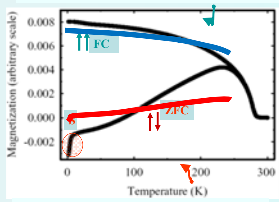
1. Abstract

The proximity effect for thin pure bilayer F/S and trilayer F/S/F, where F is ferromagnetic metal, and S is superconductor, is investigated on the base of new boundary-value problem for the Eilenberger function. For both systems the dependencies of critical temperature on an exchange field of the F metal, electronic correlations in the S and F metals, and thicknesses of layers F and S are derived. It is shown that the possibility of the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state observation is especially increased in the asymmetrical trilayers F/S/F' for which **solitary reentrant superconductivity** is predicted. We propose new method of probe of electronic correlations and exchange field. It allows us to predict the sign and value of the constant of electron-electron interaction in gadolinium and to explain a surprisingly high critical temperature (T_c ~ 5K) in the short-periodic Gd/La superlattice

2. Experimental background

Superconductivity in the short-periodic Gd/La superlattice

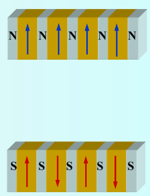
Field cooling (FC) results in ferromagnetic alignment of the Gd layers and the suppression of superconductivity.



Zero-field-cooled (ZFC) magnetization an antiferromagnetic alignment of the Gd (FM) layers and the onset of superconductivity (S) below T ~ 5 K.

Goff *at al.* JMMM **240**, 592 (2002) [1]

Deen *at al.* J. Phys.: Cond. Matt. **17**, 3305 (2005) [2]



Surprising facts:

Measured T_c for Gd/La superlattice **was 5K**; this value coincides with the **bulk lanthanum T_{cs}**!

Superconductivity was observed at $d_{Gd} >> d_{La}$ and
$T_c(d_{Gd} \approx 3d_{La}) \approx$ **5K** $\approx T_{cs}$[1]
$T_c(d_{Gd} \approx 2d_{La}) \approx$ **5K** $\approx T_{cs}$[2]
T_c = Const $\neq f(d_f/d_s)$!

What is new in our approach?

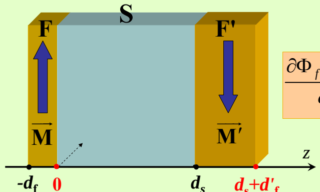
- **The order parameter Δ and electron-electron interaction λ are taken into account for both metals S and F.**

  In the previous theories (see [3-5]) Δ_F and λ_F were neglected for the ferromagnet.
- **New boundary value problem for the Eilenberger function [6]**

  We allow for the spatial changes of the Eilenberger function not only across the F and S layers, but also along the F/S interface (Umklapp processes)

3. F/S/F' trilayer: boundary value problem [6] for Eilenberger functions Φ_f and Φ_s

$$\left.\frac{\partial \Phi_f(z,\omega)}{\partial z}\right|_{z=-d_f} = 0 \qquad \left.\frac{\partial \Phi_f(z,\omega)}{\partial z}\right|_{z=d_s+d'_f} = 0$$



Cooper limit, ideal transparency

Conditions on internal boundaries

$$\Phi_s(\mathbf{p},\mathbf{q}_s,+0,\omega) = \Phi_f(\mathbf{p},\mathbf{q}_f,-0,\omega);$$

$$\xi_{sz}\left.\frac{\partial \Phi_s(\mathbf{p},\mathbf{q}_s,z,\omega)}{\partial z}\right|_{z=+0} = \xi_{fz}\left.\frac{\partial \Phi_f(\mathbf{p},\mathbf{q}_f,z,\omega)}{\partial z}\right|_{z=-0}$$

$$\Phi_s(\mathbf{p},\mathbf{q}_s,d_s-0,\omega) = e^{i\phi}\Phi'_f(\mathbf{p},\mathbf{q}_f,d_s+0,\omega); \quad \phi = 0,\pi$$

$$\xi_{sz}\left.\frac{\partial \Phi_s(\mathbf{p},\mathbf{q}_s,z,\omega)}{\partial z}\right|_{z=d_s-0} = e^{i\phi}\xi'_{fz}\left.\frac{\partial \Phi'_f(\mathbf{p},\mathbf{q}_f,z,\omega)}{\partial z}\right|_{z=d_s+0}$$

0(π)-phase superconducting state with ϕ =0 ($\phi=\pi$): $\Delta' = e^{i\phi}\Delta$
New: **π-superconductivity** for F/S/F trilayer!

$$\Delta_{s(f)}(\mathbf{q}_{s(f)},z) = 2\lambda_{s(f)}\pi T\,\mathrm{Re}\sum_{\omega>0}{}'\langle\Phi_{s(f)}(\mathbf{p},\mathbf{q}_{s(f)},z,\omega)\rangle;$$

$$\left[2\tilde{\omega}_{s(f)} - v_{s(f),z}\xi_{s(f),z}\frac{\partial^2}{\partial z^2}\right]\Phi_{s(f)}(\mathbf{p},\mathbf{q}_{s(f)},z,\omega) = 2\Delta_{s(f)}(\mathbf{q}_{s(f)},z)$$

$$\xi_{sz} = \frac{v_{sz}}{2\tilde{\omega}_s}; \quad 2\tilde{\omega}_s = 2\omega + i(\mathbf{v}_{s\perp}\mathbf{q}_s); \quad \langle\ldots\rangle = \oint\frac{d\Omega_{\mathbf{p}}}{4\pi}\ldots;$$

$$\xi_{fz} = \frac{v_{fz}}{2\tilde{\omega}_f}; \quad 2\tilde{\omega}_f = 2\omega + i\left[2I + (\mathbf{q}_f\mathbf{v}_{f\perp})\right];$$

$$\xi'_{fz} = \frac{v_{fz}}{2\tilde{\omega}'_f}; \quad 2\tilde{\omega}'_f = 2\omega + i\left[2Ie^{i\chi} + (\mathbf{q}_f\mathbf{v}_{f\perp})\right]; \quad \chi = 0,\pi$$

0(π)-phase magnetic state with χ=0 ($\chi=\pi$): $M' = e^{i\chi}M$
Compensation of paramagnetic effect in π-magnetic states

In common case four different states ($\phi\chi$) are possible in the F/S/F' trilayer

4. Critical temperature $T_c(d'_f)$

We suppose the same electronic structure of metals $\mathbf{v}_s=\mathbf{v}_f=\mathbf{v}'_f$ and the transverse FFLO momenta $\mathbf{q}_s=\mathbf{q}_f=\mathbf{q}$.

$$\ln t^{0\pi} = \frac{(c_f+c'_f)(\lambda_f-\lambda_s)}{\lambda_s\left[c_s\lambda_s+(c_f+c'_f)\lambda_f\right]} + \Psi\left(\frac{1}{2}\right) - \left\langle \mathrm{Re}\Psi\left(\frac{1}{2}+\frac{i\Gamma(\pi)}{4\pi T_{cs}t^{0\pi}}\right)\right\rangle; \quad (1)$$

$$\Gamma(\pi) = 2I(c_f - c'_f) + \vec{q}\vec{v}_\perp$$ pair-breaking factor

$t^{\phi\chi} = T_c^{\phi\chi}/T_{cs}$; $a_f = 2I/v_f$; and $c_{f(s)}$ is relative weight of layer F(S):

$$c_{f(s)} = d_{f(s)}/(d_f+d_s+d'_f);$$
$$c_f + c_s + c'_f = 1$$

$$\ln t^{\pi\pi} = \frac{(c_f-c'_f)\lambda_f-(c_f+c'_f)\lambda_s}{\lambda_s\left[c_s\lambda_s+(c_f-c'_f)\lambda_f\right]} + \Psi\left(\frac{1}{2}\right) - \left\langle \mathrm{Re}\Psi\left(\frac{1}{2}+\frac{i\Gamma(\pi)}{4\pi T_{cs}t^{\pi\pi}}\right)\right\rangle;$$

Color solid lines – BCS states (q=0),
color broken lines – FFLO states (q≠0).
Limiting cases:
black broken lines **–symmetrical trilayer** F/S/F (d_f=d'_f),

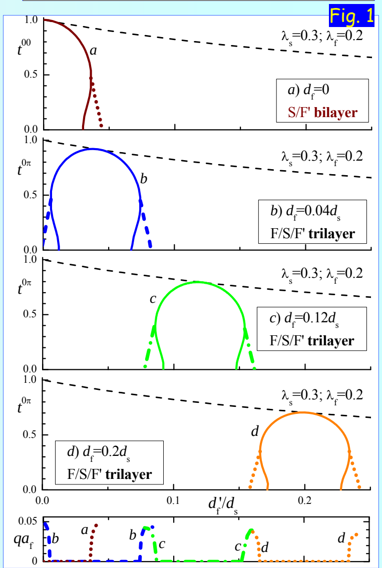
$$\ln t^{0\pi} = \frac{2c'_f(\lambda_f-\lambda_s)}{\lambda_s(c_s\lambda_s+2c'_f\lambda_f)}, \quad \lambda_f > 0; \quad (2)$$
$$\ln t^{\pi\pi} = -\frac{2c'_f}{c_s\lambda_s} \quad \lambda_f < 0,$$

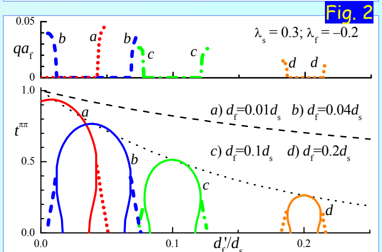
brown line - bilayer S/F' in Eq (1)
(d_f=>0 ; $\Gamma(\pi) \Rightarrow \Gamma(0) = 2I(c_f + c'_f) + \vec{q}\vec{v}_\perp$

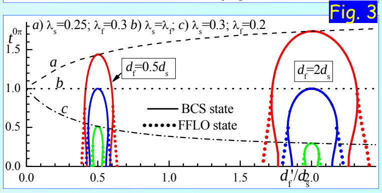
The straight dotted line b in Fig. 3 for symmetr. trilayer **explains** the Gd/La superlattices experiments [1,2]. It allows us to predict the value $\lambda_f \approx \lambda_s \approx 0.28$, because the of Eq. (2) provides $T_c^{0\pi} \approx T_{cs}$. Note, also that Eqs. (1) and (2) at $\lambda_f > \lambda_s$ predicts an increase $T_c^{0\pi} > T_{cs}$ with the F layer thickness d_f (see line a in Fig. 3).

Method. Using the well-studied BCS superconductor layer S with the known λ_s and ω_D values as a probe, we could probe the energy spectrum of pairing the spatial symmetry of the order parameter, the pairing mechanism, the exchange field I, and the magnitude and sign of electron correlations λ_f in ferromagnet F or else the order parameter symmetry in high-Tc superconductors (HTS) for the HTS/S structures.

Solitary reentrant superconductivity in asymmetrical F/S/F' trilayer







5. Conclusions

- The **solitary reentrant superconductivity** in the asymmetrical F/S/F' trilayer is predicted and the Gd/La/Gd' trilayer is proposed to observe this effect (Figs. 1-3).
- The asymmetrical F/S/F' trilayer is the real candidate to observe the **FFLO-BCS-FFLO competition** (Fig. 3).
- The **surprisingly high T_c** in the short-period Gd/La superlattice is explained and the value of the **constant** of **el.-el. attraction** in gadolinium is predicted. (Fig. 3, line b).
- The **π-phase superconductivity** for **F/S/F trilayer** is predicted in case of the el.-el. repulsion into the F layers (Fig.2).
- The **method of supercond. probing spectroscopy** to detect unknown electronic parameters of F metals is proposed.

References

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