Influence of magnons on the superconducting state in superconductor/magnet heterostructures

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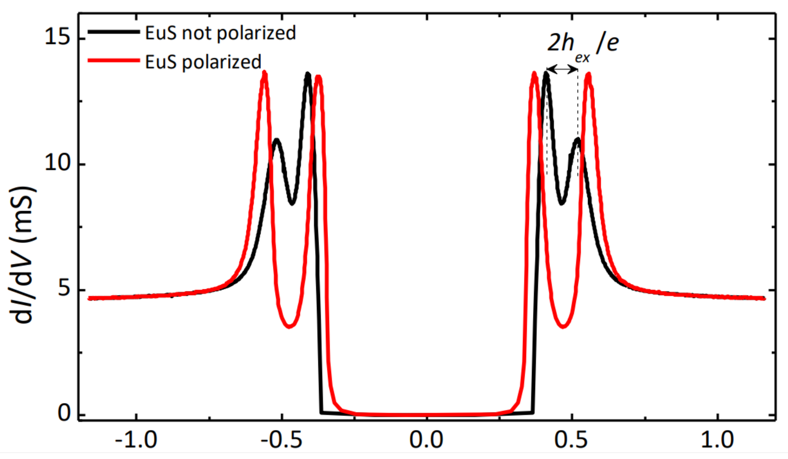
Introduction

In a thin-film ferromagnetic insulator/superconductor (FI/S) bilayers the exchange field of FIs can split the excitation spectrum of the adjacent thin-film superconductor [1]. A series of interesting phenomena have been predicted to occur in S/FI structures with spin-split DOS, such as huge thermoelectric effects [2]. By now the exchange-induced spin-splitting of the excitation spectra and DOS is studied theoretically in the mean-field approximation with respect to the exchange field.



DOS for EuS/Al bilayer. Experimental results adopted from [1].

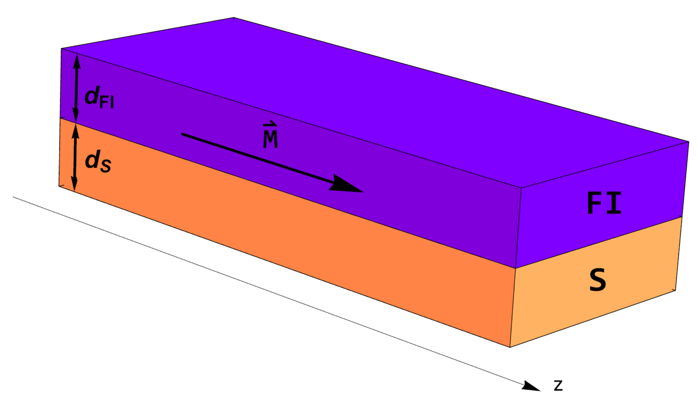
Here we investigate the influence of electron-magnon interaction on these electronic characteristics.

Model and method

$$\hat{H} = \hat{H}_S + \hat{H}_{FI} + \hat{H}_{ex}$$

$$\hat{H}_{FI} = \sum_{\boldsymbol{q}} (\omega_0 + D\boldsymbol{q}^2) b^\dagger_{\boldsymbol{q}} b_{\boldsymbol{q}},$$

System under consideration:



$$\hat{H}_S = \sum_{\boldsymbol{k}\sigma} \xi_{\boldsymbol{k}} c^\dagger_{\boldsymbol{k}\sigma} c_{\boldsymbol{k}\sigma} - \sum_{\boldsymbol{k}} \Delta c^\dagger_{\boldsymbol{k}\uparrow} c^\dagger_{-\boldsymbol{k}\downarrow} - \sum_{\boldsymbol{k}} \Delta^* c_{-\boldsymbol{k}\downarrow} c_{\boldsymbol{k}\uparrow},$$

$$\hat{H}_{ex} = -J \int d^2\boldsymbol{\rho}\, \boldsymbol{S}_{FI}(\boldsymbol{\rho}) \boldsymbol{s}_e(\boldsymbol{\rho}) =$$

$$= \tilde{U} \sum_k (c^\dagger_{k,\uparrow} c_{k,\uparrow} - c^\dagger_{k,\downarrow} c_{k,\downarrow}) + V \sum_{k,q} (b_q c^\dagger_{k,\uparrow} c_{k-q,\downarrow} + b^\dagger_q c^\dagger_{k-q,\downarrow} c_{k,\uparrow});$$

The equation on the Gor'kov Green's function:

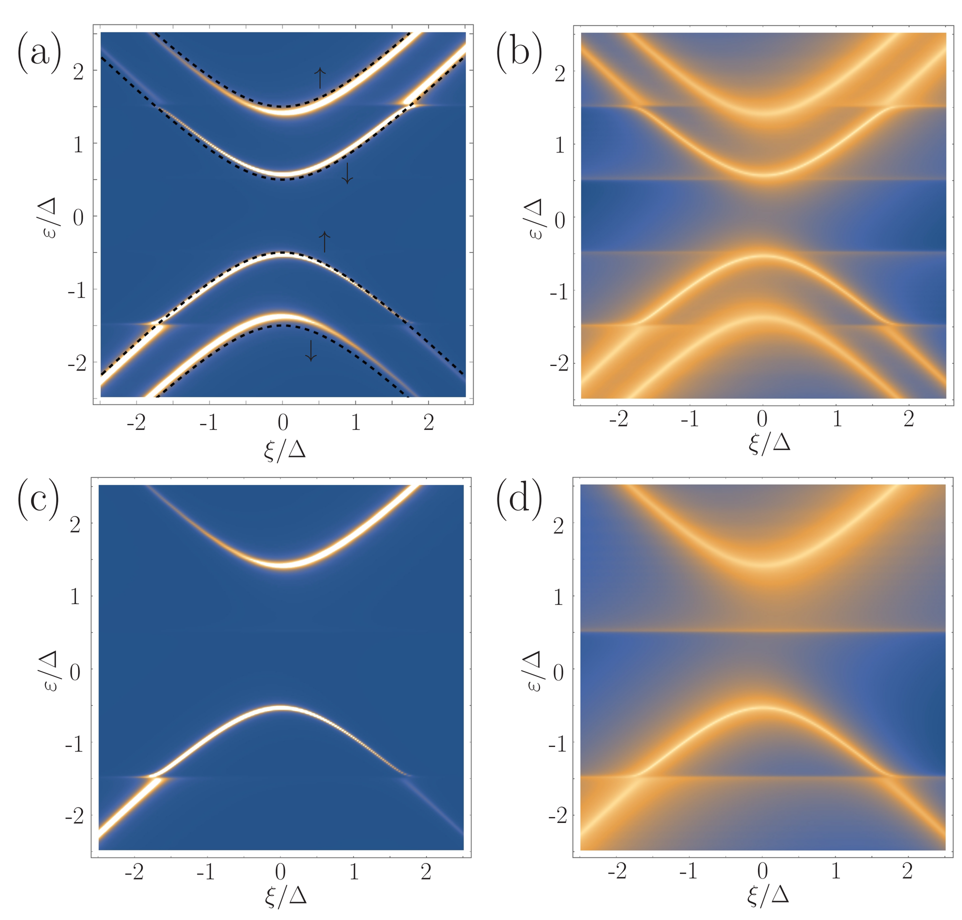
$$(\varepsilon - \xi_k \tau_z - \sigma\tilde{U} - \Delta\tau_x - \hat{\Sigma}_{m,\sigma}) \hat{G}_{\boldsymbol{k},\sigma}(\omega) = 1,$$

$$\hat{\Sigma}_{m,\sigma} = -V^2 T \sum_{\boldsymbol{q},\Omega} B_{\boldsymbol{q}}(\Omega) \hat{G}_{0,\boldsymbol{k}-\sigma\boldsymbol{q},\bar{\sigma}}(\omega - \sigma\Omega),$$

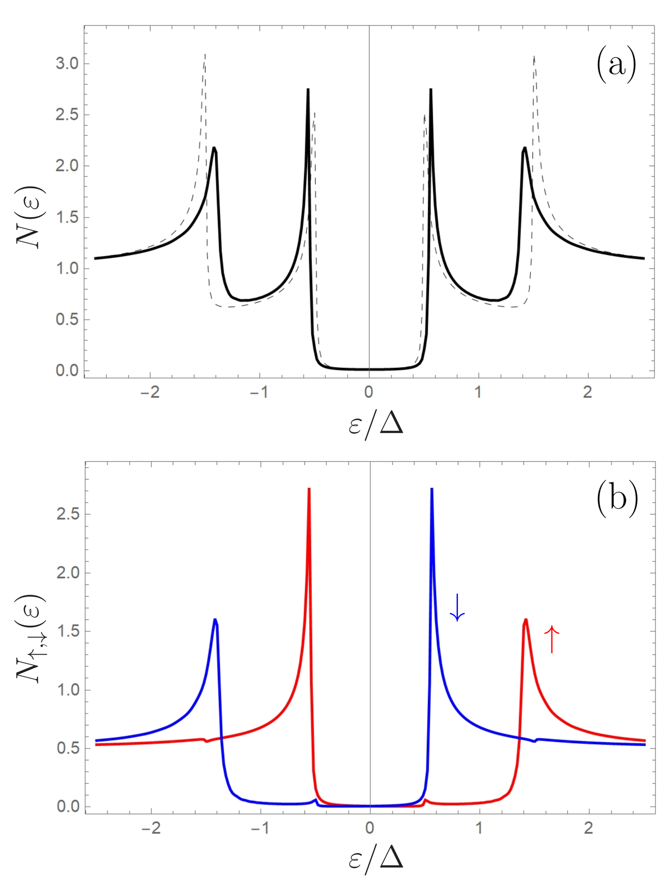
$$\tilde{U} = -\frac{J}{2|\gamma| d_S}(M_s - N_m|\gamma|), \quad B_{\boldsymbol{q}}(\Omega) = \frac{1}{i\Omega - (\omega_0 + D\boldsymbol{q}^2)}$$

LDOS and the dispersion law of S layer

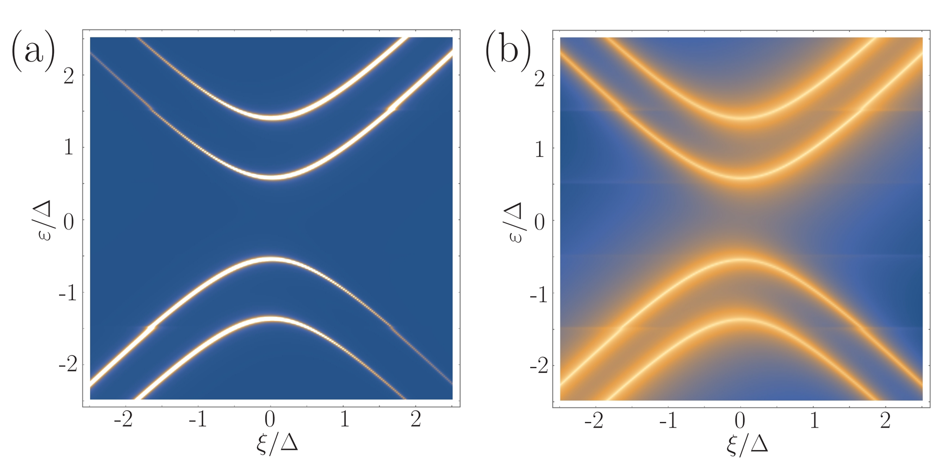
K is the dimensionless constant quantifying the strength of **the electron-magnon coupling**: $K = \frac{V^2 S_F}{4\pi\sqrt{D}} \frac{1}{d_s} = \frac{U^2(2|\gamma|/M_s)}{4\pi d_F \Delta_0^{3/2} \sqrt{D} \xi_0}$.



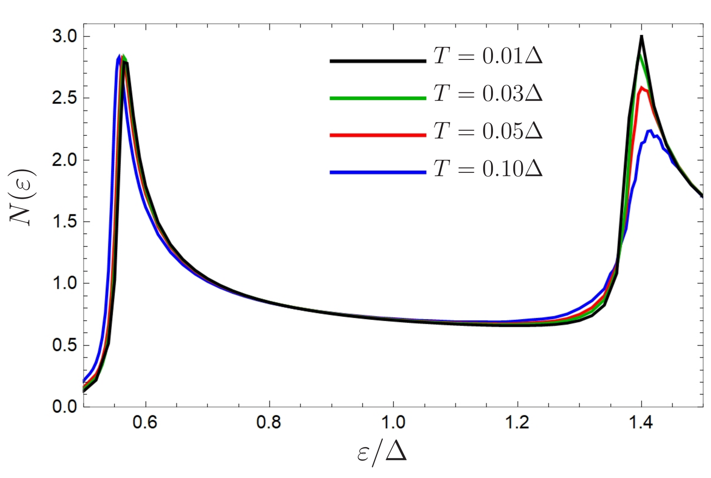
Electronic spectral function in the S layer for the both spins (a,b) and spin-up (c,d) at $K = 0.01$, $T = 0.1\Delta$, $\tilde{U} = 0.5\Delta$. Dashed lines are quasiparticle spectra at K=0.



(a) LDOS in the S layer. Dashed line is the LDOS at K=0. (b) Spin-resolved LDOS. $K = 0.01$, $T = 0.1\Delta$, $\tilde{U} = 0.5\Delta$.



Electronic spectral function in the S layer for the both spins at $K = 0.01$, $T = 0.01\Delta$, $\tilde{U} = 0.5\Delta$.



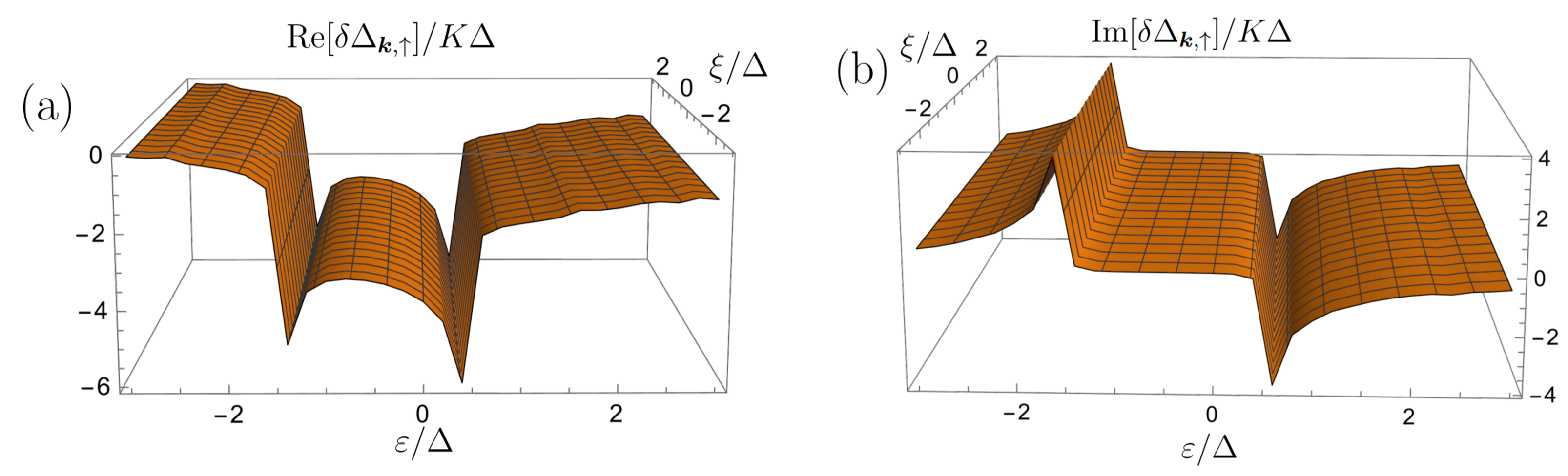
LDOS for the different temperatures. $K = 0.01$, $\tilde{U} = 0.5\Delta$.

Electron-magnon interaction leads to the temperature-dependent reconstruction of the quasiparticle spectra and LDOS.

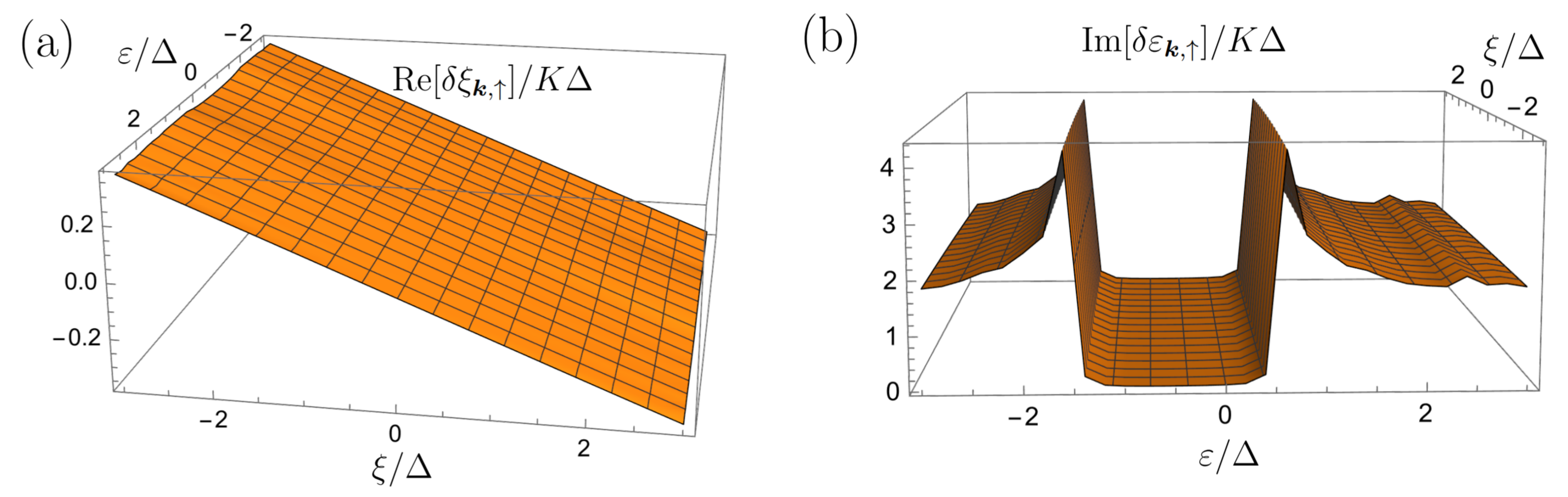
Magnonic corrections to the Green's function

$$\hat{G}_{\boldsymbol{k},\sigma}(\varepsilon) = \frac{\tilde{\varepsilon}_{\boldsymbol{k},\sigma} + \tilde{\xi}_{\boldsymbol{k},\sigma}\tau_z + \tilde{\Delta}_{\boldsymbol{k},\sigma}\tau_x}{(\tilde{\varepsilon}_{\boldsymbol{k},\sigma})^2 - (\tilde{\xi}_{\boldsymbol{k},\sigma})^2 - (\tilde{\Delta}_{\boldsymbol{k},\sigma})^2}$$

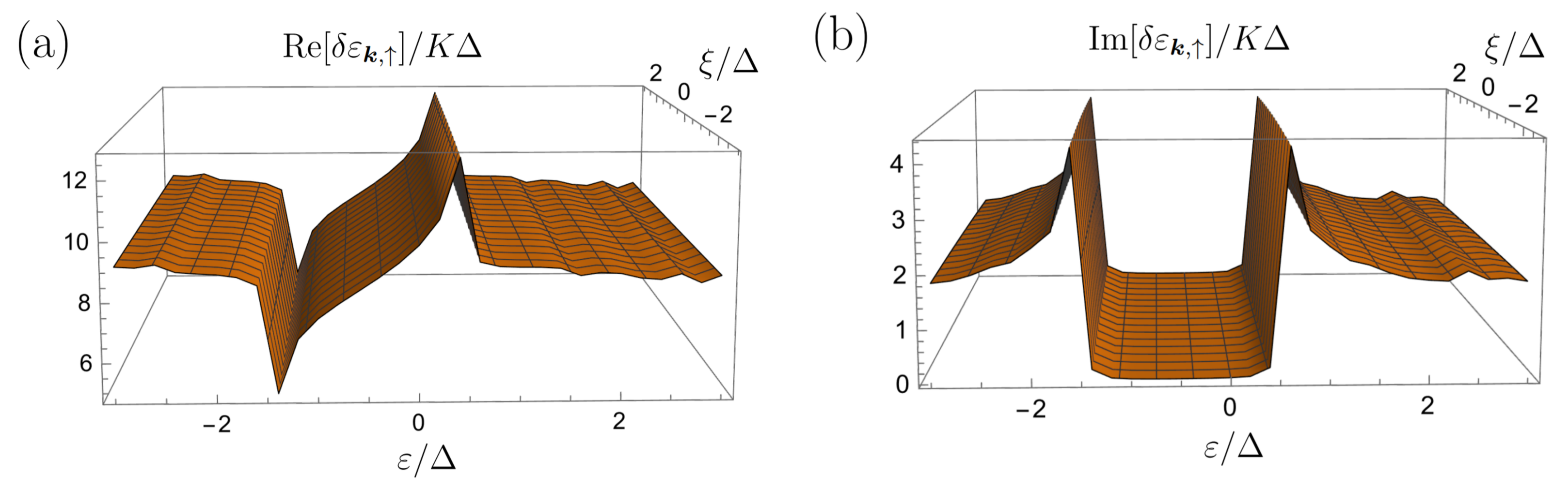
$$\tilde{\Delta}_{\boldsymbol{k},\sigma}(\varepsilon) = \Delta + \delta\Delta_{\boldsymbol{k},\sigma}(\varepsilon) = \Delta - V^2 T \sum_{\boldsymbol{q},\Omega} B_{\boldsymbol{q}}(\Omega) \frac{\Delta}{(\varepsilon - i\sigma\Omega + \tilde{U}\sigma)^2 - \xi^2_{\boldsymbol{k}-\sigma\boldsymbol{q}} - |\Delta|^2}$$



$$\tilde{\xi}_{\boldsymbol{k},\sigma}(\varepsilon) = \xi_{\boldsymbol{k}} + \delta\xi_{\boldsymbol{k},\sigma}(\varepsilon) = \xi_{\boldsymbol{k}} - V^2 T \sum_{\boldsymbol{q},\Omega} B_{\boldsymbol{q}}(\Omega) \frac{\xi_{\boldsymbol{k}-\sigma\boldsymbol{q}}}{(\varepsilon - i\sigma\Omega + \tilde{U}\sigma)^2 - \xi^2_{\boldsymbol{k}-\sigma\boldsymbol{q}} - |\Delta|^2}$$



$$\tilde{\varepsilon}_{\boldsymbol{k},\sigma}(\varepsilon) = \varepsilon - \tilde{U}\sigma + \delta\varepsilon_{\boldsymbol{k},\sigma}(\varepsilon) = \varepsilon - \tilde{U}\sigma + V^2 T \sum_{\boldsymbol{q},\Omega} B_{\boldsymbol{q}}(\Omega) \frac{\varepsilon - i\sigma\Omega + \tilde{U}\sigma}{(\varepsilon - i\sigma\Omega + \tilde{U}\sigma)^2 - \xi^2_{\boldsymbol{k}-\sigma\boldsymbol{q}} - |\Delta|^2}$$



$$\delta\varepsilon_\downarrow(\varepsilon) = -\left[\delta\varepsilon_\uparrow(-\varepsilon)\right]^*, \quad \delta\xi_{k,\downarrow}(\varepsilon) = \left[\delta\xi_{k,\uparrow}(-\varepsilon)\right]^*, \quad \delta\Delta_\downarrow(\varepsilon) = \left[\delta\Delta_\uparrow(-\varepsilon)\right]^*,$$

in Matsubaras $\delta\Delta_\uparrow(\omega) = \delta\Delta_\downarrow(-\omega) \rightarrow \Delta_t(\omega) = -\Delta_t(-\omega)$ odd − frequency order parameter

Conclusions

Interaction of electrons with thermal magnons in thin-film FI/S bilayers modifies the quasiparticle spectra and the DOS of the S film:

- The effective spin splitting of the coherence peaks is reduced with respect to the mean-field consideration.
- The outer spin-split coherence peaks are broadened, and the inner peaks remain intact. This type of broadening is a clear signature of the magnon-mediated spin flips and strongly differs from other mechanisms of the coherence peaks broadening, which usually influence all peaks.
- The order parameter acquires an effective odd-frequency spin-triplet component.
- The spin-split quasiparticle branches are partially mixed and reconstructed due to the magnon-mediated electron spin-flip processes.

References

[1] E. Strambini, V. N. Golovach, G. De Simoni, J. S. Moodera, F.S. Bergeret, F. Giazotto, Revealing the magnetic proximity effect in EuS/Al bilayers through superconducting tunneling spectroscopy, Phys. Rev. Materials **1**, 054402 (2017).

[2] F. Sebastian Bergeret, Mikhail Silaev, Pauli Virtanen, and Tero T. Heikkila, Colloquium: Nonequilibrium effects in superconductors with a spin-splitting field, Rev. Mod. Phys. **90**, 041001 (2018).

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