Spin-valve effect and parity effect in AF/S/AF systems

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Introduction

Motivation: Superconducting devices based on proximity effect in superconductor/magnetic material heterostructures are important objects for superconducting spintronics. The dependence of the critical temperature of magnetic material/superconductor/magnetic material trilayers on the angle between the magnetic layers' magnetizations leads to a spin-valve effect and gives opportunity to use such structures for spintronics applications. While superconducting spin valves with ferromagnets are well-studied, we describe AF/S/AF spin valves.

Neel triplet Cooper pairs: It was demonstrated [1] that the Neel order of the *fully compensated* AF makes the conventional singlet pairing to be partially converted into spin-triplet correlations at AF/S interfaces. Their amplitude flips sign from one lattice site to the next, just like the Neel spin order in the AF. Thus, they are called Neel triplet Cooper pairs. **Spin-valve effect** in AF/S/AF structures [2,3] is caused by sensitivity of Neel triplet Cooper pairs to mutual orientation of the Neel vectors of the AFs. Alternating sign of Neel triplets' amplitude also leads to **parity effect** [2].

Spin-valve effect, clean case

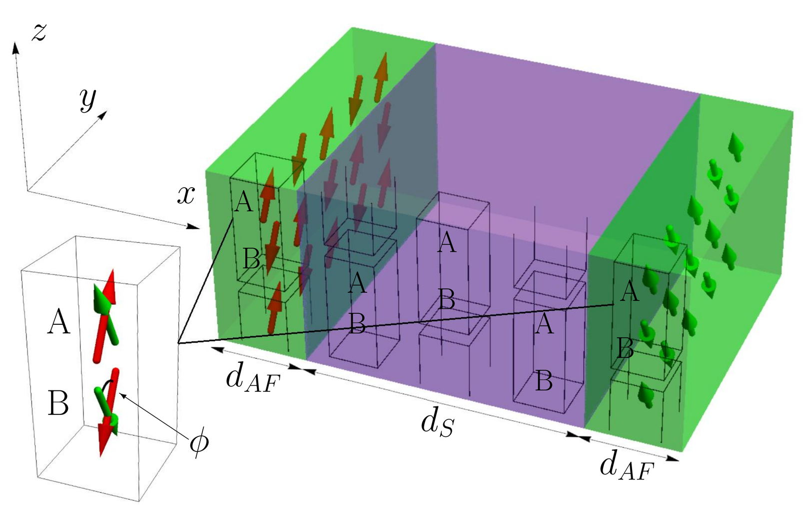

Fig.1 Sketch of the AF/S/AF system. The angle ϕ between the Neel vectors is shown.

Quasiclassical results:

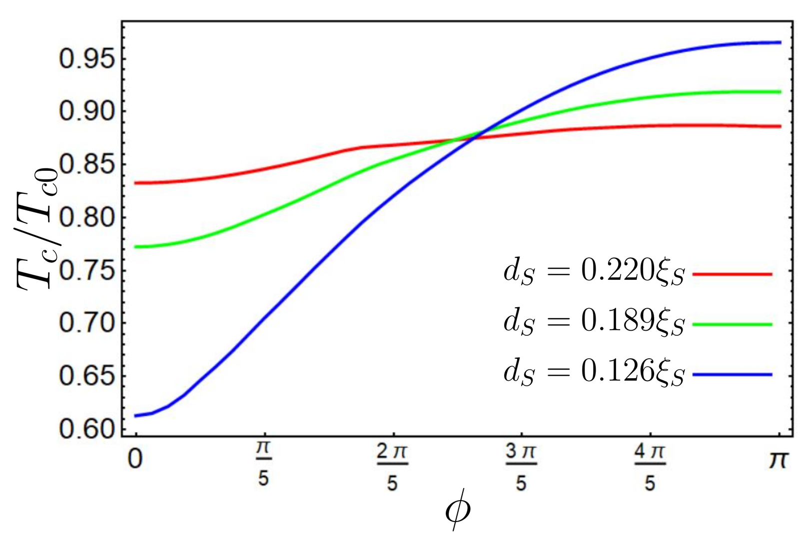

Fig.2 $T_c(\phi)$ for the AF/S/AF for fixed $h_{\rm eff} = T_{c0}$ and different d_S. $\mu_S = T_{c0}$.

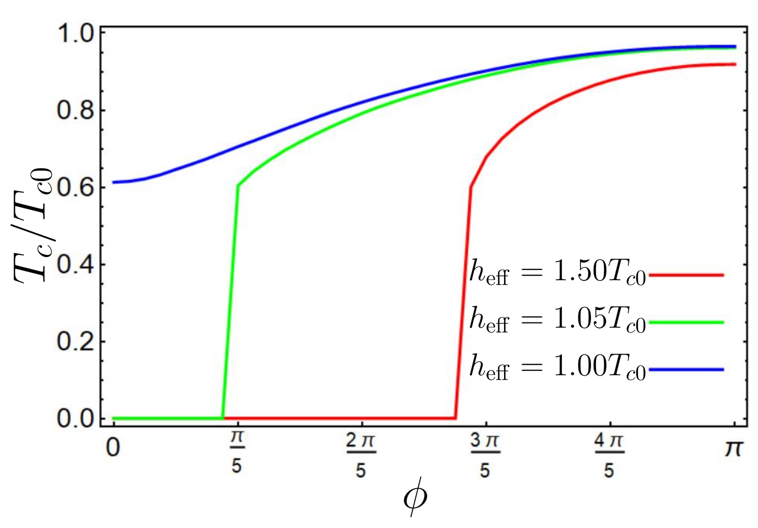

Fig.3 $T_c(\phi)$ for a fixed $d_S = 0.126\xi_S$ and different $h_{\rm eff}$. $\mu_S = T_{c0}$.

BdG results:

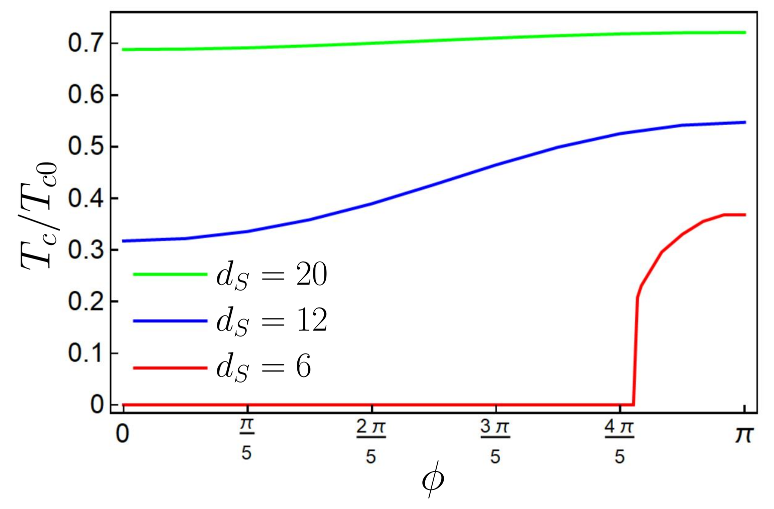

Fig.4 $T_c(\phi)$ for $\mu_S = 0$ and different d_S.

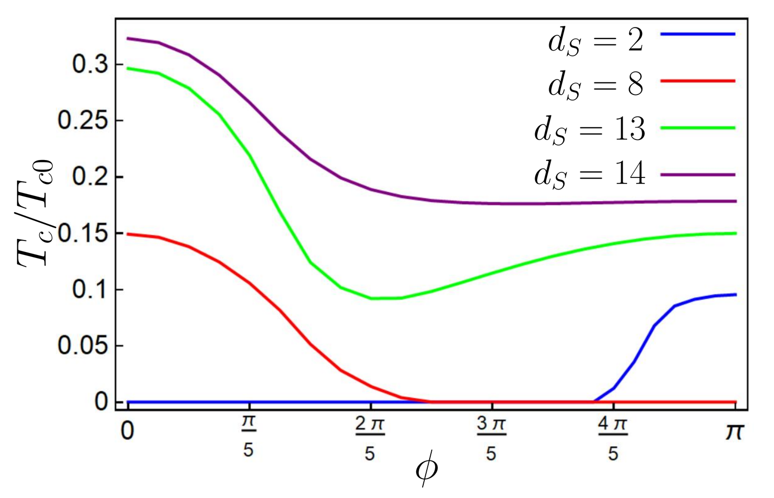

Fig.5 $T_c(\phi)$ for $\mu_S = 0.2t$ and different d_S.

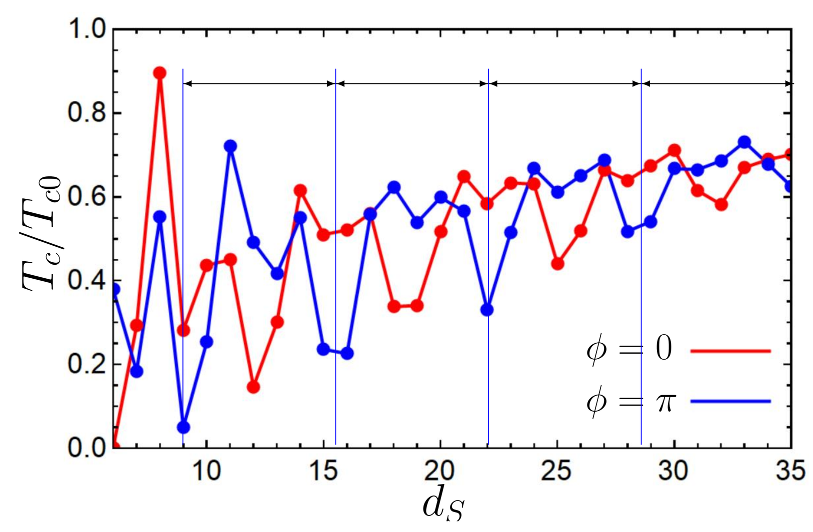

Fig.6 $T_c(0)$ and $T_c(\pi)$ as functions of d_S at $\mu_S = 0.9t$. $L_{\rm osc} = \pi v_F/\mu_S \approx 7$.

Spin-valve effect, influence of impurities

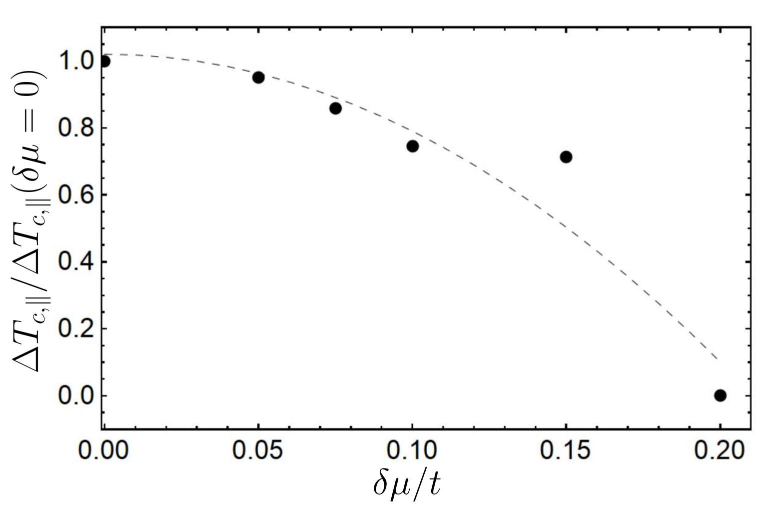

Fig.7 Suppression of spin-valve effect by impurities. $\Delta T_{c,\parallel}$ as a function of the impurity strength $\delta\mu$.

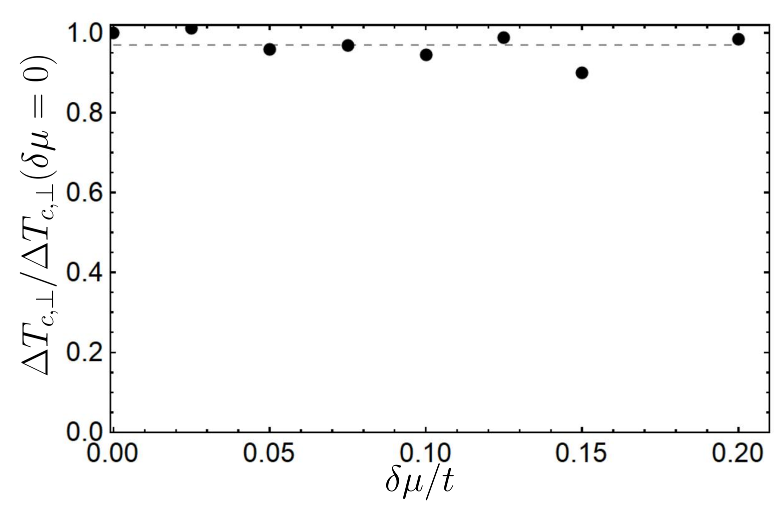

Fig.8 $\Delta T_{c,\perp}$ as a function of the impurity strength $\delta\mu$.

The "$0-\pi$" spin-valve effect $\Delta T_{c,\parallel} = [T_c(\phi = 0) - T_c(\phi = \pi)]/2$ is connected with Neel triplets and suppressed by impurities.

The "perpendicular" spin-valve effect $\Delta T_{c,\perp} = T_c(\phi = \pi/2) - [T_c(\phi = 0) + T_c(\phi = \pi)]/2$ is not suppressed by impurities.

Finite-momentum Neel triplet pairing

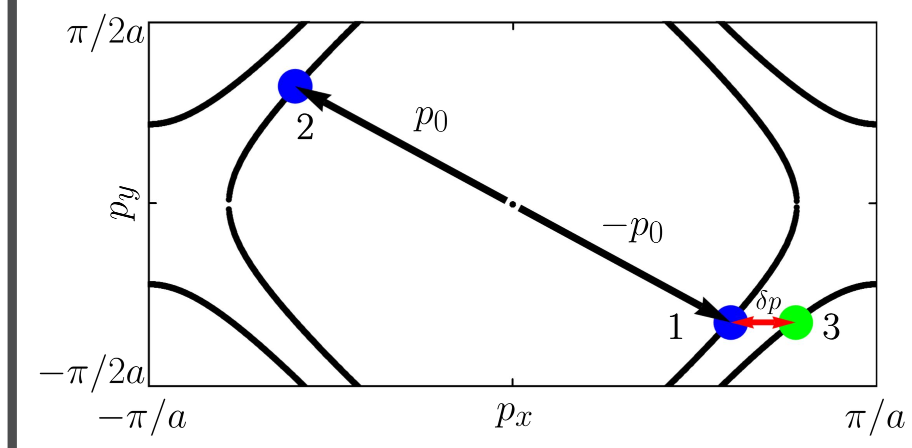

Fig.9 Brillouin zone and Fermi surface in the AF. Finite-momentum triplet pairing between electrons 2 and 3.

$$\varepsilon = -\mu + \sqrt{h^2 + 4t^2(\cos p_x a + \cos p_y a + \cos p_z a)^2}$$

$$\delta p = |p_{x3} - p_{x1}| = 2\sqrt{\mu^2 - h^2}/v_F$$

Triplet correlations oscillate with period:

$$L_{osc} = \frac{\pi v_F}{\sqrt{\mu^2 - h^2}}$$

Parity effect in AF/S/AF and F/S/F

$$H = -t\sum_{\langle \boldsymbol{ij}\rangle,\sigma} \hat{c}^\dagger_{\boldsymbol{i}\sigma}\hat{c}_{\boldsymbol{j}\sigma} + \sum_{\boldsymbol{i}}(\Delta_{\boldsymbol{i}}\hat{c}^\dagger_{\boldsymbol{i}\uparrow}\hat{c}^\dagger_{\boldsymbol{i}\downarrow} + H.c.) - \mu\sum_{\boldsymbol{i}\sigma}\hat{n}_{\boldsymbol{i}\sigma} - \frac{J}{2}\sum_{\boldsymbol{i},\alpha\beta}\hat{c}^\dagger_{\boldsymbol{i}\alpha}(\boldsymbol{h_i}\boldsymbol{\sigma})_{\alpha\beta}\hat{c}_{\boldsymbol{i}\beta}$$

Anomalous Green's function:

$$F_{\boldsymbol{i},\alpha\beta}(\omega_m) = \sum_n \left(\frac{u^{\boldsymbol{i}}_{n,\alpha}v^{\boldsymbol{i}*}_{n,\beta}}{i\omega_m - \varepsilon_n} + \frac{u^{\boldsymbol{i}}_{n,\beta}v^{\boldsymbol{i}*}_{n,\alpha}}{i\omega_m + \varepsilon_n}\right)$$

Singlet (triplet) correlations:

$$F^{s,t}_{\boldsymbol{i}}(\omega_m) = F_{\boldsymbol{i},\uparrow\downarrow}(\omega_m) \mp F_{\boldsymbol{i},\downarrow\uparrow}(\omega_m)$$

$$F^t_{\boldsymbol{i}} = \sum_{\omega_m > 0} F^t_{\boldsymbol{i}}(\omega_m)$$

F/S/F trilayers

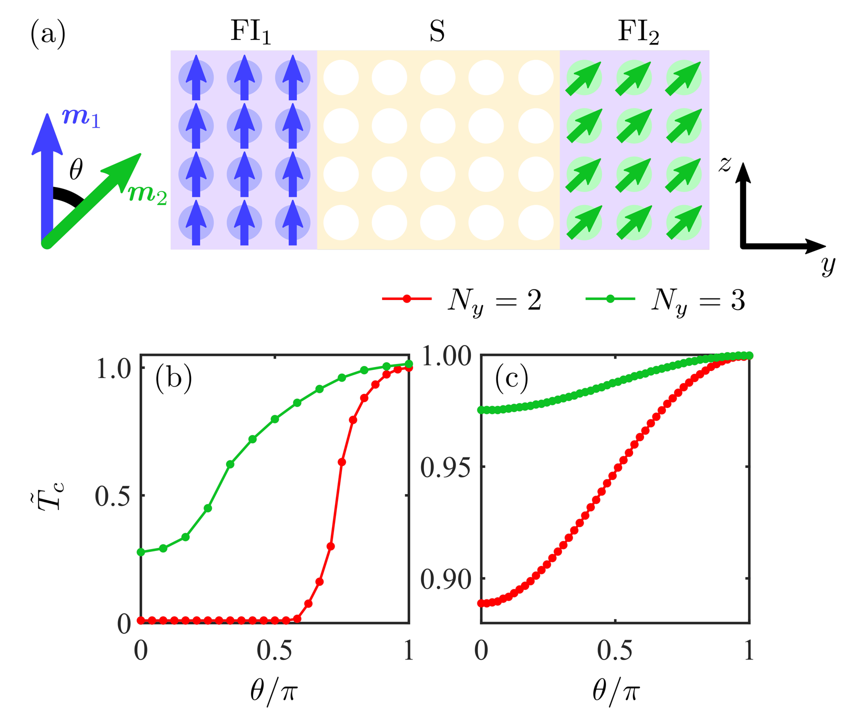

Fig.10 (a) Setup. Normalized critical temperature $\tilde{T}_c(\theta)$ for (b) stronger and (c) weaker interfacial exchange coupling J. N_y is the number of S monolayers

AF/S/AF trilayers

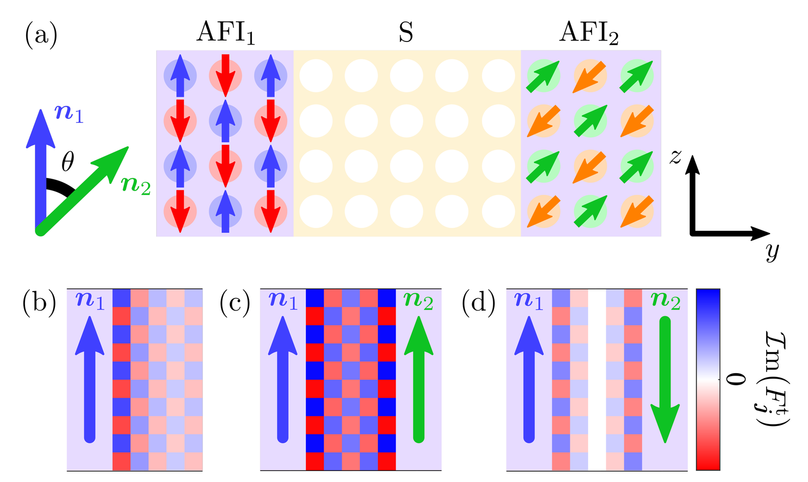

Fig.11 (a) Setup and the angle θ between the Neel vectors. Spatial variation of the triplet correlations amplitude F^t_j in (b) AF/S bilayer, (c) AF/S/AF with odd number of S monolayers and $\theta = 0$ or (d) $\theta = \pi$.

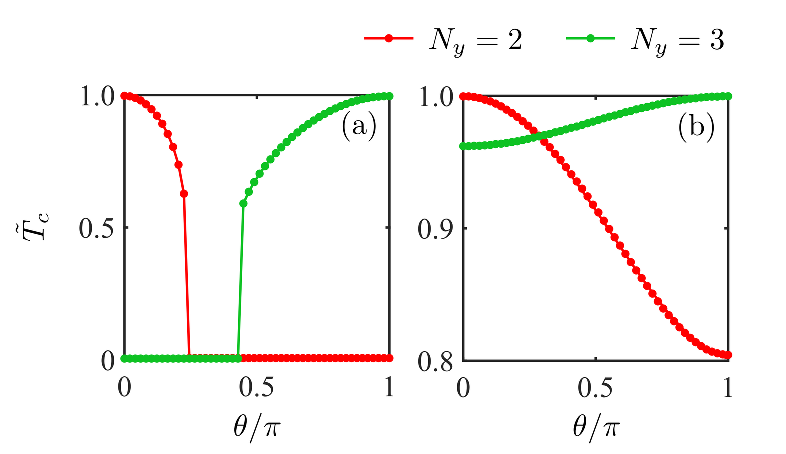

Fig.12 Normalized critical temperature $\tilde{T}_c(\theta)$ for (a) stronger and (b) weaker interfacial exchange coupling J. The variation is reversed when the number of S monolayers N_y changes from even to odd.

Conclusions

(i) Neel triplet correlations in AF/S/AF lead to spin-valve effect. The results demonstrate suppression of the valve effect at larger d_S and possibility of absolute valve effect for larger values of $h_{\rm eff}$.
(ii) Presence of impurities suppresses Neel triplets, which leads to disappearing of the "$0-\pi$" spin-valve effect.
(iii) Away from half-filling $\mu_S = 0$ the difference $T_c(\pi) - T_c(0)$ oscillates as a function of d_S due to the interference of finite-momentum Neel triplets generated by the S/AF interfaces.
(iv) For larger d_S critical temperature manifests non-monotonic dependence on the misorientation angle due to appearance of equal-spin correlations and interference effects.
(v) Angle dependence of AF/S/AF critical temperature shows the parity effect, which provides a distinct signature of the Neel triplets.

References

[1] G. A. Bobkov et al., Phys. Rev. B **106**, 144512 (2022).
[2] L. J. Kamra et al., Phys. Rev. B **108**, 144506 (2023).
[3] G. A. Bobkov et al., Phys. Rev. B **109**, 184504 (2024).

The work was supported by Grant from the ministry of science and higher education of the Russian Federation No. 075-15-2024-632.