Spin valves based on AF/S/AF heterostructures

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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 as logical elements. While superconducting spin valves with ferromagnets are well-studied [1-3], we describe AF/S/AF spin valves.

Neel triplet Cooper pairs: It was demonstrated [4] 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 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** [5].

Spin-valve effect in FI/S/FI (review)

Theory:

The average exchange field seen by a conduction electron is

$$\bar{h} = 2|\Gamma|S(a/d_S)\cos(\theta/2),$$

where θ is the angle between magnetizations of F layers [1].

This predicts suppression of superconductivity for the parallel (P) configuration and no suppression for the antiparallel (AP).

Experiment:

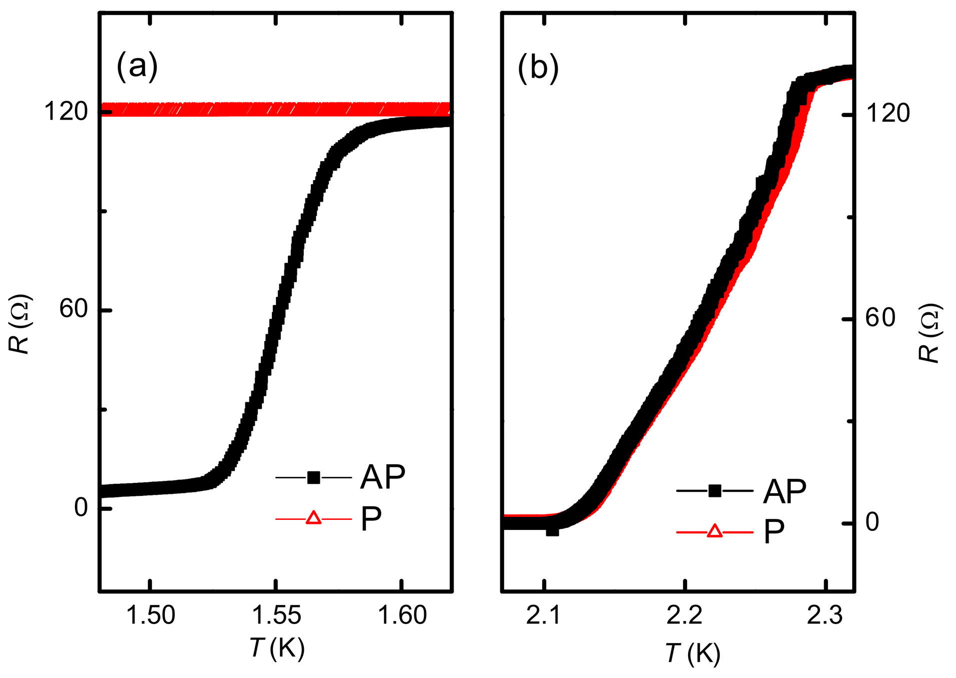

Fig.1 $R(T)$ for the P and AP configurations for (a) EuS/Al/EuS and (b) EuS/Al_2O_3/Al/Al_2O_3/EuS [2].

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

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

Anomalous Green's function:

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

Singlet (triplet) correlations:

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

$$F^t_i = \sum_{\omega_m>0}F^t_i(\omega_m)$$

AF/S/AF trilayers

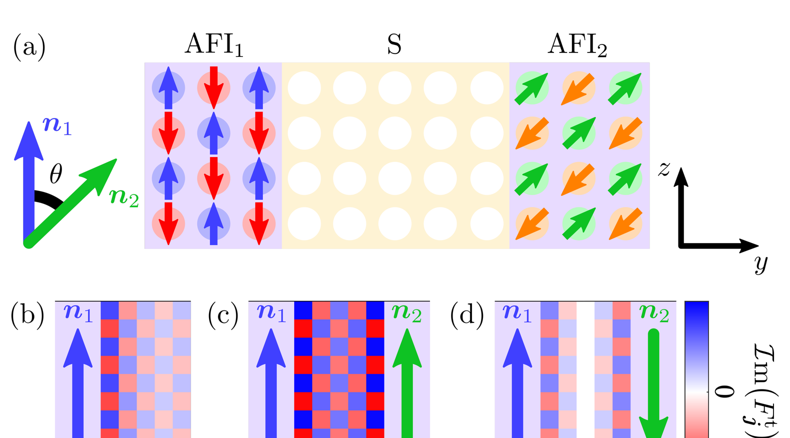

Fig.11 (a) Setup and the angle θ between the Neel vectors. Spatial variation of the triplet correlations amplitude F^t_j in (b) AF/S bilayer, (c) AF/S/AF with odd number of S monolayers and $\theta = 0$ or (d) $\theta = \pi$.

F/S/F trilayers

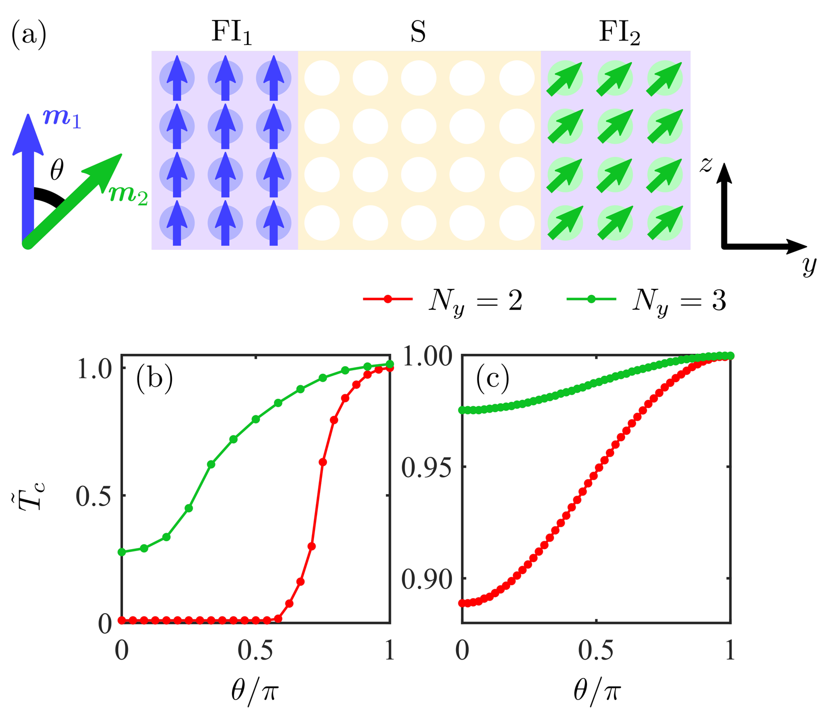

Fig.10 (a) Setup. Normalized critical temperature $\tilde{T}_c(\theta)$ for (b) stronger and (c) weaker interfacial exchange coupling J. N_y is the number of S monolayers

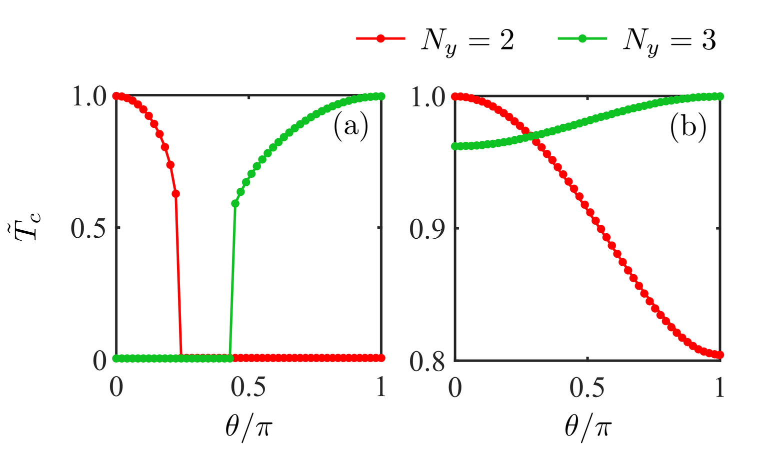

Fig.12 Normalized critical temperature $\tilde{T}_c(\theta)$ for (a) stronger and (b) weaker interfacial exchange coupling J. The variation is reversed when the number of S monolayers N_y changes from even to odd.

The work was supported by RSF project №22-22-00522.

Spin-valve effect in AF/S/AF

Dependence of the **critical temperature** T_c of the (insulating AF)/S/(insulating AF) spin valve on the angle ϕ between Neel vectors in the AFs and the impurity strength in S $\delta\mu$.

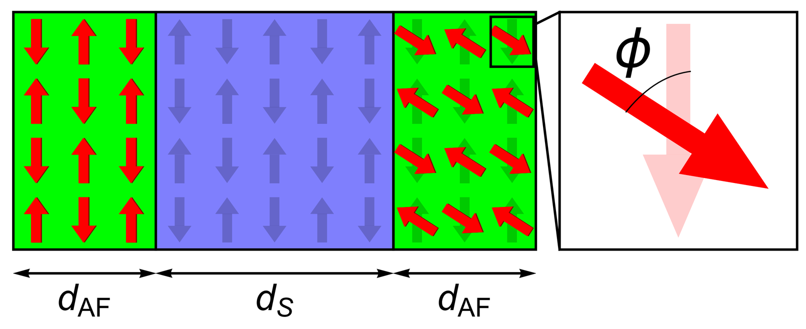

Fig.2 Setup. The angle ϕ between the Neel vectors is shown.

BdG, influence of impurities:

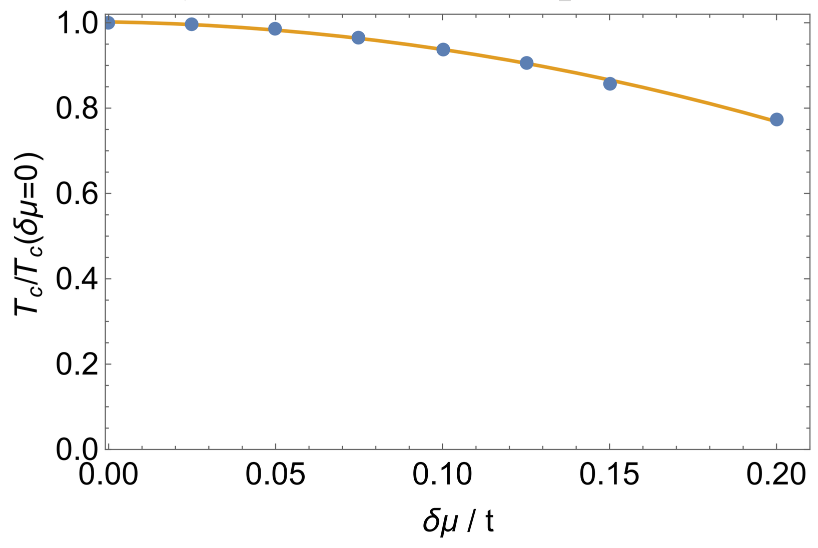

Fig.4 General suppression $T_c(\phi = 0)$ due to impurities.

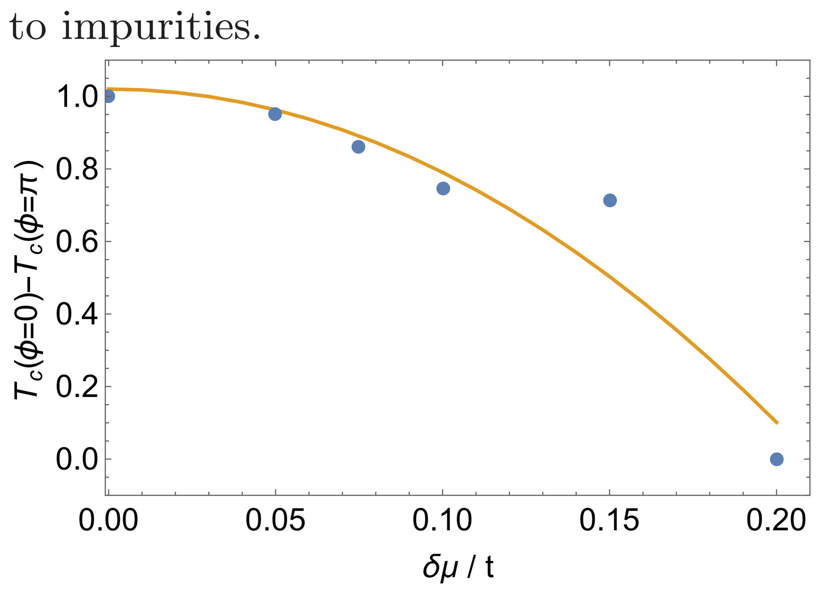

Fig.5 Suppression of spin-valve effect by impurities. $T_c(\phi = 0) - T_c(\phi = \pi)$ as a function of the impurity strength $\delta\mu$.

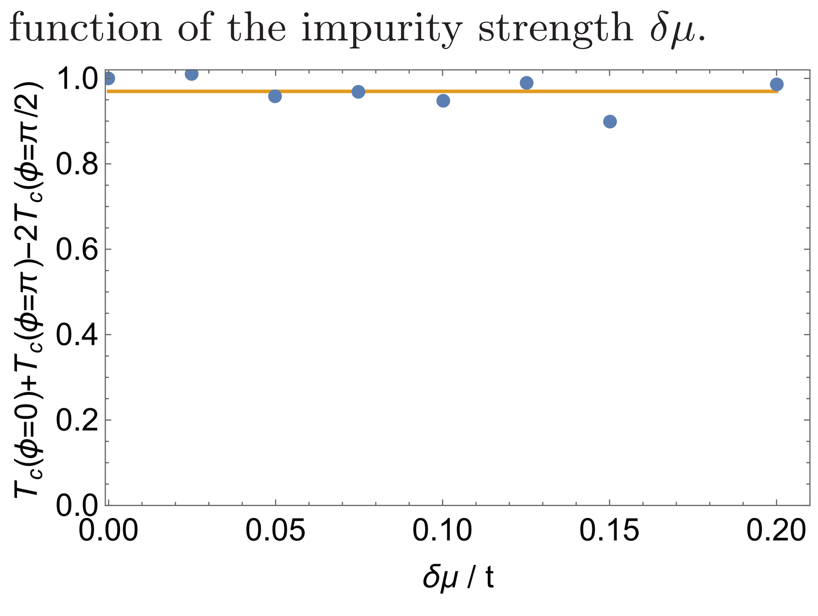

Fig.6 $T_c(\phi = 0) + T_c(\phi = \pi) - 2T_c(\phi = \pi/2)$ as a function of the impurity strength $\delta\mu$.

BdG, clean case (no impurities):

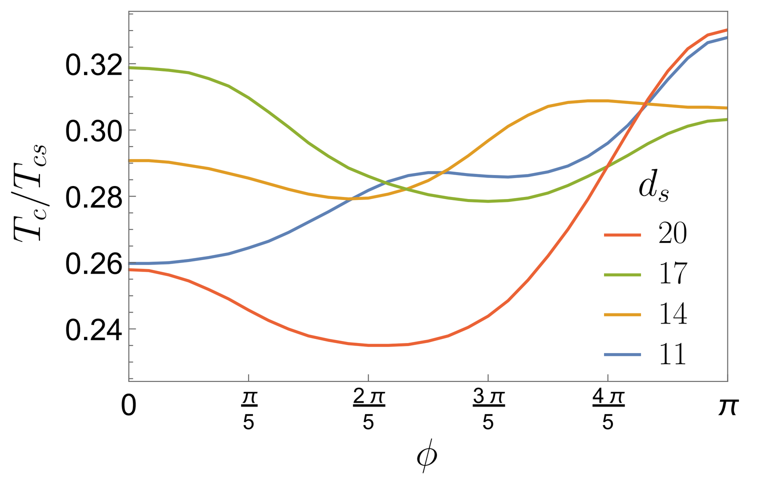

Fig.3 $T_c(\phi)$ for the AF/S/AF structure. Different curves correspond to different d_S.

Quasiclassical results, clean case:

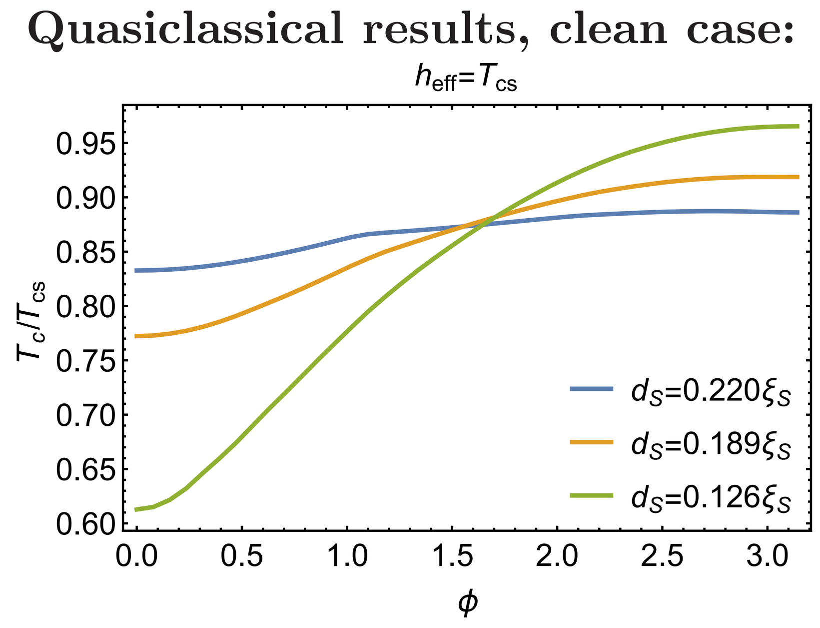

Fig.7 $T_c(\phi)$ for fixed $h_{\rm eff}$ and different d_S.

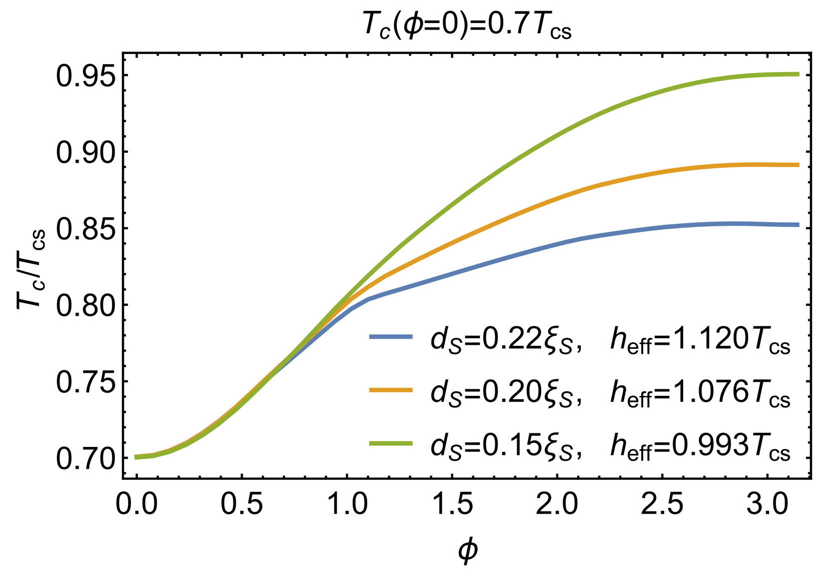

Fig.8 $T_c(\phi)$ for different d_S and $h_{\rm eff}$ chosen so that value $T_c(\phi = 0)$ was the same.

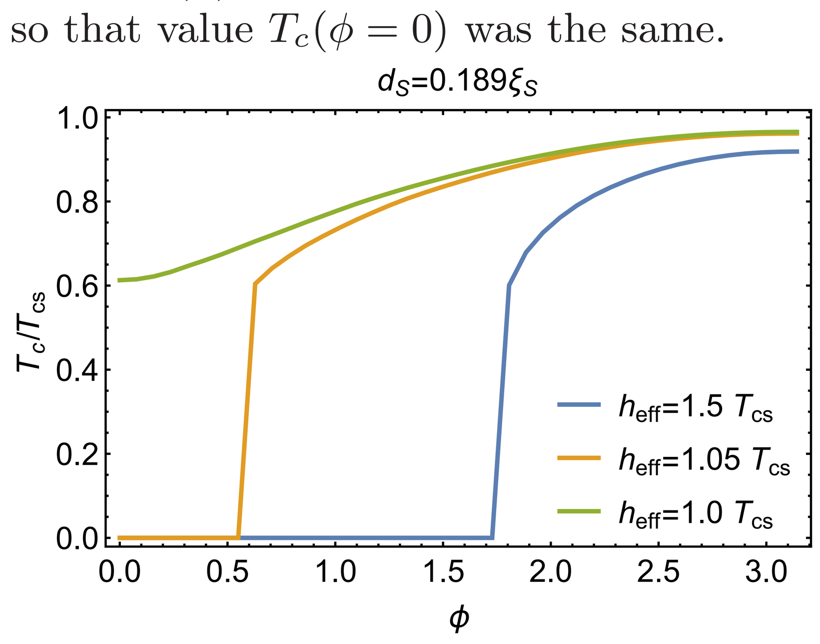

Fig.9 $T_c(\phi)$ for a fixed d_S and different $h_{\rm eff}$.

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 valve effect.
(iii) For larger d_S critical temperature manifests non-monotonic dependence on the misorientation angle due to appearance of equal-spin correlations and interference effects.
(iv) Angle dependence of AF/S/AF critical temperature shows the parity effect, which provides a distinct signature of the Neel triplets.

References

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