Spin-valve effect and parity effectin AF/S/AF systems V.M. Gordeeva¹, G.A. Bobkov¹, I.V. Bobkova^{1,2}, A.M. Bobkov¹, L. J. Kamra^{3,4}, S. Chourasia³, A. Kamra³ ¹MIPT, Dolgoprudny, Russia; ²HSE, Moscow, Russia; ³Universidad Autónoma de Madrid, Madrid, Spain; ⁴MIT, Cambridge, Massachusetts, USA

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].

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.

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

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

 $L_{osc}=$ $\sqrt{ }$ πv_F μ^2-h^2

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

Anomalous Green's function:

$$
F_{\mathbf{i},\alpha\beta}(\omega_m) = \sum_n \left(\frac{u_{n,\alpha}^{\mathbf{i}} v_{n,\beta}^{\mathbf{i}\star}}{i\omega_m - \varepsilon_n} + \frac{u_{n,\beta}^{\mathbf{i}} v_{n,\alpha}^{\mathbf{i}\star}}{i\omega_m + \varepsilon_n} \right)
$$

Singlet (triplet) correlations:

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

$$
F_{\boldsymbol{i}}^t = \sum_{\omega_m > 0} F_{\boldsymbol{i}}^t(\omega_m)
$$

AF/S/AF trilayers

Fig.11 (a) Setup and the angle θ between W_{eq} \overline{M}_{eq} and \overline{M}_{eq} \overline{M}_{eq} \overline{M}_{eq} \overline{M}_{eq} the Neel vectors. Spatial variation of the triplet correlations amplitude F_j^t in (b) $\begin{array}{ccccc} \textbf{1} & & & & & \textbf{1} & & \textbf{1} & & \textbf{1} & \textbf$ $\rm AF/S$ bilayer, (c) $\rm AF/S/AF$ with odd $number of S mon$ nolavers and $\theta = 0$ or (d spatial particle parameter \mathcal{G} in an AFI–S–AFI trilayer with odd num--- $\theta = \pi.$ j^t in (b) number of S monolayers and $\theta = 0$ or (d)

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

Parity effect in $\rm AF/S/AF$ and $\rm F/S/F$

Here, c

j,σ

bor sites with the S, Sj ≡ ≡ S, Sj ≡ ≡ S, Sj ≡ ≡ S, Sj ≡ ≡ S, Sj ≡ ≦ S, Sj ≡ S
De S, Sj ≡ S,

 \sum_{3} P. Designed between \sum_{1} and \sum_{2} and \sum_{3} are \sum_{4} and \sum_{5} and \sum_{7} and \sum_{8} and \sum_{9} and \sum_{1} and (ii) Presence of impurities suppresses Neel triplets, which leads to disappearing of the $"0 - \pi"$ spin-valve effect.

is the annihilation (creation) operator associ-

P

 $F_{\rm eff}$ \sim 2.2 Normalized critical temperature T c variation with \sim

σ,σ′ c

†

^j,σσσ,σ′ cj,σ′ is the

 \sim

FIG. IV (a) Setup. Notifianzed critical monolayers N_u $\phi = 0$ \longrightarrow \Box weaker interfacial exchange coupling J. N_y is \mathcal{L} , \mathcal{L} and \mathcal{L} is the number of S monolayers Fig.10 (a) Setup. Normalized critical temperature $T_c(\theta)$ for (b) stronger and (c)

$\left\lceil \text{conclusions of } d_S \text{ at } \right\rceil \mid \text{Conclusions}$ changes from even to odd. The weaker exchanges from even to odd. The weaker exchange (b) and the weaker exchange as per Eq. (4) in the main text. In the main text. In the main text. In both panels, NZ = 402 and U/t = 1.02 a
In the main text. In the main text. In the main text. In the main text, NZ = 402 and U/t = 1.02 and U/t = 1.02

 \mathcal{S} operator for \mathcal{S} electrons with \mathcal{S} \parallel \parallel (1), Neel, trip $\begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$ (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 \sim and \sim 1. In all panels, Nz \sim 202.02 ± 0.02 In (b), U/t $=10$ and μ and μ and μ and μ valve effect for larger values of h_{eff} .

Fig.12 Normalized critical temperature $\tilde{T}_c(\theta)$ for (a) stronger and (b) weaker via interfacial exchange onto the atomic layer closest to t interfacial exchange couphing J . In variation is reversed when the number of S \overline{C} \mathcal{G} $\mathcal{S}_{\mathbf{C}_{\mathsf{R}}}$ ven monolayers N_y changes from even to odd. $\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \end{pmatrix}$ is the contract $\begin{pmatrix} 0 \\ 0 \end{pmatrix}$ we control interfacial exchange coupling J. The

(iii) Away from half-filling $\mu_S = 0$ the difference $T_c(\pi) - T_c(0)$ oscillates as a function m Neel triplets generated by the S/AF two AFI–S interfaces [37], as briefly outlined in Fig. 1. It is analogous to the cos θ dependence in F–S–F triof 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 d distingulation d interference lagrephii correignons qua mericience of equal-spin triplets via the non-collinearity between \mathcal{L}_c misorientation angle due to appearance of equal-spin correlations and interference effects.

perature shows the parity effect, which $\mathbf \Gamma$ β orders are none are parte, α characterizes in the characterizes of $\mathbf{D} \cdot$ difference between parallel and antiparallel config- (v) Angle dependence of $AF/S/AF$ critical temperature shows the parity effect, which provides a distinct signature of the Neel triplets.

[3] G. A. Bobkov et al., Phys. Rev. B 109, 184504 (2024). $519(909)$ $\frac{0}{2}$ $\left(\begin{array}{c} 2022 \end{array} \right)$. [2] L. J. Kamra et al., Phys. Rev. B 108, 144506 (2023). terfacial exchange is strong and results in a complete T^c [1] G. A. Bobkov et al., Phys. Rev. B 106, 144512 (2022).

for (a) stronger and (b) weaker interfacial exchange coupling

 J . The variation is reversed when the variation is reversed when the number of S monolayers of S monolayers of S

N^y changes from even to odd. A complete suppression of

Tc is observed for the stronger J case (a), while the stronger Δ , while the weaker Δ

exchange (b) results in variation of Tc as per Eq. (4). (4). (c) By a per Eq. (4). (c) By a perfect of Tc as p

fitting the numerical ly evaluated T̊c(θ) to Eq. (4) for different T ϵ

 $u_{\rm max}$ urations. When it is positive (negative), the Tc is positive (negative), the Tc is larger (negati

c,∥

for the parallel (antiparallel) configuration of the mag-

change in Tc when going from parallel to perpendicular to perpendicular to perpendicular to perpendicular to p

c,∥

netic orders. On the other hand, ∆T ∑ ∑ ∑ ∆T ∑ ∆T ∆T ∆T ∆T ∆T ∴

c,[⊥] provide a

 $\overline{}$

succinct parametrization to study and present T^c

variation when the in-

References

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