Superconducting spin valves controlled by spiral re-orientation in MnSi

N. G. Pugach*
Skobeltsyn Institute of Nuclear Physics Lomonosov Moscow State University, Leninskie Gory 1(2), 119991, Moscow, Russia and National Research University Higher School of Economics, 101000, Moscow, Russia

M. Safonchik
A. F. Ioffe Physical-Technical Institute, RU-194021, St Petersburg, Russia

T. Champel
Université Grenoble Alpes/CNRS, Laboratoire de Physique et Modélisation des Milieux Condensés, B.P. 166, F-38042 Grenoble Cedex 9, France

M. E. Zhitomirsky
CEA, INAC-PHELIQS, F-38000 Grenoble, France

E. Lähderanta
Lappeentranta University of Technology, P.O. Box 20, FI-53851, Lappeenranta, Finland

M. Eschrig
Department of Physics, Royal Holloway, University of London Egham, Surrey TW20 0EX, UK

C. Lacroix
Université Grenoble-Alpes, Institut Néel, F-38042 Grenoble, France and CNRS, Institut Néel, F-38042 Grenoble, France

(Dated: March 1, 2017)

We propose a superconducting spin-triplet valve of a new type. This spin valve consists of a bilayer that involves a superconductor and an itinerant magnetic material, with the magnet showing an intrinsic non-collinear magnetic order characterized by a wave vector **Q** that may be aligned in a few equivalent preferred directions under control of a weak external magnetic field. Re-orienting the direction of **Q** allows one to controllably modify long-range spin-triplet superconducting correlations in the magnetic material, leading to spin-valve switching behavior. This new type of superconducting spin valve may be used as a magnetic memory element for cryogenic nanoelectronics. It has the following advantages in comparison with superconducting spin valves proposed earlier: (i) it contains only one magnetic layer, which may be more easily fabricated and controlled; (ii) its ground states are separated by a potential barrier, which solves the "half-select" problem of the addressed switch of such memory elements.

PACS numbers: 74.45.+c, 74.78.Fk, 75.75.+a

Introduction. Superconducting spintronics is a new field within nanoelectronics of quantum systems, which has emerged and is actively developing in the past 20 years. Its main idea is the usage of electronic spin transfer for information storage and processing, like usual spintronics, but implemented in superconducting circuits at low temperatures [1–3]. Among the basic units of superconducting spintronics are so-called superconducting spin valves (SSV). These are nano-devices in which the superconducting current is controlled through the spin degree of freedom, by changing the magnetization of magnetic elements. SSVs may serve as control units of low temperature nanoelectronics, as well as magnetic memory elements for spintronics and low-power electronics [4].

Superconducting spin-valves were theoretically proposed almost twenty years ago [5–7] as elements consisting of a thin superconducting (S) layer (assuming spin-singlet pairing) and two ferromagnetic (F) layers. Their state is switched from the superconducting to the normal conducting (N) one depending on the mutual orientation (parallel or antiparallel) of the F layer's magnetizations, analogously to usual spin valves. The SSV mechanism is based on the suppression of the superconducting critical temperature T_c by the magnetic exchange in the F layers, that influences the S layer properties via the proximity effect. The two F layers effectively act together (at parallel magnetization alignment) or at odds (antiparallel alignment) in the process of reducing superconductivity. Since the superconducting correlations are present on length scales large compared to atomic scales, SSV, in contrast to usual magnetic spin valves, can be made in two configurations: SFF [5] or FSF [6, 7], where the mag-

* pugach@magn.ru

netic layers are located at one or at the two sides of the S layer. It was shown later theoretically [8] and experimentally [9, 10] that the SFF configuration is preferable, because it provides the closest interaction between the two ferromagnets.

Interestingly, the here proposed SSV takes advantage of another physical mechanism. It was demonstrated first theoretically [11–14] that a non-collinear magnetization in the SF heterostructures also generates spin-triplet superconducting correlations with a non-zero total spin projection on the quantization axis. The exchange magnetic field does not suppress the equal spin triplet pairs, which thus penetrate far in the F region. These long-range triplet correlations (LRTC) were first revealed experimentally with the observation of long-range superconducting currents in Josephson spin-valves [15–17], which was an important breakthrough in this superconducting spintronics research [1]. The appearance of LRTC affects the proximity effect by opening a new channel for the Cooper-pair drainage from the S layer to the proximity structures. In SSVs, the influence of the LRTC on the superconducting critical temperature has already been reported in numerous experiments [9, 18–25]. A direct relation between the production of spin-polarized triplet correlations and the suppression of T_c has been observed in SSV under various peculiar conditions [22, 25–28], with a stronger T_c reduction found in the case of non-collinear magnetizations than in collinear configurations (parallel or antiparallel). Such a device is called a triplet spin valve. Note that the full switch from the S to N state requires in SSVs a T_c suppression which overcomes the typical width of the superconducting transition and has been achieved only very recently by exploiting the LRTC [27].

However, it is still an open question whether the previously studied triplet SSVs can be used as switchable elements in real devices. Indeed, in these nanostructures an additional antiferromagnetic layer is required for the pinning of one F layer by the magnetic exchange coupling, whereas the magnetization of the second F layer can be rotated freely. Nonmagnetic layers are also required to separate and decouple the two F layers, and additional Cu layers are introduced in the intermetallic interfaces to improve their quality [28]. Thus, such triplet SSVs contain several layers of different magnetic, nonmagnetic, and antiferromagnetic materials, which is highly demanding for technology and magnetic configuration controlling.

In this paper, we consider the realization of a different type of triplet SSV, which contains instead only one magnetic layer with controllable intrinsic non-collinear magnetization. Suitable magnetic materials is the family of itinerant cubic helimagnets, MnSi, (Fe,Co)Si, FeGe [29–31]. Currently, these compounds and their films are intensively investigated [32, 33] as a medium for magnetic topological defects like skyrmions. Their spiral magnetic structure characterized by the vector $\mathbf{Q}$ may be aligned in a few equivalent directions under the control of a weak

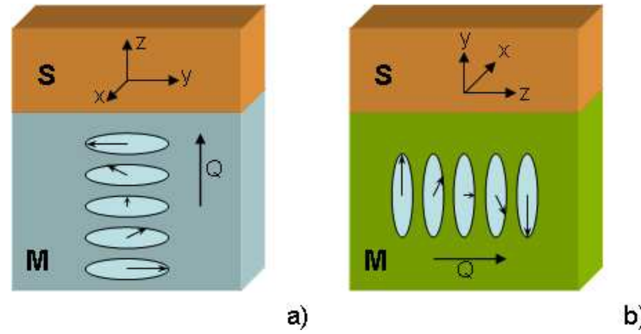

FIG. 1. The sketches of the spiral SSV in two configurations: spiral vector $\mathbf{Q}$ (a) perpendicular to the superconducting interface (opening of the LRTC channel), or (b) parallel to the superconducting interface.

external magnetic field. Importantly, these compounds are metals, and are thus susceptible to sustain the proximity effect with a superconducting layer. As shown in Refs. [34–36], a superconducting - magnetic spiral (M) bilayer with a spiral vector $\mathbf{Q}$ parallel to the interface does not generate LRTC components, while the latter are expected when $\mathbf{Q}$ is inclined with respect to the interface [11, 12, 14]. As illustrated in Fig. 1, the switch between the two spiral order directions thus controls the opening of a new channel for Cooper pairs drainage related to the LRTC creation. In the remainder of this paper, we study more quantitatively the change in the superconducting critical temperature T_c induced by the magnetic switch and finally discuss the properties of the proposed bilayer SSV.

Calculation method. For simplicity, we consider a superconducting layer with a finite thickness d_s covering a semi-infinite M layer with the spiral vector $\mathbf{Q}$ (with amplitude $Q = 2\pi/\lambda$) along OZ direction, which may be parallel, or orthogonal with respect to the interlayer interface, see the sketches on Fig. 1. For the T_c calculations, we assume the diffusive limit, because real low-temperature superconducting nanostructures made by sputtering are usually dirty. In this case the superconducting coherence lengths in the M and S layers are respectively given by $\xi_{f,s} = \sqrt{D_{f,s}/2\pi T_{cb}}$, where $D_{f,s}$ is the corresponding diffusion coefficient and T_{cb} is the critical temperature of the bulk superconductor. Close to T_c, superconducting correlations are weak, so that we can describe the underlying physics in the framework of the linearized Usadel equations.

The triplet proximity effect in the presence of a spiral or conical spiral magnet (like in Ho material) has already been intensively studied both theoretically in either the dirty [34, 35, 37–39] or the clean [22, 40, 41] regimes, and experimentally [9, 17, 24, 42–47] in complex multilayered magnetic structures designed for revealing LRTC. The theoretical work in Ref. [37, 38] treated the critical current in S-M-S Josephson junctions with a conical vector perpendicular to the interface. Ref. 38 assumed the limit of a short spiral wavelength $\lambda \ll \xi_f$, which is suitable for Ho but not for MnSi. The case of a long spiral wavelength was considered in the work [37] with a helicoidal magnet model, but the critical temperature was not investigated there. The detailed calculation of T_c in the parallel configuration (b) as depicted in Fig. 1 has been published in Refs. [34, 35], but these works only considered changes of T_c with respect to the amplitude of the spiral wave vector $\mathbf{Q}$, not with respect to its direction. The dependence on the direction of the wave vector $\mathbf{Q}$ is the topic of this paper.

The linearized Usadel equations for the singlet f_s and triplet $\mathbf{f}_t = (f_x, f_y, f_z)$ spin components of the anomalous Green's function, describing superconducting correlations, have the form [34]

$$\begin{aligned} \left(D_{f,s}\nabla^2 - 2\left|\omega\right|\right) f_s &= -2\pi\Delta + 2i\ \mathrm{sgn}(\omega)\mathbf{h}\cdot\mathbf{f}_t, \\ \left(D_{f,s}\nabla^2 - 2\left|\omega\right|\right) \mathbf{f}_t &= 2i\ \mathrm{sgn}(\omega)\mathbf{h} f_s. \end{aligned} \tag{1}$$

Here we assume that the singlet superconducting order parameter Δ is coordinate-dependent and nonzero only in the S layer, while the exchange field $\mathbf{h} = h(\cos Qz, \sin Qz, 0)$ is nonzero and aligned along the local magnetization in the M layer. The spiral vector $\mathbf{Q}$ is always taken parallel to the OZ axis. Since $h_z = 0$, the third triplet component $f_z = 0$. Using the unitary transformation $f_\pm = (\mp f_x + i f_y)\exp(\pm iQz)$ and taking into account the symmetry of the Green's functions with respect to the Matsubara frequency $\omega \equiv \omega_n = \pi T(2n+1)$, where n is an integer, we may rewrite the Usadel equations for $\omega \geq 0$ as

$$\begin{aligned} \left(D_{f,s}\nabla^2 - 2\omega\right) f_s &= -2\pi\Delta + i\ h\left[f_- - f_+\right], \\ \left(D_{f,s}\nabla^2 \mp 2iD_{f,s}Q\frac{\partial}{\partial z} - D_{f,s}Q^2 - 2\omega\right) f_\pm &= \mp 2i\ h f_s. \end{aligned} \tag{2}$$

Eqs. (2) are supplemented by boundary conditions according to Kupriyanov and Lukichev [48] at $r = 0$, where the coordinate $r = z$ or $r = y$ refers to the distance from the S/M interface depending on the chosen spiral configuration:

$$\xi_s \frac{\partial}{\partial r} f^S_{s,x,y} = \gamma \xi_f \frac{\partial}{\partial r} f_{s,x,y};\ f^S_{s,x,y} = f_{s,x,y} - \gamma_b \xi_f \frac{\partial}{\partial r} f_{s,x,y}, \tag{3}$$

with the dimensionless interface parameters $\gamma_b = R_b A \sigma_f/\xi_f$ and $\gamma = \frac{\sigma_f}{\sigma_s}\frac{\xi_s}{\xi_f}$ (R_b and A are respectively the resistance and the area of the S-M interface, and $\sigma_{f,s}$ is the conductivity of the M or S metal). Boundary conditions (3) relate the superconducting correlations coming from each side of the interface. The correlations in the S layer (located at $r < 0$) are described by the functions $f^S_{s,x,y}$, while the functions $f_{s,x,y}$ contain the information about the structure of the M layer ($r > 0$).

The r-dependence of the triplet components in the S layer, satisfying the boundary condition at the free S interface $\frac{\partial}{\partial r} f^S_{s,x,y}(-d_s) = 0$, may be written in the form:

$$f^S_x = C_x \frac{\cosh\left[k_s(r+d_s)\right]}{\sinh\left[k_s d_s\right]}, \quad i f^S_y = C_y \frac{\cosh\left[k_s(r+d_s)\right]}{\sinh\left[k_s d_s\right]}, \tag{4}$$

where $k_s = \sqrt{Q^2 + 2|\omega|/D_s}$. The coefficients C_x and C_y are found from the boundary conditions (3). One obtains via some straightforward algebra the close boundary value problem for the singlet component f^S_s with the following boundary condition at the S/M interface:

$$\xi_s \frac{\partial}{\partial r} f^S_s \Big|_{r=0} = -\,W f^S_s\big|_{r=0}. \tag{5}$$

The proximity effect in the M layer is entirely encapsulated in the real-valued quantity W. This key-quantity is the subject of the subsequent calculations considering two different spiral alignments in the M layer. The Usadel equation for the singlet component (2) includes the coordinate-dependent Δ, which should be calculated self-consistently. The transition temperature of the structure, T_c, is computed numerically from

$$\ln\frac{T_{cb}}{T_c} = \pi T_c \sum_{\omega=-\infty}^{\infty}\left(\frac{1}{|\omega|} - \frac{f^S_s}{\pi\Delta}\right) \tag{6}$$

by using the method of fundamental solution described in Refs. [35, 49, 50].

Configuration (a): The spiral vector is orthogonal to the S layer. In this case the problem becomes one-dimensional as in Ref. [37] with $r = z$ and $\nabla^2 = \frac{\partial^2}{\partial z^2}$. The M layer is infinite, so that the functions $f_{s,x,y}$ in the magnetic layer are sought under the form of decaying exponents $\exp(-kz)$ with k a wave vector determined from the characteristic equation of the linear system (2)

$$\begin{aligned} \left[(k^2 - k^2_\omega - Q^2)^2 + 4Q^2k^2\right]\left(k^2 - k^2_\omega\right) \\ +4k^4_h(k^2 - k^2_\omega - Q^2) = 0, \end{aligned} \tag{7}$$

where $k^2_\omega = 2\omega/D_f$ and $k^2_h = h/D_f$. Provided that $k^2_h \gg Q^2 > k^2_\omega$, Eq. (7) yields 3 complex-valued eigenvalues: two solutions $k_\pm = (1 \pm i)\, k_h$ of the order of k_h describing short-range correlations, and one real solution $k_0 = \sqrt{k^2_\omega + Q^2}$ of the order of Q characterizing long-range correlations. The corresponding eigenvectors are $(-1,-1,1)$, $(1,-1,1)$ for $k_\pm$, and $(0,1,1)$ for k_0. These results entirely coincide with those obtained in Ref. [37].

Therefore, considering the above inequalities, the solution of coupled Eqs. (2) reads in the M layer:

$$\begin{aligned} f_s(z) &= -A_1\exp(-k_+z) + A_2\exp(-k_-z), \\ f_\pm(z) &= \pm A_1\exp(-k_+z) \pm A_2\exp(-k_-z) + A_0\exp(-k_0z). \end{aligned} \tag{8}$$

Using boundary conditions (3) and relations (4) for the triplet components, we then get a first set of 4 equations for the coefficients $A_{0,1,2}$ and $C_{x,y}$

$$\begin{aligned} \xi_s\frac{\partial}{\partial z} f^S_x &= \gamma\xi_f\left[A_1k_+ + A_2k_- - iQA_0\right], \\ \xi_s\frac{\partial}{\partial z} f^S_y &= -\gamma\xi_f\left[A_0k_0 + iQ\left(A_1 + A_2\right)\right], \\ C_x\coth k_sd_s &= -A_1 - A_2 - \gamma_b\xi_f\left(A_1k_+ + A_2k_- - iQA_0\right), \\ C_y\coth k_sd_s &= A_0 + \gamma_b\xi_f\left[A_0k_0 + iQ\left(A_1 + A_2\right)\right]. \end{aligned} \tag{9}$$

By writing boundary conditions (3) for the singlet component, we obtain two additional equations

$$\xi_s \frac{\partial}{\partial z} f_s^S = \gamma \xi_f \left(A_1 k_+ - A_2 k_- \right), \tag{10}$$
$$f_s^S = -A_1 + A_2 - \gamma_b \xi_f \left(A_1 k_+ - A_2 k_- \right),$$

which, together with the system (9) by eliminating the coefficients $A_{0,1,2}$ and $C_{x,y}$, yield the quantity W when the M vector $\mathbf{Q}$ is orthogonal to the S layer:

$$W_\perp = \frac{\gamma \mathrm{Re}\left\{ \xi_f k_+ \left[(1+\xi_c k_-)(1+\xi_c k_0) - (\xi_c Q)^2 \right] \right\}}{\mathrm{Re}\{ (1+\gamma_b \xi_f k_+) \left[(1+\xi_c k_-)(1+\xi_c k_0) - (\xi_c Q)^2 \right] \}}, \tag{11}$$

with the effective length $\xi_c \equiv \xi_f \left[\gamma \coth(k_s d_s)/k_s \xi_s + \gamma_b \right]$. Here, the terms containing Q and k_0 typically characterize the contribution of the long-range superconducting correlations.

Configuration (b): The spiral vector is parallel to the S layer. We assume that the interface coincides with the XOZ plane. Since the structure breaks translation invariance in the $r = y$ direction and the magnetic structure is nonuniform in the z direction, the kinetic energy operator now reads $\nabla^2 = \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$. It has been shown in Ref. [35] that z-independent correlations $f_{s,\pm}$ provide the lowest T_c (i.e., they are the most favorable energetically), because they are the only solutions which realize a spatially homogeneous superconducting order parameter in the S layer at large distance from the S/M interface. In this case, we have the triplet vector $\mathbf{f}_t || \mathbf{h}$, meaning that only short-range triplet components are present.

More precisely, solutions of Eq. (2) in the M layer have again the form of decaying exponents with the wave vectors k determined by a characteristic equation, with, however, an expresion now simpler than given by Eq. (7),

$$(k^2 - k_\omega^2 - Q^2)^2 (k^2 - k_\omega^2) + 4 k_h^4 (k^2 - k_\omega^2 - Q) = 0. \tag{12}$$

This equation has an exact solution with two short-range eigenvalues $\tilde{k}_\pm = \sqrt{2k_\omega^2 + \frac{1}{2}Q^2 \pm \frac{i}{2}\sqrt{16k_h^4 - Q^4}}$ and a long-range one $k_0 = \sqrt{k_\omega^2 + Q^2}$. Under the inequalities $k_h^2 \gg Q^2$ and k_ω^2, one gets $\tilde{k}_\pm \approx k_\pm$, so that respective eigenvectors coincide with those obtained for the case of the orthogonal spiral given above. Consequently, under these conditions, the general form of the superconducting correlations in the M layer in the parallel configuration is identical to that in the orthogonal configuration. The major difference takes place only in the boundary conditions: since $\frac{\partial}{\partial y} \exp(\pm iQz) = 0$, the LRTC with the eigenvector k_0 now has no source neither in the S nor in the M layers, nor at the interface (thus $A_0 = 0$). Only short-range triplet correlations are generated. Following the same steps as in the orthogonal spiral configuration, we get after straightforward algebra the quantity W when $\mathbf{Q}$ is parallel to the S layer:

$$W_\parallel = \frac{\gamma \mathrm{Re}\left[\xi_f \tilde{k}_+ \left(1 + \xi_c \tilde{k}_- \right) \left(\sqrt{16k_h^4 - Q^4} + iQ^2 \right) \right]}{\mathrm{Re}\left[\left(1 + \gamma_b \xi_f \tilde{k}_+ \right) \left(1 + \xi_c \tilde{k}_- \right) \left(\sqrt{16k_h^4 - Q^4} + iQ^2 \right) \right]}. \tag{13}$$

In contrast to $W_\perp$, we note that $W_\parallel$ does not contain k_0 characterizing the long-range correlations.

Numerical results and discussion. For the model calculations, we have assumed a S layer made of Nb, as Nb technology is well developed, usually providing good compatibility with other elements in nanostructures. Bulk Nb has a critical temperature $T_{cb} = 9.2$ K. Other data about Nb needed for the calculations are taken from the experimental work [25], where for instance $\xi_s = 11$ nm. Ho magnets displaying conical spiral order have already been used in several hybrid structures [17, 42, 45] in combination with Nb. The successful control of the superconducting state by a change of the magnetic state has even been obtained in recent experiments [46, 47]. However, the helimagnets Ho or Er used in these experiments have a strong in-plane magnetic anisotropy (with a spiral vector remaining perpendicular to the layer plane), so they do not appear as the best choice for the proposed SSV. Furthermore, an increase of the temperature of the sample above the Curie temperature (much larger than the superconducting critical temperature T_c) is needed in order to return to the initial helimagnetic state [47], what makes this kind of magnetic switch very difficult to use in low-T electronics.

In contrast, the transition-metal compounds of the MnSi family have a weak magnetic anisotropy, which is much smaller than the exchange energy. They crystallize in a noncentrosymmetric cubic B20 structure that allows a linear gradient invariant [51]. This gives rise to a long-period spiral magnetic structure ($\lambda = 18$ nm in the case of MnSi). In MnSi, the spiral wave vector $\mathbf{Q}$ is aligned along [111] and equivalent directions of the cubic lattice. The angle between these directions is $\alpha = \arccos(1/3) = 70.5°$. To estimate the effect on T_c, we have assumed for simplicity the spiral axis to be perpendicular to the S/M interface. The existence of a domain structure with different spiral directions in neighboring domains was observed in such compounds [52]. Importantly, the magnetic spiral direction may be switched in not too large magnetic fields [53].

Transport properties of MnSi have been studied in Refs. [54, 55]. We used the following parameters for diffusive MnSi: the M superconducting coherence length $\xi_f = 4.2$ nm, and the interface parameter involving material conductivities $\gamma = 0.7$. The exchange energy for conducting electrons was estimated as $h \sim 100$ meV and the spiral wave vector $Q = 2\pi/\lambda \approx 0.35\, nm^{-1}$. As a result, one gets $k_h \sim 0.7\, nm^{-1}$ and $k_\omega \sim 0.14\, nm^{-1}$. The inequalities $k_h > Q > k_\omega$ are fulfilled, thus justifying the approximations made in the analytical derivation of the quantity W.

The numerical results for T_c are displayed in Fig. 2 for the two different spiral configurations (a) and (b), i.e., for $\mathbf{Q}$ parallel and perpendicular to the S layer. The magnetic switch from the parallel to the inclined configuration creates the condition for the LRTC appearance in the superconducting spin valve. As clearly seen, the related drainage of Cooper pairs from the S layer effectively

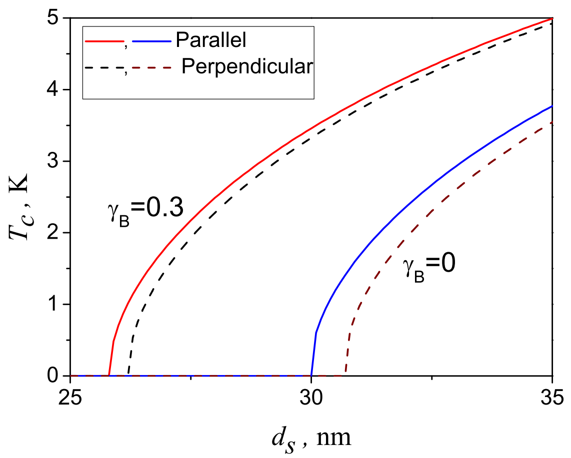

FIG. 2. Superconducting critical temperature T_c as a function of the S layer thickness d_s within the two spiral configurations shown in Fig. 1. For the right pair of curves, we have taken $\gamma_b = 0$, while for the left pair $\gamma_b = 0.3$.

increases the proximity effect and suppresses T_c. The difference δT_c between the two T_c obtained in each magnetic configuration increases when the thickness of the S layer approaches the critical thickness corresponding to a total disappearance of superconductivity. Naturally, at this thickness, the superconducting film is most sensitive to the proximity effect. Whereas the right pair of curves in Fig. 2 shows an ideal situation for the SSV where the interlayer resistance γ_b is neglected and δT_c is magnified, the left pair of curves accounts for a more realistic case by assuming $\gamma_b = 0.3$, which seems to be a more suitable value for the coupling between Nb and a weak ferromagnet [56]. As expected, the consequence of γ_b is to weaken the superconducting proximity effect, but the maximum value of $\delta T_c \sim 1$ K obtained at the working point (defined in the perpendicular configuration when the S layer turns to the normal state) is still rather significant. This theoretical result indicates a large spin-valve effect in the S-M bilayer, of the same order of magnitude as predicted [8] in triplet SFF spin-valves. In experiments such value of the effect is usually considered as "giant" [9, 23].

Superconducting spin valves structures are promising for application as elements of magnetic memory for low-temperature electronics, which has become recently a rapidly developing research direction [57, 58] related to the urgent need for energy-efficient logic for supercomputers. Usage of only one S layer and a bulk M should significantly simplify the SSV production technology. Another feature of the proposed SSV may be crucial for its application as a magnetic memory element. Indeed, the switch of a particular memory element in a random access memory (RAM) is carried out by a net of two crossed arrays of control electrodes. When the recording signal is sent along two crossed lines, the memory element located at the intersection of these lines changes its state, while all other element states in the same row or in the same column (thus receiving only one half of the signal) as the selected element remain unperturbed. Thus, the control signal should be able to switch the element state, whereas the half-amplitude signal should not cause a switch. The existence of a potential barrier between the two equilibrium spiral alignments in the magnetic part of the SSV provides an intrinsic solution to this half-select problem [59]. In contrast, this property is not present in previously studied triplet SSV based on the continuous rotation of one of the ferromagnetic layers magnetization.

In conclusion, we have proposed a new type of superconducting spin valve, consisting of a thin superconducting layer covered by a bulk spiral ferromagnet with multiple equilibrium configurations, such as MnSi. Its principle of operation is based on the controlled manipulation of long-range spin-triplet superconducting correlation in the structure. Our numerical results indicate that the spin-valve effect in these structures may reach a giant value. Such spin-valves are superior in various regards compared to previously studied spin-valve geometries. The half-select problem is solved intrinsically, which makes these spiral spin valves promising for low-temperature magnetic memory elements creation.

Acknowledgements. This work has benefited from the financial support by the Visiting Scientist Program of the Centre de Physique Théorique de Grenoble-Alpes (CPTGA), as well as from the Royal Society RFBR International Exchanges Program. N.P. thanks also the Project N T3-89 "Macroscopic quantum phenomena at low and ultralow temperatures" of the National Research University Higher School of Economics, Russia.

[1] M. Eschrig, Phys. Today **64**, No. 1, 43 (2011).
[2] J. Linder and J. W. A. Robinson, Nat. Phys. **11**, 307 (2015).
[3] M. Eschrig, Rep. Prog. Phys. **78**, 104501 (2015).
[4] D. S. Holmes, A. L. Ripple, and M. A. Manheimer, IEEE Trans. Appl. Supercond. **23**, 1701610 (2013).
[5] S. Oh, D. Youm, and M. R. Beasley, Appl. Phys. Lett. **71**, 2376 (1997).
[6] A. I. Buzdin, A. V. Vedyayev, and N. V. Ryzhanova, Europhys. Lett. **48**, 686 (1999).
[7] L. R. Tagirov, Phys. Rev. Lett. **83**, 2058 (1999).
[8] Ya. V. Fominov, A. A. Golubov, T. Y. Karminskaya, M. Yu. Kupriyanov, R. G. Deminov, and L. R. Tagirov, JETP Lett. **91**, 308 (2010).
[9] A. Singh, S. Voltan, K. Lahabi, and J. Aarts, Phys. Rev. X **5**, 021019 (2015).
[10] P. V. Leksin, A. A. Kamashev, N. N. Garif'yanov, I. A. Garifullin, Ya. V. Fominov, J. Schumann, C. Hess, V. Kataev, and B. Büchner, JETP Lett. **97**, 478 (2013).
[11] F. S. Bergeret, A. F. Volkov, and K. B. Efetov, Phys.

Rev. B **64**, 134506 (2001).
[12] A. Kadigrobov, R. I. Shekhter, and M. Jonson, Europhys. Lett. 54, 394 (2001).
[13] M. Eschrig, J. Kopu, J. C. Cuevas, and Gerd Schön, Phys. Rev. Lett. 90, 137003 (2003).
[14] F. S. Bergeret, A. F. Volkov, and K. B. Efetov, Rev. Mod. Phys. **77**, 1321 (2005).
[15] R. S. Keizer, S. T. B. Goennenwein, T. M. Klapwijk, G. Miao, G. Xiao, and A. Gupta, Nature **439**, 825 (2006).
[16] T. S. Khaire, W. P. Pratt Jr., and N. O. Birge, Phys. Rev. Lett. **104**, 137002 (2010).
[17] J. W. A. Robinson, J. D. S. Witt, M. G. Blamire, Science **329**, 59 (2010).
[18] K. Westerholt, D. Sprungmann, H. Zabel, R. Brucas, B. Hjorvarsson, D. A. Tikhonov, and I. A. Garifullin, Phys. Rev. Lett. **95**, 097003 (2005).
[19] P. V. Leksin, N. N. Garif'yanov, I. A. Garifullin, Y. V. Fominov, J. Schumann, Y. Krupskaya, V. Kataev, O. G. Schmidt, and B. Büchner, Phys. Rev. Lett. **109**, 057005 (2012).
[20] V. I. Zdravkov, J. Kehrle, G. Obermeier, D. Lenk, H. -A. Krug von Nidda, C. Müller, M. Yu. Kupriyanov, A. S. Sidorenko, S. Horn, R. Tidecks, and L. R. Tagirov, Phys. Rev. B **87**, 144507 (2013).
[21] A. Iovan, T. Golod, and V. M. Krasnov, Phys. Rev. B **90**, 134514 (2014).
[22] A. A. Jara, C. Safranski, I. N. Krivorotov, C.-T. Wu, A. N. Malmi-Kakkada, O. T. Valls, and K. Halterman, Phys. Rev. B **89**, 184502 (2014).
[23] X. L. Wang, A. Di Bernardo, N. Banerjee, A. Wells, F. S. Bergeret, M. G. Blamire, and J. W. A. Robinson, Phys. Rev. B **89**, 140508 (2014).
[24] N. Banerjee, C. B. Smiet, R. G. J. Smits, A. Ozaeta, F. S. Bergeret, M. G. Blamire, and J. W. A. Robinson, Nat. Commun. **5**, 048 (2014).
[25] M. G. Flokstra, T. C. Cunningham, J. Kim, N. Satchell, G. Burnell, P. J. Curran, S. J. Bending, C. J. Kinane, J. F. K. Cooper, S. Langridge, A. Isidori, N. Pugach, M. Eschrig, and S. L. Lee, Phys. Rev. B **91**, 060501(R) (2015).
[26] R. G. Deminov, L. R. Tagirov, R. R. Garifullin, T. Yu. Karminskaya, M. Yu. Kuprianov, Ya. V. Fominov, and A. A. Golubov, J. Magn. Magn. Mater. **373**, 16 (2015).
[27] P. V. Leksin, N. N. Garif'yanov, A. A. Kamashev, A. A. Validov, Ya. V. Fominov, J. Schumann, V. Kataev, J. Thomas, B. Büchner, and I. A. Garifullin, Phys. Rev. B **93**, 100502 (2016).
[28] P. V. Leksin, A. A. Kamashev, J. Schumann, V. E. Kataev, J. Thomas, B. Büchner, and I. A. Garifullin, Nano Research **9**, 1005 (2016).
[29] Y. Ishikawa, G. Shirane, J. A. Tarvin, and M. Kohgi, Phys. Rev. B **16**, 4956 (1977).
[30] C. Pfleiderer, S. R. Julian, and G. G. Lonzarich, Nature **414**, 427 (2001).
[31] M. Uchida, Y. Onose, Y. Matsui, and Y. Tokura, Science **311**, 359 (2006).
[32] S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Böni, Science **323**, 915 (2009).
[33] A. Fert, V. Cros, and J. Sampaio, Nature Nanotech. **8**, 152 (2013).
[34] T. Champel and M. Eschrig, Phys. Rev. B **71**, 220506(R) (2005).
[35] T. Champel and M. Eschrig, Phys. Rev. B **72**, 054523 (2005).
[36] T. Champel, T. Löfwander, and M. Eschrig, Phys. Rev. Lett. **100**, 077003 (2008).
[37] A. F. Volkov, A. Anishchanka, and K. B. Efetov, Phys. Rev. B **73**, 104412 (2006).
[38] G. B. Halász, J. W. A. Robinson, J. F. Annett, and M. G. Blamire, Phys. Rev. B **79**, 224505 (2009).
[39] G. B. Halász, M. G. Blamire, and J. W. A. Robinson, Phys. Rev. B **84**, 024517 (2011).
[40] C.-T. Wu, O. T. Valls, and K. Halterman. Phys. Rev. B **86**, 184517 (2012).
[41] K. Halterman and M. Alidoust, Phys. Rev. B **94**, 064503 (2016).
[42] I. Sosnin, H. Cho, V. T. Petrashov, and A. F. Volkov, Phys. Rev. Lett. **96**, 157002 (2006).
[43] L. Y. Zhu, Y. Liu, F. S. Bergeret, J. E. Pearson, S. G. E. te Velthuis, S. D. Bader, and J. S. Jiang, Phys. Rev. Lett. **110**, 177001 (2013).
[44] F. Chiodi, J. D. S. Witt, R. G. J. Smits, L. Qu, G. B. Halász, C.-T. Wu, O. T. Valls, K. Halterman, J. W. A. Robinson, and M. G. Blamire, Europhys. Lett. **101**, 37002 (2013).
[45] Y. Gu, G. B. Halász, J. W. A. Robinson, and M. G. Blamire, Phys. Rev. Lett. **115**, 067201 (2015).
[46] A. Di Bernardo, S. Diesch, Y. Gu, J. Linder, G. Divitini, C. Ducati, E. Scheer, M.G. Blamire, and J.W.A. Robinson, Nat. Commun. **6**, 8053 (2015).
[47] N. Satchell, J. D. S. Witt, M. G. Flokstra, S. L. Lee, J. F. K. Cooper, C. J. Kinane, S. Langridge, and G. Burnell, arXiv:1701.08065 (unpublished).
[48] M. Yu. Kuprianov and V. F. Lukichev, Zh. Eksp. Teor. Fiz. **94**, 139 (1988) [Sov. Phys. JETP **67**, 1163 (1988)].
[49] Ya. V. Fominov, N. M. Chtchelkatchev, and A. A. Golubov, Phys. Rev. B **66**, 014507 (2002).
[50] T. Löfwander, T. Champel, and M. Eschrig, Phys. Rev. B **75**, 014512 (2007).
[51] P. Bak and M. H. Jensen, J. Phys. C: Solid State Phys. **13**, L881 (1980).
[52] S. V. Grigoriev, S. V. Maleyev, A. I. Okorokov, Yu. O. Chetverikov, P. Böni, R. Georgii, D. Lamago, H. Eckerlebe, and K. Pranzas, Phys. Rev. B **74**, 214414 (2006).
[53] S. V. Grigoriev, S. V. Maleyev, A. I. Okorokov, Yu. O. Chetverikov, and H. Eckerlebe, Phys. Rev. B **73**, 224440 (2006).
[54] M. Lee, Y. Onose, Y. Tokura, and N. P. Ong, Phys. Rev. B **75**, 172403 (2007).
[55] F. Jonietz, S. Mühlbauer, C. Pfleiderer, A. Neubauer, W. Münzer, A. Bauer, T. Adams, R. Georgii, P. Böni, R. A. Duine, K. Everschor, M. Garst, and A. Rosch, Science **330**, 1648 (2010).
[56] V. A. Oboznov, V. V. Bol'ginov, A. K. Feofanov, V. V. Ryazanov, and A. I. Buzdin, Phys. Rev. Lett. **96**, 197003 (2006).
[57] B. Baek, W. H. Rippard, S. P. Benz, S. E. Russek, and P. D. Dresselhaus, Nat. Commun. **5**, 3888 (2014).
[58] B. M. Niedzielski, S. G. Diesch, E. C. Gingrich, Y. Wang, R. Loloee, W. P. Pratt, and N. O. Birge, IEEE Trans. Appl. Sup. **24** (4), 1800307 (2014).
[59] I. V. Vernik, V. V. Bol'ginov, S. V. Bakurskiy, A. A. Golubov, M. Yu. Kupriyanov, V. V. Ryazanov, and O. A. Mukhanov, IEEE Trans. Appl. Supercond. **23**, 1701208 (2013).