Сверхпроводниковые спиновые вентили на основе спиральных магнетиков

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SF proximity effect and FFLO states

What happens when the Cooper pair ↑↓ penetrates into F?

In F the sum momentum of the pair ↑↓ cannot be zero.

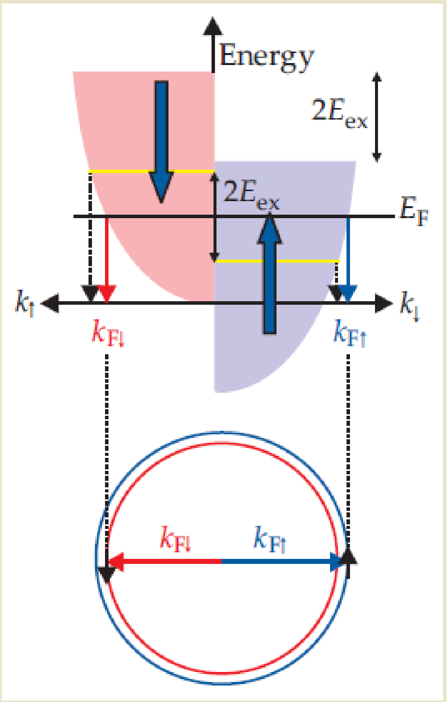
$k_{F\uparrow} \neq k_{F\downarrow}$, $k_{F\uparrow} - k_{F\downarrow} \sim h$, $\boldsymbol{h}$ - exchange field, $\mu_B \boldsymbol{h} > \Delta$,

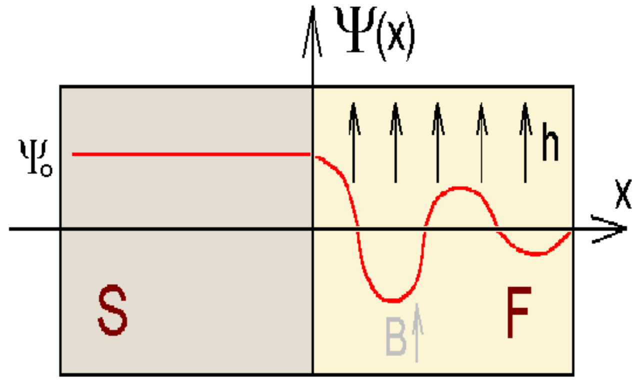
nonzero pair momentum

Non-uniform superconducting order parameter in F

$$\Psi=\Psi_0 \cos(Qr),$$

***Q** is wave-vector, **Q ~ h/v**$_F$,*

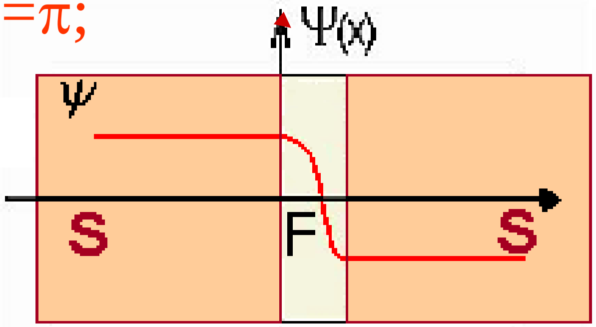




spatially nonuniform states

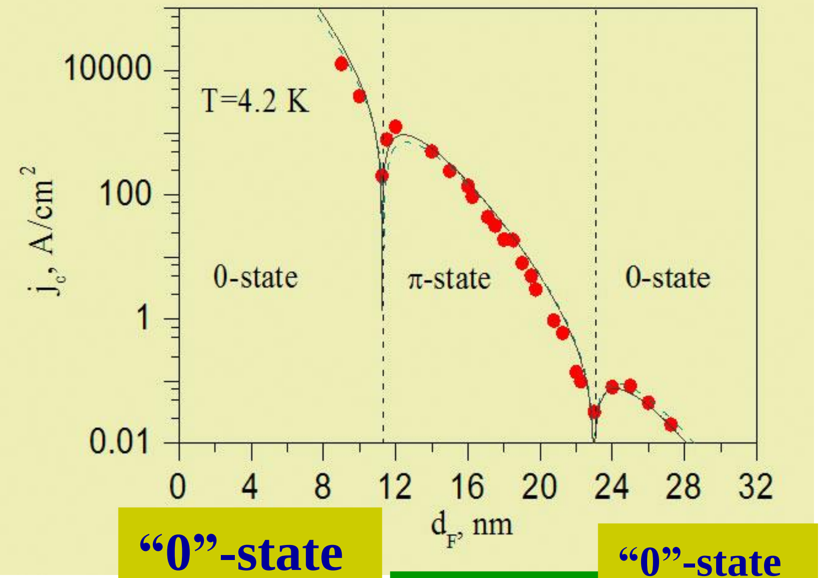
Fulde, Ferrel (1964), Larkin, Ovchinnikov (1964)

Qx=π;



π-junction

$$E = E_J[1-\cos(\pi+\varphi)] = E_J[1+\cos\varphi]$$



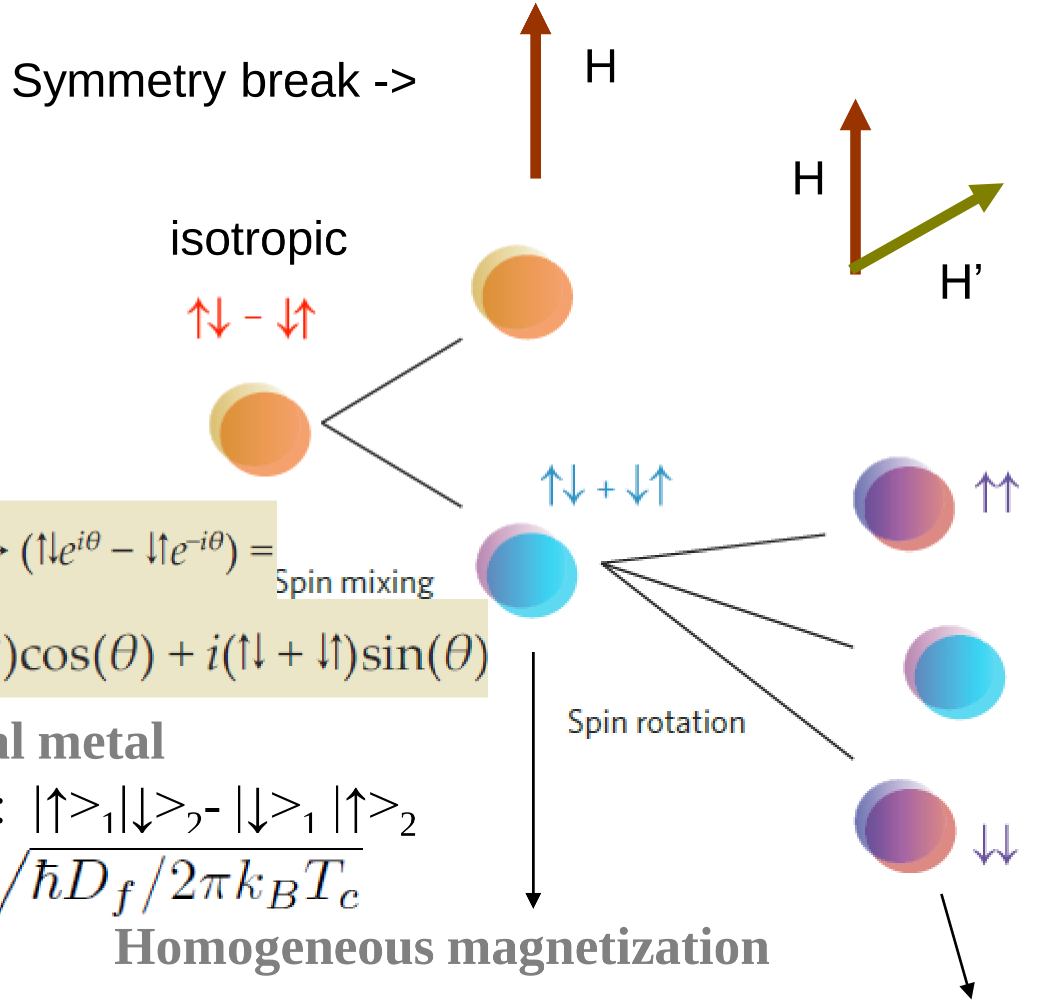
“0”-state
$I=I_c\sin\varphi$

π-state

“0”-state
$I=I_c\sin\varphi$

$I=I_c\sin(\varphi+\pi)= - I_c\sin(\varphi)$

Prehistory: Long range proximity effect



$$(\uparrow\downarrow - \downarrow\uparrow) \to (\uparrow\downarrow e^{i\theta} - \downarrow\uparrow e^{-i\theta}) = (\uparrow\downarrow - \downarrow\uparrow)\cos(\theta) + i(\uparrow\downarrow + \downarrow\uparrow)\sin(\theta)$$

Normal metal

singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$

$$\xi_0 = \sqrt{\hbar D_f / 2\pi k_B T_c}$$

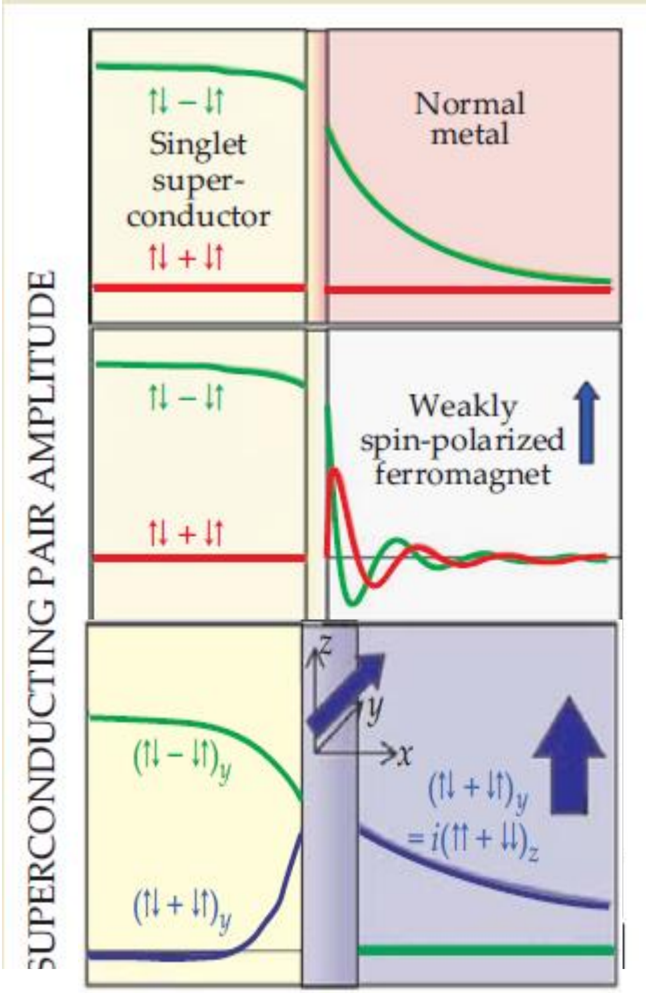
Homogeneous magnetization

singlet S=0: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$

triplet S_z=0: $|\uparrow>_1|\downarrow>_2 + |\downarrow>_1|\uparrow>_2$

$$\xi^{-1} = \xi_1^{-1} + i\xi_2^{-1}$$

$$\xi_1 = \xi_2 = \sqrt{\hbar D_f / h}$$



© M. Eschrig (2011)

Nonhomogeneous magnetization

$$\left.\begin{array}{l}\text{singlet } S=0\text{: } |\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2 \\ \text{triplet } S_z=0\text{: } |\uparrow>_1|\downarrow>_2 + |\downarrow>_1|\uparrow>_2\end{array}\right\}\xi_f$$

$$\left.\begin{array}{l}\text{triplet } S_z=1\text{: } |\uparrow>_1|\uparrow>_2, \\ \text{triplet } S_z=-1\text{: } |\downarrow>_1|\downarrow>_2\end{array}\right\}\xi_0$$

Cooper pair in the dirty limit

Normal metal

singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1 |\uparrow>_2$

$$\xi_0 = \sqrt{\hbar D_f / 2\pi k_B T_c}$$

Homogeneous magnetization

singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1 |\uparrow>_2$

triplet $S_z=0$: $|\uparrow>_1|\downarrow>_2 + |\downarrow>_1 |\uparrow>_2$

Complex coherence length

$\xi^{-1}=\xi_1^{-1} + i\, \xi_2^{-1}$:

$$\xi_f = \sqrt{\hbar D_f / h},$$

Nonhomogeneous magnetization

singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1 |\uparrow>_2$

triplet $S_z=0$: $|\uparrow>_1|\downarrow>_2 + |\downarrow>_1 |\uparrow>_2$ => ξ_f

triplet $S_z=1$: $|\uparrow>_1 |\uparrow>_2$

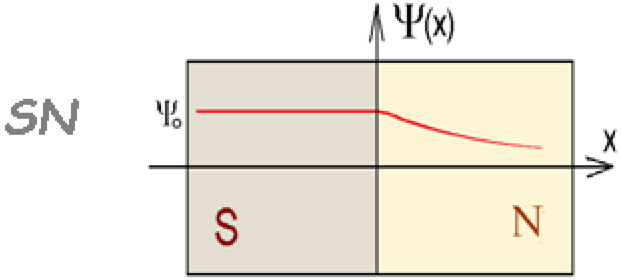
triplet $S_z= -1$: $|\downarrow>_1 |\downarrow>_2$ => ξ_0

Bergeret, Volkov, Efetov (2001)
Kadigrobov, Shekhter, Jonson (2001)

Cooper pair in the dirty limit

Dirty limit: Usadel equations $T \sim T_c$ – linearized. Strong scattering:
in superconductor $l \ll \xi \Rightarrow T_c \tau_f \ll 1$, in the ferromagnet: $l \ll \xi_f \Rightarrow H\tau_f < 1$
h - exchange magnetic energy, τ_f *- scattering time*

Normal metal



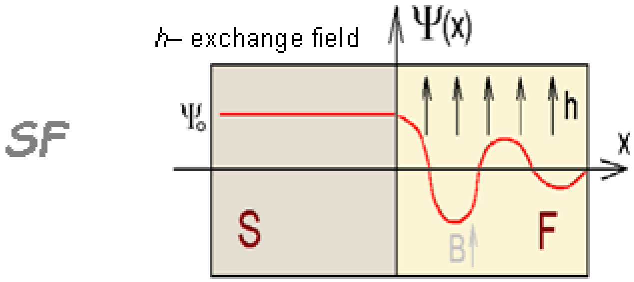
singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$ $\quad \xi_0 = \sqrt{\hbar D_f/2\pi k_B T_c}$

Homogeneous magnetization

singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$ $\quad$ triplet $S_z=0$: $|\uparrow>_1|\downarrow>_2 + |\downarrow>_1|\uparrow>_2$

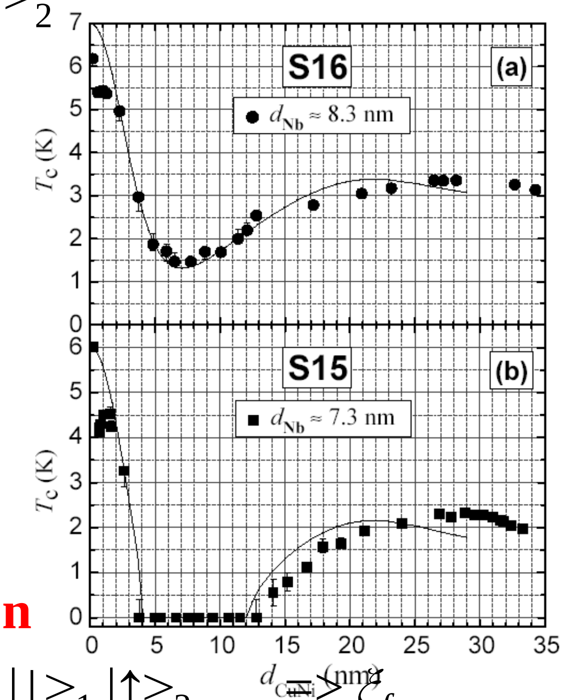
Complex coherence length

$\xi^{-1} = \xi_1^{-1} + i\,\xi_2^{-1}$: $\quad \xi_f = \sqrt{\hbar D_f/h},$



Reentrant Superconductivity

Zdravkov et al.
PRL 97 (2006) 057004



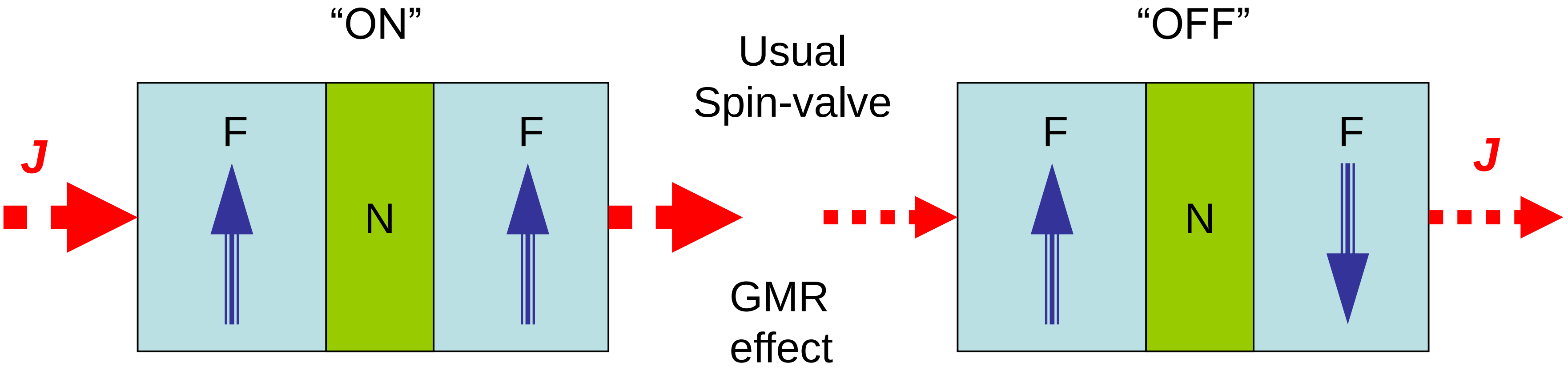
Nonhomogeneous magnetization

singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$ $\quad$ triplet $S_z=0$: $|\uparrow>_1|\downarrow>_2 + |\downarrow>_1|\uparrow>_2$ $\quad \Rightarrow \xi_f$

triplet $S_z=1$: $|\uparrow>_1|\uparrow>_2$ $\quad$ triplet $S_z=-1$: $|\downarrow>_1|\downarrow>_2$ $\quad \Rightarrow \xi_0$

Bergeret, Volkov, Efetov (2001); Kadigrobov, Shekhter, Jonson (2001)

History



Usual Spin-valve

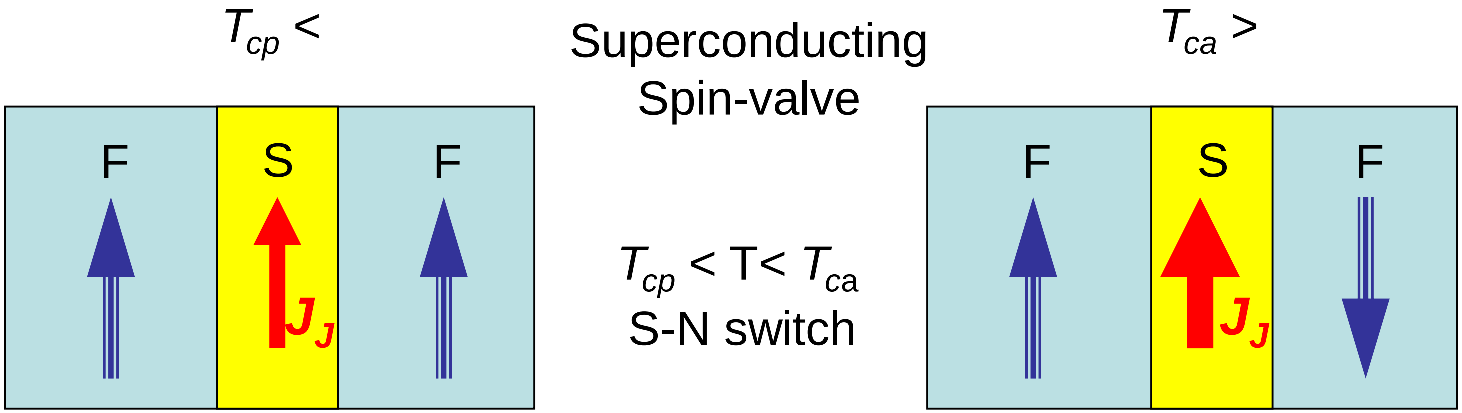
GMR effect

L. R. Tagirov, Phys. Rev. Lett. 83, 2058 (1999)

A. I. Buzdin, A. V. Vedyayev, and N. V. Ryzhanova, Eur. Phys. Lett. 48, 686 (1999)

S. Oh, D. Youm, and M. R. Beasley, Appl. Phys. Lett. 71, 2376 (1997) **SFF**

J. Y. Gu, C.-Y. You, J. S. Jiang, J. Pearson, Ya. B. Bazaliy, and S. D. Bader, Phys. Rev. Lett. 89, 267001 (2002) **CuNi/Nb/CuNi**

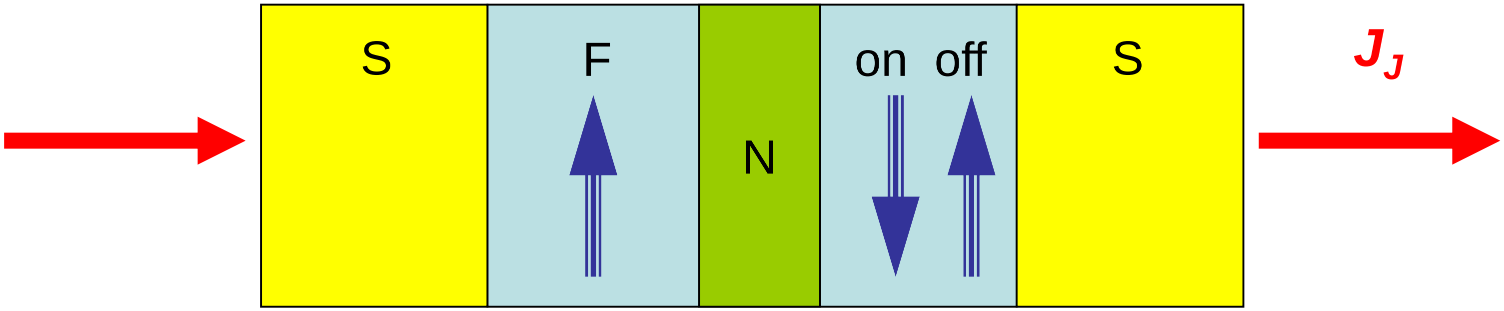


Superconducting Spin-valve

$T_{cp} < T < T_{ca}$

S-N switch

Josephson spin valves



Controllable Josephson effect

A. Vedyayev, C. Lacroix, N. Pugach and N. Ryzhanova. Europhys. Lett. **71**, 679 (2005).
Spin-valve magnetic sandwich in a Josephson junction

Triplet:

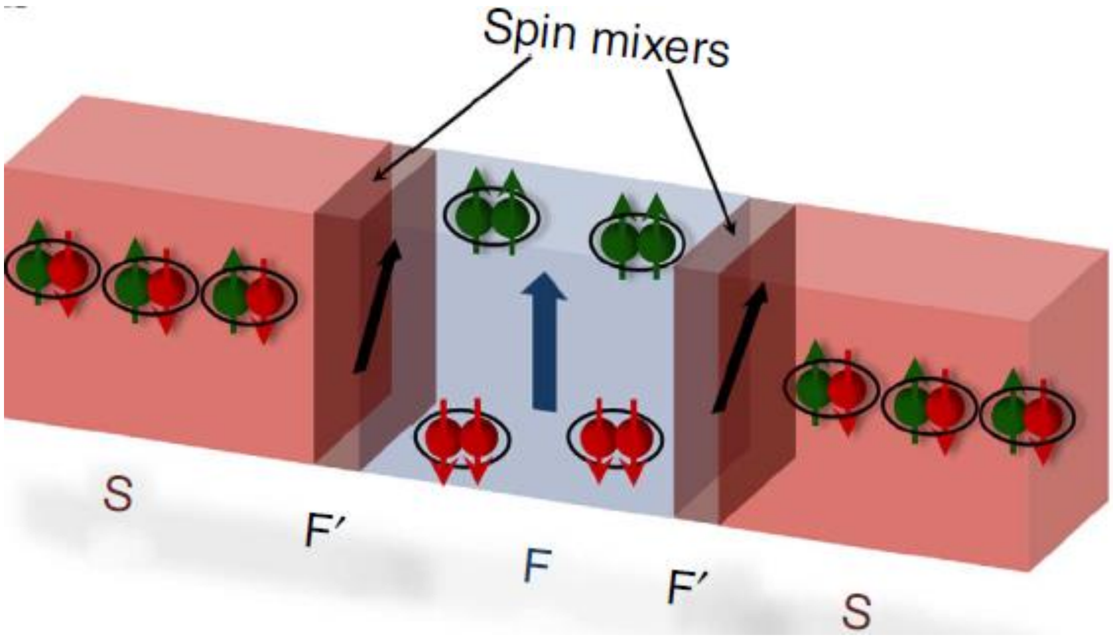
M. Houzet and A. I. Buzdin, Phys. Rev. B **76**, 060504 (2007). **SFFFS**

C. Richard, M. Houzet, and J. S. Meyer. Phys. Rev. Lett. **110**, 217004 (2013) **SFFS**

Iovan, T. Golod, and V. M. Krasnov. PRB 90, 134514 (2014) “Scissors” **SFFS**

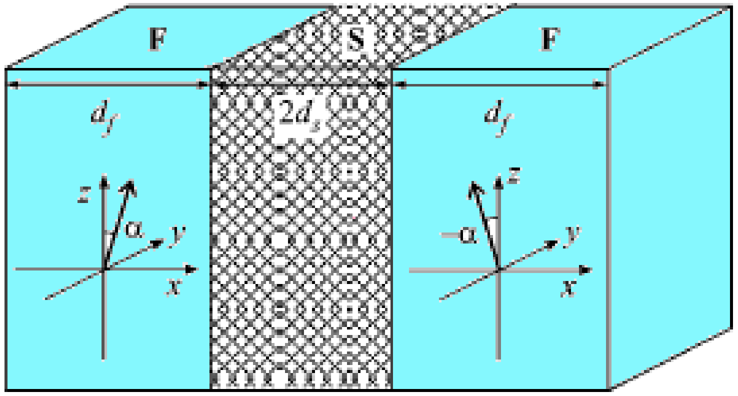
N. Banerjee, J.W.A. Robinson, M.G. Blamire, Nature Comm. 5, 4771 (2014). **SFFFS**

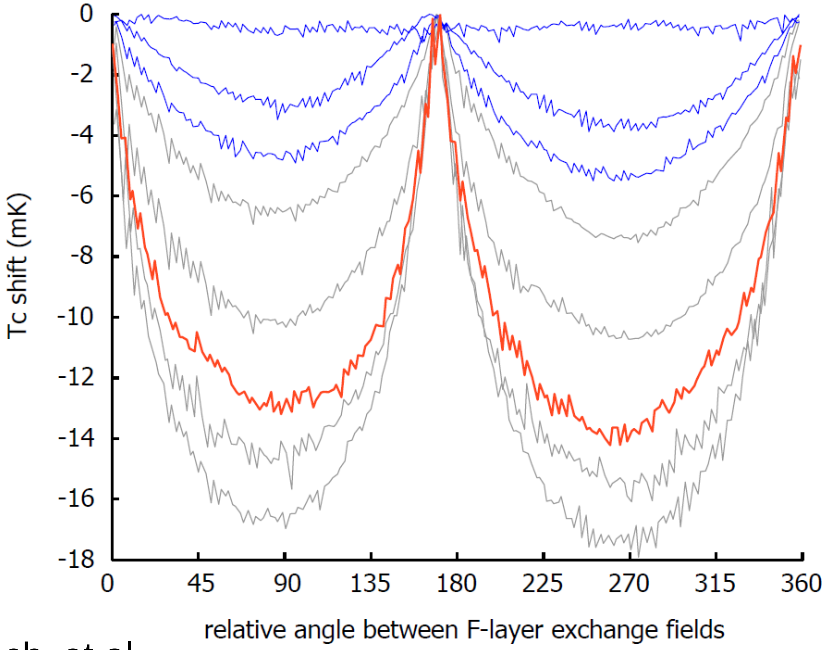
W. Martinez, W.P. Pratt, Jr., N. O. Birge, arXiv:1510.02144 (2015) **SF…F”…FS**

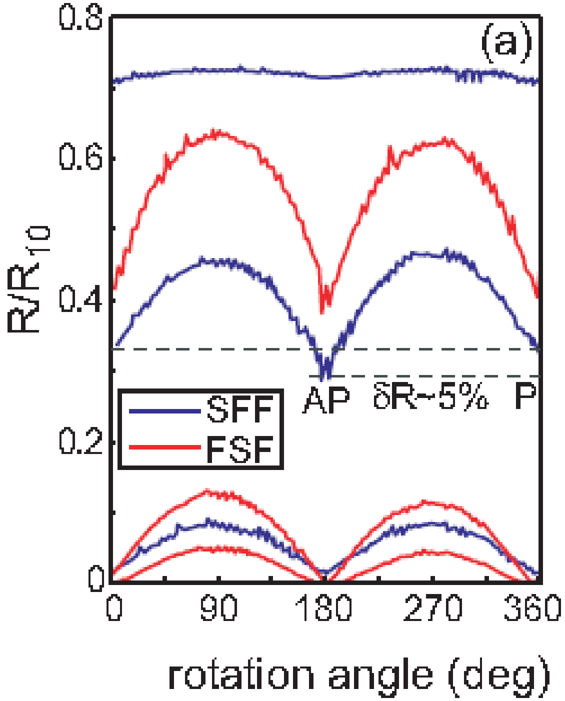


FSF spin-valves

Transport experiment: T_c for FSF and SFF structures with misaligned magnetization







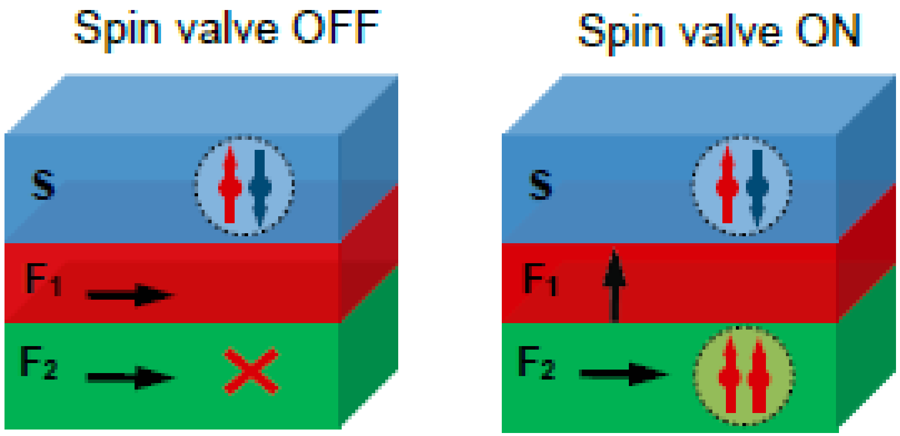
M. Flokstra,...N.Pugach, et.al.
Phys. Rev. B **91**,
060501(R) (2015)

Theory: Ya. V. Fominov, A. A. Golubov, and M. Yu. Kupriyanov (dirty limit) (2003)

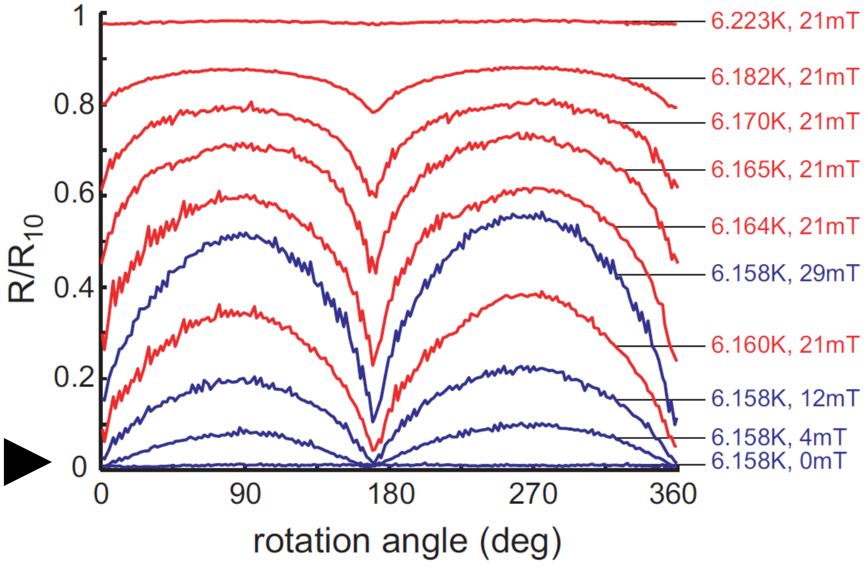
Clean FSF (BDG): K. Halterman, O. T. Valls, P. H. Barsic (2008) (clean limit) give only monotonous angular dependence of T_c without any minima for weak ferromagnets

Clean and dirty FSF: S. Mironov, A. Buzdin (2014).

SFF Spin-valves



•M. G. Flokstra, T. C. Cunningham, J. Ki 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. PRB 91, 060501(R) (2015), Appl. Phys. Lett. 107, 262602 (2015), **Nature Phys**. 12, 57 (2016) **Nb/Co/Cu/Co**



“Giant” spin-valve effect

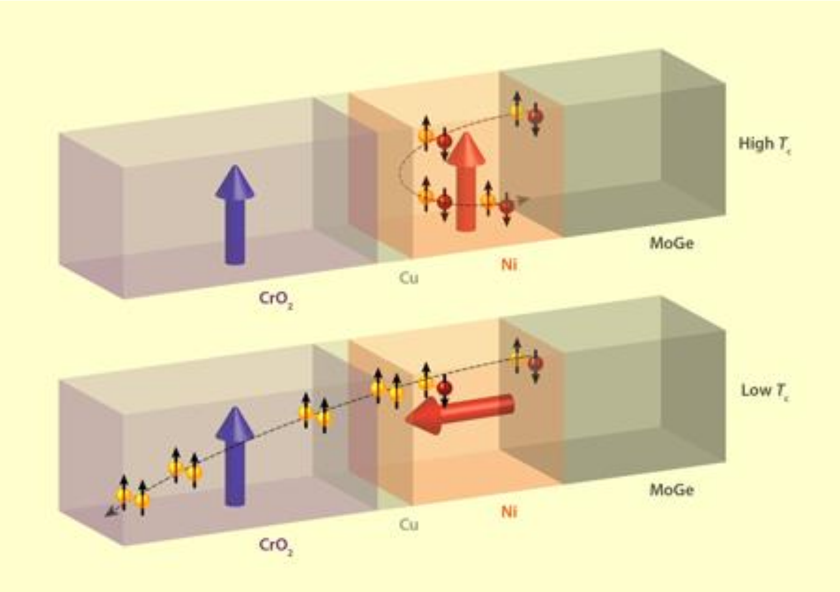
* P.V. Leksin, N. N. Garif’yanov, I. A. Garifullin, et.al.,
PRL 109, 057005 (2012) **CoOx/Fe/Cu/Fe/Pb**

* V. I. Zdravkov,1,2 J. Kehrle,1 G. Obermeier, et.al.
PRB **87**,144507 (2013) **Nb/CuNi/normalNb/Co/CoO$_x$**

* X. L. Wang, M. G. Blamire, J. W. A. Robinson, et. al.
PRB 89, 140508(R) (2014) **Cu/Co/Cu/Py/Cu/Nb**

* Ya.V. Fominov, A.A. Golubov, T.Yu. Karminskaya, M.Yu. Kupriyanov, R.G. Deminov, L.R. Tagirov, Pis’ma ZETF 91, 329 (2010) **Theory SFF**

***** A. Singh, S. Voltan, K. Lahabi, J. Aarts,
PRX 5, 021019 (2015) **CrO2/Cu/Ni/MoGe** ≡ ≡ ▶



Helical magnets based SSV

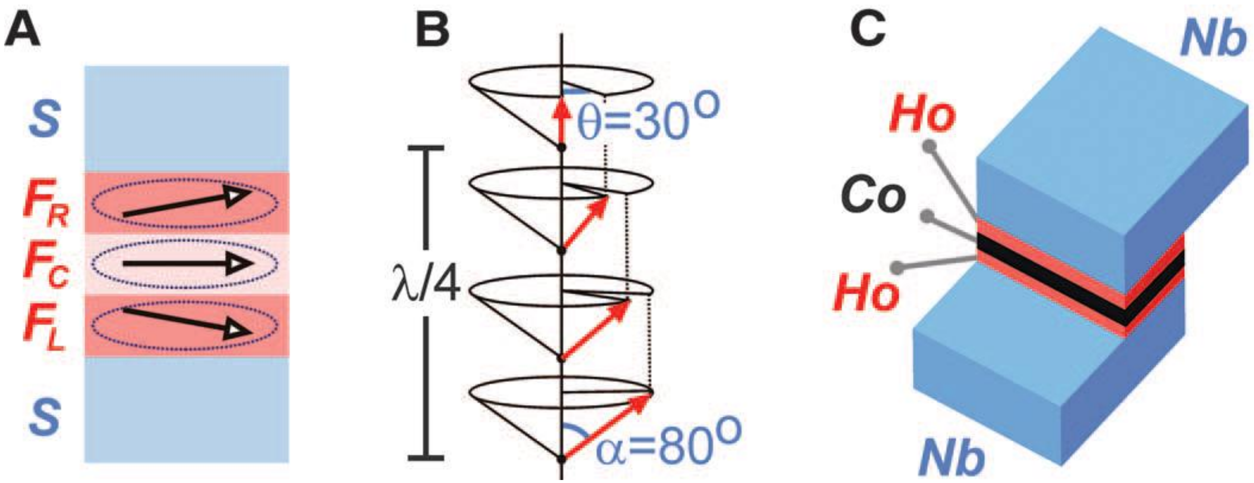
Spiral magntization in Ho

J. W. A. Robinson,

J. D. S. Witt, M. G. Blamire

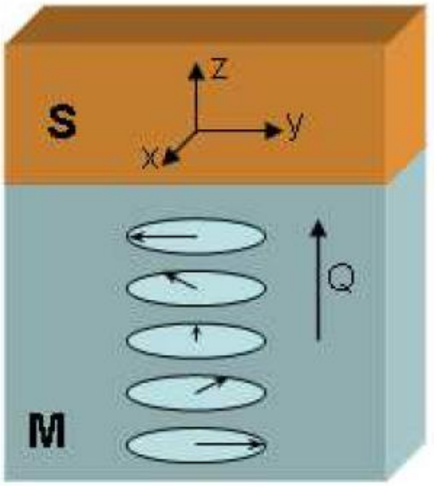
Science 329, 59 (2010) =>

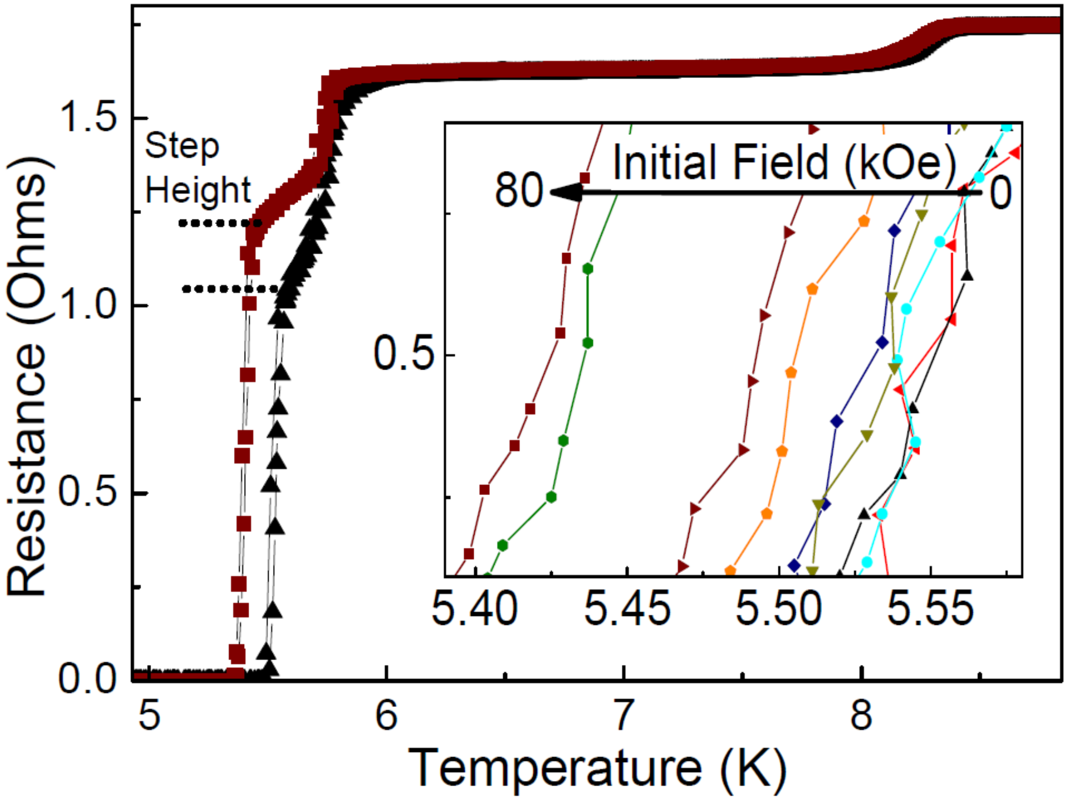
Long-range Josephson effect



Spiral Er-Nb bilayer

N. Satchell, J. D. S. Witt,
M. G. Flokstra, S. L. Lee,
J. F. K. Cooper, C. J. Kinane,
S. Langridge, and G. Burnell (2017)

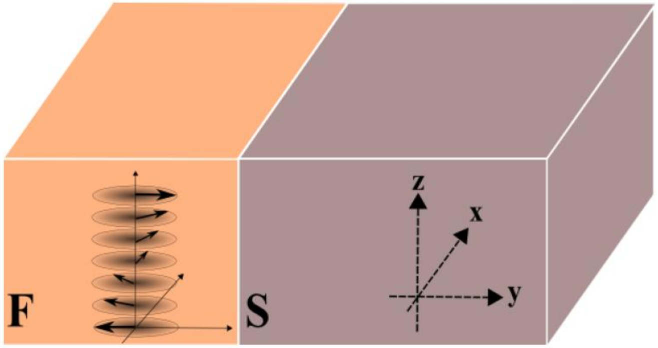




Proximity effect with a spiral magnet

Usadel equations

For the spiral magnetization with the vector of the spiral **Q** = (0,0,Q), Q = 2π/λ



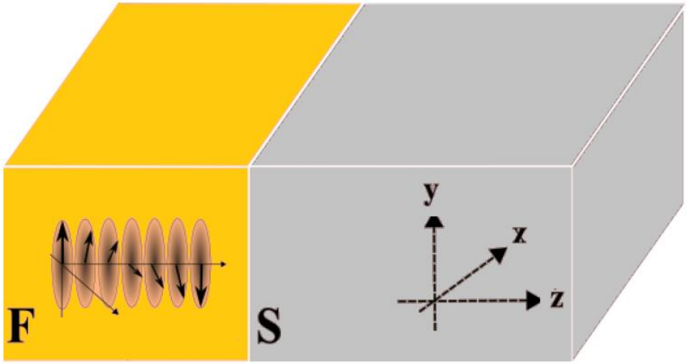
$$\begin{aligned} \left(D\nabla^2 - 2\left|\omega\right|\right) f_s &= -2\pi\Delta + 2i\; sgn(\omega)\,\overrightarrow{h}\cdot\overrightarrow{f_t}\,, \\ \left(D\nabla^2 - 2\left|\omega\right|\right) \overrightarrow{f_t} &= 2i\; sgn(\omega)\,\overrightarrow{h}\, f_s\,. \end{aligned}$$

The linear transformation

$$f_+ = (-f_x + if_y)\exp(iQz), \qquad f_- = (f_x + if_y)\exp(-iQz)$$

Yields

$$\begin{aligned} \left(D\nabla^2 - 2\omega\right) f_s &= i\, h\,[f_- - f_+] \\ \left(D\nabla^2 - 2iDQ\frac{\partial}{\partial z} - DQ^2 - 2\omega\right) f_+ &= -2i\, h f_s, \\ \left(D\nabla^2 + 2iDQ\frac{\partial}{\partial z} - DQ^2 - 2\omega\right) f_- &= 2i\, h f_s. \end{aligned}$$



$$k_h^2 \gg Q^2,\ k_\omega^2$$

$$k_h = \sqrt{h/D}$$

$$k_\omega = \sqrt{2\omega/D}$$

The eigenvalues:

$$k_0 = \sqrt{k_\omega^2 + Q^2}$$

$$k_\pm = (1 \pm \mathrm{i})k_h$$

T. Champel, M. Eschrig.
Phys. Rev. B, Lett (2005-2007)

A. F. Volkov and A. Anishchanka,
K.B. Efetov. *Phys. Rev.* B (2005)

Spiral superconducting spin valve

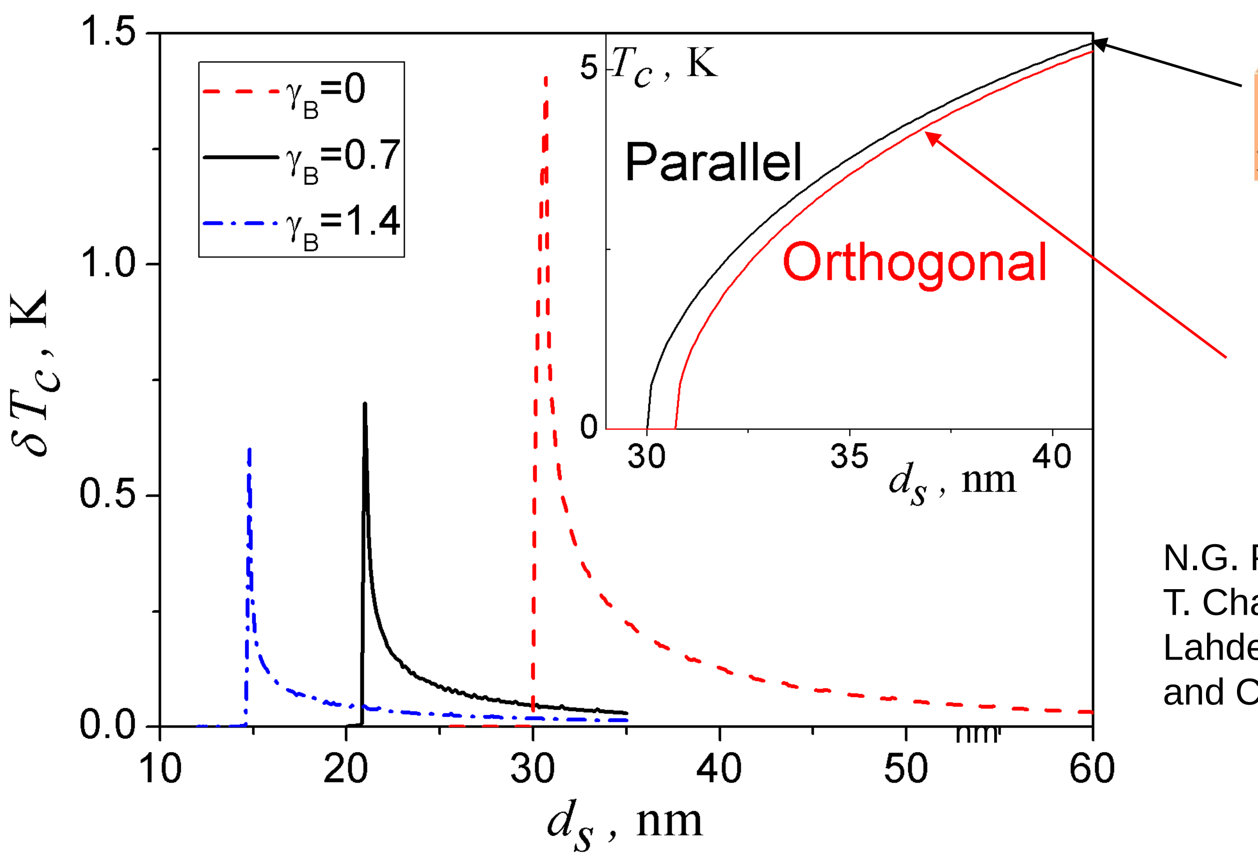
MnSi family compounds (CoSi, FeCoSi, MnGe, FeGe, MnFeGe)

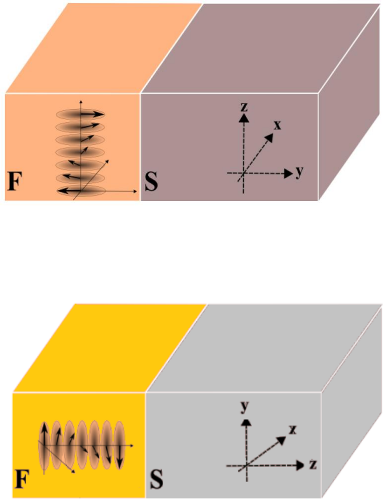
Cubic and complex noncentrosymmetric crystal lattice => DM SO interaction

Magnetic spiral may be realized in 3 equivalent directions (111), (1-11), (-1-11)

λ~18nm (MnSi)>>ξ_f

The spiral direction may be switched => LRTC switch => T_c change



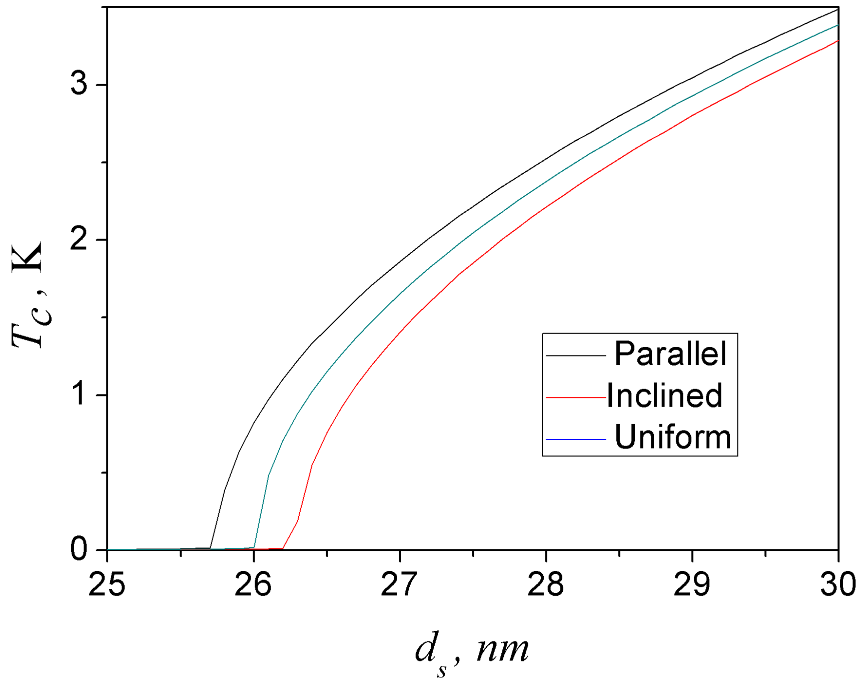


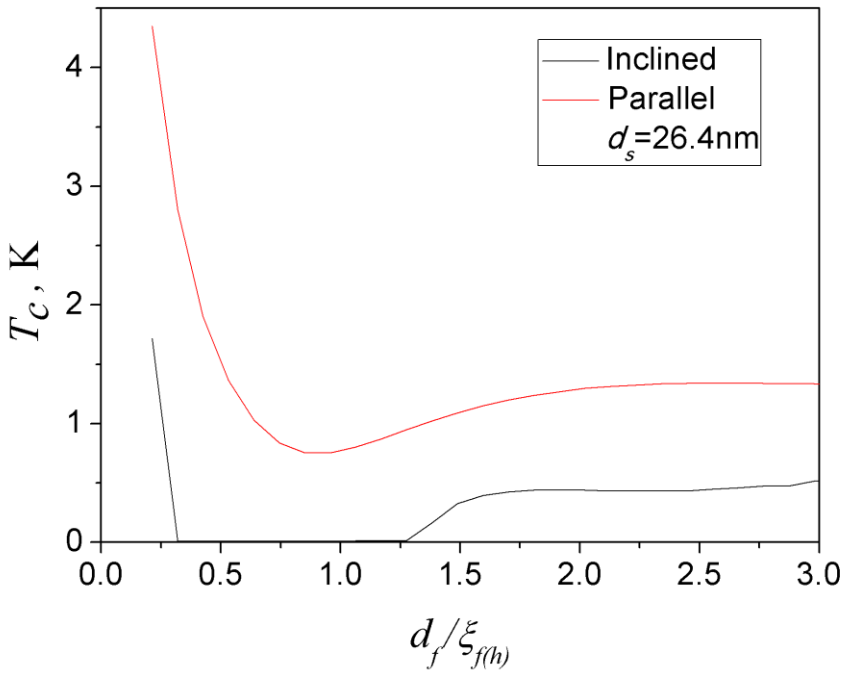
N.G. Pugach, M.Safonchik,
T. Champel, M.E.Zhitomirsky, E.
Lahderanta, M. Eschrig,
and C. Lacroix
Appl. Phys. Lett.
111, 162601 (2017).

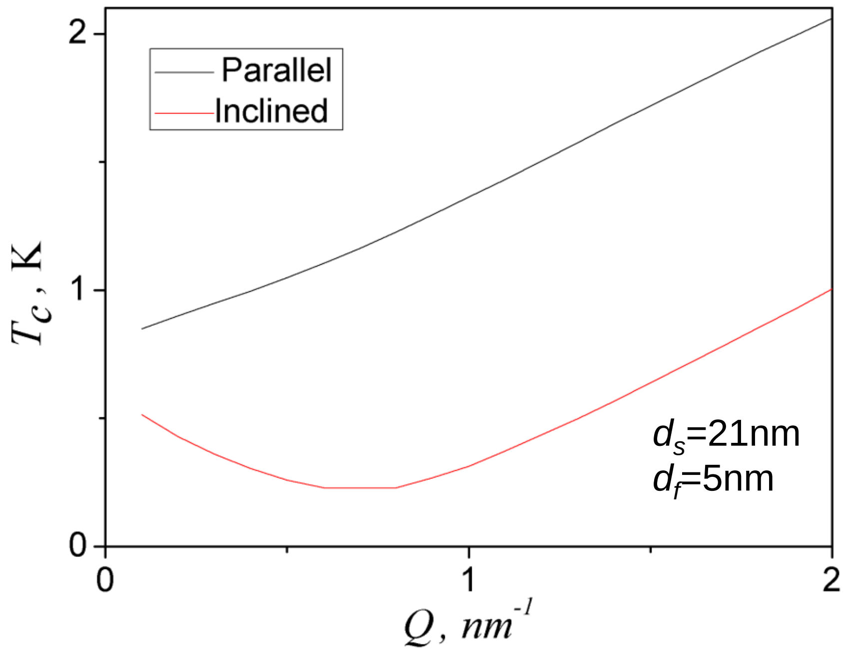
Properties of the spiral spin valve

Switchable reentrant superconductivity

T_c oscillations <= short-range
triplet comp. oscillations,
Remains LRTC
Exchange splitting h~100 meV

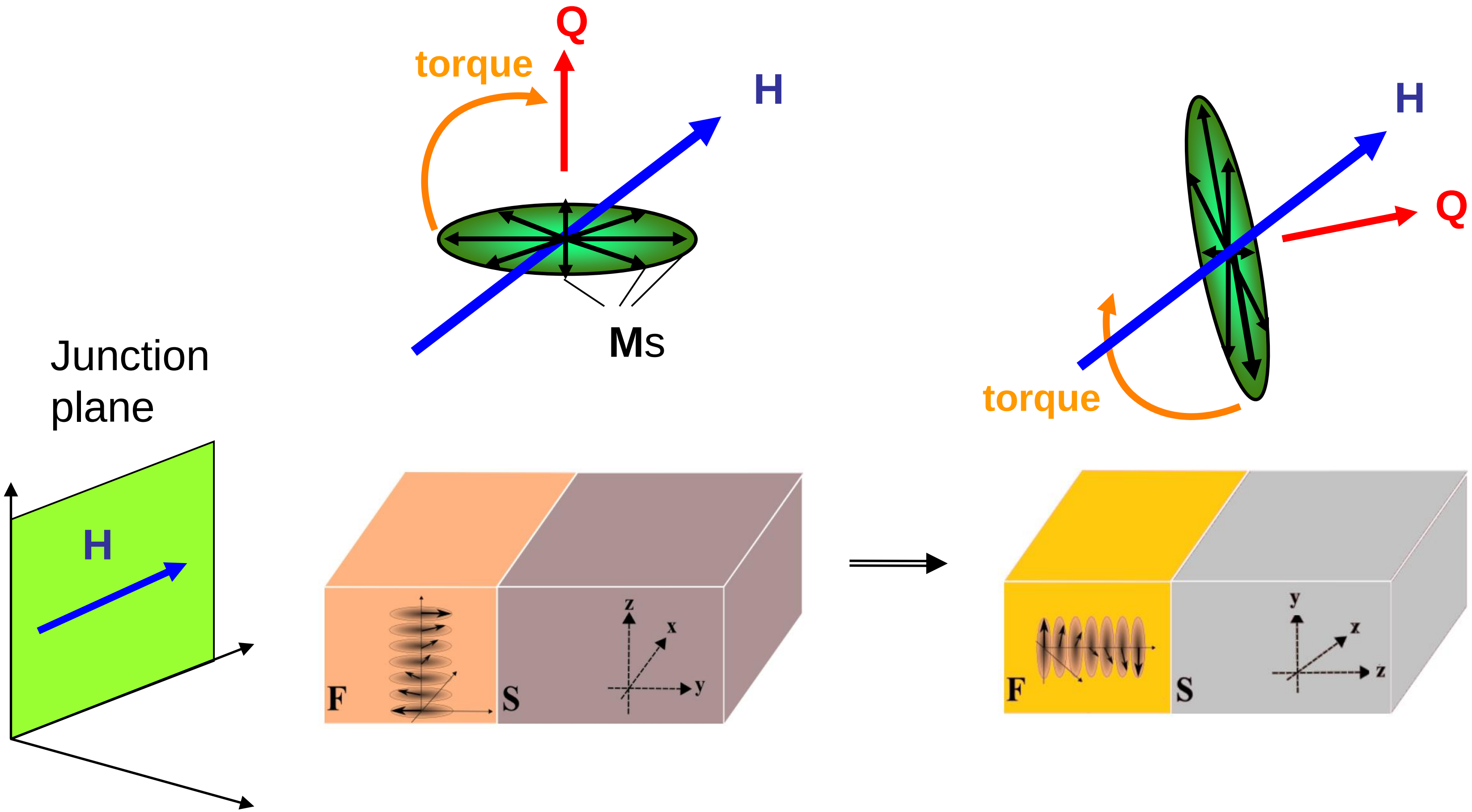






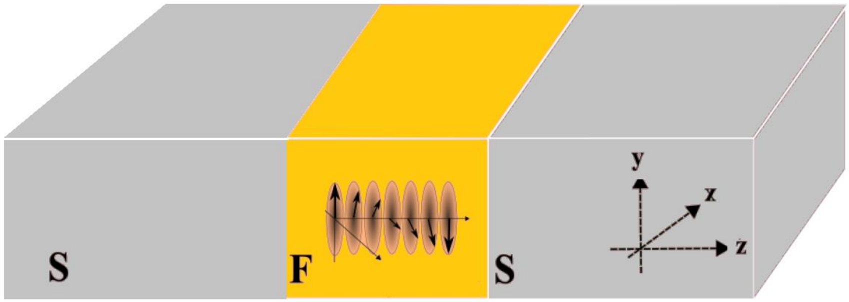
Magnetic switch

magnetic field (short pulse) → spin precession (torque)



H always lies in the plane of the interface

Josephson junction



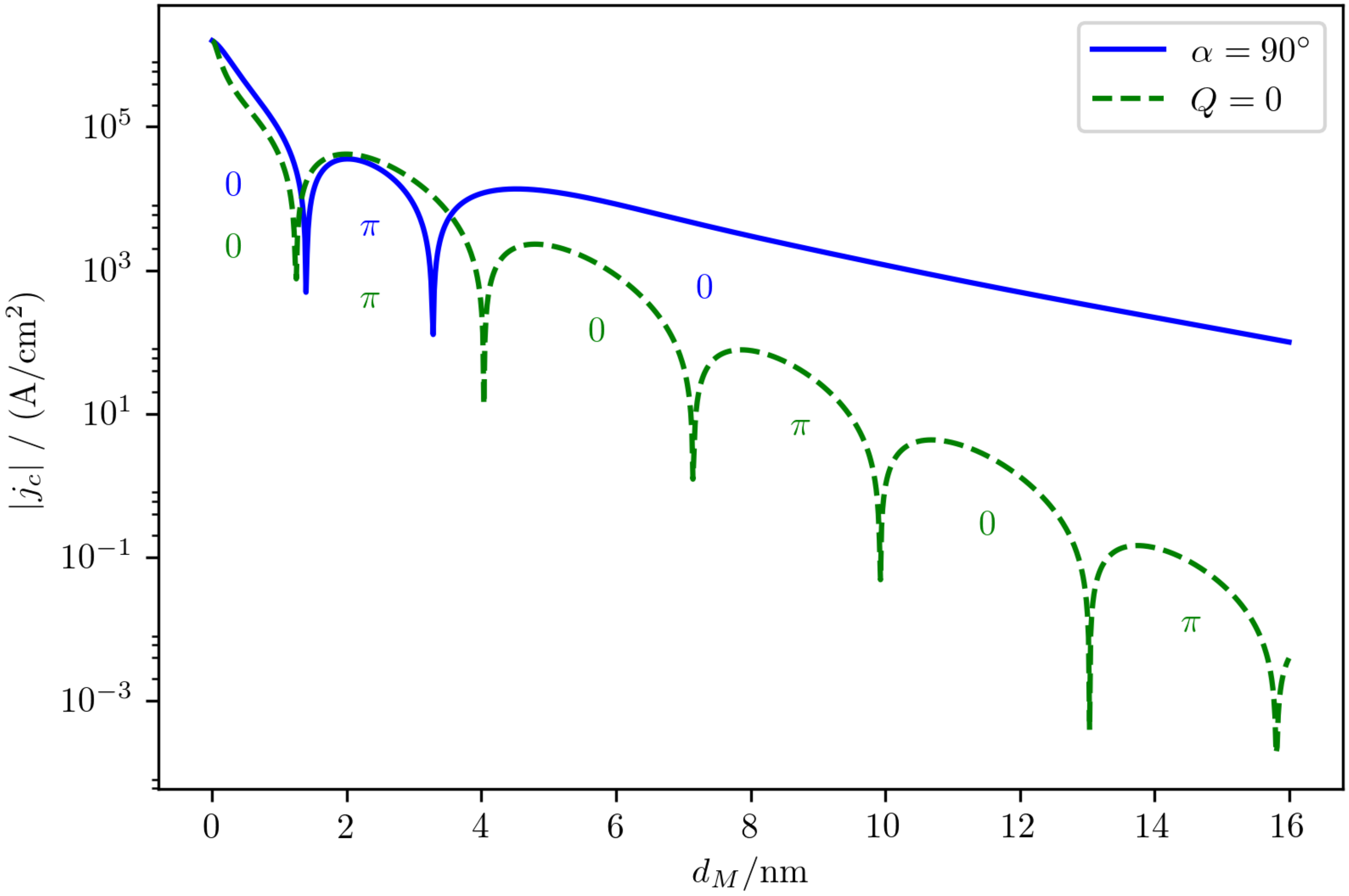
- ***Q*** is switches to the uniform magnetization
- Josephson current changes
- Ground states are well defined
- One layer: easy to fabricate

$$j \equiv j_c \sin\varphi = \frac{\pi T}{e\rho}\sum_{\omega>0} \mathrm{Im}\left[f_s{}^*\partial_z f_s - \left(f_-{}^*\partial_z f_- + f_+{}^*\partial_z f_+\right)/2\right]_{z=0}$$

- New type of superconducting memory element,
- better compatible with other Josephson devices

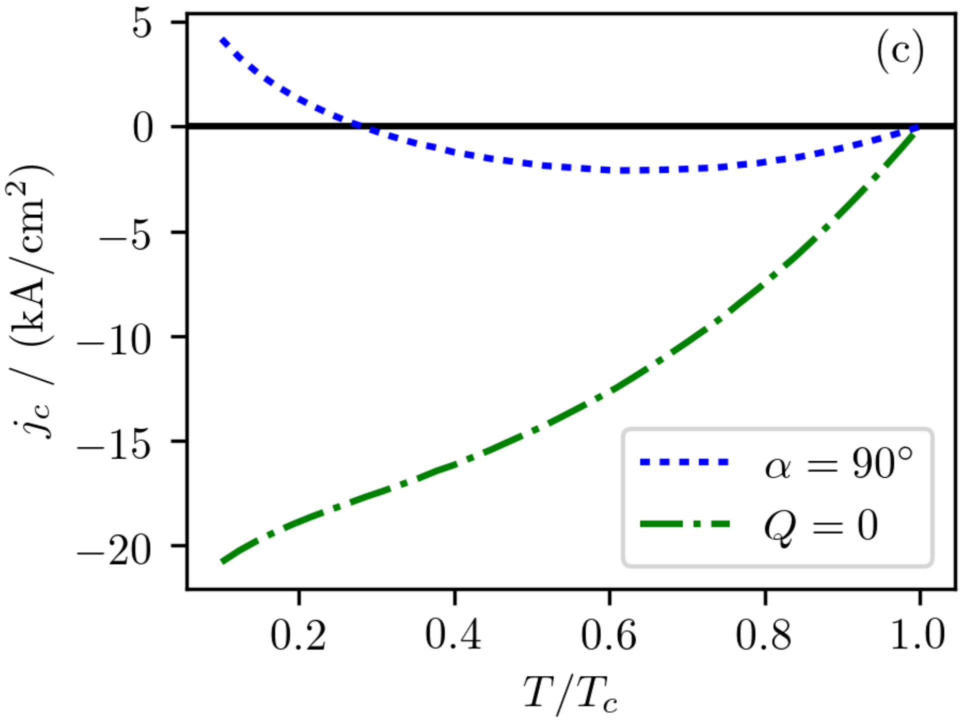
T. Champel et al. PRB 72 (2005), PRL 100 (2008); A. E. Volkov et al. PRB 73 (2006)

Critical current density

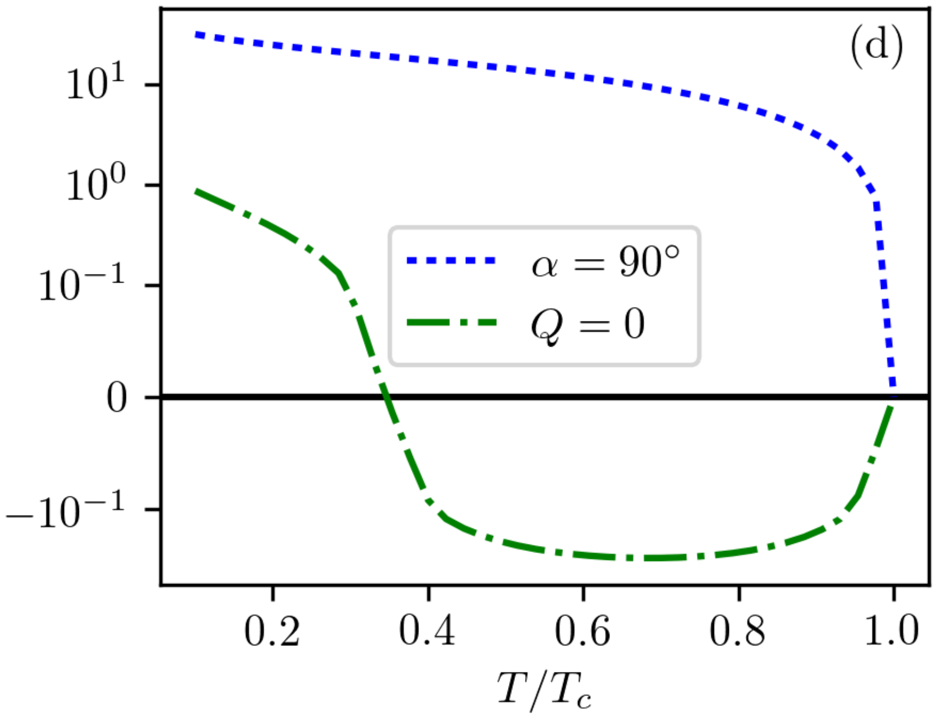


Critical current density: *temperature induced 0-pi transitions*

$d_f = 3.2$ nm



$d_f = 4.0$ nm

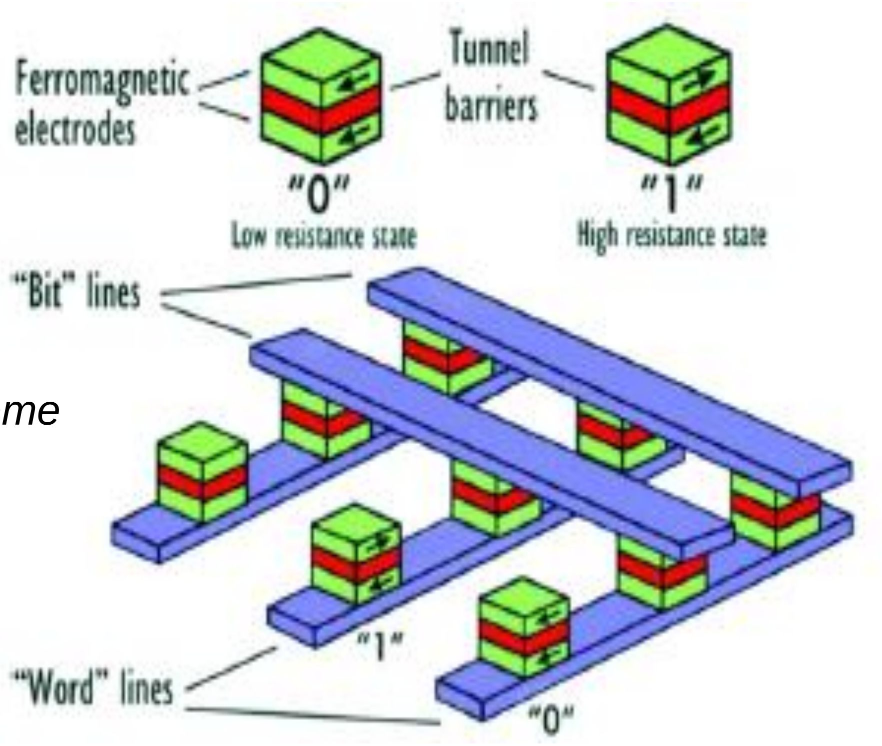


The magnetic switch is possible not only between small j_c and large j_c,

But also between 0 and π states on the same junction

Advantages of spiral SSV as a memory element

- simple structure (bilayer, where M may be bulk for a spin-valve)
- T_c change may be appreciable ~ 1K
- J_c change may be of few orders of magnitude
- **half-select problem** solution



Savchenko scheme

In production

from 2006

- N. G. Pugach, M. Safonchik, T. Champel, M. E. Zhitomirsky, E. Lahderanta, M. Eschrig, and C. Lacroix. Appl. Phys. Lett. 111, 162601 (2017)
- N. G. Pugach, M. Safonchik, JETP Lett. 107 N5, 320 (2018)

Towards superconducting spin valves

Triplet superconducting spin valve

S. Oh et al., Appl. Phys. Lett. **71**, 2376 (1997)

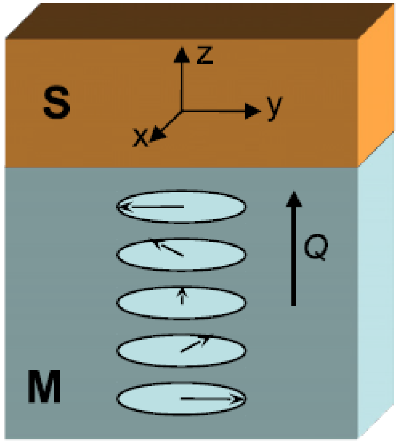
High grade of complexity:

- additional AF pinning layer
- additional non-magnetic separation layer

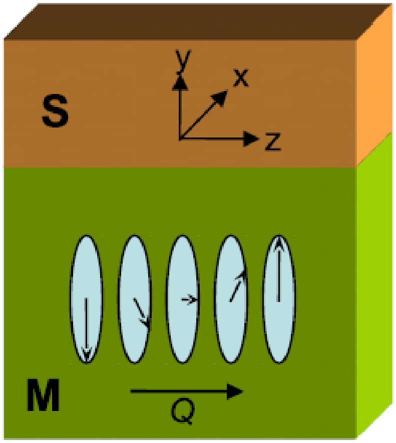
Alternative concept:

- Single magnetic layer with controllable intrinsic non-collinear magnetization

N. Pugach et al., Appl. Phys. Lett. **111**, 162601 (2017)



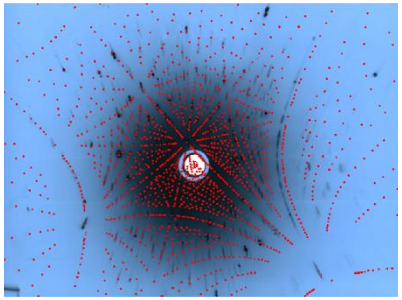
orthogonal



parallel

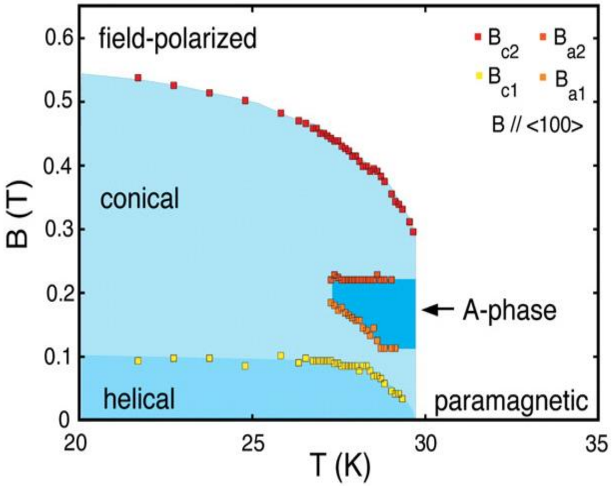
Experimental approach

Growth of MnSi single crystals for the use as non-collinear magnetic substrate



Preparation of [111] oriented flat (~ 0.5 mm) samples

Deposition of thin Nb film ($T_C = 9{,}25\ \mathrm{K},\ \xi_{GL} = 39\ \mathrm{nm}$) using MBE

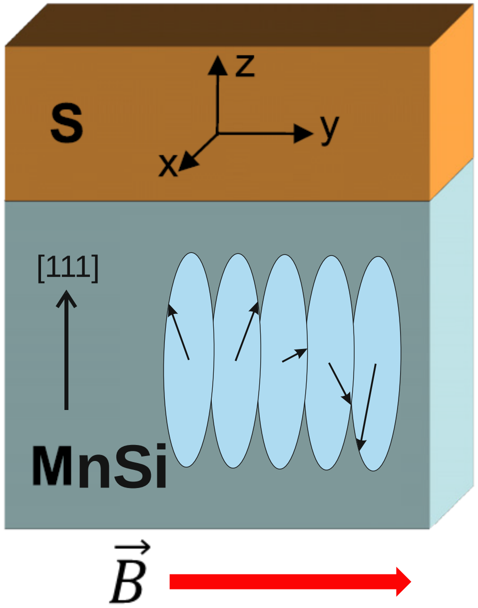


$\vec{B} = 0$:

Helix oriented in [111] orientation orthogonal to Nb layer

$\vec{B} \neq 0$:

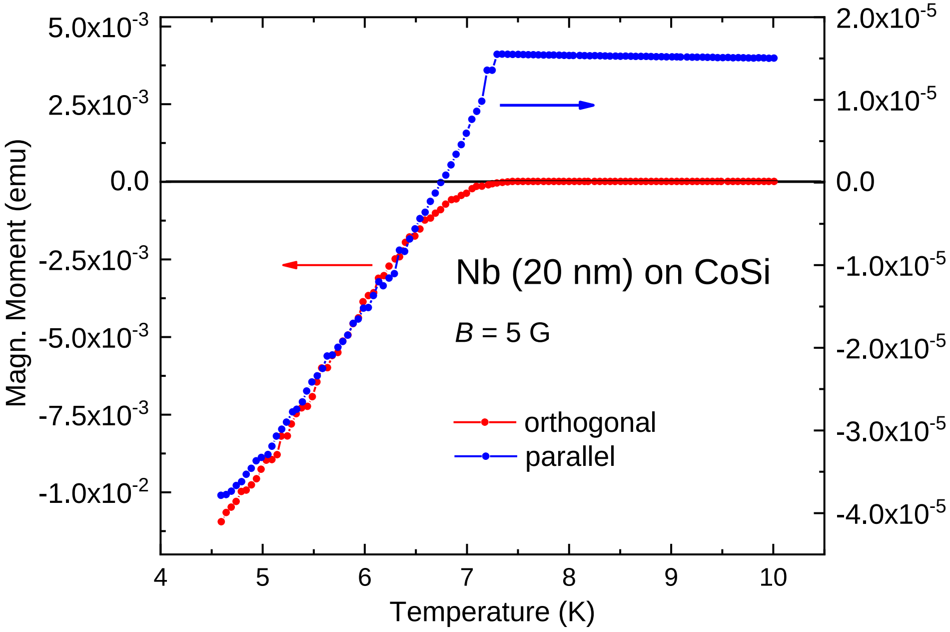
Helix turns towards magnetic field direction parallel to Nb layer



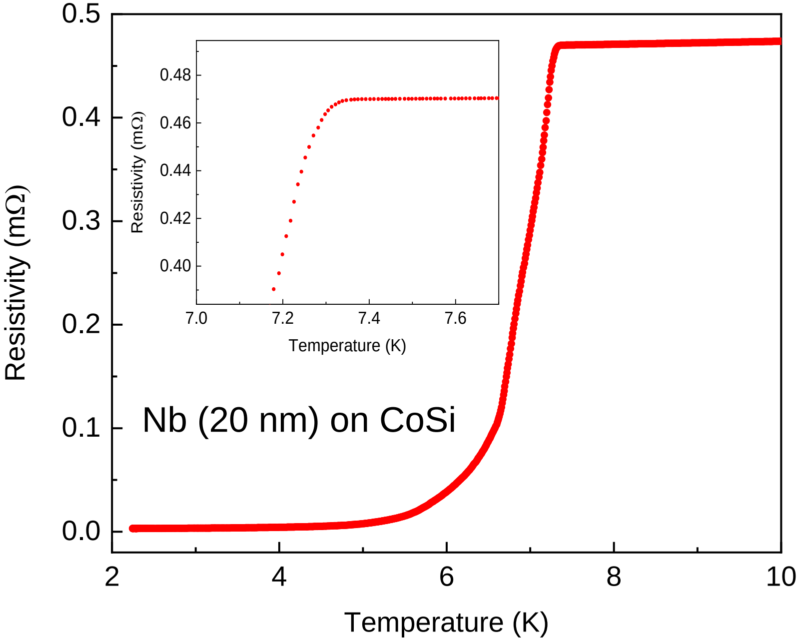
First results

Reference: Nb film (20 nm) on diamagnetic CoSi

Magnetization



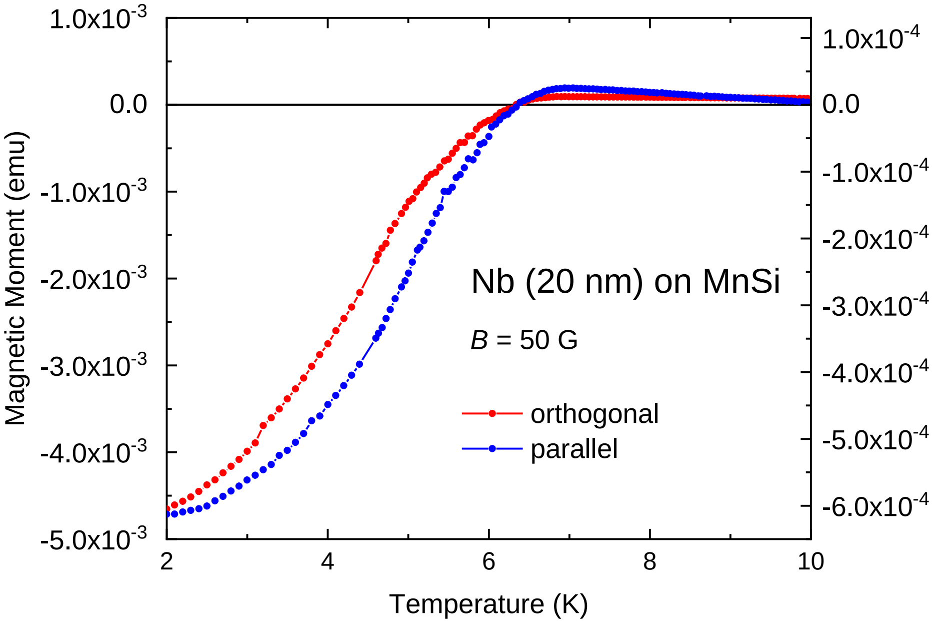
Resistivity



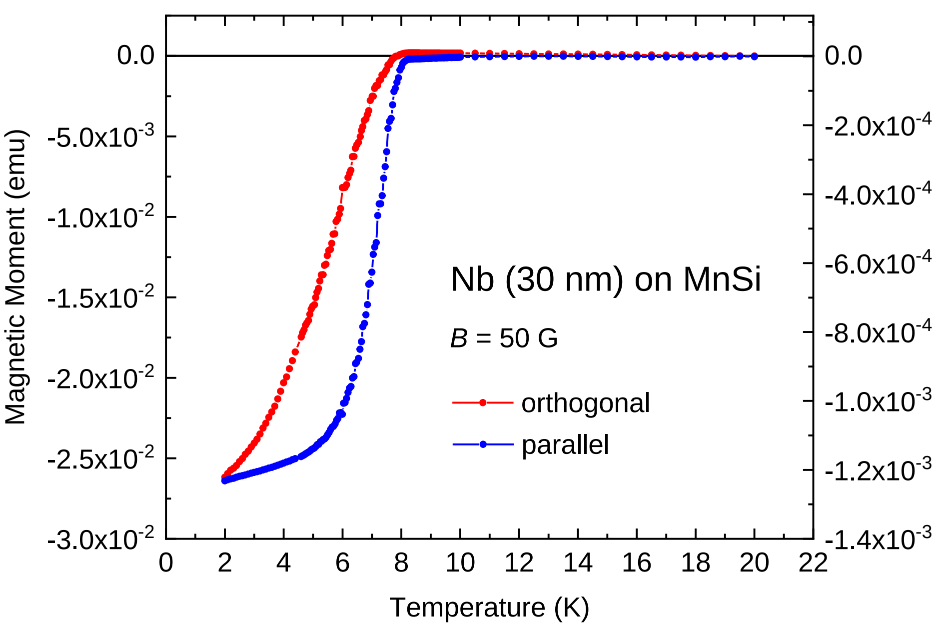
First results

Nb film on chiral magnet MnSi

20 nm Nb film



30 nm Nb film



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Thank you for attention!