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EXPERT OPINION

Tailoring the Fulde-Ferrell-Larkin-Ovchinnikov state

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Imagine a piece of paper, 8 km long, 700 m wide, and 0.1 mm thick. Now scale that down by a factor of 10^5 – to 80 mm times 7 mm, and correspondingly its thickness to 10 nm, and you have an idea about the precision and control necessary to create thin films in experiments like the one published recently in Annalen der Physik by Jan-Michael Kehrle and co-workers [1]. The motivation for creating such extraordinarily thin films over comparatively large areas was a prediction that if a thin layer of a conventional superconductor is sandwiched between two ferromagnetic films, then the superconducting transition temperature of this trilayer structure, after initially being suppressed, would show a reentrance behaviour when the thickness of one or both of the ferromagnetic layers is varied.

The mechanism for such a reentrant behaviour of the superconducting critical temperature can ultimately be traced back to the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) effect. Peter Fulde and Richard Ferrell, working at the time at the University of Maryland, published their article in August 1964 in Physical Review B (Ref. 3 in [1]). Independently, working at the Moscow Physico-Technical Institute, Anatoly Larkin and Yuri Ovchinnikov published in September 1964 an article about similar effects in Zhurnal Eksperimental'noi i Teoricheskoi Fiziki (which appeared translated in March 1965 in Soviet Physics JETP) (Ref. 4 in [1]).

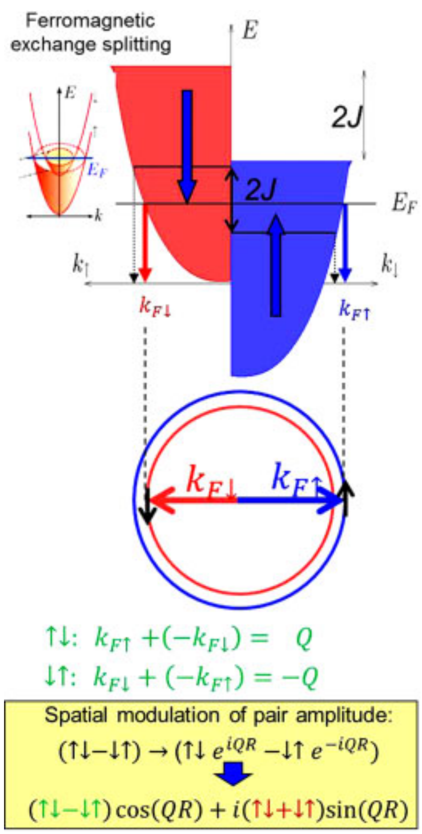

Figure (online color at: www.ann-phys.org) Illustration of the Fulde-Ferrell-Larkin-Ovchinnikov effect, leading to spatial oscillations as well as to singlet-triplet mixing of the superconducting pair amplitudes in a ferromagnet.

The main physical mechanism of the FFLO effect is described in Fig. 1 (modified after [2]). Consider superconductivity in a weakly spin-polarised ferromagnetic material. Electronic spin bands are shifted with respect to each other by an amount $2J$. This shift can be translated into a resulting center of mass momentum $\pm\boldsymbol{Q}$ for the Cooper pairs, provided a certain preferred direction is chosen by the system (spontaneously or due to crystal anisotropy). This process is accompanied by the development of an $|s = 1, m = 0\rangle$ spin-triplet pair amplitude, and both the singlet and triplet pair amplitudes spatially oscillate out of phase. Originally such a state had been predicted for a bulk material. However, a similar state can be realized also in proximity structures, where superconducting pairs leak into a ferromagnet due to the superconducting proximity effect. These proximity-induced pairs are in turn modified by the FFLO effect. The spatially oscillating pair amplitudes in the ferromagnetic regions act back on the superconducting singlet pair potential in the superconducting region. How exactly this interaction between pair potential and FFLO amplitudes takes place must be determined numerically, however the oscillating nature of the FFLO amplitudes ultimately leads to oscillations in the modulus of the pair potential (and thus in the transition temperature) as function of the geometric dimensions of the hybrid structure.

In the 1970's and 1980's, Lev Bulaevskii and Alexander Buzdin, at the time both at the Lebedev Physical Institute in Moscow, discovered that a so-called π-junction could be realized in a Josephson device [3, 4]. Based on their work, in the 1990's

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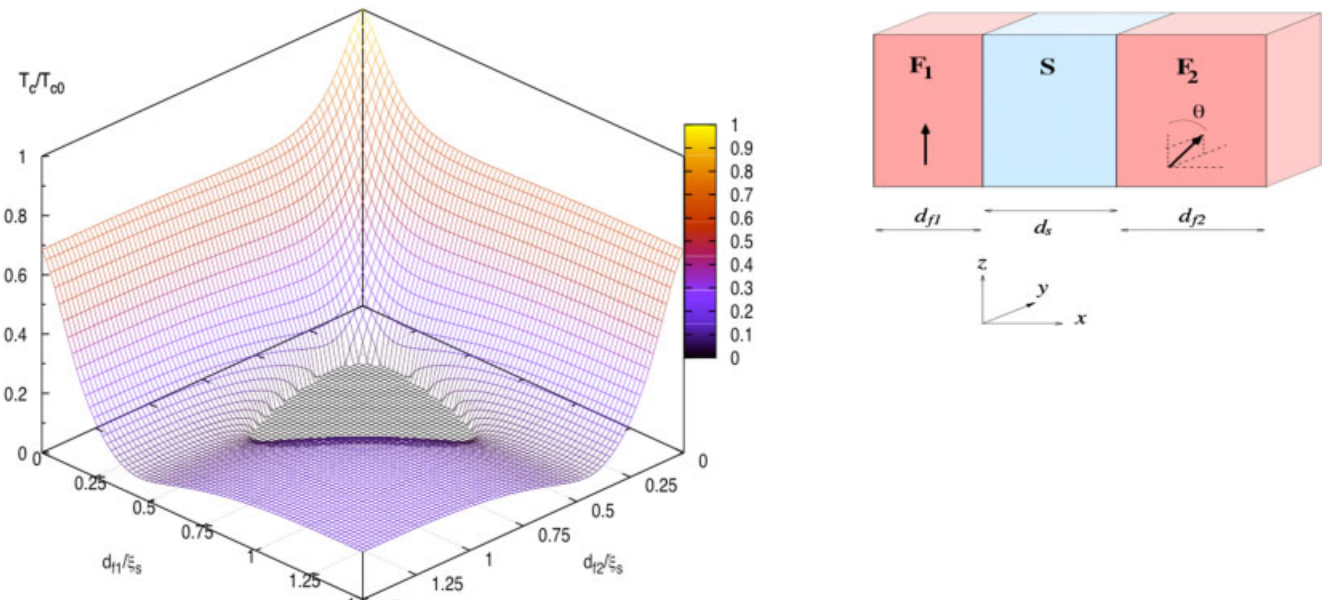
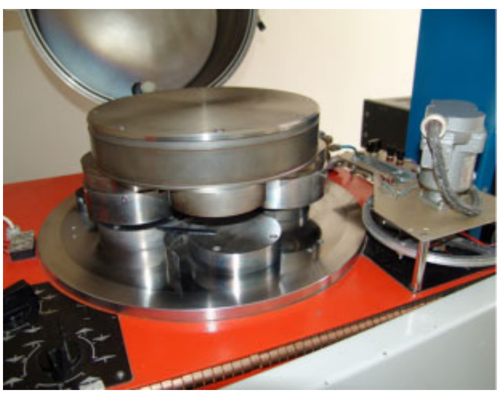


a)



b)

Figure 2 (online color at: www.ann-phys.org) Trilayer consisting of a superconductor sandwiched between two ferromagnets. The transition temperature T_c of the trilayer varies as function of the thicknesses d_{f1}, d_{f2} of both ferromagnetic layers (here for parallel magnetizations). Note the region of zero Tc. b) Device designed by Sidorenko, Zdravkov, and Morari, for high-quality superconductor-ferromagnet nanostructure deposition (courtesy of Anatoli Sidorenko).

an oscillatory behavior in the dependence of the critical temperature T_c on the thickness of the ferromagnetic layer in a superconductor-ferromagnet bilayer had been discovered. Motivated by experimental results from 1986 on V/Fe superlattices by Hong-Kuen Wong *et al.* in the group of John Ketterson at Northwestern University [5], early theoretical work was provided by Alexander Buzdin and Mikhail Kupriyanov (Moscow State University) [6], by Zoran Radović (Institute of Physics, Belgrade) and co-workers (Ref. 18 in [1]), and by Lenar Tagirov (Kazan State University), who in particular developed a theory for the phenomenon of re-entrant superconductivity in such systems (Refs. 20 and 25 in [1]). Extension of the theory beyond the diffusive limit was the focus of Yakov Fominov and Nikolai Chtchelkachev from the Landau Institute for Theoretical Physics in Chernogolovka, and Alexander Golubov from University of Twente [7].

The dependence of the critical transition temperature in a trilayer consisting of a superconductor sandwiched between two ferromagnets is illustrated in panel (a) of Fig. 2 (modified after [8]). The transition temperature T_c of the trilayer varies as function of the thicknesses d_{f1} and d_{f2} of both ferromagnetic layers (which are given here in units of the coherence length in the superconductor, ξ_S). Regions of complete suppression of superconductivity change with regions of finite transition temperature, leading to the possibility of re-entrant effects when tracing certain paths in that phase diagram.

These theoretical predictions have been confirmed in numerous experimental studies, starting with the work of Christoph Strunk and co-workers in the group of Hilbert von Löhneysen, University of Karlsruhe, in 1994 (Ref. 61 in [1]), the work of Jidong Jiang and co-workers in the group of Chia-Ling Chien, John

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Hopkins University, in 1995 (Ref. 19 in [1]), and the work of Thorsten Mühge et al. in 1996, a collaboration of Kazan Physico-Technical Institute, Kazan State University, and the group of Hartmut Zabel at University of Bochum [9]. Within the same Kazan-Bochum collaboration, Il'giz Garifullin et al. reported in 2002 experimental discovery of re-entrant superconductivity in Fe/V/Fe trilayers (Ref. 58 in [1]).

Further progress was made possible due to advances in technology. A magnetron sputtering device designed and patented by Anatoli Sidorenko, Vladimir Zdravkov, and Roman Morari (Refs. 21, 22, and 43 in [1]) from the Institute of Electronic Engineering and Nanotechnologies in Kishinev, allowed for the production of entire batches of samples with different (and controlled) layer thicknesses under literally identical conditions. The device is shown in panel b) of Fig. 2. On the right an electromotor with gear and transmission is seen, that ensures precise movement of the magnetron in the vacuum chamber during film deposition. In the center a silicon substrate, 80 mm long, placed on the substrate-holder, is visible. The flat cylinder above the substrate is the magnetron, which is in motion during the deposition. With this device wedge-shaped master samples were produced, each of which were then cut into a multitude of smaller samples with various layer thicknesses. Measurements were conducted within the group of Siegfried Horn of the University of Augsburg [1]. By this procedure it has become possible to tailor the FFLO state according to the desired superconducting properties of the sample. With theoretical support by Lenar Tagirov from Kazan State University in Tatarstan, this German-Moldovan-Russian collaboration has led to a detailed study of re-entrant superconductivity, including the first experimental realization of double extinction and multiple re-entrant superconductivity in 2009/10 (Refs. 22 and 23 in [1]).

Although currently the research still concentrates on studying fundamental questions, applications can be imagined in various ways. The most obvious application would be the development of a spin-valve device. Re-entrant phenomena are predicted not only as function of thickness of the adjacent ferromagnetic layers, but also as function of other parameters, e.g. the degree of magnetic inhomogeneity, as in ferromagnets with spiral order [10]. An important aspect is the combination of such applications with the intensely studied long-range triplet supercurrents in ferromagnetic Josephson devices (see [2] for a recent overview). And last but not least, non-equilibrium effects are expected to lead to interesting new physics in this field, largely unexplored to date.

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