Spin-triplet supercurrent in Co-based Josephson junctions

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Abstract

In the past year several groups have reported experimental evidence for spin-triplet supercurrents in Josephson junctions containing strong ferromagnetic materials. In this paper we present several new experimental results that follow up on our previous work. We study Josephson junctions of the form S/X/N/SAF/N/X/S, where S is a superconductor (Nb), N is a normal metal, SAF is a synthetic antiferromagnet of the form Co/Ru/Co and X is an ferromagnetic layer necessary to induce spin-triplet correlations in the structure. Our work is distinguished by the fact that the generation of spin-triplet correlations is tuned by the type and thickness of the X layers. The most important new result reported here is the discovery that a conventional, strong ferromagnetic material, Ni, performs well as the X layer, if it is sufficiently thin. This discovery rules out our earlier hypothesis that out-of-plane magnetocrystalline anisotropy is an important attribute of the X layers. These results suggest that the spin-triplet correlations are most likely induced by noncollinear magnetization between the X layers and adjacent Co layers.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The superconducting proximity effect in superconductor(S)/normal(N) systems has been studied since the 1960s [1]. Pair correlations penetrate into the N metal over a distance scale called the ‘normal metal coherence length’, equal to $\xi_N = (\hbar D_N/2\pi k_B T)^{1/2}$ in the diffusive limit, where $D_N$ is the diffusion constant of the N metal and $T$ is the temperature. In diffusive S/N/S Josephson junctions, the supercurrent decays on the same length scale. If the normal metal is replaced by a ferromagnetic material (F), the physics is quite different. When a conventional spin-singlet Cooper pair crosses the interface from S to F, the two electrons enter different spin bands in F and the pair wavefunction acquires a center-of-mass momentum [2]. The pair correlations oscillate in sign and decay over a distance scale called the ‘ferromagnetic coherence length’, equal to $\xi_F = (\hbar D_F/E_{ex})^{1/2}$ in the diffusive limit, where $D_F$ and $E_{ex}$ are the diffusion constant and exchange energy in F, respectively [3]. Because exchange energies in ferromagnetic materials can be comparable to an electronvolt, $\xi_F$ is typically of the order of one to a few nanometers. The physics of the spin-singlet proximity effect in S/F bilayers and S/F/S Josephson junctions is now well understood, with many theoretical predictions confirmed by experiments [4]. The oscillations in the pair correlations lead to alternating 0- and $\pi$-junctions in S/F/S devices, which have been observed by several groups using both strong and weak F materials [5–11].

A new frontier in S/F physics was opened several years ago with the prediction that spin-triplet correlations could be induced in S/F systems in the presence of certain kinds of magnetic inhomogeneity encompassing noncollinear magnetizations [12–15]. Spin-triplet pairs are not subject to the exchange energy when they enter F, hence they propagate as far in F as they would in a nonmagnetic metal N. Until very recently, however, convincing experimental evidence for spin-triplet correlations has been hard to come by. A few experiments reported a decade ago appeared to show a long-

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1 To be precise, only the spin-triplet components with $m_s = \pm 1$ are long range in F, where $m_s$ is the projection of the spin onto the axis of magnetization. The $m_s = 0$ triplet component, which is always generated in S/F systems even without noncollinear magnetization, is short range in F. In this paper we always mean the $m_s = \pm 1$ components when we use the term, ‘spin-triplet’. 
range proximity effect in mesoscopic F wires connected to S electrodes [16–18], but there were not sufficient control experiments to rule out alternative explanations. Then in 2006, Keizer et al [19] reported observation of a supercurrent through half-metallic CrO$_2$, which they attributed to spin-triplet correlations. At about the same time, Sosnin et al [20] reported a phase-sensitive resistance modulation of a 300 nm long mesoscopic Ho wire connected to two S electrodes, and suggested that the underlying long-range phase coherence must be due to spin-triplet correlations. These two experiments were tantalizing, but there was no attempt to control the amplitude of the spin-triplet correlations in either one. Several major breakthroughs were published in 2010. Our group reported the observation of a long-range supercurrent in S/F/S Josephson junctions containing Co—a very strong F material—when additional weakly ferromagnetic X layers were placed between the central Co and the outer S electrodes [21]. The amplitude of the supercurrent varied systematically with the thickness $d_X$ of the X layers, starting very small, increasing to a maximum for $d_X$ of a few nanometers, then falling again for larger $d_X$. A few months later, Robinson et al [22] reported qualitatively similar behavior in S/F/S devices of a similar construction, but with Ho as the X material. In their devices, the amplitude of the supercurrent rose and fell twice with increasing Ho thickness, apparently in relation to the number of periods of the spiral magnetization of the Ho in the device. Possible evidence for spin-triplet supercurrent was reported by Sprungmann et al [23] in S/F/S junctions containing the Heusler alloy, Cu$_2$MnAl, as the F material. Also Anwar et al [24] reported a new study of S/F/S junctions with CrO$_2$, following up on the earlier work of Keizer et al [19]. Perhaps the biggest surprise was the discovery by Wang et al [25] of a Josephson current in single-crystal Co nanowires as long as 600 nm. Those authors did not intentionally introduce noncollinear magnetization into their samples, but suggested that it appeared accidentally as a result of the process of fabricating electrical contacts to the Co nanowires.

In this paper we present several experiments that follow up on our previous work [21]. First, we present data over an extended range of thicknesses of our ferromagnetic layers, which allows us to estimate the spin-triplet decay length. Unfortunately, the quality of the data deteriorates as the junctions are made thicker, so the estimate presented here should be viewed as a lower bound on the triplet decay length. Second, we present data on devices where we have used the conventional strong ferromagnetic material, Ni, as the X layer. These data help resolve a debate in our earlier paper regarding the origin of the noncollinear magnetization essential for triplet generation. Finally, we present the temperature dependence of the supercurrent, which shows that our samples are in the short-junction limit rather than the long-junction limit. Those data suggest that much thicker junctions will be required to measure the true triplet decay length in these samples.

2. Sample design and fabrication

A schematic of our sample design is shown in figure 1. The current flows in the vertical direction, perpendicular to the layer planes. The core of each sample is the Co/Ru/Co trilayer, which forms a synthetic antiferromagnet (SAF) due to antiferromagnetic exchange coupling of the two Co layers by the 0.6 nm thick Ru layer. The purpose of using an SAF rather than just a single F layer is to cancel the magnetic flux produced by the Co domain structure inside the junction. Samples containing only a single Co layer instead of the SAF exhibit random and complex ‘Fraunhofer patterns’ when the critical current is measured as a function of a magnetic field applied perpendicular to the current direction. Samples containing the SAF, in contrast, exhibit nearly perfect Fraunhofer patterns, indicating that the supercurrent density is uniform across the area of the junction. The maximum value of the critical current is then easily extracted from the central peak in the Fraunhofer pattern. This issue is discussed more in [26].

The layers labeled X in the figure are crucial for generation of the spin-triplet supercurrent. Samples without X layers were studied in [26] and showed no evidence of spin-triplet supercurrent. Instead, the critical current decayed exponentially with total Co thickness, with a very short decay length of 2.3 ± 0.1 nm. In contrast, samples with X = Pd$_{0.88}$Ni$_{0.12}$ or Cu$_{0.48}$Ni$_{0.52}$ weakly ferromagnetic alloys exhibited a much larger supercurrent, which did not appear to decay over Co thicknesses in the range of 12–30 nm [21]. This long-range behavior of the supercurrent provides convincing evidence for its spin-triplet nature. For a fixed total Co thickness of 20 nm, we studied the dependence of the supercurrent on the X layer thickness, $d_X$, and found that it reached a maximum for $d_X$ in the range of 3–6 nm for X = PdNi alloy, and 2–4 nm for X = CuNi alloy. The 10 nm Cu layers separating the X layers from the central Co layers are essential to magnetically decouple the X layers from the Co layers. Samples without these Cu spacers exhibit no more supercurrent than samples with the X layers omitted entirely. The 5 nm outer Cu spacers are probably not necessary; we have included them in all our samples since an earlier study in which we found that Co layers grow better on Cu than directly on Nb [26]. We have not studied systematically whether these outer Cu spacers are necessary in the samples discussed here.
The data presented here were obtained from the 10 and 20 fabrication steps are carried out inside a clean room. Most of contamination by dust particles, even though many of the largest pillars rarely provide useful data, possibly due to photoresist is lifted off in acetone. A short ion mill is used to barrier is deposited immediately after ion milling, and then the two pillars of 10 μm diameter, two of 20 μm diameter and a few from the 40 μm diameter. We have found that the spin-singlet supercurrent exists. The latter number may characterize the decay of the spin-triplet supercurrent, and is indeed much longer than the spin-singlet decay length. If one supposes that 16.5 nm is equal to the normal metal coherence length for Co, the spin-triplet supercurrent and, then one obtains a diffusion constant of sample-to-sample variations, due mostly to variations in the magnetic domain structure. A single pillar may give a different value of Ic on different cooldowns.) For the datasets with X layers, there appears to be a peak in IcRn in the vicinity of DCo = 24–30 nm. We do not understand the origin of this peak; we attributed it to sample-to-sample variation in our previous paper before we had data showing a similar peak occurring with X = CuNi. While the data for X = CuNi are not extensive enough to allow us to extract a decay length, we can fit the data for X = PdNi to the sum of two decaying exponentials. We obtain decay lengths of 2.4 ± 0.7 nm for the fast decay and 16.5 ± 2.2 nm for the slow decay. The former value agrees well with the decay length of the critical current in the samples with no X layer (2.3 ± 0.1 nm), where only a spin-singlet supercurrent exists. The latter number may characterize the decay of the spin-triplet supercurrent, and is indeed much longer than the spin-singlet decay length. If one supposes that 16.5 nm is equal to the normal metal coherence length for Co, the spin-triplet supercurrent and, then one obtains a diffusion constant of 9.4 × 10⁻⁴ m² s⁻¹. That value lies between our previous rough estimates of the majority and minority band diffusion constants for Co,² so the above supposition could be correct. We will see later in this paper, however, that the temperature dependence of Ic is not consistent with this supposition. Our own interpretation of the data with X = PdNi is that the data for the thicker samples represent an underestimate of the true critical current, the entire multilayer up through the thin Au layer is sputtered in one run without breaking vacuum. The sputtering chamber has a base pressure of about 10⁻⁸ mbar, and up to six sputtering guns can run simultaneously. A computer-controlled stepper motor moves the substrates over the different guns, so the time elapsed between sputtering of subsequent layers is typically less than one second. After sputtering, the multilayer is patterned into six pillars of different diameters using photolithography and Ar ion milling. An SiO₂ insulating barrier is deposited immediately after ion milling, and then the photoresist is lifted off in acetone. A short ion mill is used to clean off any resist residue remaining on the Au and finally the six top Nb contacts are sputtered through a mechanical mask. The thin Au layer is superconducting due to the proximity effect from the surrounding Nb layers. Each substrate contains two pillars of 10 μm diameter, two of 20 μm diameter and one each of 40 and 80 μm diameter. We have found that the largest pillars rarely provide useful data, possibly due to contamination by dust particles, even though many of the fabrication steps are carried out inside a clean room. Most of the data presented here were obtained from the 10 and 20 μm pillars, and a few from the 40 μm pillars.

3. New experimental results
3.1. Decay length of spin-triplet supercurrent
As stated in section 1, the spin-triplet supercurrent is expected to decay in the central Co layers on the relatively long length scale ξN rather than the very short length scale ξp characterizing spin-singlet pairs. In fact, the decay length may be shorter than ξN due to spin-flip or spin–orbit scattering. The spin memory length in our sputtered Co films is believed to be greater than 40 nm [27]. ξN is not easy to determine a priori, because the diffusion constants of the majority and minority bands are quite different in a strong ferromagnet such as Co. For these reasons as well as for its intrinsic experimental interest, we wish to determine the decay length of the spin-triplet supercurrent in our samples.

In our previous work [21], we fabricated and measured samples with total Co thickness, DCo = 2dCo, ranging from 4 to 28 nm, with X = PdNi and a fixed X layer thickness of 4 nm. The enhancement of the critical current relative to that in samples not containing X layers became quite apparent for DCo ≥ 12 nm. Over the range DCo = 12–28 nm, however, the critical current did not appear to decay at all, but even appeared to increase slightly in the thicker samples. To determine the decay length of the triplet supercurrent, we have fabricated and measured samples with thicker Co layers. In figure 2 we present critical current data measured at T = 4.2 K for samples with X = PdNi, covering an extended Co thickness range up to DCo = 50 nm. The figure also shows new data for samples with X = CuNi covering the Co thickness range DCo = 12–38 nm, as well as our older data on samples containing no X layer for comparison. We plot the quantity IcRn, the product of critical current times normal-state resistance, which is normally independent of the pillar area. Each data point in the figure represents a single Josephson junction pillar. The scatter in the data provides an estimate of sample-to-sample variations, due mostly to variations in the magnetic domain structure. (A single pillar may give a different value of Ic on different cooldowns.) For the datasets with X layers, there appears to be a peak in IcRn in the vicinity of DCo = 24–30 nm. We do not understand the origin of this peak; we attributed it to sample-to-sample variation in our previous paper before we had data showing a similar peak occurring with X = CuNi. While the data for X = CuNi are not extensive enough to allow us to extract a decay length, we can fit the data for X = PdNi to the sum of two decaying exponentials. We obtain decay lengths of 2.4 ± 0.7 nm for the fast decay and 16.5 ± 2.2 nm for the slow decay. The former value agrees well with the decay length of the critical current in the samples with no X layer (2.3 ± 0.1 nm), where only a spin-singlet supercurrent exists. The latter number may characterize the decay of the spin-triplet supercurrent, and is indeed much longer than the spin-singlet decay length. If one supposes that 16.5 nm is equal to the normal metal coherence length for Co, the spin-triplet supercurrent and, then one obtains a diffusion constant of DCo = 9.4 × 10⁻⁴ m² s⁻¹. That value lies between our previous rough estimates of the majority and minority band diffusion constants for Co,² so the above supposition could be correct. We will see later in this paper, however, that the temperature dependence of Ic is not consistent with this supposition. Our own interpretation of the data with X = PdNi is that the data for the thicker samples represent an underestimate of the true critical current, due to the proximity effect from the surrounding Nb layers. Each substrate contains two pillars of 10 μm diameter, two of 20 μm diameter and one each of 40 and 80 μm diameter. We have found that the largest pillars rarely provide useful data, possibly due to contamination by dust particles, even though many of the fabrication steps are carried out inside a clean room. Most of the data presented here were obtained from the 10 and 20 μm pillars, and a few from the 40 μm pillars.

![Figure 2](image-url)
Figure 3. Critical current versus magnetic field (Fraunhofer patterns) for Josephson junctions with $X = \text{PdNi}$ and fixed $d_{\text{PdNi}} = 4$ nm, for six different cobalt thicknesses. For panels (a)–(f), the values of $D_{\text{Co}}$ are respectively 4, 14, 26, 36, 44 and 50 nm, and the pillar diameters are respectively 20, 20, 10, 20, 10 and 10 $\mu$m. The data shown in panels (a)–(d) are representative of many pillars measured, whereas those shown in panels (e) and (f) are the best Fraunhofer patterns we obtained for pillars made with such thick cobalt. The relatively low quality of the last two patterns suggests that our measured values of $I_c R_N$ for samples with $D_{\text{Co}} > 40$ nm underestimate the value one would obtain if the magnetization in the sample were uniform. Hence the measured decay constant of 16.5 nm should be viewed as a lower bound on the true decay length of the spin-triplet correlations. That interpretation is supported by the representative Fraunhofer patterns shown in figure 3 for several samples with different Co thicknesses. As $D_{\text{Co}}$ exceeds 30 nm, the quality of the Fraunhofer patterns deteriorates, probably due to a failure of the central SAF to maintain antiparallel coupling of the Co domains. These non-ideal Fraunhofer patterns are reminiscent of what one obtains in Josephson junctions containing a single multi-domain F layer [30, 31, 26, where the complex domain structure leads to a complex and random-looking Fraunhofer pattern. Such random patterns indicate that the current density is not uniform in the junction, so the maximum critical current one extracts from the pattern is smaller than one would measure in a similar junction without magnetic flux. (Indeed, a comparison of figures 2 and 3 in [26] shows that the maximum critical current density one measures in an S/F/S junction with a complex domain structure is much smaller than in an S/SAF/S junction with similar total thickness of the ferromagnetic layer.)

3.2. Origin of noncollinear magnetization

An important question raised in our original work was regarding the source of noncollinear magnetization responsible for the generation of spin-triplet correlations. Since samples without X layers exhibit no sign of spin-triplet supercurrent, it is natural to think of the X layers as the ‘triplet generators’, and this is indeed the way we first thought of them. (This is also the impression one gets from the nice account of our work provided by Klapwijk [32].) In this picture, neighboring domains in the X layer have noncollinear magnetization, and Cooper pairs entering the X layer near a domain wall undergo singlet-to-triplet conversion. We suggested that out-of-plane magneto-crystalline anisotropy, known to exist in both PdNi and CuNi alloys [31, 33], might play an important role in enhancing noncollinearity between X layer domains by causing the domain magnetizations to cant slightly out of plane. An alternative picture was provided by Houzet and Buzdin (HB) [34] in a theoretical paper that appeared in 2007—well before our experiments. (See also Eschrig and...
Figure 4. Critical current versus magnetic field (Fraunhofer patterns) for Josephson junctions with $X = \text{Ni}$, for four different nickel thicknesses, with fixed $D_{\text{Co}} = 20$ nm. For panels (a)–(d), the values of $d_{\text{Ni}}$ are respectively 0.5, 1.5, 2.5 and 3.5 nm, and the pillar diameters are respectively 10, 10, 20 and 40 $\mu$m. Not surprisingly, the Fraunhofer patterns get progressively worse as $d_{\text{Ni}}$ increases. What is remarkable is the high quality of the patterns and the very small field shift of the central peak in panels (a) and (b).

Löfwander [35], who considered spin-active interfaces in place of the X layers.) In their picture, all that is needed is that the X layer magnetization be noncollinear with the magnetization of the nearest Co layer; the X layer magnetization itself could even be perfectly homogeneous. Consideration of the length scales in the problem favors the HB hypothesis. The coherence length of Cooper pairs in our sputtered Nb films is $\xi_S \approx 15$ nm, while the singlet Cooper pair decay length in PdNi is of the order of 8 nm [31]. While the domain structure of our PdNi films is not known, measurements on CuNi alloys suggest a domain size of about 100 nm [33], quite a bit larger than $\xi_S$ for Nb or $\xi_F$ for PdNi. Hence only a small fraction of the Cooper pairs entering F are likely to experience noncollinear magnetization at X layer domain walls. In addition, if spin transport through a domain wall is adiabatic—i.e. if the spin rotates coherently as it traverses a domain wall—then no singlet-to-triplet conversion will take place [36]. In the HB hypothesis, the Cooper pairs need only cross the 10 nm of Cu separating the X layer from the nearest Co layer to experience noncollinear magnetization. Since Cu is nonmagnetic, the Cooper pair decay length is long: using our measured Cu resistivity of 5 $\mu\Omega$ m and the Einstein relation gives $\xi_N = 116$ nm for Cu at $T = 4.2$ K.

To address this question experimentally, we have fabricated and measured samples with Ni as the X layer material. From measurements of magnetization versus magnetic field on separately fabricated Ni/Cu multilayers, we have determined that our sputtered thin Ni films have dominant in-plane shape anisotropy; in addition, we expect the typical domain size to be larger than in the PdNi and CuNi alloys. It is unlikely that the neighboring domains in the Ni layers provide enough noncollinear magnetization at the right length scale to be efficient at converting spin-singlet pairs to spin-triplet pairs. Hence if samples with $X = \text{Ni}$ exhibit sizable spin-triplet supercurrent, that would support the HB picture. A potential concern is that Ni has large magnetization, hence the uncompensated magnetic flux in the two Ni layers may destroy the nice Fraunhofer patterns of our Josephson junctions. (The magnetic flux contributed by the weak alloys, PdNi and CuNi, is so small as to hardly affect the Fraunhofer patterns [31, 37].) A mitigating factor, however, is that large magnetization implies short $\xi_F$, hence only a thin Ni layer should be required to induce singlet-to-triplet conversion; so perhaps the flux problem will not be too severe. To determine if Ni is effective at generating spin-triplet supercurrent, we fabricated and measured a set of Josephson junctions with fixed $D_{\text{Co}} = 20$ nm and varying $d_X$. Figure 4 shows Fraunhofer patterns for Josephson junctions with $X = \text{Ni}$, for several values of $d_{\text{Ni}}$. The patterns are surprisingly good and start to deteriorate substantially only for $d_{\text{Ni}} > 2$ nm. Figure 5 shows $I_c R_N$ versus $d_X$ for the new samples with $X = \text{Ni}$, as well as for our previous samples with $X = \text{PdNi}$ and $X = \text{CuNi}$ for comparison. The figure shows that Ni is even more effective than PdNi at generating spin-triplet supercurrent. With only 1.5 nm of Ni, $I_c R_N$ increases by a factor of 300 relative to samples with no X layer. The fact that $I_c R_N$ reaches its peak at such a small value of $d_{\text{Ni}}$ (compared to the case of PdNi) is consistent with the larger exchange energy and smaller $\xi_F$ in Ni. Taken as a whole, the data presented in figure 5 paint a picture that is fully consistent with the theoretical predictions of HB.
3.3. Temperature dependence of spin-triplet supercurrent

We explained earlier that we do not trust the estimate of the triplet supercurrent decay length obtained from the data in figure 2, because the Fraunhofer patterns deteriorate in quality as \( D_{\text{Co}} \) increases above 30 nm or so. Measuring the temperature dependence of the critical current provides an alternative way to ascertain what length regime the samples are in. For example, it is known that the \( I_c R_N \) product in short Josephson junctions is proportional to the gap \( \Delta \) in the superconducting electrodes, whereas in long junctions it is proportional to the Thouless energy, given by \( E_c = \hbar D_{\text{Co}} / L^2 \) in the diffusive limit, where \( L \) is the thickness of the junction (i.e. the distance between the superconducting electrodes). A junction is defined as ‘short’ or ‘long’ depending on whether \( L \) is shorter or longer than \( \xi_c \), the coherence length in the S electrodes. (Equivalently, it is determined by the relative size of \( \Delta \) and \( E_c \).) It is in the long-junction limit that the supercurrent decays over the length scale \( \xi_N = (\hbar D_{\text{Co}} / 2 \pi k_B T)^{1/2} \) discussed at the beginning of this paper [38]. In this limit, the temperature dependence of \( I_c \) is also governed by \( E_c \), hence a measurement of \( I_c \) versus \( T \) can help us determine if our samples are indeed in this limit.

Figure 6 shows \( I_c R_N \) versus \( T \), normalized to its value at the lowest temperature measured, for two samples that exhibit strong spin-triplet supercurrent—one with \( D_{\text{Co}} = 26 \) nm and the other with \( D_{\text{Co}} = 50 \) nm. (In the thicker sample, the critical current was too small to measure at temperatures above about 7 K.) The temperature dependence of \( I_c R_N \) in these two samples is nearly identical. If the samples were in the long-junction limit, we would expect to see \( I_c R_N \) decay on a temperature scale given by \( E_c \), which should differ by nearly a factor of four between these two samples. Clearly, these samples are not in the long-junction limit. This observation further supports the conclusion presented earlier that the decay length estimated from the data in figure 2 does not correspond to \( \xi_N \). Instead, we believe that the decay observed in those data is more likely due to problems with the Co/Ru/Co SAF as the Co thickness increases. A reliable estimation of the spin-triplet decay length may require fabrication of samples in a lateral rather than vertical geometry.

Since the temperature dependence of \( I_c \) shown in figure 6 implies that our samples are not in the long-junction limit, it is natural to ask if \( I_c(T) \) obeys short-junction formulae. The answer is no. Kulik and Omelyanchuk derived an expression for the temperature dependence of \( I_c \) valid for diffusive junctions in the short-junction limit (i.e. \( l_c < L < \xi_s \), where \( l_c \) is the electron mean free path) [39]. Their expression predicts that \( I_c \) approaches zero linearly as \( T \) approaches \( T_c \) (see figure 6 in [40]). In contrast, our data (shown on a linear scale in the inset to figure 6) approach zero in a strongly curved manner. At this time we do not know of an appropriate theoretical expression to fit our \( I_c(T) \) data.

4. Theoretical analysis

One of the main conclusions to be drawn from this paper is that the spin-triplet pairs are generated by noncollinear magnetizations of the X layers with respect to the nearest Co layer [34, 35]. The theoretical paper by Houzet and Buzdin [34], however, makes several simplifying assumptions, and does not explicitly deal with the SAF in the middle of our samples. Two recent theoretical papers address the physics specific to our sample geometry. The first of these, by Volkov and Efetov [41], solves the Usadel equations, which are valid in the diffusive limit. Since our samples contain Co and sometimes Ni, both of which are strong ferromagnets with \( \xi_F < l_c \), diffusive limit calculations are, strictly speaking, not applicable. Nevertheless, one expects the conclusions of [41] to be qualitatively applicable to our samples. A second
theoretical paper, by Trifunovic and Radovic [42], solves the Eilenberger equations, which are valid in the clean and moderately diffusive limits. The conclusions in [42] are indeed qualitatively similar to those in [41]. We mention that many theoretical papers relating to spin-triplet correlations in S/F systems have been published. We do not attempt to summarize them here, but refer the interested reader to [41].

5. Conclusions

In this paper we have presented new data regarding spin-triplet supercurrents in Josephson junctions of the form S/X/N/S/SAF/N/X/S. First, we have extended the thickness range of the Co layers forming the central SAF. From those data we extract a triplet decay length of 16.5 nm, which we argue is a lower bound on the true triplet decay length. Second, we show that Ni works well as the X layer as long as the Ni layers are thin enough not to disrupt the Fraunhofer patterns of the Josephson junctions. Since Ni has in-plane magnetization and probably much larger domains than PdNi or CuNi, the success of Ni as the X layer supports the picture [34, 35] where conversion of spin-singlet pairs to spin-triplet pairs occurs due to noncollinear magnetizations of an X layer and the closest Co layer. Finally, we present data showing the temperature dependence of $I_c$. The similarity of such data for junctions with very different Co thicknesses implies that our junctions are in the short-junction limit; hence we cannot expect to be able to extract the triplet-spin triplet decay length from these samples.

There are several obvious directions for future experiments. We are currently trying to make samples with a lateral geometry, with the current flowing in the plane of the substrate. Such samples will be in the long-junction limit, hence we should be able to measure the triplet decay length accurately. We are also planning to magnetize some of our samples to see how the magnetic configuration of the X layers influences the amplitude of the spin-triplet supercurrent. Finally, we are exploring other methods of probing spin-triplet correlations in S/F systems, for example by tunneling experiments [43, 44].

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