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# Heat transport and electron cooling in ballistic normal-metal/spin-filter/superconductor junctions

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ABSTRACT

We investigate electron cooling based on a clean normal-metal/spin-filter/superconductor junction. Due to the suppression of the Andreev reflection by the spin-filter effect, the cooling power of the system is found to be extremely higher than that for conventional normal-metal/nonmagnetic-insulator/superconductor coolers. Therefore we can extract large amount of heat from normal metals. Our results strongly indicate the practical usefulness of the spin-filter effect for cooling detectors, sensors, and quantum bits.



## 1. Introduction

The quasiparticle transport across a normal-metal/insulator/superconductor (N/I/S) junction is governed by single and Andreev processes. When the energy $E$ of quasiparticles is larger than the superconducting gap $\Delta$, single quasiparticles can tunnel through the barrier I. This selective tunneling of "hot" quasiparticles gives rise to electron cooling of the normal metal in an N/I/S junction [1–3]. Experimentally, the cooling of a normal metal from 300 mK down to below 100 mK has been demonstrated [1,4].

On the other hand, an energy $E$ below the gap ($E < \Delta$), as a result of the Andreev reflection, two quasiparticles can tunnel into S from N and form a Cooper pair in the S electrodes. A limitation of the performance of N/I/S coolers results from such two-particle Andreev processes. The Andreev current does not transfer heat through the N/I/S interface but rather generates the so-called Andreev Joule heating [5–7]. At low temperature regimes, the Andreev Joule heating exceeds the single-particle cooling.

A simple way to enhance the cooling power is to reduce the N/I/S junction transparency. However, small barrier transparency hinders "hot" single-quasiparticle transport and leads to a serious limitation in the achievable cooling powers. In order to increase the barrier transparency and to reduce the Andreev Joule heating, it was suggested to use ferromagnetic metals (FM) as an interlayer [8–10]. Giazotto and co-workers have investigated the cooling of a clean N/FM/S junction theoretically and found the enhancement of the cooling power compared to conventional N/I/S junctions due to the suppression of the Andreev Joule heating [8]. However in order to realize such an efficient cooler, impractical FMs with extremely-high spin-polarization $P > 0.94$ like half metals [11] are needed.

Recently, influences of the spin-filter effect in ferromagnetic-semiconductors [12–14] on the proximity effect [15–21], the Josephson effect [22–32], and macroscopic quantum phenomena [33–36] have been investigated theoretically. Moreover, superconducting tunnel junctions with spin-filters have also been realized experimentally [37–40]. In this work we propose an novel electron-cooler based on clean N/spin-filter/S junctions [see Fig. 1(a)] and show that the cooling power is drastically enhanced due to the suppression of the Andreev reflection by the spin-filter effect as described in Fig. 1(b). Preliminary result of this work has been reported in [41]. In this paper we will discuss about the theoretical derivation of the cooling power in more detail.

## 2. Theory

Let us first consider an one-dimensional ballistic N/SF/F junction as shown in Fig. 1(a). The spin-filtering barrier at $x = 0$ can be

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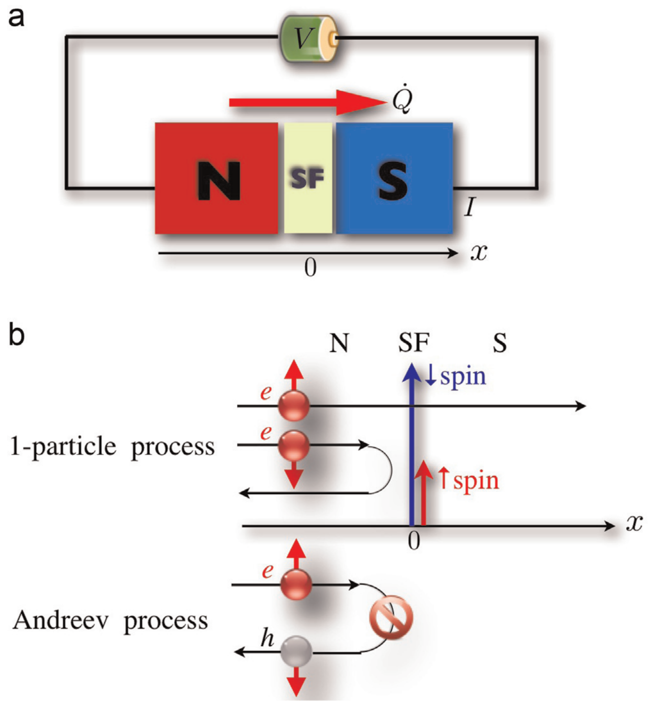


**Fig. 1.** (a) Schematic diagram of a normal-metal/spin-filter/superconductor (N/SF/S) cooler and (b) the delta-function model of a SF barrier. In the SF interface ($x=0$), the transmission probability of electrons or holes for one spin-channel is much larger than the other one. This allows the suppression of the Andreev reflection at the SF interface.

described by a spin-dependent delta-function potential [see Fig. 1 (b)], i.e.

$$V_\sigma(x) = (V + \rho_\sigma U)\delta(x), \tag{1}$$

where $V$ is a spin-independent part of the potential, $U$ is the exchange-splitting, and $\rho_\sigma = +(-)1$ for up (down) spins [22,42].

The spin-filtering property of the barrier is qualitatively characterized by the spin-filtering efficiency

$$P = \frac{|t_\uparrow - t_\downarrow|}{t_\uparrow + t_\downarrow}, \tag{2}$$

where

$$t_\sigma = \frac{1}{1 + (Z + \rho_\sigma S)^2}, \tag{3}$$

is the transmission probability of the spin-filtering barrier for spin $\sigma$ with $m$ and $k_F$ being the mass of electrons and the Fermi wave number. The normalized spin-independent and -dependent potential barrier-height are given by

$$Z \equiv \frac{mV}{\hbar^2 k_F}, \tag{4}$$

$$S \equiv \frac{mU}{\hbar^2 k_F}. \tag{5}$$

For a perfect spin-filter with $t_\uparrow > 0$ and $t_\downarrow = 0$, we get $P=1$. On the other hand, we have $P=0$ for the conventional non-magnetic barrier with $U=0$ ($t_\uparrow = t_\downarrow$).

The system can be described by the Bogoliubov–de Gennes (BdG) equation [22]

$$\begin{bmatrix} H_0 - \rho_\sigma U\delta(x) & \Delta(x) \\ \Delta^*(x) & -H_0 + \rho_\sigma U(x)\delta(x) \end{bmatrix} \Phi_\sigma(x) = E\Phi_\sigma(x), \tag{6}$$

where $H_0$ is the spin-independent part of the single-particle Hamiltonian, i.e.

$$H_0 = -\frac{\hbar^2\nabla^2}{2m} + V\delta(x) - \mu_F, \tag{7}$$

($\mu_F$ is the chemical potential),

$$\Delta(x) = \Delta(T)e^{i\phi}\Theta(x) \tag{8}$$

is a pair potential [$\phi$ is the phase of the pair potential and $\Theta(x)$ is the Heaviside step function],

$$\Phi_\uparrow(x) = \begin{bmatrix} u_\uparrow(x) \\ v_\downarrow(x) \end{bmatrix}, \tag{9}$$

$$\Phi_\downarrow(x) = \begin{bmatrix} u_\downarrow(x) \\ v_\uparrow(x) \end{bmatrix} \tag{10}$$

are the eigenvectors, and the eigenenergy $E$ is measured from $\mu_F$.

The wave function in $N$ ($x < 0$) and S ($x > 0$) is given by

$$\Psi_\sigma^N(x) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{ik^+x} + \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{-ik^+x} r_\sigma^{ee} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{ik^-x} r_\sigma^{he}, \tag{11}$$

$$\Psi_\sigma^S(x) = \begin{pmatrix} u_0 \\ v_0 e^{-i\phi} \end{pmatrix} e^{iq^+x} t_\sigma^{ee} + \begin{pmatrix} v_0 e^{i\phi} \\ u_0 \end{pmatrix} e^{-iq^-x} t_\sigma^{he}, \tag{12}$$

where

$$u_0 = \sqrt{\frac{1}{2}\left(1 + \frac{\Omega}{E}\right)}, \tag{13}$$

$$v_0 = \sqrt{\frac{1}{2}\left(1 - \frac{\Omega}{E}\right)}, \tag{14}$$

$$k^\pm = k_F\sqrt{1 \pm \frac{E}{\mu_F}}, \tag{15}$$

$$q^\pm = k_F\sqrt{1 \pm \frac{\Omega}{\mu_F}}, \tag{16}$$

with

$$\Omega = i\sqrt{\Delta(T)^2 - E^2}. \tag{17}$$

The normal reflection coefficient $r_\sigma^{ee}$ and the Andreev reflection coefficient $r_\sigma^{he}$ can be obtained by solving the BdG equation with two boundary conditions at the spin-filtering barrier ($x=0$)

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