9-24-2013

Comment on "Unified Formalism of Adreev Reflection at a Ferromagnet/Superconductor Interface"

M. Eschrig
Royal Holloway, University of London, Matthias.Eschrig@rhul.ac.uk

A. A. Golubov
MESA+ Institute of Nanotechnology, University of Twente, A.A.Golubov@utwente.nl

I. I. Mazin
Naval Research Laboratory

B. Nadgorny
Wayne State University, nadgorny@physics.wayne.edu

Y. Tanaka
Nagoya University

See next page for additional authors

Comment on "Unified Formalism of Andreev Reflection at a Ferromagnet/Superconductor Interface"

Recently, a "unified" Andreev reflection (AR) formalism, claimed to be "the most general to date," was suggested [1]. Here, we show that while there are numerous works [2–7] correctly solving the problem formulated in Ref. [1] for arbitrary spin polarization P, Ref. [1] fails to correctly incorporate $P \neq 0$ effects and is incompatible with basic physical laws.

At $P = 0$, the approach [1] is identical to the nonmagnetic 1D Blonder-Tinkham-Klapwijk (BTK) model [8]. For $P \neq 0$, they postulate an AR wave function with an additional evanescent wave at $x < 0$: $\psi_{\mathrm{AR}} = a\{^{0}_{1}\}\exp[(\alpha + i)q^{+}x]$ and $\alpha = 2\sqrt{P/(1-P)}$. This is completely unsubstantiated, and the proposed wave function violates charge conservation [9]: its current density is $j_{\mathrm{AR}}(x) \propto \mathrm{Im}[\psi^{*}_{\mathrm{AR}}\nabla\psi_{\mathrm{AR}}] \propto q^{+}|a|^{2}\exp[2\alpha q^{+}x]$. For any $0 < \alpha < \infty$, i.e., $0 < P < 1$, the divergence of the *total* current is finite for $-1/2\alpha q^{+} \lesssim x$ and the total charge is not conserved, signaling that ψ_{AR} is unphysical. This is such a fundamental error that none of the results that follow can be trusted.

Even for a half-metal (HM, $P = 1$), where this expression correctly gives $j_{\mathrm{AR}} = 0$, it remains false. Reference [1] postulates an infinitesimally small decay length of the AR electron into a HM, while, in fact, it decays with a finite length, depending on the electronic structure, primarily the gap in the nonmetallic spin channel [10].

The rationale for introducing a new ψ_{AR} [1] was that (a) allegedly, the result in Ref. [3] only applies to HM with $\tilde{\psi}_{\mathrm{AR}} = a\{^{0}_{1}\}\exp(\kappa x)$ and a nonmagnetic metal with $\tilde{\psi}_{\mathrm{AR}} = a\{^{0}_{1}\}\exp(ikx)$, while the current for an intermediate P is assumed to be a linear combination of these cases, (b) no prior work had treated the $0 < P < 1$ case, and (c) one can define P for an individual electron. Regarding (a) and (b), the derivation in Ref. [3] and in other works [4–7] is rigorous for any P. Regarding (c), one cannot define a single channel BTK model with an arbitrary P [11]: any given electron in a metal Andreev reflects into either a propagating or evanescent wave. Finite P means that while some current-carrying electrons propagate, others evanesce; one can only define spin polarization in a multielectron system, where the numbers of states at the Fermi surface (FS) (conductivity channels) for the two spin directions differ. If the 2D wave vector $\mathbf{k}_{\parallel}$, parallel to the interface, is conserved [12], then after quantization of $\mathbf{k}_{\parallel}$, the total number of conductivity channels in the x direction for a given spin is proportional to the area of the FS projection on the interface $n = \langle N(E_F)v_{Fx}\rangle_{\mathrm{FS}}$ [3]. After summation over *all* states, the total current *is* a linear combination (with the weights defined by P) of the solutions of the BTK model with $P = 0$ and $P = 1$. This was *derived* in numerous papers (see Ref. [7]).

In contrast to the "universal" P in Ref. [1], independent of electronic mass, k_F's, or any band structure at all, the real transport spin polarization in AR depends on the *overall* FS properties. Moreover, there is no unique spin polarization; it depends on an experimental probe. In fact, the definition used in Ref. [1] (neglecting the velocities) does not correspond to the AR but rather to spin-polarized photoemission [13].

Reference [1] has overlooked the previous works where the posed problem has been correctly solved for an arbitrary P and has replaced this solution with an incorrect formula, postulating an unphysical wave function that does not conserve charge and has an incorrect HM limit. They calculated the current due to ψ_{AR} at $x = 0$, but the actual current is measured far away from the interface (where they would predict zero j_{AR} for any P). They erroneously assumed that the decay length for an electron inside the band gap is uniquely defined by the spin polarization (these two quantities are unrelated). While the formula postulated in Ref. [1] provides a fit for their experimental data, which is essentially identical to using Ref. [3], this does not constitute an argument for the validity of this approach, particularly considering unphysical predictions of this formalism in the finite Z case (kinks at zero bias and notches near the gap; see Fig. 2(c) of Ref. [1]). The inclusion of inelastic scattering by adding broadening, another claimed novelty, was done previously [6,14].

M. Eschrig,[1] A. A. Golubov,[2] I. I. Mazin,[3] B. Nadgorny,[4] Y. Tanaka,[5] O. T. Valls,[6] and Igor Žutić[7]
[1]Department of Physics
Royal Holloway
University of London
Egham, Surrey TW20 0EX
United Kingdom
[2]Faculty of Science and Technology
and MESA+ Institute of Nanotechnology
University of Twente
7500 AE Enschede, Netherlands
[3]Naval Research Laboratory
Washington, D.C., 20375, USA
[4]Department of Physics and Astronomy
Wayne State University
Detroit, Michigan 48201, USA
[5]Department of Applied Physics
Nagoya University
Aichi 464-8603, Japan
[6]School of Physics and Astronomy
University of Minnesota
Minneapolis, Minnesota 55455, USA
[7]Department of Physics
University at Buffalo
SUNY, Buffalo, New York 14260, USA

Received 15 January 2013; published 24 September 2013
DOI: 10.1103/PhysRevLett.111.139703
PACS numbers: 72.25.−b, 74.25.F−, 75.47.−m, 85.75.−d

[1] T. Y. Chen, Z. Tesanovic, and C. L. Chien, Phys. Rev. Lett. **109**, 146602 (2012).
[2] M. J. M. de Jong and C. W. J. Beenakker, Phys. Rev. Lett. **74**, 1657 (1995).

[3] I. I. Mazin, A. A. Golubov, and B. Nadgorny, J. Appl. Phys. **89**, 7576 (2001); G. T. Woods, R. J. Soulen, Jr., I. I. Mazin, B. Nadgorny, M. S. Osofsky, J. Sanders, H. Srikanth, W. F. Egelhoff, and R. Datla, Phys. Rev. B **70**, 054416 (2004).
[4] S. Kashiwaya, Y. Tanaka, N. Yoshida, and M. R. Beasley, Phys. Rev. B **60**, 3572 (1999).
[5] I. Žutić and O. T. Valls, Phys. Rev. B **61**, 1555 (2000) see Eq. (2.8); I. Žutić and S. Das Sarma, Phys. Rev. B **60**, R16322 (1999).
[6] P. Chalsani, S. K. Upadhyay, O. Ozatay, and R. A. Buhrman, Phys. Rev. B **75**, 094417 (2007).
[7] R. Grein, T. Lofwander, G. Metalidis, and M. Eschrig, Phys. Rev. B **81**, 094508 (2010).
[8] G. E. Blonder, M. Tinkham, and T. M. Klapwijk, Phys. Rev. B **25**, 4515 (1982).
[9] The quasiparticle current conservation is also violated.
[10] Earlier works often used the limit of infinitely short decay because the final result hardly depends on this parameter, but it is important to use in the derivation a physically meaningful wave function that allows for a finite decay.
[11] That requires introducing a finite exchange splitting and having different Fermi velocities for the two spins.
[12] This holds for a ballistic flat interface.
[13] I. I. Mazin, Phys. Rev. Lett. **83**, 1427 (1999).
[14] Y. Bugoslavsky, Y. Miyoshi, S. K. Clowes, W. R. Branford, M. Lake, I. Brown, A. D. Caplin, and L. F. Cohen, Phys. Rev. B **71**, 104523 (2005).