Transport characteristics of phase-separated Fe-based superconductor heterostructures

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Introduction

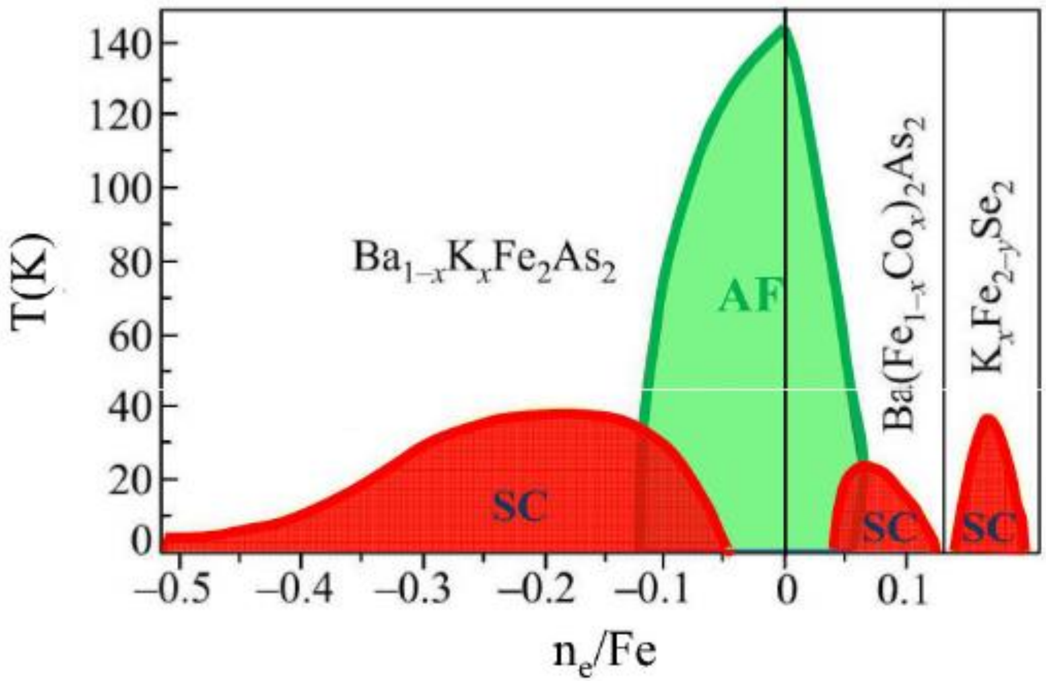
Introduction

Table 1 | Properties of different classes of superconductor

Property	Conventional superconductors	Copper oxides	MgB_2	Iron-based superconductors
T_c (maximum)	<30 K	134 K	39 K	56 K
Correlation effects	None (nearly-free electrons)	Strong local electronic interaction	None (nearly-free electrons)	Long-range (non-local) magnetic correlations
Relationship to magnetism	No magnetism	Parent compounds are magnetic insulators	No magnetism	Parent compounds are magnetic metals
Order parameter	One band, same-sign *s* wave	One band, sign-changing *d* wave	Two band, same-sign *s* wave	Two band, presumably sign-changing *s* wave
Pairing interaction	Electron–phonon	Probably magnetic (no consensus)	Electron–phonon	Presumably magnetic
Dimensionality	Three dimensional	Two dimensional	Three dimensional	Variable

Typical ingredients found in systems with competing interactions are inhomogeneity, anisotropy, disorder and glassiness. Compelling evidence for the presence of nanoscale phase separation between superconductivity and antiferromagnetism in some iron-based superconductors has been observed.

Introduction



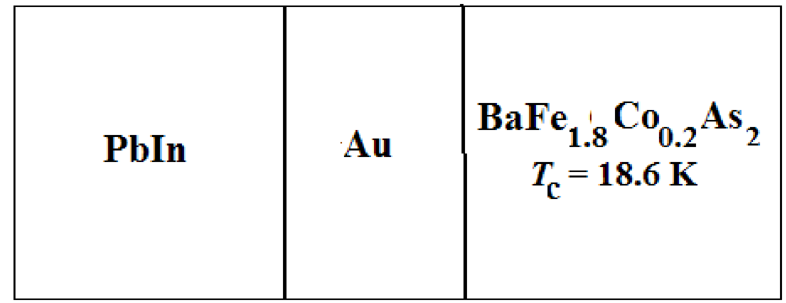
Typical electronic phase diagram for the 122 family of pnictide materials as a function of extra-electrons per Fe atom, both in the case of hole- and electron-doping.

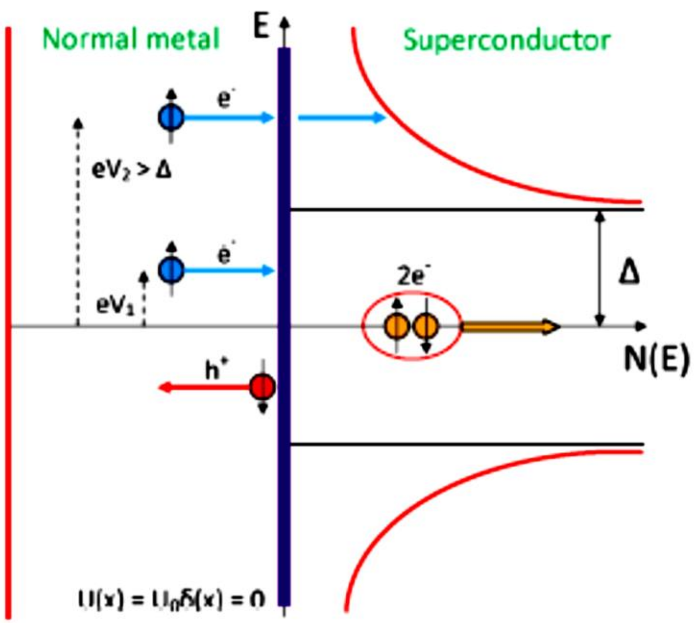
Our results for $SmFeAsO_{1-x}F_x$ (x = 0.15 and x = 0.2) indicate that: the 4*f* electrons of Sm^{3+} ions are coupled to a sea of weakly itinerant and antiferromagnetically interacting fermions.

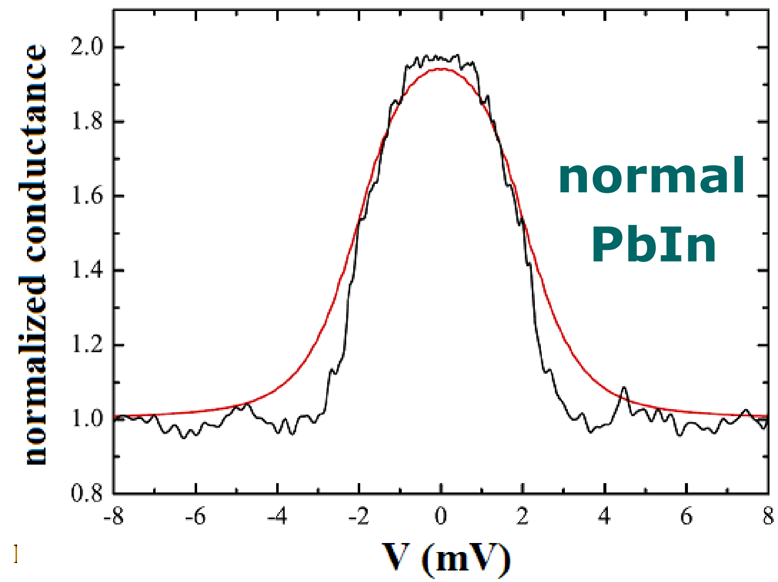
from P. Carretta et al., arXiv: 1307.8283

Striking discrepancy between gap values extracted from point-contact and Josephson data: an experimental observation

Striking discrepancy between gap values extracted from point-contact and Josephson data





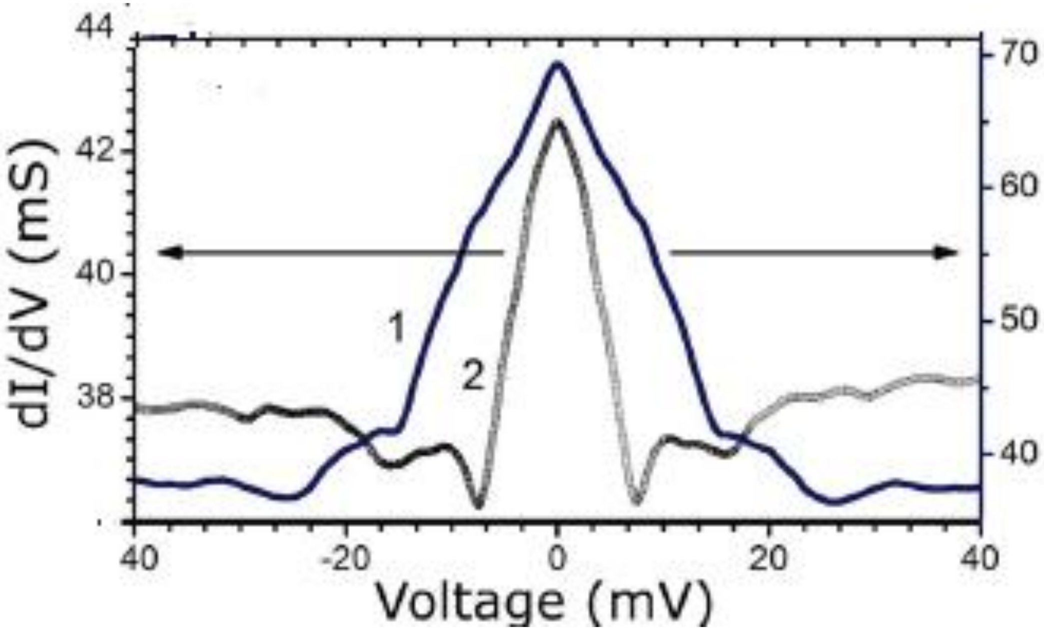


from S. Schmidt et al., Physics Procedia (2012)

Striking discrepancy between gap values extracted from point-contact and Josephson data

Large variation of reported values of energy gaps in Co-doped $BaFe_2As_2$ epitaxial superconducting thin films

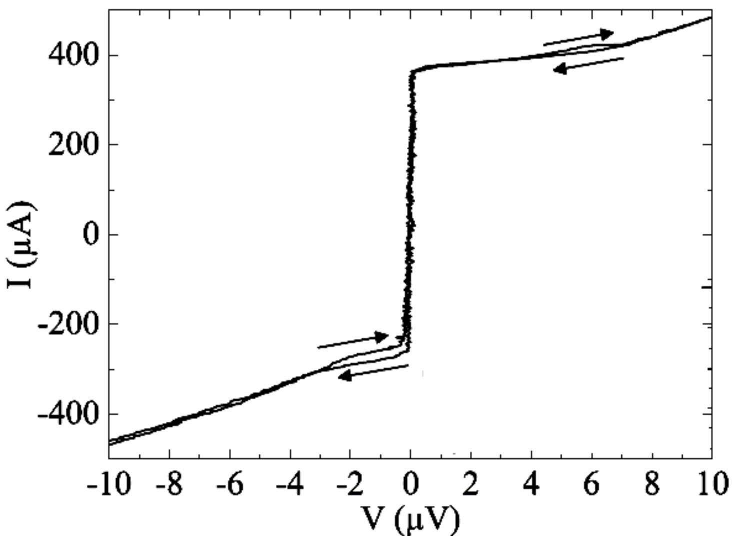
After ion beam etching



from T. Plecenik et al., Applied Physics Letters (2013)

Striking discrepancy between gap values extracted from point-contact and Josephson data

PbIn	Au	$BaFe_{1.8}Co_{0.2}As_2$ $T_c = 18.6$ K



$$I_c R_N \approx 4.2\ \mu\mathrm{V}$$

$$I_c R_N \approx \frac{\pi}{e} \frac{\Delta_L \Delta_R}{\Delta_L + \Delta_R}$$

from S. Schmidt et al., Physics Procedia (2012)

Striking discrepancy between gap values extracted from point-contact and Josephson data

Three kinds of junctions showed similar characteristics with $I_c R_N$ products:

20.2 μV	**-**	**grain-boundary devices**
18.4 μV	**-**	**planar S′NS structures**
12.3 μV	**-**	**edge-type junctions**

from S. Döring et al., IEEE Trans. Appl. Supercond. (2013)

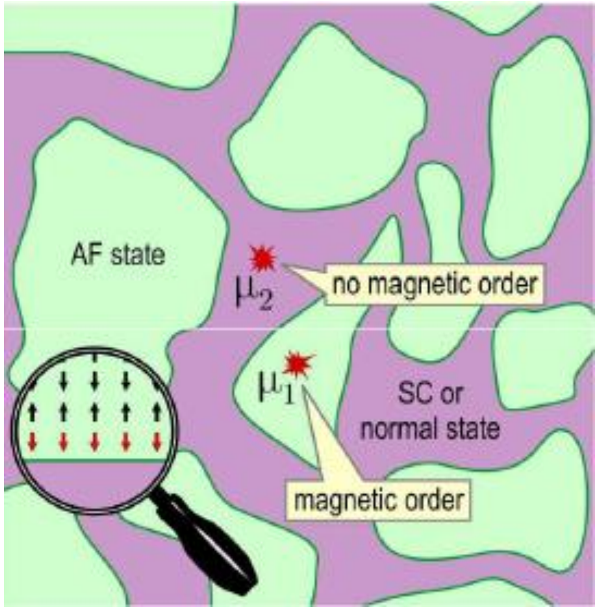
$I_c R_N$ of nearly 90 μV for Ba-122-TiO$_x$-Pb

***from S. Döring et al., arXiv:* 1309.2331**

A “minimal” model able to explain the striking discrepancy between gap values extracted from point-contact and Josephson data

Is the discrepancy an effect of the phase separation into antiferromagnetic and superconducting regions?

Nanoscale phase separation and chemical inhomogeneity were directly observed in $BaFe_2(As_{1-x}P_x)_2$ superconductors [*Hefei Hu, PhD Thesis (2012)*]

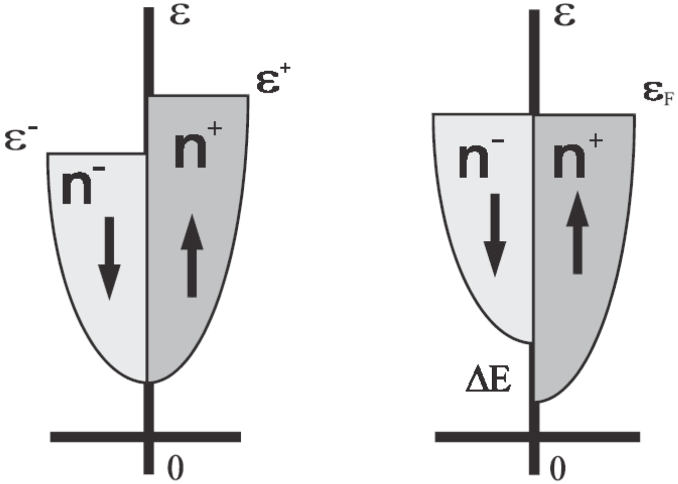


Sketchy representation of the model of phase-separated antiferromagnetic and superconductiing orderings

Two possible scenarios of the metallic antiferromagnet
- the local moment magnetic metal
- spin density wave metal

from P. Carretta et al., arXiv: 1307.8283

Phase separation between antiferromagnetic and superconducting regions



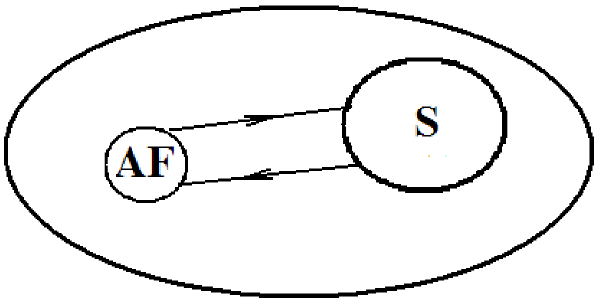
Stoner theory of itinerant electron magnetism

$$\mathbf{H}_{\mathrm{AF}} = \sum_{\mathbf{p},\sigma} \left\{ \left(\gamma_{\mathbf{p}} + \frac{1}{2}\sigma h_s \right) \mathbf{a}^{+}_{\mathbf{p}\sigma}\mathbf{a}_{\mathbf{p}\sigma} + \left(\gamma_{\mathbf{p}} - \frac{1}{2}\sigma h_s \right) \mathbf{b}^{+}_{\mathbf{p}\sigma}\mathbf{b}_{\mathbf{p}\sigma} + t_{\mathbf{p}} \left(\mathbf{a}^{+}_{\mathbf{p}\sigma}\mathbf{b}_{\mathbf{p}\sigma} + \mathbf{b}^{+}_{\mathbf{p}\sigma}\mathbf{a}_{\mathbf{p}\sigma} \right) \right\}$$

T. Moriya, *Spin Fluctuations in Itinerant Electron Magnetism* (Springer-Verlag, Berlin, 1985).

Phase separation between antiferromagnetic and superconducting regions

Generalization of the McMillan proximity-effect tunneling model (1968)



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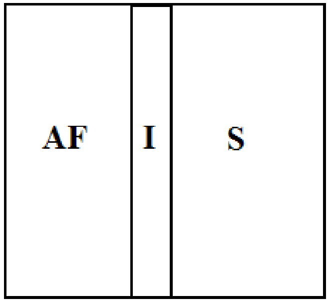


$$\Delta_{\mathrm{S}}(\varepsilon) = \frac{Z_{\mathrm{S}}^{(0)}(\varepsilon)\Delta_{\mathrm{S}}^{(0)}(\varepsilon) + i\sum_{\sigma}\Gamma_{\mathrm{S}}^{\sigma}\dfrac{\Delta_{\mathrm{AF}}^{\sigma}(\varepsilon)}{\sqrt{\varepsilon^2 - \Delta_{\mathrm{AF}}^{\sigma\;2}(\varepsilon)}}}{1 + i\sum_{\sigma}\dfrac{\Gamma_{\mathrm{S}}^{\sigma}}{\sqrt{\varepsilon^2 - \Delta_{\mathrm{AF}}^{\sigma\;2}(\varepsilon)}}}$$

$$\Delta_{\mathrm{AF}}^{\sigma}(\varepsilon) = \frac{i\dfrac{\Gamma_{\mathrm{AF}}^{\sigma}\Delta_{\mathrm{S}}(\varepsilon)}{\sqrt{\varepsilon^2 - \Delta_{\mathrm{S}}^{\;2}(\varepsilon)}}}{1 + i\dfrac{\Gamma_{\mathrm{AF}}^{\sigma}}{\sqrt{\varepsilon^2 - \Delta_{\mathrm{S}}^{\;2}(\varepsilon)}}}$$

$$\Gamma_{\mathrm{S}}^{\sigma} \sim \left\langle \left(T_{\mathbf{kp}}^{\sigma}\right)^2 \right\rangle \Omega_{\mathrm{AF}} N_{\mathrm{AF}}^{\sigma}(0)$$

$$\Gamma_{\mathrm{AF}}^{\sigma} \sim \left\langle \left(T_{\mathbf{kp}}^{\sigma}\right)^2 \right\rangle \Omega_{\mathrm{S}} N_{\mathrm{S}}(0)$$

$$N_{\mathrm{AF}}(\varepsilon) = \sum\nolimits_{\sigma} N_{\mathrm{AF}}^{\sigma}(\varepsilon)$$

Phase separation between antiferromagnetic and superconducting regions

$$I_c R_N = \frac{\pi\Delta_0}{2e}\frac{\tanh(\Delta_0/2k_B T)}{[1\text{-}\left(\mathrm{dRe}\Delta(\omega)d\omega\right)_{\omega=\Delta_0}]} - \frac{1}{e}\int_{\Delta_0}^{\infty} d\Omega \tanh\left(\frac{\Omega}{2k_B T}\right)\mathrm{Im}\left\{\frac{\Delta^2(\Omega)}{\Omega^2-\Delta^2(\Omega)}\right\}$$

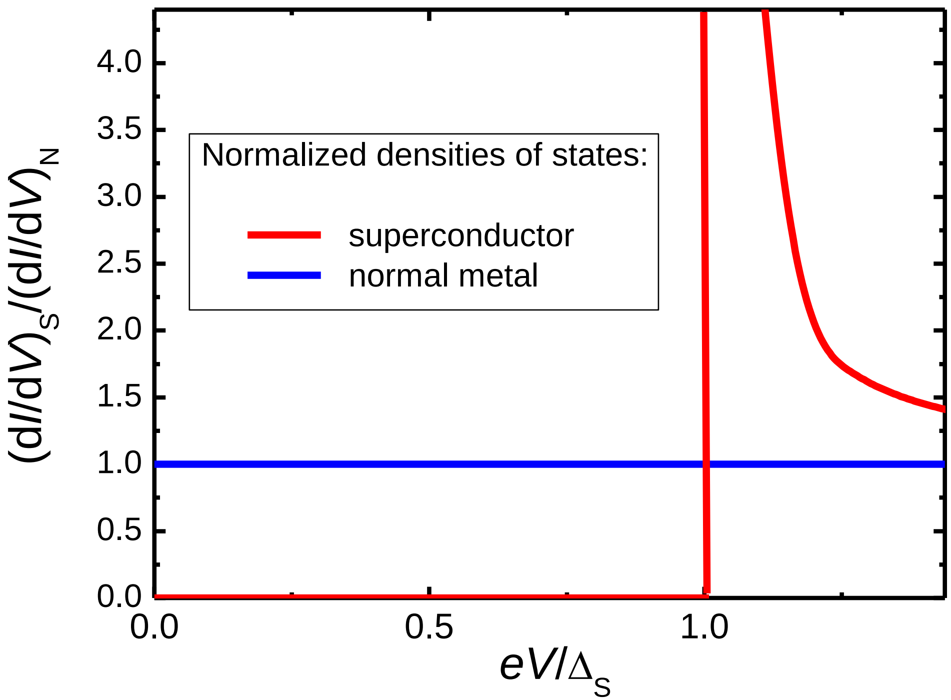
Δ_0 is the minimal value of Ω for which Ω = Re $\Delta(\Omega)$ and Im $\Delta(\Omega)$ = 0

from T.A. Fulton and D.E. McCumber, Phys. Rev. (1968)

$$\frac{dI(V)}{dV}R_N = 1 + \left|\frac{\Delta(eV)}{eV+\sqrt{(eV)^2-\Delta^2(eV)}}\right|^2$$

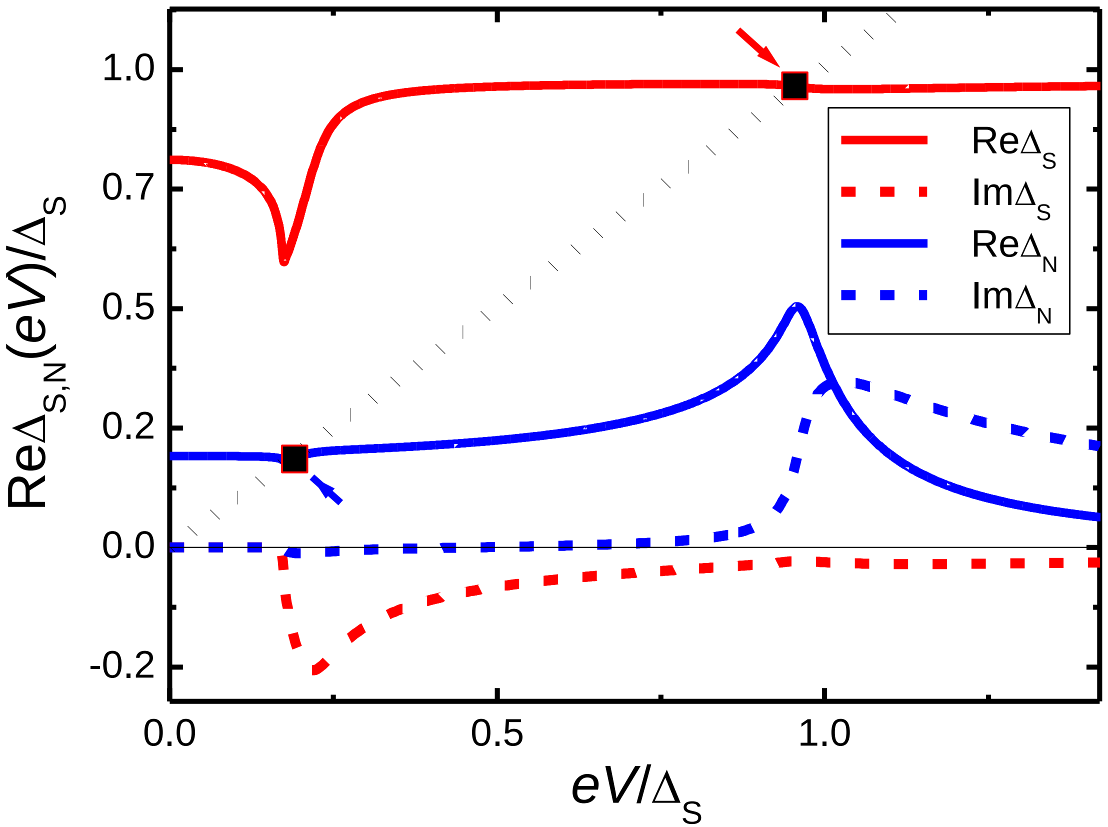
from A.N. Omelyanchuk et al., Fiz. Nizk. Temp. (1988)

Striking difference between gap values extracted from contact and Josephson data



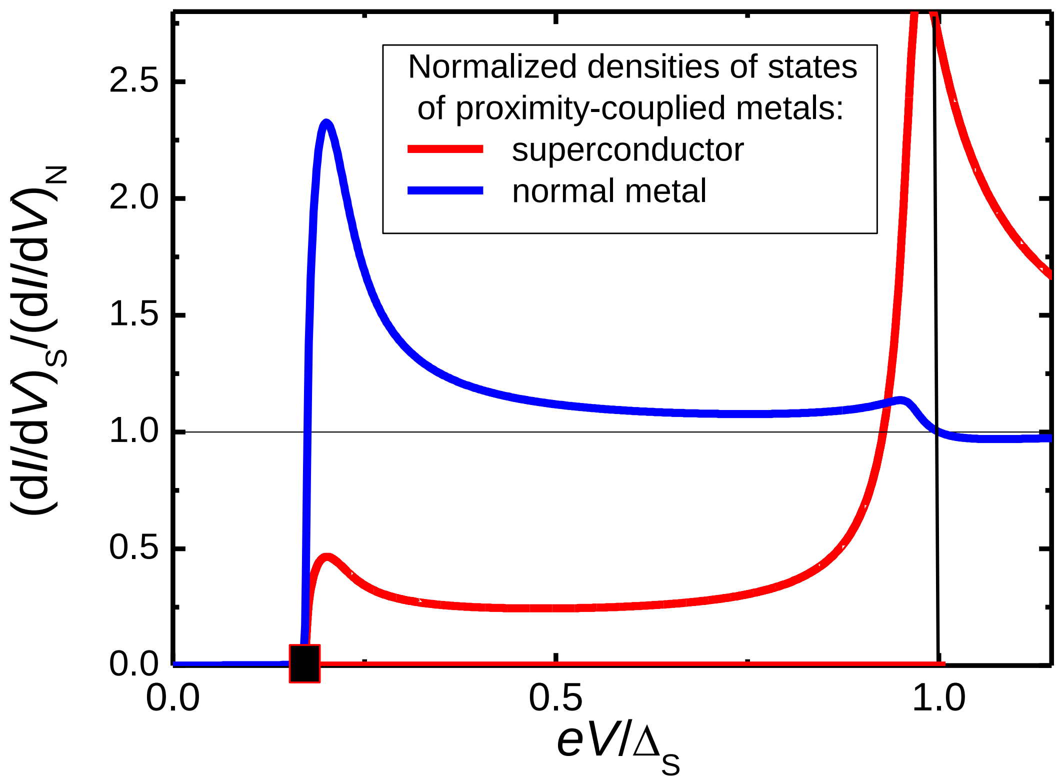
V_S = 0.4 ; V_N = 0

Striking difference between gap values extracted from contact and Josephson data



V_S = 0.4 ; V_N = 0 ; Γ_S/Γ_N = 0.2

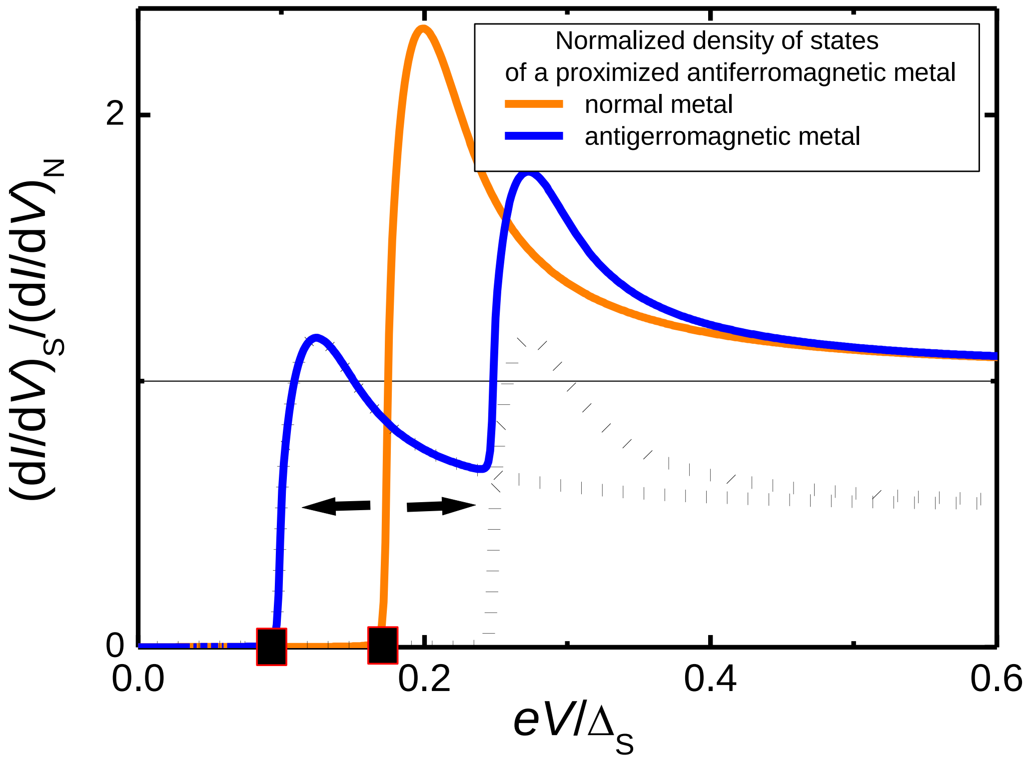
Striking difference between gap values extracted from contact and Josephson data



V_S = 0.4 ; V_N = 0 ; Γ_S/Γ_N = 0.2

Striking difference between gap values extracted from contact and Josephson data

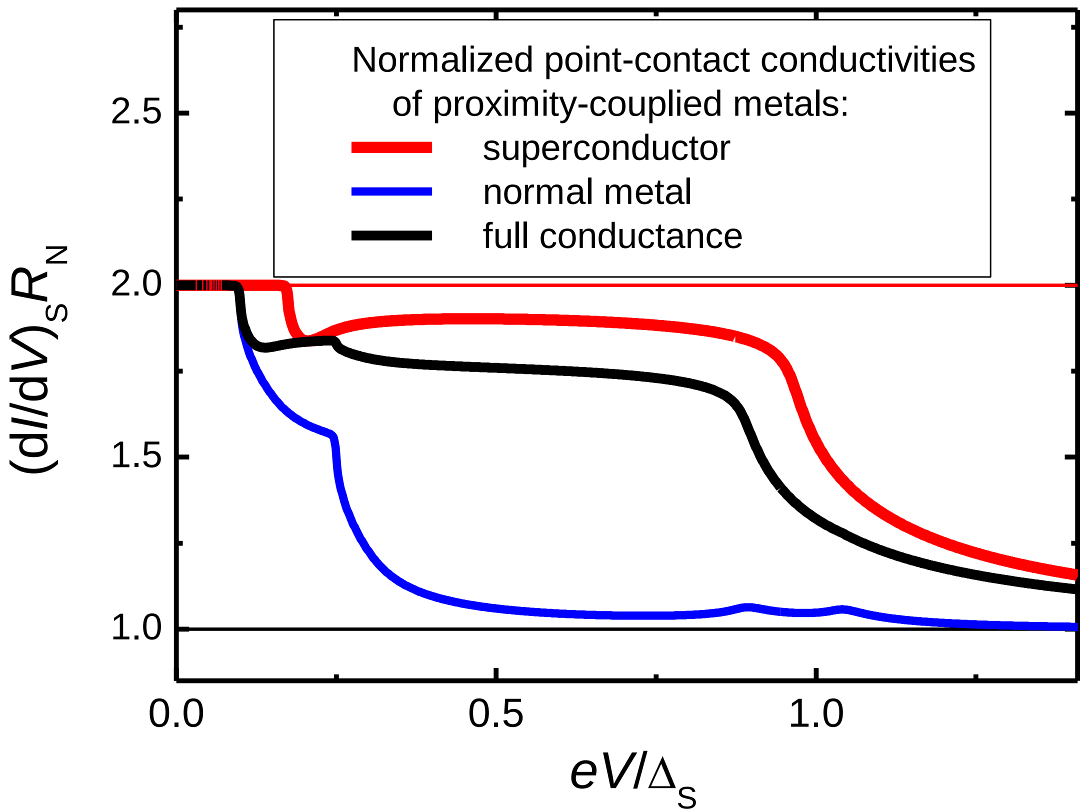
An effect of the spin-splitting field



$V_S = 0.4$; $V_{AF} = 0$; $\Gamma_S/\Gamma_{AF} = 0.2$; $h = 0.075\,\Delta_S$

Striking difference between gap values extracted from contact and Josephson data

Point-contact spectra



$V_S = 0.4$; $V_{AF} = 0$; $\Gamma_S/\Gamma_{AF} = 0.2$; $h = 0.075\ \Delta_S$

Striking difference between gap values extracted from contact and Josephson data

Simulation results:

- the $I_c R_N$ product for Josephson junctions with an AFM-SC bilayer is reduced by an order of magnitude comparing with that for an SC film;

- at the same time the “gap” feature in the normalized conductance is shifted towards lower voltages by -~ 30 percent.

THE END