Josephson coupling through a magnetic dot

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M. Fogelström, PRB **B 62** 11812 (2000)
J. C. Cuevas and M. Fogelström, PRB **B 64** 104502 (2001)
M. Andersson, J. C. Cuevas and M. Fogelström, Physica **C 62** 117 (2002)

Invited Talk given at: First International workshop on the Symmetry in Macroscopic Quantum states - Quantitative Experiments and Theory-, Augsburg, April 21-23, 2002

Outline:

- Experiments on SFS structures
- Modeling SF-structures in quasiclassical theory, energy scales
- Phenomenological boundary conditions for spin-active interfaces
- Impenetrable magnetic surface, Andreev surface states
- Josephson coupling through a magnetic dot
- Multiple Andreev Reflections (MAR) and IV-charactaristics
- conclusions

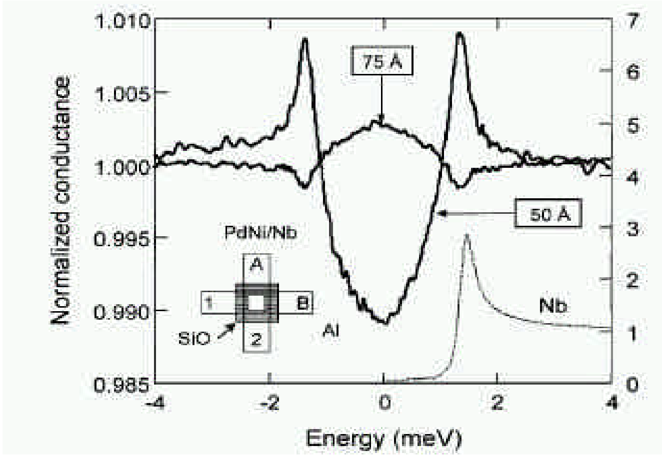
Experiments on S-F structures

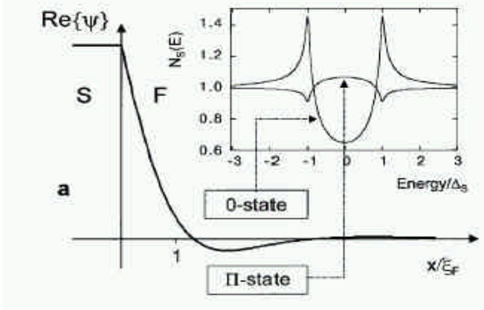
SFN-structures

T.Kontos, *et al*. PRL **86** 304 (2001)

•Damped, oscillating “OP” in a ferromagnetic thin film,

Proximity effect, $\chi_F \propto$ **1-10nm**



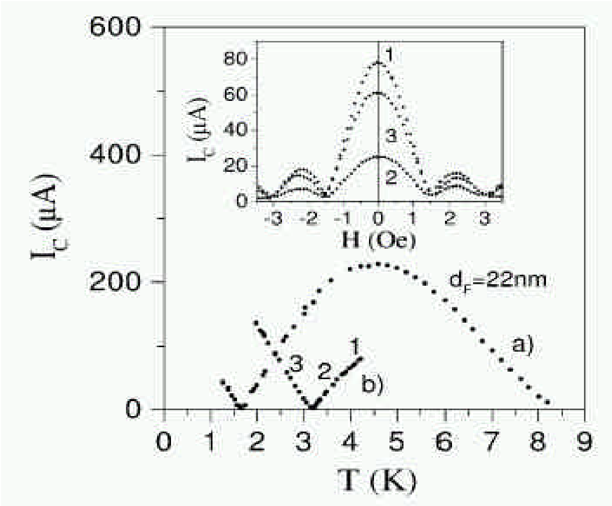


SFS-structures

V. V. Ryazanov, *et al.* PRL **86** 2427 (2001)

•non-zero critical current

•non-monotonous T-dependence of critical current, 0 to π junction switching



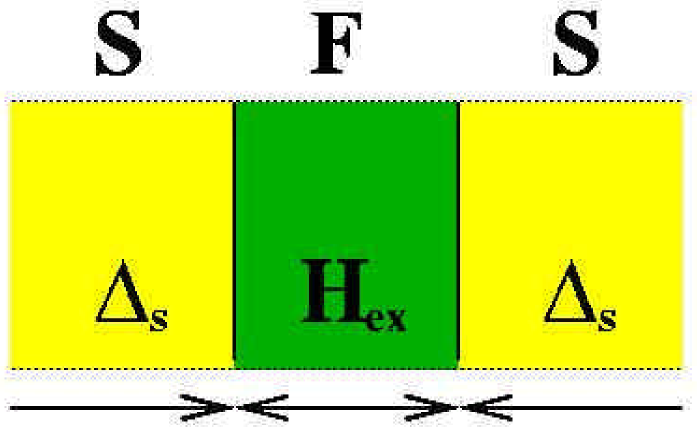
Quasiclassical modeling of SF-structures

General problem in modeling SFS structures is usually the difference in energy scales:

$$\mathrm{D} \ll \mathbf{H_{ex}} \ll \mathbf{E_F}$$

Weak ferromagnet: D ~ $\mathbf{H_{ex}}$

$\Rightarrow$ spatial extension of ferromagnet

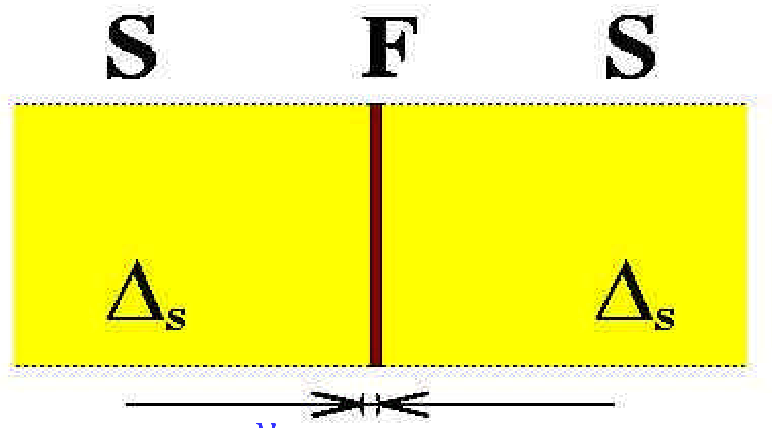


$$x_S = \frac{v_f}{\Delta_S} \approx x_F = \frac{v_f}{\mathrm{H_{ex}}}$$

A. I. Buzdin, *et al*, JETP **35**, 178 (1982)
V. V. Ryazanov, *et al*, PRL **86** 2427 (2001)
M. Zareyan, *et al*, PRL **86** 308, (2001)

Strong ferromagnet: D <<$\mathbf{H_{ex}}$ ~ $\mathbf{E_F}$

$\Rightarrow$ ferromagnet treated as boundary conditions



$$x_S = \frac{v_f}{\Delta_S} >> x_F \approx k_F^{-1}$$

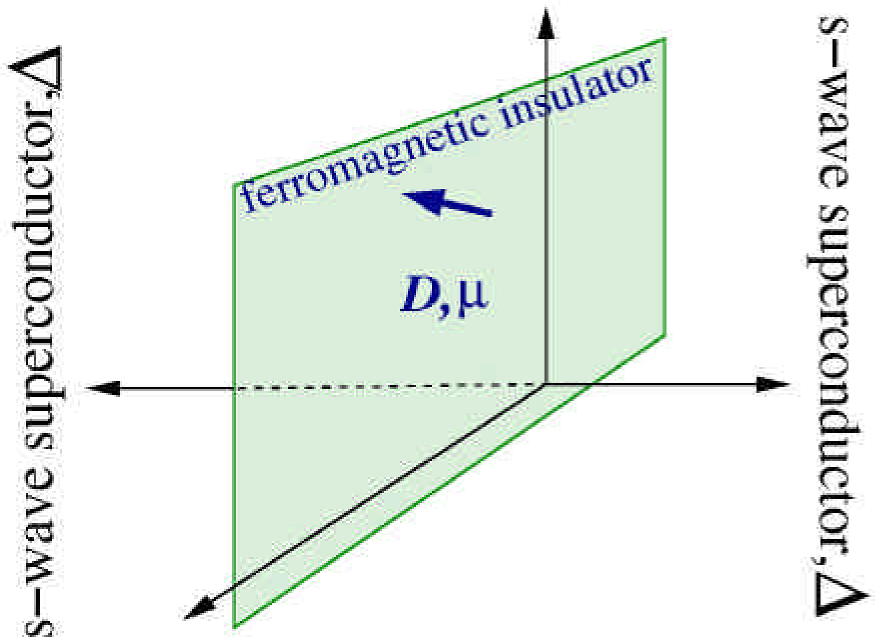
A. Millis, D. Rainer & J. A. Sauls, PRB **B 38** 4505 (1988)
M. Fogelström, PRB **B 62** 11812 (2000)
J. C. Cuevas and M. Fogelström, PRB **B 64** 104502 (2001)

Manipulating the spin degree of freedom

Andreev equation in spin⊗particle-hole space

$$\left(i v_F \cdot \nabla_R \hat{g} + [\hat{e} - \hat{\Delta} - \hat{\Sigma}_{imp}, \hat{g}] = 0 \right)$$

$$i\boldsymbol{v}_F \cdot \nabla_R \begin{bmatrix} u_\uparrow \\ u_\downarrow \\ v_\uparrow \\ v_\downarrow \end{bmatrix} + \begin{bmatrix} e & 0 & 0 & \Delta \\ 0 & e & -\Delta & 0 \\ 0 & \Delta^* & -e & 0 \\ -\Delta^* & 0 & 0 & -e \end{bmatrix} \begin{bmatrix} u_\uparrow \\ u_\downarrow \\ v_\uparrow \\ v_\downarrow \end{bmatrix} = 0$$



S-matrix for a spin-active interface:

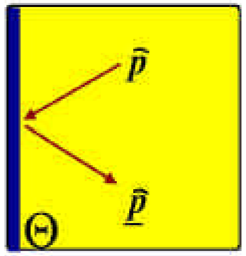
$$\hat{S} = \begin{pmatrix} r & t \\ t & -r \end{pmatrix} e^{i\frac{T}{2}(\hat{\boldsymbol{\mu}} \cdot \boldsymbol{s})}, D = |t|^2$$

$\hat{\boldsymbol{\mu}}$ = moment direction

$\boldsymbol{s}$ = quasiparticle spin

T related to the exchange field H_{ex}

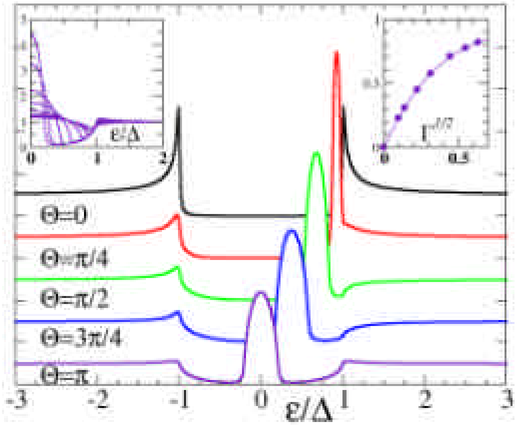
Q is a phenomenological spin-mixing angle

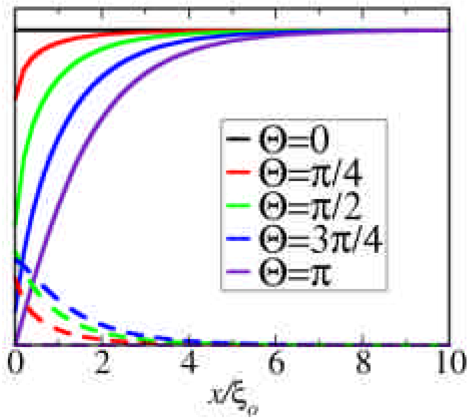


Andreev surface states at an SF-surface

(T. Tokuyasu, J.A. Sauls & D. Rainer, PRB **B 38** 8823 (1988), M. Fogelström, PRB **B 62** 11812 (2000))

$$R(T;\hat{\mu}) = e^{i\frac{T}{2}(\hat{\mu}\cdot s)}$$





The spin-mixing angle Θ rotates the quasiparticle spin in the otherwise specular scattering off the surface. This leads to:

•“tunable” surface bound states at:

$$e_B = \pm D \ \mathbf{cos} \ Q/2$$

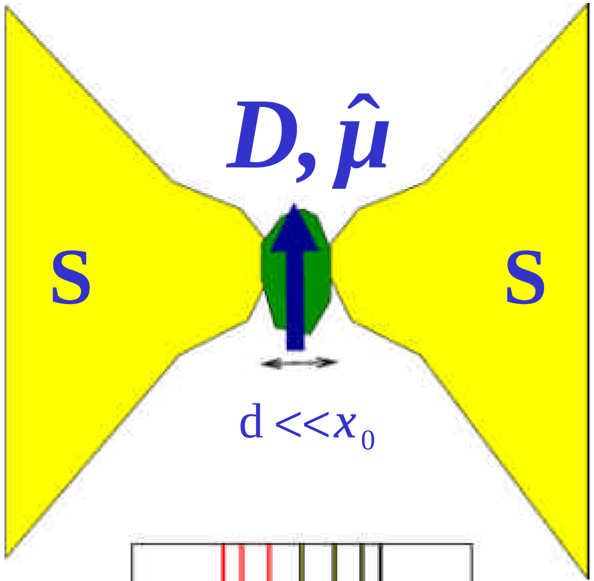
•suppression of the order parameter near the surface with increasing Θ

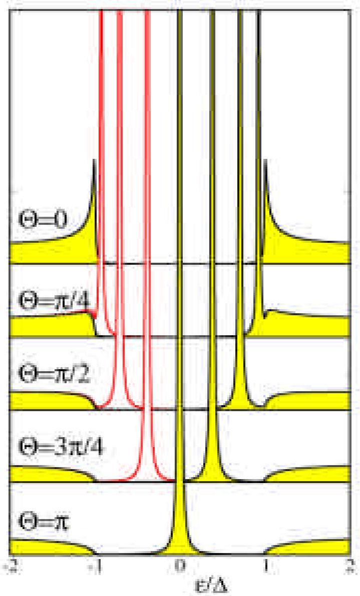
• an induced exchange field in the superconductor

•width of bound states depends on non-magnetic impurity scattering, in the Born limit at, e=**0**

$$\text{peak width } \propto \sqrt{\Gamma\cdot\Delta}$$

Magnetic dot between two s-wave SC





Two conventional s-wave superconductors coupled by a magnetic grain of size $d << x_0$

with a large classical moment $\hat{\mu} \Rightarrow T$

and a transmission, ***D***

Þ ***Tunable magnetic pinhole or point contact with variable transmission***

The smallness of the hole allows us to neglect de-pairing, and hence broadening of the bound state by impurity scattering

Josephson coupling over the dot

Interface states now depend on the phase difference, χ and on D

$$e_J(\chi) = \pm\Delta\sqrt{\cos^2\frac{\Theta}{2} - D\cos\Theta\sin^2\frac{\chi}{2} \pm \sqrt{D}\sin\Theta\sin\frac{\chi}{2}\sqrt{1 - D\sin^2\frac{\chi}{2}}}$$

Limits: (normal s-wave junction) (~45°/45° d-wave junction)

$\Theta = 0 \quad \Rightarrow e_J(\chi) = \pm\Delta\sqrt{1 - D\sin^2\frac{\chi}{2}}$

$\Theta = \pi \quad \Rightarrow e_J(\chi) = \pm\Delta\sqrt{D}\left|\sin\frac{\chi}{2}\right|$

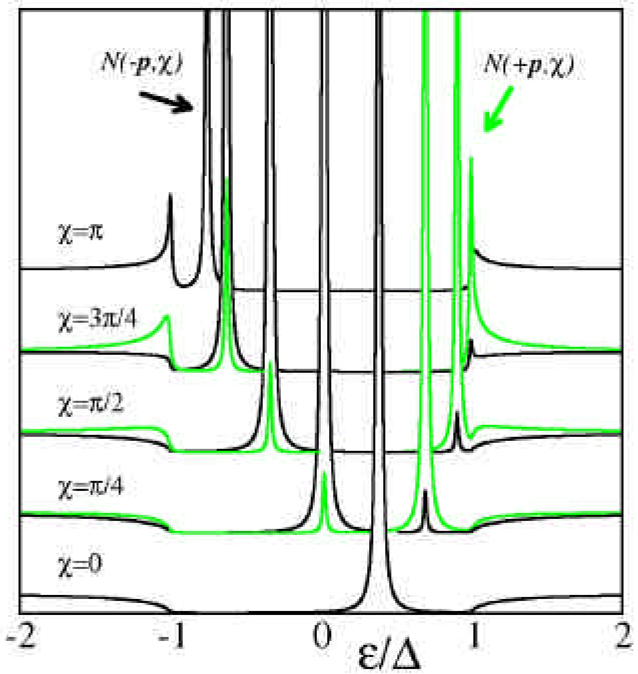
These states carry the dominant part of the Josephson current

$$j(\chi;T) = -2eN_f\sum_\alpha\int d\varepsilon\left\langle v_f\left(N_\alpha(p_f;\varepsilon) - N_\alpha(-p_f;\varepsilon)\right)\right\rangle_{+p_f}\tanh\frac{\varepsilon}{2T}$$

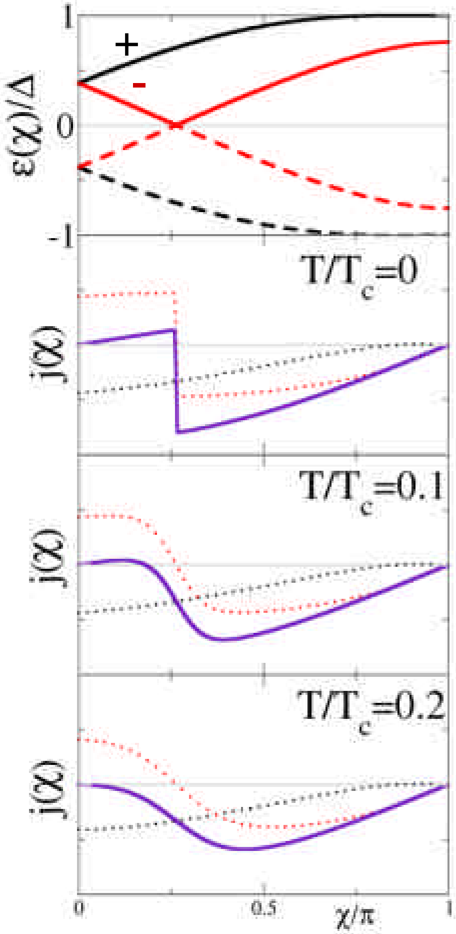
J. C. Cuevas and M. Fogelström, PRB **B 64** 104502 (2001),M. Andersson, J. C. Cuevas and M. Fogelström, Physica **C 62** 117 (2002), Yu. S. Barash & I.V Bobkova, PRB **65**, 144502 (2002)
H. Shiba & T. Soda, Prog. Theo. Phys. **41**, 25 (1968), L. N. Bulaevskii, *et al*, JETP **25**, 290 (1977)

high transmission, D=0.9 and Θ=3π/4

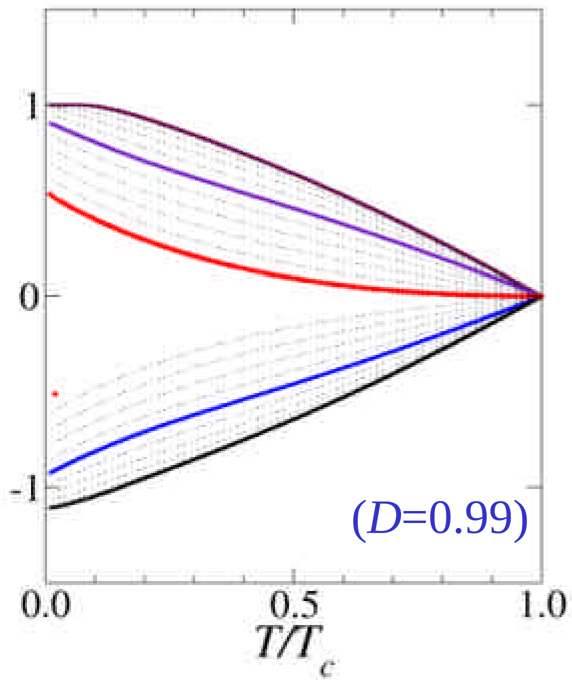
Density of states



current-phase relations



critical currents for 0<Θ<π

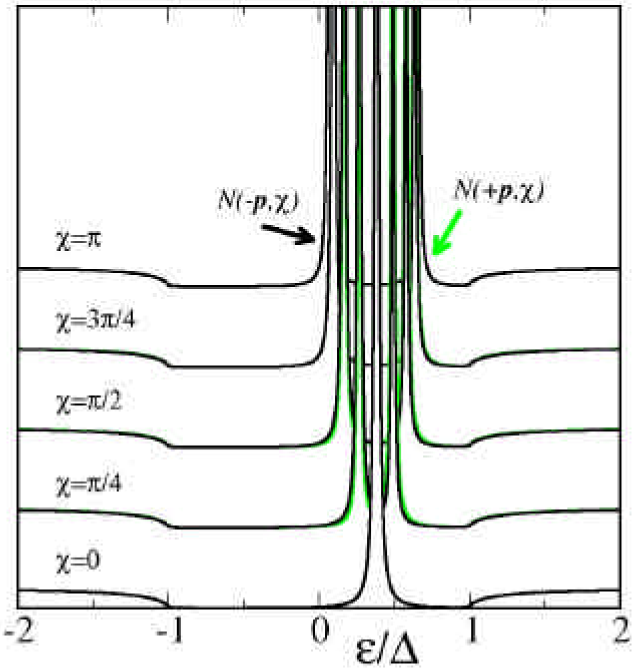


Spectrally resolved current:

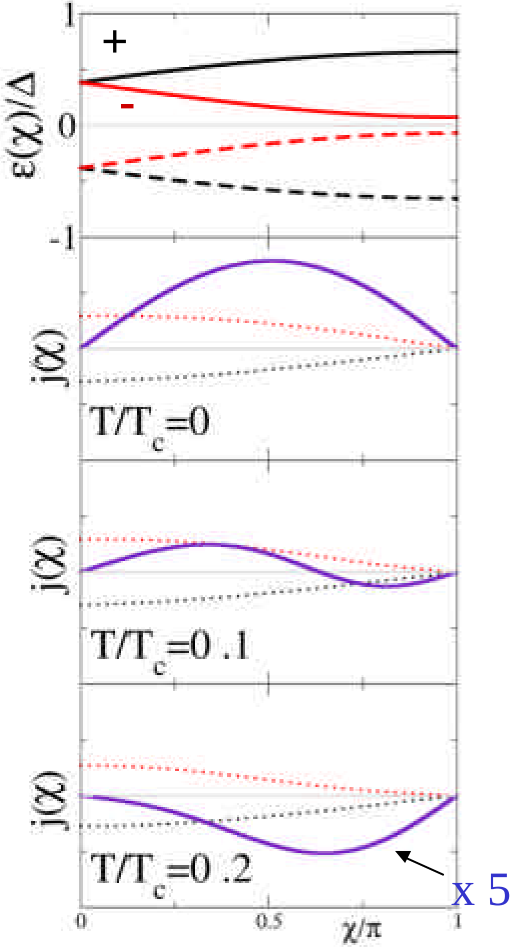
$$J(c,T) = -2e\sum_{\pm} \frac{\partial e_{J,\pm}(c)}{\partial c}\tanh\left[\frac{e_{J,\pm}(c)}{2T}\right]$$

low transmission, D=0.1, Θ=3π/4

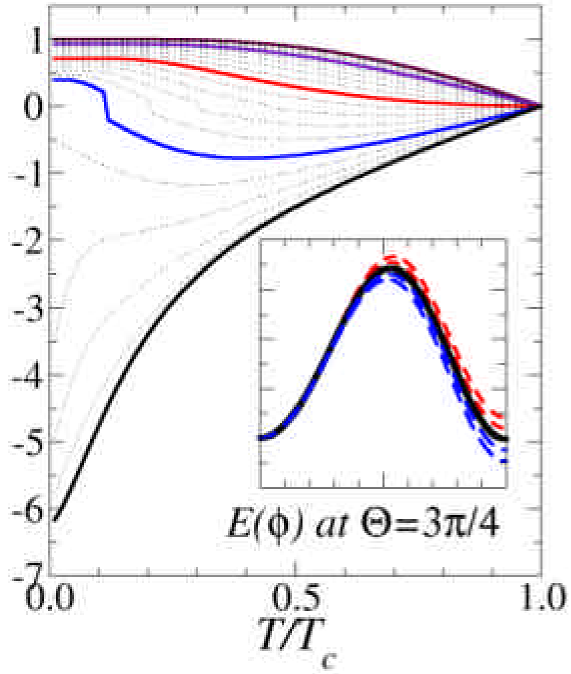
Density of states



current-phase relations



critical currents for 0<Θ<π



Spectrally resolved current:

$$J(c,T) = -2e\sum_{\pm} \frac{\partial e_{J,\pm}(c)}{\partial c} \tanh\left[\frac{e_{J,\pm}(c)}{2T}\right]$$

summarizing:

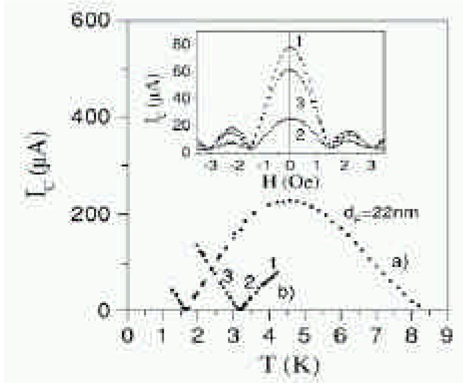
•rich interface spectra tuned by parameters D,Θ,χ

•both 0- and π-junctions for all transparencies

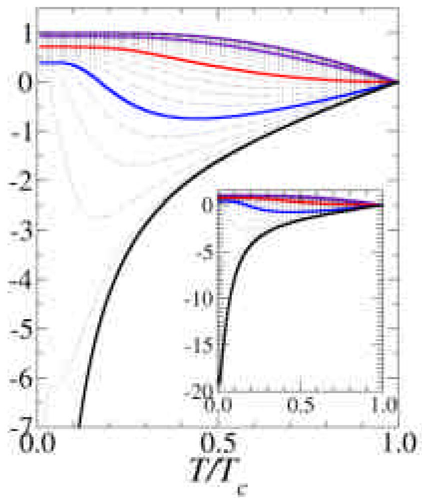
• ”tunable” transitions between 0 and π states for small D either by tuning T or Θ

•For D<<1 and Θ close to π, the critical current ~ 1/T (cf: d-wave sc)

•1/T-dependence is cut off by either by finite D or by inelasitc scattering, $t_{inelastic}$



Critical currents for
D=0.01



current-voltage characteristics

M. Andersson, J. C. Cuevas and M. Fogelström, Physica **C 62** 117 (2002)

- Apply a voltage over the magnetic dot $\Rightarrow$ Multiple Andreev Reflections (MAR) $\Rightarrow$ subharmonic gap structure in the IV-characteristics of the magnetic dot
- Structures in the IV-curves (or SV-curves) give information about the current-carrying channels (D,Θ) E. Scheer, et al, Nature **394,** 154 (1998), R. Cron et.al. PRL **86,** 4104 (2001)
- Need different quantities to pin down D and Θ
- The spin-mixing angle, Θ, will change the IV-curves in a Θ-specific way

Multiple Andreev Reflections (MAR)

- **no dot Þ no bound states**

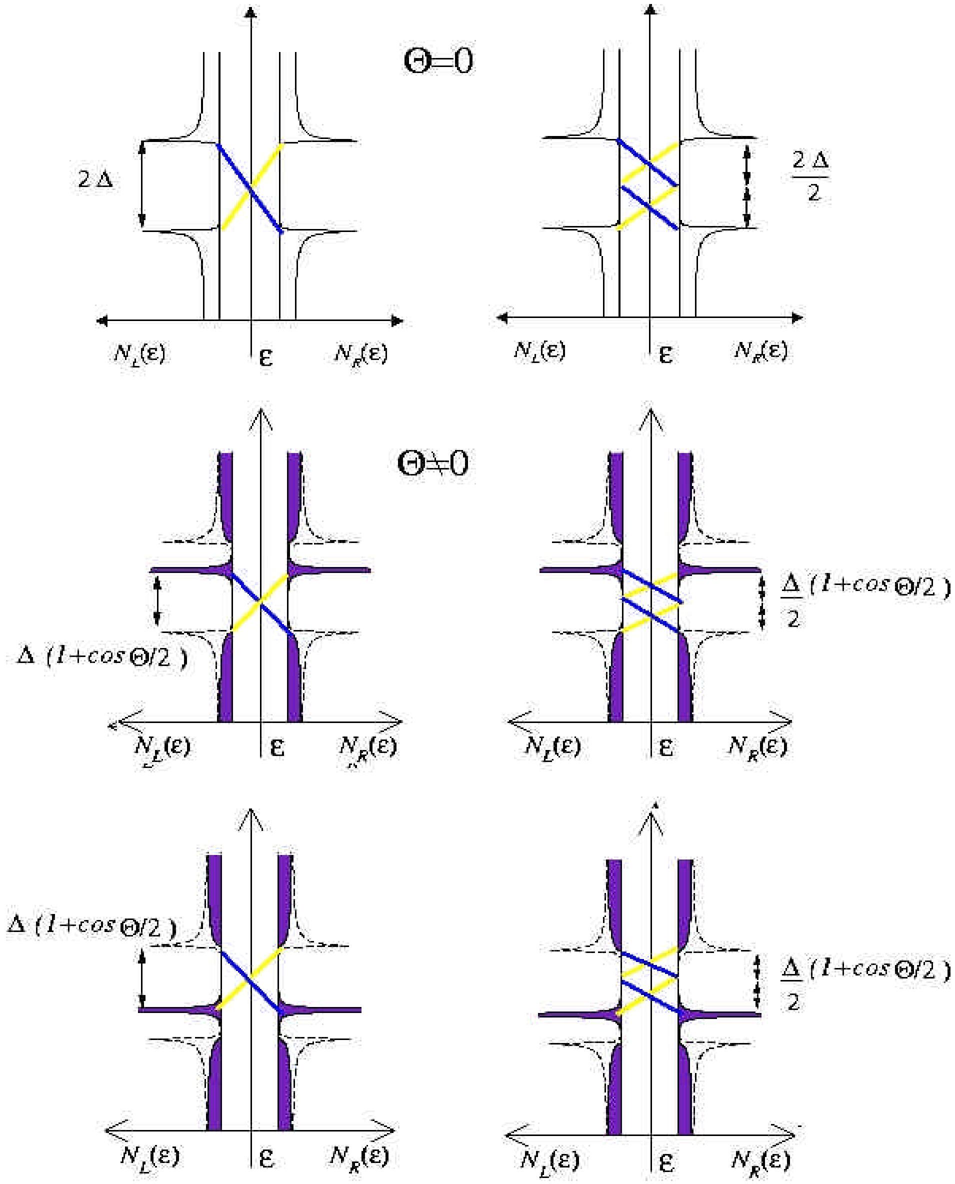
  MAR between gap edges
  ⇒subharmonic gap structure in the IV-curves at

  eV=2 D **/n**

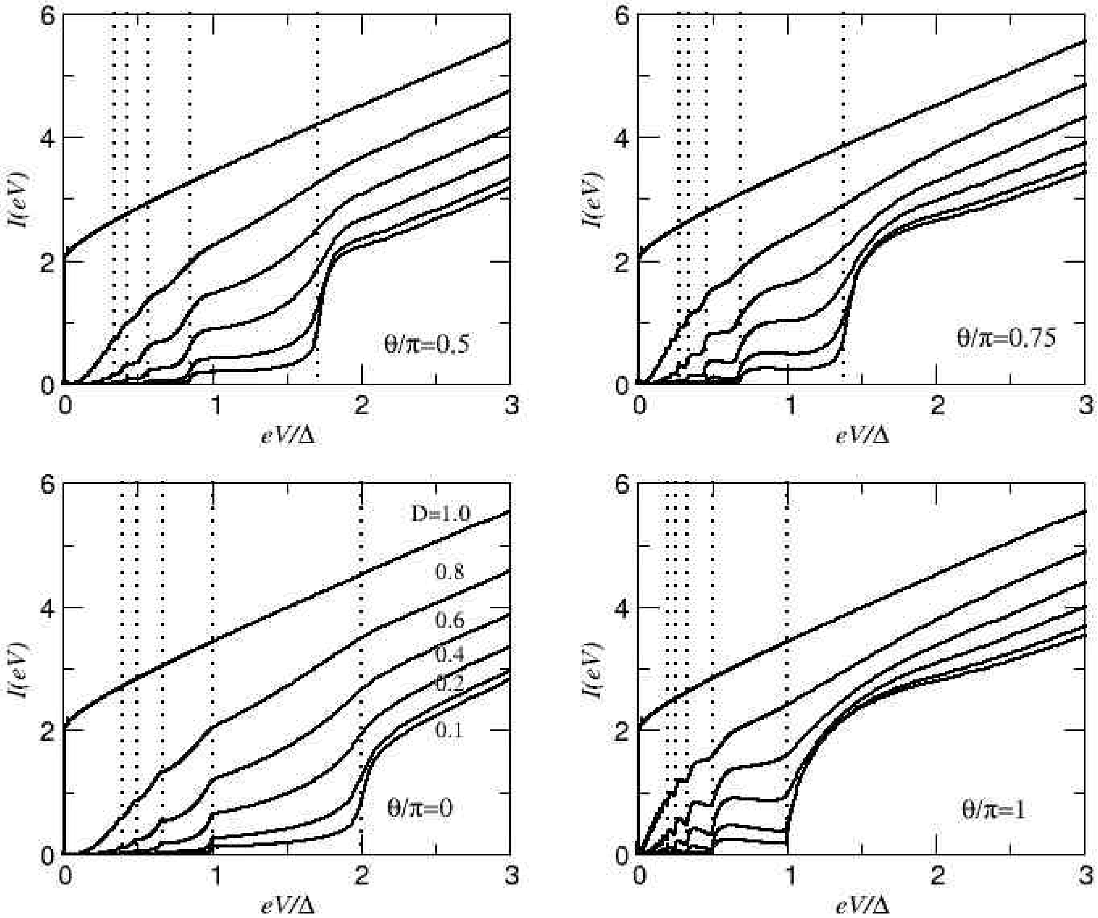
- **dot Þ bound states** e=± D **cos**Q**/2**

  MAR between gap edge and bound state ⇒subharmonic gap structure in the IV-curves at

  eV= (1+ cosQ**/2)** D **/n**



IV-characteristics



Indeed the structures in the IV-curves are located at voltages:

eV=(1+cosQ/2) D/n

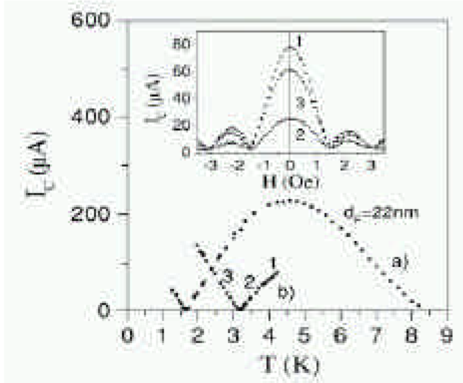
Iv:s contain information not only of the trans-mission, *D*, but also of the spin-mixing angle Q

(cf. : E. Scheer, et al, Nature **394** 154 (1998))

Conclusions

- Discussed quasiclassical modeling of SF-structures
- Show the presence of Andreev surface states, $e_B = \pm D$ **cos** Q**/2**
- The magnetic dot shows a rich interface spectra that may be "tuned" by parameters *D*,Θ,χ
- both 0- and π-junctions realised for all transparencies
- "tunable" transitions between 0 and π states for small *D* either by tuning *T* or Θ
- For *D*<<1 and Θ close to π, the critical current ~ 1/*T* (cf: d-wave)
- 1/*T*-dependence is cut off by either by finite *D* or by inelasitc scattering, $t_{inelastic}$
- Further information of the junction parameters contained in the current-voltage characteristics, subharmonic gap structures at

eV=(1+cosQ**/2)** D/**n**



Critical currents for
D=0.01