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Resonant Andreev reflection in a ferromagnetic normal metal - magnetic quantum dot – superconductor structure in magnetic field

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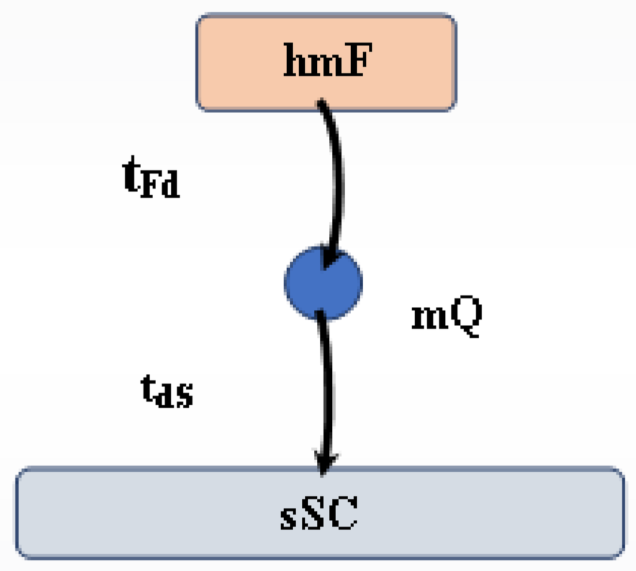
Spin-dependent resonant tunneling through a quantum dot (QD), a small system characterized by discrete electronic states, coupled with a ferromagnetic normal-metal (F) and s-wave superconductor (S), F-QD-S system is a subject of our investigations. In addition to the basic interest such hybrid meso-nano-structured systems are considered as functional materials in future electronic devices which employ both the charge and spin degree of freedom of electrons (see, e.g., [1]).

In this work, we investigate the electron tunneling through a F-mQD-S system. Different from Ref. [2] where discrete levels of the QD are spin independent, here we assume that the QD has spin-splitted discrete levels (magnetic QD, mQD) and this splitting can be varied by external magnetic field. The Keldysh nonequilibrium-Green's-function method is used to derive the current and, particularly, a probability of Andreev reflection (AR), $T^A(\omega)$, for the F-mQD-S structure. The sensitivity of the $T^A(\omega)$ on an external magnetic field (i.e., on the mQD level's spin-splitting) has been studied in detail.

Contact structure



The model

$$H = H_F + H_{SC} + H_{mdot} + H_T$$

$$H_F = \sum_{k\sigma}(E_{k\sigma} + \sigma M - eV)a^+_{k\sigma}a_{k\sigma}$$

$$H_{mdot} = \sum_{i,\sigma}(\varepsilon_i^0 + \sigma\mu_B H - ev_g)\,d^+_{i\sigma}d_{i\sigma}$$

$$H_T(\tau) = \sum_{k\sigma}\{(t_{Fd}a^+_{k\sigma}d_{i\sigma} + h.c.) + (t_{Sd}e^{ieV_s\tau}b^+_{k\sigma}d_{i\sigma} + h.c.)\}$$

Current through a quantum dot

The tunnel current can be presented as a sum of three different contributions:

$$I_{tot} = I^{(A)} + I_{q\uparrow} + I_{q\downarrow},$$

where $I^{(A)}$ arises from the AR processes and $I_{q\uparrow}$ and $I_{q\downarrow}$ are the quasiparticle currents with spin "up" ("down")

$$I^{(A)} = \frac{2e}{\hbar}\int\frac{d\omega}{2\pi}\Gamma_{F\uparrow}\Gamma_{F\downarrow}\times\{|G^r_{\uparrow\downarrow}(\omega)|^2[n_{F\uparrow}(\omega+eV_F-eV_S)-n_{F\downarrow}((\omega-eV_F+eV_S))]+|G^r_{\uparrow\downarrow}(\omega)|^2[n_{F\downarrow}(\omega+eV_F-eV_S)-n_{F\uparrow}(\omega-eV_F+eV_S)]\},$$

$$G^r_{\uparrow\downarrow}(\omega) = G^r_{\uparrow\uparrow}(\omega)\frac{i}{2}\Gamma_S\frac{\Delta}{\sqrt{\omega^2-\Delta^2}}A^r_{\downarrow\downarrow}(\omega)$$

$$G^r_{\uparrow\uparrow}(\omega) = \left[(\sum_i\frac{1}{\omega-\epsilon_{i\uparrow}(h)+eV_F-eV_g})^{-1}+\frac{i}{2}\Gamma_{F\uparrow}+\frac{i}{2}\Gamma_S\frac{|\omega|}{\sqrt{\omega^2-\Delta^2}}+\frac{{\Gamma_S}^2}{4}\Gamma_S\frac{\Delta^2}{\omega^2-\Delta^2}A^r_{\downarrow\downarrow}(\omega)\right]^{-1}$$

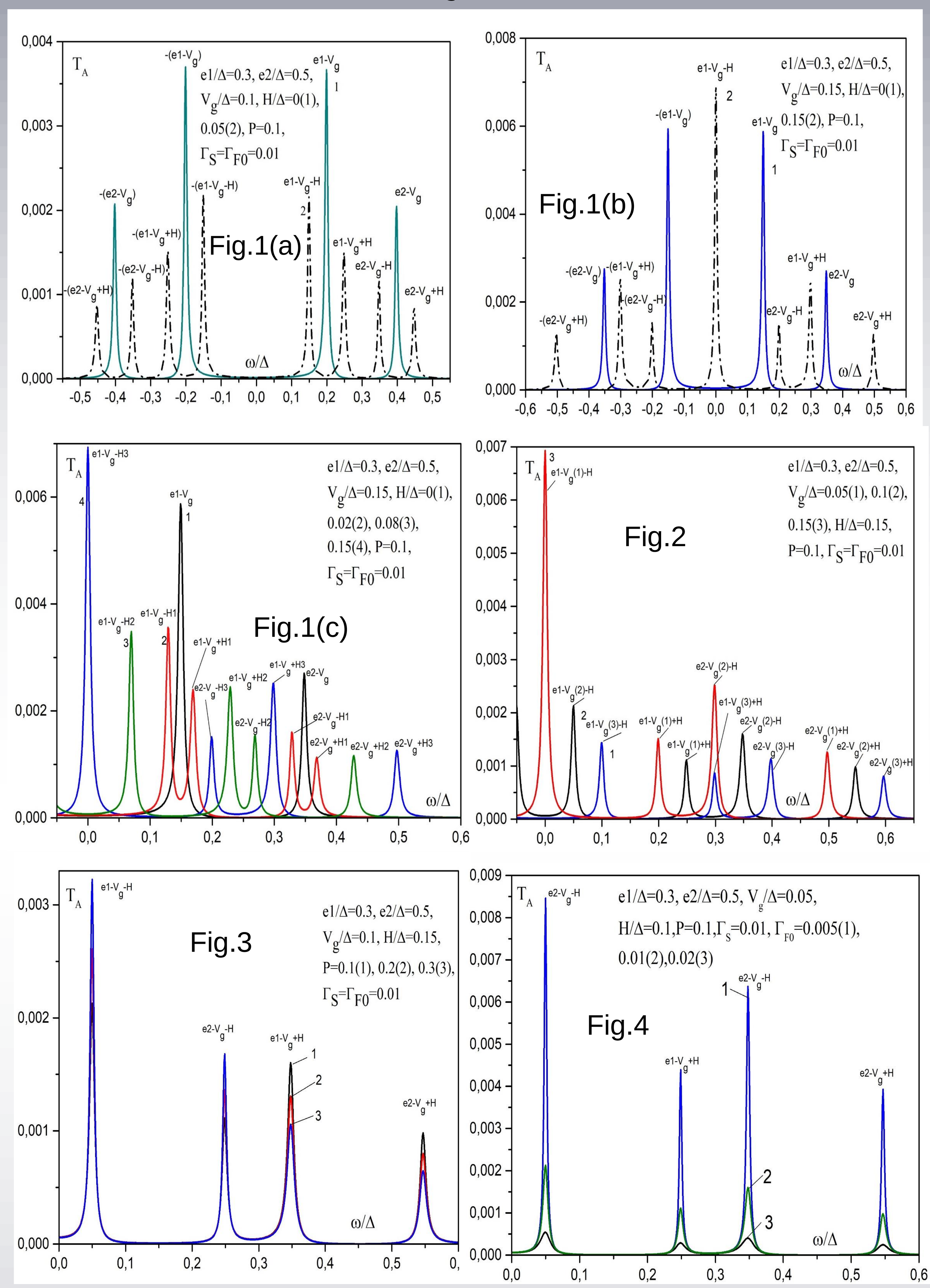
$$A^r_{\downarrow\downarrow} = \left[(\sum_i\frac{1}{\omega-\epsilon_{i\downarrow}(h)+eV_F-eV_g})^{-1}+\frac{i}{2}\Gamma_{F\downarrow}+\frac{i}{2}\Gamma_S\frac{|\omega|}{\sqrt{\omega^2-\Delta^2}}\right]^{-1}$$

$$G^r_{\downarrow\uparrow}(\omega) = G^r_{\downarrow\downarrow}(\omega)\frac{i}{2}\Gamma_S\frac{\Delta}{\sqrt{\omega^2-\Delta^2}}A^r_{\uparrow\uparrow}(\omega)$$

$$G^r_{\downarrow\downarrow}(\omega) = \left[(\sum_i\frac{1}{\omega-\epsilon_{i\downarrow}(h)+eV_F-eV_g})^{-1}+\frac{i}{2}\Gamma_{F\downarrow}+\frac{i}{2}\Gamma_S\frac{|\omega|}{\sqrt{\omega^2-\Delta^2}}+\frac{{\Gamma_S}^2}{4}\Gamma_S\frac{\Delta^2}{\omega^2-\Delta^2}A^r_{\uparrow\uparrow}(\omega)\right]^{-1}$$

$$A^r_{\uparrow\uparrow}(\omega) = \left[(\sum_i\frac{1}{\omega-\epsilon_{i\uparrow}(h)+eV_F-eV_g})^{-1}+\frac{i}{2}\Gamma_{F\uparrow}+\frac{i}{2}\Gamma_S\frac{|\omega|}{\sqrt{\omega^2-\Delta^2}}\right]^{-1}$$

A probability of Andreev Reflection for F-mQD-S structure



The resonant Andreev refection probability $T_A(\omega)$ vs energy. The dependence on the spin-splitting of the mQD levels under the effect of the effective (proximity induced and external) Zeeman energy H (Fig. 1(a,b,c), on the gate voltage V_g(Fig. 2), on the spin polarization of the F-lead current P (Fig. 3) and on linewidth Γ_{F0} (Fig. 4).

Conclusions

For this simple model system, we found interesting results. In addition to the resonant behavior of the Andreev tunneling as obtained in previous works, we find that Andreev reflection probability behavior exhibits different kinds of peaks, depending on: (i) the value of external magnetic field and spin-splitting under the effect of the Zeeman energy, (ii) gate voltage, (iii) F-lead current spin polarization and (iv) the F-lead linewidth. The results open a way for exploring such systems in tunable spintronic devices.

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