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# Spin-dependent splitting of the tunnel conductivity peaks in the magnetic field for junctions involving CDW metals

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## Abstract

Current-voltage characteristics for junctions involving normal and superconducting charge-density-wave metals in the magnetic field were calculated. Spin-splitting was found both for symmetrical and non-symmetrical junctions.

*Key words:* superconductivity, charge density waves, ferromagnet, tunneling, paramagnetic effect
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Tunneling between $s$-wave superconductors (S) and ferromagnets (FM) in the external magnetic field $H$ is a powerful method for studying both electron properties of the paired states and the spin-split band structure of the itinerant electron spectrum [1]. The main practical goal of those investigations consists in the determination of the electron spin polarization $P$ inside the ferromagnet at its Fermi level. The spin splitting of the gap-like maxima in the voltage, $V$, dependence of the dynamical conductance $G(V) = dJ/dV$, where $J$ is the quasiparticle current, into two components, $G(V) = G^+(V) + G^-(V)$, corresponding to the contributions of current carriers with different spin orientations with respect to the applied field $H$, is the origin of the effect obtained in the junction device. There is an obstacle, which always acts harmfully in such experiments. It is a strong orbital Meissner effect. To overcome it, a thin-film geometry is used, so that the paramagnetic influence of $H$ on Cooper pairs may manifest itself. The smearing of the $G^\pm(V)$ maxima by a spin-orbital scattering constitutes another prominent difficulty negatively influencing the method. In this situation, any supplement in the set of gap-possessing objects suitable for probing $P$ would be highly desirable.

As those, we propose charge-density-wave (CDW) normal metals and superconductors. Indeed, their paramagnetic properties are very similar to those of $s$-wave superconductors because due to the electron-hole and electron-electron attraction, respectively, both are in the spin-singlet paired state. That is why the spin-splitting of $G(V)$ should be like. Nevertheless, one can expect substantial differences since the CDW metals (CDWMs) are gapped only partially, i.e. the nested (d) sections of the Fermi surface (FS) are gapped by the CDW order parameter $\Sigma = |\Sigma| e^{i\varphi}$, whereas the other FS sections (nd) remain intact at temperatures, $T$, below the structural transition one, $T_d$ [2]. The relative portion of the gapped FS is determined by the parameter $0 \leq \mu \leq 1$.

In the magnetic field $H$, which is large enough to conspicuously move apart the gap-induced maxima $G^\pm(V)$ but substantially smaller than the so-called paramagnetic limit, $H_p$, one may expect to observe the effect depending also on $\varphi$. This is a feature distinguishing the CDW case from the superconducting one. One should also note that $H_p$ in normal and superconducting CDWMs substantially differs [3] from its Clogston-

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Chandrasekhar superconducting analog [1].

We predict one more effect to be observed in symmetrical (or non-symmetrical) junctions involving CDWMs only. Namely, due to the fact that both d and nd FS sections contribute to the current $J$, both the spin-split peaks $G^{\pm}(V)$ should reveal themselves there, although in junctions between conventional superconductors such a splitting does not occur because the states for each spin projection in both electrodes shift by the same energy and the positions of the peaks $G^{\pm}(V)$ do not depend on $H$ [1].

Calculations of the current-voltage characteristics (CVC) have been done on the basis of our theory [4]. The results for the normalized $G(V)$ appropriate to the non-symmetrical junction FM/I/CDWM, where I stands for an insulator, are shown in Fig. 1. The CVCs are non-symmetrical, contrary to what is inherent to superconductors. It is important that the $H$-driven splitting of the $G(V)$ peak takes place irrespective of the peak attribution. Of course, if superconductivity is absent, the normal CDWM reveals similar behavior but with only one pair of spin-split peaks.

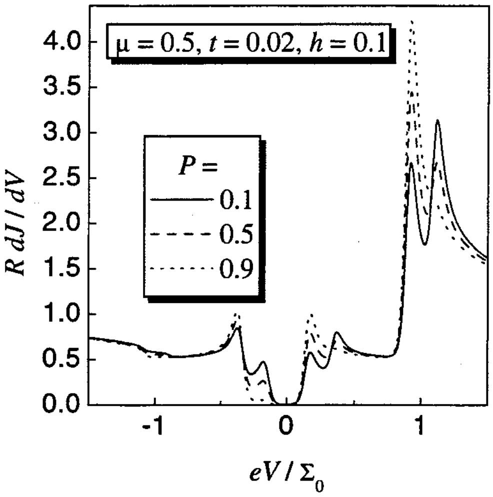

Fig. 1. Bias dependences of the dimensionless conductances $R\,dJ/dV$ for FM/I/CDWM junction, where $R$ is the normal state resistance, for various polarizations $P$. Here the phase $\varphi$ of the CDW order parameter is 0, $h = \mu_B^* H/\Sigma_0$, $\Sigma_0 \equiv \frac{\pi}{\gamma} T_d$, $\mu_B^*$ is the effective Bohr magneton, $t = k_B T/\Sigma_0$ the reduced temperature, $k_B$ the Boltzmann constant, and $\gamma = 1.78\ldots$ the Euler constant

In Fig. 2, the normalized $G(V)$ is shown for a symmetrical junction CDWM/I/CDWM. Some peaks do split in the magnetic field, whereas the others do not. The split peaks correspond to the tunneling between the d FS sections from one electrode and the nd sections from another. Hence, four peaks for $H = 0$, with two of them split at $H \neq 0$, can be regarded as an evidence for a CDW background in a superconductor.

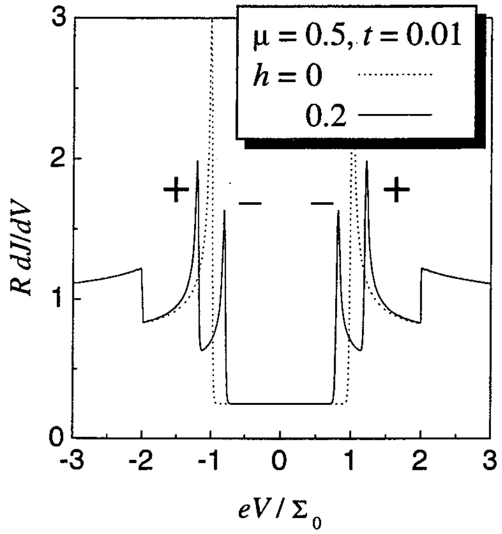

Fig. 2. The same as in Fig. 2 but for CDWM/I/CDWM junction and various $h$

There are plenty of normal and superconducting CDWMs with a large variety of CDW gaps $|\Sigma|$. One can mention, e.g., $2H$-NbSe$_2$, $\alpha$-(ET)$_2$MHg(SCN)$_4$, Per$_2$[M(mnt)$_2$] (M = Au, Pt), Sr$_{14-x}$Ca$_x$Cu$_{24}$O$_{41}$, and Ca$_{2-x}$Na$_x$CuO$_2$Cl$_2$. They allow us to select a suitable object for tunnel experiments depending on the available magnetic fields in the laboratory. The problem of the spin-orbit scattering remains detrimental as for superconductors. But the Meissner effect is inherent only to superconducting CDWMs below $T_c$.

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