IV. CONCLUSIONS

In this paper we have considered spectral and transport properties of a single-level quantum dot connected to external ferromagnetic leads and exchange-coupled to a nonmagnetic reservoir. Using the numerical renormalization group method we have calculated the zero-temperature d-level spectral function and the conductance through the dot. We have shown that in the antiparallel configuration, depending on the strength of the exchange interaction J, the Kondo singlet ground state can form, in which the conduction electrons either in the ferromagnetic leads or in the nonmagnetic reservoir are involved. In the former case, the conductance is maximum, whereas in the latter case the conductance becomes fully suppressed. For a certain critical value of J, $J_{\rm c}^{\rm AP}$, both electron channels try to screen the dot's spin and the conductance is equal to a half of its maximum value. The boundary between the two ground states is a quantum phase transition.

In the parallel magnetic configuration, on the other hand, the Kondo effect is generally destroyed due to an effective spin splitting of the dot level caused by the presence of ferromagnetic leads. However, there are still small side peaks – reminiscent of the Kondo effect – which occur on both sides of the Fermi level for energies of the order of effective exchange field. Nevertheless, with increasing the exchange constant J, these peaks become suppressed.

We have also considered the influence of an external magnetic field on the d-level spectral function and shown that in the parallel configuration the Kondo effect can be restored by applying appropriately tuned compensating magnetic field for $J < \tilde{J}_{\rm c}^{\rm P}$, where $\tilde{J}_{\rm c}^{\rm P}$ is the critical value of J in the compensating magnetic field. If, however, $J > \tilde{J}_{\rm c}^{\rm P}$, the full Kondo effect cannot be restored by a magnetic field. In addition, we have found that the quantum critical behavior, which is suppressed in the parallel configuration, can also be recovered by tuning the external magnetic field.

Acknowledgments

This work was supported by funds of the Polish Ministry of Science and Higher Education as a research project for years 2006-2009. I.W. also acknowledges support from the Alexander von Humboldt Foundation, the Foundation for Polish Science and funds of the Polish Ministry of Science and Higher Education as a research project for years 2008-2010. Financial support by the Excellence Cluster "Nanosystems Initiative Munich (NIM)" is gratefully acknowledged.

---

* Electronic address: weymann@amu.edu.pl

[1] D. Goldhaber-Gordon, H. Shtrikman, D. Mahalu, D. Abusch-Magder, U. Meirav, and M. A. Kastner, Nature (London) 391, 156 (1998).

[2] S. Cronenwett, T. H. Oosterkamp, and L. P. Kouwenhoven, Science 281, 182 (1998).

[3] A. C. Hewson, *The Kondo Problem to Heavy Fermions* (Cambridge University Press, Cambridge, 1993).

[4] Rosa Lopez and David Sanchez, Phys. Rev. Lett. **90**, 116602 (2003).

[5] J. Martinek, Y. Utsumi, H. Imamura, J. Barnaś, S. Maekawa, J. König, and G. Schön, Phys. Rev. Lett. **91**, 127203 (2003).

[6] J. Martinek, M. Sindel, L. Borda, J. Barnaś, J. König, G. Schön, and J. von Delft, Phys. Rev. Lett. **91**, 247202 (2003).

[7] Mahn-Soo Choi, David Sanchez, and Rosa Lopez, Phys. Rev. Lett. **92**, 056601 (2004).

[8] Daisuke Matsubayashi and Mikio Eto, Phys. Rev. B **75**, 165319 (2007).

[9] P. Simon, P. S. Cornaglia, D. Feinberg, and C. A. Balseiro, Phys. Rev. B **75**, 045310 (2007).

[10] J. Martinek, M. Sindel, L. Borda, J. Barnaś, R. Bulla, J. König, G. Schön, S. Maekawa, J. von Delft, Phys. Rev. B **72**, 121302(R) (2005).

[11] M. Sindel, L. Borda, J. Martinek, R. Bulla, J. König, G. Schön, S. Maekawa, and J. von Delft, Phys. Rev. B **76**, 045321 (2007).

[12] A. N. Pasupathy, R. C. Bialczak, J. Martinek, J. E. Grose, L. A. K. Donev, P. L. McEuen, and D. C. Ralph, Science 306, 86 (2004).

[13] H. B. Heersche, Z. de Groot, J. A. Folk, L. P. Kouwenhoven, H. S. van der Zant, A. A. Houck, J. Labaziewicz, and I. L. Chuang, Phys. Rev. Lett. 96, 017205 (2006).

[14] K. Hamaya, M. Kitabatake, K. Shibata, M. Jung, M. Kawamura, K. Hirakawa, T. Machida, T. Taniyama, S. Ishida and Y. Arakawa, Appl. Phys. Lett. **91**, 232105 (2007).

[15] K. Hamaya, M. Kitabatake, K. Shibata, M. Jung, M. Kawamura, S. Ishida, T. Taniyama, K. Hirakawa, Y. Arakawa, and T. Machida, Phys. Rev. B 77, 081302(R) (2008).

[16] J. Hauptmann, J. Paaske, P. Lindelof, Nature Phys. 4, 373 (2008).

[17] H. Yang, S.-H. Yang, S. S. P. Parkin, Nano Lett. **8**, 340 (2008).

[18] Y. Oreg and D. Goldhaber-Gordon, Phys. Rev. Lett. **90**, 136602 (2003).

[19] P. Nozieres and A. Blandin, J. Phys. **41**, 193 (1980).

[20] A. Zawadowski, Pys. Rev. Lett. **45**, 211 (1980).

[21] I. Affleck, A. W. W. Ludwig, Phys. Rev. B **48**, 7297 (1993).

[22] D. C. Ralph, A. W. W. Ludwig, J. von Delft, R. A. Buhrman, Phys. Rev. Lett. **72**, 1064 (1994).

[23] M. H. Hettler, J. Kroha, S. Hershfield, Phys. Rev. Lett. **73**, 1967 (1994).

[24] N. Andrei and A. Jerez, Phys. Rev. Lett. **74**, 4507 (1995).

[25] E. Lebanon, A. Schiller, F. B. Anders, Phys. Rev. B **68**, 155301 (2003).

[26] S. Florens, A. Rosch, Phys. Rev. Lett. **92**, 216601 (2004).

[27] R. M. Potok, I. G. Rau, Hadas Shtrikman, Yuval Oreg,