# Quartet-rule-coupling engineering of Majorana fermions in FM-SC heterostructures and topological states in all AFM films

G. Livanas[1], N. Vanas[1], M. Sigrist[2] and G. Varelogiannis[1]

[1] *Department of Physics, National Technical University of Athens, GR-15780 Athens, Greece*
[2] *Institut für Theoretische Physik, ETH Zürich, CH-8093 Zürich, Switzerland*

Quartet-Rule-Coupling (QRC) introduced by one of us (GV) is a universal hidden interaction that is triggered only when any three members of quartets of fields and/or order parameters with représentations obeying a specific rule coexist and induces the missing fourth one. For example, particle-hole asymmetry with CDW and SDW and FM form a quartet proposed to explain colossal magnetoresistance in manganites [1]. Particle-hole asymmetry with SDW and d-wave-SC and staggered π-triplet SC form another quartet proposed to explain the high field induced SDW state in the SC state CeCoIn5 [2]. Dozens of other quartets have been identified and verified numerically and analytically.

Exploiting the rule that allows to predict quartets [3], we noticed that the coexistence of current with ordinary s-SC and a Zeeman field triggers QRC inducing p-wave triplet SC that combined with other related quartets led us to the discovery of *alternative paths for the realization and manipulation of Majorana fermions* in ferromagnet-superconductor heterostructures without need of any material or structure with intrinsic spin-orbit coupling [4]. We propose an original platform [5] for the manipulation of multiple Majorana qubits based on supercurrents and/or gate voltage manipulation of the polarization of ferromagnetic insulators able to produce braiding operations for all necessary topological quantum gates with available technology.

Some recent extraordinary results in collaboration with the group of Dr. T. Kontos (ENS Paris) for QRC engineering of topological states in any antiferromagnetic film [6], their relation with previous results on topological density-wave condensates and their potential for hosting Majorana zero modes will be briefly presented as well.

[1] G. Varelogiannis, *"Ferromagnetism and colossal magnetoresistance from phase competition"*, Phys. Rev. Lett. **85**, 4172 (2000)
[2] A. Aperis, G. Varelogiannis and P.B. Littlewood, *"Magnetic-Field-Induced Pattern of Coexisting Condensates in the Superconducting State of CeCoIn5"*,
Phys. Rev. Lett. **104**, 216403 (2010)
[3] G. Varelogiannis, *"General rule predicting hidden induced order parameters and the formation of quartets and patterns of condensates"*.
Preprint at, http://arxiv.org/abs/1305.2976 (2013).
[4] G. Livanas, M. Sigrist and G. Varelogiannis, *"Alternative paths to realize Majorana Fermions in superconductor-Ferromagnet Heterostructures",* Sci. Rep. **9**, 6259 (2019).
(see also related extended supplementary material)
[5] G Livanas, N Vanas, M Sigrist and G Varelogiannis, *"Platform for controllable Majorana zero modes using superconductor/ferromagnet heterostructures"*, Eur. Phys. J. B **95**, 47 (2022)
[6] G. Livanas, N. Vanas, T. Kontos, M. Delbecq, A. Cottet, M. Sigrist and G. Varelogiannis, *"Quartet-rule-coupling inducing imaginary spin density waves in commensurate canted antiferromagnets and engineering skyrmion-like spin current textures in the bulk and modulated spin-orbit coupling at the edges in antiferromagnetic films"*, Preprint