Magnetic properties of self-assembled ferrofluids of nanomagnets

**Keywords:** nanomagnetism, electron microscopy, magnetometry, x-ray spectroscopy

**Scientific description:** This Master thesis proposal aims at a quantitative leap in the understanding of the structural and magnetic properties of self-assembled nanomagnets used for technological and biomedical applications. The student will investigate ferrofluids, which are colloidal suspensions of magnetic nanoparticles synthesized by soft chemistry routes and dispersed in a liquid. Particles are composed of a ferro/ferrimagnetic material (CoFe$_2$O$_4$, MnFe$_2$O$_4$) with a typical diameter in the 5-25 nm range, each of them being regarded as a single magnetic dipole. Since their invention by NASA in the 60’s, ferrofluids have found numerous applications in biomedicine (cancer treatment), technology (car dampers), and art, which take advantage of magnetically driven changes in the macroscopic properties [1]. This effect finds its origin in the nanoscale organization of particles under an applied magnetic field, which aggregate to form linear chain-like structures (Figure left) resulting from strong interparticle interactions. When the latter are large enough, nanoparticles can self-assemble into chains or rings even at zero magnetic field (Figure right). Recent investigations have underlined the relevance of studying particle assemblies in ferrofluids, in order to optimize applications or develop new materials [2].

Ferrofluids offering a large interplay of magnetic dipole interactions have already been synthesized at PHENIX laboratory (Sorbonne Univ.) in the frame of a joint ANR project: nanoflowers, nanospheres and nanocubes with different sizes and compositions are already available. A cross-curricular combination of in-situ advanced magnetometry, cryogenic transmission electron microscopy and x-ray magnetic spectroscopy [3] (SOLEIL synchrotron) will be used to build a comprehensive multi-scale picture of these ferrofluids, from the collective behavior down to the nanoparticle level. Chaining phenomena occurring with and without an external magnetic field will be characterized, as well as the magnetic properties. Results will contribute to understand how nanoscale particle organization controls the macroscopic magnetic properties of ferrofluids.

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**Techniques/methods in use:** cryogenic Transmission Electron Microscopy, magnetometry measurements (VSM, FORC), x-ray magnetic spectroscopies at SOLEIL synchrotron

**Applicant skills:** Good experimental skills and basic knowledge of nanomagnetism

**Industrial partnership:** N

**Internship supervisors:** Dr. Amélie JUHIN (IMPMC) amelie.juhin@upmc.fr / 0144272245, Dr. Claire CARVALLO (IMPMC), Dr. Dario Daverna (IMPMC).

**Internship location:** IMPMC

**Possibility for a Doctoral thesis:** Y (PhD fellowship of Ecole Doctorale 397)