Experimental report

24/05/2022

Proposal: **5-54-349** **Council:** 10/2020

Title: Magnetic correlations in Fe-oxide nanoflowers for cancer treatment byhyperthermia

Research area: Materials

This proposal is a new proposal

Main proposer: **Luis FERNANDEZ BARQUIN**

Experimental team: Nina-Juliane STEINKE
Philipp BENDER
Elizabeth MARTIN JEFREMOVAS

Local contacts: Nina-Juliane STEINKE

Samples: Fe2O3/Fe3O4 powder SNF
Fe2O3/Fe3O4 powder MNF
Fe2O3/Fe3O4 powder BNF
Fe2O3/Fe3O4 powder in solution D20 BNF
Fe2O3/Fe3O4 powder in solution D20 MNF
Fe2O3/Fe3O4 powder in solution D20 SNF

Instrument	Requested days	Allocated days	From	To
D33	5	4	28/06/2021	02/07/2021

Abstract:

Cancer is a very common cause of death with more than 10 million cases worldwide. New strategies are needed to improve the existing treatments. Magnetic hyperthermia based on the use of magnetic nanoparticles (MNPs) is a step forward and object of overwhelming number of studies. Most of suitable MNPs contain cores of magnetite/maghemite harmless to human beings. Recently a new family of MNPs forming nanoflowers were produced with a relevant performance. These are multicore MNPs grouped closely. The origin of the performance is not obvious as a combination of sizes, magnetic anisotropy, interactions among cores and interations among MNPS are combined. With SANS experiments (POLARIS) it is possible the evaluation of supermagnetic and inner order of MNPS ensembles of nanoflowers. We aim to disclose the modification in the supermagnetic and intra magnetic coupling by using a set of nanoflowers with different sizes of the core (10 - 30 nm) and of the nanoflower (30-280 nm) in powder and D2O solutions.

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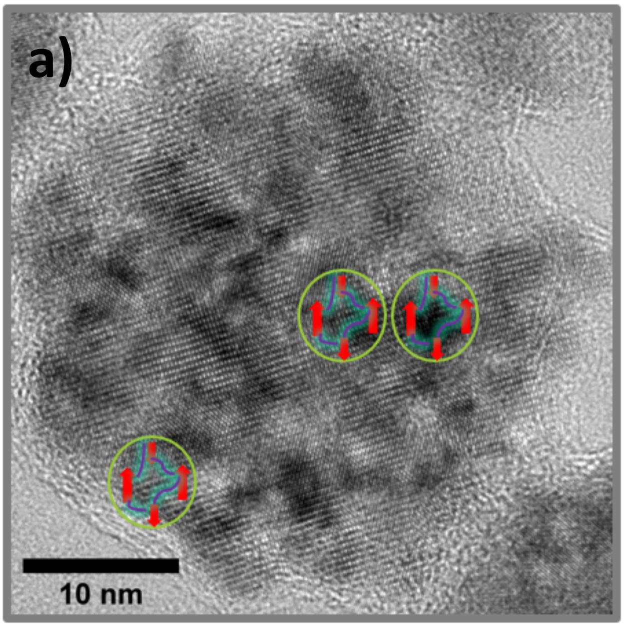
Cancer is a major cause of human death nowadays with more than 10 million global annual cases. New treatment strategies are being demanded to alleviate the terrible number through specific new routes and/or probing supplementary methods to act in combination to conventional therapies [1]. Within these new strategies, the use of Fe oxide-based magnetic nanoparticles has been prominent, by means of their high biocompatibility. More precisely, in recent years, lots of attention has been paid to aggregates of maghemite (γ-Fe_2O_3) MNPs arranged like nanoflowers (NFs). This particular configuration leads to the establishment of a hierarchical magnetic structure, where three different magnetic correlation scales coexists: (i) the cores (petals) are arranged ferrimagnetically; (ii) the whole nanoflower correlates all the petals to behave like a superferromagnetic entity; and (iii) several nanoflowers can be correlated, building up a supraferromagnetic ensemble [2] (see sketch in Fig. 1). At each stage, the spin dynamics of the magnetic structure is different, and deserves the experimental efforts to unravel the particular interactions among each magnetic moment.

Nevertheless, not only are the NFs fascinating owing to fundamental understanding: In recent years, these ensembles have been reported as excellent candidates for magnetic hyperthermia treatments, by means of their high specific loss power (alternatively, specific absorption rate) values [2,3]. Notwithstanding, the origin of their performance is not obvious, as a combination of sizes, magnetic anisotropy, interactions among cores and interactions among MNPs are combined. Given so, a good understanding on the magnetic structure is mandatory to elucidate which are the main parameters affecting the hyperthermia performance of these NFs. It may happen that the shape of petals can also vary greatly the anisotropy and coercivity due to modifications in the ferrimagnetic core arrangement.

SANS experiments, and more precisely, those performed with polarized neutrons (POLARIS), make possible to evaluate the supermagnetic and inner order of MNPS ensembles of nanoflowers. **We aim to disclose the modification in the supermagnetic and intra magnetic coupling by using a set of nanoflowers with different sizes of the core** (around 5 nm) **and of the nanoflower** (40-100 nm) in powder and D_2O solutions.



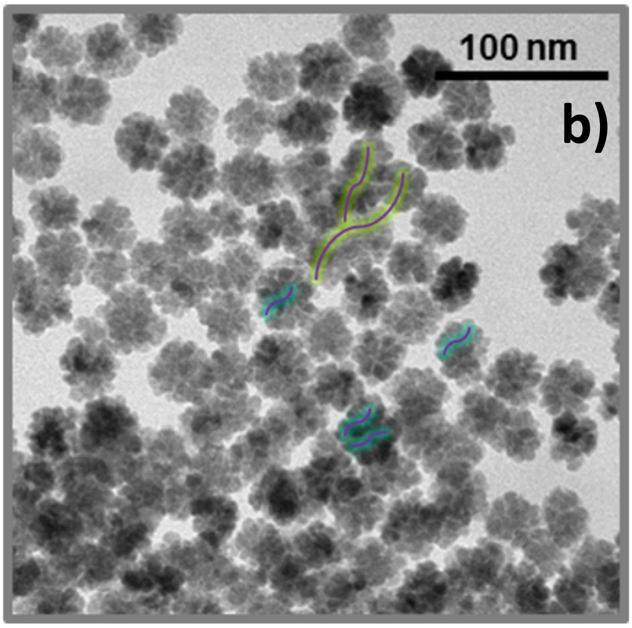


Fig. 1: Sketch of the different magnetic correlations established among the magnetic moments for **a)** within the cores (ferrimagnetic) and **b)** among the cores (superferromagnetic) and nanoflowers (supraferromagnetic).

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To this aim, we have focused our efforts on NF37 and NF100 in powder (pellet). We have measured each sample at room temperature at several applied fields (0, 32.1, 132, 257, 1000, 2507 and 10000 Oe) at two detector distances: 5.3 and 12.8 m, in order to cover a q range between 0.02 and 0.3 nm^{-1}. For each measurement, we measured the four spin-resolved scattering cross-sections $I^{--/++/-+/+-}$, in order to gain access to the underlying magnetic and nuclear correlation functions. As a first analysis, we are presenting here the four spin components added to constitute the UNPOLARIZED signal. This can be used as a first approach towards achieving the nuclear and magnetic structure of the nanoflowers.

Fig. 2a showcases the I vs Q measurements for NF37. At this field, the nanoflowers are almost saturated (see Fig. 2b). The geometrical dimension for these NFs are 37(9) nm for the whole NF and 6(1) nm for the core. The inspection of Fig. 1a allow us to establish the existence of two correlation lengths by means of the bending of the SANS intensity. There are two humps, one located at q = 0.256 nm-1, and a second one, at q = 0.177 nm-1. These correspond to real space values of 245 and 35.5 nm, respectively. Whereas the second value (35.5 nm) matches very well the nanoflower size, the first one (245 nm) would not account for any geometrical structure found at the MNPs, a fact that may suggest the magnetic origin for this correlation length. Taking int account the magnetic characterization of the samples, a hierarchical magnetic structure can be asset for these samples, in the same fashion as it has been reported in other NF systems [2]. Here, what we are observing is the magnetic correlation that correlates the nanocrystallites (the cores) to build up the superferromagnetic coupling of these cores forming the nanoflowers. This corresponds to the correlation length found at 0.177 nm-1. Besides, the correlation length found at 0.0256 nm-1 is accounting for the coupling among several superferromagnetic nanoflowers (~ 7 nanoflowers), which is on top of this hierarchical magnetic structure by means of a supraferromagnetic state. The analysis of the POLARIS measurements is still in process.

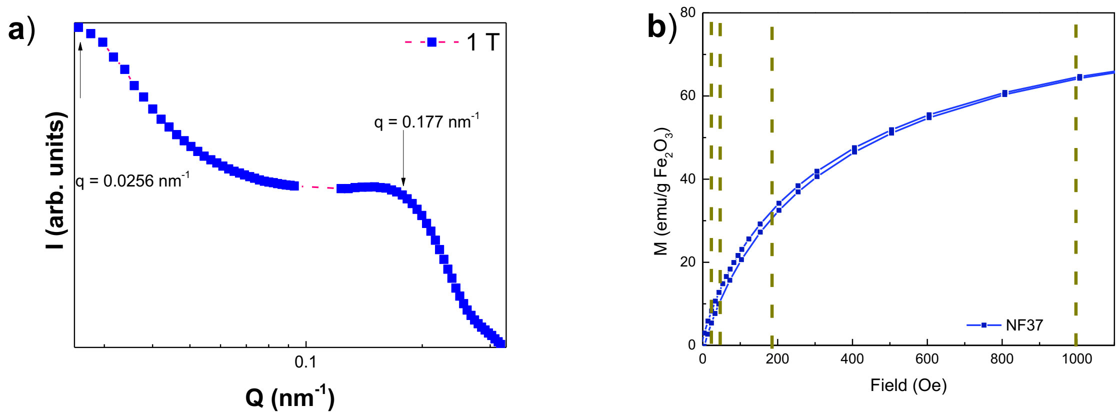

*Fig. 2: **a)** SANS intensity vs. q of the NF37 sample measured at 1 T. **b)** M vs. H (room temperature) of NF37 sample.*

In order to complete the lowest stage of the hierarchical magnetic structure (i.e., the spin structure within each core), Transmission X-Ray Microscopy experiments (STXM) have been conducted in MISTRAL beamline (ALBA Synchrotron) in February 2022. The preliminary results reveal the existence of a spin texture within the cores.

Fig. 3a includes the I vs Q measurements for NF100 (unpolarized) corresponding to 1T. At this field, the nanoflowers are also saturated (see Fig. 2b). The geometrical dimension for these NFs is 121(13) nm for the whole NF and 5(2) nm for the core. The bending of the SANS intensity at q = 0.55 nm^{-1} allow us to establish the existence of a correlation length at 120 nm, which matches the NF size. Here, the correlation corresponding to the cores and/or to the magnetic suprastructure would lie above the experimental resolution of the technique. Therefore, no trace for these can be found in the SANS pattern.

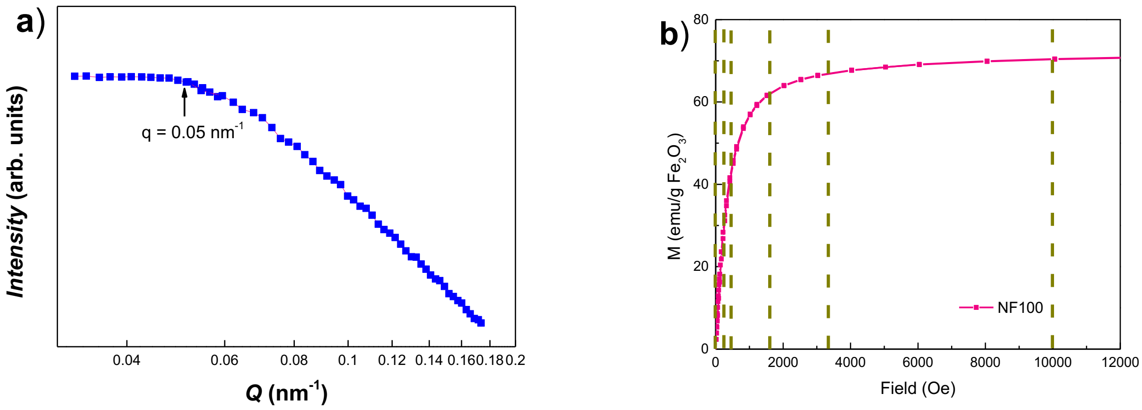

*Fig. 3: **a)** SANS intensity vs. q of the NF100 sample measured at 1 T. **b)** M vs. H (room temperature) of NF100 sample.*

Finally, it is worth commenting the fact that we were also aiming to measure both samples (NF37 and NF100) in liquid (D_2O water). However, the beamline scientist (Dr. Nina-Julianne Steinke) notified us that the samples were evaporated when starting mounting (it was a fully remote experiment, COVID). There were some inconveniences with the pellets regarding NF200 sample as well. Given so, we decided to focus on NF37 and NF100 samples, collecting more fields and detector distances, as well as we measured POLARIS in each field and detector distance.

References

[1] Q. A. Pankhurst et al., "Progress in applications of magnetic nanoparticles in biomedicine." *Journal of Physics D: Applied Physics* 42, 224001 (2009); N. K. Than, “Clinical applications of Magnetic Nanoparticles” (CRC, 2018).

[2] Philipp Bender, Dirk Honecker, and Luis Fernández Barquín. “Supraferromagnetic correlations in clusters of magnetic nanoflowers”. *Applied Physics Letters* 115, 132406 (2019).

[3] Elizabeth M Jefremovas et al. "Nanoflowers versus Magnetosomes: Comparison between two promising candidates for magnetic hyperthermia therapy." *IEEE Access* 9, 99552 (2021).