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Direct Evidence of a Graded Magnetic Interface in Bimagnetic Core/Shell Nanoparticles Using Electron Magnetic Circular Dichroism (EMCD)

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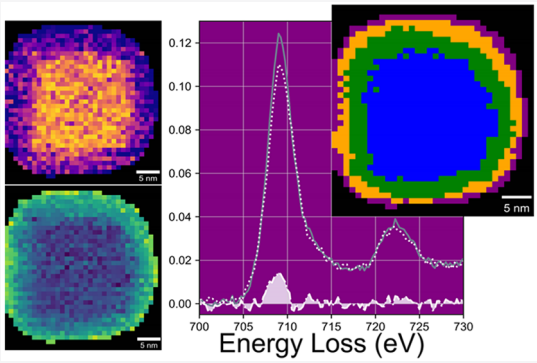
ABSTRACT: Interfaces play a crucial role in composite magnetic materials and particularly in bimagnetic core/shell nanoparticles. However, resolving the microscopic magnetic structure of these nanoparticles is rather complex. Here, we investigate the local magnetization of antiferromagnetic/ferrimagnetic FeO/Fe_3O_4 core/shell nanocubes by electron magnetic circular dichroism (EMCD). The electron energy-loss spectroscopy (EELS) compositional analysis of the samples shows the presence of an oxidation gradient at the interface between the FeO core and the Fe_3O_4 shell. The EMCD measurements show that the nanoparticles are composed of four different zones with distinct magnetic moment in a concentric, onion-type, structure. These magnetic areas correlate spatially with the oxidation and composition gradient with the magnetic moment being largest at the surface and decreasing toward the core. The results show that the combination of EELS compositional mapping and EMCD can provide very valuable information on the inner magnetic structure and its correlation to the microstructure of magnetic nanoparticles.



KEYWORDS: *EMCD, EELS, Magnetic Nanoparticles, Core/Shell Nanoparticles, Graded Interfaces*

■ INTRODUCTION

Understanding the interface structure between the different components of nanocomposite structures constitutes the keystone to harness the functional properties of the material.[1−8] In particular, graded interfaces (where there is some degree of chemical intermixing between the two counterparts at the interface; also denoted as rough or interdiffused interfaces) have been shown to play a critical role in tuning the properties of diverse materials[1−7] and specifically in core/shell nanoparticles.[3,9−12] However, despite the paramount importance of interfaces, the process of gaining detailed information about them can be rather complex, since specialized tools must be used to characterize interfaces of core/shell nanoparticles at the atomic level in real space, including compositional information (e.g., transmission electron microscopy, TEM, combined with electron energy-loss spectroscopy, EELS; anomalous small-angle X-ray scattering, ASAXS; extended X-ray absorption fine structure, EXAFS; or complex X-ray diffraction analysis).[11,13−15]

The degree of complexity increases in bimagnetic core/shell nanoparticles, a widespread type of core/shell particles due to their remarkable fundamental properties and the broad range of applications. In these systems, both the core and the shell exhibit magnetic properties (i.e., ferromagnetic, ferrimagnetic, antiferromagnetic).[3,7,14−16] Here, not only is the structural/morphological interface important but also the magnetic arrangement at the interface (e.g., strength of the exchange coupling, ferromagnetic versus antiferromagnetic interface coupling, graded anisotropy or proximity effects)[12,17−19] can play a crucial role in the properties and performance of the nanoparticles. However, obtaining information on the interface magnetic structure in nanoparticles is particularly challenging. Indirect information on the magnetic structure at the interface can sometimes be inferred from magnetization, X-ray magnetic circular dichroism (XMCD), Mössbauer spectroscopy, and other techniques.[20−22] However, these techniques give information on the whole sample, thus their lack of direct spatial resolution precludes establishing a one-to-one correlation between the magnetic behavior and the structural/morphological features at the atomic scale. To obtain a straightforward correlation between the structural and

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magnetic interface, small angle neutron scattering (SANS) can be used, although it has been used only occasionally in bimagnetic core/shell nanoparticles.[23,24] However, SANS averages over long lateral distances (typically, the whole sample), thus certain specifics of the structural−magnetic correlation can be easily overlooked. To gain a more microscopic insight of the structural−magnetic interface correlation, high-resolution magnetic transmission electron microscopy techniques like e-holography could potentially be applied, although it has been rarely used to study bimagnetic core/shell nanoparticles.[25,26]

A very specific TEM-based technique to study the magnetic information at an atomic/nanometric length scale is energy-loss chiral magnetic dichroism, or electron magnetic circular dichroism (EMCD).[27,28] EMCD is based on studying the difference between two EEL spectra acquired under the appropriate scattering conditions inside the TEM.[27,29,30] Although this approach allows obtaining the local magnetic moment with subnanometer precision, it has seldom been utilized on nanoparticles.[29,31]

Here, we demonstrate that EMCD can disentangle the magnetic properties of iron oxide-based core/shell nanocubes, consisting of a ferrimagnetic magnetite (Fe_3O_4) shell and an antiferromagnetic wüstite (FeO) core. Combining a high spatial resolution (0.45 nm) with clustering techniques for EELS data analysis,[32] the existence of a graded magnetic interface, associated with an oxidation gradient between the shell and core, is unambiguously established. It is interesting to note that an in-depth comprehension of the magnetic structure in bimagnetic nanoparticles[3,16,18,20] and, specifically, in FeO/Fe_3O_4 core/shell systems is essential not only from a more fundamental magnetic point of view but also for the optimization of their magnetic properties for their use in diverse fields like biomedical applications (e.g., magnetic hyperthermia or magnetic bioassays) or microwave absorbers.[33−36]

■ RESULTS AND DISCUSSION

Morphological Characterization. The FeO/Fe_3O_4 core/shell nanoparticles, synthesized by thermal decomposition (see Methods in Supporting Information), show a rather regular square shape and a high crystallinity with an average particle size of 29 ± 3 nm (Figure 1a). The core/shell structure was verified by means of annular bright-field (ABF) and annular dark-field (ADF) scanning transmission electron microscopy (STEM) images, evidencing a rather homogeneous morphology with a shell thickness of about 5−6 nm (Figure 1b,c) along with a cubic shape core, in agreement with previous studies on similar nanoparticles.[37,38] In contrast to other oxide core/shell nanoparticles,[39] it is worth noting that the core/shell structure (and oxidation states; see below) remains very stable under the current imaging conditions (200 kV acceleration voltage, beam currents of tens of pA), even after prolonged electron beam exposure. Pure Fe_3O_4 nanoparticles were also grown by thermal decomposition to serve as a reference. They also show a good cubic morphology with an excellent crystallinity, and the same particle size of 29 ± 3 nm as the FeO/Fe_3O_4 core/shell nanoparticles (Figure S1).

Oxidation State and Compositional Analysis. Figure 2a depicts the spatial map of the Fe oxidation state obtained from the distance between the oxygen K edge and the L_3 iron white line (method ii, see Methods in Supporting Information). Note that the signal at the left-hand side of the image corresponds to a neighboring particle. Although in the image they appear to be in contact, the particles are not overlapping as shown in Figure S2. Additional analysis of the EELS data using alternative calculation approaches[40−47] are presented in Figures S3a−c. All of the four methods used show very similar results (see Methods in Supporting Information for details). The core/shell structure can be clearly identified in these oxidation state maps. The profile of the oxidation state presented in Figure 2b (left axis) has been calculated from the mean values obtained for the four calculation methods with an additional vertical average within the dotted box in Figure 2a, to improve signal-to-noise ratio. The oxidation state of the shell is close to the expected +2.65 for Fe_3O_4. On the other hand, within the core regions the value of the oxidation state is closer to +2.2, a value that is larger than the one corresponding to FeO (+2.0). This finding is probably a consequence of the measurements representing a 2D projection of 3D structure of the particles, that is, the shell covering the core. Since the

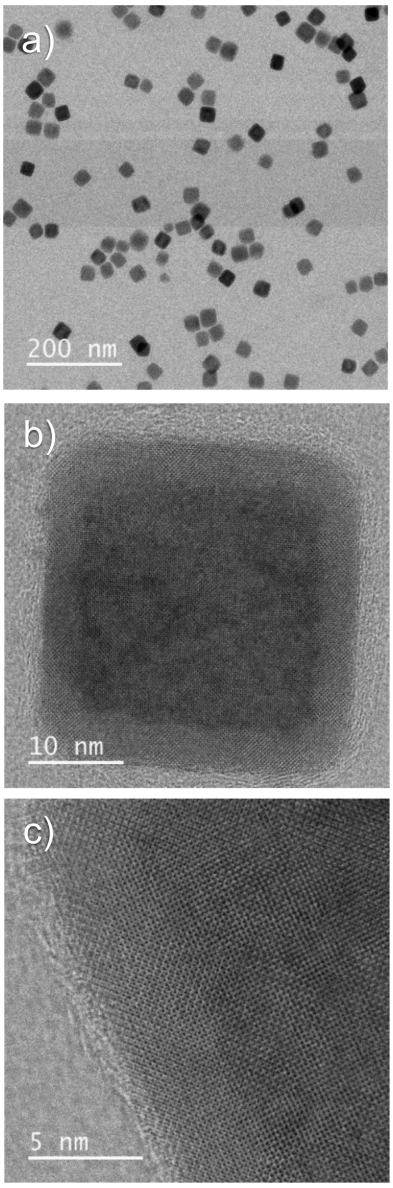

Figure 1. (a) ABF STEM image at low magnification of the FeO/Fe_3O_4 core/shell nanocubes. (b,c) ABF STEM images of an individual core/shell nanocube at higher magnification.

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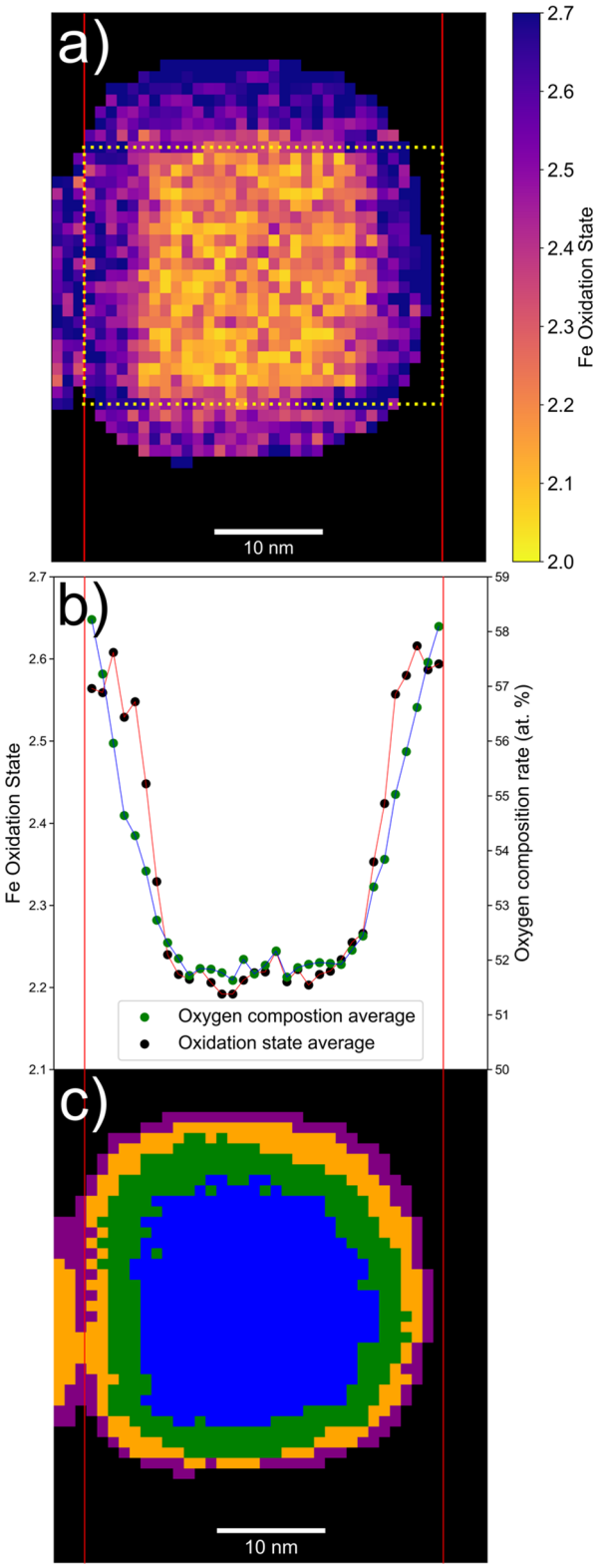

Figure 2. (a) Color map of the iron oxidation states of a FeO/Fe_3O_4 core/shell nanocube obtained from the distance between the oxygen K edge and the L_3 iron white line (method ii, see Methods in Supporting Information). (b) Line profiles of the averaged oxidation state (black dots) and the oxygen elemental composition (green dots; see Figure S3d) (in both cases averaged vertically within the dotted box in (a), and in the first case for the four analysis methods; see Figure S3). (c) Color map with the results of the clustering analysis.

electrons must go through the whole particle (core and both upper and lower shells), the shells also contribute to the EELS signal represented in the core regions.

An elemental quantification was also extracted from the EELS data. The results are shown in the color map of Figure S3d, where it is presented the oxygen elemental composition in atomic percent (atom %). This map also shows the core/shell structure, exhibiting an oxygen composition of about 57 atom % for the shell regions (in agreement to the magnetite stoichiometry), and an oxygen composition of around 52 atom % for the core region, which is a slightly higher than the expected stoichiometry for wüstite (50 atom %) but consistent with having the upper and lower magnetite shells. The oxygen concentration profile presented in Figure 2b (right axis) has been also calculated by averaging the corresponding values inside the dotted box in Figure 2a.

The results of these averaged quantifications (oxidation state and oxygen composition) definitely confirm the presence of an oxidation gradient near the core/shell interface extending about 3.0 ± 0.5 nm from the interface (as depicted in Figure 2b). In addition, there is an almost perfect agreement between the oxidation gradient and the composition gradient. Thus, the sample could be better described as $FeO/Fe_xO_y/Fe_3O_4$. Note that although the presence of such a graded interface had already been proposed for FeO/Fe_3O_4 nanoparticles using diverse approaches (lattice parameter examination, X-ray analysis, and Mössbauer analysis).[13,48−50] The EELS oxidation and compositional maps give a definitive proof of the origin of the gradient, which is mainly related to the change of the oxidation state.

To further confirm the graded interface in the FeO/Fe_3O_4 nanocubes, we used principal component analysis (PCA)[51] (to reduce the noise) and k-means clustering algorithm[32] (to identify different zones in the nanoparticle) (see Methods in Supporting Information). This latter technique allows detecting areas in the nanoparticle with analogous EELS characteristics. Interestingly, the clustering algorithm identifies four concentric areas of distinct properties, that is, inner core/outer core/inner shell/outer shell (Figure 2c). When comparing these clusters with the averaged oxidation state, the second and third clusters coincide with the oxidation and compositional gradients (Figure 2). Thus, the interface region (where the gradients are found) is identified by the clustering algorithm as two clusters, which is independently verified by the elemental quantification and oxidation state analysis. Consequently, the gradient zone is composed of two dissimilar regions, which can be interpreted as the nanoparticle being formed by a multishell, "onionlike", structure, $FeO/Fe_{1+x}O/Fe_{3-\delta}O_4/Fe_3O_4$, as proposed by Ichikawa et al.[13]

Finally, note that the pure Fe_3O_4 nanoparticles exhibit a very homogeneous oxidation state (+2.65 ± 0.05; using the four analysis approaches) as well as a homogeneous oxygen composition over the whole particle (Figure S1d,e), corroborating that the graded oxidation interphase in the bimagnetic system is an intrinsic configuration at the core−shell interface rather than to a spurious self-reduction/oxidation process of the Fe_3O_4 phase or the surrounding medium.[52,53]

Electron Magnetic Circular Dichroism (EMCD). In order to investigate the effect of the graded interface on the magnetic structure of the FeO/Fe_3O_4 nanocubes, we carried out an EMCD study at low temperature. Two EEL spectra with different chirality were obtained in two-beam conditions for each nanocube (see Methods in Supporting Information).

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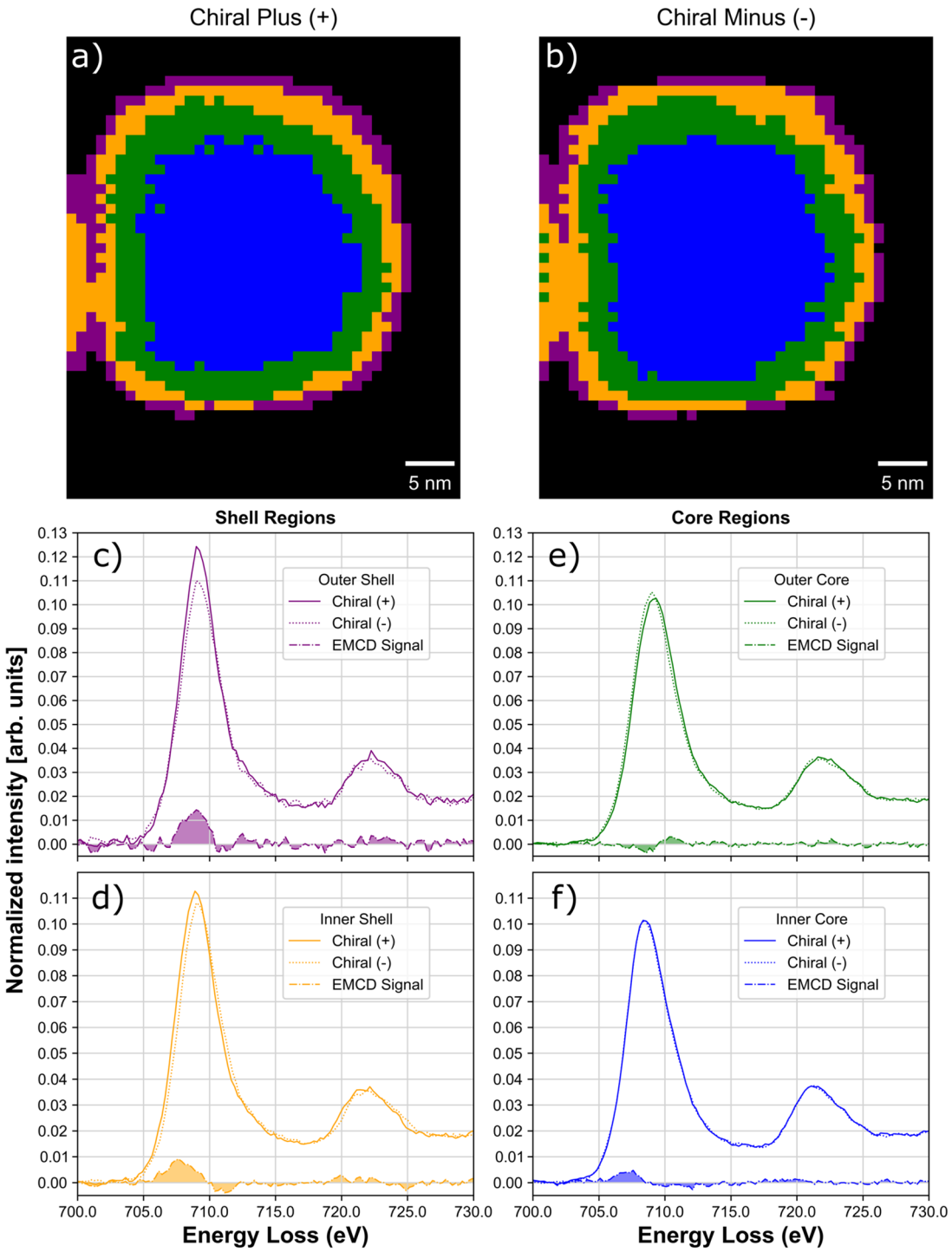

Figure 3. Color maps resulting from the clustering analysis for (a) chiral (+) and (b) chiral (−) configuration of a core/shell nanocube. (c−f) Spectra of the + and − chiralities for each section identified in the clustering and the corresponding EMCD signal: (c) outer shell (violet); (d) inner shell (orange); (e) outer core (green); and (f) inner core (blue).

The spectra correspond to the "chiral +" (right circular polarization) and the "chiral − " (left circular polarization), respectively. The + and − spectra were subject to the same previous corrections and clustering algorithms (see Methods in Supporting Information).

First, we analyzed several pure Fe_3O_4 nanocubes to serve as reference. The clustering analysis of the + and − spectra revealed homogeneous EEL spectra over the whole sample. Figure S4 shows the EEL spectra corresponding to the two different chiralities. The spectra are clearly different (Figure S4). Subtracting the + from the − spectra, we obtain the EMCD signal corresponding to the Fe_3O_4 nanocubes (Figure S4). The EMCD results obtained for the different particles are quite similar and comparable to literature data on Fe_3O_4 films and nanoparticles.[29−31]

Next, we analyzed the + and − EEL spectra for the core/shell nanocubes. Importantly, since a pixel-by-pixel comparison would be extremely complex in our case due to the weak and

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noisy signal and the small thermal drifts during the acquisition of the two different chiralities (resulting from small temperature fluctuations), we used the clustering algorithm to identify equivalent regions for each chirality. Note that the clustering procedure allows in a simple and efficient way, to classify the large quantity of spectra from the nanocubes and to reduce the intrinsic noise in data by averaging all of the spectra within a given cluster. As expected, the clustering results (i.e., areas with analogous characteristics) were very similar for both chiralities (Figure 3a,b). Similar to the pure Fe_3O_4 nanocubes, when comparing the EEL spectra of equivalent clusters in the two chiralities it can be clearly seen that the ± EEL spectra are slightly different (Figure 3c−f). By subtracting the + and − spectra for the equivalent regions, we obtain the EMCD spectra of that given area (see Figure 3c−f).[54,55] Remarkably, the EMCD spectra for all of the four regions are distinctly different. This implies that the oxidation gradient induces unambiguous changes in the magnetic structure of the nanocubes. Notably, although the intensity decreases the shape of the spectra for the four regions is somewhat similar (and similar to the Fe_3O_4 reference sample). This is somewhat expected for the surface and inner shell since they are both mainly Fe_3O_4. However, the outer and inner regions of the core are mostly FeO, thus some changes in the EMCD spectra could potentially be anticipated. The inner FeO core should be antiferromagnetic at 100 K (Néel temperature $T_N \sim 200$ K; Figure S5),[37] thus no circular dichroism would be expected. Hence, the dichroic signal should arise mainly from the contribution of the Fe_3O_4 shells (since the electrons have to go through the shell before and after they probe the core). Concerning the $Fe_{1+x}O$ outer core, it is well-known that the vacancies in $Fe_{1+x}O$ tend to cluster, forming Fe_3O_4-like regions inside an FeO matrix.[56] Consequently, it is not surprising that the EMCD spectrum of the $Fe_{1+x}O$ outer core is similar to the shell signals.

To get further insight into the magnetic structure, we tried to quantify the dichroic signal of the different regions. Unfortunately, the measuring conditions do not allow to obtain the absolute magnetic moment for each region.[57] However, since all of the measurements were carried out in the same conditions, relative magnetic moments can be obtained by integrating the area of the EMCD peaks and compared among them. As can be seen in Figure 4, a clear trend emerges from the relative moments. The outer shell has the largest magnetic moment, which decreases toward the inner shell becoming the smallest in the two core regions (Figure 4), evidencing that the oxidation gradient induces a magnetic gradient in the nanoparticles. However, two unusual features can be identified. First, the magnetic moment of the shell seems to be larger than the reference pure Fe_3O_4 nanocubes. This is somewhat unexpected since in pure Fe_3O_4 nanoparticles the surface tends to have a lower magnetic moment than the bulk due to surface disorder.[29] Nevertheless, it is important to emphasize that magnetic moments considerably larger than bulk values have been often reported in Fe_3O_4 (and other ferrites) thin films.[58−61] These enhanced moments are typically reported to occur for very thin films or at surfaces and are usually linked to specific defects such as grain boundaries, vacancies, or antiphase boundaries.[58−61] Thus, common defects often observed in this type of (and similar) nanoparticles, such as cation inversion, lattice distortions, Fe^{2+} vacancies, or grain boundaries could also contribute to the enhanced moment.[37,49,62,63] The second possible uncommon

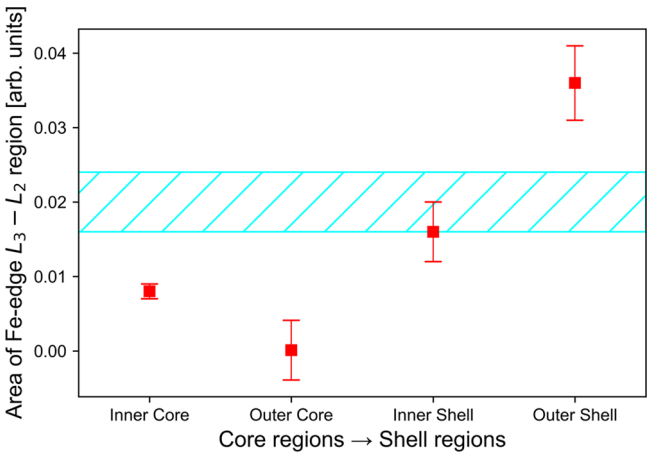

Figure 4. Area of the EMCD spectra for the different clusters. The blue region depicts the area calculated for the pure Fe_3O_4 nanocubes (see Figure S4) where the width of the band corresponds to the standard deviation of the results for the different particles.

effect that can be inferred for the magnetic moment is the unusually low moment in the outer $Fe_{1+x}O$ core. Namely, due to vacancy clustering $Fe_{1+x}O$ is expected to have larger moment than FeO. In contrast, the moment of the $Fe_{1+x}O$ region seems to be slightly smaller than the one in the FeO region. This implies that the intrinsic moment of the $Fe_{1+x}O$ outer core should be opposite to the concomitant contribution of the $Fe_{3-\delta}O_4/Fe_3O_4$ shells (arising from the path of the electrons). The simplest way to account for this effect is probably to assume an antiferromagnetic coupling between the Fe_3O_4 shell and the vacancy-induced ferrimagnetic-like spins of the core (as predicted theoretically and hinted experimentally for FeO/Fe_3O_4 and actually observed for other FeO-based systems[63−65]). In fact, this assumption could be supported by the unusually large downturn in $M(T)$ below T_N of FeO (Figure S5). Note that antiferromagnetic core/shell interface coupling has actually been reported in other iron oxide-based bimagnetic core/shell nanoparticles.[17,66]

In addition, the overall results of the same type of analysis applied to other particles (by studying a section of the nanoparticle rather than the whole nanoparticle) were comparable, confirming the presence of a gradual change of the oxidation state at the interface leading to a magnetic gradient (see Supporting Information; Figure S6).

Notably, this STEM-based EELS approach merging compositional and magnetic information is not only limited to oxide-based core/shell nanoparticles, but it could also be applied to other types of core/shell structures (e.g., metal/metal, metal/oxide) and to other morphologies (e.g., Janus nanoparticles) or even inhomogeneous nanoparticles (e.g., phase segregation) or nanostructured composites.

■ CONCLUSIONS

In summary, we have demonstrated that the combination of EELS compositional mapping and EMCD is an excellent option to unravel the correlation between the structural/morphological and magnetic structure in bimagnetic core/shell nanoparticles. Importantly, by using a clustering algorithm the analysis of the EMCD can be greatly simplified but still achieve nanometer resolution. The results show that the FeO/Fe_3O_4 nanocubes have an interdiffused interface leading to a $FeO/Fe_{1+x}O/Fe_{3-\delta}O_4/Fe_3O_4$ onionlike structure. This structure

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results in a graded magnetic configuration with some unusual features, like an enhanced moment for the surface Fe_3O_4 shell. These results open new avenues for studying the magnetic properties of not only complex magnetic nanoparticles but also nanostructured materials.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.1c02089.

Descriptions and details of the experimental methods: nanoparticles synthesis, morphological characterization, electron energy-loss spectroscopy, determination of oxidation state, determination of the elemental composition, the electron magnetic circular dichroism technique, and magnetic characterization; Figures S1 to S9 (PDF)

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Notes

The authors declare no competing financial interest.

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