magnetochemistry

Editorial

Advances in Magnetic Nanomaterials and Nanostructures

Francesco Congiu * and Giorgio Concas *

Dipartimento di Fisica, Università di Cagliari, S.P. Monserrato-Sestu km 0.700, Monserrato, 09042 Cagliari, Italy
* Correspondence: franco.congiu@dsf.unica.it (F.C.); gconcas@unica.it (G.C.)

Magnetic nanomaterials, in which non-bulk magnetic properties emerge because of their low dimension, are a class of materials with huge application potential in several areas, providing, at the same time, an exciting field of fundamental research. Continuous advances in the synthesis techniques of magnetic nanoparticles, thin films, nanotubes/nanowires, and nanodots with controlled size, morphology, chemical composition, and surface chemistry are making tailoring the magnetic properties of high-performance magnetic materials and devices more and more effective, giving rise to technological applications in different fields such as nanomedicine (imaging, drug delivery, therapeutic hyperthermia, and sensors), catalysis, high-density magnetic storage, spintronics, and thermoelectric systems for energy harvesting, just to name just a few.

This Special Issue of *Magnetochemistry*, 'Advances in Magnetic Nanomaterials and Nanostructures', is dedicated to gathering recent results in the synthesis, fabrication, and characterization of nanostructured magnetic materials and devices with potential applications in the aforementioned research fields. It consists of nine papers by eminent researchers active in this field, including seven research articles, and two review articles.

The article 'On the Distribution of Magnetic Moments in a System of Magnetic Nanoparticles' by Max Javier Jáuregui Rodríguez, Denner Serafim Vieira, Renato Cardoso Nery, Gustavo Sanguino Dias, Ivair Aparecido dos Santos, Renio dos Santos Mendes, and Luiz Fernando Cotica, from the State University of Maringá, Maringà, Paraná, Brazil (R.dS.M. also from the National Institute of Science and Technology for Complex Systems, Rio de Janeiro, Rio de Janeiro, Brazil) [1] focuses on the magnetic moment distribution in magnetic nanoparticle (MNP) systems, challenging the traditional view that a lognormal probability density function (PDF) universally describes this distribution. The study shows that alternative models, such as gamma and Weibull PDFs, can also fit magnetization curves effectively, suggesting that no single model is universally applicable. The differences in these probability density functions raise questions about the true nature of magnetic moment distributions. The study proposes a method to identify the actual distribution directly from magnetization curves, although noise and coercivity in the data can cause difficulties. This approach could extend beyond ferrimagnetic systems to other magnetic orders, such as ferromagnetism or antiferromagnetism. Despite these challenges, the research offers a fresh perspective on superparamagnetism and nanomagnetism, contributing to a deeper understanding of MNP behavior.

Two-dimensional and layered materials, which are of great interest for a variety of technological applications in sectors such as batteries, catalysis, electronics, gas sensing, and spintronics, are the subject of the article by Samuel W. Kimmel, Barry D. Koehne, Ben Gibson, Wilhelmus J. Geerts, Nikoleta Theodoropoulou, and Christopher P. Rhodes from the Texas State University, San Marcos, TX, USA. In this paper, entitled 'Structure and Magnetism of Iron-Substituted Nickel Hydroxide Nanosheets', the authors in [2] examine the effect of iron substitution on the structure and magnetism of nickel hydroxide ($Ni(OH)_2$) nanosheets synthesized using a microwave-assisted hydrothermal method. Iron is incorporated into the $Ni(OH)_2$ lattice, altering both the structure and magnetic properties of the nanosheets. At lower Fe concentrations, the material exhibits ferromagnetism, while at

check for updates

Citation: Congiu, F.; Concas, G. Advances in Magnetic Nanomaterials and Nanostructures. *Magnetochemistry* **2024**, *10*, 108. https://doi.org/10.3390/magnetochemistry10120108

Received: 11 December 2024
Accepted: 13 December 2024
Published: 18 December 2024

higher concentrations, it transitions to ferrimagnetism due to interactions between magnetic sublattices and shape anisotropy. The study shows a correlation between increased Fe content and higher magnetic anisotropy, which leads to elevated coercivity. This anisotropy is influenced by variations in the crystalline domain sizes. The findings reveal how Fe substitution affects electron interactions in layered materials and highlight the potential for controlling magnetic and structural properties in two-dimensional materials through careful manipulation of their chemical composition.

With the paper 'Magnetic Hyperthermia and Antibacterial Response of $CuCo_2O_4$ Nanoparticles Synthesized through Laser Ablation of Bulk Alloy' [3] by Imran Ali, Yasir Jamil, Saeed Ahmed Khan, Yunxiang Pan, Aqeel Ahmed Shah, Ali Dad Chandio, Sadaf Jamal Gilani, May Nasser Bin Jumah, Yusra Fazal, Jun Chen, and Zhonghua Shen from the University of Science and Technology, Nanjing, China (I.A., Y.P., Y.F., and Z.S.), the University of Agriculture, Faisalabad, Pakistan (Y.J.), the Sukkur IBA University, Sukkur, Pakistan (S.A.K.), the NED University of Engineering and Technology, Karachi, Pakistan (A.A.S. and A.D.C.), the Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia (S.J.G. and M.N.B.J.), and Nanjing University of Science and Technology, Nanjing, China (J.C.), we enter the interesting field of medical applications of nanomagnetic particles. This study investigates the synthesis and properties of copper–cobalt oxide ($CuCo_2O_4$) nanoparticles, created using an arc-melted copper–cobalt alloy and a laser ablation method. Various techniques, including TEM, SEM, and DLS, confirm the spherical shape and nanoscale size of the particles. The antibacterial activity of the NPs is successfully tested, showing effective inhibition, suggesting potential for antibacterial applications. Furthermore, the NPs demonstrate non-mutagenic properties against certain bacterial strains, highlighting their safety for biomedical use. The study also explores the magnetic hyperthermia potential of the NPs, which could be valuable in cancer treatment, as the nanoparticles show promising specific absorption rates under varying magnetic field strengths. Overall, the research highlights the multifunctional capabilities of $CuCo_2O_4$ NPs, suggesting their potential in medical treatments, particularly in antibacterial and cancer therapies.

In the theoretical paper 'Influence of Mn Doping on Local Spin Moments and Stacking Fault Energies in Co(Mn) Alloys', the authors, Kayla Cole-Piepke, Prabandha Nakarmi, Alicia Koenig, Gregory B. Thompson, Tim Mewes, Claudia Mewes, Ronald Noebe, and Alex Leary from the University of Alabama, Tuscaloosa, AL, USA (K.C.P, P.N., T.M., C.M., A.K., and G.B.T.), and the NASA Glenn Research Center, Cleveland, OH, USA (R.N. and A.L.), explore the effects of manganese doping on the local magnetic moments and stacking fault energies (SFEs) in face-centered cubic cobalt systems using first principles calculations [4]. The introduction of Mn significantly influences both the magnetic and structural properties of Co. The research shows that Mn doping enhances the stability of intrinsic stacking faults, especially when Mn atoms are positioned away from the fault interface. Systems with higher Mn concentrations are likely to experience increased faulting, which could improve mechanical properties. Additionally, Mn doping slightly increases the average magnetic moment per atom compared to pure Co, potentially benefiting the material's magnetic properties, such as permeability. These results suggest that Mn doping in Co could be used to customize the material's SFEs and magnetic properties for specific applications, although further investigation is needed on its anisotropy.

In the paper 'Hydrothermal Synthesis and Magnetic Properties of Zn/Mn Oxides Nano Particles', the authors Izabela Kuryliszyn-Kudelska, Witold Dobrowolski, Monika Arciszewska, Branka Hadžić, Nebojsa Romčević, Maja Romčevi ́, Daniel Sibera, and Urszula Narkiewicz from the Polish Academy of Sciences, Warsaw, Poland (I.K.K., W.D., and M.A.), the Belgrade University, Belgrade, Serbia (B.H., N.R., and M.R.), and the West Pomeranian University of Technology, Szczecin, Poland (D.S., U.N.), explore the magnetic properties of nanocrystalline zinc–manganese oxide compounds synthesized using a hydrothermal method [5]. The samples show a range of magnetic behaviors depending on the manganese oxide content. At lower concentrations of manganese oxide, the samples exhibit Curie–Weiss paramagnetic behavior, with antiferromagnetic interactions predominating. As the amount of manganese oxide increases, weak ferromagnetic and spin-glass-like behaviors appear, with spin-glass freezing observed at low temperatures. The hydrothermal method results in more complex magnetic responses compared to the calcination method, which produces ferrimagnetism linked mainly to the Mn_3O_4 phase. The presence of manganese oxide contributes to distinct responses in AC magnetic susceptibility. Overall, these findings highlight how the synthesis method significantly influences the final magnetic properties of the nanocomposites, with hydrothermal synthesis leading to a broader variety of magnetic phases and interactions than calcination, which yields a simpler ferrimagnetic behavior.

The article 'Magnetoelectric Coupling Effects in Tb-Doped $BiFeO_3$ Nanoparticles' [6] by Iliana Apostolova from the University of Forestry, Sofia, Bulgaria, Angel Apostolov from the University of Architecture, Sofia, Bulgaria, and Julia Wesselinowa from the Sofia University "St. Kliment Ohridski", Sofia, Bulgaria, investigates the magnetic, electric, and optical properties of Tb-doped $BiFeO_3$ nanoparticles, focusing on the effects of size and doping concentrations. The results show enhanced multiferroic properties and band-gap tuning due to the combination of doping and nanoscale effects. As the nanoparticle size decreases and Tb-doping concentration increases, magnetization and polarization improve. While the Néel temperature remains stable, the Curie temperature decreases with higher doping. The dielectric constant and band gap are influenced by the size, doping, and magnetic field. Tb-doping induces weak ferromagnetism and modifies the ferroelectric order through magnetoelectric coupling. This coupling, along with lattice distortion and Coulomb interactions, also explains the reduced band-gap. Overall, the Tb-doping and size reduction significantly enhance the magnetoelectric effect, highlighting the strong interdependence of structural, magnetic, electric, and optical properties in these nanoparticles.

The study 'Synthesis and Characterization of Magnetite/Gold Core Shell Nanoparticles Stabilized with a β-Cyclodextrin Nanosponge to Develop a Magneto-Plasmonic System' [7] reports the synthesis of magnetite–gold core–shell nanoparticles using tetramethylammonium hydroxide (TMAH) to enhance the interface between the magnetite core and the gold shell. The authors, Sebastián Salazar Sandoval, Daniel Santibáñez, Ana Riveros, Fabián Araneda, Tamara Bruna, Nataly Silva, Nicolás Yutronic, Marcelo J. Kogan, and Paul Jara from the Universidad de Chile, Ñuñoa, Chile (S.S.S., D.S., N.Y., and P.J.), the Universidad de Chile, Santiago, Chile (S.S.S., A.R., M.J.K., and F.A.), Universidad de Chile, Independencia, Chile (S.S.S., A.R., and M.J.K.), Universidad del Desarrollo, Las Condes, Chile (S.S.S. and N.S.), and the Universidad Santo Tomás, Santiago, Chile (T.B.), make use of various characterization techniques to prove that the synthesized NPs present a core–shell structure with a narrow size distribution and to highlight their plasmonic and superparamagnetic properties. The NPs, stabilized using a cyclodextrin nanosponge (CDNSs), result in a magneto-plasmonic system for potential biomedical applications, such as drug encapsulation and controlled release. Characterization of the CDNSs-magnetite–gold system confirms that the nanosponge maintains the integrity of the NPs, although it slightly reduces the saturation magnetization due to its diamagnetic properties. Despite this, this study shows that the system offers promising potential for pharmaceutical formulations and drug delivery applications.

The review paper 'Magnetic Nanomaterials and Nanostructures in Sample Preparation Prior to Liquid Chromatography' [8] by Georgios Antoniou and Victoria Samanidou from the Aristotle University of Thessaloniki, Thessaloniki, Greece, focuses on the applications of magnetic nanomaterials and nanostructures in sample preparation prior to liquid chromatography (LC). Their unique properties, such as superparamagnetism, biocompatibility, and selectivity, make them highly efficient for extracting and enriching analytes, even at low concentrations. Magnetic solid-phase extraction (MSPE) and dispersive liquid–liquid microextraction (DLLME) are highlighted as the most significant applications, where magnetic materials act as sorbents to improve accuracy and sensitivity when combined with LC. The development of automated techniques, such as online-SPE, further enhances the potential for more efficient assays. Magnetic ionic liquids (MILs) are also discussed, offering an effective solution for extracting a wide range of analytes in complex samples thanks to their combined physicochemical properties and magnetic susceptibility. Despite their promising performance, MILs still have room for improvement, especially in terms of synthesis and interaction with analytes.

The review article by Simge Balaban Hanoglu, Duygu Harmanci, Nursima Ucar, Serap Evran, and Suna Timur, from the Ege University, Izmir, Turkey, entitled 'Recent Approaches in Magnetic Nanoparticle-Based Biosensors of miRNA Detection' [9] focuses on the use of MNPs for detecting miRNAs in biological samples. Magnetic nanoparticles have gained prominence due to their biocompatibility, easy surface modification, and high chemical stability, making them ideal for applications like cancer detection. miRNAs—small circulating molecules crucial for early disease diagnosis—are difficult to detect. However, MNPs enable the separation and rapid detection of miRNAs from complex samples, such as blood or urine, even at low concentrations. Coating and functionalizing magnetic nanoparticles helps reduce toxicity, a major concern in their use. MNPs are also utilized in biosensors for separating and concentrating analytes, improving their signal and selectivity. Despite challenges in size, shape, and surface coating, MNP-based detection systems show promise in miRNA detection. In the future, these systems could integrate with machine learning to enhance early disease detection and prediction. Further development is required to address limitations related to sample complexity and measurement conditions.

We believe that this Special Issue can provide valuable insights into the very current topic of nanomagnetic materials and that it can be of interest to a large community of researchers in the field of materials science and magnetism. It is a great pleasure for us to thank all the authors who, with their very high-quality submissions, made the publication of this Special Issue possible. Thanks also go to all the *Magnetochemistry* editorial staff for their constant assistance during the preparation of this Special Issue.

Author Contributions: F.C. and G.C. contributed to the writing of this editorial. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Rodríguez, M.J.J.; Vieira, D.S.; Nery, R.C.; Dias, G.S.; dos Santos, I.A.; Mendes, R.d.S.; Cotica, L.F. On the Distribution of Magnetic Moments in a System of Magnetic Nanoparticles. *Magnetochemistry* **2022**, *8*, 129. [CrossRef]
2. Kimmel, S.W.; Koehne, B.D.; Gibson, B.; Geerts, W.J.; Theodoropoulou, N.; Rhodes, C.P. Structure and Magnetism of Iron-Substituted Nickel Hydroxide Nanosheets. *Magnetochemistry* **2023**, *9*, 25. [CrossRef]
3. Ali, I.; Jamil, Y.; Khan, S.A.; Pan, Y.; Shah, A.A.; Chandio, A.D.; Gilani, S.J.; Bin Jumah, M.N.; Fazal, Y.; Chen, J.; et al. Magnetic Hyperthermia and Antibacterial Response of $CuCo_2O_4$ Nanoparticles Synthesized through Laser Ablation of Bulk Alloy. *Magnetochemistry* **2023**, *9*, 68. [CrossRef]
4. Cole-Piepke, K.; Nakarmi, P.; Koenig, A.; Thompson, G.B.; Mewes, T.; Mewes, C.; Noebe, R.; Leary, A. Influence of Mn Doping on Local Spin Moments and Stacking Fault Energies in Co(Mn) Alloys. *Magnetochemistry* **2023**, *9*, 138. [CrossRef]
5. Kuryliszyn-Kudelska, I.; Dobrowolski, W.; Arciszewska, M.; Hadžić, B.; Romčević, N.; Romčević, M.; Sibera, D.; Narkiewicz, U. Hydrothermal Synthesis and Magnetic Properties of Zn/Mn Oxides Nano Particles. *Magnetochemistry* **2023**, *9*, 139. [CrossRef]
6. Apostolova, I.; Apostolov, A.; Wesselinowa, J. Magnetoelectric Coupling Effects in Tb-Doped BiFeO3 Nanoparticles. *Magnetochemistry* **2023**, *9*, 142. [CrossRef]
7. Salazar Sandoval, S.; Santibáñez, D.; Riveros, A.; Araneda, F.; Bruna, T.; Silva, N.; Yutronic, N.; Kogan, M.J.; Jara, P. Synthesis and Characterization of Magnetite/Gold Core Shell Nanoparticles Stabilized with a β-Cyclodextrin Nanosponge to Develop a Magneto-Plasmonic System. *Magnetochemistry* **2023**, *9*, 202. [CrossRef]
8. Antoniou, G.; Samanidou, V. Magnetic Nanomaterials and Nanostructures in Sample Preparation Prior to Liquid Chromatography. *Magnetochemistry* **2022**, *8*, 29. [CrossRef]
9. Balaban Hanoglu, S.; Harmanci, D.; Ucar, N.; Evran, S.; Timur, S. Recent Approaches in Magnetic Nanoparticle-Based Biosensors of miRNA Detection. *Magnetochemistry* **2023**, *9*, 23. [CrossRef]