MA 39: Magnetic Particles

Time: Thursday 9:30–13:15 Location: H31

MA 39.1 Thu 9:30 H31

Wechselwirkung magnetischer, hydrodynamischer und thermodynamischer Kräfte und die Dynamik von suspendierten Mikropartikel: Selbstorganisation und Anwendungen — •Claus Fütterer — Biophysical Tools GmbH/Forschung, 04317 Leipzig, Germany

Superparamagnetische Mikro- und Nanopartikel haben rasch zahlreiche Einsatzmöglichkeiten in der Biophysik, der Biotechnologie und Materialforschung gefunden. Insbesondere die Aufreinigung von Molekülen und Zellen ist heute so einfach wie nie zuvor und der Automatisierung zugänglich gemacht worden. Die Möglichkeiten sind damit jedoch bei Weitem noch nicht ausgeschöpft.

Das einzigartige Kleeblatt-Potential mit positiven und negativen Anziehungszonen suspendierter Partikel in Wechselwirkung mit hydrodynamischen Feldern sowie thermodynamischen Fluktuationen ist nicht nur verantwortlich für eine ungewöhnlich dynamische Selbstorganisation von Mikrostrukturen (Aggregation und Separation), sondern auch für neue Anwendungen wie zum Beispiel die massiv parallele Untersuchung von Wechselwirkungsdynamiken von Einzelmolekülen in hoher Präzision. Hierzu werden ein Abriss der Theorie, experimentelle Daten sowie Perspektiven für mögliche zukünftige Anwendungen präsentiert.

MA 39.2 Thu 9:45 H31

Structural and magnetic properties of self-assembled 3D nanoparticle macrocrystals — •Michael Smik, Genevieve Wilbs, Elisa Volkmann, Emmanuel Kentzinger, Jörg Persson, Ulrich Rücker, Oleg Petracic, and Thomas Brückel — Jülich Centre for Neutron Science JCNS and Peter Grünberg Institut PGI, JARA-FIT, Forschungszentrum Jülich GmbH, 52425 Jülich

We have used centrifuge assisted sedimentation to fabricate 3D nanoparticle 'macrocrystals' from commercially available spherical iron oxide nanoparticles. The assembly of macrocrystals up to 300 μm in size was possible. The samples were characterized using scanning electron microscopy, which allowed for the identification of single crystals, which could then be isolated for further study. Using small angle x-ray scattering (SAXS) using the new in-house instrument 'GALAXI' (Gallium Anode Low-Angle X-ray Instrument) the supercrystalline structure could be identified to be face-centered cubic. The magnetic structure was investigated by a variety of magnetometric methods, including zero field cooled and field cooled curves, thermo remanent and isothermal remanent magnetization, as well as ac susceptibility. All methods hint toward a spin-glass-like structure, however, deviations from the expected results for a spin-glass indicate a novel kind of magnetic ordering.

MA 39.3 Thu 10:00 H31

Strain and Electric Control of Magnetism in Supercrystalline Iron Oxide Nanoparticle - BaTiO3 composites — •Liming Wang[1], Oleg Petracic[1], Emmanuel Kentzinger[1], Ulrich Rücker[1], Alexandros Koutsioumpas[2], Stefan Mattauch[2], and Thomas Brückel[1,2] — [1]Jülich Centre for Neutron Science JCNS and Peter Grünberg Institut PGI, JARA-FIT, Forschungszentrum Jülich GmbH, Jülich — [2]Jülich Centre for Neutron Science JCNS at Heinz Maier-Leibnitz Zentrum MLZ, Forschungszentrum Jülich GmbH, n, Lichtenbergsrtr. 1, Graching

The manipulation of magnetism of self-assembled iron oxide nanoparticle (NP) monolayers on top of BaTiO3 (BTO) single crystals is reported. We observe strain induced magnetoelectric coupling (MEC) as shown by measurements of both the magnetization and magnetoelectric ac susceptibility (MEACS). The magnetization, coercivity, remanent magnetization and MEACS signal as function of temperature shows abrupt jumps at the BTO phase transitions temperatures. A magnetic "hardening effect" is observed with variation of strain or electric field. Grazing incident small angle X-ray scattering (GISAXS) and scanning electron microscopy (SEM) confirms a hexagonal close-packed supercrystalline order of the NP monolayers.

MA 39.4 Thu 10:15 H31

GMR sensors for detection of magnetic nanoparticles in lubricants — •Thomas Rempel, Martin Gottschalk, and Andreas Hütten — Center for Spinelectronic Materials and Devices, Physics Department, Bielefeld University, PB 100131, D-33501 Bielefeld, Germany

Magnetic nanoparticles are growing of technological interest and show beneficial characteristics in a wide field of applications. One emerging field of application is the use of magnetic nanoparticles in lubricants to e.g. tune the lubricant's friction coefficient. As particle concentration and agglomeration influence the lubricants properties, an on-site quality control device is necessary for real life application. We demonstrate our first approach based on a GMR sensor to face these challenges. Therefore, serpentine shaped sensors are fabricated by lithographic methods on which solvents with magnetic nanoparticles are placed. The sensor's response will be discussed for different geometries. To characterize the particle dispersion and agglomeration inside the lubricant, microscopic techniques with resolutions on the nanometer length scale are necessary. We present an approach to get an insight of the nanoparticle distribution and agglomeration with a dual beam focused ion beam (FIB) and a scanning electron microscope.

MA 39.5 Thu 10:30 H31

Ultra high magnetic anisotropy in octapod shaped iron oxide nanoparticles — •P Anil Kumar[1,2], Gurvinder Singh[3], Joachim Landers[1], Giuseppe Muscas[4,5], Davide Peddis[5], Heiko Wende[1], and Roland Mathieu[2] — [1]Faculty of Physics and CENIDE, University of Duisburg - Essen, Duisburg 47048, Germany — [2]Department of Engineering Sciences, Uppsala University, 751 21 Uppsala, Sweden — [3]Department of Materials Science and Engineering, NTNU, N-7491, Trondheim, Norway — [4]Department of Physics, Uppsala University, 751 21 Uppsala, Sweden — [5]ISM-CNR, Area della Ricerca, C.P. 10-00016 Monterotondo Scalo, Roma, Italy

The shape of the magnetic nanoparticles is known to effect the magnetic anisotropy of the particles apart from the surface anisotropy. Here, we present results of macroscopic magnetic measurements and Mössbauer spectroscopy on octapod shaped Fe_3O_4 nanoparticles (of $\sim$ 20 nm size) obtained by controlling the growth of selective crystal orientations. These octapod particles show a distinct superparamagnetic transition indicative of a narrow size distribution. Interestingly, the isothermal magnetic hysteresis loops measured at 5 K and up to a field of 9 T are unconventional of any iron oxide system. The hysteresis loop remains open and the magnetization is unsaturated even up to 9 T field, indicating a very high magnetic anisotropy of these particles. Temperature dependent and in-field Mössbauer spectroscopy analysis also supports the inferences drawn from the macroscopic magnetic measurements. We will discuss possible reasons for such a high magnetic anisotropy in these particles.

MA 39.6 Thu 10:45 H31

Theory of nano-spintronic logic functionalities on a Ni_4 cluster — •Wolfgang Hübner, Georgios Lefkidis, and Debapriya Chaudhuri — Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, 67653 Kaiserslautern, Germany

Starting from high level, *ab initio* calculations, we present several new all-spin-based nano-logic functionalities, which require a minimum of four active magnetic centers. The underlying mechanisms for all operations are coherent Λ processes, driven by suitably tailored laser pulses.

Our calculations indicate, that in the geometrically optimized Ni_4 cluster the spin density exhibits a high degree of localization. In addition to ultrafast (90 fs) optically triggered *local spin flips* and *spin transfers*, which require only one or two atomic magnetic centers, we demonstrate the following operations with sufficiently high fidelity: spin bifurcation and its reverse (spin association/ merging), as well as the *which path* interference. We construct two nano-logic elements: a 4-bit cyclic SHIFT register [1] and a pure-spin OR gate [2]. The former depends on the appropriate combinations of the spin transfer scenarios whereas the latter depends on the *spin association*. The *which path* interference employs the phase of the final spin state of a two-step spin transfer process which depends on the exact path traveled by the spin.

The scenarios provide the necessary basic functionalities for nanologic applications.

[1] G. D. Mahan, Phys. Rev. Lett. **102**, 016801 (2009).
[2] D. Chaudhuri, University of Kaiserslautern, Ph.D. Thesis (2016).

15 min. break

MA 39.7 Thu 11:15 H31

Experimental investigation of the spin structure in MnO nanoparticles, powder and single crystal — •Xiao Sun[1], Alice Klapper[1], Yixi Su[2], Kirill Nemkovski[2], Oskar Köhler[3], Heiko Bauer[3], Anna Schilmann[3], Wolfgang Tremel[3], Oleg Petracic[1], and Thomas Brückel[1] — [1]Jülich Centre for Neutron Science JCNS and Peter Grünberg Institut PGI, JARA-FIT, Forschungszentrum Jülich GmbH, Jülich — [2]Jülich Centre for Neutron Science JCNS at Heinz Maier-Leibnitz Zentrum MLZ, Forschungszentrum Jülich GmbH, Garching — [3]Institut für Anorganische und Analytische Chemie, Johannes Gutenberg-Universität Mainz, Mainz

We have studied the magnetic spin structure of antiferromagnetic (AF) MnO nanoparticles (NPs), powder and single crystal using both magnetometry and polarized neutron scattering. MnO NPs show a peculiar peak at low temperatures (ca. 25K) instead at the Néel temperature of 120K in the magnetization curves. However, polarized neutron scattering results show the expected behavior of the AF order parameter of MnO. For MnO powder and single crystal, features at both the low temperature and Néel temperature have been found in magnetometry. A phase transition at the peak temperature in the MnO single crystal has been observed in neutron scattering. This peak temperature matches the Tc of Mn2O3 or Mn3O4. We conclude that the magnetic behavior of MnO NPs can be explained by a superposition of superparamagnetic-like thermal fluctuations of the AF Néel vector inside an AF core and a strong magnetic coupling to a FM Mn2O3 or Mn3O4 shell.

MA 39.8 Thu 11:30 H31

Strain analysis with atomic resolution at FePt-substrate interfaces — •S. Wicht[1,2], S. H. Wee[3], O. Hellwig[3], D. Weller[3], and B. Rellinghaus[1] — [1]IFW Dresden, Helmholtzstr. 20, D-01069 Dresden, Germany. — [2]TU Dresden, IFWW, D-01062 Dresden, Germany. — [3]HGST, 3403 Yerba Buena Rd, San Jose, CA-95135, USA.

Highly textured $L1_0$-ordered FePt films are foreseen to overcome the performance of state of the art CoCrPt based perpendicular media and achieve storage densities beyond 1.5 $TBit/in^2$. A crucial criteria to develope the full potential of the film is a distinct (001) texture of the $L1_0$ phase. The common way to achieve an out-of-plane (oop) texture is to growth FePt epitaxially on an appropriate seed layer, namely MgO. MgO, however, causes some drawbacks like a poor wetting behavior of FePt and a certain misalignment of the easy axis orientation. To further investigate this phenomenon and the influence of the lattice mismatch between the unit cells of FePt and the substrate, discontinuous FePt films are grown on single crystals of $(La,Sr)(Al,Ta)O_3$, $SrTiO_3$, $MgAl_2O_4$ and MgO. The FePt films exhibit mainly oop textured islands. Nevertheless, undesired fractions of $L1_2$-ordered and in-plane oriented crystals are occur at reduced lattice mismatches. Quantitative HRTEM analyses reveal that enhanced lattice mismatches are accompanied by an increased density of dislocations at the interface, which goes along with a broadened FePt (002) rocking curve. The correlations of these findings will be discussed within the presentation.

MA 39.9 Thu 11:45 H31

Solid state NMR - a powerful tool to characterize magnetic nanoparticle assemblies — •Franziska Hammerath[1,2], Markus Gellesch[2], Maik Scholz[2], Rasha Ghunaim[2], Maria Eleni Belesi[2], Alexey Alfonsov[2], Heike Schlörb[2], Silke Hampel[2], Sabine Wurmehl[2], and Bernd Büchner[2] — [1]Institute for Solid State Physics, Dresden Technical University, TU Dresden, 01062 Dresden, Germany — [2]IFW Dresden, Institute for Solid State Research, PF 270116, 01171 Dresden, Germany

We present nuclear magnetic resonance (NMR) measurements on magnetic nanoparticles, most of them synthesized inside carbon nanotubes, with unary, binary and ternary precursor conditions. Our studies on Co, Fe, CoFe, CoGa, Co_2FeGa and Mn_3O_4 nanoparticles show that nuclear magnetic resonance is the method of choice to identify and quantify different chemical compositions, local environments and crystallographic structures of intermetallic magnetic nanoparticle assemblies. Advantages of this method compared to standard characterization methods such as powder X-ray diffraction or TEM-EDX will be discussed.

MA 39.10 Thu 12:00 H31

SmCo nanoparticles from the gas-phase: On the stability of intermetallic $SmCo_5$ at the nanoscale. — •Frank Schmidt[1,2], Ludwig Schultz[1], and Bernd Rellinghaus[1] — [1]IFW Dresden, Helmholtzstraße 20, D-01069 Dresden, Germany — [2]TU Dresden, IFWW, D- 01062 Dresden, Germany

$SmCo_5$ is among the magnetic materials with the highest magnetocrystalline anisotropies and Curie temperatures, T_C, respectively. The latter are indispensable for high temperature applications, where $Nd_2Fe_{14}B$ can no longer be used. In the present study, we investigate the formation and phase stability of SmCo nanoparticles from the gas phase, which could serve as a model system for their (nanostructured) bulk counterparts. Particular attention is paid to the question, if the intermetallic phase $SmCo_5$ (or one of its derivates) forms in particles with only a few nanometer in size, which grow without contact to any solid or liquid matrix in a low pressure Ar atmosphere. This question is closely related to the possible occurrence of segregation that is frequently observed in nanoscale materials and that goes along with a deterioration of the magnetic properties. Aberration-corrected transmission electron microscopy is used in combination with spectroscopic methods to determine the local structure and the chemical composition. It is found that, depending on the phase formation temperature, SmCo nanoparticles tend to de-mix. The magnetic properties of the particle ensembles, as determined from VSM measurements, are correlated with the predominant core-shell structure of the SmCo particles.

MA 39.11 Thu 12:15 H31

Superparamagnetic Response from Nanoparticles in Splenic Macrophages — •Ulf Wiedwald, Marina Spasova, Anna Elsukova, and Michael Farle — Faculty of Physics and Center for Nanointegration (CENIDE), University Duisburg-Essen, Lotharstr. 1, 47057 Duisburg, Germany

We have identified that murine spleen macrophages harbor an enormous amount of endogenous nanoparticles with monodisperse crystal size and unexpected superparamagnetic properties [1]. It is well established that macrophages contain the 12 nm disk-shaped protein ferritin with an 8 nm cage that can buffer up to 4500 iron atoms in the form of the antiferromagnetic compound ferrihydrite [2]. Although the diameter and iron content identified by transmission electron microscopy support the presence of ferritin, the strong magnetic response is incompatible with the nature of ferrihydrite. We characterized these nanoparticles form splenic macrophages by SQUID magnetometry and found an average magnetic moment of $8600\mu_B$ per particle in the superparamagnetic state at T = 300 K. This indicates the presence of magnetic phases different from the expected antiferromagnetic ferrihydrite. As a result, the intrinsic superparamagnetism of splenic macrophages contaminates cell isolates in magnetic cell separation [1]. This work is a collaboration with the Institute of Experimental Immunology, University of Bonn, Germany.

[1] L. Franken et al., Scientific Reports 5, 12940 (2015).
[2] P. M. Harrison et al., Adv. Inorg. Chem. 36, 449 (1991).
[3] S. Gider et al., Science 268, 77 (1995).

MA 39.12 Thu 12:30 H31

Positioning and Detection of Magnetic Nanoparticles for Lab-on-Chip systems — •Benjamin Riedmüller, Shalini Easwardas, Florian Ostermaier, and Ulrich Herr — Institute für Mikro- und Nanomaterialien, Universität Ulm, Ulm, Deutschland

Magnetic nanoparticles are interesting in combination with magnetoresistive sensors for Lab-on-Chip systems. In such applications, superparamagnetic particles are typically used, to which biological analytes can be specifically bound. By detecting the particles, the presence of the bio-species can be confirmed. For detection, the particles have to be positioned in the vicinity of the active sensor area. Here, a common principle for positioning of superparamagnetic particles is the application of magnetic field gradients by which a force on the particles is generated. In a previous work we derived a quantitative model for the force on a superparamagnetic particle by a combination of the field gradient produced by tapered conductor lines and a superimposed, homogeneous magnetic field. By this, the limitation by which particles can only be attracted towards the conductor is overcome. We demonstrated that this approach allows positioning a single superparamagnetic particle in two dimensions on length scales > 100 um with a precision of < 1 um. Based on this technique a particle lens consisting of a conductor ring can be constructed by which a single particle is first guided and then fixed at a pre-defined position with high accuracy. Our results further show that these manipulation concepts can be easily combined with common micro-structured magneto-resistive sensors which allow the real-time detection of the motion of the particle.

MA 39.13 Thu 12:45 H31

Magnetically patterned rolled-up exchange bias tubes:

A paternoster for superparamagnetic beads — •Timo Ueltzhöffer[1], Robert Streubel[2,3], Iris Koch[1], Dennis Holzinger[1], Denys Makarov[2,4], Oliver G. Schmidt[2,5], and Arno Ehresmann[1] — [1]Department of Physics and Center for Interdisciplinary Nanostructure Science and Technology (CINSaT), University of Kassel, Heinrich-Plett-Str. 40, 34132 Kassel (Germany) — [2]Leibniz Institute for Solid State and Materials Research Dresden, Helmholtzstrasse 20, 01069 Dresden (Germany) — [3]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720 (USA) — [4]Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf e.V., 01328 Dresden (Germany) — [5]Technische Universität Chemnitz, Strasse der Nationen 62, 09111 Chemnitz (Germany)

Artificially engineered parallel stripe magnetic domains in exchange bias layer systems were rolled-up into tubular architectures with azimuthally aligned magnetic domain patterns.[1] These objects were used for a paternoster-like transport of superparamagnetic beads through and above the tube by applying periodic pulse sequences of very weak external magnetic fields. This approach paves the way towards novel perspectives and applications in biotechnology, including particle transport related phenomena and lab-on-a-chip devices.

[1] Schmidt, O.G. and Eberl, K. Nanotechnology: Thin solid films roll up into nanotubes. Nature 410, 168 (2001).

MA 39.14 Thu 13:00 H31

ferromagnetic resonance spectroscopy of magnetotactic bacteria — •Sara Ghaisari[1], Stefan Klumpp[2], and Damien Faivre[1] — [1]Max Planck Institute of Colloids and Interfaces — [2]Institut für Nichtlineare Dynamik, Georg-August-Universität Göttingen

Magnetotactic bacteria (MTB) are micro-organisms capable of forming intracellular magnetic nanoparticles inside vesicles called magnetosomes. Magnetosomes consist of a lipid membrane surrounding a ferromagnetic crystal, which is magnetite Fe3O4 or greigite Fe3S4. The size of the particles (40-100 nm) provides the organisms with a permanent magnetization. In addition, these particles are arranged into a chain such that their dipole moments add up, resulting in a strong enough magnetic moment to get aligned in the Earth*s magnetic field. Due to these unique magnetic and morphology properties, magnetosome particles are attracting interests in many interdisciplinary areas. One key advantage is the strong uniaxial anisotropy and restricted direction of magnetization. Ferromagnetic Resonance (FMR) is a powerful tool for determining the magnetic anisotropies of a ferromagnetic material. Here, we use FMR to investigate and characterize magnetosomes in different strains of magnetotactic bacteria. Different spectra are observed for different strains that can be correlated to the organization of particles and crystalline structure observed by electron microscopy. Simulations of the FMR spectra using an ellipsoid model and their quantitative comparison with the experimental spectra are used to interpret different magnetic parameters and their effect on the spectrum.