European School on Multi-Ferroics (ESMF2010)

Univ. of L'Aquila (Italy)
September 26th - October 1st 2010

1) Summary (up to 1 page)

The fourth edition of the European School on Multi-Ferroics (ESMF2010) was held in L'Aquila (Italy) from September 26th to October 1st 2010. Multiferroics, materials showing a coexistence of magnetic and ferroelectric properties, is an actively evolving area in condensed matter, so that a yearly school - both to introduce people willing to enter the field and to illustrate the progresses to those already working in the area - is definitely felt as needed by the scientific community. ESMF2010 gathered 86 participants, in particular 68 students (mainly Europeans, but also including few participants from USA, Japan, South-Africa, etc) and 18 speakers (again, mostly Europeans with three coming from USA). The number of students has been as large as previous editions (compared to same cases, even higher), showing that multiferroics continue to attract enormous interests all over the international scientific community. All the lessons were prepared in a way adequate to PhD students, most of the lectures showing first an introductory part with basic concepts and then moving to recent scientific results, in order to give to young participants a flavor of current research activities. In this respect, the lessons were interesting both for people new to the field as well as for participants with longstanding experience in the area. All the speakers were extremely qualified: plenty of examples were given, so as to make the general concepts clear to everybody when applied to specific materials, cases, mechanisms, etc. The schedule implied 4 lessons per day (90 minutes each + 15 minutes of discussions), excluding Wednesday (due to social excursion and dinner) and Friday (closing day) when two lectures only were held. A poster session, including a prize for the best poster presentation, was held on Tuesday September 28th. The organization of the school schedule was largely appreciated by most of the students.

The choice of the location of the ESMF school in 2010 had a somewhat special meaning, since L'Aquila was struck by a tremendous quake in April 2009 causing 300 casualties and about 60.000 evacuees. After 18 months, the situation was still rather severe in L'Aquila (for example, all the historical center, denoted as "red zone", was not accessible to people and nobody was – and is - allowed to live there or even enter there). Despite many logistic problems that the local-organizer/director had to solve before the event, the school was held at the Faculty of Mathematical, Physical and Natural Sciences of the University of L'Aquila, with its building located in the peripheral area of L'Aquila. Being newer and recently constructed, in general less damages were caused by the quake in this area, so that the lesson room as well as the entire building was accessible and available. Moreover, several hotels could be found nearby and a shuttle-bus service connecting the hotels and the university was arranged for the participants.

2) Description of the scientific content of and discussion at the event (up to 4 pages)

The main goal of the school was to present a comprehensive overview in the exciting and fastly developing field of multiferroics.
After two introductory lectures on ferroelectrics (*J. M. Triscone*) and magnetic oxides (*M. J. Coey*) in the first day of the school, containing basic concepts and exhaustive historical reviews (plus some exciting perspectives, see next section), the talks were specifically focused on:

- the (co)-existence and cross-coupling between different long-range orders (magnetic, dipolar, ferroelastic, toroidal);
- the search for new materials showing strong magneto-electric coupling and multiferroicity, including handles [such as strain-engineering (*K. Dörr*) or materials design (*C. Ederer*)] to tune the relevant properties;
- the novel physical mechanisms at the basis of complex magnetic phase diagrams, encompassing ferroelectricity (statically) induced by magnetic or charge order as well as dynamical magnetoelectric effects (including electromagnons and domain wall dynamics);
- advanced experimental techniques [neutrons (*V. Simonet*), X-ray magnetic scattering (*A. Bombardi*), piezo-force microscopy (*S. Fusil*), high-resolution transmission electron microscopy (*M. Varela*), etc] particularly suited for the characterization and analysis of multiferroics and magnetoelectrics
- examples of theoretical modelling of "electronic" multiferroics, with examples of ferroelectricity induced by spin, charge or orbital degrees of freedom, in turn interacting with lattice degrees of freedom *(J. van den Brink and D. Khomskii*)
- the importance of symmetry analysis (*L. Chapon*) and Landau theory in this field, complemented by practical examples of multiferroics with complex and exotic spin ordering
- perspectives for multifunctional applications, including electrically controllable spintronic devices [for example through exchange-bias phenomena at the interface between a ferromagnet and a multiferroic (*J. Fontcuberta*) or tunnel electro-magnetic junction (*M. Bibes*)]. These lectures gave a flavor of the potential for future technology represented by multiferroics and magnetoelectric effects.

Systems of interest ranged from *bulk* compounds [manganites (in their hexagonal and orthorhombic phases, either under equilibrium or strained), nickelates, cobaltates, BiFeO3, EuTiO3, etc] to *composites*, from (strained) *thin films* to (hybrid) *nanostructures*. A lesson given by *Joel E. Moore* on Topological insulators (TI, a topic currently attracting lots of interest all over the world), was included in the program, in particular focused on the connection between TI and orbital magnetoelectric responses.

The program included a poster session, formally held on Tuesday 28th in the afternoon; we note, however, that posters could be put up in the first day of the school and could be shown in the lobby of the Sciences building for the whole school duration. Indeed, since rather long breaks were planned between talks and for lunches, many discussions were held during these breaks, stimulated by the posters. It goes

without saying that this was a wonderful opportunity for the young students to show their work to the renowned and experienced speakers. Moreover, we decided to award a small prize (a hard-disk) for the best poster presentation. Three votes (in order of priority) were casted by each invited speaker and collected on Wednesday (the prize was officially given at the social dinner on Wednesday evening). The results clearly indicated the prize winner: Ms. Pauline Rovillain, for her work on BiFeO3.

The discussion was lively for all the duration of the school. Indeed, the schedule of the school was intentionally built to stimulate comments: 15 minutes, after each 90-minutes talk, were planned to be devoted to Q&A sessions. Almost all the speakers stayed on time, so the 15-minutes allotted time could be indeed used for clarifications and comments after all the lessons. What was very encouraging was that, in addition to the speakers, even the young students could cast many good questions.

Finally, we remark that a school website was created well before the beginning of the school and continuously updated during the weeks before the school as well as during the school (in particular to upload all the presentations given by the speakers so that they could be publicly downloaded):

http://www.casti.aquila.infn.it/homepages/bismuth/ESMF2010/index.html

The website contained/contains all the relevant information on the school and in particular on:

- poster session (including lilst of poster abstracts)
- talks (including slides shown during the talks at the school)
- accommodation (list of hotels, maps, etc)
- practical info on how to reach L'Aquila and the University
- registration procedure (forms, etc)
- schedule of lessons

3) Assessment of the results and impact of the event on the future direction of the field (up to 2 pages)

- *Next ESMF*: Since ESMF is now a consolidated activity, in early 2010 a board of the ESMF directors of previous editions was established, with the aim of coordinating the activites and events in the field of multiferroics. In this particular occasion of ESMF2010, discussions previous and during the school were active in the board to establish where and when to held the next ESMF school (along with the choice of the main organizer of the next edition). After several offers from many scientists willing to organize the school (showing again how lively is the field), Michel Kenzelmann (Paul Scherrer Institute, Switzerland) and Nicola Spaldin (to start at ETH Zurich in January 2011) were chosen to organize the next ESMF in Switzerland. Both scientists have contributed in a clearly substantial way to the progresses of the multiferroics area; moreover, ESMF has never been organized in Switzerland. One of the possible choices for the location is currently in Ascona, Lago Maggiore, even though the final details of the date and location will be given in the coming months. It is however sure that ESMF will go on with a coming edition, for the benefit of students who would like to contribute to this active area.

- *Future directions of the field:* during their talks, many speakers gave important clues on the avenues to be developed in the coming months/years. Among them, we recall only a few (due to space limitations):

- Prof. Jean Marc Triscone mentioned several directions in the field of ferroelectrics, such as oxide heterostructures (with particular emphasys on PbTiO3/SrTiO3 superlattices), domain wall control in standard ferroelectrics (such as PbTiO3 and BaTiO3), size effects in ferroelectric nanostructures;
- Dr. Kathrin Dörr mentioned several directions in the field of strain engineering, starting from the well established knowledge that orbital, spin and dipolar degrees of freedom are very sensitive to lattice deformation (i.e. strain). Among the most interesting examples, she showed i) the nowadays capability of integrating standard ferroelectrics (BaTiO3, BaO) on silicon; ii) the rotation of the direction of P by applying strain (for example by inducing a structural phase transition between rhombohedral and tetragonal crystal structures); iii) how to tune the spin-state by applying strain (for example in cobaltates where low to intermediate to high spin configurations are competing and can be controlled by applying strain); iv) multiferroics by design (for example EuTiO3 where strain is believed to induce a simultaneous transition from antiferromagnetic to ferromagnetic and from paraelectric to ferroelectric); v) manganites, such as CaMnO3 or SrMnO3, that are not ferroelectric at equilibrium but that can become ferroelectric under strain (due to stabilization of ferroelectric modes - given by off-centering of the transition metal ion in the octahedral oxygen cage - compared to centrosymmetric antiferrodistortive modes - given by octahedral tilting, otherwise prevailing at equilibrium-).
- Dr Manuel Bibes offered some technologically appealing perspectives, based on ferroelectric and magnetic tunnel barriers using oxides (such as BaTiO3, BiFeO3, PZT, etc). In particular, he showed examples of i) combining tunneling electroresistance (TER) and tunneling magnetoresistance (TMR) in Au/LaBiMnO3/LaSrMnO3 heterostructures or, more recently, in

Fe/BaTiO3/LaSrMnO3 and ii) electrical readouts of polarization in nanoscale ferroelectric dots.

- Prof. Ingrid Mertig presented some first principles calculations on interfaces of various kinds. When interfacing standard ferromagnets (Fe, Co, etc) with standard ferroelectrics (BaTiO3, PbTiO3, etc), she showed that i) the magnetoelectric coupling can be changed depending on the number of layers in the magnetic films and ii) there is a change of the magnetic order from ferromagnetic to ferrimagnetic with the number of Fe layers (not obtained for Co) as well as a stabilization of ferromagnetism in Fe/BaTiO3 by alloying with Co. Interestingly, she also showed a nice example of fruitful interaction between theory and experiments in Fe thin islands deposited on Cu (111) surfaces: they showed that the magnetic state of Fe islands (either bcc ferromagnetic or fcc antiferromagnetic) could be controlled via the application of an electric field (locally applied via an STM tip).

Given the stimulating atmosphere and the many discussions held at the school, it is likely that many of the ideas that were put forward in L'Aquila will be developed in the coming months and may eventually lead to publications on international scientific sjournals.

4) Final programme of the meeting

Sunday Sept 26th
18:00-19:30 Welcome party (with soft drinks and snacks)
19:30-20:30 Seminar for a general audience on *"L'Aquila earthquake in April 6th 2009*"
(given by Prof. Gianluca Ferrini, Geology Dept, Univ. L'Aquila)

Monday Sept. 27th
9:00-9:30: **Silvia Picozzi, Ruggero Vaglio**, CNR-SPIN (IT), "*Opening*"
9:30-11:15: **Jean Marc Triscone**, University of Geneva (CH), "*Ferroelectric materials: an introduction to the field and some examples of recent developments*"
11:45-13:39: **Michael Coey**, Trinity College Dublin (IE), "*Magnetic Oxides; Introduction and New Directions*"
15:00:16:45: **Claude Ederer**, Trinity College Dublin (IE*), "First principles studies of multiferroic materials"*
17:15-19:00: **Joel Moore**, Dept. of Physics, Univ. of California, Berkeley (US), "*Topological insulators and orbital magnetoelectric coupling*"

Tuesday Sept. 28th
9:00-10:45: **Katrin Dörr**, IFW-Leibniz Institut Dresden (DE), *"Strain effects in ferroic oxide films"*
11:15-13:00: **Jeroen Van den Brink**, IFW, Leibniz Institute for Solid State and Materials Research (DE), "*Multiferroics: Hamiltonian modeling*"
13:00-15:00: Poster session
15:00-16:45: **Alessandro Bombardi**, Diamond Light Source Ltd, Rutherford Appleton Lab (UK), "*An introduction to x-ray non-resonant and resonant scattering applied to multiferroics*"
17:15-19:00: **Virginie Simonet**, Institut Nel CNRS Grnoble (FR), "*Neutron scattering a probe for multiferroics and magnetoelectrics"*

Wednesday Sept. 29th
9:00-10:45: **Maria Varela**, Oak Ridge National Lab, TN (USA), "*An atomic resolution view at complex oxides: progress challenges and applications*"
11:15-13:00: **Stephane Fusil**, Unit Mixte de Physique CNRS-Thales (FR), "*BiFeO3 or the Guinea pig of multiferroics under the magnifier of piezoresponse force microscopy"*
15:00-23:00: Social excursion + dinner

Thursday Sept. 30th
9:00-10:45: **Manuel Bibes**, Unit Mixte de Physique CNRS-Thales (FR), *"Ferroic and multiferroic tunnel junctions"*
11:15-13:00: **Sang-Wook Cheong**, Rutgers University, NJ (USA), *"Multiferroic Vortices"*
14:30-16:15: **Ingrid Mertig**, MPI fr Mikrostrukturphysik Halle and Martin- Luther-Universitt Halle-Wittenberg (DE), *"Magnetoelectric coupling at multi- ferroic interfaces"*
16:45-18:30: **Laurent Chapon**, ISIS, Rutherford Appleton Lab (UK), *"Symmetry applied to magnetoelectrics and multiferroics"*

Friday Oct. 1st
9:00-10:45: **Daniel Khomskii**, Univ. Koeln (DE), "*Multiferroics and beyond*"
11:15-13:00: **Josep Fontcuberta**, Institut de Ciencia de Materials (ICMAB) - CSIC, Barcelona (ES), "*Electric and magnetic control of magnetization and polarization in multiferroic heterostructures and devices*"
13:00-13:15: Closing

Speakers (18)

1. Dr. Manuel Bibes Palaiseau, (FR)
2. Dr. Alessandro Bombardi Didcot, (UK)
3. Dr. Laurent Chapon Didcot, (UK)
4. Professor Sang-Wook Cheong Piscataway, (US)
5. Professor Michael Coey Dublin, (IE)
6. Dr. Kathrin Doerr Dresden, (DE)
7. Dr. Claude Ederer Dublin, (IE)
8. Professor Josep Fontcuberta Barcelona, (ES)
9. Dr. Stephane Fusil Palaiseau, (FR)
10. Professor Daniel Khomskii Koeln, (DE)
11. Professor Ingrid Mertig Halle, (DE)
12. Professor Joel Moore Berkeley, (US)
13. Dr. Silvia Picozzi L'Aquila, (IT)
14. Dr. Virginie Simonet Grenoble, (FR)
15. Professor Jean-Marc Triscone Geneve, (CH)
16. Professor Ruggero Vaglio Napoli, (IT)
17. Professor Jeroen Van den Brink Dresden, (DE)
18. Dr. Maria Varela Oak Ridge, (US)

Participants (68)

1. Mr. Sebastian Albiez Cologne, (DE)
2. Mr. Sergey Artyukhin Groningen, (NL)
3. Mr. Carmine Autieri Salerno, (IT)
4. Dr. Jaita Banerjee Kolkata, (IN)
5. Mr. Jose' Barbosa Braga, (PT)
6. Dr. Paolo Barone L'Aquila, (IT)
7. Mr. Carsten Becher Bonn, (DE)
8. Mr. Federico Bisti L'Aquila, (IT)
9. Ms. Emilie Bruyer Lens, (FR)
10. Ms. Nuala Caffrey Dublin, (IE)
11. Ms. Teresa Carvalho Vila Real, (PT)
12. Dr. Giuseppe Colizzi Cagliari, (IT)
13. Ms. Vera Cuartero Zaragoza , (ES)
14. Dr. Lavinia-Petronela Curecheriu Iasi, (RO)
15. Mr. Luca D'ortenzi L'Aquila, (IT)
16. Mr. Hena Das Kolkata, (IN)
17. Dr. Gabriella Maria De Luca Napoli, (IT)
18. Mr. Nitin Deepak Cork, (IE)
19. Dr. Kris Delaney Santa Barbara, (US)
20. Ms. Flavia Viola Di Girolamo Naples, (IT)
21. Mr Domenico Di Sante, L'Aquila (IT)
22. Ms. Marta Elzo Aizarna Grenoble, (FR)
23. Ms. Saeedeh Farokhipoor Groningen, (NL)
24. Dr. Daniel Fritsch Dublin, (IE)
25. Dr. Tetsuya Fukushima L'Aquila, (IT)
26. Dr. Livia Giordano Milano, (IT)
27. Mr. Joao Goncalves Aveiro, (PT)

28. Mr. Christoph Gruber Vienna, (AT)
29. Dr. Gisele Gruener Tours, (FR)
30. Mr. Alexander Hearmon Oxford, (UK)
31. Mr. Johan Hellsvik Uppsala, (SE)
32. Dr. Jeroen Heuver Groningen, (NL)
33. Mr. Yuji Hiraoka Osaka, (JP)
34. Dr. Tim Hoffmann Bonn, (DE)
35. Mr. Jiawang Hong Beijing, (CN)
36. Mr. Tanveer Hussain Uppsala, (SE)
37. Ms. Diana Iusan Uppsala, (SE)
38. Mr. Adam Jacobsson Juelich, (DE)
39. Dr. Marjana Lezaic Juelich, (DE)
40. Ms. Jia Liu Raleigh, (US)
41. Dr. Giorgia Maria Lopez Monserrato , (IT)
42. Mr. Luca Matteo Martini Trento , (IT)
43. Mr. Shlomi Matityahu Nordiyya, (IL)
44. Dr. Francesco Mezzadri Parma, (IT)
45. Ms. Elise Pachoud CAEN , (FR)
46. Dr. Krisztian Palotas Budapest, (HU)
47. Mr. Jonathan Peace Coventry, (UK)
48. Mr. Daniele Preziosi Napoli, (IT)
49. Mr. Danilo Puggioni Cagliari, (IT)
50. Ms. Carmen Elena Quiroga Rodriguez Muenchen, (DE)
51. Mr. Kourosh Rahmanizadeh Juelich, (DE)
52. Dr. Abdulrafiu Raji Cape Town, (ZA)
53. Dr. Muhammad Riaz Napoli, (IT)
54. Mr. Mirko Rocci Madrid, (ES)
55. Dr. James Rondinelli Santa Barbara, (US)
56. Mr. Pauline Rovillain Paris, (FR)
57. Dr. Konstantin Rushchanskii Juelich, (DE)
58. Dr. Tanusri Saha-Dasgupta Kolkata, (IN)
59. Dr. Andrea Scaramucci Groningen, (NL)
60. Mr. Martin Schlipf Juelich, (DE)
61. Ms. sharmila shirodkar Jakkur, (IN)
62. Mr. Oleksandr Shvets Groningen, (NL)
63. Dr. Kiran Singh Caen, (FR)
64. Dr. Ivetta Slipukhina Juelich, (DE)
65. Dr. Alessandro Stroppa L'Aquila, (IT)
66. Mr. Alexey Ushakov Koeln, (DE)
67. Mr. Justin Varghese Cork, (IE)
68. Dr. Kunihiko Yamauchi L'Aquila, (IT)