# Shape coexistence and electric monopole transitions in atomic nuclei


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## I. SCIENTIFIC ISSUE

Shape coexistence, i.e. the observation of different shapes within a given nucleus at low excitation energy, has attracted a very large interest of the nuclear structure community [1, 2]. On the experimental side large progress has been made in determining not only level schemes, but also electromagnetic transition properties and nuclear electromagnetic moments in both excited and ground states (see, e.g., [3]), which is matched on the theoretical side by more and more refined methods to go "beyond" the mean-field approach [4, 5], using Large Scale or Monte Carlo Shell model calculations [6, 7], and IBM-based approaches [8]. It is therefore timely to review the recent progress and project into the future what development are needed both on the experimental and theoretical side.

A specific topic which we would like to emphasise during the workshop is the electric monopole (E0) excitation and decay modes of nuclei. E0 decay occurs primarily between $0^+$ states, but can also occur between states of non-zero spin. Excited $0^+$ states have been interpreted in various ways, as vibrational excitation modes, as vibrations of the pair field or as fingerprints of shape coexistence. In general, the strength of E0 transitions gives a model-independent view of the mean-square radii of the $0^+$ configurations underlying the transition.

Low lying $0^+$ states are one of the fingerprints of shape coexistence as they can be interpreted as the ground state of secondary minima in the potential energy surface of the nucleus at the mean-field level or as pair excitation across shell gaps in a more microscopic view. Such secondary minima are expected in many regions of the nuclear chart [2]. There is, however, a justified expectation that low-lying excited $0^+$ states may have escaped experimental observation, in particular if the excited $0^+$ state is the first excited state. In that case only an E0 decay is possible and dedicated experiments sensitive to conversion-electron (CE) emission or internal pair creation (IPC) are necessary. We are therefore planning to review progress in the detection of E0 decays (including possible long-lived isomeric states) and the theoretical progress to calculate E0 transition rates. In addition, we will explore the relationship of the low-energy E0 mode related to shape coexistence, to nuclear surface vibrations and to the cluster structure and the link to the Giant Monopole Resonance, the high-energy "breathing mode" of the nucleus.

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The experimental observations of band structures on top of the low-lying $0^+$ states have supported the description of the shape coexistence by the competition of two configurations (*spherical vs. deformed* or *oblate vs. prolate deformed*) for the ground state in a given nuclei. The B(E$\lambda$) and B(M$\lambda$) transition probabilities, within the respective bands and between them, as well as the spectroscopic moments, are excellent probes for the comparison with advanced theoretical models. Recently, large sets of electromagnetic transition probabilities and spectroscopic moments became available in several mass regions where shape coexistence has been identified using both ISOL facilities, offering post-accelerated radioactive ion beams at the Coulomb barrier, and in-flight separators.
However, the complex correlations within these nuclei persist to challenge even the most advanced theoretical calculations:

Comparing systematically the experimental data with theoretical calculations, one observes agreement in the global properties, but large discrepancies still remain. We believe that a succesful future of these studies demands

- a theoretical effort to identify key isotopes, which can serve as benchmarks for a coherent and universal description of the shape coexistence all along the nuclear chart by advanced theoretical models,
- an experimental effort to make precise and reliable data available in these isotopes or isotopic chains.

In this workshop we are therefore planning to review several isotopic chains and/or mass regions for which exhaustive and reliable data could already be taken and which can provide a complete comparison with predictions using different approaches to identify key cases to be investigated in the future. Since the two topics, shape coexistence and electric monopole transitions, are closely related and common experts are available, a joint workshop of 4.5 days will be organised.

## II. GOALS OF THE PROJECT

In summary, the goals of the project are

1. Review the available experimental data, both for nuclear ground state and for excited states, in several isotopic chains in which shape coexistence is observed, and identified benchmark cases for theory.
2. Review the theoretical predictions for these benchmark cases and discuss possible new experimental approaches.
3. Review progress in the detection of E0 decays (including long-lived isomeric states) and the theoretical progress to calculate E0 transition rates; explore the link between the low-energy electric monopole mode, nuclear cluster structure and the Giant Monopole Resonance.
4. Identify any significant missing contributions both from the experimental and theoretical point of view.

## III. PROGRAMME AND SPEAKERS

Among the speakers, we have invited

- experts in different theoretical techniques applicable to the experimental observations (mean-field based models, using different energy density functionals, variants of the shell model, phenomenological approaches) to discuss the status of their developments and the most seminal future experimental studies.
- experimental physicists to cover the majority of experimental programs related to shape coexistence as well as recent experimental progress in the detection methods in major European and international facilities.

*Invited speakers :*

- M. Bender, IPN Lyon, France, "Beyond-mean-field models for the description of shape coexistence"
- E. Clément, GANIL, France, "Shape coexistence in the Sr-Zr mass region around A$\sim$100"
- T. Cocolios, IKS, KU Leuven, Belgium, "Nuclear charge radii and shape coexistence"
- S. Courtin, IPHC Strasbourg, France, "Electromagnetic transitions as a probe of cluster states in nuclei"

- J. P. Ebran, CEA DIF/DAM, France "Nuclear clustering in the Energy-Density-Functional approach"
- A. Garnsworthy, Triumf, Vancouver, Canada, "Decay and in-beam Conversion Electron spectroscopy at TRIUMF"
- P. Garrett, Univ. of Guelph, Canada, "Collective excitations and shape coexistence in Cd/Sn isotopes"
- L. Gaudefroy, CEA DAM/DIF, France, "Shape evolution and coexistence at N=28"
- A. Görgen, Univ. Oslo, Norway, "Shape coexistence in N∼Z nuclei around A∼70"
- K. Heyde, U. Gent, Belgium, "Shape coexistence in atomic nuclei: the long and winding road"
- T. Kibedi, ANU, Canberra, Australia, "Introduction to E0 excitation/decay mode"
- S. N. Liddick, Michigan State University, USA "Shape coexistence in the N∼40 mass region around $^{68}$Ni"
- T. Nikšić, University of Zagreb, Croatia,Coexistence of nuclear shapes: mean-field and beyond
- T. Otsuka, University of Tokyo, Japan, "Shape coexistence and quantum phase transition in the Monte-Carlo Shell Model"
- J. Pakarinen, Univ. of Jyväskylä, Finland, "Conversion-electron spectroscopy at JYFL and ISOLDE"
- S. Péru, CEA DAM/DIF, Bruyères-le-Chatel, France, "Transition Probabilities in the QRPA approximation"
- A. Poves, Universidad Autónoma de Madrid, Spain, "Nuclear Shapes: A monopole guided tour into the quadrupole realm"
- R. Raabe, IKS, KU Leuven, Belgium, (tbc) "Experimental status of the N=20 region around $^{32}$Mg"
- T. R. Rodrìguez, Universidad Autónoma de Madrid, Spain, "Collective and Single-Particle Motion in Beyond Mean Field Approaches"
- D. Rowe, Univ. Toronto, Canada, "An algebraic mean-field theory of shape coexistence in nuclei"
- H. Scheit, TU Darmstadt, Germany, "Nuclear two-photon decay of $0^+$ states"
- P. Van Duppen, IKS, KU Leuven, Belgium, "Shape coexistence in the vicinity of Z= 82"
- P. Van Isacker, GANIL, France, "Correlations between charge radii, E0 transitions and summed M1 strength"
- M. Venhart, Slovak Academy of Sciences, Slovakia, "The TATRA decay station at ISOLDE and shape coexistence in odd-mass Au nuclei"
- D. Verney, IPN Orsay, France, "Shape coexistence around $^{78}$Ni"
- J. Wood, Georgia Institute of Technology, Atlanta, USA, "An introduction to experimental shape coexistence studies"
- M. Zielinska, CEA IRFU/SPhN, Saclay, France, "Shape coexistence at Z=20"

## IV. PRELIMINARY PROGRAM

| | Monday 23/10 | Tuesday 24/10 | Wednesday 25/10 | Thursday 26/10 | Friday 27/10 |
|---|---|---|---|---|---|
| *09:00* | Heyde*(45') | Rowe (45') | Ebran (45') | Kibedi (45') | Rodriguez (45') |
| *10:00* | Wood (45') | Poves (45') | Niksic (45') | Garnsworthy (45') | Peru (45') |
| *11:00* | *Coffee break* | *Coffee break* | *Coffee break* | *Coffee break* | *Coffee break* |
| *11:30* | Verney (30') | Liddick (30') | Courtin (30') | Pakarinen (30') | Raabe (30') |
| *12:00* | **Discussion** | **Discussion** | **Discussion** | **Discussion** | **Discussion** |
| *12:45* | *Lunch break* | *Lunch break* | *Lunch break* | *Lunch break* | *Lunch break* |
| *14:00* | Van Isacker (45') | Otsuka (45') | Bender (45') | Scheit (45') | Breakout groups |
| *15:00* | Van Duppen (30') | Görgen (30') | Gaudefroy (30') | Cocolios (30') | |
| *15:30* | **Discussion** | **Discussion** | **Discussion** | **Discussion** | |
| *16:15* | *Coffee break* | *Coffee break* | *Coffee break* | *Coffee break* | |
| *16:45* | Venhart (30') | Clement (30') | Zielinska (30') | Garrett (30') | |
| *17:15* | **Discussion** | **Discussion** | **Discussion** | **Discussion** | |
| *18:00* | *End* | *End* | *End* | *End* | |

*speaker to be confirmed

The program is composed of 45 minutes talks introducing most of the theoretical approaches, which are currently employed to understand shape evolution and shape coexistence, and experimental talks (30 minutes) on specific subjects/mass regions or experimental techniques, which will be followed by discussion sessions. However the program will be handled flexible to allow for sufficient discussion time at any time. During the discussion short contributions (few slides) will be possible. Friday afternoon is kept free for follow-up discussions in smaller groups.


[1] K. Heyde and J. L. Wood, *Shape coexistence in atomic nuclei* Rev. Mod. Phys 83 (2011) 1467.

[2] P. Moeller et al., *Global Calculation of Nuclear Shape Isomers* Phys. Rev. Lett. 103 (2009) 212501.

[3] A. Goergen and W. Korten, *Coulomb excitation studies of shape coexistence in atomic nuclei* J. Phys. G: Nucl. Part. Phys. 43 (2016) 024002.

[4] J.-P. Delaroche et al., *Structure of even-even nuclei using a mapped collective Hamiltonian and the D1S Gogny interaction* Phys. Rev. C 81, (2010) 014303

[5] T. R. Rodríguez, A. Arzhanov, and G. Martínez-Pinedo *Toward global beyond-mean-field calculations of nuclear masses and low-energy spectra* Phys. Rev. C 91,(2015) 044315

[6] A. Poves, *Shape coexistence : the shell model view* J. Phys. G: Nucl. Part. Phys. 43 (2016) 024010.

[7] T. Togashi, Y. Tsunoda, T. Otsuka, and N. Shimizu, *Quantum phase transition in the shape of Zr isotopes* Phys. Rev. Lett.117, 172502 (2016).

[8] K. Nomura and T. Otsuka and P. Van Isacker, *Shape Coexistence in the microscopically guided interacting boson model* J. Phys. G: Nucl. Part. Phys. 43 (2016) 024008.