Linear Response Theory : from infinite nuclear matter to finite nuclei

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I. SCIENTIFIC ISSUE

Linear response theory is a common technique adopted in nuclear structure calculations to study the excited states of a system. In calculating collective excitations of nuclear systems, we act on it with a weak external field (probe) that introduces small changes of the nuclear density, which can be treated at the linear order. The system starts to oscillate with the external field and provides with resonances whenever the frequency of the field is close to an excitation energy of the system. To find the self-frequences of the oscillating system we just have to look for the solutions of the secular equation in the limit of vanishing external field ; these are exactly the RPA equations (or QRPA in case of superfluid systems).

The first QRPA calculations for finite nuclei can be dated starting from the early 60's (see D.J. Rowe [1] and references therein), although using simplified residual interactions (*i.e.* quadrupole-quadrupole or Landau-Migdal) they were able to give a reasonable explanation of several experimental findings.

To calculate the response function of an infinite nuclear matter system, the Green Function formalism at zero temperature and it's extension to finite temperature is the standard method. In this case one has to solve the Bethe-Salpeter equation, so obtaining an analytic expression that describes the behavior of the system in the different channels excited by the external probe. The first systematic studies in this direction where made by Garcia-Recio *et al.* [2], who used a simplified phenomenological contact-interaction (Skyrme), neglecting tensor terms and spin-orbit components [3], to analyzed the behavior of infinite nuclear matter at zero and finite temperature [5]. Recently these calculations were extended in the Symmetric Nuclear Matter [4] case to include all the remaining terms of the Skyrme functional. Extensive studies of response functions in Symmetric Nuclear Matter had shown that linear response theory can be used as a tool to improve the fitting procedure of modern functional, since it can help avoiding the region of unphysical instabilities (*i.e.* regions of parameters that can give rise to unphysical solutions)[6].

The Green Function formalism can be also applied to study the excitations in the inner crust of neuron stars [8][9], in fact this system is characterized by a proton lattice immersed in a uniform gas of neutrons [7]. The calculations in this systems have a great astrophysical interest since it has been show that excitations its influence the neutrino mean free path, and though the cooling mechanism of a neutron star.

For finite nuclei the most used method is the matrix formulation of the (Q)RPA problem [10], a certain number of fully self-consistent codes (*i.e.* using the same interaction is used to determine the properties of the ground state and of the excited states) are nowadays available for contact-forces Skyrme and finite-range Gogny [13][14] and 'bare forces' [15]. In 2008 J. Terasaki and J. Engel [11][12] performed the first systematic calculations of the first 2^+ state for all spherical nuclei of the nuclear-chart. Unfortunately a similar approach can not be done for deformed states (that represent the majority of know nuclei) since the dimension of the problem grows very fast and it soon becomes to time consuming to find the exact solution [16]. A solution to this problem was then found recently by T.

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Nakatsukasa [17][18], who suggested to adopt an iterative method named Finite Amplitude Method (FAM) to find an approximation to the response function of the system to a given probe. The numerical implementation of this method for axially deformed system done by M. Stoitsov [19] open a new era, since has demonstrated that is now possible to obtain the response function of deformed nucleus within a very good precision using very few CPU time. Having the possibility of performing fast and efficient QRPA calculation give us also the possibility to study charge-echange process and so accessing a vast area of experimental findings on β-decay modes of spherical [21][20] and deformed systems, thus allowing to improve the constraint on the coupling constant of the phenomenological functionals.

Although the different communities work on the same topic of the linear response, we clearly see that different systems present different problems and different solutions have been presented to solve them. The goal of this workshop is to bring together scientist working on different domains of the nuclear structure and compare the advantages and disadvantages of the different employed techniques.

II. GOALS OF THE WORKSHOP

In summary, the goals of the workshop are

1. present the recent developments of the linear response theory in different nuclear systems with finite-range and zero-range interactions
2. discuss the possible application of linear response to detect instabilities in finite nuclei and infinite systems.
3. discuss the use of QRPA to analyze different exciting modes : charge exchange, spin-modes.

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III. LIST OF SPEAKERS

– 30 May

1. N. Van Giai (nguyen@ipno.in2p3.fr) *"Linear response functions in infinite matter with Skyrme-type interaction"*
2. A. Pastore (pastore@ipnl.in2p3.fr) *"Linear Response Theory as tool to detect instabilities in Skyrme functionals"*
3. G. Coló (colo@mi.infn.it) *"The Skyrme-RPA model and the tensor force"*
4. M. Urban (urban@ipno.in2p3.fr) *"Collective modes in the neutron star inner crust and in ultracold atoms"*

5. M. Grasso (grasso@ipno.in2p3.fr) *" Low-energy excitations in nuclear systems : From exotic nuclei to the crust of neutron stars"*

– 31st May

1. J. Navarro (Jesus.Navarro@ific.uv.es) *"Instabilities of infinite matter and effective tensor interactions"*
2. V. Hellemans (veerle.hellemans@ulb.ac.be) *"Finite-size instabilities in nuclear energy density functionals : finite nuclei"*
3. N. Schunck *"Finite-size Spin Instabilities in Odd-Mass Nuclei"*
4. S. Péru (sophie.peru-desenfants@cea.fr) *"QRPA with Gogny force"*
5. P. Papakonstantinou (papakonst@ipno.in2p3.fr) *"RPA++ methods with realistic interactions : why and how"*

– 1 June

1. S. Baroni (simone.baroni@gmail.com) *" GCM and QRPA"*
2. P.-H. Heenen (phheenen@ulb.ac.be) *"Concluding remarks"*
3. J. Toivanen (jutato@phys.jyu.fi) *"Efficient solution methods for Quasiparticle Random Phase Approximation equations"*

IV. PROGRAM

30th May	31st May	1st June
10h00 Van Giai	10h00 Navarro	10h00 Toivanen
11h00 **Break**	11h00 **Break**	11h00 **Break**
11h30 Pastore	11h30 Hellemans	11h30 Baroni
		12h15 Heenen
12h30 **Lunch**	12h30 **Lunch**	13h00 **Lunch**
14h30 Coló	14h30 Schunck	
15h30 Urban	15h30 Péru	15h00 **End**
16h30 **Break**	16h30 **Break**	
17h00 Grasso	17.00 Papakostantinou	
18h00 **End**	18h00 **End**	

V. RESULTS OF THE WORKSHOP

The main goal of the atelier ESNT “Linear response theory : from infinite matter to finite nuclei” has been to bring together physicists that use the linear response theory (or Random Phase Approximation) as a tool for their researches.

The seminars have covered a vast area of the nuclear structure and cold atoms physics. The first day has been devoted to the study of large or infinite systems as atoms in a trap, Wigner-Seitz cells in the inner crust of neutron stars and infinite nuclear matter ; the resulting discussions have allowed to put in evidence the similarities and the main differences of the various approaches that have been shown. The second and the third day have been devoted to the application of the linear response theory and higher order approximations (as Particle Vibration Coupling and Second Random Phase Approximation) to study the properties of ground states and excited states of finite nuclei. The parallel among the infinite systems and the finite size systems has enlightened some common points in the results, that could be used in future analysis.

During the three days of the workshop, we have remarked a continuous and stimulating discussion among the invited persons that will probably lead to new scientific collaborations among the different groups.