Importance of continuum coupling for nuclei close to the drip-lines

N. Michel*
Centre de Saclay, IRFU/Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France

T. Duguet†
Centre de Saclay, IRFU/Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA and
Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

M. Płoszajczak‡
Grand Accélérateur National d'Ions Lourds (GANIL),
CEA/DSM – CNRS/IN2P3, BP 55027, F-14076 Caen Cedex 5, France

W. Nazarewicz§
Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA
Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
Institute of Theoretical Physics, Warsaw University, ul. Hoża 69, PL-00681, Warsaw, Poland

Workshop of the Espace de Structure Nucléaire Théorique at Saclay

May 18th-20th 2009

CEA/SPhN, Orme des Merisiers, build. 703, rooms 125-135, F-91191 Gif-sur-Yvette Cedex

I. PROBLEMATIC

The precise description of nuclei close to or beyond drip-lines is a challenge for both current nuclear theory and experimental studies. With the advent of radioactive beam facilities, it is possible to create very short-lived nuclei with a large proton-neutron ratio, providing a large set of data which have to be explained at the theoretical level. The most exotic of such nuclei, contrary to those located in the vicinity of the valley of stability, exhibit special features arising from the proximity of neutron/proton emission threshold. One of the most interesting phenomenon is the appearance of halos, i.e. nuclei extending very far beyond the classically allowed region. Due to enhanced coupling to the continuum of scattering states, nuclear correlations and continuum effects are intertwined and hence give rise to complex nuclear structure. One can mention the existence of Borromean nuclei for which all binary subsystems are unbound such that the system itself is bound due to the nuclear interaction between its subparts. While these features can be found on both proton and neutron drip-lines, proton drip-line presents unique properties, such as two-proton radioactivity discovered just a few years ago. Another peculiarity is the redistribution of shell closures close to the drip-lines. One can also mention new continuum excitation modes arising in exotic nuclei, such as Bound States Embedded in the Continuum (BSEC) and Fano resonances. Due to the very different nature of nuclei in the valley of stability and at the drip-lines, new theoretical models have to be devised to provide a consistent description of all of them. It is the aim of this workshop to present recent theoretical advances in the domain of weakly bound and resonant nuclei, as well as discussing associated experimental studies.

For light nuclei, extensions of standard shell model have been effected, with the real-energy Shell Model Embedded in the Continuum (SMEC), based on the Hilbert space Feshbach separation, and the complex-energy Gamow Shell Model (GSM), where bound, resonant and scattering one-body states, forming the so-called Berggren basis, are used instead of harmonic oscillator states to generate Slater Determinants many-body basis states. Efficient diagonalization techniques, allowing one to deal with shell model spaces well beyond the possibilities of standard Lanczos method,

*Electronic address: nicolas-l.michel@cea.fr
†Electronic address: thomas.duguet@cea.fr
‡Electronic address: ploszajczak@ganil.fr
§Electronic address: witek@utk.edu

are currently under investigation with Density Matrix Renormalization Group (DMRG) and Coupled Clusters (CC) methods. Due to important clusterization of nucleons in this area of the nuclear chart, few-body models are also widely used. For that, nuclei are modelled as two and three-body interacting clusters, from which determination of decay widths is effected using R-matrix formalism, or with complex scaling in the Cluster Orbital Shell Model (COSM). Thanks to well-defined wave function asymptotics, few-body approaches provide a convenient tool to calculate reaction cross sections. The No Core Shell Model (NCSM), complemented with Resonating Group Method (RGM), allows to describe reactions between correlated clusters, the latter being expanded with large harmonic oscillator bases using realistic interactions, while their remaining degrees of freedom are dealt with relative-motion scattering wave functions. The lightest nuclei have been also considered with the Green Function Monte-Carlo (GFMC) method, which is presently the most precise method to calculate nuclear wave functions up to $A \sim 10$. Initially devised for nuclear structure, it can now be used for reactions involving two fragments.

Concerning medium and heavy mass nuclei, generalization of Hartree-Fock-Bogoliubov (HFB) and Quasi Particle Random Phase Approximation (QRPA) methods to the domain of weakly bound nuclei is necessary, as shell model techniques cannot be utilized therein. In these approaches, quasiparticle states are directly integrated with coordinate-space methods or expanded with Transformed Harmonic Oscillator basis, which allow to precisely evaluate weakly bound nuclear ground states of spherical and axial symmetry. Other sets of basis states, such as Woods-Saxon, Pöschl-Teller-Ginocchio, Bessel functions and Berggren basis, have been recently introduced to solve HFB equations precisely for weakly bound nuclei. Consideration of drip-line nuclei is also much involved in the context of Relativistic Hartree-Bogoliubov framework.

Within traditional reaction frameworks, which take continuum into account by definition, description of correlations is limited due to the lack of nuclear structure features entering the utilized wave functions. Hence, they have to be complemented with methods inserting more correlations into nuclear wave functions, as in the NCSM + RGM method. Using few-body physics approaches, Continuum Discretized Coupled Channels (CDCC) method is a very powerful reaction tool, with which as many as four clusters have been included. It is widely used for reactions involving light and heavy nuclei. The Lorentz Integral Transform (LIT), applied for photoreactions of very light nuclei, has also been considered with realistic interactions. Along with CDCC, they can include continuum effects using bound states expansion of normalizable wave functions. Spectroscopic factors, which play a particularly important role in reaction theory, are very much studied in the context of exotic nuclei. As they quantitatively measure correlations in nuclei, they can provide important information about nuclear structure close to drip-lines. However, questions remain concerning the model-dependence of experimental extraction of spectroscopic factors, due to simplifying assumptions of current reaction models. In particular, they can be strongly modified by continuum coupling, with the appearances of so-called Wigner cusps when new emission channels open.

The study of drip-line nuclei is a much more demanding task than the study of those of the valley of stability, as very powerful machines are necessary to synthesize them on the one hand, and on the other hand computational cost of devised theoretical models becomes very expensive due to the explicit inclusion of continuum degrees of freedom. Their description will allow to better understand nuclear interaction at large isospin, as well as astrophysical reactions, in which exotic nuclei play a prominent role.

II. GOALS OF THE WORKSHOP

The goals of the proposed workshop are the following :

1. present the most recent works on shell model (SMEC, GSM, DMRG) and other few-body methods (cluster models, COSM) with coupling to the continuum,
2. discuss quasi-exact methods (CC, GFMC) performed in terms of realistic interactions
3. discuss the different methods available for HFB, QRPA, TDHF(B) calculations of weakly bound and possibly unbound nuclei
4. discuss phenomena specific to drip-lines (halos, proton and neutron emission, resonant states, shell closures, BSEC, Fano resonances, collective effects)
5. present reaction models for drip-line nuclei (CDCC, LIT), and consider the problem of a model-independent determination of spectroscopic factors,
6. review experimental methods used to study exotic nuclei.

III. USEFUL REFERENCES

– G. A. Lalazissis et al., Nucl. Phys. A 632, 363 (1998)

– K. Bennaceur et al., Phys. Lett. B 496, 154 (2000)
– M. Grasso et al., Phys. Rev. C 64, 064321 (2001)
– R. Id Betan et al., Phys. Rev. Lett. 89, 042501 (2002)
– E. Khan et al., Phys. Rev. C 66, 024309 (2002)
– N. Michel et al., Phys. Rev. C 67, 054311 (2003)
– A. S. Jensen et al., Rev. Mod. Phys. 76, 215 (2004)
– T. Nakatsukasa and K. Yamabana, Phys. Rev. C 71, 024301 (2005)
– J. Rotureau et al., Phys. Rev. Lett. 95, 042503 (2005)
– J. Rotureau et al., Phys. Rev. Lett. 97, 110603 (2006)
– K. Yoshida et al., Nucl. Phys. A 779, 99 (2006)
– S.E.A. Orrigo et al., Phys. Lett. B 633, 469 (2006)
– D. Gazit et al., Phys. Rev. Lett. 96, 112301 (2006)
– G. Hagen et al., Phys. Lett. B 656, 169 (2007)
– N. Michel et al., Phys. Rev. C 75, 031301 (2007)
– K. M. Nollett et al., Phys. Rev. Lett. 99, 022502 (2007)
– M. Theeten et al., Phys. Rev. C 76, 054003 (2007)
– H. Masui et al., Phys. Rev. C 75, 034316 (2007)
– T. Lesinski et al., Phys. Rev. C 76, 014312 (2007)
– B. Bastin et al., Phys. Rev. Lett. 99, 022503 (2007)
– J. Giovinazzo et al., Phys. Rev. Lett. 99, 102501 (2007)
– M. Stoitsov et al., Phys. Rev. C 77, 054301 (2008)
– M. Rodríguez-Gallardo et al., Phys. Rev. C 77, 064609 (2008)
– A. Gade et al., Phys. Rev. C 77, 044306 (2008)
– N. Schunck and J. L. Egido, Phys. Rev. C 77, 011301 (2008)
– M. Stanoiu et al., Phys. Rev. C 78, 034315 (2008)
– V. Rotival and T. Duguet, nucl-th/0702050, accepted for publication in Phys. Rev. C
– N. Michel et al., J. Phys. G : Nucl. Part. Phys., Topical Review 36, 013101 (2009)

IV. LIST OF MAIN PARTICIPANTS

– K. Bennaceur, Université Claude Bernard Lyon I, Lyon, France (k.bennaceur@ipnl.in2p3.fr)
– P. Chau Huu-Tai, CEA, Bruyères le Châtel, France (huu-tai.chau@cea.fr)
– P. Descouvemont, Université Libre de Bruxelles, Bruxelles, Belgique (pdesc@ulb.ac.be)
– G. Hagen, Oak Ridge National Laboratory, Oak Ridge TN, USA (hageng@ornl.gov)
– N. Hinohara, RIKEN, Wako, Japan (hinohara@riken.jp)
– H. Masui, Kitami institut of technology, Kitami, Japan (hgmasui@mail.kitami-it.ac.jp)
– E. Khan, Institut de Physique Nucléaire, Orsay, France (khan@ipno.in2p3.fr)
– D. Lacroix, GANIL, Caen, France (lacroix@ganil.fr)
– K. Nollett, Argonne National Laboratory, Argonne IL, USA (nollett@anl.gov)
– G. Orlandini, Facolt'a di Scienze, Trento, Italy (giuseppina.orlandini@unitn.it)
– N. Orr, GANIL, Caen, France (orr@lpccaen.in2p3.fr)
– G. Papadimitriou, Oak Ridge National Laboratory, Oak Ridge TN, USA (gpapadim@ornl.gov)
– P. Ring, Technische Universität München, Germany (ring@ph.tum.de)
– J. Rotureau, University of Arizona, Tucson, France (rotureaujj@ornl.gov)
– N. Schunck, Oak Ridge National Laboratory, Oak Ridge TN, USA (schuncknf@ornl.gov)
– I. Tanihata, RIKEN, Wako, Japan (tanihata@rikaxp.riken.go.jp)
– J. Tostevin, University of Surrey, Surrey, UK (j.tostevin@surrey.ac.uk)
– T. Vertse, INRHAS, Debrecen, Hungary (vertse@atomki.hu)
– K. Yoshida, RIKEN, Wako, Japan (Kenichi.Yoshida@riken.jp)

V. LIST OF TALKS

– K. Bennaceur, "Skyrme functional and halo systems"
– P. Chau Huu-Tai, "CDCC and deformed nuclei"
– P. Descouvemont, "Cluster models"
– G. Hagen, "CC method"

- N. Hinohara, "Oblate-prolate shape mixing in proton-rich Se isotopes as large amplitude collective motion"
- H. Masui, "COSM"
- E. Khan, "QRPA calculations"
- D. Lacroix, "Time-dependent density matrix method and the breakup of Borromean systems"
- N. Michel, "Gamow Shell Model and Gamow/HFB"
- K. Nollett, "GFMC"
- G. Orlandini, "LIT"
- N. Orr, "Structure of unbound nuclei beyond drip-line"
- G. Papadimitriou, "Charge radii in halo nuclei"
- P. Ring, "RMF"
- J. Rotureau, "DMRG and SMEC"
- N. Schunck, "HFB using a Woods-Saxon basis expansion"
- I. Tanihata, "Halos in light nuclei"
- J. Tostevin, "Spectroscopic factors"
- T. Vertse, "Complex Energy Shell Model"
- K. Yoshida, "Collective modes of excitation in deformed neutron-rich nuclei"

VI. PROGRAM

Monday 18 (room 125)	Tuesday 19 (room 135)	Wednesday 20 (room 135)
9h15 E. Khan	9h15 P. Chau Huu-Tai	9h15 N. Orr
10h00 K. Yoshida	10h00 D. Lacroix	10h00 J. Tostevin
10h45 **Break**	10h45 **Break**	10h45 **Break**
11h15 N. Hinohara	11h15 G. Orlandini	11h15 N. Schunck
12h00 G. Papadimitriou	12h00 K. Nollett	12h00 P. Ring
12h45 **Lunch**	12h45 **Lunch**	12h45 **Lunch**
14h30 T. Vertse	14h30 P. Descouvemont	14h30 K. Bennaceur
15h15 G. Hagen	15h15 I. Tanihata	15h15 N. Michel
16h00 **Break**	16h00 **Break**	16h00 **End**
16h30 J. Rotureau	16h30 H. Masui	
17h15 **End**	17h15 **End**	