Radioactive Ion Beam Experiments and Three-Nucleon Forces

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Project of the *Espace de Structure et de réactions Nucléaires Théorique*
http://esnt.cea.fr

Period: 31 March – 11 April, 2014

CEA, SPhN, Orme des Merisiers, build. 703, room 135, F-91191 Gif-sur-Yvette

I. SCIENTIFIC ISSUE

Chiral effective field theory (EFT) provides a link between the symmetries of QCD and the nuclear interactions used as the basis of many-body methods aiming to describe medium and heavy-mass nuclei. To best disentangle contributions from competing physical effects, these many-body forces are now included from an ab initio point of view, where the role of the three-nucleon (3N) forces in particular has proven decisive in understanding the evolution of binding energies and magic numbers in the O and Ca chains. The main issue of this project is to confront the evolution of experimental observables key for identifying new shell closures, such as neutron separation energies S_n, 2_1^+ excitation energies E_x, and transition rates $B(E2)$, with the theoretical trends predicted by ab-initio nuclear theories. We can then explore how data emerging from rare-isotope beam facilities worldwide can best be used to constrain different theoretical approaches.

In oxygen, the new shell gaps found in ^{22}O and ^{24}O and the location of the neutron drip-line at ^{24}O, contrast with the expectations of the standard shell-model picture. With just one extra proton, the fluorine isotopes bind at least 6 extra neutrons and exhibit only weak signatures of magic numbers at $N = 14, 16$. The amount of data in this very neutron-rich region has been increasing dramatically in recent years, with the low-lying spectroscopy of these isotopes being extensively studied in the new experimental programs, in particular at RIKEN using the RIBF facility. Similarly in the calcium isotopes, new, albeit weak, magic numbers at $N = 32, 34$ have been discovered beyond the standard ^{40,48}Ca shell closures. Since the possibility exists for an $N = 40$ closure, there are now plans to measure excited states in Ca at the RIBF facility out to ^{60}Ca. Furthermore, the last known Ca isotope ^{58}Ca could still be very far from the dripline, with many calculations predicting a bound ^{70}Ca.

The question to be addressed is how sensitive these striking new features of the nuclear landscape are to various physical effects included in ab-initio many-body methods – assumptions and treatment of NN and 3N forces and their undetermined coupling constants, treatment of many-body correlations, and the role played by coupling to continuum degrees of freedom – as well as the many-body methods themselves. For instance, as shown in Ref. [1], the location of the O dripline is obtained at N=16 with ^{24}O, provided 3N forces are included. Recently, other calculations were done to obtain the systematics of binding energies for the Oxygen isotopes including 3N forces within the Gorkov-Green function framework [2], the In-Medium Similarity Renormalization Group approach [3] and coupled-cluster theory with coupling to the continuum [4]. Also the magicity of ^{52,54}Ca and the mechanisms driving their formation have been widely debated between different phenomenological and quasi-microscopic models for over a decade [5–9]. However, in the first ab-initio studies for calcium isotopes [11, 12], it was shown that 3NFs and an extended valence space are key to explain the $N = 28$ magic number and predicting the semi-closed nature of ^{52,54}Ca. Recent coupled-cluster results including 3N forces and continuum coupling effects also pointed towards the weak magicity of ^{54}Ca [13]. Furthermore, fully ab-initio calculations have addressed the Ca isotopes [14] and are extending their reach to the neighboring chains [15].

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We are now at the point where it is essential to compare the different theoretical scenarios proposed by various approaches to nuclear forces and the many-body problem to develop a clear and consistent picture of exotic nuclei from first principles calculations. Experiment and theory should play a complementary and mutually active role in answering such questions as

- How can we put constraints on the microscopic parameters of a given ab-initio theory with a global data set of observables such as ground state or excitation energies?
- Would the excitation energies located above the neutron energy threshold offer an increased sensitivity to the nuclear many-body forces?
- Within various sets of ab-initio theories with different 3NF prescriptions, could we identify a set of observables offering key tests of the microscopic inputs?

To investigate these questions, the first steps would be to gather experimentalists and theorists who would show, during the discussion sessions, the evolution of the measured observables and of the corresponding calculated values, respectively. The observables for the oxygen and calcium isotopes would represent the benchmarks for testing the validity or sensitivity of the various calculations. Being aware of the benchmarks offered by emerging experimental data, we must discuss the role they play in constraining theory: what can we learn from data on the ground state (gs) energies (e.g masses of exotic Ca [16]), nuclear excitations to bound or unbound states in exotic weakly bound nuclei (e.g. ^{24}O [17], ^{54}Ca [18]), do we have new information if we consider unbound nuclei (e.g. ^{26,28}O)?
For this project, we plan to focus the discussion on the observables for the low-lying spectroscopy (gs binding energies, matter root mean square -rms- radii, energies of the first excited states or transition strength between gs and first excited states). These studies of the correlations between the microscopic nuclear parameters and the predicted values of the observables are needed to reach a quantitative understanding of the microscopic inputs and to decisively assess the importance of the measurement of new data set to discriminate between nuclear forces.

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II. GOALS OF THE PROJECT

The main goals of the project are:

1. To examine observables (gs binding energies, matter rms radii, low-lying excited states, transition rates) for O and Ca isotopes, to make the comparison with the calculations proposing various interpretations of the shell effects;
2. To compare the assumptions of the various ab-initio many-body theories: methods, specificity, limitations;
3. To discuss the influence of 2N and 3N contributions and to check the sensitivity of the calculated observables to the parameters of the nuclear interactions.

In particular, the various theoretical frameworks proposed to describe the O and Ca chains will be compared. With the experts of the field, the project will emphasize the issues related to the treatment of the 3N forces and the role played by the few-body correlations and by the tensor force in the various approaches. The influence of the continuum of resonant, non resonant and scattering states will also be discussed.

Useful references:

• *Three-body forces: From cold atoms to nuclei*, H.-W. Hammer, A. Nogga, and A. Schwenk, Rev. Mod. Phys. **85**, 197 (2013).
• *Coupling to the continuum*: J. Dobaczewski, N. Michel, W. Nazarewicz, M. Ploszajczak, and J. Rotureau, Prog. Part. Nucl. Phys. **59**, 432 (2007).
• *Observables related to shell evolution*: O. Sorlin and M.-G. Porquet, Prog. Part. Nucl. Phys **61**, 602 (2008).

III. STRUCTURE OF THE PROJECT

During the two weeks of the project, ESNT will host expert visitors who develop calculations within frameworks including 3N forces: Heiko Hergert (The Ohio State University, USA) and Jason D. Holt (TU Darmstadt).
The experimentalists of the nuclear structure groups, in particular, from SPhN, IPN-Orsay, GANIL and CSNSM physicists working in the nuclear mass measurements, are expected to join the project and to participate to the open sessions. The ESNT will also host O. Sorlin (GANIL) during the 2-day sessions about nuclear shell effects.

The program will be lightly structured, leaving plenty of time for both open discussion sessions and more targeted working groups. In the first two days of each week, open sessions are envisioned: an informal seminar in the morning will set the basis for the day's discussions. Physicists willing to come and discuss are welcome in these sessions. They will have to inform the organizers of their venue and register by sending an e-mail to the SPhN contact organizer.
Wednesdays and Thursdays will be instead dedicated to discussions in smaller groups on specific, more technical issues. Two SPhN seminars (at 11 a.m.) will be given by the project guests with talks about:
– *Exploring the nuclear landscape at the extremes: 3-body forces and the physics of exotic nuclei*, J.D. Holt, on 4^{th};
– *Pushing the Boundaries of Ab-Initio Nuclear Structure*, by Heiko Hergert, on Monday 7^{th}.
A round-table will be organized at the end of the period, to give an overview of the status of the calculations using 3NFs and to draw conclusions about the works done within the project. Throughout the project, it is expected that there will be discussions between theorists and experimentalists about the sensitivity of observables with the theory parameters and also explanations about the comparison of the probes used for nuclear excitations.

IV. PROGRAM

During the first week, the work sessions will be devoted to the discussions about the observables for the ground state properties, binding energies and rms radii of proton, neutron and matter density distributions of the O and Ca isotopes. We will also present the measured and calculated evolutions of the first excited states and transitions strengths.

Week 1	*Mar 31*	*Apr 1*	*Apr 2-3*	*Apr 4*	*Week 2*	*Apr 7*	*Apr 8*	*Apr 9-10*	*Apr 11*
09h30	Informal seminar *V. Somà*	Informal seminar *V. Lapoux*	*Working group*	SPhN seminar *J. Holt*	*09h30*	SPhN seminar *H. Hergert*	Discussions *visio* *A. Obertelli*	*Working group*	*Project summary perspectives*
12h30		*lunch*		*lunch*	*12h30*		*lunch*		*lunch*
14h00 – –	*Discussions rms radii Observables*	*Round Table Continuum*	*Working group*	*Working group*	*14h00* – –	*O. Sorlin Shell gaps*	*Works Open Discussions*	*Working group*	*Working group*

During the second week, the comparisons and calculations will be focused on the nuclear shell properties which can be deduced, depending on the assumptions made on the $2NF$ and $3NF$ parameters used in the ab-initio theories.