Training in Advanced Low Energy Nuclear Theory

Course 8 – Atomic Nuclei as Open Quantum Systems: Unifying Nuclear Structure and Reactions

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1 Introduction

Only 288 of the several thousand isotopes known to inhabit the nuclear landscape are either stable or practically stable. By moving away from this valley of stability, by adding nucleons, we enter the vast territory of short-lived radioactive nuclei.

The territory at our beyond the limits of nuclear binding is a very fertile ground for research in nuclear structure physics. In addition, astrophysical rapid proton and neutron capture processes operate very close to the drip lines; hence, the properties of very exotic, weakly bound nuclei directly impacts the way the elements are produced in stars.

From the theoretical point of view, the description of nuclear systems in this regime is a demanding task as it requires the understanding and control of three crucial aspects of the nuclear many-body problem: interaction, correlation, and coupling to the low-lying particle continuum. Systems that are greatly affected by a continuum of decay channels are known as open quantum systems.

In this course, students will learn about the fundamental concepts of open quantum systems and they will be introduced to state-of-the-art methods that can be used to model such systems. The main focus of the course will be on the coupling between nuclear structure and reaction aspects of nuclei. In particular, the lectures will elucidate the open and non-stationary nature of nuclei and will highlight the impact of decay channels on nuclear properties. The theoretical material covered is crucial for understanding weakly bound/unbound nuclei close to the particle drip-lines, and studying

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structures and reactions with those exotic systems. A solid theoretical background will be presented through lectures and made available via extensive online material. Learning and experience with the material are expected to be achieved through course participation and discussions, and various analytic and computational projects and hands-on exercises.

2 Course plan

The following subsections contain the course plan for the first edition of TALENT, course 8: Atomic Nuclei as Open Quantum Systems: Unifying Nuclear Structure and Reactions.

2.1 Aims and learning outcomes

The learning outcomes of this course are:

- gain an in-depth understanding of basic concepts of open quantum systems;
- learn about the recent developments, open challenges, and research opportunities in the specific context of exotic nuclei and structure of weakly bound/unbound nuclear states;
- get familiar with mathematical methods and state-of-the-art computational techniques pertaining to the nuclear open quantum many-body problem, with a focus on continuum coupling;
- participate in teamwork exercises having well-defined deliverables;
- deliver a paper on a computational nuclear physics project.

The experience gained in this course will give the participants the necessary proficiancy to tackle a broad spectrum of research problems in nuclear physics and beyond. In spite of the specific features of nuclear interactions, open quantum systems also display generic properties that are common to all weakly bound/unbound systems close to threshold.

2.2 Teaching

The course will take the form of an intensive program of three weeks, with a total time of 45 h of lectures and directed exercises, about 75 h devoted to various computational projects (out of which 60 h are supervised), and a final assignment worth approximately 2 weeks (80 h) of work. The total workload will amount to 200 hours, corresponding to 7.5 ECTS in Europe. The final assignment will be graded with marks A, B, C, D, E and failed for Master students and passed/not passed for PhD students. The proposed organization of the day is as follows:

Organization of the day	
09:00 – 10:30	Lectures
10:30 – 11:00	Coffee
11:00 – 12:30	Lectures / Directed excercises
12:30 – 13:30	Lunch
13:30 – 15:30	Hands-on sessions, computational projects
15:30 – 16:00	Coffee
16:00 – 17:30	Hands-on sessions, computational projects
17:30 – 18:00	Discussions, Wrap-up of the day

2.3 Prerequisites

Students should have working proficiency in quantum mechanics at graduate level. This includes knowledge of the following basic physics concepts and mathematical physics tools: concept of wave function, Schrödinger equation, spin, Hilbert spaces, complex variables, Fourier transform, linear algebra. Students are also expected to have operating programming skills in Fortran, C/C++, and/or Python. Other programming languages are allowed but may not be supported by the teaching staff.

2.4 Detailed week-by-week schedule

Week 1 — Open quantum systems: basic concepts

General: Introduction, analytic results, simple numerical studies, phenomenology of nuclear decays (2 experimental lectures).

1. **Overview of reaction theory (4 lectures)**
2. **Resonances and decay processes (5 lectures)**
3. **Basic properties of multichannel systems (6 lectures)**
4. **Real-energy continuum Shell Model (I) (3 lectures)**
5. **Overview of nuclear decays (2 lectures)**

Week 2 — Methods and applications (I)

General: Major theoretical frameworks and concepts.

6. **Real-energy continuum Shell Model (II) (4 lectures)**
7. **Shell Model in the complex energy plane (7 lectures)**
8. **Collective phenomena (5 lectures)**
9. **Continuum in nuclear Density Functional Theory (2 lectures)**
10. **Effects of decay and coupling to continuum (I) (2 lectures)**

Week 3 — Methods and applications (II)

General: Ab initio approaches, examples of applications, nuclear decays (including 2 experimental lectures), project work.

11. **Effects of decay and coupling to continuum (II) (3 lectures)**
12. **Ab initio approaches (7 lectures)**
13. **Nuclear decays (10 lectures)**