Program for Nuclear Talent course on Many-body methods for nuclear physics

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Motivation and introduction

To understand why matter is stable, and thereby shed light on the limits of nuclear stability, is one of the overarching aims and intellectual challenges of basic research in nuclear physics. To relate the stability of matter to the underlying fundamental forces and particles of nature as manifested in nuclear matter, is central to present and planned rare isotope facilities.

Important properties of nuclear systems which can reveal information about these topics are for example masses, and thereby binding energies, and density distributions of nuclei. These are quantities which convey important information on the shell structure of nuclei, with their pertinent magic numbers and shell closures or the eventual disappearence of the latter away from the valley of stability.

During the last decade, the study of nuclear structure and the models used to describe atomic nuclei are experiencing a renaissance. This is driven by three technological revolutions: accelerators capable of producing and accelerating exotic nuclei far from stability; instrumentation capable of detecting the resulting reaction products and gamma radiation, often on an event-by-event basis, in situations where data rates may be many orders of magnitude less than has been traditional; and computing power adequate to analyze the resulting data, often on-line, and to carry out sophisticated theoretical calculations to understand these nuclei at the limits of stability and to unravel what they tell us about nuclei and their structural evolution.

The nuclear shell model plays a central role in guiding our analysis of this wealth of experimental data. It provides an excellent link to the underlying nuclear forces and the pertinent laws of motion, allowing nuclear physicists to interpret complicated experiments in terms of various components of the nuclear Hamiltonian and to understand a swath of nuclei by following chains of isotopes and isotoones over wide ranges of nucleon numbers. The nuclear shell model allows us to see how the structure of nuclei changes and how the occupation of specific nucleonic orbits affects the interplay of residual interactions and configuration mixing. The computed expectation values and transition probabilities can be directly linked to experiment, with the potential to single out new phenomena and guide future experiments. Large-scale shell-model calculations represent also challenging computational and theoretical topics, spanning from efficient usage of high-performance computing facilities to consistent theories for deriving effective Hamiltonians and operators. Alltogether, these various facets of nuclear theory represent important elements in our endeavors to understand nuclei and their limits of stability. It is the goal and motivation of this course to introduce and develop the nuclear structure tools needed to carry out forefront research using the shell model as the central tool. The various projects will focus on the development of a shell-model code for simpler systems like *sd*-shell nuclei, giving the participants the essential ideas of configuration interaction methods. During the first two weeks the aim is to develop such a shell-model code. With these insights, the students can divert into several directions the last week, from the usage of the NushellX suite of nuclear structure programs to further developing their own shell-model program. After completion, it is our hope that the participants have understood the overarching ideas behind central theoretical tools used to analyse nuclear structure experiments.

Aims and Learning Outcomes

This three-week TALENT course on nuclear theory will focus on the

Format: We propose approximately forty-five hours of lectures over three weeks and a comparable amount of practical computer and exercise sessions, including the setting of individual problems and the organization of various individual projects.

The mornings will consist of lectures and the afternoons will be devoted to exercises meant to shed light on the exposed theory, and the computational projects. These components will be coordinated to foster student engagement, maximize learning and create lasting value for the students. For the benefit of the TALENT series and of the community, material (courses, slides, problems and solutions, reports on students' projects) will be made publicly available using version control software like *git* and posted electronically on github.

As with previous TALENT courses, we envision the following features for the afternoon sessions:

- We will use both individual and group work to carry out tasks that are very specific in technical instructions, but leave freedom for creativity.
- Groups will be carefully put together to maximize diversity of backgrounds.
- Results will be presented in a conference-like setting to create accountability.
- We will organize events where individuals and groups exchange their experiences, difficulties and successes to foster interaction.
- During the school, on-line and lecture-based training tailored to technical issues will be provided. Students will learn to use and interpret the results of computer-based and hand calculations of nuclear models. The lectures will be aligned with the practical computational projects and exercises and the lecturers will be available to help students and work with them during the exercise sessions.
- These interactions will raise topics not originally envisioned for the course but which are recognized to be valuable for the students. There will be flexibility to organize mini-lectures and discussion sessions on an ad-hoc basis in such cases.
- Each group of students will maintain an online logbook of their activities and results.
- Training modules, codes, lectures, practical exercise instructions, online logbooks, instructions and information created by participants will be merged into a comprehensive website that will be available to the community and the public for self-guided training or for use in various educational settings (for example, a graduate course at a university could assign some of the projects as homework or an extra credit project, etc).

Objectives and learning outcomes: At the end of the course the students should have a basic understanding of

- Configuration interaction methods (nuclear shell-model here) as a central tool to interpret nuclear structure experiment
- Have an understanding of single-particle basis functions and the construction of many-body basis states built thereupon. Examples are basis states from a Woods-Saxon potential, harmonic oscillator states and mean-field based states from a Hartree-Fock calculation. The single-particle basis states are orthonormal and are used to construct a corresponding orthonormal basis set of Slater determinants.

- Develop an understanding of what defines an observable.
- Understand how theory can be used to interpret experimental quantities (separation energies and shell gaps for example).
- Understand how second-quantization is used to represent states and compute expectation values and transition probabilities of operators
- Understand how the Hamiltonian matrix is constructed from this orthonormal basis set of many-body states (linear expansion of Slater determinants)
- The students will also learn to understand the basic elements of effective shell-model Hamiltonians and how to interpret the calculated properties in terms of various components of the nuclear forces (spin-orbit force, tensor force, central force etc). We will provide the students with the necessary tools to perform such analyses.
- Understand how to use shell-model calculations to calculate decay rates and transition probabilities and relate these to various electromagnetic transition operators and operators for beta-decays and double-beta decays.
- Develop a critical understanding the limits of shell-model studies and how these can be related to interpretations of data such as results from in-beam and decay experiments.

Course Content and detailed plan

Lectures are approximately 45 min each with a small break between each lecture. The morning sessions are scheduled to end around 1230pm.

Week 1.

Day		Lecture Topics and lecturer	Projects and exercises
Monday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Tuesday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Wednesday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Thursday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Friday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		

Week 2.

Day		Lecture Topics and lecturer	Projects and exercises
Monday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Tuesday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Wednesday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Thursday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Friday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		

Week 3.

Day		Lecture Topics and lecturer	Projects and exercises
Monday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Tuesday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Wednesday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Thursday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		
Friday	9am-1230pm		
	1230pm-230pm	Lunch +own activities	
	230pm-6pm		

Teaching and projects

The course will be taught as an intensive course of duration of three weeks, with a total time of 45 h of lectures, 45 h of exercises and a final assignment of 2 weeks of work for those of you wish to receive 7 ECTS credits for the course. The total load, with the additional project to be handed in later, will be approximately 160-170 hours, corresponding to **7 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.

A course certificate will be issued for students requiring it from the University of Trento. This certificate states that you have completed the equivalent of 7 ECTS at the graduate level. We plan also to issue a certificate for those of you who have attended the course but did not want to do the final project. This certificate will most likely correspond to 4 ECTS at the graduate level.

The organization of a typical course day is as follows:

Time	Activity
9am-1230pm	Lectures, project relevant information and directed exercises
1230pm-230pm	Lunch
230pm-6pm	Computational projects, exercises and hands-on sessions
6pm-7pm	Wrap-up of the day and eventual student presentations

Teachers and organizers

The organizers are

1. Alex Brown, National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

2. Morten Hjorth-Jensen, National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA and Department of Physics, University of Oslo, N-0316 Oslo, Norway

Morten Hjorth-Jensen will also function as student advisor and coordinator.

The teachers are

1. Alex Brown, National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

2. Alexandra Gade National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

3. Robert Grzywacz at Oak Ridge National Laboratory, Oak Ridge, TN 37831 and Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996-1200, USA

4. Morten Hjorth-Jensen at National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA and Department of Physics, University of Oslo, N-0316 Oslo, Norway

5. Gustav Jansen at Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Audience and Prerequisites

You are expected to have operating programming skills in in compiled programming languages like Fortran or C++ or alternatively an interpreted language like Python and knowledge of quantum mechanics at an intermediate level. Preparatory modules on second quantization, Wick's theorem, representation of Hamiltonians and calculations of Hamiltonian matrix elements, independent particle models and Hartree-Fock theory are provided at the website of the course. Students who have not studied the above topics are expected to gain this knowledge prior to attendance. Additional modules for self-teaching on Fortran and/or C++ or Python are also provided.