Training in Advanced Low Energy Nuclear Theory

I. INTRODUCTION TO THE TALENT COURSES

A recently established initiative, **TALENT: Training in Advanced Low Energy Nuclear Theory**, see www.nucleartalent.org, aims to provide an advanced and comprehensive training to graduate students and young researchers in low-energy nuclear theory. The initiative is a multi-national network between several European and North American institutions and aims to develop a broad curriculum that serves as a platform for cutting-edge theory of nuclei and their reactions. The graduate program is divided into 9 modules. Each module includes a series of lectures, commissioned from experienced teachers who are practicing researchers in nuclear theory, but is driven by problem-based learning, providing hands-on experience. The educational material generated, that will evolve under this program, will be collected in the form of WEB-based courses, textbooks, and a variety of modern educational resources.

The advanced training network in nuclear theory will also provide students (both theorists and experimentalists) with a broad background in more interdisciplinary methods and techniques - that have applications to other domains of science and technology. The characteristic feature of this initiative is training in multi-scale nuclear physics. This knowledge is crucial, not only for a basic understanding of atomic nuclei, but also for further development of knowledge-oriented industry; from nanotechnology and material science to biological sciences, from energy to high performance computing.

Because the program builds strong connections between universities, research laboratories and institutes worldwide, it provides a unique training ground for the future generation of nuclear physicists.

The first TALENT course, Course 9: *High-performance computing and computational tools for nuclear physics*, took place at the ECT* in Trento, Italy, in June and July 2012. What follows is a detailed description of the second TALENT course, Course 6: *Theory for exploring nuclear reaction experiments*, to be delivered at GANIL, at Caen, France, from 1 - 19 July 2013.

II. COURSE 6: THEORY FOR EXPLORING NUCLEAR REACTION EXPERIMENTS

A. Motivation and background

Nuclear reaction methods are used to both predict reaction yields and analyze experimental data to extract reaction rate, cross section and nuclear structure (spectroscopic) information. The new capabilities of rare-isotope facilities, where short-lived nuclear species are produced as secondary or re-accelerated beams, means that nuclear reactions are both a primary production mechanism and also the probe of the produced nuclei – their structure and their dynamics. The beam energies, methods and approximations used are quite diverse. They range from low-energy capture, fusion and transfer reactions at energies near or well below that of the Coulomb barrier, through the description of nuclear and Coulomb breakup, Coulomb excitation, charge exchange and other direct reactions at fragmentation beam energies in excess of 100 MeV per nucleon. Reactions are often performed in inverse kinematics. The objective of this TALENT course is to enable younger researchers to gain the necessary background knowledge for more advanced study, by exposure to both formal methods and practical experience of the use of direct reaction methods - including the use of some associated codes. The aims are to develop both (i) background knowledge and (ii) confidence in making choices of methods and physical parameter selections to solve (approximately) the quantum many-body reaction problems using available theoretical tools. The course will provide discussions of the underlying principles and approximations and their limitations. The acquired skills should enable the participants to ask critical questions of published work and the results of codes, and to begin to work with existing reactions machinery. Participants will be exposed to the knowledge necessary to then tackle new and related research problems. The course will give feedback on scientific report writing via the final project assignment which will be graded.

B. Course Content

The course aims to introduce the underpinning theoretical constructs of approaches used to describe the scattering and reactions of nuclear systems in different energy regimes. Formal aspects of scattering and reaction theory, that underpin all of the practical methodologies, will be presented in structured lectures, with recommended reading and exercises. Topics covered will include the basis of the optical model, first-order theories (such as DWBA), and non-perturbative, all-order, coupled channels and semi-classical few- and many-body approaches. All of these methods are built upon common basic concepts, the quantum mechanical descriptions of bound, resonant and multi-channel scattering problems and phenomena. The course will present scattering theory results, that form the basis of widely-used reaction methods, through formal presentations, and give practical experience through elementary and more open-ended computational tasks, assignments and projects. The provisional plan of the detail of the material covered in the 2013 course is presented below. The specific methods and emphasis of the work may vary in this and subsequent years, depending on the course teachers and the stated research interests of the selected participants. In all cases the main focus will be on the underpinning concepts and implementations of practical nuclear reactions methods at an advanced Masters level.

1. Detailed Course Content

This course on nuclear reaction methods will be run at GANIL, in Caen, France. It will start on July 1st and end on July 19th in 2013. The course will focus on direct reaction theory and methods, and their applications to reactions of light and heavy-ions from low (near-Coulomb barrier) energies through intermediate and relativistic energies (of 100 MeV/nucleon and greater).
Exposure to such systems will introduce both specific and more generic inputs needed to describe nuclear collisions and direct reactions. Use will be made of examples that are simple, but realistic enough to allow participants to develop confidence in using both the concepts and associated codes to solve selected reaction problems - exploiting and consolidating understanding of the more formal taught elements.
The more detailed outline of the course is as follows:

First week
Expectations: the student will be exposed to and will develop the formal aspects of scattering theory, and so appreciate the basic ingredients that support more advanced computations.

- Background - from many-body collisions to model descriptions with a few degrees of freedom, reaction classifications and timescales, effective interactions and Hamiltonians, the optical potential and mean-field. Review and hands-on studies of solutions of bound, resonant and continuum quantum two-body problems. (Monday, Week 1)

- Scattering theory I: boundary conditions, differential and integral equation forms for single-channel, two-body systems. The R-matrix reaction approach. Study of the role of complex and Coulomb interactions on elastic scattering, examples and exercises. (Tuesday, Week 1)

- Scattering theory II: The Born series, the two-potential forms, exact and development of perturbative schemes. Comparison of differential and integral equation techniques. (Wednesday, Week 1)

- Scattering theory III: generalisation of differential and integral forms for many-channel problems, Born approximation and coupled channels, Feshbach P's and Q's, bare and effective channel interactions, illustrative examples and exercises. (Thursday, Week 1)

- Coupling interactions: Collective and cluster-like Coulomb and strong interaction couplings, nucleon and cluster-folding models, multipole expansions, B(Eλ) transition strengths and transition densities. Examples: e.g. inelastic reaction for a collective (rotational) nucleus, Coulomb excitation. (Friday, Week 1)

Second week
Expectations: The student will be introduced to a number of methods for practical applications for the analysis of experiments, and gain confidence in selection of the inputs involved and the validity of the approximations used.

- Channel Coupling: Continuum: the bin representation and continuum-continuum couplings. The interfaces between nuclear structure and reactions, nucleon and cluster models, overlap functions of one and two particles, spectroscopic strengths and associated form-factors. (Monday, week 2)

- Semiclassical concepts: time dependent approaches, Coulomb excitation, first-order perturbation theory and higher-order corrections, post-acceleration, virtual photon description. Example: Coulomb dissociation of halo nuclei. (Tuesday, week 2)

- Eikonal methods: derived eikonal equations for point particles, the eikonal solutions for phase shifts and the S-matrix. Eikonal and optical limit techniques for composite projectiles. Elastic, reaction and other cross sections and the content of momentum distributions. Example: analysis of knockout reactions including momentum distributions. (Wednesday, week 2)

- Transfer reactions: Approximations. From exact and perturbative amplitudes, Q-value, momentum and L-transfer matching, periphery analysis. The adiabatic approximation for breakup and transfer, Johnson and Soper-like methods for transfer, zero-range and finite range effects. Example: analysis of (d,p) reactions including extraction and sensitivity to spectroscopic factors and the ANC. (Thursday, week 2)

- WKB approximation. Capture reactions: direct and resonant, S-factor, low-energy behaviour. Fusion reactions and barrier penetration methods. Channel-coupling and fusion enhancement. Examples: determine the capture reaction cross sections for an E1 process assuming simplified states, Coupled-channels barrier-passing fusion calculations. (Friday, week 2)

Third week
Expectations: The student workload will include both formal and research project preparation effort. Students will begin consideration and literature study for their more-extended research project (requiring them to select their area of project work). They will prepare a short research plan. The final project report will be in the format of a scientific paper with relevant referencing.

- R-matrix method, computational and phenomenological aspects. Resolution of the Schrodinger equation with the computational R-matrix. Example: determining scattering cross sections from optical potentials. Analysis of experimental cross sections with the phenomenological R-matrix. Example: extracting energies and widths of resonances from actual data. Extensions to multichannel problems and to radiative capture. (Monday and Tuesday, week 3)
- Microscopic descriptions of reactions based on cluster models: explicit antisymmetrization and the resonating group method (RGM). Equivalence between the RGM and the Generator Coordinate Method (GCM). Applications to simple systems: alpha+nucleon and alpha+alpha. Generalizations to multi-cluster system descriptions, and to ab-initio calculations. (Wednesday/part Thursday, week 3)
- Q&A session. Discussion of final project timescales, expectations and selection. (part Thursday, week 3)
- Review. Collective and/or individual discussions of final research project (Friday, week 3)

The course ends with the final project assignment. The project assignment will be graded A, B, C, D, E or failed for Master students and passed/not passed for PhD student participants. Feedback on the project will be provided.

C. Teaching

The course will be taught as an intensive course of three weeks duration, with a total time of 45 hours of lectures, 45 hours of exercises and a final assignment of 2 weeks of work. The total load will be approximately 240 hours, corresponding to **10 ECTS** in Europe. Organization of the day: 9-12 lectures, time for exercises with assistance (including lunch) until 18 (3 hours of allocated exercise sessions per day). Summary and questions and student presentations till 19. The course will be run at the premises GANIL in Caen, France, from July 1st to July 19th in 2013.

D. Teachers

Jeff Tostevin (University of Surrey, UK), Filomena Nunes (Michigan State University, USA), Pierre Descouvemont (Universite Libre de Bruxelles, Belgium), Antonio Moro (Universidad de Sevilla, Spain) and Edward Simpson (University of Surrey, UK). Persons responsible for the course: Jeff Tostevin and Filomena Nunes.

E. Prerequisites

The student participants are expected to have some experience in programming and be familiar with data manipulation and graphical utilities, etc. A good foundation in both standard mathematical methods for scientists and a practitioners knowledge of intermediate level (advanced undergraduate/postgraduate) quantum mechanics.
Recommended preparatory reading on quantum scattering theory will be provided prior to the course start. Students who have not previously studied the above topics formally are expected to study these materials prior to the course. Additional links for self-teaching, or conversion/familiarisation with Fortran programming language constructs will also be provided.

F. Admission

Registration is now open. The target groups of participants are Master of Science and PhD students. Early-career post-doctoral fellows will also be considered. Applications are welcomed from both experimentalists and theorists. More senior staff will be considered, space permitting, on a fully-self-supported basis only. The maximum number of students will be of order 25. Local support is only available for at most 20 participants. The lecture hall can accommodate additional, self-supported participants, without desk space. The process of selection of the students will be managed by the organizers in agreement with the University of Caen and GANIL.

All applications should be made electronically to talent-school@ganil.fr. Applications should include: a curriculum vitae, a description of academic and scientific achievements to date (any publications, awards, etc.), a short letter expressing the applicants personal motivation for attending the course, and a statement if local support is needed. A reference letter from the candidates academic supervisor should also be included or sent separately to talent-school@ganil.fr.

Deadline for applications is April 5, 2013.

III. MORE MATERIAL ON THE TALENT PROGRAM

A. Other courses planned

- **Course 1**: *Nuclear forces and their impact in nuclear structure*
  Institute for Nuclear Theory in Seattle, July 1 - July 19, 2013.
- **Course 2**: *Many-body methods for nuclear physics*
- **Course 3**: *Few-body methods and nuclear reactions*
- **Course 4**: *Density functional theory and self-consistent methods*
- **Course 5**: *Theory for exploring nuclear structure experiments*
  Planned for 2014.
- **Course 6**: *Theory for exploring nuclear reaction experiments*
  GANIL in Caen, July 1 - July 19, 2013.
- **Course 7**: *Nuclear theory for astrophysics*
  Michigan State University in May/June 2014.
- **Course 8**: *Theoretical approaches to describe exotic nuclei*