**Master-thesis proposals for the year 2014-2015**

The subjects proposed by the Nuclear Physics and Quantum Physics research unit (joint unit of the Sciences Faculty and of the École polytechnique de Bruxelles) are theoretical in nature and usually involve mathematical and numerical modeling. The formalism used is that of quantum physics and most applications include nuclear physics.

Our research unit is part of an Interuniversity Attraction Poles (IAP) program, BriX (The Belgian Research Initiative on eXotic nuclei for atomic, nuclear and astrophysics studies), in which we collaborate with other nuclear-physics groups, both theoretical and experimental, in Belgium and abroad. Through this collaboration, there is a possibility for very motivated students to realize their thesis on experimental subjects at the KULeuven or at the Uliège, under the joint direction of KUL/ULiège and ULB supervisors. See possible research themes at the end of this document; for precise subjects, please contact Jean-Marc Sparenberg.

**THEORETICAL NUCLEAR PHYSICS**

1. **Construction of baryon-baryon interaction potentials by inversion of elastic and inelastic collision data**  
   *J.-M. Sparenberg, P. Capel*

   In quantum theory of collisions, the inverse problem is the construction of an interaction potential from collision cross sections. A related problem is the construction of phase-equivalent potentials, that is to say different potentials which have the same cross sections. These two issues will be addressed by the method of supersymmetric quantum mechanics [1], mathematically (possibly with the help of a symbolic computation software such as SymPy) and/or numerically (Python and/or Fortran program), and applied to the data of elastic and inelastic collisions for nucleon-nucleon [2] and/or hyperon-hyperon systems, both for single-channel and coupled-channel cases [3]. These interactions are essential for the modeling of nuclei and hypernuclei and could still reveal some surprises.


2. **Building of a phenomenological potential from microscopic interactions, application to the $^{15}$C case.**  
   *P. Capel, D. Baye and J.-M. Sparenberg*

   Current reaction models are usually based on simple description of the colliding nuclei. For instance, halo nuclei are usually described as made up of two or three clusters interacting through phenomenological potentials that are fitted to reproduce a few physical properties of
the nucleus: its binding energy, the spin and parity of its ground state and some of its excited states. Unfortunately these properties are not enough to fully constrain the parameter of the potentials, leading to significant variations in theoretical predictions of the reaction cross sections [1]. To improve the predictive power of reaction calculations, we would like to derive these phenomenological potentials from microscopic calculations that are based on more fundamental principles. Such a model has been developed in our department and successfully applied for $^{15}$C [2]. The goal of this work is to adjust a phenomenological $^{14}$C-n potential on the results of the microscopic model for $^{15}$C using the tools developed with supersymmetric quantum mechanics. The potential hence obtained would then be used within various models of reactions involving $^{15}$C, such as its Coulomb breakup or the radiative capture $^{14}$C(n,$\gamma$)$^{15}$C. The calculations using this potential would then be compared to experimental data to evaluate the interest of such a construction. It will also help us understand the interest of including microscopic descriptions of the colliding nuclei within accurate reaction models.


3. Analysis of the ratio method
P. Capel

The development of radioactive-ion beams has enabled nuclear physicists to explore the nuclear landscape far away from the valley of stability. This has led to the discovery of exotic nuclear structures such as halo nuclei. Halo nuclei are light nuclei located close to the neutron dripline, which exhibit a matter radius much larger than expected. This large size is now understood as being due to the low binding energy for one or two neutrons of these nuclei. Thanks to the tunnel effect, these neutrons exhibit a high probability of presence at a large distance from the other nucleons and hence form a sort of halo around the core of the nucleus.

Being short-lived, halo nuclei cannot be studied through usual spectroscopic techniques, and one must resort to indirect methods to study their structure. Nuclear reactions are the best tools for such indirect studies. From reaction cross section one hopes to get information about the halo structure. Unfortunately the analysis of reactions is not without bias. In particular the potentials used to describe the interaction between the projectile and the target are poorly known and introduce significant uncertainty on the theoretical analysis of experimental data.

Recently, a new method of analysis has been suggested that removes this uncertainty [1]. It consists in considering the ratio of cross sections for different processes, such as elastic scattering and breakup. This ratio has been shown to be nearly independent of the projectile-target potentials, leading to an observable much more sensitive to the projectile structure than usual reaction cross sections.

The goal of this Master thesis is to study in more detail this ratio method, see if it can be used at different beam energies or for other projectile structures.

THEORETICAL NUCLEAR ASTROPHYSICS

3. Inferring the cross section for the radiative-capture $^{14}\text{C}(n,\gamma)^{15}\text{C}$ from the Coulomb breakup of $^{15}\text{C}$

P. Capel

Measuring radiative capture, such as $^{14}\text{C}(n,\gamma)^{15}\text{C}$, at low energy is a very difficult task. To circumvent this problem, various indirect methods have been proposed. In the Coulomb-breakup reaction, the final product of the radiative capture ($^{15}\text{C}$ in the present case), is broken up into its constituents ($^{14}\text{C}$ and a neutron in this case) through its interaction with a heavy target, like Pb. In a simple model the Coulomb breakup can be seen as the time-reversed reaction of the radiative capture: the breakup taking place by the exchange of virtual photons between the projectile and the target [1].

Recent analyses of the Coulomb breakup of $^{15}\text{C}$ have shown that a precise model of the reaction is needed to infer reliable radiative-capture cross section from breakup measurements [2, 3]. The goal of this work is to study in detail the influence of the projectile description on breakup calculations and their influence on the extracted radiative-capture cross section. Using codes developed in our department [4, 5], the student will be asked to perform a series of breakup calculations using different models of $^{15}\text{C}$ to evaluate the reliability of the Coulomb breakup method to infer radiative-capture cross sections. Depending on the progress of these calculations, extensions of this study to other reactions/nuclei can be envisaged.


THEORETICAL QUANTUM PHYSICS

4. Microscopic modeling of a cloud-chamber-type quantum-measurement apparatus on the basis of quantum scattering theory

J.-M. Sparenberg

A possible explanation for the seemingly random nature of the result of a measurement in quantum mechanics is that this result is in fact determined by the microscopic state of the measuring device [1]. The purpose of this work is to test this hypothesis in the case of the detection of a spherical wave (alpha-radioactivity type) in a cloud chamber, in order to explain the observation of straight paths that seem inconsistent with a spherical-wave emission. To do this, the interaction between the detected wave and the atoms of the chamber will be treated by the Born approximation of quantum collision theory, approximation whose validity will be tested numerically.

Master of Science in Physics
Specialisation Physics at the femtometer scale: nuclear physics

Thesis subjects

The following list contains general themes for master thesis subjects for students starting in 2014-2014.

For students who want to develop a more international profile, there are many opportunities to be involved in international collaborations or to do (part of) the thesis research abroad in the framework of the Erasmus programme. All research groups have strong international collaborations so when you are interested in the Erasmus programme and you have decided on your specialization, contact the trajectory responsible for additional information”.

Students in the Dutch masters program, following the ‘onderwijs optie’ can also choose to make a thesis related to education research. This topic is described at the end of the document, and it can be chosen as a thesis subject in each of the four specializations.

February 2014
Specialisation: *Physics at the femtometer scale: Nuclear Physics*

Are you fascinated by the world of subatomic particles? Do you want to explore the boundaries of the existence by studying the properties of exotic nuclei? Or do you rather wonder about the truth of the assumptions stipulated in the Standard Model? Are you practically oriented and do you like to participate in new technical developments to improve our experiments? Or do you prefer the assimilation and interpretation of data? Would you like to be part of research performed in an international environment, where you would experiment at international accelerator facilities in a team of scientists, but with a visible proper contribution?

Then, the specialization 'Physics at the Femtometer scale: Nuclear physics', is undoubtedly your thing. We offer you a broad, theoretical as well as experimental, training on the different contemporary large themes of nuclear physics. At the same time you get acquainted with advanced experimental techniques developed by our own research groups or in collaboration with international groups and applied to perform experiments all over the world (from CERN-Genève, over GANIL-Caen and GSI-Darmstadt, to North-America). You will take part in at least one such experiment (that typically lasts for 1 week), you will analyze and interpret the data or assist in developing and finalizing a part of the experimental set-up.

Who will be your coach?
The ‘Instituut voor Kern- en Stralingsfysica’ consists of 4 research groups conducting research on nuclear structure and fundamental interaction physics as well as on nuclear solid state physics. This research is supervised by 7 professors, about 25 doctoral students and 10 post-doctoral researchers, as well as 6 technical persons, who are all prepared to assist you during your daily research tasks.

What can you expect?
Your research theme will be closely linked to the current research of one of the doctoral students, ensuring an optimal guidance of your research without it losing its identity. Although you will be involved in their research, a specific research question will be entrusted to you, allowing you to execute your research task in an independent way. Research on nuclear physics is almost always conducted within collaborations. You will thus get the opportunity to get in touch with other students and exchange information on a national and international level. You may choose a topic offered in collaboration with the UGent, ULB or Université de Liège, or have the occasion to perform experiments at international radioactive beam facilities like ISOLDE – CERN (Switzerland), GANIL (France), PSI (Switzerland) or GSI (Germany).

Below we give some general research themes. Within each theme, more detailed descriptions of many possible research subjects will be formulated when you start your ‘master preparation work’.

More information can be found on: [http://fys.kuleuven.be/iks/](http://fys.kuleuven.be/iks/)
Or contact the trajectory responsible: Riccardo Raabe ([Riccardo.raabe@fys.kuleuven.be](mailto:Riccardo.raabe@fys.kuleuven.be))
Theme 1: Structure of exotic nuclei as a test for current nuclear models.

Next to the approximately 300 stable and long-lived atomic nuclei that exist on our planet, there are a few thousand short-lived radioactive nuclei (that play a part in the nuclear reactions in stars). One of the most important questions in nuclear physics is how many neutrons and protons are needed to make one bound atomic nucleus. In other words: where can one find the boundaries of the existence on the nuclear chart? The answer to this question cannot yet be predicted via nuclear models, since these have until now been primarily determined in an empiric way, and are thus often only valid in the nuclear environment for which we could collect sufficient experimental data. Even more difficult is the prediction of the structure of these nuclei, although this plays a role e.g. in the evolution of stars.

The purpose of many of our research projects is to study the structure of exotic nuclei, that exist for only a fraction of a second after their production with an accelerator. Therefore, we use different experimental methods and tools: production of pure beams of exotic nuclei with laser light, reactions with radioactive nuclei, detection of radioactive decay with different types of detectors (for α, β and γ radiation), perturbation of radioactive decay emission patterns with radiofrequency fields and static magnetic fields, visualization of the hyperfine structure of exotic nuclei by means of laser light, preparation of beams of exotic nuclei with ion traps, and others.

Theoretical aspects are also considered, in the framework of a national research program: at ULB these experimental results are confronted with theoretical models, as well for the structure of exotic nuclei as for the simulation of nuclear reactions involving these nuclei; at UGent it is possible to conduct research on the development of models for proton-knockout reactions with radioactive nuclei in inverse kinematics.

Promotors: M. Huyse, G. Neyens, R. Raabe, P. Van Duppen, Pierre Capel (ULB), Pierre Descouvemont (ULB), Jean-Marc Sparenberg (ULB), Natalie Jachowicz (UGent), Jan Ryckebusch (UGent)
Theme 2: Testing the Standard Model in nuclear $\beta$-decay and with ultracold neutrons.

New physics beyond the Standard Model can be explored with powerful accelerators (LHC), but also in precision measurements at low energies. Experiments with well-chosen beta transitions and with ultracold neutrons allow searching for new appearance forms of the weak interaction that are not incorporated in the Standard Model, or test symmetries such as parity, time reversal, or Lorentz invariance.

i) Measurements of the beta spectrum shape allow searching for new types of weak interaction as well as studying the small effects induced by the strong interaction in nuclear beta decay. Two new types of beta spectrometers are being developed for this. The first uses two multi-wire drift chambers installed in a weak magnetic field. The second consists of two Si detectors in a strong magnetic field.

ii) At the Université de Liège a Magneto-Optical (laser based) Trap for Ar atoms is being developed. Once the argon atoms are trapped and cooled studies will be performed to polarize them. This will in term lead to a measurement of the beta particle emission asymmetry with $^{35}$Ar to determine the $V_{ud}$ quark mixing-matrix element.

iii) Lorentz invariance requires physical laws not to change under translations (boosts) and rotations. Only a few such tests have been performed in the weak interaction. In beta decay this can e.g. be done by polarizing radioactive nuclei and search for sinusoidal daily variations in the emission anisotropy of the beta particles. This tests whether the laboratory magnetic field is precessing around a preferred direction in space (with a magnetic field linked to it) during the daily rotation of the earth.

iv) Finally, we search for a permanent electric dipole moment of the neutron by using ultracold neutrons and radiofrequency techniques. These measurements test the time reversal symmetry for the weak interaction thus providing information on the large imbalance between the amount of matter and antimatter in our universe.

All projects require precision measurements where the behavior and properties of the experimental setups are to be known in detail. This is achieved by performing both calibration measurements and Monte Carlo simulations.

Promotors: N. Severijns, Th. Bastin (ULg)
Theme 3: Development of radiation detectors and data processing techniques

The exotic atomic nuclei reveal their secrets by the radiation they emit. In order to detect this radiation new detector set-ups are constantly being developed. This concerns semiconductor, scintillation as well as gas detectors. Whereas a few years ago one used to employ about three detectors for an experiment, nowadays ten to hundred detectors are often used.

This requires not only an ingenious ensemble of these detectors but also a new way of data acquisition and processing. All these aspects constitute challenging research themes. During these projects expertise from Leuven is combined with expertise from foreign research institutes and universities.

A large range of subjects can be treated, from extensive simulations of the detector feedback and the optimization of the set-up, the testing of new detectors and electronics (on-line and off-line) and the development of active and passive radiation screening to the implementation of new analysis algorithms.

At the same time verification strategies are developed to test the accuracy of the new methods of analysis.

Promotors: M. Huyse, G. Neyens, R. Raabe, N. Severijns, P. Van Duppen

Theme 4: Laser ionization of radioactive atomic nuclei for production and nuclear structure research

Resonant laser ionization is a very powerful tool that is used for producing pure beams of radioactive isotopes (or isomers) as well as to study in detail the properties of rarely-produced exotic nuclei. Most nuclear reactions used to produce radioactive nuclei are not very selective. Often the desired radioactive isotope is produced as a tiny fraction among the millions of other isotopes. By means of a mass separator an important fraction of this undesired nuclei can be removed, but even then the most intense isobars (isotopes with the same mass number) remain present. By means of resonant laser ionization, pure beams of exotic nuclei can be produced in an element selective way. This principle is used in the laser ion sources at the Leuven Isotope Separator On Line (LISOL) separator in Louvain-la-Neuve and in the laser ion source at ISOLDE-CERN (Switzerland). It is also used in the Collinear Resonance Ionization Spectroscopy (CRIS) beam line at ISOLDE. Our groups are involved in new developments related to laser ionization in each of these facilities, aiming at the production of very pure beams of resonantly ionized exotic nuclei for nuclear structure studies.

The method of resonant laser ionization spectroscopy furthermore allows not only to produce very pure beams of exotic isotopes. By scanning the laser frequency across the different hyperfine levels in atoms, nuclear ground and isomeric state properties such as moments, radii, and spins, can be determined in a nuclear model-independent way for beams as rare as a few ions/s. Our groups are involved in the development and further improving of these techniques, e.g. at the CRIS beam line at ISOLDE or within the framework of the Heavy Element Laser Ionization Spectroscopy (HELIOS) ERC-project. For the latter a new laser laboratory is under construction at IKS for off-line commissioning, final measurements will be performed at GANIL (France).

Promotors: M. Huyse, P. Van Duppen, G. Neyens
Theme 5: Radiation and life sciences
The radiation of short-lived atomic nuclei is also of great importance in life sciences. Within the domain of nuclear physics this clearly reveals in the contacts and collaboration with the departments of radiotherapy and nuclear medicine at the UZ university hospital (in the framework of the minor in Physics and the Ma-na-Ma training in medical radiation physics) and with the radioprotection service of the university.
For radiotherapy-related subjects, you can participate in the modeling of a real situation for a radiotherapeutic radiation, its implementation in a simulation code and the research by means of this code of the total dose endured by the patient during the radiation. This will help to minimize the radioactive dose in the healthy tissue.
In nuclear medicine, you can contribute to algorithm development in image reconstruction. In medical imaging, gamma rays emitted by radioactively labeled tracer molecules are used in emission tomography (PET and SPECT), and X-rays are used in transmission tomography (CT). Three dimensional images are reconstructed from the detected radiation. This reconstruction must essentially invert the acquisition process, and therefore requires appropriate forward models of the acquisition physics, and the development of fast optimization algorithms.
In radioprotection, the measurement of samples with very low activity and the determination of the presence of small amounts of radioisotopes is crucial. This requires a specific measurement set-up with a very good shield against background radiation. Thereafter, the measured data are combined with the simulation results for the response of the considered radiation detectors.
Finally, we are involved in the MYRRHA-project of the SCK-CEN at Mol that wants to verify the possibility to convert long-lived (up to a few million years) radioactive residual products from nuclear power stations into much shorter living isotopes (a few hundred years) by radiation with high-energetic protons.


Theme 6: Nuclear Solid state physics
The techniques which have been developed in nuclear physics, have shown to be extremely suitable in condensed matter research. Nuclear solid state physics is an interdisciplinary research field which makes use of advanced nuclear approaches, based on either hyperfine interactions and/or energetic particle beams, to (i) synthesize new materials, to (ii) modify their properties and to (iii) characterize the properties of these systems at the atomic scale. This can be realized in several ways: one example is inserting (radioactive) probe atoms in the crystal lattice. These probe atoms will act as 'spies' to reveal the structural, electronic, magnetic etc. features of its immediate vicinity (specific examples are Mössbauer spectroscopy and emission channeling). Another example is to analyse the nuclear interaction between an energetic particle beam and a solid to deduce the physical properties of the solid (examples are Rutherford backscattering of ion beams, nuclear scattering of x-rays and neutrons). Our research focuses on the structural (e.g. crystallography, phase formation) and functional properties (e.g. electronic structure, magnetism, superconductivity) of thin films and nanoscale solids, where our aim is to exploit the unique complementarity of specific nuclear (local-probing) techniques and more conventional 'integrating' techniques.
To this end, we make intensive use of the three accelerators within the Ion and Molecular Beam Laboratory, complemented with campaigns at large-scale facilities such as radioactive ion beams at CERN-ISOLDE, high-flux photon beams at the ESRF synchrotron, and neutron beams at the HZB Berlin or the ILL Grenoble.

Promotors: A. Vantomme, K. Temst, W. Vandervorst