ÉCOLE POLYTECHNIQUE DE BRUXELLES
FACULTÉ DES SCIENCES
Nuclear Physics and Quantum Physics
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Master-thesis proposals for the year 2019-2020

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 or atomic physics.

Our research unit is involved in several networks, in which we collaborate with other nuclear-physics groups, both theoretical and experimental, in Belgium and abroad. Through these networks, there is a possibility for very motivated ULB students to realize their thesis on experimental subjects, for instance at the KULeuven or at the SCK-CEN Mol, under the joint direction of KUL/Mol and ULB supervisors. For further information, please contact Jean-Marc Sparenberg.

http://academy.sckcen.be/en/Your_thesis_internship/Bachelor_and_Master_thesis/Topics

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ATOMIC PHYSICS

1. **Description of the antiprotonic helium atom spectrum**
   J.-M. Sparenberg & J. Dohet-Eraly

   The antiprotonic helium atom $\bar{p}\mathrm{He}^+$ is a quantum system composed of a helium nucleus, an antiproton, and an electron. Its study for high total orbital angular momentum L allowed researchers to provide the most accurate determination of the antiproton mass. Recently, the structure of the antiprotonic helium atom for a large range of total orbital angular momentum values (from L=0 to L=80) has been described in the framework of the Lagrange-mesh method [1]. Although this method provides very accurate values for most part of the considered spectrum, it fails to describe properly resonances from L=22 to L=28, a region where the structure of the antiprotonic helium is the least well-known. In this master thesis, we propose to the student to undertake an accurate study of the $\bar{p}\mathrm{He}^+$ spectrum by a different numerical approach, namely by combining the correlated Gaussian approach with the complex-scaling method, which appears to be very accurate while challenging for describing the $\bar{p}\mathrm{He}^+$ spectrum around L=35. If needed, alternative numerical methods could also be considered.

   [1] D. Baye, J. Dohet-Eraly, P. Schoofs, Phys. Rev. A 99 (2019) 022508
   [2] Y. Kino, H. Kudo, and M. Kamimura, Mod. Phys. Lett. A 18 (2003) 388

2. **Helium atom under pressure**
   J.-M. Sparenberg & J. Dohet-Eraly

   The effects of high pressure on a helium gas can be estimated by studying the helium atom in a hard confinement, i.e. confined at the centre of an impenetrable spherical cavity, for different cavity radii. Contrary to the free helium atom, the confined helium has not been described with a high accuracy until recently [1]. No other calculation of the confined helium has been ever able to reach this level of accuracy. In this master thesis, we propose to develop a new method for studying the confined helium based on a specific choice of three-body coordinates used in Ref. [2]. With this set of coordinates, ground-state energy for the free helium has been obtained with 17 significant digits. A similar accuracy is expected for the confined helium. This calculation should benchmark and surpass the previous one [1].

[1] D. Baye, J. Dohet-Eraly, Phys. Chem. Chem. Phys. 17 (2015) 31417
[2] S. P. Goldman, Phys. Rev. A 57 (1998)

MATHEMATICAL PHYSICS

1. **Construction of phase-equivalent potentials with supersymmetric quantum mechanics**
J.-M. Sparenberg

Supersymmetric quantum mechanics is a very efficient tool to solve the scattering inverse problem, i.e. the construction of interaction potentials from scattering data [1]. In particular, SUSYQM with confluent transformations allows to deal with the unicity problem, i.e. the construction of all phase-equivalent potentials sharing scattering phase shifts but with different bound spectra. A new approach to confluent transformations was proposed a few years ago [2]. The aim of this work is to explore its interest for the problem of phase-equivalent potentials, in particular for coupled channels. For that, analytic, symbolic and numerical calculations will be used (programming language: Python, interfaced with Fortran to use existing subroutines and complemented by Mathematica if needed). If successful, the method will be applied to the construction of exactly-solvable neutron-proton potentials.

[1] D. Baye and J.-M. Sparenberg, J. Phys. A 37 (2004) 10223
[2] D. Bermudez *et al.*, Phys. Lett. A 376 (2011) 692

NUCLEAR PHYSICS

1. **Stopping power of ionizing particles in an active-target gas detector**
J.-M. Sparenberg & D. Gaspard

Active-targets gas detectors [1] have become an essential tool in experimental low-energy nuclear physics, in particular for the study of nuclear reactions taking place in astrophysical contexts (big bang and stellar nucleosynthesis). In these detectors, the gas mixture used creates an electric signal to record the tracks of the ionizing particles by a time-projection technique, but also slows down these particles down to energies of astrophysical interest. It is thus essential to know the stopping power of the gas for the studied ionizing particles and experimental campaigns are ongoing with this respect [2]. The purpose of this work is to explore a theoretical model of this stopping power based on a free-electron-gas medium [3]. This model seems efficient in condensed matter but has never been applied to gases up to now. It is proposed to test its validity in the context of active-target detectors and to compare it analytically with the Bethe formula and numerically (in Python) with softwares usually used.

[1] S. Beceiro-Novo *et al.*, Prog. Part. Nucl. Phys. 84 (2015) 124
[2] D. Torresi *et al.*, Nucl. Instrum. Meth.Phys. Res. B 389–390 (2016) 1
[3] C. Yang et al., J. Comp. Electron. 1 (2002) 24

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FOUNDATIONS OF QUANTUM PHYSICS

2. **Microscopic modeling of a ionization-chamber-type quantum measurement apparatus on the basis of quantum scattering theory**
   J.-M. Sparenberg & D. Gaspard

   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 an ionization tracking chamber (cloud chamber, wire chamber...), in order to explain the observation of straight paths that seem inconsistent with a spherical-wave emission. To do this, simplified models based on quantum scattering theory will be studied, either in one [2] or in three dimensions, both analytically and numerically (programming language: Python, with possible Fortran interfacing). Possible connections with the decoherence pressure concept observed in matter-wave interferometry [3] and might also be explored.

[1] J.-M. Sparenberg, R. Nour and A. Manço, EPJ web of conferences 58 (2013) 01016
[2] J.-M. Sparenberg and D. Gaspard, Found. Phys. 48 (2018) 429
[3] K. Hornberger et al., Phys. Rev. Lett. 90 (2003) 160401