ÉCOLE POLYTECHNIQUE DE BRUXELLES
FACULTÉ DES SCIENCES
Nuclear Physics and Quantum Physics
http://pnpq.ulb.ac.be
Jean-Marc Sparenberg jmspar@ulb.ac.be
Jérémy Dohet-Eraly Jeremy.Dohet-Eraly@ulb.be
Michele Sferrazza Michele.Sferrazza@ulb.be

UNIVERSITÉ LIBRE DE BRUXELLES

Master-thesis proposals for the year 2025-2026

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 mostly theoretical in nature and usually involve mathematical and numerical modeling. The formalism used is that of quantum physics and most applications include nuclear, atomic or molecular 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 are possibilities for motivated students to realize their thesis on experimental subjects, for instance at the Interuniversity Institute for High-Energy Physics at ULB, at the IKS institute of the KU Leuven or at the SCK-CEN Mol, under the joint direction of an external and internal supervisors.
For further information, please contact Jean-Marc Sparenberg.

https://www.iihe.ac.be/ulb/ulb-sujets-de-stage-et-de-memoire

https://www.sckcen.be/en/thesis-and-internship-topics?type=78

https://fys.kuleuven.be/iks/ns/phd-master-theses

NUCLEAR PHYSICS

1. Construction of deep nucleon-nucleon potentials from supersymmetric quantum mechanism

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 [1,2]. 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 [3] and allowed us recently to obtain a compact analytical expression for a potential with bound states. This leads to new perspectives for the construction of deep nucleon-nucleon potentials [4], which could serve as a simplified basic ingredient for nuclear-physics structure and reaction calculations. The aim of this work is to explore the interest of such potentials and to generalize the inversion method to coupled channels. For that, analytic, symbolic and numerical calculations will be used. The default programming language will be Python, possibly interfaced with Fortran to use existing subroutines and complemented by Mathematica if needed; a GUI (Graphical User Interface) for SUSYQM inversion could also be developed in the framework of the PP (Potential Program) open-source project [5].

[1] D. Baye and J.-M. Sparenberg, J. Phys. A 37 (2004) 10223
[2] D. Baye, J.-M. Sparenberg, A. M. Pupasov, B. F. Samsonov, J. Phys. A 47 (2014) 243001
[3] D. Bermudez et al., Phys. Lett. A 376 (2011) 692
[4] J.-M. Sparenberg, Eur. Phys. Lett. 59 (2002) 507
[5] https://gitlab.ulb.be/jmspar/PP

ÉCOLE POLYTECHNIQUE DE BRUXELLES
FACULTÉ DES SCIENCES
Nuclear Physics and Quantum Physics
http://pnpq.ulb.ac.be
Jean-Marc Sparenberg jmspar@ulb.ac.be
Jérémy Dohet-Eraly Jeremy.Dohet-Eraly@ulb.be
Michele Sferrazza Michele.Sferrazza@ulb.be

ULB
UNIVERSITÉ LIBRE DE BRUXELLES

ATOMIC PHYSICS

2. Photodetachment of the positronium negative ion

Jérémy Dohet-Eraly

Photo-emission and photo-absorption processes (photoionization, photodetachment, photodisintegration, radiative de-excitation, radiative captures, …) are an important subject of study in atomic and nuclear physics. In particular, they provide an efficient tool to study experimentally the resonances in helium-like systems, such as the positronium negative ion Ps^- [1]. The Ps^- ion is a three-body exotic system made of a positron and two electrons. Recently, a shape resonance of $^1P^o$ symmetry has been observed, near the Ps (n=2) formation threshold, by studying the single-photon absorption of Ps^-, i.e. the reaction $Ps^- + \gamma \rightarrow Ps + e^-$. While the measured resonance energy is in perfect agreement with the theoretical one, recent accurate calculations have revealed a disagreement between experiment and theory for the resonance width [2]. In this master thesis, we propose to compute the photodetachment of the Ps^- ion, whose wave function will be described by a Lagrange-mesh in perimetric coordinates [2,3]. A direct method as well as indirect approaches [4], avoiding the explicit construction of $Ps+e^-$ continuum, will be explored.

[1] K. Michishio et al., Observation of a shape resonance of the positronium negative ion, Nature communications 7 (2016) 11060.
[2] J. Servais, Resonances in three-body atomic systems by Lagrange-mesh methods, PhD thesis, Université libre de Bruxelles, 2024.
[3] M. Hesse, D. Baye, Journal of Physics B 32 (1999) 5605–5617.
[4] Y. Suzuki, W. Horiuchi, D. Baye, Green's function method for strength function in three-body continuum, Progress of Theoretical Physics 123 (2010) 547–568.

3. Deeply-bound pionic atoms by a Lagrange-mesh method

Jérémy Dohet-Eraly

Pionic atoms (or ions) are exotic atomic systems made of a nucleus, a negatively charged pion, and possibly one or several electrons. In contrast to the electron, the pion is unstable making the experimental and theoretical study of pionic atoms even more challenging than their non-exotic counterparts. The study of pionic systems is motivated by the research of in-medium properties of pions, which is relevant to chiral symmetry restoration (see Ref. [1] and references therein), and by the experimental determination of the negative pion mass, which, if the accuracy of its value were sufficient, would provide constraints on the mass of the antineutrino of muon flavor [2]. In this master thesis, we propose to study theoretically hydrogen-like systems made of a nucleus and a negative pion, and, more specifically, the deeply bound states present in their spectra [3]. For this purpose, the student will solve the appropriate Klein-Gordon equation on a Lagrange mesh [4]. The obtained wave functions will then be used to analyze the radiative decay of the excited deeply bound states.

[1] T. Yamazaki, S. Hirenzaki, R. S. Hayano, and H. Toki, Deeply bound pionic states in heavy nuclei, Physics Reports 514 (2012) 1-87.
[2] M. Hori, Anna Sótér, and V. I. Korobov, Proposed method for laser spectroscopy of pionic helium atoms to determine the charged-pion mass, Physical Review A 89 (2014) 042515.

ÉCOLE POLYTECHNIQUE DE BRUXELLES
FACULTÉ DES SCIENCES
Nuclear Physics and Quantum Physics
http://pnpq.ulb.ac.be
Jean-Marc Sparenberg jmspar@ulb.ac.be
Jérémy Dohet-Eraly Jeremy.Dohet-Eraly@ulb.be
Michele Sferrazza Michele.Sferrazza@ulb.be

[3] H. Toki, S. Hirenzaki, T. Yamazaki, R. S. Hayano, and H. Toki, Structure and formation of deeply-bound pionic atoms, Nuclear Physics A 501 (1989) 653-671.
[4] D. Baye, Klein-Gordon equation on a Lagrange mesh, Physical Review E 109 (2024) 045303.

4. Finite-volume effects on the relativistic spectrum of hydrogen-like systems

Jérémy Dohet-Eraly

The relativistic description of the hydrogen atom is based on the Dirac equation. When the interaction between the proton and the electron is described by a purely Coulomb potential, this equation can be solved exactly. However, when the potential is adapted to take the finite size of the proton into account, numerical methods are needed to get (approximate) solutions of the Dirac equation. In this master thesis, we propose to solve numerically the Dirac equation by means of the R-matrix method on a Lagrange mesh and to analyze the impact of the finite size of the proton on the hydrogen spectrum. The approach will be then applied to a more exotic system: the muonic hydrogen, which is made of a proton and a muon. Due to its bigger mass, the muon is more sensitive than the electron to the finite-size of the proton and therefore, the (theoretical and experimental) study of the muonic hydrogen spectrum enables a much more accurate determination of the proton radius than the study of the normal hydrogen [2]. If time allows, other hydrogen-like systems could also be investigated.

[1] D. Baye, Phys. Rev. A 92 (2015) 042112.
[2] R. Pohl, et al., Nature 466 (2010) 213.

5. Electron-hydrogen scattering above the H(n=2)+e⁻ threshold

Jérémy Dohet-Eraly

The study of electron–atom or –ion collisions is an important topic in atomic physics and is also relevant in other areas of physics such as plasma physics and astrophysics [1]. Among these collisions, the electron-hydrogen scattering is particularly interesting because the hydrogen is the most abundant atom in the universe and because its relative simplicity makes it an excellent candidate for probing the accuracy of numerical methods. Recently, a new approach based on a Lagrange mesh has been developed to describe S-wave scattering of $\mathrm{H} + e^-$ at low energy [2]. While this approach has been proven to be very accurate at energies below the $\mathrm{H}(n{=}2) + e^-$ threshold, it is far less accurate at energies above this threshold. The reason of this is the presence of a long-range dipole potential coupling the 2s and 2p degenerate states of the hydrogen [1,3], which has not been taken into account in the asymptotic description of the collision wave function. In this master thesis, we propose to first compute numerically the asymptotic solutions of the Schrödinger equation, including explicitly the long-range dipole potential, at energies between the $\mathrm{H}(n{=}2) + e^-$ and $\mathrm{H}(n{=}3) + e^-$ thresholds, and then to include these solutions in the Lagrange-mesh method developed in Ref. [2]. This is expected to correct the problem of poor accuracy of the method appearing when the $\mathrm{H}(2s) + e^-$ and $\mathrm{H}(2p) + e^-$ channels open.

[1] Philip G. Burke, R-Matrix Theory of Atomic Collisions, Springer Berlin, Heidelberg, 2011.
[2] J. Servais and J. Dohet-Eraly, Low-energy S-wave scattering of $\mathrm{H} + e^-$ by a Lagrange-mesh method, Physical Review A 109 (2024) 052818.
[3] Y. Wang and J. Callaway, Direct numerical approach to electron-hydrogen scattering. II. $L > 0$, Physical Review A 50 (1994) 2327.

ÉCOLE POLYTECHNIQUE DE BRUXELLES
FACULTÉ DES SCIENCES
Nuclear Physics and Quantum Physics
http://pnpq.ulb.ac.be
Jean-Marc Sparenberg jmspar@ulb.ac.be
Jérémy Dohet-Eraly Jeremy.Dohet-Eraly@ulb.be
Michele Sferrazza Michele.Sferrazza@ulb.be

FOUNDATIONS OF QUANTUM PHYSICS

6. Emergent space-time from quantum intrication with the electromagnetic field

J.-M. Sparenberg

Physical theories in which time is not a fundamental concept, but rather a quantity emerging from a deeper level, are generally considered as quite exotic. Nevertheless, they received regular attention over the years, both in classical physics/general relativity [1-3] as in quantum physics. There, in 1983, Page and Wootters proposed a theory where time emerges from the quantum intrication of subentities in physical systems, one being seen as the quantum system under study and the other one being seen as a clock [4]. A few years ago, this mechanism was formulated in terms of (generalized) coherent states describing the clock, making classical time emerge [5]. Similarly, in 2004, Braun *et al.*, made time emerge from the interaction of a quantum system with the electromagnetic field, as described with coherent states [6]. Page and Wootters' idea was recently generalized to space-time, instead of time only [7]. The aim of the present work is to understand this new idea in depth and to implement it in terms of intrication with free (scalar) massless quantum fields, formulated in terms of coherent states. The long-term project is to derive relativistic wave equations for a massive particle from its intrication with the electromagnetic field which bathes the Universe (cosmic microwave background), making the finite speed limit for the massive particle emerge from the speed of the field with which it is intricated.

[1] J. Barbour, *The End of Time* (Oxford University Press, 1999)
[2] E. P. Verlinde, JHEP 4 (2011) 29
[3] A. Schlatter and R. E. Kastner, J. Phys. Commun. 7 (2023) 065009
[4] D. N. Page and W. K. Wootters, Phys. Rev. D 27 (1983) 2885
[5] C. Foti *et al.,* Nat. Commun. 12 (2021) 1787
[6] L. Braun, W. T. Strunz and J. S. Briggs, Phys. Rev. A 70 (2004) 033814
[7] T. Favalli, *On the Emergence of Time and Space in Closed Quantum Systems*, PhD Thesis (Springer Thesis, 2024)

ÉCOLE POLYTECHNIQUE DE BRUXELLES
FACULTÉ DES SCIENCES
Nuclear Physics and Quantum Physics
http://pnpq.ulb.ac.be
Jean-Marc Sparenberg jmspar@ulb.ac.be
Jérémy Dohet-Eraly Jeremy.Dohet-Eraly@ulb.be
Michele Sferrazza Michele.Sferrazza@ulb.be

7. Microscopic quantum scattering modeling of a schematic 1D quantum measurement apparatus

J.-M. Sparenberg & B. Lorent

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]. For instance, in the so-called Mott problem, i.e. the detection of a spherical wave (alpha-radioactivity type) in an ionization tracking chamber (cloud chamber, wire chamber...), the observation of straight paths, that seems inconsistent with a spherical-wave emission, might be explained by the positions of the detector constituents (atoms or molecules). This hypothesis was recently tested in a two-dimensional model, with a much simplified model where the particle-atom interaction is a contact term with no excitation for the atoms [2]. The purpose of this work is to test this hypothesis in the case of a schematic gaseous detector in one dimension [3], where excitated states of atoms can be taken into account, through a numerical resolution (programming language: Python) of the time-independent and/or the time-dependent Schrödinger-equations, based on the Green function formalism and/or the transfer-matrix method.

[1] J.-M. Sparenberg, R. Nour and A. Manço, EPJ web of conferences 58 (2013) 01016
[2] D. Gaspard and J.-M. Sparenberg, Phys. Rev. A 109 (2024) 062211
[3] J.-M. Sparenberg and D. Gaspard, Found. Phys. 48 (2018) 429