ÉCOLE POLYTECHNIQUE DE BRUXELLES
FACULTÉ DES SCIENCES
Nuclear Physics and Quantum Physics
http://pnpq.ulb.ac.be
Jean-Marc Sparenberg jmspar@ulb.ac.be
Pierre Descouvemont pdesc@ulb.ac.be

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Master-thesis proposals for the year 2022-2023

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.

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NUCLEAR ASTROPHYSICS

1. Study of coupled-channel effects on the ^{12}C+alpha system in nuclear astrophysics

J.-M. Sparenberg

The ^{12}C+alpha radiative capture leading to ^{16}O is of utmost importance in the nucleosynthesis helium-burning cycle of red giant stars [1]. Unfortunately, the corresponding reaction rate is too low to be directly measured experimentally at energies of astrophysical importance, hence the interest of theoretical estimates. However, such theoretical analyses are made complicated by the presence of ^{16}O bound states lying just below the ^{12}C+alpha threshold, which are known to have an impact on the reaction cross section similar to resonances. Recently [2], a new parametrization of the ^{12}C+alpha elastic-scattering phase shifts led to the surprising conclusion that one of these bound states might have an imaginary asymptotic normalization constant (ANC). The origin of this effect is still unknown. The aim of this work is to test on simple phenomenological coupled-channel potential models (coupled square wells, Woods-Saxon…) whether it could be due to a coupling with other channels than the ^{12}C+alpha one, and to evaluate its impact on the capture cross section. To do so, analytical and numerical calculations will be performed (Python program with Fortran interface).

[1] A. Coc, F. Hammache and J. Kiener, Eur. Phys. J. A (2015) 51
[2] O. L. Ramírez Suárez and J.-M. Sparenberg, Phys. Rev. C 96 (2017) 034601

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ATOMIC PHYSICS

2. The He_2 system by a correlated Gaussian approach

Jérémy Dohet-Eraly and Pierre-Yves Duerinck

In spite of the fact that the helium atom is a noble gas, the existence of loosely-bound molecules composed by few helium atoms has been predicted by theory [1-3] and, in the case of the He-He molecule, experimentally established using diffraction experiments [4]. Since the helium atoms are loosely bound in the He-He molecule, they are (in average) very far from each other. They can thus be seen as pointlike particles interacting via effective potentials, which enable one to consider within a good approximation the He-He molecule as a two-body system. In this master thesis, we propose to develop a two-body computational approach based on correlated Gaussians [5] for studying the He-He bound state as well as the elastic scattering between two helium atoms. Several types of correlated Gaussians will be considered and their respective performances will be investigated. Efficient ways to generalize the developed approach to three- and more-body systems will be explored.

[1] E. Hiyama and M. Kamimura, Few-Body Systems 54 (2013) 1551.
[2] M. Gattobigio, A. Kievsky, and M. Viviani, Physical Review A 84 (2011) 052503.
[3] A. Kievsky and M. Gattobigio, Physical Review A 87 (2013) 052719.
[4] R. E. Grisenti et al., Phys. Rev. Lett. 85 (2000) 2284.
[5] Y. Suzuki, K. Varga, Stochastic Variational Approach to Quantum-Mechanical Few-Body Problems, vol. 54, Lecture Notes in Physics, Springer, Berlin, 1998.

3. 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.

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MATHEMATICAL PHYSICS

4. 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 [1,2]. 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]. 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. 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 [4]. If successful, the method will be applied to the construction of deep exactly-solvable nucleon-nucleon potentials [5], which could serve as a basic ingredient for nuclear-physics structure and reaction calculations.

[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] https://github.com/jmspar/PP
[5] J.-M. Sparenberg, Eur. Phys. Lett. 59 (2002) 507

FOUNDATIONS OF QUANTUM PHYSICS

5. Microscopic quantum scattering modeling of a schematic 1D or 3D quantum measurement apparatus

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]. 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, electrons). The purpose of this work is to test this hypothesis in the case of a schematic gaseous detector, either in one dimension [2] or in three dimensions [3], through a numerical resolution (programming language: Python) of the time-independent and/or the time-dependent Schrödinger-equations, based on the Green function formalism.

[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] D. Gaspard and J.-M. Sparenberg, Int. J. Quantum Information 17 (2019) 1941004; Phys. Rev. A 105 (2022) 042204; Phys. Rev. A 105 (2022) 04405