ÉCOLE POLYTECHNIQUE DE BRUXELLES
FACULTÉ DES SCIENCES
Nuclear Physics and Quantum Physics
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UNIVERSITÉ LIBRE DE BRUXELLES

Master-thesis proposals for the year 2018-2019

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 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.

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THEORETICAL NUCLEAR PHYSICS AND NUCLEAR ASTROPHYSICS

1. **Parametrization of low-energy nuclear-astrophysics reactions with a simplified effective-range function**
J.-M. Sparenberg & P. Descouvemont

A simplified effective-range function (ERF) allowing to parametrize elastic-scattering phase shifts for charged particles in a given partial wave was recently proposed [1]. This led to interesting speculations on the ^{12}C+alpha system [1], which is of utmost importance in the nucleosynthesis cycle of red giant stars, and to interesting discussions on the mathematical justification of such a simplified ERF [2]. A first aim of this work is to apply this method to systems relevant to nuclear astrophysics for the description of big-bang or stellar nucleosynthesis, and well studied by other methods (alpha+alpha, ^{16}O+p, alpha+d…). To do so, existing codes (Python programs with possible Fortran or Mathematica interface) will be adapted and generalized. Further aims could be (i) to generalize the SERF to coupled channels, either analytically or numerically, (ii) to compare it with more usual functions (S-matrix, R-matrix…), in particular in the complex energy plane, (iii) to extend its use to high energies, for instance for the nucleon-nucleon system.

[1] O. L. Ramírez Suárez and J.-M. Sparenberg, Phys. Rev. C 96 (2017) 034601
[2] D. Gaspard and J.-M. Sparenberg, Phys. Rev. C 97 (2018) 044003

2. **Continuum-discretized-coupled-channel approach to three-body scattering states with the reaction-matrix method**
J.-M. Sparenberg & J. Dohet-Eraly

For two-body systems, the reaction-matrix (R-matrix) method is an efficient way of numerically treating continuum energies [1], by imposing a fixed boundary condition at finite a distance (the so-called channel radius), which leads to mathematical discrete two-body states which are used as a basis. In particular, precise two-body scattering phase shifts can be obtained in this way, provided *all* discrete states are taken into account. For three-body systems, the R-matrix method can also be used to calculate three-body phase

shifts, provided hyperspherical coordinates are used, but this requires a very large channel radius because of the slow decrease of the interaction potential [1].
An alternative approach, called CDCC [2], is to discretize one of the two-body continuum and to treat the discrete states as coupled channels, i.e. as a basis on which the three-body states are expanded. The CDCC method is usually used to model two-body collisions (projectile on target), taking into account the two-body structure of the projectile, and shows good convergence with a limited number of coupled channels. However, the method is not a priori designed to calculate three-body phase shifts. The aim of this project is to attempt such a calculation by combining the two-body R-matrix, taking into account *all* discrete states, with the CDCC method. Various test cases could be considered, ranging from nuclear physics (^{6}He halo nucleus) to atomic physics (^{6}Li-atom trimer). A Python code will be written from scratch by the student, first for two bodies, then for three bodies.

[1] P. Descouvemont and D. Baye, Rep. Prog. Phys. 73 (2010) 036301
[2] T. Druet *et al.,* Nucl. Phys. A 845 (2010) 88

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).

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

FOUNDATIONS OF QUANTUM PHYSICS

1. **Test of a quantum emergent-time theory on simple systems**
   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, 2] as in quantum physics. There, in 1983, Page and Wootters proposed a theory where time emerges from the coexistence of subentities in physical systems [3]. These ideas were recently implemented experimentally in photonic systems [4]. The aim of this work is to understand this theory in depth, in particular through the related concepts of time, entropy and partial trace, and to apply it to simple test systems like a pair of spin ½ particles in a magnetic field,

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two particles in a 1D box, or a massive particle evolving in a free scalar or electromagnetic field [5].

[1] J. Barbour, *The End of Time* (Oxford University Press, 1999)
[2] E. P. Verlinde, JHEP 4 (2011) 29
[3] D. N. Page and W. K. Wootters, Phys. Rev. D 27 (1983) 2885
[4] E. Moreva, G. Brida, M. Gramegna, V. Giovannetti, L. Maccone, M. Genovese, Phys. Rev. A 89 (2014) 052122
[5] L. Braun, W. T. Strunz and J. S. Briggs, Phys. Rev. A 70 (2004) 033814

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 [3] dimensions, both analytically and numerically (programming language: Python, with possible Fortran interfacing). Possible connections with the decoherence pressure concept observed in matter-wave interferometry [4] and the stopping power behaviour in the Bragg peak [5] might also be explored.

[1] J.-M. Sparenberg, R. Nour and A. Mançо, EPJ web of conferences 58 (2013) 01016
[2] J.-M. Sparenberg and D. Gaspard, Found. Phys. 48 (2018) 429
[3] C. Cacciapuoti, R. Carlone, R. Figari, J. Phys. A 40 (2007) 249
[4] K. Hornberger et al., Phys. Rev. Lett. 90 (2003) 160401
[5] C. Yang et al., Ion Implantation Technology (2002)