

Section 2.0c: the nuclear quantum many-body problem

The aim of theoretical nuclear physics

The aim of theoretical nuclear physics is to study the **quantum many-particle aspects of two of nature's four fundamental forces**: the strong and the weak interaction. Atomic nuclei and nuclear reactions exhibit a richness of phenomena not found in any other area of physics. Depending upon the relative energy of the nuclear constituents, very different theoretical descriptions are needed:

Low-energy phenomena are usually described in terms of *protons and neutrons interacting via an effective non-relativistic potential* that depends on the positions, momenta, spins and isospins of the nucleons. For relatively light nuclei, non-relativistic “ab-initio” calculations are possible, but heavier systems require a mean-field approximation. Alternatively, relativistic mean-field theories have been developed in which pointlike nucleons are described by the Dirac equation, interacting via classical meson fields.

In the **medium-energy regime, particle creation and annihilation** becomes a dominant feature; also, it is no longer sufficient to consider just the nucleons themselves, but other low-lying baryonic resonances and light mesons must be taken into account. The appropriate theoretical framework is the *quantum theory of interacting baryon and meson fields*.

Finally, at **relativistic energies**, the *quark substructure* of the baryons and mesons comes into play, and the proper starting point of the theory is the Lagrangian of *Quantum Chromodynamics (QCD)*.

The physical world: interacting quantum many-particle systems

One basic problem that is common to many areas of physics - and other natural sciences such as chemistry - is the *quantum many-particle problem*. Theorists working in atomic and molecular physics, quantum chemistry, condensed matter physics, nuclear physics, and astrophysics (and a small fraction of elementary particle physics) face a very similar challenge: how to describe, at the quantum level, the features of many particle systems in terms suitable constituent particles and the fundamental interactions between them. The aim of nuclear theory is to study the quantum many-particle aspects of the strong interaction, which is one of the four fundamental forces of nature.

There are essentially two different approaches to the quantum many-particle problem which might be termed phenomenological and fundamental. In the first case, one tries to simplify the physical system to such an extent that the arising physical “model” can be solved analytically or with little computational effort. This approach is often the first stage in the development of a theory. As the research field begins to mature, attention shifts from simple intuitive models to a “fundamental” understanding, i.e. one attempts to describe physical systems “ab initio” starting from the most basic equations and physical principles. Computational physicists prefer the second approach.

Almost all interacting quantum many-particle systems cannot be formulated in terms of perturbation theory, a powerful tool which governs most of elementary particle physics. Because of the large coupling constant of the strong interaction, the vast majority of nuclear phenomena cannot be treated in perturbation theory and require large-scale numerical calculations. In fact, the interesting physical observables (e.g. the Hartree-Fock or BCS ground state energy of the many-body quantum system) is equivalent to an infinite sum of perturbative diagrams! This requires

the development of *new quantum many-body approximation schemes*. Because of the mathematical complexity of the quantum many-body equations, a numerical implementation on scientific workstations and supercomputers becomes necessary.

Computational physics: “physics of the third kind”

Computational physics has emerged as the new third branch of physics besides the traditional branches of experimental and theoretical physics. The purpose of computational physics is not to crunch numbers, but to gain insight. This is particularly true if scientific workstations and supercomputers are coupled to sophisticated tools of visualization. During the last decade we have witnessed an almost exponential growth in computing power. This unparalleled growth has redefined the classes of physics problems we are able to solve. What seemed at the forefront of research ten years ago can now be done on a high-speed scientific workstation. Today’s massively parallel supercomputers allow us to address, at a fundamental rather than phenomenological level, some of the most challenging theoretical problems of modern-day physics.

The essence of computational physics lies in the observation that many of the fundamental equations of physics have a similar mathematical structure: for example, the many-particle Schrödinger and Dirac equations as well as the nonrelativistic or relativistic hydrodynamics equations are all partial differential equations in space and time. All of the above-mentioned basic equations of physics can be implemented on spatial coordinate lattices; there will still be differences between many of the physics problems to be studied, for example short-range vs. long-range interactions, uniform vs. non-uniform lattice spacing etc. Nevertheless, with careful planning, computational physicists are capable of developing numerical methods and algorithms that can be utilized in a transparent manner in many subfields of physics. Computational physics is truly interdisciplinary.