Power Counting and Chiral Interaction

TECHNISCHE UNIVERSITÄT DARMSTADT

Abstract

Nuclear Structure and Nuclear Astrophysics Seminar - 16.06.2016

Steven Vereeken

Introduction

Although the nucleons have been known to exist for over 80 years now, their interaction is not yet fully understood. Early on, Yukawa postulated that the nuclear force is mediated by a meson. A couple of decades later a bunch of those mesons had been discovered, which led to development of the one-boson- and multi-pion-exchange models. High-precision potentials, like the Bonn- or Argonne-Potential, incorporate certain aspects of that model and describe the nucleon-nucleon phase shifts rather successfully. However, more nucleon interactions cannot be added easily and they lack an obvious connection to the underlying theory of the strong interaction, which is nowadays believed to be responsible for the nuclear force.

The theory describing the strong interaction is quantum chromodynamics (QCD). Deriving a potential using QCD directly is not yet possible due to its running coupling constant, which becomes large at low energies (or equivalently long distances), i.e. the energy region of the nuclear force. Therefore, one has to resort to a different method: effective models. In order to give the model a strong foundation it needs to have a firm link with QCD. This link is provided if the model Lagrangian exhibits the same symmetries as QCD. The most important symmetry is the chiral symmetry, which also gives the resulting interaction its name: chiral interaction. The downside of the effective models is that one has to use the most general Lagrangian/Hamiltonian possible, which has an infinite number of terms. It is therefore important to organise those terms by the order of their contribution. This is done using power counting, a dimensional analysis of the terms/diagrams that actually contribute to the observable one wishes to calculate, e.g. a scattering amplitude from which an effective nuclear potential is eventually derived.

Modelling the Nuclear Force

Effective models are widely used in physics to describe phenomena at a certain energy scale. They have the great benefit that one can use degrees of freedom, that are appropriate for the energy scales involved. As a result, one does not really need to know what kind of (perhaps unknown) physics is occurring at higher energy scales. These (unknown) effects are, however, included in the parameters that enter the model.

In the context of the nuclear force, the appropriate degrees of freedom are nucleons and pions, since the energy scale at which the nuclear force occurs is too low to resolve the substructure of the nucleons. The pions act as exchange particles that mediate the interaction. The long-range interaction is mediated by the one-pion exchange. Two-pion exchanges are responsible for the attraction at intermediate distances. The strong short distance repulsion is modelled by direct contact interactions of the nucleons. The upper energy boundary (or hard scale) Λ of the theory, that is, the energy at which the actual interaction of quarks and gluons becomes important for the dynamics of the system, lies somewhere between the mass of the nucleon and the mass of the pion. Since the mass of, e.g. the ρ-meson, which is not included in the model, lies within that region, the hard scale can be set to its mass $\Lambda \approx m_\rho$.

To derive an effective potential, one starts with the most general Lagrangian density, that exhibits chiral symmetry. After expanding the Lagrangian in $^{Q}/_{\Lambda}$, the terms/diagrams that contribute to the scattering process is finite at every order of the expansion. Therefore, one can organise the diagrams by the order of the expansion (chiral dimension) and use those diagrams to calculate scattering amplitudes and systematically improve the accuracy of the result by taking higher order terms into account. The order of a given diagram can be calculated by carefully counting the powers of the soft scale (power counting).

This approach gives rise to what has become known as the hierarchy of nuclear forces, since , e.g., diagrams contributing to the three nucleon force first appear two orders after the first diagrams that contribute to the two nucleon force.