Chapter 1

Introduction

1.1 Meson Exchange in the Era of QCD

It should be of no surprise that the study of nuclear forces has attracted the interest of many theoretical as well as experimental physicists and has been the topic of vigorous research for more than fifty years. It not only represents the force between two nucleons and the basis for an understanding of nuclei, but it is also a prominent example of a strong interaction between particles.

Nowadays, almost everybody believes that quantum chromodynamics (QCD)is the theory of strong interactions. Therefore, the nucleon-nucleon (NN) interaction is completely determined by the underlying dynamics of the fundamental constituents of hadrons, i.e., quarks and gluons. Nevertheless, the meson exchange picture keeps its validity as a suitable effective description of the NN interaction in the low-energy region relevant in nuclear physics for the following reasons: Due to asymptotic freedom, QCD in terms of quarks and gluons can be treated perturbatively only for large momentum transfers, i.e., at distances smaller than 0.2 fm or so, which typically occur in high-energy physics processes. At larger distances relevant in nuclear physics, a description of strong interaction processes in terms of the fundamental constituents, because of the highly non-perturbative character of QCD in this region, becomes extremely complicated and is not possible, neither at present no in the foreseeable future.

Fortunately, at distances larger than the nucleon extension, which dominate nuclear physics phenomena, color confinement dictates that nucleons can only interact by exchanging colorless objects, i.e., just mesons. Only at smaller distances, at which the two nucleons overlap, genuinely new processes may occur involving explicit quark-gluon exchange. Due to the repulsive core of the NN interaction, however, both nucleons do not come very close to each other unless the scattering energy is rather high. Thus, there is good reason to believe these processes not to dominate the NN interaction for energies relevant in nuclear physics. Consequently, meson exchange (to be considered as a convenient, effective description of complicated quark-gluon processes) should remain a valid concept for deriving a realistic NN interaction, representing a reliable starting point for nuclear structure calculations.

1.2 What Do We Know Empirically About the Nuclear Force?

The basic qualitative features of the nuclear force are the following [1]:

a) Nuclear forces have a finite range, in contract to the Coulomb force. This can be easily deduced from the saturation properties of heavy nuclei: Here, the binding energy per nucleon as well as the density are nearly constant. If the nuclear force were of long range, both quantities would increase with the nucleon number.

b) The nuclear force is attractive at intermediate ranges. The attractive character of the nuclear force is clearly established in nuclear binding. The range of this attraction can be obtained from the central density of heavy nuclei, which is about 0.17 fm^{-3}, giving to each nucleon a volume of about 6 fm^3. Therefore, in the interior of a heavy nucleus, the average distance between two nucleons is roughly 2 fm.

c) The nuclear force is repulsive at short distances. This is most easily seen in the empirical $^1S_0$ and $^1D_2$ NN partial wave phase shifts (in the conventional notation $^{2S+1}L_J$, where $L(J)$ denotes the orbital (total) angular momentum and S the total spin), which are deduced from NN scattering data (cross sections, polarization observables) by means of a phase shift analysis. For small lab energies (up to about 250 MeV), the $^1S_0$ phase shift is positive, which corresponds to attraction. For high energies, it becomes negative (equivalent to repulsion), whereas the $^1D_2$ phase shift stays positive up to about 800 MeV. This is consistent with a repulsion of short range since an S-state is sensitive to the inner part of the force, whereas in a D-state the nucleons are kept apart by the centrifugal barrier.

d) The nuclear force contains a tensor part. This is most clearly established in the presence of a deuteron quadrupole moment and the so-called D/S ratio of the deuteron wave function [2].

e) The nuclear force contains a spin-orbit part. This is clearly seen in nuclear spectra. Furthermore, a quantitative description of triplet-P waves require a strong spin-orbit force.

There are additional spin-dependent terms in the NN force, namely a spin-spin and a quadratic spin-orbit term. They are, however, of minor importance.

In fact, from general invariance principles (translation, Galilei, rotation, parity, time-reversal), the most general form of a nonrelativistic potential contains just these five terms, i.e., central (c), spin-spin(s), tensor (t), spin-orbit (LS) and quadratic spin-orbit (LL):

$$V = \sum_i V_i \, O_i \tag{1.1}$$

with

$$\begin{aligned} O_c &= \mathbf{1} \\ O_s &= \vec{\sigma}_1 \cdot \vec{\sigma}_2 \\ O_t &\equiv S_{12} \equiv \frac{3\vec{\sigma} \cdot \vec{r}\, \vec{\sigma}_2 \cdot \vec{r}}{r^2} - \vec{\sigma}_1 \cdot \vec{\sigma}_2 \\ O_{LS} &= \vec{L} \cdot \vec{S} \\ O_{LL} &= (\vec{L} \cdot \vec{S})^2 \end{aligned} \tag{1.2}$$

where $\vec{S} = \frac{1}{2} (\vec{\sigma}_1 + \vec{\sigma}_2)$.

The coefficients V_i can in general depend on the distance r, the relative momentum $\vec{p}^{\,2}$ and $\vec{L}^2$; they are completely undetermined. Phenomenological potentials like the Hamada-Johnson [3], the Reid [4] potential or its update by the Nijmegen group make an ansatz for $V_i(r)$, with a total of about 50 parameters, and fix these by adjusting them to the NN scattering data. However, such potentials cannot provide any basic understanding of the interaction mechanism, and the parameters have no physical meaning.

1.3 Historical Background

The development of a microscopic theory of nuclear forces started around 1935 with Yukawa's fundamental hypothesis [5] that the nuclear force is generated by massive-particle exchange, leading to an interaction of the type $\frac{e^{-m_\alpha r}}{r}$ where m_α is the mass of the exchange particle and r is the distance between two nucleons. This is quite analogous to the electromagnetic case in which the interaction is known to be generated by (massless) photon exchange yielding the well-known Coulomb-potential being proportional to $\frac{1}{r}$.

The original Yukawa idea of a scalar field interacting with nucleons was soon extended to vectors (Proca [6]) and to pseudoscalar and pseudovector fields (Kemmer [7]). The consideration of a pseudoscalar field was dictated by the discovery of the quadrupole moment of the deuteron [8], whose sign was correctly given by the exchange of an (isovector) pseudoscalar meson. Almost ten years later, in 1947, a pseudoscalar meson, the pion, was indeed found [9].

The next period started around 1950, and again Japanese physicists initiated it. Taketani, Nakamura and Sasaki [10] (TNS) proposed to subdivide the range of the nuclear force into three regions: a "classical" (long range, $r > 2\ fm$), a "dynamical" (intermediate range, $1\ fm < r < 2\ fm$) and a "core" (short range, $r \leq 1\ fm$) region. The classical region is dominated by one-pion exchange (OPE). In the intermediate range, the two-pion exchange (TPE) is supposed to dominate, although heavier-meson exchange (to be introduced later) become relevant, too. Finally, in the core region, many different processes should play a role: multi-pion, heavy-meson and (according to our current understanding) genuine quark-gluon exchange. Thus, in view of QCD-inspired approaches to the nuclear force, this division is still most meaningful.

In the 1950's, the one-pion exchange became well established as the long-range part of the nuclear force. Tremendous problems occurred, however, when the 2π exchange contribution to the NN interaction was attacked. Apart from various uncertainties in the results (the best known being those of Taketani, Machida and Onuma [11], and Brueckner and Watson [12]), it was impossible to derive a sufficient spin-orbit force from the 2π exchange [13]. For that reason, Breit [14] in 1960 suggested to look for heavy vector bosons in order to account for the empirically well-established, short-ranged spin-orbit force. In fact, such mesons (ρ, ω) with a mass of nearly 800 MeV were soon discovered [15].

This led to the next step, namely the development of one-boson exchange (OBE) models. Their basic assumption is that multi-pion exchange can be well accounted for by the exchange of multi-pion resonances, i.e., that uncorrelated multi-pion exchange (apart from iterative contributions which are generated by the unitarizing equation) can be neglected. Such OBE models [16, 17, 18] (the contribution of the Bonn group is reviewed in Ref.. [17]), provide a relatively simple expression for the nuclear force; indeed, they can account quantitatively for the empirical NN data using only very few parameters and thus convincingly demonstrate the importance of correlated interactions with two (or more) pions.

In all OBE models, the intermediate-range attraction is generated by the exchange of a scalar-isoscalar boson with a mass around 600 MeV (representing a $2\pi S$-wave resonance), which, although appearing in Particle Data Tables of the sixties, has not been confirmed empirically. This has to be considered as a serious drawback of OBE models. Therefore, the program of a realistic 2π-exchange calculation was taken up again; however, in contract to the fifties, with the goal to include not only the uncorrelated 2π-exchange contribution involving nucleon intermediate states, but also those involving nucleon excitations like the Δ isobar. Furthermore, from the experience with OBE models, it was clear from the beginning that correlated 2π exchanges should be included, too.

In the dispersion-theoretic approach to the 2π exchange, empirical πN- (and $\pi\pi-$) data are used to derive the corresponding NN amplitude, with the help of causality, unitarity and crossing. Correlated as well as uncorrelated 2π exchange is automatically included.

Corresponding NN potentials are developed in the 1970's, in particular by the Stony Brook [19] and the Paris [20] group, adding to the dispersion-theoretic 2π-exchange contribution OPE- and ω-exchange as well as some arbitrary phenomenological potential of essentially short-range nature. In case of the Paris-potential, the final result is parameterized by means of static Yukawa terms [21].

However, such a simplified representation of the nuclear force is probably insufficient in many areas of nuclear physics. For example, a consistent evaluation of three-body forces and meson-exchange current corrections to the electromagnetic properties of nuclei requires an explicit and consistent description of the NN interaction in terms of field-theoretic vertices. Also, a well-defined off-shell behavior and modifications of the nuclear force when inserted into the many-body problem (e.g., Pauli-blocking of the 2π-exchange contribution) are natural consequences of meson exchange. Only a field-theoretical approach can account for these.

Work along the field theoretical line was taken up in the late 1960's by Lomon and collaborators [22, 23]. They evaluated the 2π-exchange Feynman diagrams with nucleons and represented their result in the framework of the relativistic three-dimensional reduction of the (four-dimensional) Bethe-Salpeter [24] equation, suggested by Blankenbecler and Sugar [25]. In subsequent work [23], they also studied the correlated $2\pi S$-wave contribution. However, they did not include processes involving the Δ-isobar (an excited state of the nucleon with a mass of 1232 MeV and spin-isospin 3/2) in intermediate states, which are known to contribute substantially to the nuclear force. Further, nonresonant 3π- and 4π-exchange has to be considered since their range is about that of ω-exchange, which is included in all models.

Since the 1970's the Bonn group has pursued a program that includes all relevant diagrams in a field-theoretical model. In the early period [26], a relativistic three-dimensional equation was used together with the principle of minimal relativity [27]; later the treatment has been based on relativistic, time-ordered perturbation theory [28]. A final status of the Bonn model is described in detail in Ref. [29].

Let me finally mention attempts to derive the nucleon-nucleon interaction in the constituent quark model, based on one-gluon exchange. Corresponding calculations started about 15 years ago and many groups have been involved [30]. Indeed, certain qualitative features of the short-range part of the NN interaction emerged, namely some inner repulsion and spin-orbit force. However, all models of this kind create either too little or no intermediate-range attraction (which is sometimes artificially cured by adding a suitable attraction arising from scalar boson exchange). Note that pion exchange has to be added in any case. Thus, the meson exchange concept for constructing the NN interaction clearly keeps its validity at the low and intermediate energies relevant to nuclear physics.

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