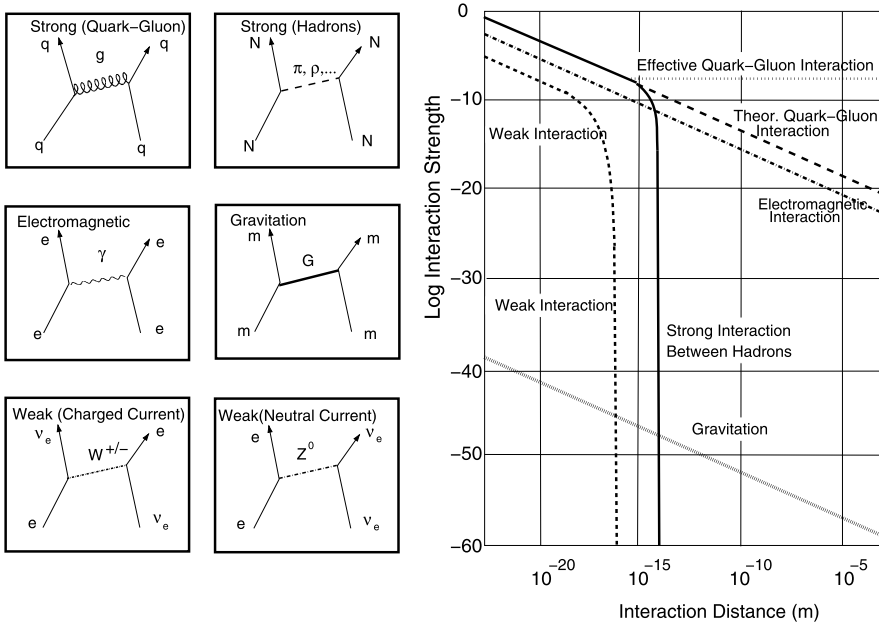


# Preface

Nuclei and nuclear reactions are a playground (or a laboratory) of three of the four (in special cases four) fundamental interactions in nature (the reactions have predominantly to do with the hadronic strong and the electromagnetic interactions). Figure 1 shows the characteristic features of the relevant forces. Nuclei are complex many-particle systems of nucleons (hadrons). These proved to be—mainly by performing scattering experiments with leptons (electrons, muons, and neutrinos)—extended objects with complex internal structure: Constituent quarks, gluons, whose exchange binds the quarks together, sea-quarks (quark-antiquark pairs, into which the gluons transform and vice versa) and—to the outside—virtual mesons, surrounding an inner nuclear region (the *bag*). Figure 2 depicts schematically this internal structure of the nucleons and their interactions via exchange of virtual bosons (especially mesons). The virtual mesons clouds surrounding the nucleons are—by their mutual exchange of mesons—the cause of the nucleon-nucleon interaction. This exchange is therefore responsible for the existence of nuclei, their rich structure, and the variety of their interactions. Especially the spin structure of the nucleons, i.e. the way the spins and orbital angular momenta of the constituents act together to form the nucleon spin has been of great concern (“Spin Crisis”) and prompted many experimental investigations, often using spin-polarized particles. It turned out, however, that the internal structure of the nucleons has comparatively little influence on the behavior of the nucleons in nuclei, i.e. nuclear structure and nuclear reactions. Thus, nuclear physics—and especially nuclear reactions—is a field of science in its own right, even without much recourse to subnuclear degrees of freedom.

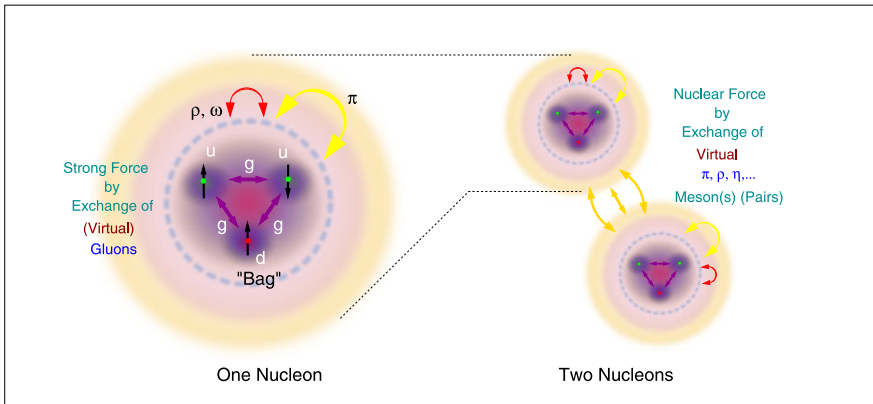
## Historical Remark

Elastic scattering of particles off each other is a special class of nuclear reactions, i.e. one without change of the identity of the particles involved. In this sense the famous Rutherford/Geiger/Marsden scattering experiment started the field of nuclear reactions around 1911 in Manchester. Energetic particles from radioactive sources were



**Fig. 1** Unified view of the fundamental forces of nature. All can be described as caused by the exchange of bosons between the constituent particles where massless exchange bosons lead to forces of infinite range (the photon, the graviton, and—in principle—the gluon). However, the strong interaction is special in two ways: the confinement of QCD causes the finite range of the “effective” quark-gluon interaction, and the interaction takes place also between the exchange bosons, the gluons. The masses of the other exchange bosons determine the range of the interactions via Heisenberg’s uncertainty relation:  $\approx 1.4$  fm for the nuclear force due to the meson masses of a few hundred MeV,  $\approx 10^{-18}$  m for the weak interaction due to the high masses of the  $W$  or  $Z$  bosons. Although the cornerstone of the standard model and responsible for the particle masses, the *Higgs* boson, has recently been found in agreement with the standard model the values of the masses of all particles as well as the very different strengths of the forces are still unexplained leaving the standard model an incomplete theory

used as projectiles ( $\alpha$ ’s from heavy elements such as “radium emanation” ( $^{222}_{86}\text{Rn}$ ) with sufficiently high energies and intensities). Figure 3 shows the original setup used by Geiger and Marsden displaying already all features of a modern scattering chamber, e.g. a thin-foil target, a detector registering single scattering events, the rotation of the detector around the target for angular distributions, the collimation of the projectiles for a good definition of the  $z$  axis etc. The scattering experiments were tedious: A MBq (in  $4\pi$  solid angle) source corresponds to an incident “beam” current into a solid angle, small enough to define a reasonable scattering geometry, of only  $\approx 10^{-6}$  nA. Single scintillation events had to be counted by observing them on a ZnS screen in the dark. The first “true” nuclear reaction (i.e. one with transmutation into different particles) was discovered by Rutherford in 1919 (after



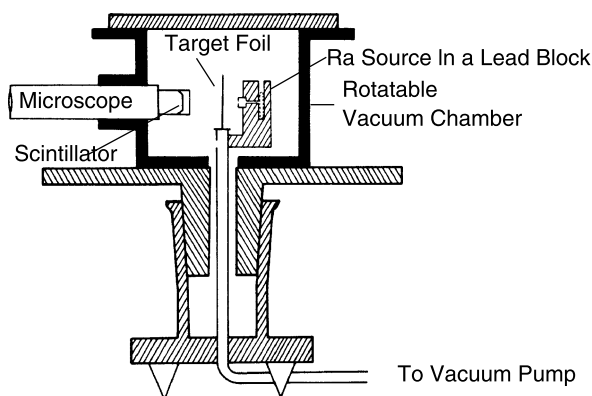
**Fig. 2** Structure of the nucleons (*left*, here for a proton with  $u, u$ , and  $d$  quarks—for a neutron it would be  $d, d$ , and  $u$ ). The core (“bag”) is surrounded by virtual meson clouds of different ranges, depending on their masses. The picture of the quark-gluon structure inside a nucleon depends on the resolution with which we observe it; here we have rather a low-energy picture with three *constituent* quarks interacting via gluons, no sea-quarks (quark-antiquark pairs), no heavier quarks, and no gluon-gluon interactions. At much better resolution their importance grows, see Sect. 2.3. The coupling of the quark spins to form the nucleon spin as shown is a crude simplification because the role of the spin  $J^P = 1^-$  of the gluons as well as of the orbital angular momenta is still somewhat unclear and under investigation using spin-polarized probes. In any case, the quark-spin contribution is much smaller than suggested by the simple picture, and the gluon-spin contribution also appears too small to overcome what has been called “*Nucleon-Spin Crisis*”. On the *right* the *nuclear force* is depicted as resulting from the exchange of virtual mesons or meson pairs. For two protons, in addition, the electromagnetic force is mediated by the exchange of virtual photons. Although the nuclear force is predominantly a two-body interaction (a *saturation* property), multi-nucleon forces cannot be excluded that are defined as “simultaneous” interactions between more than two nucleons not accounted for by a sum of two-nucleon forces (see Chap. 9). In principle, also the exchange of  $Z^0$  and  $W^\pm$  bosons mediating the weak interaction must also be considered, e.g. in the parity-violating part of the interaction, which is, however, weaker by a factor of  $\approx 10^{-7}$ .

earlier work together with Ernest Marsden), in which particles with larger range,  $^1\text{H}$  nuclei, than that of the  $\alpha$ ’s in scattering from different targets were observed:

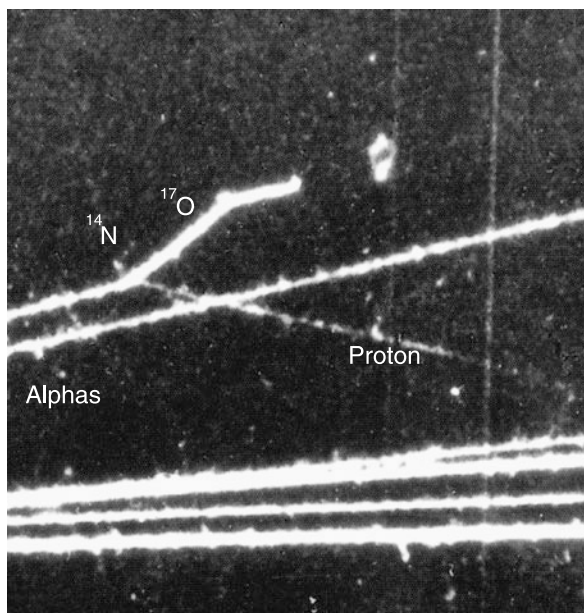


using 6 MeV  $\alpha$ ’s from a radioactive source, observed with an apparatus quite similar to the above mentioned setup. Figure 4 shows such an event in a cloud chamber, including also an event of “Rutherford” scattering of the recoil  $^{17}\text{O}$  nucleus on an  $^{14}\text{N}$  nucleus [BLA25, GEN40]. The cloud chamber, which is still unsurpassed as an instrument for visualizing such events but also cosmic rays etc. was invented by Charles Wilson following 1911, but developed for practical use by Blackett only since 1921, was not yet used by Rutherford. Consequently the  $^1\text{H}$  nuclei were identified as part of all nuclei and Rutherford coined the term “proton”. However, the still remaining basic puzzles about the true structure of nuclei were only resolved after the neutron was discovered by James Chadwick in 1932 (after Rutherford had already speculated about neutrons in nuclei and others had mistakenly interpreted

**Fig. 3** The original setup of E. Rutherford, H.W. Geiger, and E. Marsden for  $\alpha$  scattering from a gold foil [RUT11,GEI13]



**Fig. 4** Cloud chamber photograph by Blackett of the first nuclear reaction  $\alpha + {}^{14}\text{N} \rightarrow {}^{17}\text{O} + p$  observed by Rutherford in 1919 [RUT19,BLA25]



the neutron radiation from the reaction  $\alpha + {}^9\text{Be} \rightarrow {}^{12}\text{C} + n$  (with  $\alpha$ 's from a polonium source) to be an energetic  $\gamma$  radiation). It is evident that the use of radioactive sources imposed severe restrictions: fixed or very limited energy range and extremely low intensities. It is clear that the field of nuclear reactions could only progress with the invention of particle accelerators. The first accelerator prototype important for nuclear physics was the linear accelerator ("LINAC") developed and published in 1929 by Ralf Wideröe at the Aachen Institute of Technology, also laying the ground for the betatron, which was realized by Kerst and Serber in 1940, and the cyclotron by Lawrence in 1931. Wideröe's ideas also included the synchrotron

and storage-ring schemes. The first nuclear reaction initiated with accelerated beams was the reaction



by Cockroft and Walton in 1932 at the Cavendish Laboratory at Cambridge using a DC high voltage across several accelerating gaps and produced by the De-lon/Greinacher voltage multiplication scheme. This and the ensuing developments in nuclear and particle physics up to the present energies of up to 14 TeV (at the Large Hadron collider LHC at CERN/Geneva) are intimately connected with the achievements in accelerator physics and technology. Likewise the development of detector technologies—from the first scintillators, later equipped with photomultipliers, to the cloud and the bubble chambers, the ionization chamber, Geiger-Müller counter, multiwire ionization chambers, and the large field of solid-state detectors—was essential. Not unjustifiably accelerators have been called “tools of our culture” or “Engines of Discovery” (so the title of an opulent book by Sessler and Wilson [SES07]). Their impact reaches now into social applications such as tumor diagnosis and therapy, materials identification and modification, age and provenience analyses in archaeology, geology, arts, environmental science etc., see Part III. Many nuclear-physics textbooks deal also with applications, a comprehensive text is e.g. Ref. [HER99].

The—possibly somewhat underestimated—importance of accelerators and their developments for nuclear and particle physics will be stressed in this text by chapters on their principles, about ion sources, ion optics and other important features, see Chap. 16.

With the discovery of the *neutron* by Chadwick (1932) another branch of nuclear physics and especially nuclear reactions opened up that only partly depends on accelerators. Not only was the discovery of the neutron the keystone to the fundamental structure of nuclei removing all kinds of inconsistencies about e.g. about nuclear isotopes, but immediately it incited Heisenberg to formulate the idea of charge independence of the nuclear interaction and the fundamental symmetry of *isospin*. The neutrality of the neutron facilitates the description of nuclear reactions. On the other hand, production of neutrons for nuclear reactions as well as the detection methods are more complicated (see Sect. 17.4). Normally, except when neutrons from nuclear reactions are used, the choice or selection of specific neutron energies requires additional methods such as moderation by elastic collisions with light nuclei and/or chopper and time-of-flight facilities. Much of neutron work relies on neutrons from fission in reactors (an example is the high-flux 660 MW research reactor with a thermal flux of  $>1 \cdot 10^{15} \text{ s}^{-1} \text{ cm}^{-2}$ , at the Institute Laue-Langevin (ILL Grenoble)) or on spallation neutron sources where intense proton beams in the GeV and mA range incident on (liquid) metal targets release many (up to 30) neutrons per proton with high energies (a typical research center is the LANSCE facility with a proton LINAC, originally designed as *meson factory* at Los Alamos, New Mexico, another the spallation neutron source (SNS) at Oak Ridge, Tennessee, with 1.4 MW beam power and  $4.8 \cdot 10^{16}$  neutrons/s.) The neutron has also fundamental properties in its own right that have been studied:

- $\beta$  decay.
- The internal (quark + gluon) structure and charge and magnetic-moment distributions. They have been studied e.g. by elastic and inelastic electron scattering where deuterons and especially  $^3\text{He}$  served as neutron targets. Polarized  $^3\text{He}$  is an almost pure polarized neutron target. The charge and magnetic-moment distributions inside the neutron are proof of its inner structure.
- The possible electric dipole moment and thus time-reversal and parity violations were studied where the absence of the Coulomb force is experimentally advantageous.
- The wave nature of neutrons of low energies was studied in reflection, diffraction, and interference experiments.
- Especially ultracold neutrons offer many interesting properties and applications, e.g. its interaction with the gravitational field or that of its magnetic moment with magnetic fields.

## Observables

In this text the term *observable* is used repeatedly. In quantum mechanics the most widely used definition is

**Definition of “Observable”** An observable is an operator in Hilbert space corresponding to a physically measurable quantity that must be hermitean in order to have real eigenvalues (the measurable quantities).

This definition lacks uniqueness in the sense that only a small fraction of all hermitean operators corresponds to measurable quantities. Without going into the details of the still ongoing discussion of different interpretations of quantum mechanics (e.g. the “Copenhagen” interpretation, which includes the interaction between a macroscopic measuring apparatus with the microscopic quantum world, or the question of *decoherence* etc.) the term *observable* will be used more loosely in the sense of *measurable quantity*. Thus, anything that can be measured is an observable in this sense, and a state vector  $\Psi$  is not an observable. A special role is played by the measurable quantity *time* to which no operator can be assigned. On the other hand energy (cf. Hamilton operator), coordinates of space and momentum, components of angular momentum, also spin, and spin operators are observables, also in the strict sense of the above definition.

## About This Book

This book contains the essential material that was presented in nuclear-physics courses for graduate students at the University of Cologne. Therefore, the references in this book, but especially the list of general references in the front part of the book

contain also selected textbooks in German that may not be accessible easily to an international readership.

The author, an experimental nuclear physicist, considers the intertwining of experimental facts, experimental methods, and tools, with basic theoretical knowledge a good method to teach the subject.

The problems attached to each chapter serve rather to elucidate and detail physical ideas that could not be presented in full detail in this text, than to give an ample collection for classroom use which would exceed the space available. Many good (older) books contain such collections.

Subjects such as (relativistic or non-relativistic) kinematics will therefore not be treated extensively. However, a basic knowledge of both is a prerequisite for understanding nuclear reactions and the connections to particle and high-energy physics.

## Acknowledgments

The author acknowledges many fruitful discussions, not only on few-body problems, with his friend Walter Glöckle, who passed away, much too early, in 2012. He gave few-body theory an entirely new impact and scope and, thus, incited also many important experiments.

Thanks go to Claus Kiefer, Cologne, for an enlightening discussion on different aspects of the term “Observable”.

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Nuclear Reactions

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