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Discoveries and consequences

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To my wife Sybille who patiently supported me during the writing of this and other work.

Contents

Preface

With the 'age' of nuclear physics reaching 100 years it seems appropriate to consider in detail the historical aspects of how new knowledge has appeared. It is fascinating to look at theoretical developments in the field of subatomic physics in step with the grand new ideas of the 20th century, such as quantum theory and the theory of relativity, opening entirely new perspectives on the world. Experimental progress has given hints of 'new physics' (e.g. the stepwise deciphering of the structure and composition of nuclei led to the idea of two new interactions, the weak and the strong force and their theoretical description) and experiments were needed to decide between alternative theoretical interpretations (e.g. 'Are neutrinos Dirac or Majorana particles?', 'Do neutrinos have mass or not?' or 'Are electrons, neutrinos, muons and protons point particles or extended objects?').

In this respect it is worth studying the often fascinating details of early (in particular 'first') experiments. Quite often epoch-making results were obtained with very simple means, e.g. the discovery of nuclear fission. But all these experiments were based on earlier attempts that were carefully refined to yield unambiguous evidence, not pure serendipity (e.g. the carefully planned layout of the experiment to 'find' the neutrino).

This book is designed to give an outline of the key experiments in nuclear reactions. It is also motivated by an earlier book in German that I have often found very useful myself (Bodenstedt E 1972 *Experimente der Kernphysik und ihre Deutung* (Mannheim: BI Wissenschaftsverlag)), which comprises three volumes and also covers many nuclear structure experiments. The current book is restricted to nuclear reactions which seems justified, also because of the increased specialization of the subfields of nuclear physics.

In this book the 'crucial' or 'key' experiments that often, but not always, have been the first in a subfield are described in some detail, often including original drawings or set-ups because these may illustrate the igniting idea of a new field better than later and more sophisticated set-ups. Nevertheless in many instances later progress is briefly described. The theoretical background is given, but is kept compact and, if necessary, the usual textbooks or original literature will have to be consulted. Therefore, at the end of the introduction chapter references for general reading and other useful works are listed. Insisting on the reproduction of original drawings would result in reduced quality of the figures in some cases—therefore for these the figures have been redrawn or the text has been replaced.

About the author

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Born 1938 in Coburg, Germany. Studies of Physics, Mathematics, and Philosophy at Universities at Stuttgart, Hamburg, and Basel. Physics Diploma (1964) and Dr. phil. (1966) from the University of Basel. 1967–1970 Postdoc at Basel and Ohio State University, Columbus, OH. 1970 Visiting Assistant Professor at OSU. Since 1971 at the University of Cologne. Habilitation 1973. Apl. Professor 1978, University Professor since 1983. Retired since 2004. Member of the German Physical Society DPG, member and fellow of the American Physical Society APS. Author of books and many scientific articles in refereed journals.

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Chapter 1

Introduction

Key experiments are those which open up entirely new insights into unknown 'territories' and start new fields of more detailed investigations in these areas. One indicator of key experiments can be the awarding of Nobel Prizes to the principal investigators (examples are Robert Hofstadter (1961), and Jerome Isaac Friedman, Henry Way Kendall and Richard Edward Taylor (1990), for the study of the external and internal structure, respectively, of the proton by electron scattering).

In nuclear physics, a field of science which, by definition, has existed for only around 100 years, these key developments are *radioactivity* and the active investigation of nuclei, either their *structure* or their interactions in *nuclear reactions*. Both are intimately connected with the continuing progress in the development of particle accelerators and, in part, nuclear reactors.

1.1 Rutherford and evidence for the nuclear atom

Around 1911 in Manchester, UK, the famous Rutherford scattering experiment initiated the study of nuclear reactions. The behavior of α particles elastically scattered from gold and other nuclei suggested a very small (from the point of view of that time) and compact nucleus (i.e. containing most of the atom's mass and all of the positive charge Ze compensating that of the atomic electrons). Energetic particles from radioactive sources were used as projectiles (α particles from heavy elements such as 'radium emanation' ($^{222}_{86}$Rn) with sufficiently high energies and intensities). Even then scattering experiments were tedious: a MBq (in a 4π solid angle) source corresponds to an incident 'beam' current into a solid angle, small enough to define a reasonable scattering geometry, of only $\approx 1 \cdot 10^{-6}$ nA. Single scintillation events had to be counted by observing them on a ZnS screen in the dark.

1.2 The first true nuclear reaction

Around 1917 Ernest Rutherford, using techniques similar to those of the famous scattering experiment, recognized that a different type of particle emerged from the

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interaction of α particles from radioactive sources with gas molecules. This new particle had a longer range in matter than the α and proved to be the nucleus of the hydrogen atom. Rutherford had therefore performed the first true nuclear reaction with a rearrangement of the particles involved. Although the existence of negatively charged constituents (the atomic electrons) and positive ions had been seen in gas discharges, only Rutherford identified the particle which emerged from the

$$^{14}\mathrm{N} + \alpha \rightarrow {}^{17}\mathrm{O} + \mathrm{p} \tag{1.1}$$

reaction as the very small nucleus of H and coined the term 'proton'. Thus, he solved one part of the riddle of the structure and composition of nuclei; the other had to wait until the discovery of the neutron.

The nuclear charge number is identical to the element number of the periodic table and the Z dependence of the Rutherford cross section confirmed the periodic system of the elements. The explanation of the existence of isotopes and their correct placement in the chart of nuclides (Z versus N) required the discovery of the neutron in 1932. Rutherford could already—by comparing the measured scattering angular distribution of α particles on gold with his ansatz of a point-Coulomb interaction—conclude that the nucleus is an object smaller than the scattering distances (order of magnitude: $1\ \mathrm{fm} = 1 \cdot 10^{-15}\ \mathrm{m}$). The very fact that scattering at backward angles occurred, showed that the scattering center had to be heavier than the α (this is pure kinematics). The electron cloud relative to this is very large (order-of-magnitude radius: $1\ \text{Å} = 1 \cdot 10^{-10}\ \mathrm{m}$) and carries the charge $-Ze$ such that the atom is exactly neutral.

After the invention of accelerators the use of α particles of much higher energies with penetration into the target nucleus was possible and the extension (the radius) of nuclei could be obtained by the onset of deviations from the point-Coulomb scattering. A key role is played here by the *charge form factor* and its Fourier transform, the *charge density distribution*. It expresses how strongly the Coulomb potential of an extended (often simply assumed to be homogeneous) charge distribution in the nuclear interior deviates from that of a point charge or what the influence of the (hadronic) nuclear interaction on the observables is, see figure 4.3.

Using charged leptons, which have no measurable extension and do not feel the strong interaction, as probes, charge (and current) distributions in nuclei and nucleons have been determined. At higher momentum transfer (i.e. at high energies and large scattering angles via *inelastic or quasi-elastic scattering*) excited states of the nucleon and, later, (via deep-inelastic scattering) substructures of the nucleons (*partons*) were discovered which had all the properties of quarks—1/3 charges, spin $1/2\hbar$, color charge and confinement—characteristics of truly elementary particles (point shape, no internal structure) and, also by probing with neutrinos, they proved to be sources of the strong, electromagnetic and weak interactions.

1.3 The role of accelerators

It is evident that the use of radioactive sources imposed severe restrictions: a 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 Donald Kerst and Robert Serber in 1940, and the cyclotron by Ernest O 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

$$p + {}^{7}\mathrm{Li} \rightarrow 2\alpha \tag{1.2}$$

by John Cockroft and Ernest Walton in 1932 at the Cavendish Laboratory at Cambridge using a dc high voltage across several accelerating gaps and produced by the Delon/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 at CERN/Geneva) are intimately connected with the achievements in accelerator physics and technology. Not unjustifiably, accelerators have been called 'tools of our culture' and 'engines of discovery' (see e.g. the book with that title by Sessler and Wilson [18]).

A very important part of this is the development of a variety of ion source types adapted to the special needs of different experiments. In many cases acceleration of negative ions is advantageous or required (e.g. in tandem Van de Graaff accelerators). The study of the spin dependence of nuclear reactions became possible with sophisticated sources of spin-polarized ions as well as spin-polarized targets. The possibility to produce and accelerate ions of very many isotopes is a prerequisite for, in particular, nuclear structure studies and, using exotic (e.g. radioactive) beams, the limits of the chart of nuclides are also being explored.

1.4 Detection methods

The fact that nuclear radiation cannot be seen (or felt) directly requires more or less sophisticated equipment to visualize or register the existence and interactions of different types of radiations such as α, β and γ particles, light and heavy ions up to fission product nuclei, neutrons and transuranium nuclei, etc. Thus, parallel to accelerator developments the development of detector technologies—from the first scintillators, later equipped with photomultipliers, to the cloud, spark and bubble chambers, the ionization chamber, the Geiger–Müller counter, multiwire ionization chambers and the large field of solid-state detectors—was essential. The impact of accelerators, especially in conjunction with modern detector technologies such as computed tomography for three-dimensional images, now extends into social applications such as tumor diagnosis and therapy, the identification and modification of materials, age and provenience analyses in archaeology, geology, arts, environmental science, security questions, etc.

1.5 The neutron and the correct composition of nuclei

With the detection of the *neutron* by James Chadwick (1932) (see also chapter 7) another branch of nuclear physics and, in particular, nuclear reactions opened up that only partly depends on accelerators. Not only was the discovery of the neutron the key to the fundamental structure of nuclei, removing all kinds of inconsistencies about, e.g., nuclear isotopes, but it also immediately 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 and also the execution of nuclear reactions. On the other hand, the production of neutrons for nuclear reactions as well as the detection methods are more complicated. 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 the work on neutrons relies on neutrons from fission in reactors (an example is the high-flux 660 MW research reactor with a thermal flux of $>1 \cdot 10^{15}$ s^{-1} cm^{-2}, at the Institut 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 a meson factory at Los Alamos, New Mexico, another is the spallation neutron source (SNS) at Oak Ridge, Tennessee, with 1.4 MW beam power and $4.8 \cdot 10^{16}$ neutrons s^{-1}.

The neutron has fundamental properties in its own right which have been studied:

- β decay.
- The internal (quark + gluon) structure and charge and magnetic moment distributions. These have been studied, e.g., using elastic and inelastic electron scattering where deuterons and, in particular, ^{3}He served as the neutron targets. Polarized ^{3}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.
- Ultracold neutrons in particular offer many interesting properties and applications, e.g. their interaction with the gravitational field or the interaction of their magnetic moment with magnetic fields.

1.6 Nuclear spectroscopy

We define nuclear spectroscopy as the science of learning all about the properties of the thousands of nuclides, each with individual and also collective properties. Aside from early studies of radioactive decays, nuclear reactions have been the main tool to investigate the action of nuclear forces (in the sense of an interplay of the strong interaction proper, and the electromagnetic and the weak force). In high-density situations, e.g. in neutron stars, even the gravitational force enters the stage via the density dependence of the nuclear interactions. The aim of modern nuclear spectroscopy is now moving away from stable nuclei, from deformed highly excited nuclei with high angular momenta to the investigation of nuclei in the regions near the limits of known nuclei with either high neutron excess, high neutron deficiency, or the region of new elements, the superheavy nuclei. These can be characterized by their isospin $T = (N - Z)/A$.

1.7 Higher energies

With higher energies available nuclear reactions produced a wealth of phenomena in intermediate- and high-energy physics, such as the *particle zoo* with thousands of more or less short-lived particles that do not exist naturally, ordered by the quark model. The inner structure of the hadrons (mesons composed of a quark and an antiquark, baryons consisting of three constituent quarks) could be investigated, as well as the deeper role of old and new conservation laws or invariances. The nature of the different forces and their interactions via the exchange of bosons, and their ranges and strengths are manifested in reactions, as is the answer to the fundamental question of how particles acquire mass (via the Higgs field or Higgs boson).

1.8 General references and resources

The specific source literature connected with each key experiment and given in each chapter is supplemented by the (selected) references of more general interest and the resources included in the bibliography of this chapter.

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