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Vladimir G. Plekhanov

Isotopes in Condensed Matter

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Isotopes in Condensed Matter

Springer

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To my kids and grandchildren

Preface

This book describes the manifestations of the isotope effect in all branches of physics: nuclear, atomic and molecular as well as condensed matter and its applications in *human health* and *medicine*, *geochronology*, industry, research in academic and applied fields. This book is intended both as a tutorial and as a reference. It is a concise introduction to isotopetronics, developing the basic elements of this new branch of nanoscience. The problem of the enigma mass in microphysics is briefly discussed.

The science of the nuclear, atoms and simple molecules and the science of matter from microstructures to larger scales, are well established. A remaining, extremely important, size—related challenge is at the atomic scale—roughly the dimensional scales between 1 and 10 molecular sizes—where the fundamental properties of materials are determined and can be engineered. This field of science—isotopetronics—is a broad and interdisciplinary field of emerging research and development. Isotopetronics technology is concerned with materials, structures and systems whose components, as in nanoscience, exhibit novel and significantly modified physical, chemical and biological properties due to their small sizes. A principal goal of isotopetronics technology is to control and exploit these properties in structures and devices at atomic and molecular levels. To realise this goal, it is essential to learn how to fabricate and use these devices efficiently. Practical implementations of isotopetronics science and technology have great importance, and they depend critically on training people in these fields. Thus, modern education needs to address the rapidly evolving facets of isotopetronics science and applications. With the purpose of contributing to education in the *isotopetronics* as a new branch of *nanoscience* I present this book providing a unifying framework for the basic ideas needed to understand recent developments underlying isotopetronics science and technology, as applied to nanoelectronics and quantum information. Quantum information is a field which at present is undergoing intensive development and, owing to the novelty of the concepts involved, it seems to me it should be as interest to a broad range of scientists beyond those actually working in the field. I have tried to present a simple and systematic treatment of the isotopetronics, such that the reader might understand the material presented without the need for consulting other books.

With numerous illustrations, this book will be of great interest to undergraduate and graduate students taking courses in mesoscopic physics or nanoelectronics as well as quantum information, and academic and industrial researches working in this field.

The references I cite are those with which I am most familiar and which have helped us understand the subject as presented here. While there has been no attempt to give credit to each contributor, I have tried to cite the original papers, which brought new and important results (methods) to the isotope effect applications in all branches of microphysics.

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Tallinn *Vladimir G. Plekhanov*

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Chapter 1
Introduction

The aim of this book is to outline the basic physical concepts and device applications related to isotope effect in all the branches of *microphysics* [1]—new direction of nanoscience (subnanoscience). The experience of the past shows that throughout constant technology improvement microelectronics has become more reliable, faster, more powerful and less expensive by reducing the dimensions of integrated circuits. As demonstrated in this book, when the dimensions of a solid are reduced to the atomic size, new physical properties due to quantum effects become apparent. These novel properties are manifestated in various ways, first we should indicate low-dimensional structures in isotope-mixed solids (*quantum wells, wires, dots*). Besides that we should underline the specific dependence of elastic thermal and vibrational properties of bulk isotope-mixed materials as well as low-dimensional structures from such materials. In the last two decades the unique properties of isotopes are used in the quantum information processing devices as well as in developing of processors of the quantum computers [2].

In the last four decades we have witnessed a remarkable progress in the development of *epitaxial crystal growth* techniques such as molecular beam epitaxy (MBE), metal-organic chemical vapor deposition (MOCVD) and their various variations such as chemical beam epitaxy (CBE), atomic layer epitaxy (ALE), etc. which have allowed the growth of quality semiconductors (insulators), their alloy and heterostructures (see, e.g. [5, 6]). A variety of interesting structures, such as quantum wells, quantum wires and quantum dots, has been fabricated with abrupt changes in composition and/or doping characteristics and their structural, electronic and optical properties have been investigated in considerable detail (see, e.g. [3–12]). Many of these structures, especially those based on quantum wells, have found important applications in a number of electronic and *opto-electronic* devices such as high-electron mobility transistors, lasers, light-emitting diodes (LEDs), photodetectors, spatial light modulators [5, 8, 12]. The use of these devices in opto-electronics, quantum information, for example, has literally revolutionized these fields during the last two decades. Before we study the effects of reduced size and dimensionality on the properties of solids, we review in first chapters those

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concepts of isotopes and solids which are essential for understanding the behaviour of quantum nanostructures. For instance, the behaviour of electrons in a quantum well is very different from the case of bulk solids if their motion is across the potential barriers confining the quantum well, but is very similar if the motion is parallel to the interfaces [3, 4, 7].

It is increasingly clear that quantum mechanical principles are not just exotic theoretical statements but fundamental for a new technology of practical information processing [2, 13]. *Quantum communication, quantum cryptography* as well as *quantum teleportation* represent exciting new arenas which exploit intrinsic quantum mechanical correlations [14–16]. In the first step we should analyse the exciton in *quantum dot*, it possible as *qubit* in assembly of quantum dots in isotope-mixed crystals [2].

As we know, at present time only three particles, the proton, the electron and the photon, are stable. Another particle, the neutron, is stable when it is bound within a nucleus, and is unstable with life time of 887 ± 2 s when it is free. Since nuclei are involved in a wide variety of applied and pure research, nuclear physics overlaps with a number of other fields of physics: particles; astrophysics; stellar evolution, etc. Therefore, the primary aim of nuclear physics is to understand the force between nucleons, the structure of nuclei and how nuclei interact with each other and with other subatomic particles. These three questions are, to a large extent, related with each other. Modern experimenters can create such nuclei using artificially induced fusion or nucleon transfer reactions, employing ion beams from different sources. Beams with even higher energies (e.g. from accelerator) can be used to create nuclei at very high temperatures, and there are signs that these experiments have produced phase transition from normal nuclear matter to a new state, the *quarks condensate*, the *quark-gluonplasma*, in which the quarks mingle with one another, rather than being segregated in triplets as they are in neutrons and protons. If in the nuclear physics the meaning of isotope is establishing [1] then application isotope effect in atomic and molecular physics allows to get the results, which are difficult to overestimate so far as owing to this results it was to construct the "building" of the science of the twentieth century the quantum mechanics. In the last fifty years the isotope effect is one of the modern and power methods to investigation of structure and properties of solids. This conclusion supports the numerous reviews and first monographs dedicated to isotope effect of stable and *radioactive isotopes*. Moreover, it is obviously a leading role of the isotope physics in the study of the nature-nuclear interactions and reconstruction of *nucleogenesys* process in the *Universe* which could be explained as the observable in nature relative to spreading of chemical elements. Such wide field of isotope applications stimulates necessity for examination and critical analysis from one point of view the microscopical nature of isotope effect. Such approach to isotope physics allows to make known not only the intrinsic contradiction inherent in this area of physics but also determine the borders of the effect.

It is well known [17] that reflectance and absorption spectra of different solids often show structure for photon energies just below the *energy gap*, where we might expect the crystal to be transparent. This structure is caused by the *absorption* of photon with the creation of a bound electron - hole pair. An electron and a hole may be bound together by their attractive *Coulomb interaction* [18–20], just as an electron is bound to a proton to form a neutral hydrogen atom. The bound electron–hole pair is called by exciton [17]. An *exciton* can move through the crystal and transport energy; it does not transport charge because it is electrically neutral. This task was first studied by Wannier–Mott [18, 19] and later by Slater [20] who showed that if one assumes that the electron and hole wavefunctions are extended over many lattice constants, the exciton can be described as consisting an electron and a hole with effective band masses m_e^* and m_h^*, respectively, coupled together with coulomb potential screened by the static dielectric constant ε_0 [21]. In the *Wannier–Mott model*, the Schrödinger equation for the exciton is resolved into the function of a hydrogen-like atom whose effective charge is $Z_e = \mathrm{e}/\varepsilon_0$ (ε_0 being the dielectric constant of medium), and the energies of the exciton states are described by the hydrogen-like expression of the form (see, e.g. [22])

$$E(\overrightarrow{k}) = E_g - \frac{\mu \mathrm{e}^4}{2\hbar\varepsilon_0^2 \mathrm{n}^2} + \frac{\hbar^2 \overrightarrow{k}^2}{2(m_e^* + m_h^*)}, \tag{1.1}$$

where $\overrightarrow{k}$ is the quasi-momentum of the exciton; μ, n are its reduced mass and principal quantum number and the translational mass of the exciton (M) is equal to the sum of the effective masses of electron (m_e^*) and hole (m_h^*). By analogy with formula of the binding energy of an electron in a hydrogen atom on the nuclear mass (M_N)(Ryd $= 2\pi^2 \frac{me^4}{\hbar^3 c(1+m/M_N)}$), the binding energy of exciton $E_b = -\frac{\mu \mathrm{e}^4}{2\hbar\varepsilon_0^2 n^2}$ is practically independent of the nuclear mass. Hence, we come to the natural conclusion that there is no isotopic effect in a frozen crystal lattice on the levels of the Wannier–Mott exciton [23]. This simplified treatment, however, does not take into account the exciton–phonon interaction, which to a certain extent is nonadiabatic (see, for example [24]). The constant of exciton–phonon interaction depends on the frequency of phonons and hence on the mass of isotopes [1]. The isotopic dependence of the binding energy of large-radius exciton was observed experimentally with LiH and LiD crystals in Ref. [25], where the reflection spectra of these crystals at low temperature were measured for the first time (see, also [25]). As will be shown below, the discovered dependence of E_b on the isotopic composition of the lattice has opened unique opportunities for the use of excitons in the characterisation of bulk isotope mixed crystals as well as quantum low-dimensional structures in such systems [2].

This book comprises of six chapters. Chapter 2 begins by reviewing the present state of the modern picture of isotopes. This chapter introduces the reader with physical base of isotopes and describes its manifestations in nuclear physics. The origin of the *mass* is briefly discussed in this chapter too. Chapters 3 and 4 are devoted to description of the manifestations of the isotope effect in atomic and molecular physics as well as in condensed matter. Although these manifestations vary, they have one common feature—all depend on mass. Such view allows to see the success and failure as well as the borders of the isotope effect. Chapter 5 describes the effects related to isotopic disorder in solids: diffusion and thermal properties.

The objective of the second part (Chap. 6) is to expose the reader to the traditional applications of stable and *radioactive isotopes*. In the first part of this chapter we describe stable isotope applications in neutron transmutative doping (NTD) of semiconductors as well as in optical fibre. There is a brief description about the new nuclear technology for the preparation of the fibre. In the second part of this chapter, the reader can find description of the applications of radiactive isotopes: human health and medicine, geochronometry, solid state, etc. Throughout this book, the author interweaves experimental results with the appropriate theoretical formalism.

From the immense volume of the literature concerned with isotopes in condensed matter and their applications, we primarily selected those reviews and monographs which contain extensive references.

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Chapter 2
Sub-Nucleonic Structure and the Modern Picture of Isotopes

2.1 History and Overview

Investigations of the *atomic nucleus*, and the fundamental forces that determine *nuclear* structure as is well known offer fascinating insights into the nature of the physical world [1–10]. We all known well that the history of the nuclear physics dates from the latter years of the nineteenth century when Henry Becqeurel in 1896 discovered the radioactivity. He was working with compounds containing the element uranium. Becqeurel found that photographic plates covered to keep out light became fogged, or partially exposed, when these uranium compounds were anywhere near the plates. Two years after Becquerel's discovery, Pierre and Marie Curie in France and Rutherford in England succeeded in separating a naturally occurring radioactive element, radium ($Z = 88$), from the ore. It was soon revealed that there are three, distinctly different types of radiation emitted by radioactive substances. They were called *alpha* (α), *beta* (β) and *gamma* (γ) rays—terms which have been retained in ours days. When a radioactive source was placed in a magnetic field, it was found that there were three different activities, as the trajectories of some of the rays emitted were deflected to one direction, some to the opposite direction and some not affected at all. Subsequently it was found that α-rays consist of positively charged ^{4}He nuclei, β-rays are made of electrons (positrons) and γ-rays are nothing but electromagnetic radiation that carries no net charge. The existence of the nucleus as the small central part of an atom was first proposed by Rutherford in 1911. Rutherford proposed that the atom does consist of a small, heavy positively charged centre surrounded by orbiting electrons which occupy the vast bulk of the atoms volume. The simplest atom—hydrogen—consisted of a proton and a single orbital electron. Later, in 1920, the radii of a few heavy nuclei were measured by Chadwick and were found to be in the order of 10^{-14} m, much smaller than the order of 10^{-10} m for atomic radii (for details, see e.g. [4–9]).

The building blocks of nuclei are *neutrons* and *protons*, two aspects, or quantum states, of the same particle, the *nucleon*. Since a neutron does not carry any net electric charge and is unstable as an isolated particle (see, below), it was not discovered

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Table 2.1 Fundamental interactions

Interaction	FQ	Mass	Range (m)	RS	Spin	T C-S (m^2)	TTS (s)
Strong	Gluon	0	10^{-15}	1	1	10^{-30}	10^{-23}
Weak	$W^{\mp}$; Z	81; 93 GeV/c^2	10^{-18}	10^{-5}	1;1	10^{-44}	10^{-8}
Electromagnetic	Photon	0	∞	$\alpha = 1/137$	1	10^{-33}	10^{-20}
Gravity	Graviton	0	∞	10^{-30}	2	–	–

Here *FQ* field quant, *RS* relative strength, *TC-S* typical cross-section, *TTS* typical time scale

until 1932 by Chadwick, whose existence has been anticipated by Rutherford as early as 1920. Since only positive charges (protons) are present in nucleus, the electromagnetic force inside a nucleus is repulsive and the nucleons cannot be held together unless there is another source of force that is attractive and stronger than Coulomb's (see, also [10]). Here we have our first encounter with *strong interaction* (see, also Table 2.1). In 1934 Hideki Yukawa proposed the first significant theory of the *strong force* to explain how the nucleus holds together. As we know, with Fermi and Yukawa's papers the modern model of the atom was complete [2–6].

Studies of the structure of the nucleus have shown that it is composed of protons and neutrons, and more recently studies [11–14] of very high energy collisions have shown that these protons and neutrons are themselves composed of elusive particles called *quarks*. Particle physics deals with the world of the quarks and all other particles still thought to be fundamental. One may argue that, since nuclear force is only one aspect of the strong interaction between quarks, all we need therefore to do is to understand *quantum chromodynamics* (QCD)[1] (for details see [12–15] and below). The structure of neutrons and protons is discerned only at very high energies (see, e.g. [15]) and, for all practical purpose concerning nuclear structure, research and nuclear physics applications in the modern world, the neutron–proton model of the nucleus is entirely adequate.

Thus, our present knowledge of physical phenomena suggests that there are four types of forces between physical objects:

1. Gravitational;
2. Electromagnetic;
3. Strong and
4. Weak.

Both *gravitational* and *electromagnetic* forces are infinite in range and their interaction strength diminishes with the square of the distance of separation. Clearly, nuclear force cannot follow the same radial dependence. Being much stronger, it would have pulled the nucleons in different nuclei together into a single unit and destroy all the atomic structure we are familiar with. In fact, *nuclear force* has a

[1] QCD is the modern theory of the strong interaction. QCD, the theory of quarks, gluons and their interactions, is a self-contained part of the Standard Model (see below) of elementary particles. Historically its route is in nuclear physics and the description of ordinary matter—understanding what protons and neutrons are (and their structure) and how they interact. Nowadays QCD is used to describe most of what goes at high-energy accelerators.

very short distance. As we know at present time, only three particles, the proton, the electron and the photon, are stable. Another particle, the neutron, is stable when it is bound within a nucleus, and is unstable with life time of 887 ± 2 s when it is free (for details see, also [11–14]). Since nuclei are involved in a wide variety of applied and pure research, nuclear physics overlaps with a number of other fields of physics: particles; astrophysics; stellar evolution, etc. Therefore, the primary aim of nuclear physics is to understand the force between nucleons, the structure of nuclei and how nuclei interact with each other and with other *subatomic particles*. These three questions are, to a large extent, related with each other. Much of the current research in nuclear physics (see, e.g. [1–10]) relates to the study of nuclei under extreme conditions such as high spin and excitation energy. Nuclei may also have extreme shapes (for instance similar to that American footballs) or extreme neutron-to-proton ratios. Modern experimenters can create such nuclei using artificially induced fusion or nucleon transfer reactions, employing ion beams from different sources. Beams with even higher energies (e.g. from accelerator) can be used to create nuclei at very high temperatures, and there are signs that these experiments have produced phase transition from normal nuclear matter to a new state, the quarks condensate, the quark-gluon plasma, in which the quarks mingle with one another, rather than being segregated in triplets as they are in neutrons and protons.

If in the nuclear physics the meaning of isotope is establishing one [7, 9, 10, 15], then application of isotope effect in atomic [16–19] and molecular [20–22] physics allows to get the results, which are difficult to overestimate so far as owing to this results it was to construct the "building" of the science of the twentieth century—the quantum mechanics. In the last 50 years the isotope effect is one of the modern and power methods used in investigation of structure and properties of solids. This conclusion supports the numerous reviews (see, e.g. [23–25]) and first monographs [26, 27, 29] dedicated to isotope effect of stable isotopes. In the last years, more and more investigations of solid-state physics are conducted by using *radioactive isotopes*, which give evidence of already comprehensive list of references (see, for instance [28, 30, 31]). It is a well known fact that large and successful application of the radioactive elements in medicine [32–35], the direction in isotope physics, is more finance supportive in different states (see, for example, [36] and references therein). Moreover, it is obviously a leading role of the isotope physics in the study of the nature–nuclear interactions and reconstruction of nucleogenesys process in the Universe [37–40] which could be explained as the observable in nature relative to spreading of chemical elements.

Such wide field of isotope applications stimulate necessity for examination and critical analysis from point of view of the microscopical nature of isotope effect.[2]

[2] With the aim of the ground of nature of isotope effect, a detailed analysis of the neutron and proton structure and their mutual transformation in the *weak interaction* process was conducted. Note that the main characteristics of isotope effect—the mass of free particles (proton and neutron)—does not conserve in the weak interaction process. This contradiction is removed although partly if we take into account the modern presentation [42–44] that the mass of proton (neutron) is created from quark condensate (not from constituent quarks [15, 44]) which is the coherent superposition of the states with different chirality. Thus the elucidation of the reason of origin of the nucleon

Table 2.2 The basic properties of the atomic constituents

Particle	Charge	Mass (u)	Spin (ħ)	Magnetic moment (JT^{-1})
Proton	e	1.007276	1/2	1.411×10^{-26}
Neutron	0	1.008665	1/2	-9.66×10^{-27}
Electron	−e	0.000549	1/2	9.28×10^{-24}

Such approach to isotope physics allows to make known not only the intrinsic contradiction inherent this area of physics but also determine the borders of the effect. A step-by-step comparison with existing theoretical models not only reveals the degree of agreement (or disagreement) but also provides a new impulse for both the development of new theoretical ideas and for conducting new experiments (see, also [41]).

2.2 The Structure of Atomic Nucleus

An atom consists of an extremely small, positively charged nucleus (see Fig. 2.1) surrounded by a cloud of negatively charged electrons. Although typically the nucleus is less than one ten-thousandth the size of the atom, the nucleus contains more than 99.9% of the mass of the atom. Atomic nucleus is the small, central part of an atom consisting of A-nucleons, Z-protons and N-neutrons (Fig. 2.2). The atomic mass of the nucleus, A, is equal to Z+N. A given element can have many different isotopes, which differ from one another by the number of neutrons contained in the nuclei [58, 59]. In a neutral atom, the number of electrons orbiting the nucleus equals the number of protons in the nucleus. As usual, *nuclear size* is measured in fermis ($1\text{fm} = 10^{-15}$ m, also called femtometers). The basic properties of the atomic constituents can be read in Table 2.2.

As we can see from this table, protons have a positive charge of magnitude $e = 1.6022 \times 10^{-19}$ C (Coulomb's) equal and opposite to that of the electrons. Neutrons are uncharged. Thus a neutral atom (A, Z) contains Z electrons and can be written symbolically as ${}^{A}_{Z}X_{N}$ (see also Fig. 2.2). Here X is chemical symbol and N is neutron number and is equal $N = A - Z$.[3] The masses of proton and neutron are almost the same, approximately 1836 and 1839 electron masses (m_e), respectively. Apart from electric charge, the proton and neutron have almost the same properties. This is why there is a common name of them: *nucleon*. Both the proton and neutron are nucleons.

(Footnote 2 continued)
mass is taken down to elucidation of the reason to break down the chiral symmetry in *Quantum Chromodynamics* [45–56].

[3] Nuclei with the same N and different Z are called *isotones*, and *nuclides* with the same mass number A are known as *isobars*. In a symbolic representation of a nuclear specie or nuclide, it is usual to omit the N and Z subscripts and include only the mass number as a superscript, since A = N+Z and the symbol X represents the chemical elements.

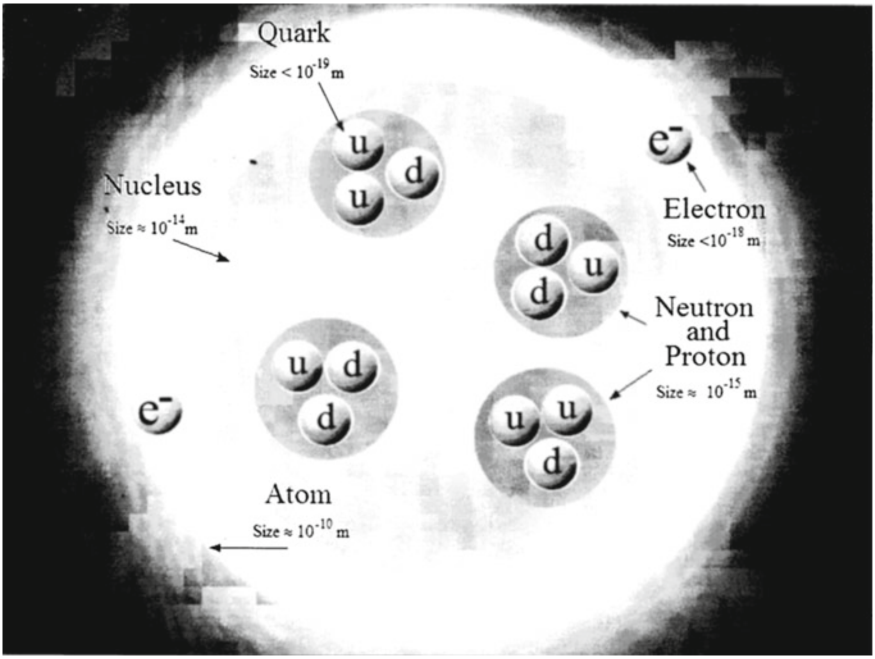
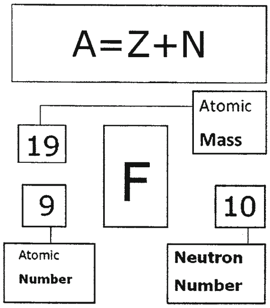


Fig. 2.1 Structure within the atom. If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across (after http://www.lbl.gov/abc/wallchart/)

Fig. 2.2 Atomic nomenclature



We know well that the proton is denoted by letter p and the neutron by n. Chemical properties of an element are determined by the charge of its atomic nucleus, i.e. by the number of protons (electrons). It should be added that although it is true that the neutron has zero net charge, it is nonetheless composed of electrically charged quarks (see below), in the same way that a neutral atom is nonetheless composed of protons and electrons. As such, the neutron experiences the electromagnetic interaction. The net charge is zero, so if we are far enough away from the neutron that it appears to occupy no volume, then the total effect of the electric force will add up to zero. The

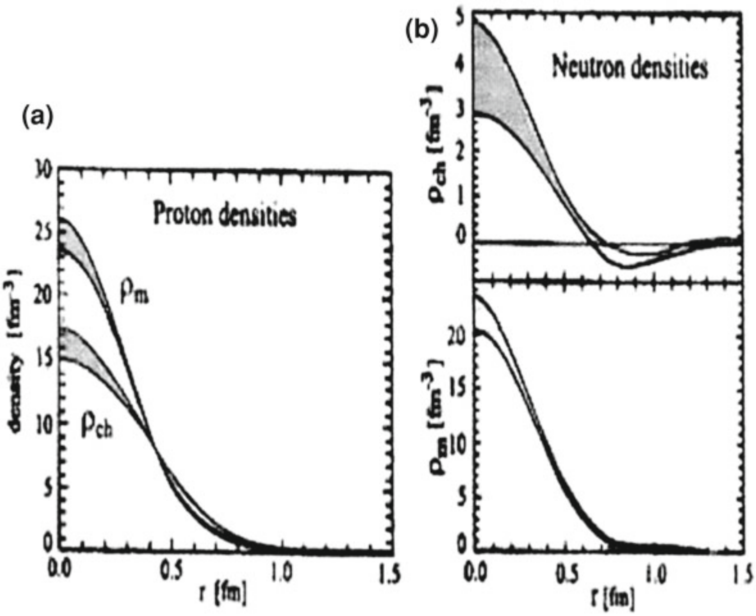


Fig. 2.3 Comparison between charge (ρ_{ch}) and magnetization (ρ_m) for the proton (**a**) and neutron (**b**). Both densities are normalized to $\int$ drr$^2\rho = 1$(r) (after [62–64])

movement of the charges inside the neutrons does not cancel, however, and this is what gives the neutron its non-zero magnetic moment.

Each of the atomic constituencies, a spin 1/2 in units of $\hbar (= h/2\pi)$ and is an example of the class of particles of half-integer spin known as fermions. Fermions obey the exclusion principle of Pauli (see, e.g. [9]), which determines the way electrons can occupy atomic energy states. The same rule applies, as will be shown below, to nucleons in nuclei. Associated with the spin is a magnetic dipole moment. Compared with the magnetic moment of electron, nuclear moment is very small. However, they play an important role in the theory of nuclear structure. It may be surprising that the uncharged neutron has a magnetic moment. This reflects the fact that it has an underlying *quark substructure* (see, e.g. [60]), consisting of charged components. Electron scattering off these basic nuclear constituents (proton and neutron) makes up for the ideal probe to obtain a detailed view of the internal structure. A very detailed analysis using the best available data has been carried out recently by Kelly [61]. These data originate from recoil or target polarizations experiments (see, also [62–64]). In Fig. 2.3, the proton charge and magnetization distribution are given. What should be noted is the softer charge distribution compared to the magnetic one for proton. These resulting densities are quite similar to Gaussian density distributions that can be expected starting from quark picture (for details, see below) and, at the same time more realistic than the exponential density distributions [61]. The neutron charge and magnetization are also given in Fig. 2.3. What is striking is that

Table 2.3 Sample values of nuclear magnetic dipole moments (after [65])

Nuclide	$\mu(\mu_N)$
n	− 1.9130418
p	+ 2.7928456
^{2}H(D)	+ 0.8574376
^{17}O	− 1.89379
^{57}Fe	+ 0.09062293
^{57}Co	+ 4.733
^{93}Nb	+ 6.1705

magnetization distribution resembles very closely the corresponding proton distribution. Since scattering on neutrons normally carries the larger error (see, e.g. [6, 7]), the neutron charge distribution is not precisely fixed. Nonetheless, one notices that the interior charge density is balanced by a negative charge density, situated at the neutron surface region, thereby making up for the integral vanishing of the total charge of the neutron.

We may recall from atomic physics that the quantity e$\hbar$/2m is called *magneton*. For atomic motion we use the electron mass and obtain the Bohr magneton $\mu_{\mathrm{B}} = 5.7884 \times 10^{-5}$ eV/T. Putting in the proton mass we have the nuclear magneton $\mu_{\mathrm{N}} = 3.1525 \times 10^{-8}$ eV/T. Note that $\mu_N \ll \mu_B$ owing to the difference in the masses, thus, under most circumstances atomic magnetism has much larger effects than *nuclear* magnetism. Ordinary magnetic interactions of matter (ferromagnetism, for example) are determined by *atomic magnetism*.

We can write

$$\mu = \mathrm{g}_l l \mu_N, \tag{2.1}$$

where g_l is the *g-factor* associated with the orbital angular momentum l. For protons $g_l = 1$, because neutrons have no electric charge; we can use Eq. (2.1) to describe the orbital motion of neutrons if we put $g_l = 0$. We have thus been considering only the orbital motion of nucleons. Protons and neutrons, like electrons, as above mentioned above also have intrinsic or spin magnetic moments, which have no classical analog but which we write in the same form as Eq (2.1):

$$\mu = g_s s \mu_N, \tag{2.2}$$

where $s = 1/2$ for protons, neutrons and electrons (see Table 2.2). The quantity g_s is known as the spin *g-factor* and is calculated by solving a relativistic quantum mechanics equation (see, also [9]). For free nucleons, the experimental values are far from the expected value for point particles: proton—$g_s = 5.5856912 \pm 0.0000022$ and neutron—$g_s = 3.8260837 \pm 0.0000018$. Table 2.3 gives some representative values of nuclear magnetic dipole moments according [65]. The next non-vanishing moment is the electric quadrupole moment. The *quadrupole moment* eQ of a classical point charge e is of the form $e(3z^2 - r^2)$. If the particle moves with spherical symmetry, then (on the average) $z^2 = x^2 = y^2 = r^2/3$ and the

Table 2.4 Some values of nuclear electric quadrupole moments (after [65])

^{2}H(D)	+ 0.00288
^{17}O	− 0.02578
^{59}Co	+ 0.40
^{63}Cu	− 0.209
^{133}Cs	− 0.003
^{161}Dy	+ 2.4
^{176}Lu	+ 8.0
^{209}Bi	− 0.37

quadrupole moment vanishes (for details, see [8]). Some examples of the values of *nuclear electric quadrupole moments* are presented in Table 2.4.

Inside a nucleus, neutrons and protons interact with each other and are bound within (as mentioned above) the nuclear volume under the competing influences of attractive nuclear and repulsive electromagnetic forces. This binding energy has a direct effect on the mass of an atom. It is therefore not possible to separate a discussion of nuclear binding energy; if it were, then nucleon would have masses given by $Z_{m_p} + Z_{m_n}$ and the subject would hardly be of interest.

As it is well known, in 1905, Einstein presented the equivalence relationship between mass and energy: $E = mc^2$. From this formula, we see that the speed of light c is very large and so even a small mass is equivalent to a large amount of energy. This is why in nuclear physics it is more convenient to use a much smaller unit called *mega electron volt* ($1\ \text{MeV} = 1.602 \times 10^{-13}$ J). On the atomic scale, 1u is equivalent to 931.5 MeV/c^2, which is why energy changes in atoms of a few electron-volt cause insignificant changes in the mass of atom. Nuclear energies, on the other hand, are millions of electron-volts and their effects on atomic mass are easily detectable. For example, the theoretical mass of $^{35}_{17}$Cl is $17 \times 1.00782503 + 18 \times\ 1.00866491 = 35.28899389$ amu. Its measured (see below) mass is only 34.96995 amu. Therefore, the mass defect and binding energy of $^{35}_{17}$Cl are

$$\begin{aligned} &\Delta = 0.32014389\,\text{amu}. \\ &E_B = \tfrac{0.32014389 \times 931.5}{35} = 8.520\ \text{MeV/nucleon} \end{aligned} \tag{2.3}$$

and in common sense the binding energy is determined by next relation

$$E_B = Zm_p + Nm_n - B/c^2, \tag{2.4}$$

where B/c^2 is the actual nuclear mass.

As we can see below, the *binding energy* of the atoms of most elements have values ranging from about 7.5 to 8.8 MeV [2–5]. The binding energy per nucleon rises slightly with increasing mass number and reaches a maximum value for ^{62}Ni. Thereafter the binding energies decline slowly with increasing mass number. The

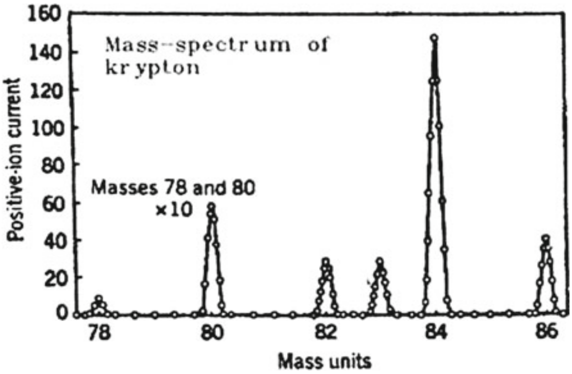


Fig. 2.4 A mass-spectrum analysis of krypton. The ordinates for the peaks at mass positions 78 and 80 should be divided by 10 to show these peaks in their true relation to the others (after [5])

binding energies of the atoms of H, He, Li and Be are lower than the binding energies of the other elements (see, also Fig. 2.5 below).

The measurement of nuclear masses occupies an extremely important place in the development of nuclear physics. Mass spectrometry (see, e.g. [66, 67]) was the first technique of high precision available to the experimenter, and since the mass of a nucleus increases in a regular way with the addition of one proton or neutron. In mass spectrometers, a flux of identical nuclei (ions), accelerated (see, e.g. Fig. 3.13 in [14]) to a certain energy, is directed to a screen (photoplate) where it makes a visible mark. Before striking the screen, this flux passes through magnetic field, which is perpendicular to velocity of the nuclei. As a result, the flux is deflected to certain angle. The greater mass, the smaller is the angle. Thus, measuring the displacement of the mark from the center of the screen, we can find the deflection angle and then calculate the mass. The example of a *mass-spectrum* of a different isotopes of krypton is shown in Fig. 2.4. From the relative areas of the peaks it can be determine the abundance of the stable isotopes of krypton (for details see [65]).

Relative masses of nuclei can also be determined from the results of nuclear reactions or nuclear decay. For example, if a nucleus is *radioactive* and emits an α-*particle*, we know from energy conservation that it mass must be greater than that of decay products by the amount of energy released in the decay. Therefore, if we measure the latter, we can determine either of the initial or final nuclear masses if one of them is unknown. An example of this is presented briefly below. At present we shall illustrate some typical reactions, bridging the gap between "classical" methods and the more advanced "high-energy" types of experiments (see, also [7, 61]).

The possible, natural *decay processes* can also be brought into the class of reaction processes with the conditions: no incoming light particle α and Q > 0. We list them in the following sequence:

α - decay:

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A-4}_{Z-2}\,Y_{N-2} + {}^{4}_{2}\,He_{2}. \tag{2.5}$$

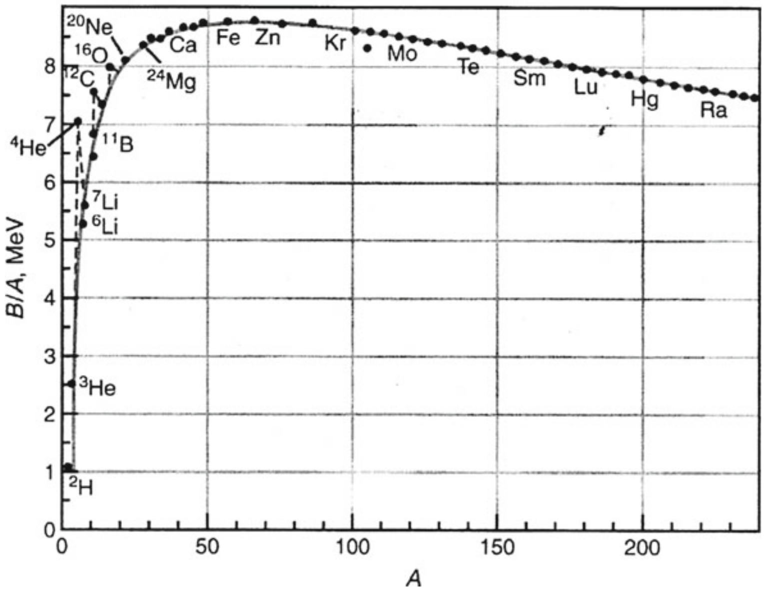


Fig. 2.5 The binding energy per nucleon B/A as a function of the nuclear mass number A (after [41])

β - decay:

$$ {}^{A}_{Z}\mathrm{X}_{N} \rightarrow {}^{A}_{Z-1}\mathrm{Y}_{N+1} + \mathrm{e}^{+} + \nu_e \quad (p \rightarrow n\text{-}type) \tag{2.6}$$

$$ {}^{A}_{Z}\mathrm{X}_{N} \rightarrow {}^{A}_{Z+1}\mathrm{Y}_{N-1} + e^{-} + \overline{\nu}_e \quad (n \rightarrow p\text{-}type) \tag{2.6$'$}$$

$$ {}^{A}_{Z}\mathrm{X}_{N+\mathrm{e}^-} + \mathrm{e}^{-} \rightarrow {}^{A}_{Z-1}\mathrm{Y}_{N+1} + \nu_e \quad (\mathrm{e}^{-}\text{-capture}). \tag{2.6$''$}$$

Here e^{-}, e^{+}, ν_e and $\overline{\nu}_e$ are electron, positron, neutrino and antineutrino.
γ - decay:

$$ {}^{A}_{Z}\mathrm{X}^{*}_{N} \rightarrow {}^{A}_{Z}\,\mathrm{X}_{N} + h\nu. \tag{2.7}$$

Here X* is excited nuclei.
Nuclear fission:

$$ {}^{A}_{Z}\mathrm{X}_{N} \rightarrow {}^{A_1}_{Z_1}\mathrm{Y}_{N_1} + {}^{A_2}_{Z_2}\,\mathrm{U}_{N_2} + x \times n. \tag{2.8}$$

Table 2.5 Masses of electron, nucleons and some nuclei (after [41])

Particle	Number of Protons	Number of Neutrons	Mass (MeV)
e	0	0	0.511
p	1	0	938.2796
n	0	1	939.5731
${}^{2}_{1}H$	1	1	1876.14
${}^{3}_{1}H$	1	2	2808.920
${}^{3}_{2}He$	2	1	2808.391
${}^{4}_{2}He$	2	2	3728.44
${}^{7}_{3}Li$	3	4	6533.832
${}^{9}_{4}Be$	4	5	8392.748
${}^{12}_{6}C$	6	6	11174.860
${}^{16}_{8}O$	8	8	14895.077
${}^{238}_{92}U$	92	146	221695.831

Since mass and energy are equivalent (see Einstein formula above), in nuclear physics it is customary to measure masses of all particles in the units of energy (MeV). Examples of masses of subatomic particles are given in Table 2.5.

As it was noted above, nuclear binding energy increases with the total number of nucleons A and, therefore, it is common to quote the average *binding energy* per nucleon (B/A) The variation of B/A with A is shown in Fig. 2.5. Several remarkable features are immediately apparent. First of all, the curve is relatively constant except for the very light nuclei. The average binding energy of most nuclei is, to within 10%, about 8 MeV per nucleon. Second, we note that the curve reaches peak near $A = 60$, where the nuclei are most tightly bound and light and very heavy nuclei contain less bound nucleons. Thus, the source of energy production in fusion of light nuclei or fission of very heavy nuclei can be a source of energy [13, 14].

While concluding this paragraph we should remember that it is often stated ${}^{56}Fe$ is the most tightly bound nucleus, but this is not correct since ^{62} Ni is more bound by a difference of 0.005 MeV/nucleon (for details see [68, 69] and references therein). In conclusion, it is very interesting to note that one cubic millimeter of *nuclear material*, if compressed together, would have a mass around 200,000 tonnes. *Neutron stars* are composed of such material.

As shown above nuclei vary from about one to a few fermis in radius. Recall that the Bohr radius of hydrogen is in the order 10^{-10} meters , so the nucleus at present time, despite its small size the nucleus has about, as was noted above, 99.9% of the mass of the atom (see, also [2, 3]). Electron scattering off nuclei is, for example, one of the most appropriate methods to deduce radii. The results of this procedure for several different nuclei are shown in Fig. 2.6. One remarkable conclusion is obvious—the central nuclear charge density is nearly the same for all nuclei. *Nucleons* do not congregate near the center of the nucleus, but instead have a fairly constant distribution out to the surface. The conclusion from measurements of the nuclear matter distribution is the same [70, 71]. Under this assumptions of saturation and

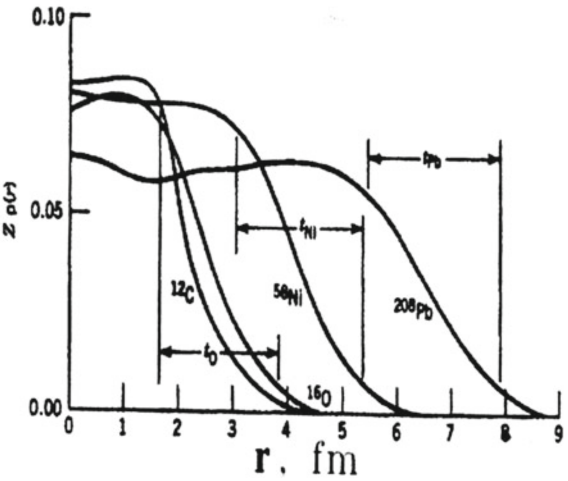


Fig. 2.6 The radial charge distribution of several nuclei determined from electron scattering. The skin thickness value t is roughly constant at 2.3 fm. The central density changes very little from the lightest nuclei to the heaviest (after [70, 71])

charge independence each nucleon occupies an almost equal size within the nucleus. Calling r_0 an elementary radius for a nucleon in the nucleus, a most naive estimate gives for the nuclear volume

$$\mathrm{V} = 4/3\pi r_0^3 \mathrm{A} \tag{2.9}$$

or

$$\mathrm{R} = r_0 \mathrm{A}^{1/3}. \tag{2.10}$$

This relation describes the variation of the nuclear radius, with value of $r_0 \simeq 1.2$ fm when deducing a "charge" radius and a "value of $r_0 \simeq 1.4$ fm for the full matter" radius (see also Figs. 3.5 and 3.9 in [5]). In a simple way the nuclear radius is defined as the distance at which the effect of the nuclear potential is comparable to that of the Coulomb's potential (see Fig. 2.7).

We should indicate another way to determine the nuclear charge radius from direct measurement of the Coulomb's energy differences of nuclei. Consider, for example, ${}^3_1\mathrm{H}_2$ and ${}^3_2\mathrm{He}_1$. To get from ${}^3\mathrm{He}_1$ to ${}^3\mathrm{H}_1$ we must change a proton into a neutron. As we know, there is strong a evidence which suggests that the nuclear force does not distinguish between protons and neutrons. Changing proton into a neutron should therefore not affect the nuclear energy of the three nucleon system: only the Coulomb's energy should change, because the two protons in ${}^3\mathrm{He}_1$ expexperience a repulsion that is not present in ^{3}H. The energy difference between ^{3}He and ^{3}H is thus a measure of the Coulomb's energy of the second proton, and the usual formula for the Coulomb's repulsion energy can be used to calculate the distance between the protons and thus the size of the nucleus.

The interactions between two nucleons (NN) is one of the central questions in physics and its importance goes beyond the properties of nuclei. Nucleons can combine to make four different few-nucleon systems, the deuteron $(p + n)$, the triton

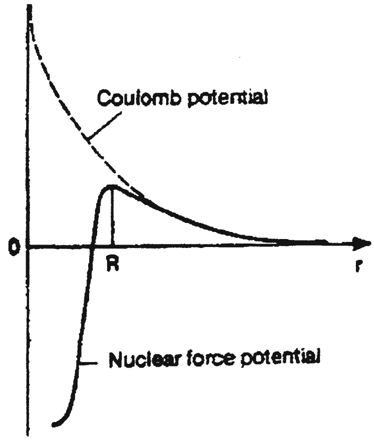


Fig. 2.7 Coulomb's potential used for defining the nuclear radius R

$(p + 2n)$, the helion $(2p + n)$ and the α-particle $(2p + 2n)$ (see, e.g. [72–75]). These particles are grouped together because they are stable (excluding from the radioactive triton which has a half-life of about 12 years and so may be treated as a stable entity for most practical purpose), have no bound excited states (except the α-particles which has two excited states at about 20 and 22 MeV) and are frequently used as projectiles in nuclear investigations. The absence of stable particles of mass of five provides a natural boundary between few-nucleon systems and heavier nuclei [38–40, 74]. Few nucleon systems provide the simplest systems to study nuclear structure. The *deuteron* provides important information about the nucleon–nucleon interaction.

Even before describing any further experimental and theoretical results to study the force between two nucleons, we can already guess at a few of the properties of the N–N force:

1. At short distances it is stronger than the *Coulomb's force*; the nuclear force can overcome the Coulomb's repulsion (see also Fig. 2.7) of protons in the nucleus.
2. At long distances, of the order of atomic sizes, the nuclear force is negligibly feeble. The interaction among nuclei in a molecule can be understood based only on the Coulomb's force.
3. Some fundamental particles are immune from the nuclear force. At present time we have not any evidence from atomic structure, for example, that electrons feel the nuclear force at all.
4. The N–N force seems to be nearly independent of whether the nucleons are neutrons or protons. As is well known this property is called *charge independence*.
5. The N–N force depends on whether the spins of the nucleons are parallel or antiparallel.
6. The N–N force includes a repulsive term, which keeps the nucleons at a certain average separation.