Chapter 1
Introduction: The World According to Physics

Ah, but a man's reach should exceed his grasp.
Or what's a heaven for?

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Abstract In this introductory chapter the subject matter as well as the methodology of Physics are briefly presented together with a list of the basic equilibrium structures of matter. The main properties of the latter can be obtained by minimizing the internal energy and are expressed in terms of universal physical constants $\hbar, c, e, m_e, m_p \approx m_n \approx u, G$.

1.1 The Nature of Physics

Modern-era Physics started as Natural Philosophy. As this former name implies, Physics is built (and continues to be developed) around the age-old, yet ever-present questions:

- *What the World and its parts are made of*? *How*?
- *Is there a hidden underlying simplicity in its immense complexity and diversity*?

The first question implies that the subject matter of Physics is the World, both natural and man-made; from its smallest constituent to the whole Universe. In this sense, Physics tends to encompass the other natural sciences (such as Chemistry and Biology) and even Engineering, while at the same time serves also as their foundation. What allows Physics to have this foundational role is its characteristic methodology. The latter is precise and quantitative, yet capable of abstraction (therefore mathematical). It is based on observations and well controlled experiments both as sources of ideas as well as tests for falsification or tentative confirmations of newly proposed and –even– established theories. Moreover, as the second question suggests, the methodology of physics requires the formulation of a few fundamental quantitative relations on which everything else is based. These features of the methodology of Physics account for its role as the foundation of

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every other science and engineering, but explain also its limited penetration into very complex, yet very important, parts of the World (such as the molecular and the biological structures). This leaves plenty of space to more specialized sciences such as Chemistry and Biology and, of course, Engineering.

Over the last 50 years or so Physics is actively concerned over another fundamental, age-old, but much more difficult question which stretches its methodology to the limit:

- *How did the World start, how did it evolve, and where is it going*?

Detailed observational data, such as the recession of distant galaxies at a speed proportional to their distance from Earth, the spectral and angular distribution of the Cosmic Microwave Background Radiation, etc, combined with established physical theories, allowed us to reconstruct roughly some of the main events in the history of the Universe. Naturally, other crucial events, including the emergence of life, remain unknown and they are the subject of on-going research. Subject to current theoretical research is also the development of a successful quantum theory of gravity, which is expected to let us describe in a concise manner the very moment of the genesis of the Universe.

1.2 The Subject Matter of Physics

The subject matter of Physics is summarized in Fig. 1.1 and Table 1.1:

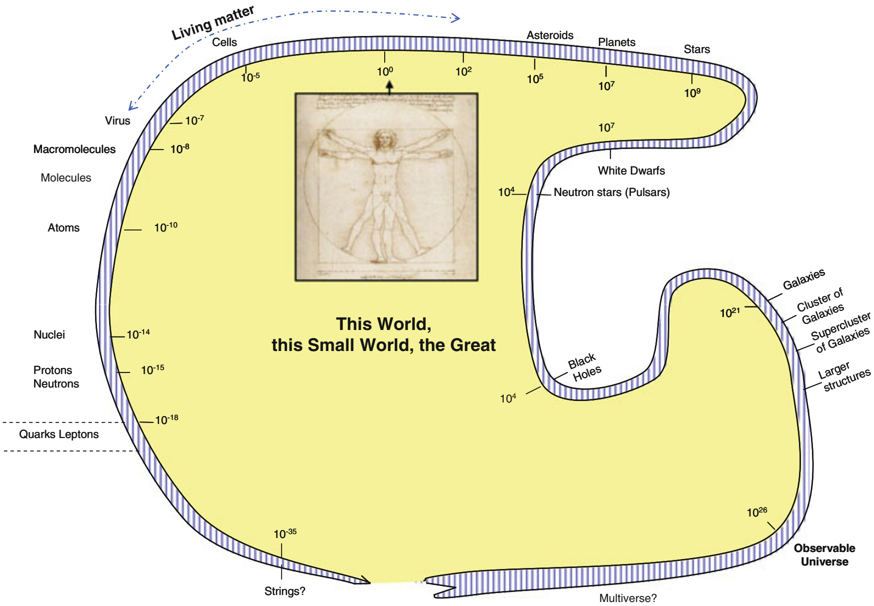

Fig. 1.1 The main structures of matter from the smallest to the largest size (*clockwise*) and the suspected connection of the two extremes (see [1]). The indicated sizes are in meters (see also next page)

Table 1.1 Levels of the structure of matter (see also [2])

Level of the structure of matter	Size (in m)	Constituents	Interaction(s) responsible for the structure
Quarks	$<10^{-18}$	It seems to be elementary	–
Electron	$<10^{-18}$	It seems to be elementary	–
Proton	10^{-15}	u, u, d quarks	Strong, weak, E/M
Neutron	10^{-15}	u, d, d quarks	Strong, weak, E/M
Nuclei	10^{-15}–10^{-14}	Protons, neutrons	Strong, E/M, weak
Atoms	10^{-10}	Nucleus, electrons	E/M
Molecules	$>10^{-10}$	Atoms and/or ions and electrons	E/M
Solids (primitive cell)	$>10^{-10}$	Atoms and/or ions and electrons	E/M
Cells	$\geq 10^{-6}$	Molecules	E/M
Biological entities (e.g., *Homo sapiens*)	10^{-8}–10^{2} (10^{0})	Molecules, cells, tissues, organs, microbes	E/M
Planets	10^{6}–10^{7}	Solids, liquids, gases	E/M, gravitational
Stars, Sun	10^{8}–10^{12},10^{9}	Electrons, nuclei, ions, photons	Gravitational, strong, weak, E/M
White dwarfs	10^{7}	Nuclei, electrons	Gravitational
Neutron stars	10^{4}	Neutrons and some protons and electrons	Gravitational
Astrophysical black holes	10^{4}	?	Gravitational
Galaxies	10^{21}	Stars, ordinary and dark matter, photons, neutrinos	Gravitational
Observable universe	10^{26}	Galaxies, dust, dark matter, dark energy	Gravitational, others?

1.3 Various Branches of Physics

In concluding these introductory remarks regarding the subject matter of Physics, we present below some of the various branches of Physics and their correspondence and/or overlap with more specialized sciences as well as some examples of the impact of Physics on important technologies (Table 1.2):

Table 1.2 Connection of branches of Physics with Technologies and other Sciences and Mathematics

Mathematics	Elementary particle physics Nuclear physics Atomic and molecular physics Condensed matter physics	Chemistry, material science
	Biophysics	Biology
	Geophysics	Geology
	Atmospheric and space physics	Meteorology, global climate
	Astrophysics, cosmology	Astronomy
Technology	E/M waves, lasers	Telecommunications
	Solid state devices Integrated circuits Magnetic devices	Computers
	X-rays γ-rays Magnetic resonance (MRI) Positron annihilation (PET)	Medical technologies

1.4 The Main Points of This Book: Basic Ideas Applied to Equilibrium Structures of Matter[1]

1. Out of the elementary matter-particles presented in Chapter 2, Table 2.1 only the *up quark* (u) and the *down quark* (d) make up the proton consisting of two u's and one d and the neutron consisting of two d's and one u. *Electrons* (e^-) are trapped around nuclei, made of protons and neutrons, to form atoms.
2. The constituents of all composite equilibrium structures are mutually attracted and self-trapped because of one or more of the four interactions presented in Table 2.2.
3. The interactions, which tend to continuously squeeze the composite structures, are counterbalanced by the pressure due to the perpetual motion of the constituents microscopic particles. This motion is of quantum nature and stems from the uncertainty principle aided by the exclusion principle (if more than two fermions (see Sect. 3.3) are involved). In other words, equilibrium of composite systems is established when the squeezing pressure of the interactions is exactly balanced by the expanding pressure of the quantum perpetual motion of the constituent particles. The equality of pressures is a consequence of the general principle of the minimization of the internal energy U (under conditions of negligible external pressure and temperature). Thus:

[1]Section 1.4 summarizes the content of this book. It may be useful for the reader to return to this section at later times.

Equilibrium of composite structures ⇔ Minimum of internal energy U. Internal energy U = Internal potential energy E_P + internal kinetic energy E_K. Internal quantum kinetic energy of N identical fermions:

$$\boxed{E_K = 2.87\frac{\hbar^2 N^{5/3}}{m\,V^{2/3}} = 1.105\frac{\hbar^2 N^{5/3}}{m\,R^2}\ \text{ non-relativistic}}$$

Internal quantum kinetic energy of N identical fermions:

$$\boxed{E_K = 2.32\frac{\hbar\,c\,N^{4/3}}{V^{1/3}} = 1.44\frac{\hbar\,c\,N^{4/3}}{R}\ \text{ extreme-relativistic}}$$

4. The combination of the first and the second law of thermodynamics leads to the following relation: The so-called Gibbs free energy, $G \equiv U + PV - TS$, under conditions of constant pressure and temperature, is always decreasing during the system's path towards equilibrium and reaches its minimum value when equilibrium is established. G reduces to U when PV and TS are negligible.
5. Dimensional analysis is a powerful method for producing physics formulae. It requires the identification of the parameters and/or the universal physical constants on which a quantity X may depend. Then the formula for X is a product (with the same dimensions as X) of appropriate powers of usually three of those parameters/physical constants times a function of their dimensionless combinations.

Next, we apply the general principles presented above to several basic equilibrium structures; the main properties of them are expressed in terms of universal physical constants.

(i) *Nuclei* consist of Z protons and N neutrons, i.e. of $A = Z + N$ nucleons. Both the strong interactions and the Coulomb interactions contribute to the potential energy: $E_P = -\frac{1}{2}AN_{nn}\mathcal{V}_s + \frac{1}{2}\sum_{ij} e^2/r_{ij}$, where N_{nn} is the number of nearest neighbors of a nucleon, $-\mathcal{V}_s$ is the strong interaction between a pair of nearest neighbor nucleons and the double summation in the Coulomb term is over all Z protons. The nuclei's radius R is proportional to the 1/3 power of A and the kinetic energy is the sum of the kinetic energy of the protons and that of the neutrons

$$E_K = 1.105\frac{\hbar^2 Z^{5/3}}{m_p\,R^2} + 1.105\frac{\hbar^2 N^{5/3}}{m_n\,R^2}$$

(ii) *Atoms* consist of a single nucleus (of Z protons) and Z electrons trapped around it by Coulomb interactions: $E_P = -\sum_i Ze^2/r_i + \frac{1}{2}\sum_{ij} e^2/r_{ij}$. The ground state energy of the electrons is found approximately by calculating the single electron atomic orbitals (see Sect. 10.3) and the corresponding energy levels; the lower ones of the latter are fully populated by the electrons, within the restrictions imposed by Pauli's principle, starting from that of lowest energy until all Z electrons are exhausted.

(iii) *Molecules* are consisting of atoms (or cations and anions) of practically unlimited combinations held together by Coulomb interactions. The molecular orbitals are approximately expressed as linear combinations of atomic orbitals or hybridized atomic orbitals.

(iv) In *solids* and *liquids* a huge number of atoms and/or molecules are coming in contact under the action of Coulomb interactions. In metals the main kinetic energy is that of *detached* electrons given approximately by $E_K = 2.87\frac{\hbar^2 N_e^{5/3}}{m_e V^{2/3}}$, while the potential energy is of Coulomb nature and of the form $E_P = -N_a E_o \gamma/\bar{r}$, where N_a is the total number of atoms, $E_o = e^2/a_B$, $a_B \equiv \hbar^2/m_e e^2$ is the so-called Bohr radius, $\bar{r}$ is connected to the volume by the relation $\frac{4\pi}{3}(\bar{r}\, a_B)^3 = (V/N_a)$, $\gamma \approx 0.56\zeta^{4/3} + 0.9\zeta^2$, and ζ is the valence. For semiconductors and insulators, as for molecules, a linear combination of atomic (hybridized or not) orbitals turns out to be a more convenient way of studying them.

(v) *Planets* are spherical objects of mass $M = N_v u$ and radius R, where $N_v = A_W N_a \approx 10^{49}$–$10^{55}$ is the total number of nucleons within all nuclei, A_W is the average atomic weight, and $u \equiv \frac{1}{12} m(C^{12})$. In planets both the Coulomb interaction as well as the gravitational one, $E_G = -a_G G M^2/R$, contribute to the potential energy, while the kinetic energy is due mainly to the electrons as in solids and liquids. The spherical shape of moons, planets and stars is a consequence of the long range character of the gravitational interaction which becomes appreciable as a result of the huge mass involved.

(vi) Dead stars are of three types: *White dwarfs* $(M < 1.4 M_S)$, *Neutron stars* $(1.4 M_S \leq M < 3 M_S)$, and *Black Holes* $(3 M_S < M)$, where M_S is the present mass of the Sun. White dwarfs have a radius comparable to that of Earth, i.e. about 100 times smaller than that of their typical previous phase as active stars. Because of this large compression all electrons have been detached from the parent atoms; thus the white dwarf consists of electrons and bare nuclei. The kinetic energy is mainly that of electrons, as in the case of metals, and the potential energy is the gravitational one. Minimization of the total energy gives the radius as a function of the mass: $R = 1.42\frac{\hbar^2}{G u^2 m_e N_v^{1/3}}$, $M = N_v u$. If the mass of the white dwarf keeps increasing, the kinetic energy of the electrons tends to the extreme relativistic limit which is of the form A/R, i.e. similar to the gravitational one, $-B/R$. Thus when $B \geq A$ the white dwarf will collapse to a neutron star. Hence, the equality $B = A$ gives the collapse critical value, which is $N_{v,cr1} = 0.77\left(\frac{\hbar c}{G u^2}\right)^{3/2}$ corresponding to $1.4 M_S$. After the collapse, the electrons will be forced within the nuclei, which in turn lose their identity; thus a neutron star consists mainly of neutrons $(N_n \approx 0.934 N_v)$ and of a small percentage of protons and electrons $(N_p = N_e \approx 0.066 N_v)$. The potential energy in a neutron star is that of gravity as given before. The kinetic energy is mainly that of neutrons and to a very small degree that of protons (both of which are non-relativistic) plus that of electrons (which is extreme relativistic). Minimizing the total energy with respect to R we obtain, $R = 3.16\left(\frac{\hbar^2}{G m_n^3 N_v^{1/3}}\right) \approx 10\,\text{km}$. This radius is smaller than that of a white dwarf by a factor of the order of $m_e/m_n \approx 10^{-3}$. As the mass of a neutron star increases the kinetic energy of both the neutrons and the protons tends to become extreme relativistic, i.e. of the form again A/R. Thus, when $A = B$ the neutron star will collapse to a black hole. The condition $A = B$ gives now $N_{vcr2} \approx 1.6\left(\frac{\hbar c}{G m_n^2}\right)^{3/2}$ which corresponds to about $3M_S$.

Both the minimum and the maximum mass of *active stars* can be expressed in terms of physical constants: $N_{v,\min} \approx 0.2\left(\frac{u}{m_e}\right)^{3/4}\left(\frac{e^2}{G u^2}\right)^{3/2}$, $N_{v,\max} \approx 100\left(\frac{\hbar c}{G u^2}\right)^{3/2}$.

The *Universe*, according to observational data as well as the general theory of relativity, is expanding in the sense that the distance R between two distant points is increasing at a rate $\dot{R}$ proportional to R, $\dot{R}/R = H$, where H is the so-called Hubble constant. The basic equation obeyed by the ratio $\dot{R}/R$ is the following: $\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}\frac{G\varepsilon}{c^2}$, where ε, the total average energy density of the Universe, consists of several contributions: $\varepsilon = \varepsilon_{ph} + \varepsilon_v + \varepsilon_b + \varepsilon_{dm} + \varepsilon_{de}$. The first term refers to photons (proportional to $1/R^4$), the second to neutrinos, the third to baryons (proportional to $1/R^3$), the fourth to dark matter (proportional to $1/R^3$), and the fifth one to the dark energy (which seems to be a constant independent of R).

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