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Universe, Matter, Condensed Matter and Materials

It is an accepted fact that our world is made of matter, a kind of objective existence (reality) independent of our consciousness; in this sense, both space and time are some kind of matter. Our world can also be called the universe, thus describing the coupling of space and time. What we call “space” is a three-dimensional sub-entity (leading to the real world in which we are living) of a larger four-dimensional entity that includes time. In this sense, space and time are two aspects of matter that cannot be separated. Depending on which generalized definition of matter (in the sense of a kind of existence) we use, consciousness or our thoughts can also be considered a form of matter. The final goal of our scientific analysis is to reveal how matter is formed – what sort of micro-, macro-, and cosmological structure it preserves, which intrinsic features these different sorts of matter exhibit, and which relationships exist between them. We need to pay close attention to the difference between time and space on one hand and their respective concepts on the other hand. The latter are the reflection of real time and space in people’s minds, which is subjective. In addition, there is a conceptional difference between matter and materials with materials being one important type of matter. Materials are specific manifestations of matter that can be used or controlled by humans and can be physically touched or characterized.

Generally speaking, our three-dimensional space is filled with matter, and this matter exists in space while depending on the time coordinate of the larger four-dimensional space (or the temporal-spatial unity and consistency). If you are interested in the deeper features of time and space, please refer to the inspiring books by Hawking and Gamow et al. [1, 2]. We will not discuss the involved concepts in depth since out focus in this book is simply condensed matter – materials. It is well-known that there are three commonly occurring phases of matter: the solid phase, the liquid phase and the gas phase. There is also an additional phase of matter, however, the plasma, which constitutes a special type of gas phase that is also often mentioned in books. The term condensed matter is commonly used to jointly describe solid and liquid phases. In addition, when we talk of materials in physical science we typically think of substances that can be and are utilized practically by humans.

Characterization of Condensed Matter: An Introduction to Composition, Microstructure, and Surface Methods, First Edition. Yujun Song and Qingwei Liao.

1.1 Features of the Universe and Fundamental Constants

One of the well-accepted facts in our scientific view of nature is that the whole universe and the matter in it are originated from the so-called Big Bang, an initial singularity of space and time, as shown in Figure 1.1. Since then, the universe has evolved (for about 13.8 billion years – up to now), in the course developing all existing matter, experiencing quantum fluctuations, inflation, the afterglow light pattern at 380 000 years, dark ages, the formation of the first star (such as our sun) after about 400 million years, the development of galaxies (such as our Milky Way or the Andromeda Nebula), planets (such as Earth or Jupiter) and their satellites (moons), and many more objects (such as, e.g., neuron stars or black holes) [3]. A black hole is a region in space where gravity is so strong that nothing – not even light! – can escape, a fact that can be deducted indirectly by detecting the super-high temperature, and large amount of γ-ray and/or X-ray radiation emitted by the black hole as it devours the matter around it [4].

The information depicted in Figure 1.1 has been collected by the Wilkinson Microwave Anisotropy Probe (WMAP), a NASA Explorer mission launched in June 2001 to perform fundamental cosmological measurements (cosmology describes the study of the universe's properties as a whole). WMAP has proven stunningly successful and played a major role in establishing the so-called Standard Model of Cosmology. The detailed all-sky picture of the infant universe created from nine years of WMAP data as shown in Figure 1.1 reveals 13.8-billion-year-old temperature fluctuations (shown as color differences) that correspond to the seeds that evolved to finally become the galaxies. The temperature range displayed in this image encompasses $\pm 200\,\mu K$.

We can even image what happened during the long evolution history of our universe. The first beam appeared about 13.8 billion years ago, our Sun was born about 4.57 billion years ago, and finally our Earth was formed about 4.57 billion years before today. First life forms appeared on Earth about 3.6 billion years ago. Anomalocaris (a Cambrian species of shrimp, Figure 1.2) evolved their eyes and became the

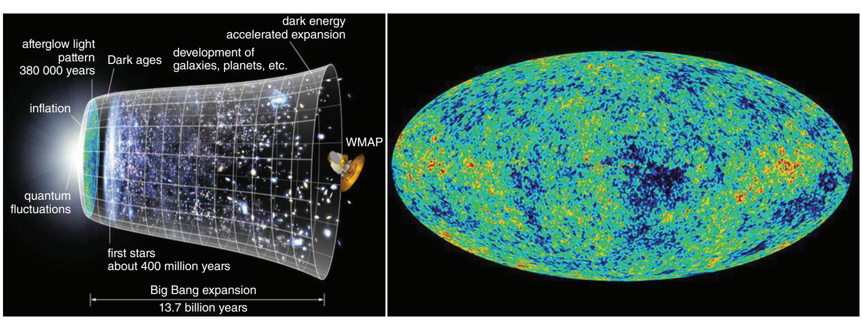


Figure 1.1 Start and evolution of our universe since the Big Bang singularity. WMAP: Wilkinson Microwave Anisotropy Probe. Source: NASA/Wilkinson Microwave Anisotropy Probe (WMAP) Science Team. http://map.gsfc.nasa.gov/ [5].

Figure 1.2 Artistic illustration of Anomalocaris – the first species in the ancient ocean to perceive the light that already existed since the Big Bang about 10 billion years earlier. Source: CHATCHAI/Adobe Stock Photos.

first species to see the light that had been around for about 10 billion years. Finally, ancient man finished the evolution from Australopithecine about 7 million years ago, starting the development of human society and the related science and technology that helps us to explore the magic universe that has already been existing for 13.8 billion years.

If we strive to understand the features of the universe we have to take into account two interactions related to matter: the first is the interaction between matter and electromagnetic waves and the second is the interaction between matter and fundamental particles. However, there are at present still two main problems with our understanding of matter: the first is antimatter and the second is dark matter and dark energy. These prove difficult to be studied by the above two methods.

In 1928, British physicist Paul Dirac wrote down an equation that combined quantum theory and special relativity to describe the behavior of an electron moving at a relativistic speed. The equation – which won Dirac the Nobel Prize in 1933 – posed a problem: Just as the equation $x^2 = 4$ has two possible solutions ($x = 2$ or $x = -2$), Dirac's equation had two solutions, one for an electron with positive energy and one for an electron with negative energy. But classical physics (and common sense) dictates that the energy of a particle must always be positive. To solve this apparent contradiction, Dirac interpreted his equation to mean that for every particle there exists a corresponding "antiparticle", exactly matching the particle but with opposite charge. For example, for the electron there should be an "antielectron" (also called "positron"), identical in every way but with a positive electric charge. The fact that one of the solutions of his equations described the exact opposite of the particle that it was designed to describe might have been brushed aside as a mere curiosity. But it wasn't. Instead, Dirac interpreted it as a description of antimatter – and, four years later (in 1932), this antimatter in fact turned up in a real-life experiment as the antielectron (or a positively charged electron) was discovered. In the 1950s, with the subsequent discovery of the antiproton and the antineutron, researchers realized that any particle might have its corresponding antiparticle in the universe. Since then, antimatter – first, antielectrons, known as positrons, and then anti-versions of all other particles of matter – has become a staple of both real science and its fictional counterparts [6].

What has until recently not been available for study, however, were entire antiatoms. Many research facilities were built to synthesize atomic antimatter such as the anti-version of the simplest atom, hydrogen. However, since the prediction and discovery of the positron and the antiproton, atomic antimatter has neither been observed nor synthesized in a laboratory for about three generations. Finally, in January 1996, the European Center for Nuclear Research (CERN) in Geneva announced that its researchers had created a total of 11 antihydrogen atoms by using CERN's Low-Energy Antiproton Ring (LEAR). Physicists are intensely excited at the prospect of being able to study this entirely new atom, because it will provide a fundamental test for their understanding of nature. At CERN, physicists produce antimatter with the aim of studying it in experiments. The starting point is the Antiproton Decelerator (AD), which slows antiprotons down so that physicists can investigate their properties.

In the meanwhile, a sizeable number of them have been produced in various laboratories, and even held on to for a few seconds. But for a long time, none of them existed long enough to be examined in detail because, famously, antimatter and matter annihilate each other on contact. That has now changed, with the preservation of several hundred of these atoms over periods of several minutes achieved by Jeffrey Hangst and his colleagues at CERN. The reason why this is so important is the fact that Dirac's equation is misleading. Antimatter cannot be the perfect opposite of matter because if this was the case, neither would exist at all. If they truly were perfect opposites, equal amounts of both would have been created in the Big Bang, and they would have annihilated each other long since, leaving only light and other forms of electromagnetic radiation to fill the universe. That galaxies, stars, and planets – and physicists to ponder such questions – do exist means that there must be a subtle asymmetry between matter and antimatter, and that nature for some strange reason favors the former. Two such asymmetries have indeed been found, but neither is big enough to explain why so much matter has survived. Being able to look at entire antiatoms might give us some further clue in the future. In November 2012, the ALPHA collaboration at CERN managed to place positrons into orbits around 38 antiprotons, thus creating antihydrogen atoms, and then kept them in magnetic traps for a few tenths of a second [7, 8]. In the meanwhile, as they report in Nature Physics, the researchers have been able to use their device to preserve antihydrogen for 16 minutes (which really means eons as far as atomic physics is concerned) [9]. This gives the antiatoms plenty of time to settle into their ground states, the most stable condition a particle or atom can attain. As a result, the scientists can study in much more detail than before in what ways antimatter might differ from its common counterpart. Their first experiment will involve nudging the trapped antiatoms with microwaves. If the frequency of these microwaves is just right, they will flip an antiatom's spin, thus reversing the polarity of the atom's magnetic field and ejecting it from the trap. The frequency needed to do this can then be compared with the one that flips the spin of an ordinary hydrogen atom. If both turn out to be different, this will provide a hint toward the nature of the mysterious cosmic asymmetry. Besides being of huge intellectual interest (it would, after all, provide a legitimate answer to the question "why are we here?"), such a result would also have a pleasing symmetry of its own. The original discovery of antimatter was a nice example of theory predicting a hitherto undiscovered fact. If the experiment would turn out as speculated, this would repay the compliment by predicting an undiscovered theory. This insight would open the possibility of entire galaxies and universes made of antimatter. But when matter and antimatter come into contact, they annihilate – disappearing in a flash of energy, whose energy release would be much more intensive than that of the hydrogen bomb. The Big Bang ought to have created equal amounts of matter and antimatter. Therefore, the fact that there is far more matter than antimatter in the universe still is a mystery.

Furthermore, scientists have also discovered that the gravitational force exhibited by the matter in some galaxy clusters exceeds that deduced from electromagnetic (EM) methods since the 1930s. Astrophysicists therefore concluded that there should exist a significant amount of matter apart from that detected by EM methods, i.e. a form of matter that does not couple to EM waves. Since this form of matter does not radiate light (or any form of electromagnetic waves), it is called dark matter or dark energy. Currently, it is assumed that our universe experiences accelerated expansion mainly due to dark energy and dark matter.

The current state of our knowledge regarding the matter density (Ω_m), the vacuum energy density or cosmological constant (Ω_Λ), the Hubble constant (H_0), and the ages of the oldest measured objects (t_0) has been summarized by Wendy L. Freeman from Carnegie Observatories [10]. Three independent types of methods for measuring the Hubble constant are considered: the measurement of time delays in multiply imaged quasars, the Sunyaev–Zel'dovich effect in clusters, and Cepheid-based extragalactic distances. Many recent independent dynamical measurements are yielding a low value for the matter density ($\Omega_\mathrm{m} = 0.2$–0.3). A wide range of Hubble constant measurements appear to be converging in the range of 60–80 km s^{-1} Mpc^{-1}.

In the context of the general theory of relativity and assumptions regarding large-scale homogeneity and isotropy, the dynamical evolution of the universe is specified by the Friedmann equation

$$H^2 = \frac{8\pi G\rho_m}{3} - \frac{k}{a^2} + \frac{\Lambda}{3} \tag{1.1}$$

where $a(t)$ is a scale factor, $H = \dot{a}/a$ is the Hubble parameter, G is the gravitational constant, ρ_m is the average mass density, k is a curvature term, and Λ is the cosmological constant, a term that represents the energy density of the vacuum. It is common practice to define the matter density ($\Omega_\mathrm{m} = 8\pi G\rho_\mathrm{m}/3{H_0}^2$, where H_0 is the Hubble constant of the present epoch), the vacuum energy density ($\Omega_\Lambda = \Lambda/3{H_0}^2$), and the curvature term ($\Omega_k = 2k/{a_0}^2{H_0}^2$). For the case of a flat universe where $k = 0$, $\Omega_\mathrm{m} + \Omega_\Lambda = 1$. The simplest case is the Einstein–de Sitter model with $\Omega_\mathrm{m} = 1$ and $\Omega_\Lambda = 0$.

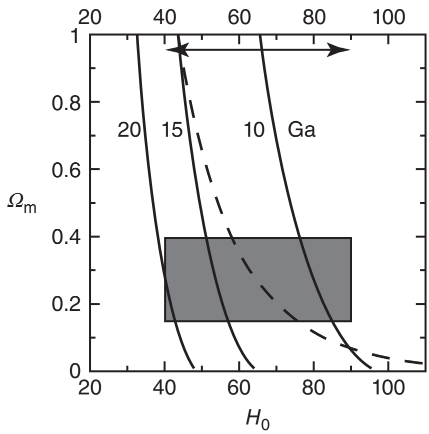


Figure 1.3 Graph of Ω_m versus H_0 showing current observational limits on cosmological parameters. Solid lines denote expansion ages for an open ($\Omega_\Lambda = 0$) universe, the dashed line indicates an expansion age of 15 Ga in the case of a flat ($\Omega_\Lambda \neq 0$) universe [10].

Figure 1.3 summarizes bounds on several cosmological parameters in the form of a plot of the matter density as a function of the Hubble constant, following Carroll et al. [11]. Solid lines represent the expansion ages for 10, 15, and 20 billion years (Ga) in an open ($\Lambda = 0$) model. The gray box is defined by values of H_0 in the range of 40–90 km s^{-1} Mpc^{-1} (1 Megaparsec = 3.09×10^{22} m) and $0.15 < \Omega_m < 0.4$. The solid arrow denotes the same range in H_0 for $\Omega_m = 1$. This plot illustrates the well-known 'age' problem that for an Einstein–de Sitter Universe ($\Omega = 1$, $\Lambda = 0$), H_0 must be less than ≈45 km s^{-1} Mpc^{-1} if the ages (t_0) of globular clusters are indeed ≈15 Ga. This discrepancy is less severe if the matter density of the universe is less than the critical density or if a nonzero value of the cosmological constant is allowed. For example, the broken line indicates an expansion age of 15 Ga in the case of a flat ($\Omega_m + \Omega_\Lambda = 1$) model for $\Lambda = 0$. As discussed, many dynamical estimates of the mass over a wide range of scale sizes are currently favoring values of $\Omega_m \approx 0.10$–0.25, lower than the critical Einstein–de Sitter density ($\Omega_m = 1$). The cosmological constant Λ was deduced to be nonzero, but of the order of 10^{-120}.

In 1915, Albert Einstein proposed a series of gravitational field equations in his general theory of relativity. His equations indicated that the universe should be continuously expanding, which was contrary to the then established view that the universe is stationary. In order to have his equations predict a stationary universe, Einstein arbitrarily introduced a specific constant, known today as the cosmological constant Λ. Much later, the Hubble Space Telescope (HST) discovered that the Universe is indeed expanding, consistent with the result from Einstein's equations without the cosmological constant. Einstein felt remorse after he learned that the universe was expanding and called the introduction of the cosmological constant the biggest fault of his life. Consequently, the cosmological constant fell (mostly) into oblivion. Recent observations suggest that the universe expands not at a constant, but at an accelerating rate, which indicates that there should be some as yet undiscovered "giant matter" in the universe [12]. Today, the cosmological constant is associated with the so-called "dark energy" – it is in fact the mathematical description of the dark energy in vacuum. This mysterious energy leads to the accelerated expansion of the universe, which turns out to be much faster than expected [13].

1.2 Structure and Composition of Matter

1.2.1 Classification and Characteristics of Matter (Radiation Coupling and Energy Conservation)

According to our current knowledge on cosmology and the above description of our universe, matter and its occurrence in the universe can be summarized as in Figure 1.4. All matter in the universe is either matter or antimatter. If matter meets antimatter, they annihilate to energy that is emitted as radiation. Only about 4% of all matter in the universe can be directly observed by EM waves (the most common characterization method), and this is called bright (or ordinary) matter. It has the following features: (i) Infinite compressibility and coupling with radiation; (ii) Conservation of mass and energy following Eq. (1.1) (where $\hat{E}$ denotes generalized energy, Δm mass change, and c the velocity of light) and Eq. (1.1) (where $\boldsymbol{v}$ denotes the velocity vectors of moving matter, ΔL the spatial distance change, and Δt the corresponding time change); (iii) Infinite divisibility, which may be still possible according to discoveries in high-energy physics. Overall, our universe consists of about 25% dark matter and about 71% dark energy that cannot be detected directly by EM waves – the remaining 4% comprise the ordinary "bright" matter we all know. The common feature of dark matter and dark energy is their omnipresence and their decoupling from EM radiation.

$$\hat{E} = \Delta mc^2 \tag{1.2}$$

$$\boldsymbol{v} = \frac{\Delta L}{\Delta t} \tag{1.3}$$

Matter can be further classified as condensed matter, fields, gas/free-ion/plasmonic matter, and energy. Condensed matter includes solid matter (such as metals, ceramics, plastics, composites) and soft matter (e.g. hydrogels). Many of these can be used to construct our modern world, which is why they are usually called materials.

1.2.2 Fundamental Particles

Although countless molecules and atoms forming our real world have been identified, the pursuit of the underlying fundamental elementary particles and the interactions between them is still on among high-energy physicists. Figure 1.5 illustrates the fundamental particles of matter and as well as the carriers of forces that make up the presently accepted "Grand Unified Theory" (GUT, sometimes also dubbed "Theory of Everything") [14, 15]. Matter is built from two kinds of the smallest elementary particles: quarks and leptons [16]. A possible quark–lepton complementarity is an

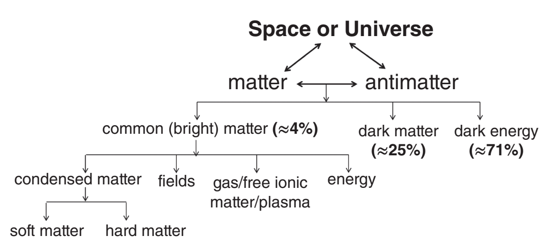


Figure 1.4 Classification and occurrence of matter in the universe.

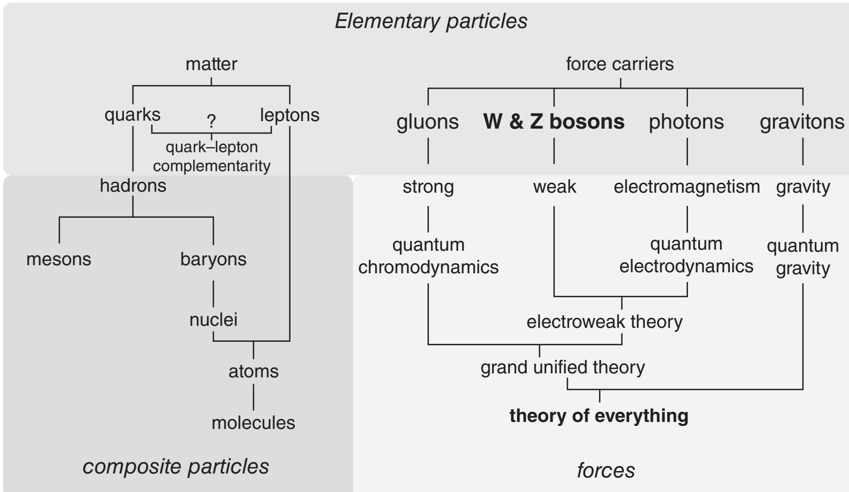


Figure 1.5 Elementary particles and forces according to the Standard Model.

active area of research [17]. According to our present understanding, matter consists of six different kinds (or "flavors") of quarks and six types of leptons. The six quarks are called up and down (which are the components of protons and neutrons), strange (forming strange particles in cosmic rays), charm, bottom and top. The six types of leptons are the electron (e^-) and the electron neutrino (ν_e), the muon (μ^-) and the muon neutrino (ν_μ), and finally the tauon (τ^-) and the tauon neutrino (ν_τ). There are still a number of open questions regarding quarks and leptons, for example the gauge and the origin of the quark and lepton complementarity [18].

Hadrons are elementary particles consisting of a combination of quarks and antiquarks; they include the proton, neutron, meson, and hyperon, which are capable of taking part in a strong nuclear interaction (the strong force), thus excluding leptons and photons [19]. Hadrons have typical radii r of the order of 1 fm (10^{-15} m), with an associated time scale r/c of the order of 10^{-23} s. The vast majority of them are highly unstable resonances, corresponding to excited states of the various quark systems, and decay to lighter hadrons by the strong interaction with lifetimes of the same order. Mesons (such as the pion and kaon) are hadrons made up of one quark and one antiquark that are held together by the strong force and have zero or an integer number of quantum units of spin. The masses of mesons are approximately 200 electron masses. Mesons are bosons with integer spin (0, 1, 2, …) and, unlike baryons, do not obey a conservation law. In contrast, baryons are hadrons with half-integer spin (i.e., they are fermions), are composed of three quarks and participate in strong interactions. Baryons are generally more massive than mesons and leptons with masses greater than or equal to that of the proton. The baryon number is the number of baryons in a system minus the number of antibaryons.

Baryons are either nucleons or hyperons. The group of nucleons comprise the proton and the neutron. Nucleons have one-half unit of spin (i.e., they are fermions) and are the basic components of all atomic nuclei. The proton is a stable particle with positive charge equal to the negative charge of an electron and is one of the two building blocks of atomic nuclei [14]. The neutron is an elementary particle with zero charge and a mass almost equal to that of a proton and is the proton's partner in building atomic nuclei [14]. Each nucleus consists of protons and neutrons that together form the nucleus, the positively charged massive center of an atom. An atom consists of this nucleus and a matching number of negatively charged electrons cycling around it.

Finally, hyperons are baryons that are not nucleons, with a baryon number of +1, which have a mass greater than that of the neutron or the proton and are not stable. The lambda hyperon is electrically neutral and has an isotopic spin 1. A molecule is an electrically neutral entity consisting of more than one atom ($n > 1$) bonded together in a particular bonding order and spatial arrangement [20]. The diameters of molecules are typically of the order of 10^{-10} m and larger. A molecule must correspond to a local minimum (a depression) on the potential energy surface that is deep enough to contain at least one vibrational state. Ions are derived from molecules or atoms by adding or removing electrons, i.e., they carry an electrical charge.

1.2.3 Fundamental Forces

As far as we currently know, there are four types of forces in nature: strong interaction, weak interaction, electromagnetic interaction, and gravity [15]. According to our present models, the first three of these are mediated by elementary particles: the strong interaction by gluons, the weak interaction by the W and Z bosons, and the electromagnetism by the photon. These three forces appear to be accurately described by the Standard Model of particle physics. It is hypothesized that gravitational interactions are mediated by a yet undiscovered elementary particle, dubbed the graviton. In the classical limit, a successful theory of gravitons would reduce to general relativity, which itself reduces to Newton's law of gravitation in the weak-field limit [21–23].

Gluons are hypothetical elementary particles without mass and are thought to be involved in binding the subatomic quarks together [15]. A gluon transmits the strong nuclear interaction, according to quantum chromodynamics (QCD). The W and Z bosons were postulated by Glashow, Weinberg, Salam in 1968 and discovered by the UA1 and UA2 collaborations in 1983. There are two kinds of W bosons with +1 and −1 units of elementary charge. The W^+ boson is the antiparticle of the W^-. In contrast, the Z boson is electrically neutral and is its own antiparticle. All three are very short-lived, with half lives of about 3×10^{-25} s. These bosons are the heavyweights among elementary particles. With masses of 80.4 and 91.2 GeV/c^2, respectively, the W and Z^0 particles are almost 100 times as massive as the proton – and heavier than entire iron atoms. The masses of these bosons are significant because they limit the range of the weak nuclear force. The electromagnetic force, by contrast, has an infinite range because its boson (the photon) is massless. All three bosons carry a spin of 1. The emission of a W^+ or W^- boson can either raise or lower the electric charge of the emitting particle by 1 unit, at the same time altering the spin also by 1 unit. In addition, a W boson can change the generation of a particle, for example changing a strange quark to an up quark. The Z^0 boson cannot change either electric charge or any other "charge" (such as strangeness, charm, etc.) but only spin and momentum, so it can never change the generation or flavor of the particle emitting it. In physics, the W and Z bosons are the elementary particles that mediate the weak force. Their discovery has been heralded as a major success for the Standard Model of particle physics. The W particle is named after the weak nuclear force. The Z particle was semi-humorously given its name because it was said to be the last particle to need discovery. Another explanation is that the Z particle derives its name from the fact that it has zero electric charge.

The most famous boson may well be the Higgs boson, often denoted the "God particle", whose spin and charge are both zero and which is a key ingredient of the Standard Model. A problem for many years has been that no experiment was able to observe the Higgs boson and thus to confirm the theory. On 4 July 2012, the ATLAS and CMS experiments at CERN's Large Hadron Collider (LHC) announced they had each observed a new particle in the mass region around 125 GeV [24]. This observed mass would be consistent with the Higgs boson as predicted by the Standard model, but further work will be necessary to ascertain whether this is indeed the case. The Higgs boson, as proposed by the Standard Model, is the simplest manifestation of the Brout–Englert–Higgs mechanism. Other types of Higgs bosons are predicted by other theories that go beyond the Standard Model. On October 8, 2013, the Nobel prize in physics was awarded jointly to François Englert and Peter Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which was recently confirmed through the discovery of the predicted fundamental particle by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

The photon is a type of elementary particle. A photon is the smallest discrete amount or "quantum" of the electromagnetic field, including electromagnetic radiation such as light and radio waves, and the force carrier of the electromagnetic force. Photons are massless, so they always move at the speed of light (299 792 458 $m\ s^{-1}$) in vacuum. The photon is a boson and the basic unit of all light. The graviton is a hypothetical elementary particle that mediates the force of gravitation in the framework of quantum field theory. There is no complete quantum field theory of gravitons due to an unresolved mathematical problem regarding renormalization in general relativity. In string theory, believed to be a consistent theory of quantum gravity, the graviton is a massless state of a fundamental string [25].

Even though gravitons are presumed to be massless, they would still be able to carry energy, as any other quantum particle. For example, photons and gluons are also carrying energy, despite being massless particles. It is unclear which variables might determine the graviton energy and the amount of energy carried by a single graviton. Alternatively, if gravitons are indeed massive, the analysis of gravitational waves yielded an upper bound on the mass of gravitons: the graviton's Compton wavelength is at least 1.6×10^{16} m or about 1.6 light-years, corresponding to a graviton mass of no more than 7.7×10^{-23} eV/c^2 [26]. This relation between wavelength and mass-energy is calculated from the Planck–Einstein relation, the same equation that relates electromagnetic wavelength to photon energy. However, if gravitons are the quanta of gravitational waves, then the relation between their wavelength and particle energy will be fundamentally different than for photons since the Compton wavelength of the graviton is not equal to the wavelength of the gravitational wave. Instead, the lower bound to the Compton wavelength of the graviton is about 9×10^9 times larger than the gravitational wavelength for the GW170104 event, which was about 1700 km. The report did not elaborate on the source of this ratio [26]. It is possible, however, that gravitons are not the quanta of gravitational waves or that the two phenomena are related in a different way.

In classical mechanics, a gravitational field is a physical quantity [27] that can be defined using Newton's law of universal gravitation. Determined in this way, the gravitational field g around a single particle of mass M is a vector field consisting, at every point of space, of a vector pointing directly toward the particle. The magnitude of the field at every position can be calculated from the gravitation law and represents the force per unit mass on any object at that point in space. Because the force field is conservative, there is a scalar potential energy per unit mass, Φ, at each point in space associated with the force fields; this is called the gravitational potential [28]. The gravitational field equation is [29]

$$\mathbf{g} = \frac{\mathbf{F}}{m} = \frac{\mathrm{d}^2\mathbf{R}}{\mathrm{d}t^2} = -GM\frac{\hat{\mathbf{R}}}{|\mathbf{R}|^2} = -\nabla\Phi \tag{1.4}$$

where $\mathbf{F}$ is the gravitational force, m is the mass of the test particle, $\mathbf{R}$ is the position of the test particle in space (or, for Newton's second law of motion, which is a time dependent function, a set of positions of test particles each occupying a particular point in space at the start of testing), $\hat{\mathbf{R}}$ is a unit vector in the radial direction of $\mathbf{R}$, t is the time, G the gravitational constant, and ∇ is the del or nabla operator.

Unambiguous detection of individual gravitons, though not prohibited by any fundamental law, is impossible with any physically reasonable detector [30]. The reason is the extremely low cross section for the interaction of gravitons with matter. For example, a detector with the mass of Jupiter and 100% efficiency, placed in close orbit around a neutron star, would only be expected to observe one graviton every 10 years, even under the most favorable conditions. It would be impossible to discriminate these events from the background of neutrinos, since the dimensions of the required neutrino shield would ensure its collapse into a black hole [30].

Observations of both the LIGO and the Virgo collaborations have directly detected gravitational waves in 2016 [26, 31]. Others have postulated that graviton scattering yields gravitational waves as particle interactions yield coherent states [32]. Although these experiments cannot detect individual gravitons, they might provide information about certain properties of the graviton [33]. For example, if gravitational waves were observed to propagate slower than c (the speed of light in a vacuum), that would imply that the graviton has mass (however, gravitational waves must propagate slower than c in a region with nonzero mass density if they are to be detectable) [34]. Recent observations of gravitational waves have put an upper bound of 1.2×10^{-22} eV/c^2 on the graviton's mass [26]. Astronomical observations of the kinematics of galaxies, especially the galaxy rotation problem and modified Newtonian dynamics, might point toward gravitons having nonzero mass [23, 35].

The principle of the strong interaction mediated by gluons is described by QCD . In theoretical physics, QCD is the theory of the strong interaction between quarks and gluons, the fundamental particles that make up composite hadrons such as the proton, neutron, and pion. QCD is a type of quantum field theory called a non-Abelian gauge theory, with symmetry group SU(3). The QCD analog of electric charge is a property called "color". Gluons are the force carriers of the theory, just as photons are the force carriers of the electromagnetic force in quantum electrodynamics. QCD is an important part of the Standard Model of particle physics, and a large body of experimental evidence for QCD has been gathered over the years. QCD exhibits two main properties: Color confinement and asymptotic freedom. The former is a consequence of the constant force between two color charges as they are separated: In order to increase the separation between two quarks within a hadron, ever-increasing amounts of energy are required. Eventually, this energy becomes so large that it will spontaneously produce a quark–antiquark pair, turning the initial hadron into a pair of hadrons instead of producing an isolated color charge. Although analytically unproven, color confinement is well established from lattice QCD calculations and decades of experiments [36]. Asymptotic freedom describes a steady reduction in the strength of interactions between quarks and gluons as the energy scale of those interactions increases (and the corresponding length scale decreases). The asymptotic freedom of QCD was discovered in 1973 by David Gross and Frank Wilczek [37] and independently by David Politzer in the same year [38]. For this work, all three shared the 2004 Nobel Prize in Physics [39].

The weak interaction among W and Z bosons and the quantum electromagnetism form the electroweak theory that describes both the electromagnetic and the weak force. Superficially, both forces appear quite different. The weak force acts only across distances smaller than an atomic nucleus, while the electromagnetic force can extend over large distances (as observed in the light of stars reaching across entire galaxies), weakening only with the square of the distance. Moreover, a comparison of the strengths of these two fundamental interactions between two protons reveals, for instance, that the weak force is some 10 million times weaker than the electromagnetic force. Yet one of the major discoveries of the twentieth century has been that these two forces are different facets of a single, more fundamental electroweak force. Although these forces appear very different at everyday low energies, the theory models them as two different aspects of the same force. Above the unification energy, which is of the order of 246 GeV, they would eventually merge into a single force. Thus, if the universe is hot enough (approximately 10^{15} K, a temperature not exceeded since shortly after the Big Bang), the electromagnetic and weak forces merge into a combined electroweak force. During the quark epoch, the electroweak force split into the electromagnetic and weak force.

Sheldon Glashow, Abdus Salam [40, 41], and Steven Weinberg [42, 43] were awarded the 1979 Nobel Prize in Physics for their contributions to the unification of the weak and electromagnetic interactions between elementary particles, known as the Weinberg–Salam theory [44, 45]. The existence of the electroweak interactions was experimentally established in two stages, the first being the discovery of neutral currents in neutrino scattering by the Gargamelle collaboration in 1973, and the second in 1983 by the UA1 and the UA2 collaborations that involved the discovery of the W and Z gauge bosons in proton–antiproton collisions at the converted Super Proton Synchrotron. In 1999, Gerardus't Hooft and Martinus Veltman were awarded the Nobel prize in Physics for showing that the electroweak theory can be renormalized [46].

Currently, the QCD for the strong interaction of gluons and the electroweak theory for the weak interaction of W and Z bosons can be unified to form the so-called GUT, which can be accurately described by the Standard Model of particle physics. However, quantum gravity is still a mere hypothesis – if can be confirmed and combined with the GUT, the result will approach what is currently called "Theory of Everything".

1.3 Fundamental Constants Describing the Universe and Matter

In the observable universe, matter is clustered in a filamentous structure. Galaxies, stars, and planets form in the densest parts. They can aggregate to form clusters of galaxies and supercluster complexes that make up "walls" in the universe (e.g., the Sloan great wall or the CfA2 great wall) (Figure 1.6). Even though the simulation processes of the different space regions and structures may differ in details, the aggregation modes are almost identical for different clusters of galaxies. If we could rewind time back to the earliest moments allowed by the laws of physics and then let it start over to evolve again for another 13.8 billion years, the resulting universe would be very similar to our existing one. The new universe would exhibit the same number of galaxies with the same masses, and they would aggregate much in the same way as in our current universe. The abundance of chemical elements would be the same as it is today. The distribution of stars and planets, dark energy, dark matter, ordinary matter and the neutrino and radiation intensity would be identical to our current universe. And – most important! – all fundamental constants would have the same values as they have today. This observation is particularly important because only when it starts from the same primary conditions, the new universe can be guaranteed to evolve on the same path that led to our current universe. Which are those fundamental constants and what are they representing? What dimensionless numbers describe and predefine our universe?

Some of these well-known physical constants, such as speed of light c, the Planck constant h and the Newtonian constant of gravitation G, are shown in Table 1.1. They all have dimensions (i.e., units), which means that their values depend on the unit in which they are measured, for example, meter, second, kilogram, etc. The universe, however, obviously does not care which particular unit we use for a specific measurement. This means that it must be possible to create dimensionless quantities from combinations of these physical constants that can be used to outline the relationships between different parts of our universe. The goal of any scientific study is to describe nature in simple terms. So, how many constants are needed to describe all the particles, the interactions among them, and the physical laws governing our

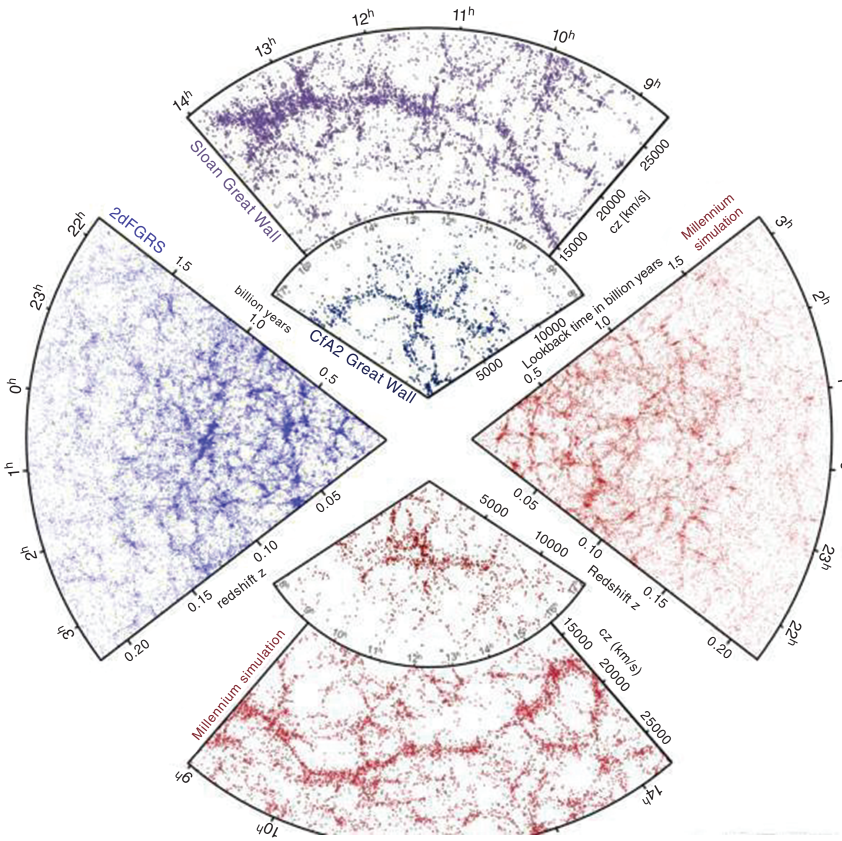


Figure 1.6 Our universe and the simulated universe.

universe? It turns out that just 26 dimensionless numbers suffice to describe our universe, and these will be defined and discussed briefly in the following.

The first constant is the fine structure constant α defining the strength of electromagnetic interactions. An EM interaction is the interaction between charged particles and the electromagnetic field and/or between charged particles via the electromagnetic field (Figure 1.7). This interaction is described by Coulomb's law, Eq. (1.5), and its strength will increase with increasing energy of the particles.

$$\vec{F} = k\frac{q_1 q_2}{r^2}\vec{e}_r \tag{1.5}$$

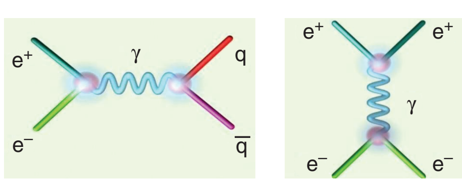


Figure 1.7 Interaction between charged particles and/or electromagnetic fields.

Table 1.1 Physical constants used to describe our universe.

Physical quantity	Symbol	Value	Unit
Velocity of light in vacuum	c	299 792 458	$m\,s^{-1}$
Permeability of vacuum	μ_0	2π	10^{-7} $N\,A^{-2}$
Permittivity of vacuum, $1/(\mu_0 c^2)$	ε_0	8.854 187 813	10^{-12} $F\,m^{-1}$
Newtonian constant of gravitation	G	6.674 30	10^{-11} $m^3\,kg^{-1}\,s^{-2}$
Planck constant	h	6.626 070 15	10^{-34} J s
$h/2\pi$	$\hbar$	1.054 571 817	10^{-34} J s
Elementary charge	e	1.602 176 634	10^{-19} C
Electron mass	m_e	0.910 938 37	10^{-30} kg
Proton mass	m_p	1.672 621 9	10^{-27} kg
Ratio of proton mass over electron mass	m_p/m_e	1836.152 673	
Fine structure constant	α	7.297 352 569 3	10^{-3}
Rydberg constant	R_∞	1.097 373 1568	10^{7} m^{-1}
Avogadro constant	N_A	6.022 140 76	10^{23} mol^{-1}
Faraday constant	F	96 485.332	$C\,mol^{-1}$
Molar gas constant	R	8.314 462	$J\,mol^{-1}\,K^{-1}$
Boltzmann constant, R/N_A	k	1.380 649	10^{-23} $J\,K^{-1}$
Stefan–Boltzmann constant, $\pi^2 k^4/60h^3c^2$	σ	5.670 37	10^{-8} $W\,m^{-2}\,K^{-4}$
Electron volt	eV	1.602 176 634	10^{-19} J
Atomic mass unit, 1/12 $m(^{12}C)$	u (amu)	1.660 539 066	10^{-27} kg

The quantization of the electromagnetic field in quantum electrodynamics is the photon field. The mass of the photon is zero, its spin is 1 and its energy is $h\nu$ (where ν is the frequency of the photon). Charged particles can emit or absorb photons, and their interaction is transported via the photon field. Pairs of positive electrons and negative electrons can annihilate to produce photons. The constant α to describe the strength of the EM interaction is the ratio of the squared elementary charge over the product of the Planck constant times the velocity of light (e^2/hc), about 1/137.036 or 0.007 297 352 569. Using perturbation theory, various physical quantities encountered in quantum electrodynamics can be expanded in powers of α for precise calculations.

The second constant is the coupling constant of the strong interactions, which describes the strength of a strong nuclear force among hadrons, i.e., the elementary particles (quarks) in protons and neutrons. The quarks and their interaction in a proton and a neutron are shown in Figure 1.8. Even though the strong interaction operates quite different from EM or gravitational forces, and also counterintuitive, its interaction strength can be parameterized using a coupling constant. This fundamental constant, much as the EM constant, depends on the energy of the system and the particles. If the gravitational force is normalized to 1, the weak interaction

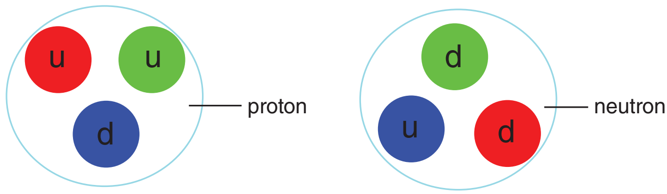


Figure 1.8 Strong interaction among up and down quarks via gluons in protons and neutrons. u: up quark; d: down (or bottom) quark.

force will be about 10^{25}, the EM force $\approx 10^{36}$ and the strong interaction force as large as 10^{38}. Clearly, the latter three are far stronger than gravity.

The 15 constants from the 3rd to the 17th constant represent the nonzero masses of the 15 elementary particles in the Standard Model. In the Standard Model, these masses are embodied by the 15 coupling constants of the Higgs field with electrons, muons (μ), tauons (τ), three corresponding types of neutrinos, six types of quarks, the W and Z bosons, and the Higgs boson. There is no coupling of the Higgs field with photons and the eight gluons, which are intrinsically zero-mass elementary particles. The energies of the elementary particles are summarized in Figure 1.9. Even though the energies and masses of the elementary particles can be measured or calculated from the Standard Model, they still constitute a problem for Theoretical Physics. Theoreticians hope that these masses are either different aspects of a single underlying quantity (which seems not to be the case), can be calculated from basic theory (which is also not yet possible), or emerge dynamically from a larger framework such as the GUT or superstring theory (SST) (at present, only a faint hope).

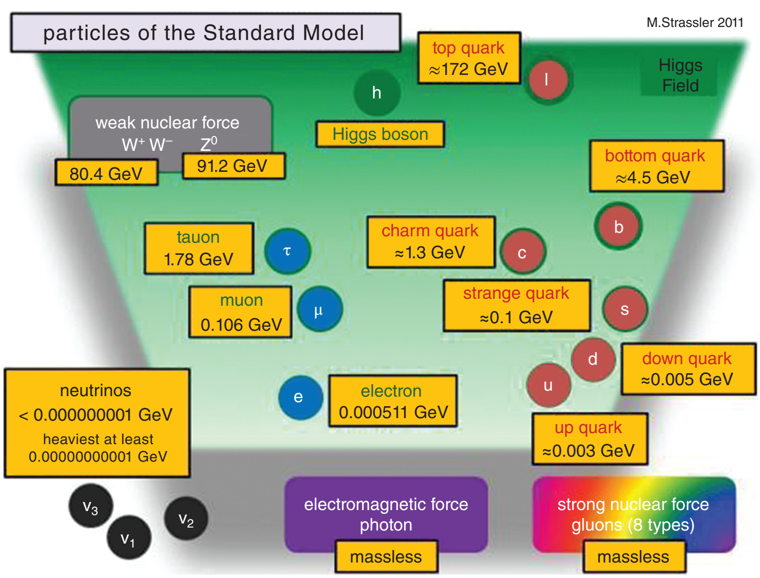


Figure 1.9 Energies or masses of the elementary particles of the Standard Model.

The four constants from the 18th to the 21st are the quark mixing parameters that define the weak nuclear interaction and allow us to calculate the probability amplitudes of radioactive decay channels. Quarks can be mixed (that is to say: converted into each other following specific rules) because the up, charm, and top quarks on the one hand and the bottom, strange, and down quarks on the other hand have the same quantum numbers. The details of this mixing are parameterized in the so-called Cabibbo–Kobayashi–Maskawa (CKM) matrix, which is constructed from three quark mixing angles and a complex phase that is the origin of CP violation. These four parameters cannot be predicted from theory but only measured experimentally.

The four constants from the 22nd to the 25th are neutrino mixing parameters. Neutrino mixing is parameterized by Maki–Nakagawa–Sakata (MNS) matrix. Similar to the situation for quarks, neutrino mixing is described by four parameters and made possible by the fact that three kinds of neutrinos have the same quantum numbers (Figure 1.10). The three mixing angles have been measured precisely, whereas the phase responsible for CP violation is only know with large uncertainties.

The 26th constant is the cosmological constant responsible for the accelerated expansion of the universe (Figure 1.11), the precise value of which cannot be measured. If the universe were to go back in time to a moment several picoseconds after the Big Bang and would start its evolution from about the same initial conditions and with the same 26 fundamental constants, almost the same universe as ours would result after 13.8 billion years of evolution. The only differences would be changed degrees of probability and initial conditions in quantum mechanics.

Not everything in our universe can be fully explained from these 26 constants. Are there other constants that have not yet been discovered? We do not know. For instance, we cannot explain the asymmetry between matter and antimatter or the

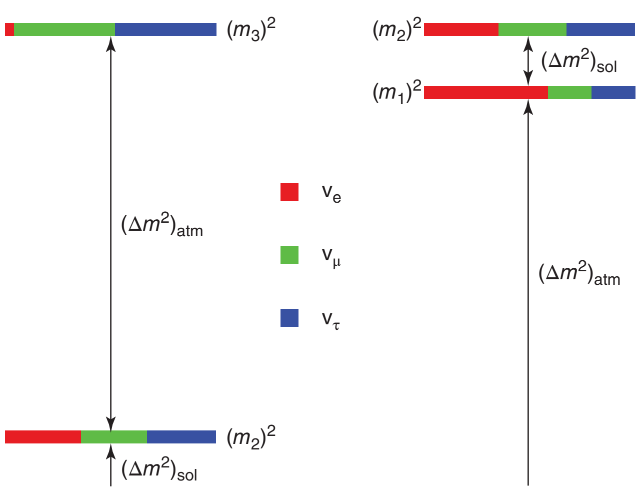


Figure 1.10 Neutrino mixing.

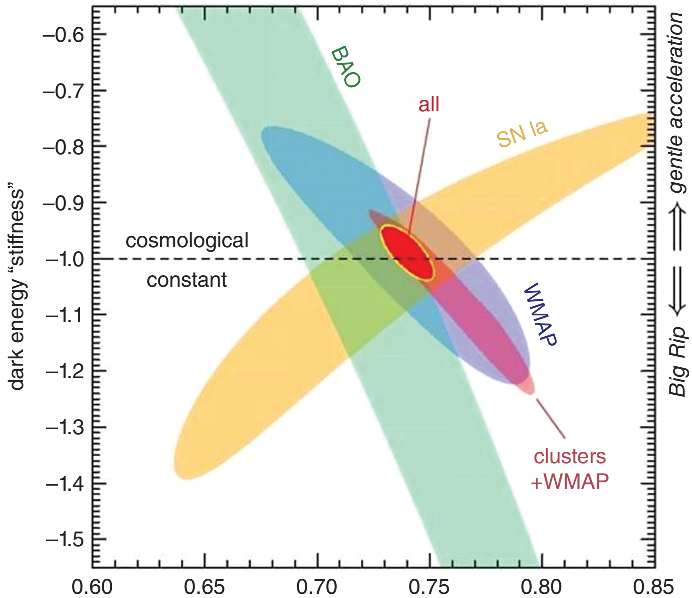
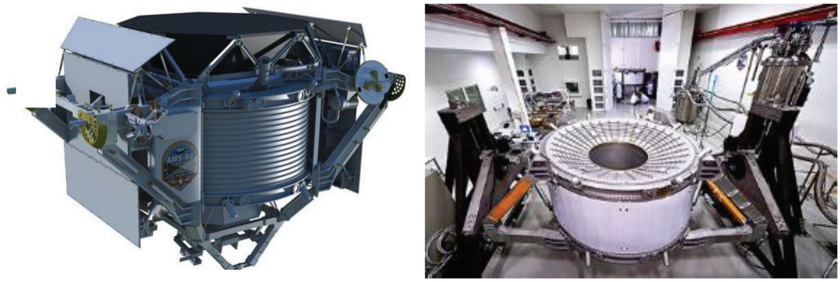


Figure 1.11 The cosmological constant and dark energy.

details of CP violation based on the known constants. For this, we may need to develop a new kind of physics with new fundamental parameters. If CP violation exists in the strong interaction, there will be a new parameter involved. If not, a physical (or symmetry) explanation that prevents strong CP invariance may bring along new constants. Does the cosmic inflation occur? If so, by which parameter is it described? What is dark matter? Dark matter should consist of particles with nonzero mass and will most likely be described by at least one or even more new fundamental parameters. However, we do not know from where these parameters will arise and whether they can be deduced or calculated from the current information in our universe. The journey for us to understand the universe is still a long one – that is the situation we are facing [47].

1.4 Experiments to Study Fundamental Particles and Forces

Many sophisticated instruments have been developed for the detection and study of elementary particles and the related investigation of dark matter and energy, such as the Linear Proton Accelerator (Linac) at Fermilab, the Linear Hadron Collider (LHC) at CERN, the Arecibo Radio Telescope (collapsed in 2020), the Five-hundred-meter Aperture Spherical Radio Telescope (FAST) in Guizhou, or the Alpha Magnetic Spectrometer (AMS), of which there are two generations,



(a) (b)

Figure 1.12 (a) Full image of the assembled Alpha Magnetic Spectrometer (AMS). Source: NASA/Wikimedia Commons/Public domain. (b) Top view of the permanent magnet. Source: CERN.

AMS-01, and AMS-02 (Figure 1.12a). AMS-02 is a magnetic spectrometer designed to perform accurate long-time measurements of cosmic radiation [48, 49]; it was shipped to the International Space Station (ISS) by STS Endeavour OV-105. With its large acceptance ($0.45\,\text{m} \approx 2\,\text{sr}$), the long duration of observation (three years) and the included state-of-the-art particle identification techniques, AMS-02 will accurately record spectra of charged cosmic rays and high-energy photons in the energy range of several hundred MeV to a few TeV. It will conduct the most sensitive search for the existence of primordial antimatter aa well as a multi-channel indirect search for dark matter.

AMS-02 is a detector for charged particles, whose core component is a permanent magnet (Figure 1.12b) that can produce a very strong magnetic field ($1.09 \times 10^5\,\text{A m}^{-1}$, about 2800 times stronger than the Earth magnetic field). It was designed and manufactured by Chinese scientists and engineers from the Institute of Electrical Engineering of the Chinese Academy of Sciences, the Institute of High Energy Physics of the China Academy of Launch Vehicle Technology and 211 production plants over a time of four years.

If HST can be called the "bodhisattva dharma-eye" that can collect weak and low radiation from very distant parts of space in the Earth orbit, AMS-02 may be a magic wand that captures the mysterious cosmic rays originating from distant galaxies. It is the first extra-atmospheric high-energy physics laboratory of humanity, whose most important mission is to find antimatter and evidence of dark matter. If Big Bang theory is self-consistent, there should be equal amounts of antimatter and matter in our universe. It is known that ordinary bright matter, such as the known galaxies and planets in the universe, only amounts to about 5% of the total matter in space, whereas the remaining 95% are dark matter and dark energy. In addition, we are interested in whether exotic forms of matter consisting of three quarks exist and if cosmic rays would endow any danger to humans if they would, for example, travel to Mars. All the above questions are waiting for AMS-02 to provide us with answers.

There are essentially three methods to hunt dark matter. The first is to produce dark matter through collision of high-energy particles using accelerators. The second is to detect dark matter indirectly by observing its gravitational field. Even though dark matter does not radiate light, it exerts a gravitational force and can therefore be observed by detecting changes of the gravitational field in a certain part of space. AMS-02, however, uses a third method. Theoretically, lots of excess positrons (whose charges are opposite to those of ordinary electrons) are produced by collisions of dark matter. We can therefore observe dark matter by detecting the abundance of positrons in a certain part of space. Although particle accelerators on earth are constantly improving (reaching up to 13 TeV for LHC at CERN in May 2015 [50]), the strongest accelerator in the universe is the universe itself, as pointed out by Samuel C. C. Ting, who shared the 1976 Nobel Prize in Physics with Burton Richter for the discovery of a new heavy particle (known as J/Ψ) and thus of the charm quark [51]. However, the high-energy particles from these infinitely rich resources are absorbed and/or attenuated by the 100 km thick atmosphere layer around the Earth. If we only could send an instrument such as the LHC to the ISS, we would acquire an immense power of observation.

Figure 1.13 shows the inner structure of AMS-02 and the basic principle how it detects cosmic rays of charged particles. As the charged particles originating from distant parts of space enter into the probe, their trajectories will deflected by the Lorentz force of the magnetic field, which is about 4000 times as strong as the Earth magnetic field. AMS-02 will record the related data and analyze them to distinguish various charged particles, e.g., positrons. The information on their masses, velocities, and charges will be submitted to ground, where they may help to assemble our picture of the origin of our universe.

Since AMS-02 has been brought to the ISS in May 2011, it has collected and analyzed the signatures of several tens of billions of cosmic particles and about 120 billion cosmic rays. Until 2014, about 10 million electrons and positrons were

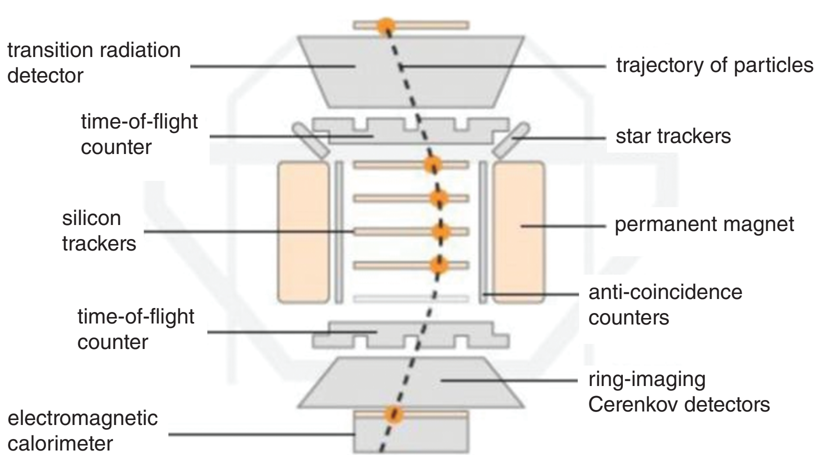


Figure 1.13 Schematic structure of AMS, designed to detect charged particles from distant parts of space.

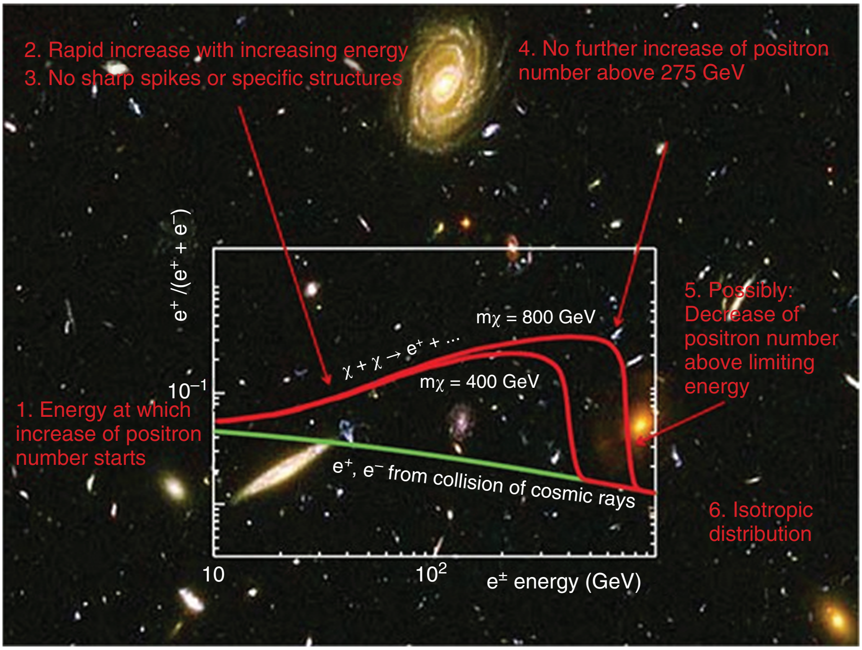


Figure 1.14 Characteristics of the excessive positrons in the cosmic rays. Source: CERN.

observed, which amounts to the largest number of positrons characterized during the past half century. According to the results reported a paper in Physical Review Letters, six characteristics of excess positrons in the cosmic rays were observed, as shown in Figure 1.14. These include: the positron number starts to increase at an energy of 8 GeV (1), the relative number of excess positron rapidly increases with the energy (2), this increase is continuous without distinct sharp peaks (3), and beyond about 275 GeV, the relative number of excess positrons ceases to increase (4). The last essential criterion needed to identify the existence of dark matter is whether the positron production rate will decrease suddenly above a certain limiting energy (5), which may need more time to confirm. The positrons are detected uniformly from all directions, i.e., their distribution is isotropic (6) [49, 52].

Samuel C. C. Ting once stated, "Rapid decrease suggests the production of positrons by collisions among dark matter. Because the energy of dark matter is limited, no more positrons cannot be produced as the energy reaches a certain value. Therefore, the amount of positrons will be reduced suddenly." As for the sense of these data, Ting said: "Up to now, none of these results is identical as others collected in the past century. Therefore, we can say that all these results will gradually change people's understanding on dark matter and dark energy." With the progress of the AMS-02 project, many answers to relevant problems may be found – for example, how far into the cosmos we are able to look (or detect particles), what can be said about antimatter, and what the origin of the dark matter might be. Answers will not be available before 2024, however.

Another type of instruments for the exploration of deep space features are space telescopes (such as spherical radio telescopes). One of the most famous space telescopes is HST (Figure 1.15a), which was launched into space by the space shuttle Discovery (STS-31) in April 1990. In May 2019, a new image of the universe was announced as "The Hubble Legacy Field (HLF)" by the HST scientists, which was (and still is) the most complete and comprehensive map of our universe. It was constructed by joining together 7500 star photographs recorded by HST during 16 years of observation, including 265 000 galaxies, some of which were as old as 13.3 billion years (Figure 1.15b–d). Their study can help improve our understanding of the early

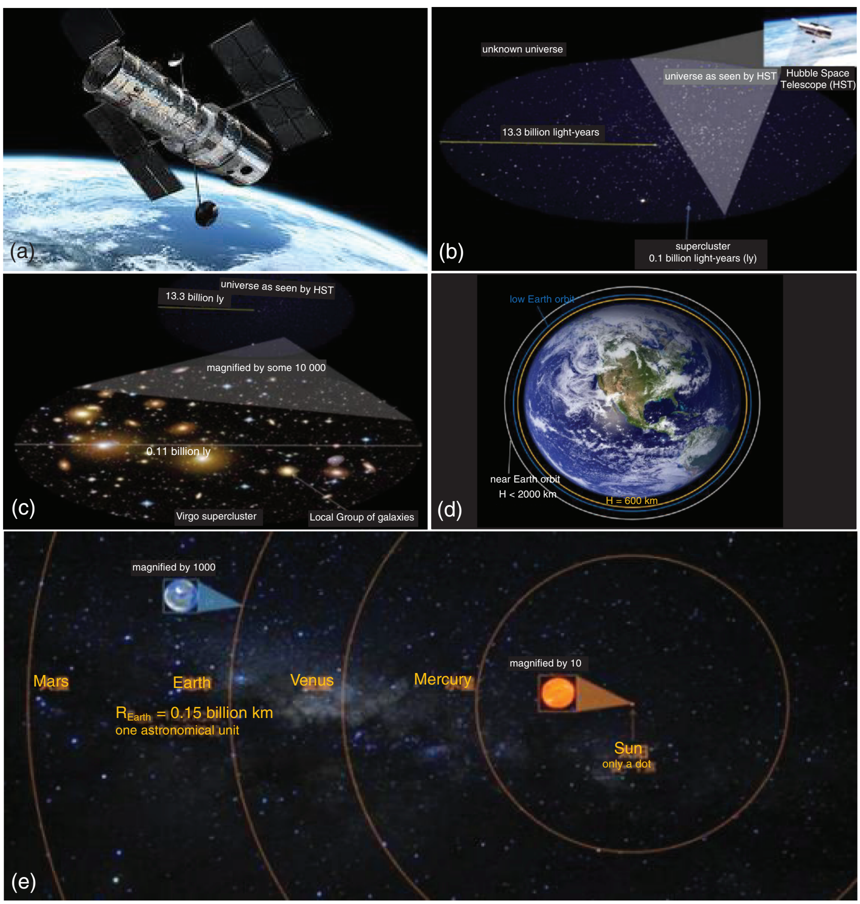


Figure 1.15 Schematic representations of the universe recorded by the HST. (a) Schematic illustration of the HST circling above the Earth. Source: European Space Agency / NASA / CC BY 4.0. (b) The universe as observed by HST compared with the full universe. (c) Excerpt of the universe magnified by a factor of some 10 000 to show the Local Group galaxies and the Virgo supercluster. (d) The orbit altitude distribution of man-made satellite used in the current four navigation systems observed by HST. (e) Solar system with our Earth and other three near-orbit planets. Source: Oksana/Adobe Stock.

history of our universe and might help to answer questions such as where and how our Earth and Sun exist (Figure 1.15e).

Based on this, we can understand the distribution of altitudes of the orbits of man-made satellites used in the four established navigation systems (Figure 1.15d). There are a number of large-aperture spherical radio telescopes constructed on Earth besides HST, such as the already mentioned FAST telescope (500 m diameter, working frequency: 70 MHz to 3.0 GHz, Guizhou, China), the now collapsed telescope of Arecibo (350 m diameter, working bands: 3 mm to 6 cm, Puerto Rico, USA, Figure 1.16a), the Green Bank Telescope (GBT; size of bow tie antennas $100\,m \times 110\,m$, working frequency: 0.29–49.8 GHz, movable spherical radio telescope, Virginia, USA, Figure 1.16b), the telescope of the Institute for Radio Astronomy in the Millimeter Range (IRAM) in the Sierra Nevada (30 diameter, bands: 3, 2, 1 mm and sub-millimeter, Spain), the Large Millimeter Telescope (LMT; 30 m diameter, 3 mm/1 mm bands, UMASS & Mexico), the Atacama Large Millimeter/Submillimeter Array (ALMA; 12 m diameter, 10 mm to 350 μm bands, Atacama desert, Chile), and also some radio telescopes designed for sub-millimeter bands (e.g., James Clerk Maxwell Telescope/JCMT: 15 m diameter, Hawaii, USA; Atacama Pathfinder Experiment/APEX: 12 m diameter, sited in Atacama desert, Chile, Figure 1.16c), etc. Their radio frequencies range from 1 to 1000 GHz based on the Earth's atmospheric radio window, and currently has reached THz bands.

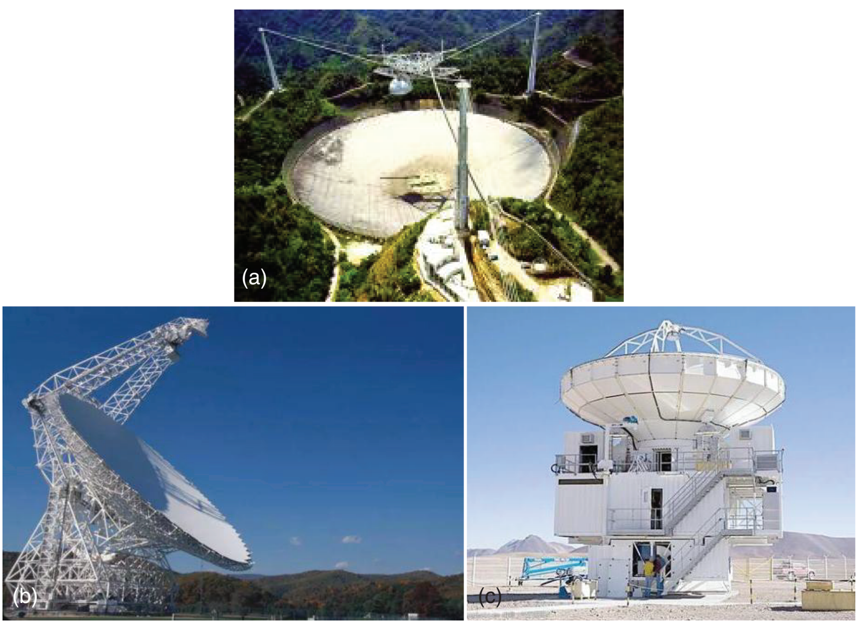


Figure 1.16 (a) The 350-m ASRT of Arecibo Observatory (now collapsed). Source: H. Schweiker/WIYN and NOAO/AURA/NSF/Wikimedia Commons/CC BY 4.0. (b) The GBT (Green Bank Telescope) movable ASRT. (c) The APEX (Atacama Pathfinder Experiment) sub-millimeter band ASRT. Source: ESO/H.H.Heyer/Wikimedia Commons/CC BY 4.0.

FAST is a radio telescope located in a natural basin (a naturally deep and round karst depression) in Pingtang County, Guizhou Province, China, which was officially inaugurated in 2016. FAST is currently the largest single-aperture radio telescope, with a receiving area as large as about 30 football fields, which enables it receive radio waves far from deep space. It consists of 4600 triangular panels and is similar in design to the Arecibo observatory, also utilizing a natural hollow (karst) to provide support for the telescope dish. As the name suggests, its diameter is about 500 m (1600 ft). Unlike Arecibo, which has a fixed spherical curvature, FAST uses an active surface that can be adjusted to create parabolas in different directions, with an effective dish size of 300 m. This means that it will not be confined to pointing directly upwards, but capable of covering the sky within 40° from the zenith, compared to Arecibo's 20° range. Its working frequency ranges from 70 MHz to 3.0 GHz, with a pointing precision of 4 arc-seconds. FAST is currently the most sensitive radio telescope and three times more sensitive than the Arecibo observatory was.

The karst depression used as the site is large enough to host the 500-m telescope and deep enough to allow a zenith angle of 40°. The active main reflector is able to correct for spherical aberrations on the ground to achieve full polarization and a wide band without involving complex feed systems. Furthermore, the lightweight feed cabin, suspended 140 m above the reflector, is be driven by cables and servomechanisms in addition to a parallel robot as a secondary adjustable system to move with high precision.

In its first year of trial operation, FAST identified multiple pulsars. Two of these, named J1859-01 and J1931-01, are 16 000 and 4100 light-years from Earth with rotation periods of 1.83 and 0.59 s, respectively. Pulsars are rapidly rotating neutron stars that are products of stellar evolution and supernova outbursts. They are extremely dense – some 10^{17} kg m^{-3}, which corresponds to about ten thousand ships with ten thousand tons of load each in a volume as small as one cube of sugar. Pulsars rotate quickly and with highly constant period, which makes them possibly the most precise clocks in universe. This specific property endows pulsars with important applications regarding precise timing, finding gravitational waves, navigating spacecraft, etc.

The above two pulsars (J1859-01 and J1931-01) were discovered through drift-scanning the southern galactic plane by China's Eye of Heaven (FAST) on August 22, 2017 and August 25, 2017. Up to now, FAST has detected more than two hundred promising pulsar candidates, some of which have been identified internationally. Discovery of pulsars is one of the FAST missions, whose observation range can reach the edge of our universe. Because FAST can detect the spectral lines of neutral hydrogen and other centimeter bands, it is able to promote scientific and technological breakthroughs in a variety of fields – from studying the origin of the universe to understanding the structure of interstellar matter, the search for weak pulsars or other weak radio sources, or the efficient search for extraterrestrial life. Furthermore, FAST will be a key platform for multidisciplinary basic research that will extend the observation of neutral hydrogen to the edge of the universe, help discover dark matter and dark energy, or assist in seeking the first generation of celestial bodies.

1.5 Introduction to Condensed Matter and Materials

Generally speaking, there are four types of physical states of matter in our world: plasma, gas, solid, and liquid. The latter two are commonly called "condensed matter". Bose-Einstein condensates (BEC), superfluid phases at ultra-low temperature (such as He at 2.17 K), superconducting materials, super-solid samples, ferromagnetic phases in magnetic media, antiferromagnetic phases and so on are all unique condensed states and are examples of condensed matter.

Among these, BEC is sometimes called a fifth state of matter. The discovery and realization of BEC states has been very important for the development of quantum mechanics and its application (e.g., the mystery of dark energy, the detection of gravity waves, the realization of ultra-low temperatures, or the design of room-temperature superconductors). BEC is a condensed state exhibiting a specific gaseous and superfluid phase as the Bose atoms are cooled almost to absolute zero. In 1995, Wolfgang Ketterle from the Massachusetts Institute of Technology (MIT), Eric A. Cornell and Carl Wieman from the University of Colorado, Boulder, obtained a BEC consisting of rubidium (Ru) atomic vapor at 170 nK. In a BEC, almost all atoms will be condensed into the lowest-energy quantum state, forming a macroscopic quantum state. About 110 similar experiments have been designed by researchers from Germany and Sweden to study the characteristics of this condensed state. One of these experiments (MAIUS 1 initiated at Kiruna Sweden) aims to demonstrate matter-wave interference under microgravity. To study the BEC state under microgravity is important for the detection of "gravity waves" in the universe as well as for measuring electrical signals of variant bands and the fine structure constant α. Special equipment is essential to cool the atoms sufficiently to obtain a BEC. In 2018, scientists from NASA proposed a solution to address this challenge by sending a sealed microchip filled with Ru atoms in the space far away (about 234 km) from the surface of the Earth surface using a probing rocket. There, the atoms in the microchip can be cooled down to –273.1499999 °C, which is lower than the temperature in the Boomerang Nebula (about −272 °C), the coldest know location in our universe [53].

In 1937, Peter Kapica (1894–1984) from the Soviet Union found that liquid He abruptly changed from its normal fluidity to superfluidity as it was cooled to below 2.17 K (−270.98 °C). The emerging new phase of liquid He can pass through ultra-small pores or slits (≈100 nm width) without hindrance and then "climb" out of a cup along its walls. Up to now, this kind of superfluidity has only been discovered in liquid He [54, 55]. In the 1970s, Anthony Leggett from England recognized that atom pairs of ^{3}He had a similar electron pair structure as metallic superconductors. He proposed a theory elucidating the mechanism how the He atoms could interact with each other to produce superfluidity. Superfluidity is a macroscopic quantum effect by which the He atoms can form a "tight" group due to Bose–Einstein condensation, and the observed superfluidity is the specific expression of this "tight"-group phenomenon. Bosonic systems are not limited by the Pauli principle and have a tendency to condense spontaneously toward their ground state energy level, which is the fundamental reason for their superfluidity. A recent study pointed that there could exist a competitive relationship between superfluidity and superconductivity. It is well-known that in superconductivity, the intrinsic electric resistivity of matter is reduced to zero below a certain temperature. In superconductors, electrons do not move individually but in pairs, forming a kind of "superfluid state" of electrons (Figure 1.17a) [56]. The nonequilibrium pair breaking in the $Ba(Fe_{1-x}Co_x)_2As_2$ type of superconductors (Figure 1.17b) was studied via THz spectroscopy (schematically illustrated in Figure 1.17c) by Ji Wang from the Ames National Laboratory. The evidence for formation of a photoinduced excitonic state in this kind of materials was revealed by combining recording of the the phase changes in the materials utilizing a picosecond pulsed laser and tracing the moving mode of the inner electrons. Based on these findings, the group of Mikahil Eremets developed a strategy for seeking high-temperature superconductors and in 2019 reported that Lanthanum hydride (LaH_{10}) preserved its superconductivity up to a temperature of −23 °C [57, 58]. These examples encourage the development of special materials for unique applications based on the progress in condensed matter theory.

Condensed matter is the type of matter we are encountering most often in our daily life. It is used to constructs the basic materials of which our food, clothing, shelter, and means of transportation exist that are the essential materials for our life. The study of their characteristics, the relationships among their structures, their composition, physicochemical properties and performance in specific applications is one of the most important scientific fields because these properties are basic for the fabrication or synthesis of materials with useful properties and practical applicability.

1.5.1 Classification of Condensed Matter

Condensed Matter is a subset of bright matter, with the associated typical features such as coupling with radiation, conservation of mass and energy, and infinite divisibility and compressibility. It can therefore be detected and investigated by a variety of EM, electric or magnetic characterization methods. Condensed matter can be further classified into hard matter and soft matter, both of which are usually called materials. According to their composition and bonding mode, materials can be classified as metals (such as Al, Ti, Mg, or steel), ceramics (such as metal or nonmetal oxides, e.g., Al_2O_3, TiO_2, SiO_2, nitrides, e.g., AlN, SiN_x, or silicides, e.g., SiC), polymers (such as polyethylene PE, polypropylene PP, polyimides PI, or carbon fibers CF), composites (such as C-fiber epoxy resins, SiC-fiber phenolic resins, glass-fiber resins, or Mo-wire-enforced SiC matrix compounds). According to their function, they can be classified as structural materials for mechanical performance (such as steel, Ti alloys, Al alloys, CF-enforced epoxy resins), semiconductors (such as Si or GaAs), magnetic materials (such as NbFeB), optical materials (such as MgF_2), dielectric materials (such as $BaTiO_3$ or Al_2O_3), or biomaterials (such as alginates, lignin, and proteins).

Since the 1090s, materials used in high technology are often called "advanced materials", a field that has been developing rapidly in recent years. High technology usually means devices or products that can be operated or perform functions using relatively intricate and sophisticated principles such as electronic equipment

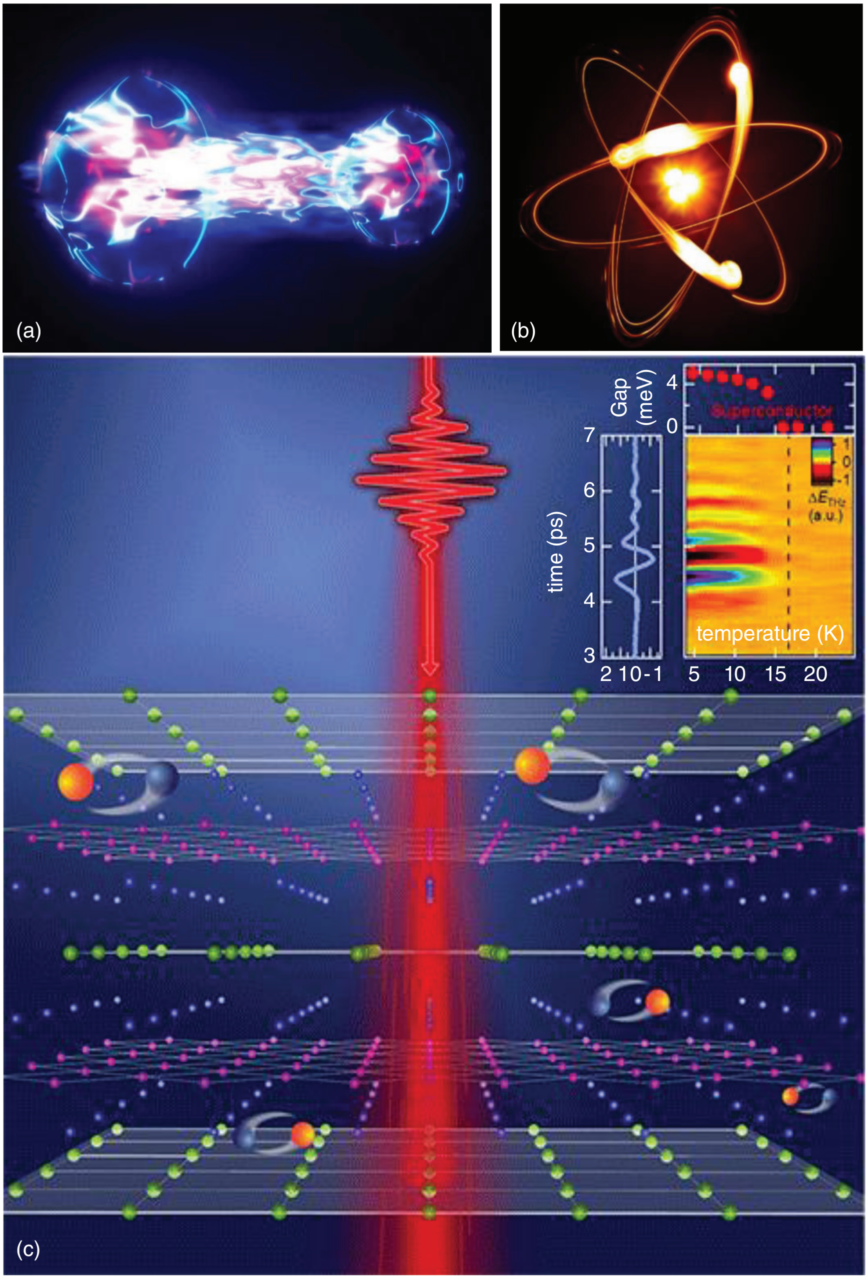


Figure 1.17 (a) Visualization of a superconductive state, emphasizing the similarity to superfluidity. (b) Visualization of the nonequilibrium electron pair breaking in $Ba(Fe_{1-x}Co_x)_2As_2$ superconductors, showing evidence for the formation of a photoinduced excitonic state. (c) Schematic representation of the THz exciting and probing process designed to break the nonequilibrium pair.

(computers, optical-electric transducers, spintronic devices), devices for optical communication, quantum computing and communication, spacecraft, rockets, aircrafts, unmanned aerial vehicles, deep sea and underwater vehicles, or equipment for polar and deep space exploration. Advanced materials are typically either traditional materials whose properties have been enhanced or are newly developed materials with a particularly high performance. Furthermore, they may consist of all types of materials and are typically relatively expensive and used for special applications, for example for lasers, magnetic information storage, quantum information storage, optical fibers, spintronics, liquid crystal displays, high-temperature turbine blades (e.g., single crystal blades, thermal barrier coatings), etc.

1.5.2 Structures and Compositions of Condensed Matter or Materials

The arrangement of internal components in condensed matter or materials is called its structure, which can be classified into four levels. The first is the subatomic structure that summarizes the arrangement of the electrons and their spins, and the nuclei (themselves consisting of protons and neutrons). Typically, the most frequently encountered consequences of the subatomic structure are related to the electrons and their spins, protons (H^+), sometimes neutron, and recently also to spin–orbit coupling. The second level is the atomic level, i.e. the arrangement of atoms in space geometry, often in the form of regular crystal lattices, which are the basis a huge variety of ordered crystal structures such as body-centered-cubic (BCC), face-centered-cubic (FCC) or hexagonal close packed (hcp) lattices, or of quasicrystals. The third level is the microscopic scale, formed by regions of ordered crystal structures with sizes from nano- to micrometers and separated by boundaries such as grain boundaries or crystal defects. The fourth level is the macroscopic scale that we can observe by our naked eyes.

Typical images and scales of the four levels are summarized in Figure 1.18. At the macroscopic level, the scale is usually more than 1 μm, which can be observed by our naked eyes, whose resolution is about 0.25 μm. The scale range of the microscopic level ranges from micro- to nanometers (10^{-9} m), which can be observed by optical microscopy (OM) or scanning electron microscopy (SEM) with resolutions from 0.2 μm to 1–3 nm. The scale of the atomic level is about 10^{-10} m and can be characterized by transmission electron microscopy (TEM), atomic force microscopy (AFM), or scanning tunneling microscopy (STM) with resolutions in the range 0.2–0.01 nm.

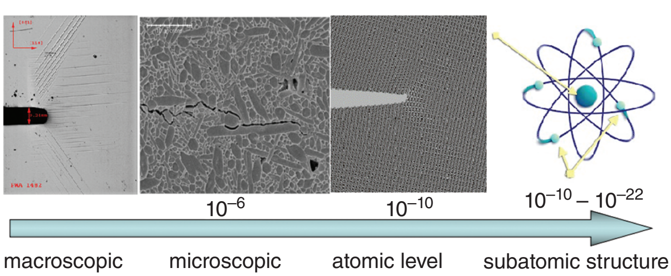


Figure 1.18 Structures of materials at different scales (meters).

The size scale of the subatomic level ranges from 10^{-10} to 10^{-20} m and can be observed directly by means of spherical-aberration-corrected scanning transmission electron microscopy (SAC-STEM, e.g. JEM-ARM300F, Titan TEM 200) with a TEM point resolution of 0.08 nm and scanning transmission electron microscopy (STEM) with a resolution of 0.082 nm, or indirectly by means of spectroscopic methods such as neutron scattering, extended X-ray absorbance fine structure (EXAFS), X-ray near-edge spectroscopy (XANES), X-ray fluorescence (XRF), or light interference (LIGO, with resolution of $\approx 10^{-22}$ m).

The arrangement of atoms in condensed matter depends on the bonding forces, which also determine their physicochemical properties (such as melting temperatures). There are two main classes of forces. The first comprises the primary bonding forces existing in ionic, covalent and metallic solids. The second (and secondary) type is found in van der Waals forces and hydrogen bonding. As shown in Figure 1.19a, when electrons are transferred from one atom to another atom, an ionic bond results. These are often found in compounds composed of electropositive elements (metals such as Na, K, Ca, Mg) with electronegative elements (nonmetals such as O, S, F, Cl). If the electrons are shared jointly by two atoms (Figure 1.19b), the result is called a covalent bond. It occurs typically in compounds with elements of similar electronegativity (e.g. most ceramics and the backbones of polymers). Sometimes, double and even triple bonds can be formed between specific atoms, ewhich can be explained by the hybridization of orbitals. In metallic materials, electrons are shared throughout the whole solid or liquid (liquid metals or alloys such as Hg or InGa alloys) (Figure 1.19c). They are called free or collective electrons, but show different properties at the surface or in the bulk. Van der Waals forces represent weak secondary bonds with bonding energy of less than 41.8 kJ mol^{-1}, often existing between molecules (CH_4, N_2, Ar) or different chains of polymers (e.g. polyethylene (PE), polyvinyl chloride (PVC)). Hydrogen bonding is a special type of secondary bond occurring between molecules or compounds containing hydrogen and elements such as oxygen, nitrogen, fluoride, or sulfur. It is found between molecules of water, ammonia, hydrofluoric acid, carboxylic acid, or ammonium fluoride.

Bonding energies and related melting temperatures of typical materials are summarized in Table 1.2. High-level bonding typically corresponds to a high bonding energies as exemplified by the triple, double and single bonds between carbon and nitrogen in their respective compounds. A high bonding energy will usually result in a high melting temperature (e.g. graphite, silicon, tungsten or iron). The occurrence

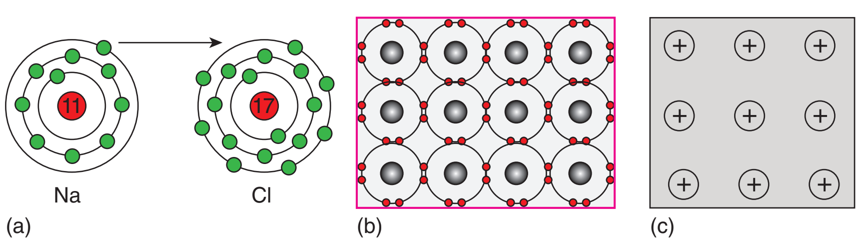


Figure 1.19 Schematic representation of three primary bond types. (a) Ionic bond. (b) Covalent bonds. (c) Metallic bonds.

Table 1.2 Bonding energies and melting temperatures for various substances.

Bonding type	Substance	Bonding energy		Melting temperature
		kJ mol^{-1}	eV (per atom)	°C
Ionic	NaCl	640	3.3	801
Covalent	Si	450	4.7	1410
	C	713	2.4	3550/3652–3697
	C–N	272		
	C=N	615		
	C≡N	891		
	B–F	644		
Metallic	Hg	68	0.7	−39
	AI	324	3.4	660
	Fe	406	4.2	1538
	W	849	8.8	3410
Van der Waals	Ar	7.3	0.08	−189
Hydrogen bond	H_2O	51	0.52	0

of hydrogen bonds in molecules can increase the melting point significantly, as seen in water as compared to argon.

1.5.3 Intrinsic Properties of Condensed Matter and Materials

A property is a trait of materials regarding the kind and magnitude of its response to a specific imposed stimulus, which depends on their microstructures on different levels (e.g. size or shape effects at the nanoscale) and is usually independent of the shape and size of the material at a macroscopic scale. Properties of materials include mechanical moduli (such as the moduli of strength, elongation, yield, and elasticity), electrical properties (resistivity/conductivity, dielectric constant), thermal properties (heat capacity, thermal conductivity, thermal diffusivity), magnetic properties (susceptibility, saturation magnetization, coercivity, magnetostriction), optical properties (light transmittance/reflection/diffraction/focusing, Rayleigh scattering, Raman scattering, optical absorbance, magneto-optic rotation), or chemical reactivity (reaction activation energy, electron affinity, catalytic properties). At the atomic scale level, the types and isotopes of the involved atoms have to be considered, their masses, electron configurations/states and their electronegativities, which all significantly affect the intrinsic physicochemical properties of materials, in particular for the magneto-electrical exchange coupling or electron spin lattice coupling in the crystal lattice of interfaces or multilayered thin films, 2D materials and/or nanohybrids.

1.6 Main Research Areas in Condensed Matter Physics

The final goals of the investigation of condensed matter are to identify suitable materials for specific applications and to produce and process them economically at large scale, both of which depend on the microstructures and physicochemical properties of these materials. The relations between processing, structures, properties, and performance are illustrated in Figure 1.20. The goal and means in this research is therefore to define the intrinsic physicochemical properties of materials that affect their performance in the desired application. When this is accomplished, suitable structures on different scales (starting from the atomic scale, including the essential elements and the necessary composition, then continuing to the microscopic and finally the macroscopic scale) can be designed in accordance with the relations between microstructures and properties of materials. Finally, suitable processing methods can be developed for the desired structures. The logical chain of relations is from processing to structure, then to properties and finally to the material's performance in application.

The study of condensed matter or materials includes two main aspects: materials science and materials engineering. Materials science involves investigating the relations between the structures and properties of materials. Materials engineering is about designing or engineering the structure of a material so as to produce a predetermined set of properties. The key to success is the precise characterization of composition, structure, and properties of the materials including the development of suitable characterization methods, since the characterization part is crucial for the study of all relations between material structures, properties, and performance and thus also for the design and fabrication of materials with desired functions and structures.

In this book, some of the most important advanced characterization methods for the investigation of materials are presented, including X-ray crystallography, X-ray diffraction, X-ray absorption (EXAFS and XANES), electron microscopy (SEM, TEM), energy dispersion spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS), wavelength-dispersion X-ray spectroscopy (WDXS), electron probe microanalysis (EPMA), AFM, Fourier-transform infrared (FTIR) spectroscopy, and

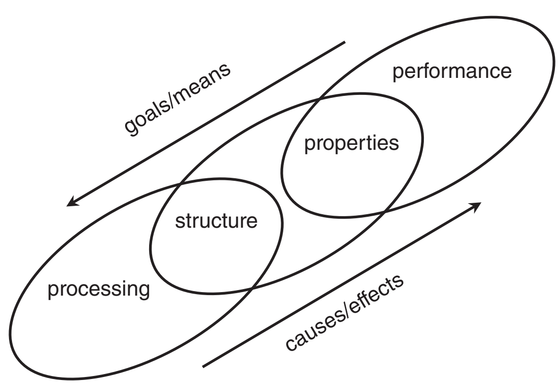


Figure 1.20 Relationships between processing, structures, properties, and performance in materials science and engineering.

so on. Their basic physical and chemical principles will be introduced and the corresponding instruments will be described. Some typical experiments will be provided to students as a training course, which will enable them to characterize the properties of typical samples (such as magnetoplasmonic thin films and nanostructured or 2D materials) using the described instruments.

Questions for Thinking

1.1 Describe the classification of matter and explain the characteristics of the different types.

1.2 Describe the different elementary particles and how they can be classified on the basis of their fundamental interactions.

1.3 Define the fundamental constants and explain their context and meaning.

1.4 Describe how scientists can deduce the existence of dark matter from gravitational observations and electromagnetic measurements and explain the proposed relation between dark matter and the accelerated universe.

1.5 Define condensed matter, explain its classification and describe the main properties of the different types.

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