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978-0-521-76511-4 — Foundations of Nuclear and Particle Physics
T. William Donnelly, Joseph A. Formaggio, Barry R. Holstein, Richard G. Milner, Bernd Surrow
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1 Introduction

The past one hundred years has witnessed enormous advances in human understanding of the physical universe in which we have evolved. For the past fifty years or so, the Standard Model of the subatomic world has been systematically developed to provide the quantum mechanical description of electricity and magnetism, the weak interaction, and the strong force. Symmetry principles, expressed mathematically via group theory, serve as the backbone of the Standard Model. At this time, the Standard Model has passed all tests in the laboratory. Notwithstanding this success, most of the matter available to experimental physicists is in the form of atomic nuclei. The most successful description of nuclei is in terms of the observable protons, neutrons, and other hadronic constituents, and not the fundamental quarks and gluons of the Standard Model. Thus, the professional particle or nuclear physicist should be comfortable in applying the hadronic description of nuclei to understanding the structure and properties of nuclei. Experimentally, lepton scattering has proved to be the cleanest and most effective tool for unraveling the complicated structure of hadrons. Its application over different energies and kinematics to the nucleon, few-body nuclei, and medium- and heavy-mass nuclei has provided the solid body of precise experimental data on which the Standard Model is built.

In addition, the current understanding of the microcosm described in this book provides answers to many basic questions: How does the Sun shine? What is the origin of the elements? How old is the Earth? Further, it underscores many aspects of modern human civilization, e.g., MRI imaging uses the spin of the proton, nuclear isotopes are essential medical tools, nuclear reactions have powered the Voyager spacecraft since 1977 into interstellar space.

The purpose of the book is to allow the graduate student to understand the foundations and structure of the Standard Model, to apply the Standard Model to understanding the physical world with particular emphasis on nuclei, and to establish the frontiers of current research. There are many outstanding questions that the Standard Model cannot answer. In particular, astrophysical observation strongly supports the existence of dark matter, whose direct detection has thus far remained elusive.

Essential to making progress in understanding the subatomic world are the sophisticated accelerators that deliver beams of particles to experiments. Existing lepton scattering facilities include Jefferson Laboratory in the US, muon beams at CERN, and University of Mainz and University of Bonn in Germany. Intense photon beams are used at the HIγS facility at Duke University in the U.S., and in Japan at LEPS at SPring-8, and at Elphs at Tohoku University. Hadrons beams are used at the TRIUMF laboratory in Vancouver, Canada, using the COSY accelerator in Juelich, Germany, at the Paul Scherrer Institute (PSI) in Switzerland, and at the Joint Institute for Nuclear Research (JINR), Dubna, Russia. Neutron beams are used for subatomic physics research at the Institut Laue-Langevin (ILL), Grenoble, France, at both the Los Alamos Neutron Science Center (LANSCE) and the Spallation Neutron Source (SNS) in the US, and at the future European Spallation Source (ESS) in Sweden. The hot, dense matter present in the early universe is studied using heavy-ion beams at the Relativistic Heavy Ion Collider (RHIC) in the US and at the Large Hadron Collider (LHC) at CERN. Of course, searches for new physics beyond the Standard Model are underway at the high-energy frontier of 13 TeV at CERN. Understanding the structure of nuclei, with particular emphasis on the limits of stability, is a major worldwide endeavor. The most powerful facility at present is the Rare Isotope Beam Facility (RIBF) at RIKEN in Japan. In the US, the frontier experiments at present are carried out at the National Superconducting Cyclotron Laboratory at Michigan State University (MSU) and at the ATLAS facility at Argonne National Laboratory. A future Facility for Rare Isotope Beams (FRIB) is under construction at MSU and is expected to have world-leading capabilities by 2022, as is a facility in South Korea, the Rare Isotope Science Project (RAON). Hadron beams for research are available at Los Alamos and the Spallation Neutron Source in the US, GSI in Germany, J-PARC in Japan, and NICA at Dubna, Russia. A major new facility FAIR is planned at GSI. Neutrino beams are generated at Fermilab, CERN, and J-PARC and directed at detectors located both at the Earth's surface and deep underground. A major new Deep Underground Neutrino Experiment (DUNE) is planned in the US using the Fermilab beam and the Sanford Underground Research Laboratory in South Dakota. Belle II, an experiment at the high luminosity e^+e^- collider SuperKEKB in Japan, will come online within the next several years and provide new stringent tests of flavor physics. Annihilation of electrons and positrons is used to probe the Standard Model at both the Double Annular ϕ Factory for Nice Experiments (DAFNE) collider in Frascati, Italy as well as the Beijing Electron Positron Collider (BEPC) in China. Finally, a high luminosity electron–ion collider has been widely identified by as the next machine to study the fundamental quark and gluon structure of nuclei and machine designs are under development in the US, Europe, and China.

To begin, let us remind the reader of the particles that comprise the Standard Model (see Fig. 1.1). As will be discussed in due course, the Standard Model starts with massless particles and then, through spontaneous symmetry breaking, these interacting particles acquire masses in almost all cases. The measured spectrum of masses is still a mystery; indeed, in the case of the neutrinos, intense effort is going into determining the actual pattern of masses in Nature. Note that at this microscopic level, but also at the hadronic/nuclear level, when one says that particles interact with one another what is meant is that some particle is exchanged between two other particles, thereby mediating the interaction. For instance, an electron can exchange a photon with a quark whereby the photon mediates the $e-q$ interaction. Or two nucleons (protons and neutrons) can exchange a pion and one has the long-range part of the NN interaction.

The organizational principle for this book centers on building from the underlying fundamental particles (leptons, quarks, and gauge bosons) to hadrons (mesons and baryons) built from $q\bar{q}$ and qqq, respectively, and on to many-body nuclei or hypernuclei built from these hadronic constituents. At very low energies and momenta the last are the relevant effective degrees of freedom, since, using the Heisenberg Uncertainty Principle, such kinematics

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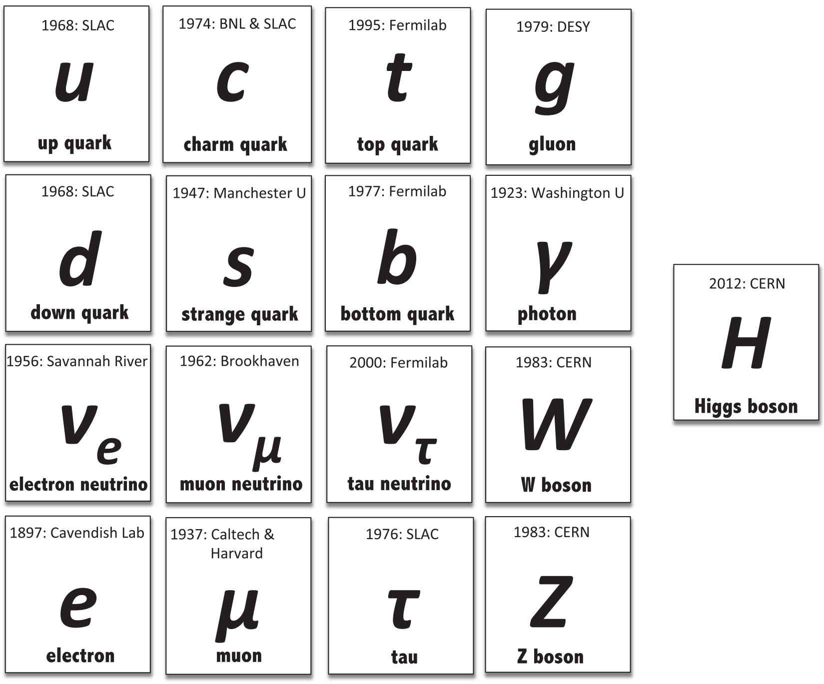

Fig. 1.1 The particles of the Standard Model.

translate into large distance scales where the microscopic ingredients are packaged into the macroscopic hadronic degrees of freedom. Then, as the energy/momentum is increased, more and more of the sub-structure becomes relevant, until at very high energy/momentum scales the QCD degrees of freedom must be used to represent what is observed.

Naturally, there can be a blending between the different degrees of freedom and, where they overlap, it may be possible to use one language or the other. And in some cases it turns out to be important to address both the "fundamental" physics issues and the larger-scale nuclear structure issues at the same time. This book attempts to present the foundations of the general field of nuclear/particle physics – sometimes called subatomic physics – in a single volume, trying to maintain a balance between the very microscopic QCD picture and the hadronic/nuclear picture.

The outline of the book is the following. After this introductory chapter, in Chapter 2 the basic ideas of symmetries are introduced. In general discussions of quantum physics it is often advantageous to exploit the exact (or at least approximate) symmetries in the problem, for then selection rules emerge where, for instance, matrix elements between specific initial and final states of certain operators can only take on a limited set of values. An example of what will be important in later discussions is the use of good angular momentum quantum numbers and the transformation properties of multipole operators (see Chapter 7) where conservation of angular momentum leads to a small set of allowed values for matrix elements of such operators taken between states that have known spins. Another example of an important (approximate) symmetry is provided by invariance under spatial

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inversion, namely, parity: to the extent that parity is a good symmetry again only specific transitions can occur. Other symmetries discussed in Chapter 2 include charge conjugation and time reversal, as well as discrete unitary flavor symmetries, the latter being important for classifying the hadrons built from constituent quarks, namely, the subject of Chapter 3.

After these introductory discussions the book proceeds to build up from particles to hadrons to many-body nuclei, starting in Chapter 4 with the Standard Model of particle physics. In this one begins with massless leptons, quarks, and gauge bosons together with the Higgs and then through spontaneous symmetry breaking generates the basic familiar building blocks with their measured masses. The recent successful discovery of the Higgs boson at the Large Hadron Collider (LHC) is summarized.

The Standard Model has proven to be extremely successful and, at the time of writing, there is as yet no clear evidence that effects beyond the Standard Model (BSM) are needed; in the final chapter of the book, Chapter 21 we return to summarize some of these BSM issues. For the present, following the path of increasing complexity, in Chapters 5 and 6 the ideas and models employed in descriptions of low-Q^2, strong coupling QCD are discussed in some detail, including what is not typically covered in a book at this level, namely, chiral symmetry.

Chapters 7 through 10 form a distinct section where the aim is to visualize the structure of the proton, neutron, and nuclei in terms of the fundamental quarks and gluons of QCD. At low and medium energies, this is carried out using lepton scattering where intense beams of high quality are available. Thus, snapshots of the nucleon charge and magnetism and quark momentum and spin distributions are directly obtainable in the form of structure functions and form factor distributions. Chapter 7 provides an introduction to lepton scattering, including both parity-conserving and parity-violating scattering. Since lepton scattering is being used as a common theme in much of the rest of the book, Chapter 7 is the first stop along the way where the multipole decomposition of the electromagnetic current is developed in some detail. This is followed in Chapter 8 by a discussion of elastic scattering from the nucleon. At this time, a direct connection between elastic scattering and QCD remains elusive and the most successful theoretical description is in terms of hadrons. Chapter 9 describes the current understanding of the structure of hadrons in terms of high-energy lepton scattering and this is directly interpretable in terms of perturbative QCD. Further, the gluon momentum and spin distributions are indirectly determined via the QCD evolution equations. The parton distributions are snapshots of nucleon structure over different spatial resolutions and with different shutter speeds. Lepton scattering constitutes a theme of the book at both high- and low-energy scales and with the full electroweak interaction. Due to the lack of suitable lepton beams, QCD is at present probed at the highest energies using hadron beams. This is the focus of Chapter 10 and the measurements extend and complement those with lepton beams in the previous chapters. For example, direct experimental information on the contribution of gluons to the spin of the proton has become possible only through polarized proton–proton collisions.

The above constitutes the first part of the book after which the building-up process moves from hadrons to nuclei. The next step is to deal with the simplest system that is not a single baryon, namely, the system of two nucleons, discussing *NN* scattering and the properties of the only bound state with baryons number two, the deuteron in

Chapter 11. For the latter the EM form factors and electrodisintegration are treated in some detail. After this, in Chapter 12 the so-called few-body nuclei, those with $A = 3$ and 4, constitute the focus.

For nuclei heavier than the $A = 2$, 3, and 4 cases, treating the many-body problem forms the basic issue, and accordingly in Chapter 13 an overview of the general nuclear "landscape" is presented, showing the typical characteristics of nuclei, including the regions where nuclei are stable (the "valley of stability") out to where they are just unstable (the "drip lines"), and their regions of especially tight binding (the "magic numbers"). Also in this chapter the concept of infinite nuclear matter and neutron matter is introduced and treated in some detail. This is followed in Chapter 14 by a discussion of a selection of typical nuclear models. As mentioned earlier, this book is not intended to be a theoretical text on nuclear many-body theory. That said, this chapter has sufficient detail that the basic issues in this area can be appreciated. Importantly, the tools used in this part of the field must be capable of dealing with nonperturbative interacting systems and accordingly this provides a theme in this chapter where discussions of the so-called Hartree–Fock (HF) and Random Phase Approximations (RPA) are provided together with an introduction to diagrammatic representations of the approximations. Also typical collective models are discussed as examples of how one may start with some classical oscillation or vibration of the nuclear fluid, make harmonic approximations to those movements, and then quantize the latter to arrive at semi-classical descriptions of nuclear excitations ("surfons," "rotons," etc.), as is done in many areas of physics where similar techniques are employed.

The above discussions are then followed by two chapters focused on electron scattering from nuclei, Chapter 15 where elastic scattering is treated in some detail, together with some applications of the models introduced in Chapter 14 for low-lying excited states. Chapter 16 continues this by treating higher-lying excitations where different modeling is required. Specifically, the Relativistic Fermi Gas (RFG) model is derived and used as a prototype for more sophisticated approaches. It is also the starting point for similar discussions of neutrino scattering from nuclei to follow in Chapter 18. Before those are presented, in Chapter 17 the weak interaction provides the focus and we see how precision beta-decay experiments can be used as a probe for beyond Standard Model physics. Chapter 18 deals with the subject of neutrinos and the fact that one flavor can oscillate into another, since neutrinos are known to have mass. At the time of writing, the detailed nature of the mass spectrum, whether or not CP violation is present in the leptonic sector and whether neutrinos are Dirac or Majorana particles are still under investigation and intensive efforts are being undertaken worldwide to shed light on these interesting questions.

In Chapter 19 the high-energy regime (essentially quark–quark scattering) is re-visited within the context of relativistic heavy-ion scattering. Here the nature of the modeling is somewhat different from that discussed in most of the rest of the book with statistical mechanics being called into play together with fluid dynamics. An informed practitioner in the general field of nuclear/particle physics should be familiar with this subject as well.

The book concludes with Chapter 20 on nuclear and particle astrophysics using many of the concepts treated in the rest of the book, and with Chapter 21 where the types of signatures of effects beyond the Standard Model are summarized, together with two appendices where some useful material is gathered.

While we strongly advocate using the book to explore both nuclear and particle physics in a coherent, balanced way, nevertheless it might be that it will also be used in a course that emphasizes one subfield or the other. Accordingly, we suggest the following "road maps" to help the reader negotiate the text for those purposes. When the emphasis is placed on particle physics we suggest paying the closest attention to Chapters 2 to 10 and 21, with some parts of Chapters 17, 18, and perhaps 19, and when the emphasis is on nuclear physics Chapters 2, 7, 11 to 18, 20 and perhaps 19.

We strongly recommend the following online resources as important tools for enhancing the material presented in this book.

1. The Review of Particle Physics, Particle Data Group
   http://pdg.lbl.gov includes a compilation and evaluation of measurements of the properties of the elementary particles. There is an extensive number of review articles on particle physics, experimental methods, and material properties as well as a summary of searches for new particles beyond the SM.
2. National Nuclear Data Center
   http://www.nndc.bnl.gov is a source of detailed information on the structure, properties, reactions, and decays of known nuclei. It contains an interactive chart of the nuclides as well as a listing of the properties for ground and isomeric states of all known nuclides.

We conclude this introductory chapter with some exercises designed to introduce some of the concepts which we hope our particle/nuclear students will be able to address.

Exercises

1.1 US Energy Production
In 2011, the United States of America required 3,856 billion kW-hours of electricity. About 20% of this power was generated by $\sim$100 nuclear fission reactors. About 67% was produced by the burning of fossil fuels, which accounted for about one-third of all greenhouse gas emissions in the US. The remaining 13% was generated using other renewable energy resources. Consider the scenario where all the fossil fuel power stations are replaced by new 1-GW nuclear fission reactors. How many such reactors would be needed?

1.2 Geothermal Heating
It is estimated that 20 TW of heating in the Earth is due to radioactive decay: 8 TW from ^{238}U decay, 8 TW from ^{232}Th decay, and 4 TW from ^{40}K decay. Estimate the total amount of ^{238}U, ^{232}Th, and ^{40}K present in the Earth in order to produce such heating.

1.3 Radioactive Thermoelectric Generators
A useful form of power for space missions which travel far from the Sun is a radioactive thermoelectric generator (RTG). Such devices were first suggested by the science fiction writer Arthur C. Clarke in 1945. An RTG uses a thermocouple

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to convert the heat released by the decay of a radioactive material into electricity by the Seebeck effect. The two Voyager spacecraft have been powered since 1977 by RTGs using ^{238}Pu. Assuming a mass of 5 kg of ^{238}Pu, estimate the heat produced and the electrical power delivered. (Do not forget to include the $\sim 5\%$ thermocouple efficiency.)

1.4 Fission versus Fusion

Energy can be produced by either nuclear fission or nuclear fusion.

a) Consider the fission of ^{235}U into ^{117}Sn and ^{118}Sn, respectively. Using the mass information from a table of isotopes, calculate (i) the energy released per fission and (ii) the energy released per atomic mass of fuel.
b) Consider the deuteron–triton fusion reaction

$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \to {}^{4}\mathrm{He} + \mathrm{n}\,.$$

Using the mass information from the periodic table of the isotopes, calculate (i) the energy released per fusion and (ii) the energy released per atomic mass unit of fuel.

1.5 Absorption Lengths

A flux of particles is incident upon a thick layer of absorbing material. Find the absorption length, the distance after which the particle intensity is reduced by a factor of $1/e \sim 37\%$ (the absorption length) for each of the following cases:

a) When the particles are thermal neutrons (i.e., neutrons having thermal energies), the absorber is cadmium, and the cross section is 24,500 barns.
b) When the particles are 2 MeV photons, the absorber is lead, and the cross section is 15.7 barns per atom.
c) When the particles are anti-neutrinos from a reactor, the absorber is the Earth, and the cross section is 10^{-19} barns per atomic electron.

2 Symmetries

2.1 Introduction

When studying quantum systems, exploiting knowledge about the inherent symmetries is usually an important step to take before addressing issues of dynamics [Sch55, Sak94, Rom64, Gri08]. This motivates a discussion of group theory, and so we shall begin by summarizing some of the basic elements needed, particularly when discussing symmetries in particle and nuclear physics. More details can be found in specialized texts on the subject [Ham62, Clo79]. Noether's theorem states that if the Hamiltonian is invariant under a continuous group of transformations, then there exist corresponding conserved quantities and accordingly one wants to discuss various natural symmetries and the conservation laws that accompany them (see [Rom64] Chapter IV for a clear discussion of Noether's theorem, and also see Exercise 2.1). Specifically, in Table 2.1 are several important examples that are believed to be absolute symmetries and hence exact conservation laws. Some of these specific examples are discussed in more detail in what follows.

Furthermore, there are symmetries that are not completely respected in Nature, although characterizing the states used in terms of eigenstates of these approximate symmetries often proves fruitful; some examples are given in Table 2.2. We shall be using all of these concepts throughout the book. Next let us turn to a brief discussion of some of the basics needed when treating symmetries using group theory.

Representations

By an n-dimensional representation of a group G one means a mapping

$$G \rightarrow GL\{p\}(n) \tag{2.1}$$

$$g \rightarrow A(g) \tag{2.2}$$

which assigns to every element g a linear operator $A(g)$ in some n-dimensional complex vector space, the so-called carrier space of the representation $GL(n)$, such that the image of the identity e is the unit operator I and that group operations are preserved

$$A(gg') = A(g)A(g') \; . \tag{2.3}$$

Throughout the book we shall frequently encounter infinite-dimensional continuous groups (Lie groups) whose elements are labeled uniquely by a set of parameters which can change continuously (see [Rom64] for an introductory discussion). An example is provided by

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Table 2.1 Exact conservation laws

Symmetry	Conservation law
translation in time	energy
translation in space	linear momentum
rotation in space	angular momentum
local gauge invariance	charge
transformations in color space	color

Table 2.2 Approximate conservation laws

Approximate symmetry	Conservation law
spatial inversion	parity, P
particle–antiparticle interchange	charge conjugation, C
temporal inversion	time-reversal invariance, T
transformations in isospace	isospin, I (or T)
transformations in flavor space	flavor

the rotation group, that is, the group of continuous rotations. For the Lie groups that are encountered frequently in this book it is sufficient to study the mapping from the Lie algebra into $GL(n)$,

$$L_\alpha \to T_\alpha \,, \tag{2.4}$$

where the $\{T_\alpha\}$ preserve the Lie-algebra commutation relations. If a subspace of the carrier space of some representation is left unchanged by all operators T_α, it is called an invariant subspace and the representation is reducible; otherwise it is irreducible. If the correspondence

$$g \to A(g) \tag{2.5}$$

defines a representation of the group G, then the correspondence

$$g \to \left(A^{-1}\right)^T (g) = A^T(g^{-1}) \tag{2.6}$$

also defines a representation of the group, the so-called conjugate representation. For a Lie group we find that the representation matrices for the conjugate representation are given by

$$(T_\alpha)_{\text{conjugate}} = -T_\alpha^* \,. \tag{2.7}$$

When discussing the implications of symmetries in particle and nuclear physics one frequently encounters the special unitary groups in N dimensions, $SU(N)$, which can be represented using $N \times N$ matrices U satisfying

$$U^{-1} = U^\dagger \text{ and } \det U = 1 \,. \tag{2.8}$$

The importance of the continuous Lie group $SU(N)$ lies in the fact that these matrices describe transformations between N basis states $\{|e_\alpha\rangle, \alpha = 1, \ldots, N\}$ preserving orthonormality

$$\langle Ue_\alpha \mid Ue_\beta \rangle = \left\langle e_\alpha \middle| U^\dagger Ue_\beta \right\rangle = \langle e_\alpha \mid e_\beta \rangle = \delta_{\alpha\beta} \; . \tag{2.9}$$

We shall see several examples of physical states labeled using various symmetries, specifically by spin and by isospin ($SU(2)$), by flavor and by color ($SU(3)$), or by higher groups, e.g., $SU(6)$ for spin-flavor. Within the context of $SU(N)$, a representation is reducible if it is possible to choose a basis in which the matrices T_α take the block form

$$T_\alpha = \begin{pmatrix} A & 0 & 0 & 0 \\ 0 & B & 0 & 0 \\ 0 & 0 & C & 0 \\ 0 & 0 & 0 & \cdots \end{pmatrix} , \tag{2.10}$$

where $A, B, C, \ldots$ are lower-dimensional irreducible sub-matrices when the original matrix T_α is fully reduced. Given an irreducible representation $\{T_\alpha\}$, the only linear operators $\mathcal{O}$ which commute with every T_α are multiples of the identity and also the converse:

$$[T_\alpha, \mathcal{O}] = 0 \; \forall \; \alpha \quad \Longrightarrow \mathcal{O} = \lambda I \; . \tag{2.11}$$

Any unitary matrix can be written as

$$U = e^{iH} = 1 + iH - \frac{1}{2!}H^2 + \cdots , \tag{2.12}$$

where H is a traceless Hermitian matrix. For a Lie group the elements of the group are characterized by a finite number of real parameters $\{a_\alpha\}$ and for $SU(N)$ one finds that there are $n = N^2 - 1$ such parameters. Accordingly, one can write

$$H = \sum_{\alpha=1}^{n} a_\alpha L_\alpha \; , \tag{2.13}$$

where the $\{L_\alpha\}$ form a basis for the $N \times N$ Hermitian matrices known as the generators of the group $SU(N)$. To study the representations, it is sufficient to study the generators and their commutation relations,

$$\left[L_\alpha, L_\beta\right] = i c_{\alpha\beta\gamma} L_\gamma \; , \tag{2.14}$$

where the latter are characterized by the antisymmetric structure constants $\left\{c_{\alpha\beta\gamma}\right\}$.

2.2 Angular Momentum and *SU*(2)

Let us begin by discussing the representations of $SU(2)$ in a systematic way. The basis space is three-dimensional and is spanned by $\boldsymbol{S} = (S_1, S_2, S_3)$, that satisfy the commutation relations [Edm74]

$$\left[S_i, S_j\right] = i\epsilon_{ijk} S_k \; , \tag{2.15}$$