Preface

The need for writing a self-contained comprehensive book on the physics of neutrino interactions had been in our minds for a long time, while teaching various graduate courses in high energy physics and nuclear physics and conducting research in the field of neutrino physics at the Aligarh Muslim University. We also realized the need for such a book while attending many topical workshops, conferences, and short-term schools like NuFact, NuInt, NuSTEC, etc., held in the USA, Europe, Japan, and elsewhere in the area of neutrino physics and while responding to questions asked by the young researchers in many formal and informal discussions. The aforementioned scientific events bring together research students and senior scientists working on various aspects of neutrino physics common to nuclear physics, particle physics, and astrophysics, which make the subject interdisciplinary. In recent times, the research activity in the field of neutrino physics, around the world, and its applications in the other areas of physics has attracted a large number of students to this field. It was, therefore, felt that this is an appropriate time to write a book on the physics of neutrino interactions focusing on introducing the basic mathematical and physical concepts and methods with the help of simple examples to illustrate the calculation of various neutrino processes relevant for applications in particle physics, nuclear physics, and astrophysics, for the benefit of all those interested in learning the subject.

The main aim of the book is to present a pedagogical account of the physics of neutrino interactions, with balance among its theoretical and experimental aspects, for describing various neutrino scattering processes from leptons, nucleons, and nuclei used in studying neutrino properties like its mass, charge, magnetic moment, and the newly discovered phenomenon of neutrino mixing and oscillations. The book is intended primarily for graduate students and young post-doctoral research scientists working in neutrino physics but it can also be used by advanced undergraduates who have some exposure to basic courses in special theory of relativity, quantum mechanics, nuclear physics, particle physics, and are interested in neutrino physics.

There is hardly a single book which discusses all the above-mentioned aspects of neutrino physics in one place. The reason is the diversity of the various aspects of neutrino physics in their origin, development, and technical details, which have been discussed and formulated at different times and are described in detail in different books devoted to a particular aspect of neutrino physics. For example, there are many books on V-A theory of weak interactions and neutrino, standard model of electroweak interactions and neutrino, and recently many books on the physics of neutrino mass, mixing and oscillations. Most of these books are excellent, but they mainly focus on the particle physics aspect of neutrinos and their interactions.

However, looking back at the origin of neutrino studies and the development of neutrino physics over the last 90 years, we see that neutrino physics has truly become an interdisciplinary subject involving particle physics, nuclear physics, and astrophysics. The basic reason for writing this book is to present neutrino physics as an interdisciplinary subject and describe it in a self-contained pedagogical manner with conceptually simple but technically rigorous treatment of various topics, with appropriate historical perspective, to keep the reader interested throughout the book as he/she goes through various topics like the mathematical preliminaries on relativistic field theory and local gauge field theories and then to the standard model and its applications to various neutrino scattering processes from leptons, nucleons, and nuclei, and finally the need for physics beyond the standard model. The book is based on the actual teaching material used by us in graduate courses at the Aligarh Muslim University for many years and also on the research work done by us during our collaboration with the experimental physicists working on the neutrino oscillation experiments at K2K, MiniBooNE, MINERvA, T2K, and DUNE.

After introducing various aspects of neutrino physics in Chapter 1, we describe briefly in Chapters 2–4 the mathematical preliminaries needed to follow the subject assuming no prior knowledge of relativistic quantum field theory in order to make the book self-contained. A historical approach is then followed in Chapters 5 and 6 to describe the phenomenological V$-$A theory of weak interactions and its development starting from the Fermi theory of β-decay to the Cabibbo–Kobayashi–Maskawa (CKM) formulation of weak interactions of three-flavors of quark and lepton doublets $(u\ d')$, $(c\ s')$, $(t\ b')$ and $(\nu_e\ e)$, $(\nu_\mu\ \mu)$ and $(\nu_\tau\ \tau)$, and their antiparticles, where we also discuss the limitations of the phenomenological V$-$A theory mediated by the massive intermediate vector bosons (IVB). The theoretical attempts for finding a convergent and renormalizable theory of weak interactions mediated by the massive intermediate vector bosons led to the concept of local gauge field theory with continuous symmetry which are spontaneously broken by the Higgs mechanism to generate mass. The concept was used by Weinberg and Salam to create a theory of leptons and their electroweak interactions which was later extended to quarks using Glashow–Iliopoulos–Maiani (GIM) mechanism to formulate the standard model (SM) for the unified theory of electromagnetic and weak interactions. All these developments are described in Chapters 7 and 8.

The standard model is then applied to perform calculations of (anti)neutrino scattering from leptons in Chapter 9 and various other scattering processes like quasielastic (QE), inelastic (IE), and deep inelastic scattering (DIS) from nucleons in Chapters 10–13, with essential details relegated to relevant appendices. Most of the (anti)neutrino scattering experiments for the cross section measurements at high energies have been done from the nuclear targets in the past while the recent experiments in the low and intermediate energy regions of few MeV to a few GeV are also being done in nuclear targets in context of neutrino oscillation experiments, where nuclear medium effects play an important role. In view of this we devote the next three chapters, 14–16, to discuss the (anti)neutrino scattering process of QE, IE, and DIS from the nuclear targets in some detail. The next two chapters, 17 and 18, are then used to discuss the various sources of neutrinos, their energy distribution, fluxes of neutrinos including the techniques used for their detection and to introduce the physics and phenomenology of neutrino mixing and oscillations and their mathematical formulation along with the present status of the progress made in understanding, theoretically as well as experimentally, the various parameters like the mass squared differences of neutrinos Δm^2_{ij}, the mixing angles $\theta_{ij}(i < j = 1-3)$, and the CP violating phase δ used for describing the phenomenology of neutrino oscillations.

Neutrinos are known to play very important role in astrophysics and cosmology, and there are excellent books written on the subject. However, we felt it useful to give an essence of the important role neutrinos play in astrophysics to motivate student's interest in this field and Chapter 19 is

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devoted to this topic highlighting the physics aspects without technical details. Notwithstanding the success of the standard model in describing the physics of neutrino interactions, the existence of neutrino mass, mixing and phenomenon of neutrino oscillation demonstrates that there is physics beyond the standard model (BSM). In fact there are many other phenomenon which imply the existence of physics beyond the standard model. We attempt to describe some of them in Chapter 20 and emphasize the need to make efforts to understand, theoretically as well as experimentally, BSM physics.

In summary the special features of the book are:

- It is comprehensive, self-contained, and requires only a basic knowledge of special theory of relativity and quantum mechanics, with some exposure to nuclear and particle physics at the undergraduate level, to follow the subject.
- It gives a pedagogical description of neutrino properties and neutrino interactions starting from the Fermi theory of β-decay to the phenomenological V–A theory formulation by Cabibbo–Kobayashi–Maskawa applicable to the three flavours of quark and lepton doublets.
- It describes the role of local gauge field theories in formulating the fundamental interactions and explains in detail the concept of spontaneous breaking of local gauge symmetry and generation of mass using Higgs mechanism in the formulation of standard model of electroweak interaction of quarks and leptons as done by Glashow, Salam, and Weinberg.
- It discusses in detail the applications of the standard model (SM) to neutrino scattering from leptons and hadrons. Processes like QE, IE, and DIS from nucleons and nuclei are presented, emphasizing the importance of nuclear medium effects.
- It introduces the physics of neutrino oscillations at a basic level including the matter enhancement due to the Mikheyev–Smirnov–Wolfenstein effect in two-flavor and three-flavor oscillation and discusses the present status of the subject with future prospects for the observation of CP violation, mass hierarchy, and sterile neutrinos.
- It highlights the role of neutrinos in astrophysics and also emphasizes the need for physics beyond the standard model (BSM) by describing the phenomenon of neutrinoless double beta decay (NDBD) and some other phenomenon like the existence of lepton flavor violation (LFV) and flavor changing neutral currents (FCNC).

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