# ADVANCED TOPICS
# IN SCIENCE AND TECHNOLOGY IN CHINA

# ADVANCED TOPICS IN SCIENCE AND TECHNOLOGY IN CHINA

---

Zhejiang University is one of the leading universities in China. In Advanced Topics in Science and Technology in China, Zhejiang University Press and Springer jointly publish monographs by Chinese scholars and professors, as well as invited authors and editors from abroad who are outstanding experts and scholars in their fields. This series will be of interest to researchers, lecturers, and graduate students alike.

Advanced Topics in Science and Technology in China aims to present the latest and most cutting-edge theories, techniques, and methodologies in various research areas in China. It covers all disciplines in the fields of natural science and technology, including but not limited to, computer science, materials science, life sciences, engineering, environmental sciences, mathematics, and physics.

Zhi-Zhong Xing
Shun Zhou

# Neutrinos in Particle Physics, Astronomy and Cosmology

With 61 figures

ZHEJIANG UNIVERSITY PRESS
浙江大学出版社

Springer

*Authors*
Prof. Dr. Zhi-Zhong Xing
Institute of High Energy Physics,
Chinese Academy of Sciences,
Beijing 100049, China
E-mail: xingzz@ihep.ac.cn

Dr. Shun Zhou
Institute of High Energy Physics,
Chinese Academy of Sciences,
Beijing 100049, China
E-mail: zhoush@ihep.ac.cn

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut),
D-80805 München, Germany
E-mail: zhoush@mppmu.mpg.de

ISSN 1995-6819 e-ISSN 1995-6827
Advanced Topics in Science and Technology in China

ISBN 978-7-308-08024-8
Zhejiang University Press, Hangzhou

ISBN 978-3-642-17559-6 e-ISBN 978-3-642-17560-2
Springer Heidelberg Dordrecht London New York

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

# Preface

Neutrinos are a kind of electrically neutral and extremely light spin-1/2 particles which only have weak and gravitational interactions with matter. Their distinctive properties make them become one of Nature's most mysterious messengers. Since the birth of neutrino physics in 1930, when Wolfgang Pauli postulated the existence of neutrinos as a "desperate remedy" for the continuous energy spectrum observed in the beta decay, intriguing puzzles and exciting discoveries have been associated with elusive neutrinos in nuclear physics, particle physics, astronomy and cosmology.

Enrico Fermi took advantage of Pauli's neutrino hypothesis and invented an effective theory of weak interactions in 1933. There were several milestones associated with neutrinos in the subsequent development of particle physics. The discovery of electron antineutrinos from nuclear reactors was made by Clyde Cowan and Frederick Reines in 1956. In the same year Tsung-Dao Lee and Chen Ning Yang published a seminal paper on parity violation in weak interactions, which was soon confirmed by a number of elegant experiments. Motivated by the experimental fact that neutrinos were almost massless and left-handed, Richard Feynman and Murray Gell-Mann proposed the $V-A$ theory of weak interactions in 1958. Leon Lederman, Melvin Schwartz and Jack Steinberger discovered the muon neutrino, a sister of the electron neutrino, by doing the first high-energy accelerator neutrino experiment in 1962. A unified gauge theory of electromagnetic and weak interactions, the so-called standard model (SM), was established by Sheldon Glashow, Steven Weinberg and Abdus Salam in the 1960's. This theory was experimentally verified in 1973, thanks to the discovery of neutral-current interactions via the neutrino-electron and antineutrino-electron scattering. The massive mediators of weak interactions (i.e., $W^{\pm}$ and $Z^0$ bosons) were finally observed by Carlo Rubbia and Simon van der Meer in 1983.

In this book we start with the SM and elaborate on the intrinsic properties and fundamental interactions of massless neutrinos. Thanks to several compelling neutrino oscillation experiments done in the 1990's and 2000's, we are now convinced that neutrinos are massive and lepton flavors are mixed. Generally speaking, one has to rely on a specific neutrino mass model when discussing massive neutrinos and their interactions with matter. But our main strategy is to focus on the model-independent properties of elusive neutrinos, such as their electromagnetic dipole moments, flavor mixing, CP violation and oscillations in vacuum and matter. To address the origin of finite neutrino masses, we shall concentrate on various seesaw mechanisms which have currently attracted a lot of interest for model building. By choosing these kinds of topics, we hope to keep us and the readers of our book as close as possible to the true theory of massive neutrinos.

Furthermore, we aim to give an introduction to two newly developed branches of astronomy and cosmology — *neutrino astronomy* and *neutrino cosmology*. The subjects of neutrino astronomy include the studies of relic neutrinos of the Big Bang, stellar neutrinos, supernova neutrinos and high-energy cosmic neutrinos. Such studies may help us to deeply understand the crucial role of neutrinos in the evolution of the Universe, the nuclear burning mechanism of stars in their interiors, the dynamics of supernova explosions, the origin of ultrahigh-energy cosmic rays and gamma rays, and so on. So far solar neutrinos have been well investigated. The deficit of solar neutrinos, which was first observed by Raymond Davis in 1968, provided us with the first experimental evidence for the phenomenon of neutrino oscillations. Another milestone in neutrino astronomy was the observation of a neutrino burst from the Supernova 1987A explosion in the Kamiokande-II experiment led by Masatoshi Koshiba. Davis and Koshiba received the Nobel Prize in Physics in 2002 for their revolutionary contributions to neutrino astronomy. With the development of more advanced experimental technologies, more discoveries and breakthroughs in neutrino astronomy are highly anticipated in the (near) future. In particular, every effort is being made to detect the cosmic neutrino background, supernova neutrinos and ultrahigh-energy cosmic neutrinos.

As an important branch of cosmology, neutrino cosmology describes the most profound interplay between neutrino physics and cosmology. The remarkable success of the standard Big Bang model of cosmology has proved the crucial role of neutrinos in the primordial nucleosynthesis, in the anisotropies of the cosmic microwave background radiation, in the formation of the large-scale structures, and so on. The cosmic neutrino background and neutrino dark matter are also hot topics in cosmology. In addition, the production and decays of heavy Majorana neutrinos in the very early Universe might be responsible for the origin of cosmological matter-antimatter asymmetry via the leptogenesis mechanism. We foresee that more reliable knowledge on the properties of massive neutrinos to be obtained from a variety of new experiments will allow us to understand the role of neutrinos in the evolution of the Universe in a better way and to a better level. On the other hand, the development of neutrino cosmology is likely to provide us with more compelling information about neutrino masses, flavor mixing and CP violation.

The text of this book can be divided into two parts: the first part consists of chapters 1—5 and is devoted to neutrino physics, and the second part is composed of chapters 6—11 and devoted to neutrino astronomy and neutrino cosmology. We admit that it is a big challenge for us to catch up with the rapid developments in neutrino physics, neutrino astronomy and neutrino cosmology, which are partly characterized by the rising number of publications everyday. Although we have tried to cover recent progress in neutrino science, a lot of interesting materials and technical details have to be skipped from this book for a given page limitation. We apologize for missing many useful references for the same reason.

We are deeply indebted to our families for their understanding and support during the writing of this book. We would like to thank many of our collaborators and colleagues who kindly allow us to quote some tables, figures and physical results from their papers. One of us (Z.Z.X.) is grateful to Harald Fritzsch for collaborating on his first scientific paper on neutrino masses in September 1995. One of us (S.Z.) is grateful to Georg G. Raffelt for suggesting the present title of this book and for his encouragement and hospitality at the Max-Planck-Institute in Munich. We would also like to thank the editorial staff of Zhejiang University Press and Springer Verlag for inviting us to write this book and coming to our assistance. This work was supported in part by the National Natural Science Foundation of China under grant No. 10425522 and No. 10875131 (Z.Z.X.), in part by the Ministry of Science and Technology of China under grant No. 2009CB825207 (Z.Z.X.), and in part by the Alexander von Humboldt Foundation of Germany (S.Z.).

*Zhi-Zhong Xing*
Beijing, August 2010

*Shun Zhou*
Munich, August 2010

# Contents