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Introduction

In 2015 Arthur B. McDonald and Takaaki Kajita were awarded with the Nobel Prize in Physics for their discovery of neutrino oscillations and the inevitable consequence that neutrinos have a mass. The perception of non-vanishing neutrino masses implies that the standard model of particle physics has to be extended. This great discovery has been achieved by measuring solar and atmospheric neutrinos. The former are emitted as a product of thermonuclear fusion reactions inside the Sun; the latter are produced in weak decays of mesons, which are generated by the reactions of cosmic particles in the top layers of the Earth's atmosphere. Indeed, the origin of the idea of neutrino oscillations can be found in the pioneering Homestake solar neutrino experiment in the early 1970s (Nobel Prize 2002). Homestake was the first experiment able to detect solar neutrinos. In addition, it proved the basic assumption of thermonuclear fusion processes in the Sun and, at the same time, it recorded a deficit in the measured solar neutrino flux, when one compares it with theoretical predictions. Yet, it took almost 30 years and several experiments until the existence of neutrino oscillations could really be proven.

Solar neutrino experiments have a second aspect, in addition to particle physics. The production of neutrinos in the Sun is sensitive to the physical conditions in the solar interior. Therefore, solar neutrino measurements can be used to determine the physical properties of the solar core.

In this book we present and discuss the actual status of solar physics with its strong link to neutrino physics. Chapter 2 deals with the physics and basic equations that are relevant to understand the stellar structure and evolution. We show how solar models can be calibrated by confronting them to the observational constraints of the age, mass, radius, and luminosity of the Sun. We present general evolutionary properties of the Sun as a star, past and future. For the present-day Sun, a detailed presentation of its internal structure is given. This is required for then discussing the solar neutrino production via the pp chains and CNO cycle, including the important role of the chemical composition of the Sun. A very important source of information about the solar interior is offered by helioseismology, the study of solar oscillations. The topic is introduced briefly, and then the most relevant results are given, again placing some emphasis on the differences arising from the assumptions made about the solar composition. The solar abundance (or solar modeling?) problem, a now more than 15 year old

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problem is discussed to some extent, both in the context of helioseismology and, very importantly, solar neutrinos. Chapter 2 closes with a description of model uncertainties and an overview about solar models beyond the standard case.

The neutrino physics is introduced in Chapter 3. First we describe neutrinos in the standard model of particle physics. Then, we introduce the concept of neutrino mass eigenstates and neutrino mixing leading to the phenomenon of neutrino oscillations. The basic equations in the case of two- and three-neutrino oscillations will be derived. As solar neutrinos are influenced by matter effects inside the Sun and at least partially also by Earth matter effects, we describe the basic impact of matter on the behavior of neutrino oscillations. In Chapter 3, we give an overview about results of neutrino oscillation experiments, which are not using solar neutrinos as source. The chapter closes with a discussion about open questions in neutrino physics. We review the concept of Dirac and Majorana neutrinos, mass ordering, and CP violation in the framework of neutrino physics. We discuss the idea of sterile neutrinos.

Solar neutrino experiments are discussed in Chapter 4. Here, we follow a historical line beginning with radiochemical experiments, where the so-called solar neutrino puzzle has been established. We continue with the description of real-time experiments, namely, Kamiokande, Super-Kamiokande, and Sudbury Neutrino Observatory (SNO). We underline the impact of these experiments on our current understanding of the solar neutrino puzzle in terms of neutrino oscillations. Finally, the performance and recent results of the Borexino experiment are reported and discussed. The chapter closes with a summary of the achievements after 50 years of solar neutrino physics and a discussion about open questions.

Chapter 5 reports a review of upcoming experiments and their capabilities to contribute to a better understanding of neutrino and solar physics. In particular, we briefly review SNO+, Jiangmen Underground Neutrino Observatory (JUNO), Low Energy Neutrino Astrophysics (LENA), Hyper-Kamiokande, and Deep Underground Neutrino Experiment (DUNE).