Preface

This compilation of articles represents a snapshot of our understanding of neutrino oscillations after nearly a decade of discovery. Observation of neutrino oscillations represents physics beyond the three massless neutrinos of the Standard Model; it implies that neutrinos must have mass.

The neutrino mass discovery has been exclusively driven by experiment since the Standard Model with massless neutrinos was written down in 1967. With the advantage of hindsight, it is clear that the first hints of neutrino mass were apparent almost 40 years ago. Its origins reach back to the Homestake Mine in South Dakota when Ray Davis and John Bahcall first began to realize that there was a discrepancy between the predicted and measured number of neutrinos coming from the Sun. Even from the first run of that historic experiment, Ray Davis noted the discrepancy and quipped to his colleague, "We are ready now, turn on the sun.[1]" Much work went into understanding that anomaly, both experimental and theoretical, but it wasn't until the Germanium experiments GALLEX and SAGE also registered fewer neutrinos than expected that the "solar neutrino anomaly" really hit the headlines. In the mean time a number of experiments also discovered neutrino anomalies in detectors designed to look for something totally different: Proton decay. Proton decay was not observed, but careful studies of the neutrino background to those experiments registered fewer muon neutrinos than expected, pointing to a similar effect as that shown by the solar anomaly.

Over the last decade, neutrino oscillations have emerged as the favored explanation of the observed neutrino anomalies. Bruno Pontecorvo first posited the idea of neutrino oscillation in 1957, whereby neutrinos could transform into anti-neutrinos by means of mass eigenstate mixing. Using the formalism of Ziro Maki, Masami Nakagawa and Shoichi Sakata, this idea developed into a theory of flavor oscillations which could explain the

[1]R. Davis, Les Prix Nobel. The Nobel Prizes 2002, Editor Tore Frängsmyr, Nobel Foundation, Stockholm, 2003

experimentally observed discrepancies. While the originally proposed oscillation between neutrinos and anti-neutrinos has not been observed, most of the present findings can indeed be explained by mixing among the three neutrino flavor eigenstates, as described in the first chapter of this volume.

Departures from the Standard Model of three massless neutrinos have now been observed in man-made sources of neutrinos. Developments of accelerators such as the high power proton synchrotrons and the magnetic horn devised by Simon Van Der Meer have enabled high power, well understood muon neutrino beams, which have been able to cut across the neutrino production uncertainties which were associated with the experiments using naturally occurring neutrinos. Having provided the source for the first detection of the neutrino, nuclear reactors, with the improved knowledge of all aspects of their operation, are now being used regularly as copious sources of neutrinos. To be able to launch the final suite of experiments which are described in this book, monumental dedication and effort have been spent on developing and building the tools and techniques to enable huge detectors with extremely low backgrounds in deep underground laboratories. These developments have transformed the field from one that observes anomalies, to one that makes precision measurements of the physics behind the anomalies.

We have had to limit this book to articles describing results which have provided major steps forward in understanding the neutrino puzzle. History is also full of reports from experiments whose results were negative, or inconclusive, or presented results that have been superseded. For these many omissions we apologize. The experiments described here summarize the current body of evidence for neutrino oscillations and indicate the gaps in our knowledge. Each chapter describes a piece of the neutrino puzzle, including past, present and future endeavors. The picture has become much clearer in the past decade, but there are still pieces missing from the puzzle. There is perhaps, still room for something rather unexpected. Current experiments could be pointing to a difference between neutrinos and anti-neutrinos at low energy. Precise measurements of the values of the mixing parameters will hopefully provide insight into an underlying symmetry of nature. Mixing between the 1 and 3 mass eigenstates could lead to the observation of CP violation in the lepton sector, which could have far reaching consequences for the field of cosmology. The search for answers to these questions is leading to a proliferation of experiments, and as the development of the neutrino mass story has taught us, there is always scope for something unforeseen.