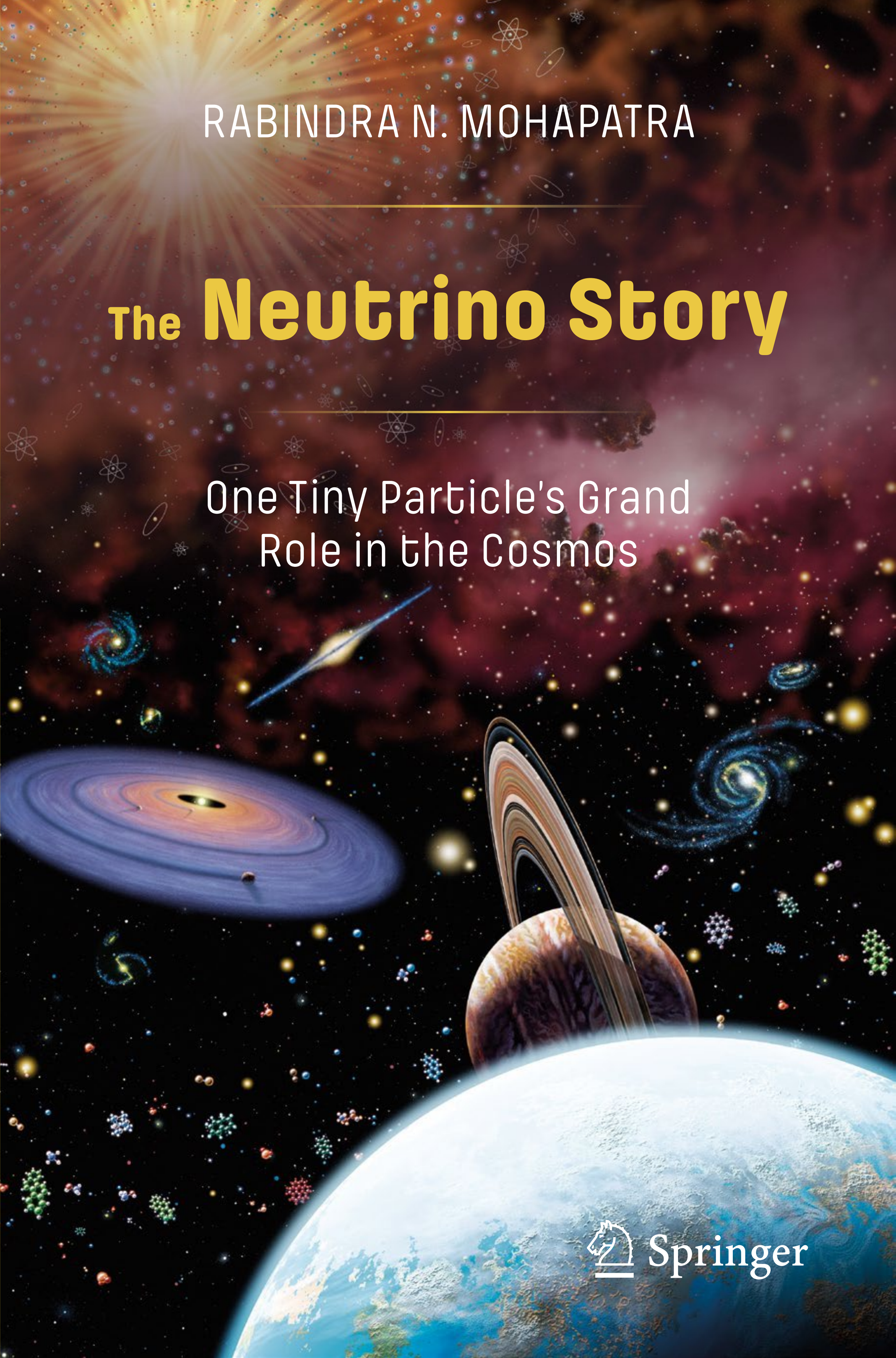
RABINDRA N. MOHAPATRA

The Neutrino Story

One Tiny Particle's Grand Role in the Cosmos



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To
Manju

Preface

Among the particles in the universe, the neutrino is the tiniest and the one with the weakest interactions, yet it has a disproportionately outsized influence on the creation of the universe that is our home today. That is why the story of the neutrino is a fascinating one. Starting with how it entered the discussion of science in 1930 to how it was discovered and how its properties were uncovered as time evolved, the neutrino's story has been laced with curiosity, suspense, hard work, and the thrill of discovery of the unanticipated. So is its promise for great societal applications in the future. The discoveries are still evolving with new investments on the international scale. The pursuit of a more complete knowledge of the neutrino is one of the most diligent scientific endeavors in the world today. Scientists are going out, all decks on hand to learn as much about this tiny particle as possible. They have set up "nets" in most unlikely places, from the deep cold Antarctica to the warm ocean floors and places around the globe. They have built instruments deep underground to catch the neutrinos from the sky, supernovae, the Sun, and the center of the galaxies. Everyday new knowledge is pouring in and being analyzed in sophisticated computer networks.

This book is an attempt to provide only a partial glimpse of the decades-long story of the neutrino, starting in 1930 when it first came into the scientific stage as a mere idea. Originally thought to be far-fetched, its existence was confirmed in the 1950s. Today many of its properties are known, uncovered by difficult experiments and scientific perseverance. Much still remains to be learned. My attempt to convey the excitement around the neutrino necessarily requires some knowledge of the basic rules of the game in the field of the sub-atomic physics, as well as some familiarity with the various stages in the evolution of the universe. The book tries to summarize them in arguably accessible terms, hoping that they can be followed without too much additional help. An attempt has been made to avoid the appearance of mathematical equations in the description of the various ideas except for one or two essential ones. The book is presented in four thematic parts, which we shall take a look at in Chapter 1: Introduction.

College Park, MD, USA Rabindra N. Mohapatra
May 2020

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Part I

1

Introduction

What is this world made of? Where did life come from? How did we get to where we are? Galaxies, planets, stars shining at night; water, trees, and a whole world of animals; how did they originate? Why does time so regularly repeat day into night and night into day, turning summer to winter and winter to summer in endless succession for billions of years, not missing a beat? Will it continue like this forever or stop and fall to a different rhythm? What, then, will happen to life and to the universe? When will that happen, if that happens? How much time do we have? What is time anyway? Does it move only in one direction or it also goes back and forth in a cycle similar to day and night? These were likely some of the questions that came to the minds of wise humans who came many centuries before us. Through their perseverance and deep intellect, they gave some of the answers that are at the heart of modern science. The story however remained incomplete then and it remains incomplete now.

The ancient Greek philosophers, and the Hindu philosophers thousands of years before them, were known to be among the earliest to think seriously about the universe and understand as much about it as possible. Few concepts had appeared then: the concept of infinity may have been in the Vedas of ancient Hindus, as may have been the concept of atoms. In ancient Greece, philosophers like Thales of Miletus, Aristotle, Pythagoras, Zeno, and Socrates tried to make their mark with new ideas, some of which have been built upon in subsequent centuries. Democritus postulated that all matter were composed of tiny particles, a concept which has endured the test of time and still remains at the foundation of physics. The famous Archimedes principle, which says that objects have apparent weight in water (or any liquid) that is less than their

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weight in empty space, was given by the Greek Mathematician and physicist by the same name. It endures until today and is in all undergraduate text books. Euclid, considered the founder of geometry, and Pythagoras, known for his famous theorem for triangles, gave mathematical results which have survived the test of time. About 300 BC, Greek philosopher Aristarchus tried to understand the lunar eclipses and concluded that it is caused by the shadow cast by Earth on the moon as the Earth goes around the Sun. That is a stunning realization, considering the prevailing wisdom at the time that the Sun went around the Earth rather than the other way. This may have been the first known heliocentric model of the solar system.

The concept of four basic elements, fire, water, Earth, and air put forth by Empedocles during those ancient times (and to which Aristotle added the aether as the fifth one) did not however survive the test of time. We now know that they are not the fundamental objects of which matter is built but derived from other more basic constituents. Nonetheless, they represented deep insightful thinking that prevailed before Christ. Similar were the thinkings in ancient Hindu philosophy circa 1000 BC about the nature of the cosmos.

Even though bits and pieces of new ideas were trickling down over the ages, well organized physics that we practice today seems to have originated around the seventeenth century. Pioneers like Copernicus, Galileo, Tyco Brahe, Kepler, and others, derived knowledge and wisdom from direct observations of stars and planets in the sky. Telescopes that helped in some of these were invented by German–Dutch lens maker Hans Lippershey in 1608.

Isaac Newton was one of the earliest pioneers. He wrote down a definitive law that told us in more concrete terms why an apple falls to the ground and does not go upward to the sky, and also, at what speed it falls. His equation enunciated in "Principia Mathematica," published on 5th July, 1687, could explain the Keplerian laws of Planetary motion, discovered several decades before Newton published his laws. It provided a unified way of understanding two diverse and apparently unrelated phenomena—an apple falling from the tree and the planet going around the Sun in the sky. His proof of Kepler's laws of planetary motion pretty much dispelled the last remaining doubts about the heliocentric view of the planetary motion. Earth was no more the center of the universe; the geocentric view of Ptolemy from second century AD was past its time and no more part of science, superseded by the heliocentric view of Nicolaus Copernicus.

Newton in England, and Gottfried Leibniz in Germany, also independently invented the new form of mathematics, called calculus, around the same time. This became a primary mathematical tool in the discussion of physical laws at the time of Newton and later. For a while, there were great disputes about who invented calculus first. The so-called calculus controversy began simmering in 1699, and broke out into full force in 1711. Leibniz published it first, in 1684, but Newton claimed that he started working on it as early as 1666. Leibniz died a frustrated man for not getting any credit during that time, although nowadays credit is given to both of them.

About a century later came Charles Augustin de Coulomb, and in the following century came Michael Faraday and James Clark Maxwell, who explained what makes the sky fill up with lightening. Gravity, electricity, and magnetism were the only kinds of phenomena known at that time. So for example, they could not tell us what makes the sun shine every day and helps it keep on shining without ever shutting down, or whether it will ever shut down. That was a matter of great interest in the nineteenth century. For example, Lord Kelvin and Herman Helmholtz pursued the idea that it could be due to gravitational contraction, but found that that could only help the sun shine for some ten million years, and not the billions of years that it has been shining for. Uncovering the actual mechanism took several more decades, far into the twentieth century. The answer to this question is intimately tied to the subject of this book, the neutrino. We discuss it later on. We now know almost completely the answer to this question and also to the question: will the sun ever stop shining and if so when? We will delve into this towards the end of this book.

The sun, like other stars, was born from the cosmic dust, four and a half billion years ago, when the universe was filled mostly with hydrogen, helium, Lithium, and little else. The sun now also pretty much contains the same elements. The story of the cosmos before and after the formation of hydrogen and helium is a fascinating one that we go into later in the book. The Earth and other planets were born from the disc around the sun by accreting and processing "dust" from nearby matter (so the theory goes). But Earth has a lot more stuff than hydrogen and helium. The Earth, which was a dust ball, became solid and developed an atmosphere that has a lot of nitrogen, oxygen, carbon dioxide along with other gases. This is a story that partly involves our topic, the neutrino. The neutrino in many ways helped to make Earth a comfortable place to live with all various chemical elements. Also in our daily life, we use chemical elements much heavier than hydrogen and helium—such as carbon, iron, nickel, etc. Where did they come from? How did a dusty universe that in its first few minutes of "life" was full of only hydrogen and helium, end up producing these heavier elements, so artfully organized in the periodic table of Mendeleev? The answer to many of these questions appears to be held by the tiny elusive particle, the neutrino. The birth and growth of the field of neutrino science as a serious field is a testament to human ingenuity and scientific prowess. The technical developments that have occurred have taken the later part of twentieth century and the early part of the twenty first by storm. The more we learn about this tiny particle and its interactions with the universe of particles, the more insight we gain into the inner workings that led to the creation of the universe as we know today. And more likely, it would tell what is in store for us in the far future.

A word about the title of the book: the universe started out as a cosmic soup of hot plasma of quarks and leptons—and it is gently (or often not so gently) guided through various phases till it reached the stage of what we see today, which is a vastly more complex and ordered system. A major actor that helped the universe in reaching its current state is the neutrino. Although, it must be made clear that the neutrinos had nothing to do with how the universe began—at least, nobody suspects so. The fate of the universe, however, would have been very different if this particle had not been part of the drama and if it behaved differently from what we know about its behavior today. Very simply put, we would not be here. In that sense the story of the evolution of the Cosmos as we know it is in large part the story of the neutrino.

The book is organized as follows: Part I of the book describes some of the background in which the intellectual birth and growth of the neutrino story occurs. The many laws and particles known before the idea of the neutrino appeared are summarized to help set the background for the understanding of the neutrino story that follows. The second part deals with the dramatic way the idea of the neutrino appears on the scene and where, starting from the idea of the particle to deep skepticism about its existence to its final discovery in a laboratory experiment. This part also includes the most recent developments in the field which have established that the neutrino has a tiny mass, contradicting decades of belief that it is massless, the later idea being an integral part of the successful standard model of forces and particles. In Part III, I discuss what the implications and future prospects are for the field following the transformational neutrino discoveries of the past two decades. I outline some scenarios for physics beyond the standard model of forces and matter implied by the neutrino mass discovery and its possible connection to the dark matter of the universe, another hot topic in physics and astronomy today. Part IV deals with two speculative ideas of the anthropic principle, i.e. an alternative approach to understanding why some or all of things are the way they are and what the future holds for the universe given what we know about the laws of nature currently.

2

Particles as Building Blocks of Matter

With the exception of dark matter and dark energy, scientists now have an almost complete idea of what this universe is made of and what keeps it together. There are fundamental building blocks and forces constantly at play. If we think of the universe as a stage of space and time, the building blocks are particles, who are like the "actors" in this stage. They play their role by using the forces to communicate with each other. The neutrino happens to be one of these particles, the tiniest among them that has emerged as a crucial actor in this story. It has not only rescued the laws of physics when they were in danger of falling apart under the weight of observations but it has also ushered in a new era of understanding to observations on both cosmic and earthly scale. This book is the story of this particle.

To understand the role of the neutrino in the evolution of our understanding of the Cosmos, we need to have a broad knowledge of what those observations were and the background in which they related to the three parts to the universe (space-time, particles, and forces). This and the following beginning chapters of the book portray the key historical scenes in this drama, each encapsulating years of dedicated scientific research that went in to building this picture and how the neutrino had to make its appearance to keep the rules of the drama coherent and consistent. It slowly became clear that the neutrino not only lent consistency to the story of the universe but it also played a key role in building it to its present stage. This is an amazingly profound story for a particle that is so tiny and so elusive.

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2.1 Protons and Electrons

All matter we see around us is built out of three "fundamental" building blocks: the proton, electron, and neutron. It took years to realize that the protons and neutrons in turn are made out of more basic constituents called quarks. There is no evidence today for anything more fundamental than quarks and electrons. How did this particle picture of matter emerge? Below we give a brief historical perspective on the development of these concepts.

Democritus of ancient Greece suggested the existence of the atom, but it took almost two millennia before the atom was placed on a solid ground as a fundamental object in physics. It goes back to John Dalton (1766–1844), who used his own analysis of chemical reactions to conclude that matter must be composed of tiny particles and suggested that they must be the atoms suggested by Democritus. Microscopist Robert Brown, who in 1827 was looking at pollen of plant Clarkia Pulchella under a microscope, found them emitting such tiny particles. This random motion of particles in the liquid became known as Brownian motion (after Robert Brown). The theory of how these particles jiggle around incessantly because they were colliding with the atoms and the molecules in the medium was given much later by Albert Einstein in one of his five famous papers in the miracle year 1905, and the idea was subsequently verified by Jean Perrin 3 years later.

The atomic picture kept getting more refined and detailed as J. J. Thompson observed the cathode rays and discovered the electron, and Rutherford scattered alpha particles, against atoms and established the existence of atomic nucleus. In 1886, Eugene Goldstein observed that while cathode rays traveled from the cathode to the anode, there were also rays traveling from anode to cathode. Those were the hydrogen nuclei (protons) although Goldstein did not know what they were or if they had a wider role in understanding the atom. Also, these experiments made it clear that electrons are negatively charged and the other rays (to be known later as protons) are positively charged. Already since the work of Charles Augustin de Coulomb in 1785, it was known that opposite charges attract each other and like charges repel, a fact that was used to determine that the cathode rays which were moving towards the anode had negative charge. They were the negatively charged electrons, and anode rays traveling in the opposite direction were positively charged and were the protons (the hydrogen nucleus). Rutherford gave the name proton to the hydrogen nucleus and argued that they are part of all atomic nuclei. Protons had positive electric charge but Rutherford also suggested that there might be other heavy particles in the nucleus, which had no electric charge or were electrically neutral. Those were identified more than two decades later and called neutrons (see below).

Ernest Rutherford was a New Zealand-born physicist who pioneered the Rutherford model of the atom, which posits that the mass of an atom is concentrated in the center of the nucleus. Thus was born the basic picture of the atom and its nucleus, which persists today. He is rightly called the father of nuclear physics. Born in the year 1871 in rural Brightwater in New Zealand's south island, he learned to invent new ways to keep himself occupied in the midst of the limited means of his parents. His mother was a school teacher who believed that knowledge was power, and his father, a hard working flax-miller. At age 19, he was awarded a scholarship to attend the Canterbury College in Christ Church, New Zealand. By age 24, he was already in Cambridge where he worked with such giants of the field of physics as Sir J. J. Thompson studying X-rays. X-rays were discovered only months before, by Wilhelm Conrad Rontzen. Working independently when Thompson was working on the electron, Rutherford discovered what he called the "alpha" and "beta" radiation. The latter consists of electron, a basic constituent building block of matter, and the former is the nucleus of the helium atom. The alpha radiation was used in the famous "gold foil experiment" by Rutherford to establish that inside each atom there was small volume where most of the atom's mass was concentrated. A clearer picture of the constituents of the atom was emerging. Soon after, Rutherford moved from England to Canada and then to the University of Manchester after that. On 7 March, 1911, Rutherford attended a meeting of the Manchester Literary and Philosophical Society, where he announced the discovery of the atomic nucleus. The American Physical Society has decided to mark this date as the beginning of a century of elementary particle physics [102].

At Manchester, Rutherford continued studying the atomic nucleus and established that the entire mass of the atom was concentrated in the nucleus. He showed this by hitting the atom with alpha particles, which bounced back as if there was a solid object at the center of the target. This led to the Rutherford model of the atom which replaced the so-called plum pudding model of the atom proposed by his one time mentor J. J. Thompson. The plum pudding model, as the name suggests, said that the atom was like a pudding and the electrons and protons were embedded in it at random.

Works of pioneers like Rutherford and Thompson were giving a clearer picture of the atom but a lot remained to be discovered in the early 1900s. More details of Dalton's atomic conjecture of 1803 were coming into shape. Dalton made several prophetic conjectures about the atom and its role. They were: