研究生前沿教材书系

Understanding the Universe

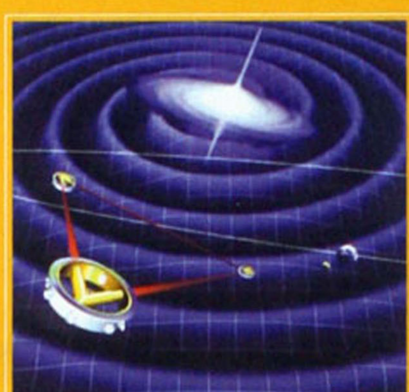
from Quarks to the Cosmos

理解宇宙

——从夸克到宇宙学

（英文影印版）

Don Lincoln
(Fermi National Accelerator Laboratory, USA)



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Don Lincoln

美国费密国立加速器实验室(Fermi National Accelerator Laboratory)实验物理学家。

1964 年出生,1993 年获得 Rice 大学物理学博士学位,之后去密歇根大学作为研究员参加 Dϕ 实验。费密实验室和 Dϕ 实验室是当今世界上设施最好、研究人员最多的两家高能物理研究机构。1998 年成为费密实验室的研究员。在 Dϕ 实验室研究期间,他主持了数百万美元的极高技术研究项目,正是这段时间,Dϕ 实验和其姊妹实验一道,成功地发现了顶夸克。他又是一位多产的作者,单独或与人合作,发表学术论文 120 多篇,出版图书多种。他还热衷于作学术报告和科普讲座。他可以用形象的比喻和插图,将五花八门的前沿研究成果,说得使缺乏科学背景的听众着迷,他讲演的足迹遍布美洲、欧亚大陆等 10 多个国家,其中给普通大众就讲述了 100 多次。他还给实验室人员培训和讲课。他认为,作为一名实验物理学家,有必要与大众分享实验成功的喜悦,《理解宇宙——从夸克到宇宙学》就是这一宗旨的具体体现。

内 容 简 介

本书作者 Don Lincoln 教授工作于当今能量最高的费密国立加速器实验室,他领导的顶级实验小组曾最早发现顶夸克。他擅长用通俗的比喻和插图讲述最前沿的科学发现,本书就是他在 2003 年写成的代表性著作之一。

本书阐述有趣的夸克和轻子的世界图景,解释操控它们行为的各种力。全书完全从实验物理学家的视角出发,舍弃数学的复杂性,集中讨论实验物理前沿和理论物理前沿如何同有趣的宇宙学领域联系在一起。亦即从高能物理实验的最新发现,追溯宇宙的大爆炸历史以及随后的物质演变规律。凡是有一定科学背景的学生都渴望弄清哪些是至今我们已经弄懂的(夸克,轻子和反物质),哪些是我们还没有弄清的(Higgs 玻色子、中微子振荡、以及宇宙中反物质为什么这样少的原因),还有哪些仅仅只是梦寐以求的(超对称性、超弦及超维度)。全书共 10 章:1. 宇宙学和原子世界的早期历史。2. 粒子物理发展史。3. 夸克和轻子,高能物理实验的研究成果。4. 物质结合力。5. 寻找 Higgs 玻色子,这是当今物理学领域费时费力的一项最前沿最巨大的工程。6. 加速器及检测设备,这是其他书中从未见过的内容。7. 宇宙创生的神秘性。8. 21 世纪物理学前沿的基础研究重点——反物质和暗能量。9. 宇宙的毁灭和创生。10. 我们为什么要这样研究。

这是一本有一定科学背景的学生都应当读且能读懂的关于 21 世纪热点科学的普及性著作。

前　言

公元前392年7月，一个炎热的白天，这天可能是一个星期二，阿卜杜拉的希腊哲学家德谟克利特断言，我们所看到的一切东西都由共同的、基本的、不可见的组分构成，这些组分如此细小以致我们的日常经验是看不到它们的。同其他伟大的观念一样，德谟克利特的这一观念也不是他本人绝对原始的想法。他的老师，Miletus 的 Leucippus 很可能就有同样的原子论看法。原子论的概念成了整整保持了两千多年的理论。直到20世纪，才证明这种外来的“原子”思想是正确的。原子论是科学中最深刻的丰富多彩的概念，它指出存在着可以认识的基本建筑块，并且存在可以理解的规律，使这些建筑块相互结合并形成我们在宇宙中看到的每一样东西。

寻找自然界基本建筑块的工作，并未因20世纪发现了原子而停止不前，原子是可分的，原子里面是原子核和电子，原子核里是中子和质子；中子和质子里面则是所谓的粒子夸克和胶子。也许夸克还不是原子论思想的最终表达，寻找真正的最小基元很可能还要花一百年甚至更长的时间。天晓得会是什么东西。一旦我们知道了夸克和其他类似的基本粒子究竟是怎么一回事，便可以勾勒出世界如何运转的一幅完整的图像。实际上，不光给出世界运转的图像，还能得出整个宇宙为何这样运转的图画。

对自然界的研究,传统上划分为不同的学科:天文学、生物学、化学、地学、物理学、动物学等等。但是自然界本身却是没有缝隙的织物。伟大的美国博物学家 John Muir 在阐述这一思想时说道:“当我们想把一件一件东西分拣开来时,却发现每样东西都同宇宙中另外的每一件东西黏连在一起”。本书作者 Don Lincoln 和他的同事在 Illinois 的 Batavia 的费密国立加速器实验室,探索夸克内部的时空结构时,同样理解了外部空间的宇宙,因为夸克和宇宙同样是连在一起的。了解自然界的基本粒子就是了解极为复杂的宇宙学问题的一个重要部分。Don Lincoln 在书中时刻提醒我们,千万不要忘记我们正在漫游于从夸克到宇宙的旅途中。Miletus 的 Leucippus 和阿卜杜拉的德谟克利特始终活在 Batavia 的 Don Lincoln 心中。

Don 是活跃在费密国立加速器实验室(这是目前世界上能量最高的位于 Batavia 的加速器实验室)的杰出物理学家。他们正在从事将质子和反质子加速到接近光速时再对撞产生新粒子性质的研究。他从事最前沿的研究工作,本书所写的就是他的研究成果之一。

Don 的写书热情不亚于他所从事的物理研究工作。给门外汉讲述物理学的工作,一直是他的爱好。他知道如何对大众介绍现代基本粒子的重要概念最能见效。

面向大众讲述基本粒子的图书已有不少,多数书都能奇迹般地把我们的所知告诉读者。Don 除了告诉大众我们所知道的,还告诉我们何以知道,甚至更为重要的是告诉读者我们为什么要去知道的道理。

《理解宇宙》又是一本讲述粒子物理发展过程中杰出科学家的传奇小说,Don 在书中讲述了这样一个故事:1957 年 1 月 4 日,纽约

市的一家上海咖吧的蛋卷午餐会上,他们如何灵感突发,想到一个重要的实验。他还在书中写到500位物理学家共同参与一个实验时出现的种种情况。伟大的发现不一定要有复杂的检测设施、复杂的机械和高级的计算机,但肯定要有一批具有广博知识的人才行。假如你担心强迫科学家坚持数年从事世界上最庞大的实验会出现什么样的情形,那就请你读读这本书吧!

Rocky Kolb
于伊利诺伊芝加哥

❖

Preface (And so ad infinitum)

> The most incomprehensible thing about the universe is that it's comprehensible at all...
>
> — Albert Einstein

The study of science is one of the most interesting endeavors ever undertaken by mankind and, in my opinion, physics is the most interesting science. The other sciences each have their fascinating questions, but none are so deeply fundamental. Even the question of the origins of life, one of the great unanswered mysteries, is likely to be answered by research in the field of organic chemistry, using knowledge which is already largely understood. And chemistry, an immense and profitable field of study, is ultimately concerned with endless and complicated combinations of atoms. The details of how atoms combine are rather tricky, but in principle they can be calculated from the well-known ideas of quantum mechanics. While chemists rightfully claim the study of the interactions of atoms as their domain, it was physicists who clarified the nature of atoms themselves. Although the boundaries between different fields of scientific endeavor were somewhat more blurred in earlier eras, physicists first discovered that atoms were not truly elemental, but rather contained smaller particles within them. Also, physicists first showed that the atom could in some ways be treated as a solar system, with tiny electrons orbiting a dense and heavy nucleus. The realization that this simple model could not possibly be the entire story led inexorably to the deeply mysterious realm of quantum mechanics. While the nucleus of the atom was first considered to be fundamental, physicists were surprised to find that the nucleus contained protons and neutrons and, in turn, that protons and neutrons themselves contained even smaller particles called quarks. Thus the question of exactly what constitutes the smallest constituent of matter, a journey that began over 2500 years ago, is still an active field of scientific effort. While it is true that our understanding is far more sophisticated than it was, there are still indications that the story is not complete.

Even within the field of physics, there are different types of efforts. Research into solid state physics and acoustics has solved the simple questions and is now attacking more difficult and complex problems. However, there remain physicists who are interested in the deepest and most fundamental questions possible. There are many questions left, for example: What is the ultimate nature of reality? Are there smallest particles or, as one looks at smaller and smaller size scales, does space itself become quantized and the smallest constituents of matter can be more properly viewed as vibrations of space (the so-called superstring hypothesis)? What forces are needed to understand the world? Are there many forces or few? While particle physicists can hope to study these questions, the approach that they follow requires an ever-increasing concentration of energy into an ever-decreasing volume. This incredible concentration of energy has not been generally present in the universe since the first fractions of a second after the Big Bang. Thus, the study of particle physics provides guidance to another deeply fundamental question, the creation and ultimate fate of the universe itself.

The current state of knowledge cannot yet answer these questions, however progress has been made in these directions. We now we know, so that they can read the theoretically speculative books with a more critical eye. I'm not picking on theorists, after all some of my best friends have actually ridden on the same bus as a theorist. (I'm kidding, of course. Most theorists I know are very bright and insightful people.) But I would like to present the material so that not just the ideas and results are explained, but also so that a flavor of the experimental techniques comes through ... the "How do you do it?" question is explained.

This book is designed to stand on its own. You don't have to read other books first. In the end you should understand quite a bit of fundamental particle physics and, unlike many books of this sort, have a pretty good idea of how we measure the things that we do and further have a good "speculation" detector. Speculative physics is fun, so towards the end of the book, I will introduce some of the unproven ideas that we are currently investigating. Gordon Kane (a theorist, but a good guy even so) in his own book *The Particle Garden*, coined the phrase "Research in Progress" (RIP) to distinguish between what is known and what isn't known, but is being investigated. I like this phrase and, in the best scientific tradition, will incorporate this good idea into this book.

Another reason that I am writing this book now is that the Fermilab accelerator is just starting again, after an upgrade that took over five years. The primary goal (although by no means the only one) of two experiments, including one on which I have been working for about ten years, is to search for the Higgs boson. This particle has not been observed (RIP!), but if it exists will have something to say about why the various known particles have the masses that they do. While the Higgs particle may not exist, something similar to it must, or our understanding of particle physics is deeply flawed. So we're looking and, because it's so interesting, I devote a chapter to the topic.

This is not a history book; it's a book on *physics*. Nonetheless, the first chapter briefly discusses the long interest that mankind has had in understanding the nature of nature, from the ancient Greeks until know of several particles that have thus far successfully resisted all attempts to find structure within them. The particles called quarks make up the protons and neutrons that, in turn, make up the atom's nucleus. Leptons are not found in the nucleus of the atom, but the most common lepton, the electron, orbits the nucleus at a (relatively) great distance. We know of four forces: gravity, which keeps the heavens in order and is currently (although hopefully not forever) outside the realm of particle physics experimentation; the electromagnetic force, which governs the behavior of electrons around atomic nuclei and forms the basis of all chemistry; the weak force, which keeps the Sun burning and is partly responsible for the Earth's volcanism and plate tectonics; and the strong force, which keeps quarks inside protons and neutrons and even holds the protons and neutrons together to form atomic nuclei. Without any of these forces, the universe would simply not exist in anything like its current form. While we now know of four forces, in the past there were thought to be more. In the late 1600s, Isaac Newton devised the theory of universal gravitation, which explained that the force governing the motion of the heavens and our weight here on Earth were really the same things, something not at all obvious. In the 1860s, James Clerk Maxwell showed that electricity and magnetism, initially thought to be different, were intimately related. In the 1960s, the electromagnetic and weak forces were actually shown to be different facets of a single electro-weak force. This history of unifying seemingly different forces has proven to be very fruitful and naturally we wonder if it is possible that the remaining four (really three) forces could be shown to be different faces of a more fundamental force.

All of creation, i.e. all of the things that you can see when you look about you, from the extremely tiny to the edge of the universe, can be explained as endless combinations of two kinds of quarks, an electron and a neutrino (a particle which we haven't yet discussed). These four particles we call a generation. Modern experiments have shown that there exist at least two additional generations (and probably only two), each containing four similar particles, but with each subsequent generation having a greater mass and with the heavier generation decaying rapidly into the familiar particles of the first generation. Of course, this raises yet even more questions. Why are there generations? More specifically, why are there three generations? Why are the unstable generations heavier, given that otherwise the generations seem nearly identical?

Each of the four forces can be explained as an exchange of a particular kind of particle, one kind for each force. These particles will eventually be discussed in detail, but their names are the photon, the gluon, the *W* and *Z* particles and (maybe) the graviton. Each of these particles are bosons, which have a particular type of quantum mechanical behavior. In contrast, the quarks and leptons are fermions, with completely different behavior. Why the force-carrying particles should be bosons, while the matter particles are fermions, is not understood. A theory, called supersymmetry, tries to make the situation more symmetric and postulates additional fermion particles that are related to the bosonic force carriers and other bosonic particles that are related to the mass-carrying fermions. Currently there exists no unambiguous experimental evidence for this idea, but the idea is theoretically so interesting that the search for supersymmetry is a field of intense study.

While many questions remain, the fact is that modern physics can explain (with the assistance of all of the offshoot sciences) most of creation, from the universe to galaxies, stars, planets, people, amoebae, molecules, atoms and finally quarks and leptons. From a size of 10^{-18} meters, through 44 orders of magnitude to the 10^{26} meter size of the visible universe, from objects that are motionless, to ones that are moving 300,000,000 meters per second (186,000 miles per second), from temperatures ranging from absolute zero to 3×10^{15}°C, matter under all of these conditions is pretty well understood. And this, as my Dad would say, impresses the hell out of me.

The fact that particle physics is intimately linked with cosmology is also a deeply fascinating concept and field of study. Recent studies have shown that there may exist in the universe dark matter … matter which adds to the gravitational behavior of the universe, but is intrinsically invisible. The idea of dark energy is a similar answer to the same question. One way in which particle physics can contribute to this debate is to look for particles which are highly massive, but also stable (i.e. don't decay) and which do not interact very much with ordinary matter (physics-ese for invisible). While it seems a bit of a reach to say that particle physics is related to cosmology, you must recall that *nuclear* physics, which is particle physics' lower-energy cousin, has made critical contributions to the physics of star formation, supernovae, black holes and neutron stars. The fascinating cosmological questions of extra dimensions, black holes, the warping of space and the unfathomably hot conditions of the Big Bang itself are all questions to which particle physics can make important contributions.

The interlinking of the fields of particle physics and cosmology to the interesting questions they address is given in the figure below. The answer to the questions of unification (the deepest nature of reality), hidden dimensions (the structure of space itself) and cosmology (the beginning and end of the universe), will require input from many

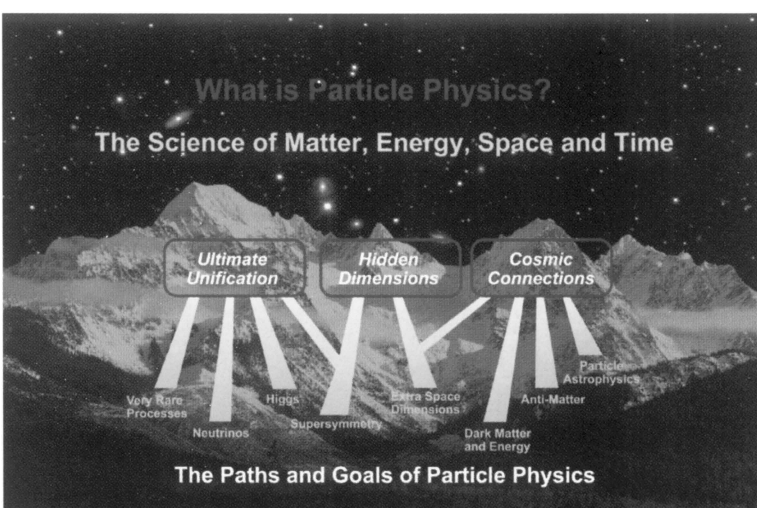

Figure The intricate interconnections between the physics of the very small and the very large. (Figure courtesy of Fermilab.)

fields. The particle physics discussed in this book will only provide a part of the answer; but a crucial part and one richly deserving study.

Naturally, not everyone can be a scientist and devote their lives to understanding all of the physics needed to explain this vast range of knowledge. That would be too large a quest even for professional scientists. However, I have been lucky. For over twenty years, I have been able to study physics in a serious manner and I was a casual student for over ten years before that. While I cannot pretend to know everything, I have finally gained enough knowledge to be able to help push back the frontiers of knowledge just a little bit. As a researcher at Fermi National Accelerator Laboratory (Fermilab), currently the highest energy particle physics laboratory in the world, I have the privilege of working with truly gifted scientists, each of whom is driven by the same goal: to better understand the world at the deepest and most fundamental level. It's all great fun.

About once a month, I am asked to speak with a group of science enthusiasts about the sorts of physics being done by modern particle physics researchers. Each and every time, I find some fraction of the audience who is deeply interested in the same questions that researchers are. While their training is not such that they can contribute directly, they want to *know*. So I talk to them and they understand. Physics really isn't so hard. An interested layman can understand the physics research that my colleagues and I do. They just need to have it explained to them clearly and in a language that is respectful of what they know. They're usually very smart people. They're just not experts.

So that's where this book comes in. There are many books on particle physics, written for the layman. Most of the people with whom I speak have read many of them. They want to know more. There are also books, often written by theoretical physicists, which discuss speculative theories. And while speculation is fun (and frequently is how science is advanced), what we *know* is interesting enough to fill a book by itself. As an experimental physicist, I have attempted to write a book so that, at the end, the reader will have a good grasp on what the beginning of the 20th century. The second chapter begins with the discovery of the electrons, x-rays and radioactivity (really the beginning of modern particle physics) and proceeds through 1960, detailing the many particle discoveries of the modern physics era. It was in the 1960s that physicists really got a handle on what was going on. Chapter 3 discusses the elementary particles (quarks and leptons) which could neatly explain the hundreds of particles discovered in the preceding sixty years. Chapter 4 discusses the forces, without which the universe would be an uninteresting place. Chapter 5 concentrates on the Higgs boson, which is needed to explain why the various particles discussed in Chapter 3 have such disparate masses and the search for (and hopefully discovery of) will consume the efforts of so many of my immediate colleagues. Chapter 6 concentrates on the experimental techniques needed to make discoveries in modern accelerator-based particle physics experiments. This sort of information is often given at best in a skimpy fashion in these types of books, but my experimentalist's nature won't allow that. In Chapter 7, I outline mysteries that are yielding up their secrets to my colleagues as I write. From neutrino oscillations to the question of why there appears to be more matter than antimatter in the universe are two really interesting nuts that are beginning to crack. Chapter 8 is where I finally indulge my more speculative nature. Modern experiments also look for hints of "new physics" i.e. stuff which we might suspect, but have little reason to expect. Supersymmetry, superstrings, extra dimensions and technicolor are just a few of the wild ideas that theorists have that just might be true. We'll cover many of these ideas here. In Chapter 9, I will spend some time discussing modern cosmology. Cosmology and particle physics are cousin fields and they are trying to address some similar questions. The linkages between the fields are deep and interesting and, by this point in the book, the reader will be ready to tackle these tricky issues. The book ends with several appendices that give really interesting information that is not strictly crucial to understanding particle physics, but which the adventurous reader will appreciate.

The title of this preface comes from a bit of verse by Augustus de Morgan (1806–1871) (who in turn was stealing from Jonathan Swift) from his book *A Budget of Paradoxes*. He was commenting on the recurring patterns one sees as one goes from larger to smaller size scales. On a big enough scale, galaxies can be treated as structure-less, but as one looks at them with a finer scale, one sees that they are made of solar systems, which in turn are made of planets and suns. The pattern of nominally structure-less objects eventually revealing a rich substructure has continued for as long as we have looked.

Great fleas have little fleas,
upon their back to bite 'em,
little fleas have lesser fleas,
and so ad infinitum...

He goes on to even more clearly underscore his point:

And the great fleas themselves, in turn,
have greater fleas to go on;
While these again have greater still,
And greater still, and so on.

I hope that you have as much fun reading this book as I had writing it. Science is a passion. Indulge it. Always study. Always learn. Always question. To do otherwise is to die a little inside.

Don Lincoln
Fermilab
October 24, 2003