

PHY

国外物理名著系列 14

(注释版)

The Principles of  
Quantum Mechanics  
(4th Edition)

量子力学原理

(第四版)

P.A.M. Dirac



科学出版社  
www.sciencep.com

国外物理名著系列 14

The Principles of Quantum Mechanics  
(4th edition)

量子力学原理(第四版)

P. A. M. Dirac



科学出版社  
北京

图字:01-2007-2787

P. A. M. Dirac: The Principles of Quantum Mechanics

© Oxford University Press 1958

The Principles of Quantum Mechanics 4/e was originally published in English in 1958. This adaptation is published by arrangement with Oxford University Press and is for sale in the Mainland(part) of the People's Republic of China only.

量子力学原理(第四版)原书英文版于1958年出版。本改编版获得牛津大学出版社授权,仅限于在中华人民共和国大陆地区销售。版权所有,翻印必究。

#### 图书在版编目(CIP)数据

量子力学原理:第4版=The Principles of Quantum Mechanics:4th edition:英文/(德)狄拉克(Dirac, P. A. M.)主编. —注释本. —北京:科学出版社,2008

(国外物理名著系列;14)

ISBN 978-7-03-021882-7

I. 量… II. 狄… III. 量子力学-英文 IV. 0413.1

中国版本图书馆 CIP 数据核字(2008)第 063976 号

责任编辑:胡凯 鄢德平 王飞龙/责任印制:赵德静/封面设计:陈敬

科学出版社出版

北京东黄城根北街16号

邮政编码:100717

<http://www.sciencep.com>

北京佳信达艺术印刷有限公司印刷

科学出版社发行 各地新华书店经销

\*

2008年5月第 一 版 开本:B5(720×1000)

2008年5月第一次印刷 印张:21

印数:1~3 000 字数:385 000

定价:58.00 元

(如有印装质量问题,我社负责调换〈佳信达〉)

## 《国外物理名著系列》专家委员会名单

(按姓氏笔画排序)

于 涿	王鼎盛	刘正猷	刘寄星	向 涛
杨国桢	邹英华	宋菲君	张元仲	赵凯华
侯伯元	聂玉昕	阎守胜	裴寿庸	戴元本

## 国外物理名著系列序言

对于国内的物理学工作者和青年学生来讲，研读国外优秀的物理学著作是系统掌握物理学知识的一个重要手段。但是，在国内并不能及时、方便地买到国外的图书，且国外图书不菲的价格往往令国内的读者却步，因此，把国外的优秀物理原著引进到国内，让国内的读者能够方便地以较低的价格购买是一项意义深远的工作，将有助于国内物理学工作者和青年学生掌握国际物理学的前沿知识，进而推动我国物理学科研究和教学的发展。

为了满足国内读者对国外优秀物理学著作的需求，科学出版社启动了引进国外优秀著作的工作，出版社的这一举措得到了国内物理学界的积极响应和支持，很快成立了专家委员会，开展了选题的推荐和筛选工作，在出版社初选的书单基础上确定了第一批引进的项目，这些图书几乎涉及了近代物理学的所有领域，既有阐述学科基本理论的经典名著，也有反映某一学科专题前沿的专著。在选择图书时，专家委员会遵循了以下原则：基础理论方面的图书强调“经典”，选择了那些经得起时间检验、对物理学的发展产生重要影响、现在还不“过时”的著作（如：狄拉克的《量子力学原理》）。反映物理学某一领域进展的著作强调“前沿”和“热点”，根据国内物理学研究发展的实际情况，选择了能够体现相关学科最新进展，对有关方向的科研人员和研究生有重要参考价值的图书。这些图书都是最新版的，多数图书都是2000年以后出版的，还有相当一部分是2006年出版的新书。因此，这套丛书具有权威性、前瞻性和应用性强的特点。由于国外出版社的要求，科学出版社对部分图书进行了少量的翻译和注释（主要是目录标题和练习题），但这并不会影响图书“原汁原味”的感觉，可能还会方便国内读者的阅读和理解。

“他山之石，可以攻玉”，希望这套丛书的出版能够为国内物理学工作者和青年学生的工作和学习提供参考，也希望国内更多专家参与到这一工作中来，推荐更多的好书。



中国科学院院士  
中国物理学会理事长

## 第四版前言

THE main change from the third edition is that the chapter on quantum electrodynamics has been rewritten. The quantum electrodynamics given in the third edition describes the motion of individual charged particles moving through the electromagnetic field, in close analogy with classical electrodynamics. It is a form of theory in which the number of charged particles is conserved and it cannot be generalized to allow of variation of the number of charged particles.

In present-day high-energy physics the creation and annihilation of charged particles is a frequent occurrence. A quantum electrodynamics which demands conservation of the number of charged particles is therefore out of touch with physical reality. So I have replaced it by a quantum electrodynamics which includes creation and annihilation of electron-positron pairs. This involves abandoning any close analogy with classical electron theory, but provides a closer description of nature. It seems that the classical concept of an electron is no longer a useful model in physics, except possibly for elementary theories that are restricted to low-energy phenomena.

P. A. M. D.

ST. JOHN'S COLLEGE, CAMBRIDGE

11 *May* 1957

## NOTE TO THE REVISION OF THE FOURTH EDITION

THE opportunity has been taken of revising parts of Chapter XII ('Quantum electrodynamics') and of adding two new sections on interpretation and applications.

P. A. M. D.

ST. JOHN'S COLLEGE, CAMBRIDGE

26 *May* 1967

## 第一版前言

THE methods of progress in theoretical physics have undergone a vast change during the present century. The classical tradition has been to consider the world to be an association of observable objects (particles, fluids, fields, etc.) moving about according to definite laws of force, so that one could form a mental picture in space and time of the whole scheme. This led to a physics whose aim was to make assumptions about the mechanism and forces connecting these observable objects, to account for their behaviour in the simplest possible way. It has become increasingly evident in recent times, however, that nature works on a different plan. Her fundamental laws do not govern the world as it appears in our mental picture in any very direct way, but instead they control a substratum of which we cannot form a mental picture without introducing irrelevancies. The formulation of these laws requires the use of the mathematics of transformations. The important things in the world appear as the invariants (or more generally the nearly invariants, or quantities with simple transformation properties) of these transformations. The things we are immediately aware of are the relations of these nearly invariants to a certain frame of reference, usually one chosen so as to introduce special simplifying features which are unimportant from the point of view of general theory.

The growth of the use of transformation theory, as applied first to relativity and later to the quantum theory, is the essence of the new method in theoretical physics. Further progress lies in the direction of making our equations invariant under wider and still wider transformations. This state of affairs is very satisfactory from a philosophical point of view, as implying an increasing recognition of the part played by the observer in himself introducing the regularities that appear in his observations, and a lack of arbitrariness in the ways of nature, but it makes things less easy for the learner of physics. The new theories, if one looks apart from their mathematical setting, are built up from physical concepts which cannot be explained in terms of things previously known to the student, which cannot even be explained adequately in words at all. Like the fundamental concepts (e.g. proximity, identity) which every one must learn on his

arrival into the world, the newer concepts of physics can be mastered only by long familiarity with their properties and uses.

From the mathematical side the approach to the new theories presents no difficulties, as the mathematics required (at any rate that which is required for the development of physics up to the present) is not essentially different from what has been current for a considerable time. Mathematics is the tool specially suited for dealing with abstract concepts of any kind and there is no limit to its power in this field. For this reason a book on the new physics, if not purely descriptive of experimental work, must be essentially mathematical. All the same the mathematics is only a tool and one should learn to hold the physical ideas in one's mind without reference to the mathematical form. In this book I have tried to keep the physics to the forefront, by beginning with an entirely physical chapter and in the later work examining the physical meaning underlying the formalism wherever possible. The amount of theoretical ground one has to cover before being able to solve problems of real practical value is rather large, but this circumstance is an inevitable consequence of the fundamental part played by transformation theory and is likely to become more pronounced in the theoretical physics of the future.

With regard to the mathematical form in which the theory can be presented, an author must decide at the outset between two methods. There is the symbolic method, which deals directly in an abstract way with the quantities of fundamental importance (the invariants, etc., of the transformations) and there is the method of coordinates or representations, which deals with sets of numbers corresponding to these quantities. The second of these has usually been used for the presentation of quantum mechanics (in fact it has been used practically exclusively with the exception of Weyl's book *Gruppentheorie und Quantenmechanik*). It is known under one or other of the two names 'Wave Mechanics' and 'Matrix Mechanics' according to which physical things receive emphasis in the treatment, the states of a system or its dynamical variables. It has the advantage that the kind of mathematics required is more familiar to the average student, and also it is the historical method.

The symbolic method, however, seems to go more deeply into the nature of things. It enables one to express the physical laws in a neat and concise way, and will probably be increasingly used in the future as it becomes better understood and its own special mathematics gets



developed. For this reason I have chosen the symbolic method, introducing the representatives later merely as an aid to practical calculation. This has necessitated a complete break from the historical line of development, but this break is an advantage through enabling the approach to the new ideas to be made as direct as possible.

P. A. M. D.

ST. JOHN'S COLLEGE, CAMBRIDGE

29 *May* 1930

## 国外物理名著系列丛书

序号	作者	书名	定价	发行号
1	欧尔萨格(Orszag, M.)	量子光学——降噪, 囚禁离子, 量子轨道和退相干	58	O · 2713
2	贝希施施特(Bchstedt, F.)	表面物理原理	58	O · 2712
3	莫泽尔(Mosel, U.)	场论中的路径积分导引	45	O · 2717
4	吕利埃(Rulliere, C.)	飞秒激光脉冲——原理及实验	68	O · 2715
5	克林舍恩(Klingshirn, C. F.)	半导体光学(第三版)	118	O · 2709
6	比克(Brick, E.)等	物理学中的拓扑和几何	65	O · 2710
7	杨(Young, M.)	光学与激光——光纤与光波导(第五版)	79	O · 2711
8	施奈德(Schneider, T.)	远程通信中的非线性光学	68	O · 2714
9	足立元成(Adachi, M.)等	自组织纳米材料	56	O · 2716
10	怀特(White, R. M.)	磁性量子理论(第三版)	68	O · 2992
11	李(Li, S. S.)	半导体物理电子学(第二版)	98	O · 2994
12	洛伊斯(Loiseau, A.)等	碳纳米管——从基础到应用	90	O · 2993
13	施瓦布(Schwabl, F.)	统计力学(第二版)	96	O · 2995
14	狄拉克(Dirac, P. A. M.)	量子力学原理(第四版)	58	O · 3172
15	郑大培(Cheng, T. P.)	基本粒子物理学的规范理论	96	O · 3173
16	迈伊(Imry, Y.)	介观物理导论(第二版)	56	O · 3174

# 目 录

第 1 章 叠加原理	1
§ 1 量子理论的需要	1
§ 2 光子的极化	4
§ 3 光子的干涉	7
§ 4 叠加与不确定性	10
§ 5 叠加原理的数学表达	14
§ 6 左矢量与右矢量	18
第 2 章 动力学变量与可观察量	23
§ 7 线性算符	23
§ 8 共轭关系	26
§ 9 本征值与本征矢量	29
§ 10 可观察量	34
§ 11 可观察量的函数	41
§ 12 普遍的物理解释	45
§ 13 对易性与相容性	49
第 3 章 表象理论	53
§ 14 基矢量	53
§ 15 $\delta$ 函数	58
§ 16 基矢量的性质	62
§ 17 线性算符的表象	67
§ 18 概率幅	72
§ 19 关于可观察量函数的若干定理	76
§ 20 符号的发展	79
第 4 章 量子条件	84
§ 21 泊松括号	84
§ 22 薛定谔表象	89
§ 23 动量表象	94
§ 24 海森伯测不准原理	97
§ 25 位移算符	99
§ 26 么正变换	103

<b>第 5 章 运动方程</b>	108
§ 27 运动方程的薛定谔形式	108
§ 28 运动方程的海森伯形式	111
§ 29 定态	116
§ 30 自由粒子	118
§ 31 波包的运动	121
§ 32 作用量原理	125
§ 33 吉布斯系综	130
<b>第 6 章 初等应用</b>	136
§ 34 谐振子	136
§ 35 角动量	140
§ 36 角动量的性质	144
§ 37 电子的自旋	149
§ 38 在有心力场中的运动	152
§ 39 氢原子的能级	156
§ 40 选择定则	159
§ 41 氢原子的塞曼效应	165
<b>第 7 章 微扰理论</b>	167
§ 42 概述	167
§ 43 微扰引起的能级变化	168
§ 44 引起跃迁的微扰	172
§ 45 对辐射的应用	175
§ 46 与时间无关的微扰引起的跃迁	178
§ 47 反常塞曼效应	181
<b>第 8 章 碰撞问题</b>	185
§ 48 概述	185
§ 49 散射系数	188
§ 50 动量表象中的解	193
§ 51 色散散射	199
§ 52 共振散射	201
§ 53 发射与吸收	204
<b>第 9 章 包含许多相同粒子的系统</b>	207
§ 54 对称态与反对称态	207
§ 55 排列作为动力学变量	211
§ 56 排列作为运动恒量	213

§ 57 能级的决定 .....	216
§ 58 对电子的应用 .....	219
<b>第 10 章 辐射理论</b> .....	225
§ 59 玻色子系集 .....	225
§ 60 玻色子与振子之间的联系 .....	227
§ 61 玻色子的发射与吸收 .....	232
§ 62 对光子的应用 .....	235
§ 63 光子与原子间的相互作用能 .....	239
§ 64 辐射的发射、吸收与散射 .....	244
§ 65 费米子系集 .....	248
<b>第 11 章 电子的相对论性理论</b> .....	253
§ 66 粒子的相对论性处理 .....	253
§ 67 电子的波方程 .....	254
§ 68 洛伦兹变换下的不变性 .....	258
§ 69 自由电子的运动 .....	261
§ 70 自旋的存在 .....	263
§ 71 过渡到极坐标变量 .....	267
§ 72 氢原子能级的精细结构 .....	269
§ 73 正电子理论 .....	273
<b>第 12 章 量子电动力学</b> .....	276
§ 74 没有物质的电磁场 .....	276
§ 75 量子条件的相对论形式 .....	280
§ 76 一个时刻的动力学变量 .....	283
§ 77 补充条件 .....	287
§ 78 电子与正电子 .....	292
§ 79 相互作用 .....	298
§ 80 物理的变量 .....	302
§ 81 诠释 .....	306
§ 82 应用 .....	310
<b>索引</b> .....	313

# CONTENTS

I. THE PRINCIPLE OF SUPERPOSITION . . . . .	1
1. The Need for a Quantum Theory . . . . .	1
2. The Polarization of Photons . . . . .	4
3. Interference of Photons . . . . .	7
4. Superposition and Indeterminacy . . . . .	10
5. Mathematical Formulation of the Principle . . . . .	14
6. Bra and Ket Vectors . . . . .	18
II. DYNAMICAL VARIABLES AND OBSERVABLES . . . . .	23
7. Linear Operators . . . . .	23
8. Conjugate Relations . . . . .	26
9. Eigenvalues and Eigenvectors . . . . .	29
10. Observables . . . . .	34
11. Functions of Observables . . . . .	41
12. The General Physical Interpretation . . . . .	45
13. Commutability and Compatibility . . . . .	49
III. REPRESENTATIONS . . . . .	53
14. Basic Vectors . . . . .	53
15. The $\delta$ Function . . . . .	58
16. Properties of the Basic Vectors . . . . .	62
17. The Representation of Linear Operators . . . . .	67
18. Probability Amplitudes . . . . .	72
19. Theorems about Functions of Observables . . . . .	76
20. Developments in Notation . . . . .	79
IV. THE QUANTUM CONDITIONS . . . . .	84
21. Poisson Brackets . . . . .	84
22. Schrödinger's Representation . . . . .	89
23. The Momentum Representation . . . . .	94
24. Heisenberg's Principle of Uncertainty . . . . .	97
25. Displacement Operators . . . . .	99
26. Unitary Transformations . . . . .	103
V. THE EQUATIONS OF MOTION . . . . .	108
27. Schrodinger's Form for the Equations of Motion . . . . .	108
28. Heisenberg's Form for the Equations of Motion . . . . .	111
29. Stationary States . . . . .	116
30. The Free Particle . . . . .	118
31. The Motion of Wave Packets . . . . .	121
32. The Action Principle . . . . .	125
33. The Gibbs Ensemble . . . . .	130
VI. ELEMENTARY APPLICATIONS . . . . .	136
34. The Harmonic Oscillator . . . . .	136
35. Angular Momentum . . . . .	140

36. Properties of Angular Momentum . . . . .	144
37. The Spin of the Electron . . . . .	149
38. Motion in a Central Field of Force . . . . .	152
39. Energy-levels of the Hydrogen Atom . . . . .	156
40. Selection Rules . . . . .	159
41. The Zeeman Effect for the Hydrogen Atom . . . . .	165
VII. PERTURBATION THEORY . . . . .	167
42. General Remarks . . . . .	167
43. The Change in the Energy-levels caused by a Perturbation . . . . .	168
44. The Perturbation considered as causing Transitions . . . . .	172
45. Application to Radiation . . . . .	175
46. Transitions caused by a Perturbation Independent of the Time . . . . .	178
47. The Anomalous Zeeman Effect . . . . .	181
VIII. COLLISION PROBLEMS . . . . .	185
48. General Remarks . . . . .	185
49. The Scattering Coefficient . . . . .	188
50. Solution with the Momentum Representation . . . . .	193
51. Dispersive Scattering . . . . .	199
52. Resonance Scattering . . . . .	201
53. Emission and Absorption . . . . .	204
IX. SYSTEMS CONTAINING SEVERAL SIMILAR PARTICLES . . . . .	207
54. Symmetrical and Antisymmetrical States . . . . .	207
55. Permutations as Dynamical Variables . . . . .	211
56. Permutations as Constants of the Motion . . . . .	213
57. Determination of the Energy-levels . . . . .	216
58. Application to Electrons . . . . .	219
X. THEORY OF RADIATION . . . . .	225
59. An Assembly of Bosons . . . . .	225
60. The Connexion between Bosons and Oscillators . . . . .	227
61. Emission and Absorption of Bosons . . . . .	232
62. Application to Photons . . . . .	235
63. The Interaction Energy between Photons and an Atom . . . . .	239
64. Emission, Absorption, and Scattering of Radiation . . . . .	244
65. An Assembly of Fermions . . . . .	248
XI. RELATIVISTIC THEORY OF THE ELECTRON . . . . .	253
66. Relativistic Treatment of a Particle . . . . .	253
67. The Wave Equation for the Electron . . . . .	254
68. Invariance under a Lorentz Transformation . . . . .	258
69. The Motion of a Free Electron . . . . .	261
70. Existence of the Spin . . . . .	263
71. Transition to Polar Variables . . . . .	267
72. The Fine-structure of the Energy-levels of Hydrogen . . . . .	269
73. Theory of the Positron . . . . .	273

# CONTENTS

xv

XII. QUANTUM ELECTRODYNAMICS . . . . .	276
74. The Electromagnetic Field in the Absence of Matter . . . . .	276
75. Relativistic Form of the Quantum Conditions . . . . .	280
76. The Dynamical Variables at one Time . . . . .	283
77. The Supplementary Conditions . . . . .	287
78. Electrons and Positrons by Themselves . . . . .	292
79. The Interaction . . . . .	298
80. The Physical Variables . . . . .	302
81. Interpretation . . . . .	306
82. Applications . . . . .	310
INDEX . . . . .	313



## 第1章 叠加原理

### 1. 量子理论的需要

CLASSICAL mechanics has been developed continuously from the time of Newton and applied to an ever-widening range of dynamical systems, including the electromagnetic field in interaction with matter. The underlying ideas and the laws governing their application form a simple and elegant scheme, which one would be inclined to think could not be seriously modified without having all its attractive features spoilt. Nevertheless it has been found possible to set up a new scheme, called quantum mechanics, which is more suitable for the description of phenomena on the atomic scale and which is in some respects more elegant and satisfying than the classical scheme. This possibility is due to the changes which the new scheme involves being of a very profound character and not clashing with the features of the classical theory that make it so attractive, as a result of which all these features can be incorporated in the new scheme.

The necessity for a departure from classical mechanics is clearly shown by experimental results. In the first place the forces known in classical electrodynamics are inadequate for the explanation of the remarkable stability of atoms and molecules, which is necessary in order that materials may have any definite physical and chemical properties at all. The introduction of new hypothetical forces will not save the situation, since there exist general principles of classical mechanics, holding for all kinds of forces, leading to results in direct disagreement with observation. For example, if an atomic system has its equilibrium disturbed in any way and is then left alone, it will be set in oscillation and the oscillations will get impressed on the surrounding electromagnetic field, so that their frequencies may be observed with a spectroscope. Now whatever the laws of force governing the equilibrium, one would expect to be able to include the various frequencies in a scheme comprising certain fundamental frequencies and their harmonics. This is not observed to be the case. Instead, there is observed a new and unexpected connexion between the frequencies, called Ritz's Combination Law of Spectroscopy, according to which all the frequencies can be expressed as differences between certain terms,