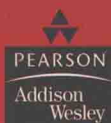


物理学经典英文教材系列



Modern Quantum Mechanics

J. J. Sakurai

Revised Edition

现代量子力学

修订版



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Modern Quantum Mechanics Revised Edition

J. J. Sakurai

Late, University of California, Los Angeles

San Fu Tuan, Editor

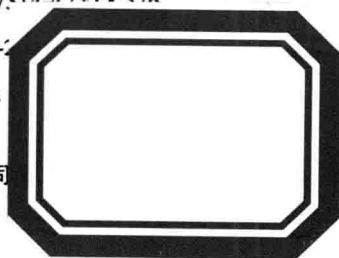
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影印版前言

本书为美籍日裔著名理论物理学家樱井 (J.J.Sakurai) 的遗作。

樱井于 1982 年不幸英年早逝。去世之前在美国加州大学洛杉矶分校 (UCLA) 任教授。在他突然去世后, 他的夫人和他的生前好友在整理其遗物时发现了本书的遗稿。其中只有 3 章完整写完, 其余的是一些草稿和经过细心修改的备课笔记。在这些材料的基础上, 美籍华裔著名物理学家, 夏威夷大学的段三复教授毅然承担了把好友的这份遗稿整理出书的责任。

本书的第 1 版由 Benjamin/Cummings 出版公司于 1985 年出版。作者署名为樱井 (J.J.Sakurai)。按照樱井生前表达的意愿, 尽管量子力学已经有了不少享有盛名并堪称经典的教材和专著, 他仍要写一本自己的书, 阐述量子力学的关键概念和纳入该领域最新和最重要的一些进展。段三复教授尽可能地沿袭了前 3 章的独特风格, 在一个统一的架构下, 完成了这部优秀的新教材的编辑工作。这本书面世之后, 受到了普遍的欢迎, 著名的诺贝尔奖得主施温格 (Julian Schwinger) 对该书给出了很高的评价。现在我们影印的是由 Addison-Wesley 出版社 1994 年出版的修订版。修订工作是由段三复教授在樱井的一些生前好友的协助下完成的, 作者署名增加了段三复。修订版改写了原书的部分内容, 增添了关于 Bell 相位和非指数衰变两个补编, 以适应樱井一贯坚持的给学生以最新实验进展的相关知识的风格。

正如施温格的评价中所强调的, 本书对于量子力学概念的介绍与传统

的做法不同，没有受制于量子力学发展的历史线索，力求从一开始就摆脱经典力学的束缚。它直接从量子力学特有的电子自旋的观测实验出发，围绕其状态的概率特征和叠加原理展开对于量子力学基本概念和基本原理的阐述。从空间平移、空间转动及时间演化等对称性变换出发，引入动量、角动量及哈密顿算符等基本力学量，讨论它们的本征值问题、它们的运动方程以及与经典力学的关系，从而直接切入量子力学的核心问题。这种被称之为“用量子力学方式来思考”的做法贯穿全书，是本书最引人瞩目之处。

我们推荐这本书，将其影印出版的另一个重要的原因，是它与我国理工科研究生教学需求密切相关。在我国一般把量子力学课分成了两门。一门叫量子力学，在大学本科讲授。而另一门叫高等量子力学，是一年级物理类研究生的必修课。国内已经出版了不少高等量子力学的教材，但与之直接对应的国外教材却并不多见。本书从其设定的读者对象、它的选材范围以及其深度与广度来看，都非常适合这方面的要求。如果从双语教学角度来考虑，它无疑也是理想教材的候选者。

中国科学院研究生院物理科学学院教授 丁亦兵

2005 年 11 月

Foreword

J. J. Sakurai was always a very welcome guest here at CERN, for he was one of those rare theorists to whom the experimental facts are even more interesting than the theoretical game itself. Nevertheless, he delighted in theoretical physics and in its teaching, a subject on which he held strong opinions. He thought that much theoretical physics teaching was both too narrow and too remote from application: "...we see a number of sophisticated, yet uneducated, theoreticians who are conversant in the LSZ formalism of the Heisenberg field operators, but do not know why an excited atom radiates, or are ignorant of the quantum theoretic derivation of Rayleigh's law that accounts for the blueness of the sky." And he insisted that the student must be able to use what has been taught: "The reader who has read the book but cannot do the exercises has learned nothing."

He put these principles to work in his fine book *Advanced Quantum Mechanics* (1967) and in *Invariance Principles and Elementary Particles* (1964), both of which have been very much used in the CERN library. This new book, *Modern Quantum Mechanics*, should be used even more, by a larger and less specialized group. The book combines breadth of interest with a thorough practicality. Its readers will find here what they need to know, with a sustained and successful effort to make it intelligible.

J. J. Sakurai's sudden death on November 1, 1982 left this book unfinished. Reinhold Bertlmann and I helped Mrs. Sakurai sort out her husband's papers at CERN. Among them we found a rough, handwritten version of most of the book and a large collection of exercises. Though only three chapters had been completely finished, it was clear that the bulk of the creative work had been done. It was also clear that much work remained to fill in gaps, polish the writing, and put the manuscript in order.

That the book is now finished is due to the determination of Noriko Sakurai and the dedication of San Fu Tuan. Upon her husband's death, Mrs. Sakurai resolved immediately that his last effort should not go to waste. With great courage and dignity she became the driving force behind the project, overcoming all obstacles and setting the high standards to be maintained. San Fu Tuan willingly gave his time and energy to the editing and completion of Sakurai's work. Perhaps only others close to the hectic field of high-energy theoretical physics can fully appreciate the sacrifice involved.

For me personally, J. J. had long been far more than just a particularly distinguished colleague. It saddens me that we will never again laugh together at physics and physicists and life in general, and that he will not see the success of his last work. But I am happy that it has been brought to fruition.

John S. Bell
CERN, Geneva

Preface to the Revised Edition

Since 1989 the Editor has enthusiastically pursued a revised edition of *Modern Quantum Mechanics* by his late great friend J. J. Sakurai, in order to extend this text's usefulness into the twenty-first century. Much consultation took place with the panel of Sakurai friends who helped with the original edition, but in particular with Professor Yasuo Hara of Tsukuba University and Professor Akio Sakurai of Kyoto Sangyo University in Japan.

This book is intended for the first year graduate student who has studied quantum mechanics at the junior or senior level. It does not provide an introduction to quantum mechanics for the beginner. The reader should have had some experience in solving time-dependent and time-independent wave equations. A familiarity with the time evolution of the Gaussian wave packet in a force-free region is assumed, as is the ability to solve one-dimensional transmission-reflection problems. Some of the general properties of the energy eigenfunctions and the energy eigenvalues should also be known to the student who uses this text.

The major motivation for this project is to revise the main text. There are three important additions and/or changes to the revised edition, which otherwise preserves the original version unchanged. These include a reworking of certain portions of Section 5.2 on time-independent perturbation theory for the degenerate case by Professor Kenneth Johnson of M.I.T., taking into account a subtle point that has not been properly treated by a number of texts on quantum mechanics in this country. Professor Roger Newton of Indiana University contributed refinements on lifetime broadening in Stark effect, additional explanations of phase shifts at resonances, the optical theorem, and on non-normalizable state. These appear as "remarks by the editor" or "editor's note" in the revised edition. Professor Thomas Fulton of the Johns Hopkins University reworked his Coulomb Scattering contribution (Section 7.13) so that it now appears as a shorter text portion emphasizing the physics, with the mathematical details relegated to Appendix C.

Though not a major part of the text, some additions were deemed necessary to take into account developments in quantum mechanics that have become prominent since November, 1 1982. To this end, two supplements are included at the end of the text. Supplement I is on adiabatic change and geometrical phase (popularized by M. V. Berry since 1983) and is actually an English translation of the supplement on this subject written by Professor Akio Sakurai for the Japanese version of *Modern Quantum Mechanics*.

(copyright © Yoshioka-Shoten Publishing of Kyoto). Supplement II is on non-exponential decays written by my colleague here, Professor Xerxes Tata, and read over by Professor E. C. G. Sudarshan of the University of Texas at Austin. Though non-exponential decays have a long history theoretically, experimental work on transition rates that tests indirectly such decays was done only in 1990. Introduction of additional material is of course a subjective matter on the part of the Editor; the readers will evaluate for themselves its appropriateness. Thanks to Professor Akio Sakurai, the revised edition has been “finely toothcombed” for misprint errors of the first ten printings of the original edition. My colleague, Professor Sandip Pakvasa, provided overall guidance and encouragement to me throughout this process of revision.

In addition to the acknowledgments above, my former students Li Ping, Shi Xiaohong, and Yasunaga Suzuki provided the sounding board for ideas on the revised edition when taking my graduate quantum mechanics course at the University of Hawaii during the spring of 1992. Suzuki provided the initial translation from Japanese of Supplement I as a course term paper. Dr. Andy Acker provided me with computer graphic assistance. The Department of Physics and Astronomy and particularly the High Energy Physics Group of the University of Hawaii at Manoa provided again both the facilities and a conducive atmosphere for me to carry out my editorial task. Finally I wish to express my gratitude to Physics (and sponsoring) Senior Editor, Stuart Johnson, and his Editorial Assistant, Jennifer Duggan, as well as Senior Production Coordinator Amy Willcutt, of Addison-Wesley for their encouragement and optimism that the revised edition will indeed materialize.

San Fu TUAN
Honolulu, Hawaii

In Memoriam

Jun John Sakurai was born in 1933 in Tokyo and came to the United States as a high school student in 1949. He studied at Harvard and at Cornell, where he received his Ph.D. in 1958. He was then appointed assistant professor of Physics at the University of Chicago, and became a full professor in 1964. He stayed at Chicago until 1970 when he moved to the University of California at Los Angeles, where he remained until his death. During his lifetime he wrote 119 articles in theoretical physics of elementary particles as well as several books and monographs on both quantum and particle theory.

The discipline of theoretical physics has as its principal aim the formulation of theoretical descriptions of the physical world that are at once concise and comprehensive. Because nature is subtle and complex, the pursuit of theoretical physics requires bold and enthusiastic ventures to the frontiers of newly discovered phenomena. This is an area in which Sakurai reigned supreme with his uncanny physical insight and intuition and also his ability to explain these phenomena in illuminating physical terms to the unsophisticated. One has but to read his very lucid textbooks on *Invariance Principles and Elementary Particles* and *Advanced Quantum Mechanics* as well as his reviews and summer school lectures to appreciate this. Without exaggeration I could say that much of what I did understand in particle physics came from these and from his articles and private tutoring.

When Sakurai was still a graduate student, he proposed what is now known as the V-A theory of weak interactions, independently of (and simultaneously with) Richard Feynman, Murray Gell-Mann, Robert Marshak, and George Sudarshan. In 1960 he published in *Annals of Physics* a prophetic paper, probably his single most important one. It was concerned with the first serious attempt to construct a theory of strong interactions based on Abelian and non-Abelian (Yang-Mills) gauge invariance. This seminal work induced theorists to attempt an understanding of the mechanisms of mass generation for gauge (vector) fields, now realized as the Higgs mechanism. Above all it stimulated the search for a realistic unification of forces under the gauge principle, now crowned with success in the celebrated Glashow-Weinberg-Salam unification of weak and electromagnetic forces. On the phenomenological side, Sakurai pursued and vigorously advocated the vector mesons dominance model of hadron dynamics. He was the first to discuss the mixing of ω and ϕ meson states. Indeed, he made numerous important contributions to particle physics phenomenology in a

much more general sense, as his heart was always close to experimental activities.

I knew Jun John for more than 25 years, and I had the greatest admiration not only for his immense powers as a theoretical physicist but also for the warmth and generosity of his spirit. Though a graduate student himself at Cornell during 1957–1958, he took time from his own pioneering research in K-nucleon dispersion relations to help me (via extensive correspondence) with my Ph.D. thesis on the same subject at Berkeley. Both Sandip Pakvasa and I were privileged to be associated with one of his last papers on weak couplings of heavy quarks, which displayed once more his infectious and intuitive style of doing physics. It is of course gratifying to us in retrospect that Jun John counted this paper among the score of his published works that he particularly enjoyed.

The physics community suffered a great loss at Jun John Sakurai's death. The personal sense of loss is a severe one for me. Hence I am profoundly thankful for the opportunity to edit and complete his manuscript on *Modern Quantum Mechanics* for publication. In my faith no greater gift can be given me than an opportunity to show my respect and love for Jun John through meaningful service.

San Fu Tuan

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Fundamental Concepts

The revolutionary change in our understanding of microscopic phenomena that took place during the first 27 years of the twentieth century is unprecedented in the history of natural sciences. Not only did we witness severe limitations in the validity of classical physics, but we found the alternative theory that replaced the classical physical theories to be far richer in scope and far richer in its range of applicability.

The most traditional way to begin a study of quantum mechanics is to follow the historical developments—Planck's radiation law, the Einstein-Debye theory of specific heats, the Bohr atom, de Broglie's matter waves, and so forth—together with careful analyses of some key experiments such as the Compton effect, the Franck-Hertz experiment, and the Davisson-Germer-Thompson experiment. In that way we may come to appreciate how the physicists in the first quarter of the twentieth century were forced to abandon, little by little, the cherished concepts of classical physics and how, despite earlier false starts and wrong turns, the great masters—Heisenberg, Schrödinger, and Dirac, among others—finally succeeded in formulating quantum mechanics as we know it today.

However, we do not follow the historical approach in this book. Instead, we start with an example that illustrates, perhaps more than any other example, the inadequacy of classical concepts in a fundamental way. We hope that by exposing the reader to a “shock treatment” at the onset, he

or she may be attuned to what we might call the “quantum-mechanical way of thinking” at a very early stage.

1.1. THE STERN-GERLACH EXPERIMENT

The example we concentrate on in this section is the Stern-Gerlach experiment, originally conceived by O. Stern in 1921 and carried out in Frankfurt by him in collaboration with W. Gerlach in 1922. This experiment illustrates in a dramatic manner the necessity for a radical departure from the concepts of classical mechanics. In the subsequent sections the basic formalism of quantum mechanics is presented in a somewhat axiomatic manner but always with the example of the Stern-Gerlach experiment in the back of our minds. In a certain sense, a two-state system of the Stern-Gerlach type is the least classical, most quantum-mechanical system. A solid understanding of problems involving two-state systems will turn out to be rewarding to any serious student of quantum mechanics. It is for this reason that we refer repeatedly to two-state problems throughout this book.

Description of the Experiment

We now present a brief discussion of the Stern-Gerlach experiment, which is discussed in almost any book on modern physics.* First, silver (Ag) atoms are heated in an oven. The oven has a small hole through which some of the silver atoms escape. As shown in Figure 1.1, the beam goes through a collimator and is then subjected to an inhomogeneous magnetic field produced by a pair of pole pieces, one of which has a very sharp edge.

We must now work out the effect of the magnetic field on the silver atoms. For our purpose the following oversimplified model of the silver atom suffices. The silver atom is made up of a nucleus and 47 electrons, where 46 out of the 47 electrons can be visualized as forming a spherically symmetrical electron cloud with no net angular momentum. If we ignore the nuclear spin, which is irrelevant to our discussion, we see that the atom as a whole does have an angular momentum, which is due solely to the spin—intrinsic as opposed to orbital—angular momentum of the single 47th ($5s$) electron. The 47 electrons are attached to the nucleus, which is $\sim 2 \times 10^5$ times heavier than the electron; as a result, the heavy atom as a whole possesses a magnetic moment equal to the spin magnetic moment of the 47th electron. In other words, the magnetic moment μ of the atom is

* For an elementary but enlightening discussion of the Stern-Gerlach experiment, see French and Taylor (1978, 432–38).

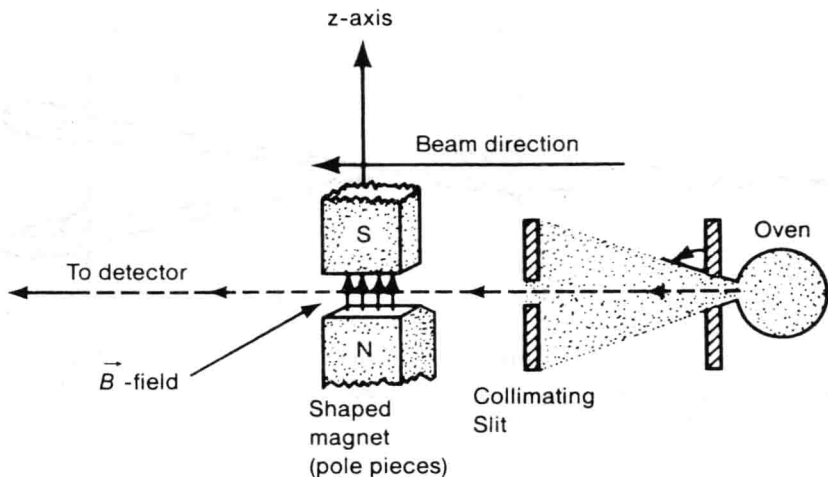


FIGURE 1.1. The Stern-Gerlach experiment.

proportional to the electron spin \mathbf{S} ,

$$\boldsymbol{\mu} \propto \mathbf{S}, \quad (1.1.1)$$

where the precise proportionality factor turns out to be $e/m_e c$ ($e < 0$ in this book) to an accuracy of about 0.2%.

Because the interaction energy of the magnetic moment with the magnetic field is just $-\boldsymbol{\mu} \cdot \mathbf{B}$, the z -component of the force experienced by the atom is given by

$$F_z = \frac{\partial}{\partial z} (\boldsymbol{\mu} \cdot \mathbf{B}) = \mu_z \frac{\partial B_z}{\partial z}, \quad (1.1.2)$$

where we have ignored the components of \mathbf{B} in directions other than the z -direction. Because the atom as a whole is very heavy, we expect that the classical concept of trajectory can be legitimately applied, a point which can be justified using the Heisenberg uncertainty principle to be derived later. With the arrangement of Figure 1.1, the $\mu_z > 0$ ($S_z < 0$) atom experiences a downward force, while the $\mu_z < 0$ ($S_z > 0$) atom experiences an upward force. The beam is then expected to get split according to the values of μ_z . In other words, the SG (Stern-Gerlach) apparatus “measures” the z -component of $\boldsymbol{\mu}$ or, equivalently, the z -component of \mathbf{S} up to a proportionality factor.

The atoms in the oven are randomly oriented; there is no preferred direction for the orientation of $\boldsymbol{\mu}$. If the electron were like a classical spinning object, we would expect all values of μ_z to be realized between $|\boldsymbol{\mu}|$ and $-|\boldsymbol{\mu}|$. This would lead us to expect a continuous bundle of beams coming out of the SG apparatus, as shown in Figure 1.2a. Instead, what we

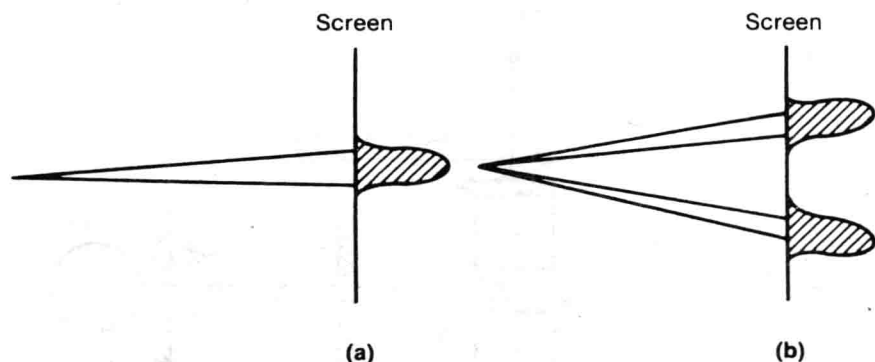


FIGURE 1.2. Beams from the SG apparatus; (a) is expected from classical physics, while (b) is actually observed.

experimentally observe is more like the situation in Figure 1.2b. In other words, the SG apparatus splits the original silver beam from the oven into *two distinct* components, a phenomenon referred to in the early days of quantum theory as “space quantization.” To the extent that μ can be identified within a proportionality factor with the electron spin S , only two possible values of the z -component of S are observed to be possible, S_z up and S_z down, which we call $S_z +$ and $S_z -$. The two possible values of S_z are multiples of some fundamental unit of angular momentum; numerically it turns out that $S_z = \hbar/2$ and $-\hbar/2$, where

$$\begin{aligned}\hbar &= 1.0546 \times 10^{-27} \text{ erg-s} \\ &= 6.5822 \times 10^{-16} \text{ eV-s}\end{aligned}\quad (1.1.3)$$

This “quantization” of the electron spin angular momentum is the first important feature we deduce from the Stern-Gerlach experiment.

Of course, there is nothing sacred about the up-down direction or the z -axis. We could just as well have applied an inhomogeneous field in a horizontal direction, say in the x -direction, with the beam proceeding in the y -direction. In this manner we could have separated the beam from the oven into an $S_x +$ component and an $S_x -$ component.

Sequential Stern-Gerlach Experiments

Let us now consider a sequential Stern-Gerlach experiment. By this we mean that the atomic beam goes through two or more SG apparatuses in sequence. The first arrangement we consider is relatively straightforward. We subject the beam coming out of the oven to the arrangement shown in Figure 1.3a, where SG \hat{z} stands for an apparatus with the inhomogeneous magnetic field in the z -direction, as usual. We then block the $S_z -$ compo-