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978-1-108-47322-4 — Modern Quantum Mechanics
Jun John Sakurai , Jim Napolitano
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Modern Quantum Mechanics

Modern Quantum Mechanics is a classic graduate level textbook, covering the main quantum mechanics concepts in a clear, organized, and engaging manner. The original author, J. J. Sakurai, was a renowned theorist in particle theory. The Third Edition, revised by Jim Napolitano, introduces topics that extend the text's usefulness into the twenty-first century such as advanced mathematical techniques associated with quantum-mechanical calculations, while at the same time retaining classic developments such as neutron interferometer experiments, Feynman path integrals, correlation measurements, and Bell's inequality. A solution manual for instructors using this textbook can be downloaded from www.cambridge.org/sakurai3.

J. J. Sakurai was a noted theorist in particle physics and Professor of Physics at UCLA (1970–1982) and University of Chicago (1964–1970). He received his Ph.D. from Cornell University in 1958. He contributed greatly to the field of particle physics before passing away at the age of 49 in 1982, while he was visiting CERN in Geneva.

In addition he held visiting staff appointments at the California Institute of Technology, Universities of Tokyo and Nagoya, University of Paris d'Orsay, Scuola Normale Superiore at Pisa, Stanford Linear Accelerator, CERN at Geneva, and Max Planck Institute at Munich. He was a Sloan Fellow (1962–1966), Fellow of the American Physical Society (1964–1982), a Guggenheim Fellow (1975–1976) and a von Humboldt Fellow (1981–1982).

Jim Napolitano is Professor of Physics and Department Chair at the College of Science and Technology, Temple University. He is an experimental nuclear physicist, with over 320 articles published in refereed journals and an h-index of 81. He shared in the 2016 Breakthrough Prize in Fundamental Physics and currently works on experiments using parity-violating electron scattering. An innovative educator, he has developed coursework and curricula at Rensselaer Polytechnic Institute and Temple University. In all cases, his teaching and instructional development make use of modern techniques. Professor Napolitano has also published textbooks on quantum mechanics, experimental physics, and using MATHEMATICA for physics.

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Modern Quantum Mechanics

Third Edition

J. J. SAKURAI

JIM NAPOLITANO

Temple University, Philadelphia, PA

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Preface

This book covers the material on quantum mechanics typically found in a first year graduate physics curriculum. The approach emphasizes states, operators, eigenvalues, and representations from the start. Building on these foundations, the reader sees, for example, how the Schrödinger representation is just one of several ways to realize quantum dynamics, and how classical physics emerges as an approximation. This approach also helps the reader gain an appreciation of purely quantum-mechanical phenomena, for example the magnetic moment and spin of an electron, that have no classical analogue.

The intended audience is the same as for earlier editions, that is, students having taken upper level undergraduate coursework in quantum physics, classical mechanics and electromagnetism, multivariable calculus, and ordinary and partial differential equations.

Professor Jun John Sakurai originally conceived the idea for this textbook, I think inspired by Dirac's monograph. Sakurai's life was cut short suddenly, as he was preparing the first manuscript. His colleague San Fu Tuan took over as Editor, completing a seven chapter manuscript for Addison-Wesley, who published the First Edition in 1985 and a Revised Edition in 1993. Some time later, I started work on the Second Edition for Pearson (who had since acquired Addison-Wesley). This volume contained a lot of new material, including an eighth chapter, and was published in 2010. The text was reissued by Cambridge University Press in 2017, which was also when I started work on the Third Edition.

Quantum mechanics has always fascinated me, but it was the First Edition of *Modern Quantum Mechanics* that finally explained to me the logical progression from fundamental assumptions to practical applications, with classical physics emerging as an approximation. When I first taught this material at Rensselaer Polytechnic Institute, I used the Revised Edition, but found myself supplementing with my own notes on solutions of the Schrödinger equation and other topics. I also tried to use my course to prepare students for quantum field theory, introducing second quantization and relativistic quantum mechanics, neither of which were included in Sakurai's book.

I was therefore pleased to be asked to take on the Second Edition. Sections were added to Chapters Two and Three on solutions to the Schrödinger equation. I reversed the order of Chapters Six and Seven, so that Scattering Theory came first, and I reworked the treatment so that it was based on the formal theory of time-dependent perturbations. The following chapter on Identical Particles was augmented to include second quantization and the quantization of the free electromagnetic field, and I added a new chapter on Relativistic Quantum Mechanics. I also included several connections throughout the book to experimental measurements, and worked to fix a number of idiosyncrasies that I found when I taught out of the book.

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The result was a text that, I thought, achieved my goal of a high level treatment respecting Sakurai's vision, adding reference to additional modern concepts and experiment, and preparing the reader for quantum field theory and beyond. The first two chapters lay the mathematical and physical foundations for the rest of the book, and connect the reader to undergraduate topics in wave mechanics. Chapter Three covers angular momentum from the perspective of the rotation operator, with strong connections to important concepts such as the density operator, central potentials, and Bell's inequality. Groups are also introduced here, with further exposition in Chapter Four. Applications to "real world" problems are the focus of Chapters Five and Six, all the while keeping to the focus of building on the fundamentals. Chapters Seven and Eight move the discussion towards the "next" course in quantum mechanics, covering many-body formalism and the inclusion of special relativity.

The Third Edition keeps the same ordering of the eight chapters. Significant new material has been added, but I also worked to clarify some of the discussions and to fix various issues that I discovered after teaching out of the Second Edition. In fact, I compiled a long list of "Typographical Errors, Mistakes, and Comments" based on covering nearly the entire book in class, and working through all of the end-of-chapter problems. The Third Edition addresses all of the errors. It also addresses most of the comments, having to give up on some only for lack of time.

There are three new sections of new material. Despite its increasing use in condensed matter physics, I found no treatments of density functional theory in any quantum mechanics textbook. So, I added Section 7.6 to introduce the subject and take it through to its application in the helium atom. A reviewer's suggestion inspired me to add Section 8.1.5 to show how the Klein–Gordon field, built using second quantization, fixes the problems of negative energies and nonpositive definite probability currents in the Klein–Gordon wave equation. The Second Edition treated spontaneous emission only as an end-of-chapter problem, but Section 5.8.4 now goes through the derivation, with some details and numerical calculations left as problems.

I added new appendices on the Hamiltonian for a Charge in an Electromagnetic Field, Notes on Complex Analysis, and Calculating Clebsch–Gordan Coefficients. The appendix on Electromagnetic Units has been significantly revised, and I updated the appendix on Elementary Solutions to Schrödinger's Wave Equation to better connect to the discussions in the text.

Instructors may elect to pick and choose from topics in the book, and not necessarily in the order of presentation. Chapter One should be covered first, since it lays down the notation and fundamental assumptions. One could then, for example, take parts of Chapters Three and Four to expand on operators, observables, and symmetries, prior to discussing dynamics in Chapter Two. Many other combinations are possible. Indeed, throughout the book, I have tried to refer to other places in the text where relevant related material is covered or discussed.

As befits a graduate level textbook, the strategy here is to lay down the principles, following up with implications by deduction. Some example calculations are carried through in the text, but the end-of-chapter problems are generally meant to extend the discussion, and not simply practice what was covered. As such, I recommend that

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instructors choose problems, from the text or otherwise, that follow this idea, including connection to experimental measurements, where practical.

In several places in the book, either explicitly or implicitly, computer calculations are necessary to completely follow the arguments or to work the problems. I worked through these using MATHEMATICA, and am happy to share the code with anyone who would like to see it, but any other programming language or application can also be used, of course.

Producing the Second Edition was a long process that would not have been possible without help from many, many people. Colleagues in physics include John Cummings, Jack Fishburn, Joel Giedt, David Hertzog, Barry Holstein, Bob Jaffe, Matthew Kirby, Joe Levinger, Alan Litke, Kam-Biu Luk, Bob McKeown, Harry Nelson, Joe Paki, Murray Peshkin, Olivier Pfister, Mike Snow, John Townsend, San Fu Tuan, David Van Baak, Dirk Walecka, and Tony Zee. The people at Addison-Wesley/Pearson who guided me included Adam Black, Ashley Eklund, Deb Greco, Dyan Menezes, John Rogosich, and Jim Smith.

So many others were very helpful to me as I developed the Third Edition. This includes colleagues Kieron Burke, Mark Caprio, Carl Carlson, Benjamin Chandran, Chris Cocuzza, Martha Constantinou, Patrick Fasano, Jeremias Gonzalez, Aaron Kaplan (with special thanks for helping me learn DFT), Toh-Ming Lu, Carl Maes, Andreas Metz, Jerry Miller, Djordje Minic, Adilson Motter, Nick Murphy, Steve Naculich, Celso Nishi, John Perdew, Jon Rosner, and Roland Winkler. I am forever grateful to Simon Capelin at Cambridge University Press, for first bringing to me the possibility of republishing the Second Edition, and encouraging me to consider a Third Edition. Other key people at CUP include Jane Adams, Nick Gibbons, Lisa Pinto, and Ilaria Tassistro.

I can only offer my sincere apologies to people I should have listed, but whose name doesn't appear because I've been careless with note keeping. There are also the very many people who, over the past several years, offered comments, some of which I've not been able to incorporate.

Finally, I give a special acknowledgement for Stuart Freedman, my mentor, colleague, and friend. Stuart's Ph.D. thesis experiment was the first verification of the violation of Bell's inequality, and he used this to stoke my interest in quantum mechanics. His guidance during my years as a graduate student and young scientist shaped my career, and he remained my friend and counselor until his untimely passing.

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Philadelphia, PA

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Preface to the Revised First 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

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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.

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In Memoriam to J. J. Sakurai

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

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(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
(From the First Edition)

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Foreword from the First Edition

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.

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