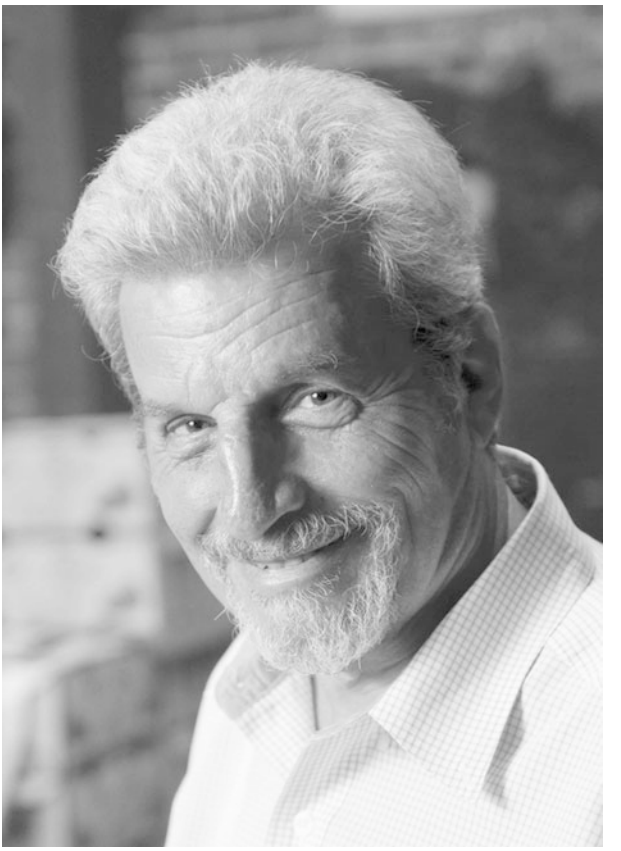
Quantum Theory: A Two-Time Success Story



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Quantum Theory: A Two-Time Success Story

Yakir Aharonov Festschrift

Springer

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Preface

This volume, "Quantum Theory: A Two-Time Success Story," is part of a number of new initiatives, started in 2012, to honor and advance the vision of Yakir Aharonov during the year of his 80th birthday. Starting with a conference held at Chapman University from August 16–18, 2012, these initiatives also included the launch of a new Institute for Quantum Studies,[1] the dedication of the Aharonov alcove in Chapman's library, and the introduction of a new journal called *Quantum Studies: Mathematics and Foundations*, with Yakir as the chief-editor and administered through the Institute.[2]

We all know that quantum mechanics is the most successful scientific theory in history and resulted in technological advances that drive our economy, such as the entire computer revolution, electronics, and the nuclear power industry. In addition, it impacts many other disciplines such as genetics, medicine and mathematics.

However, the foundations of the theory are so non-intuitive that there is no consensus as to the meaning of the theory. This may be impeding the development of new forms of quantum theory required for its extension to new frontiers such as cosmology, gravity, and high energy particle physics. It is to the advancement of those foundational questions to which this volume is dedicated. As Nobel Laureate David Gross emphasized in his chapter:

> "...the deep conceptual mysteries of quantum mechanics are still with us. Over most of [Yakir's] eighty years (for which this Festschrift is a celebration), Yakir successfully struggled to better understand these extraordinary aspects and to use them to construct new and surprising results."

Indeed, even after a career spanning 6 decades, Yakir's production of major scientific discoveries has continued to increase and deepen to this very day. Perhaps Sir Michael Berry said it best at the beginning of his contribution to this Festschrift:

> "for Yakir Aharonov on his 80th birthday: still quick, still deep, still subtle"

[1] The Institute's website is quantum.chapman.edu.

[2] The journals' website is www.birkhauser-science.com/QSMF.

Sir Michael Berry was paraphrasing his own article which he offered 20 years ago for Yakir's 60th birthday, an article which all but launched a new field of mathematics.

Yakir's contributions to physics are too many to mention. The contributors to this book tended to focus on a few of them which deserve special attention. Originally discovered and/or inspired by Yakir, they comprise a series of studies which set out a new interpretation of quantum theory. Elements of this interpretation include topological phases (the Aharonov-Bohm effect and its generalizations), "weak" measurements and "weak" values, time-symmetric boundary conditions, nonlocal measurements and relativistic causality, "modular" variables, and new axioms for quantum theory, to name a few.

We briefly focus on 2 of these items:

1. **Topological phases:** In 1959, Aharonov and Bohm discovered the AB effect[3] which revolutionized our understanding of the role of potentials in physics and appears in most modern texts on quantum mechanics. The impact of the AB effect has been huge and has continued to grow very rapidly. For the first time, they showed that a particle moving in a field-free region could be affected by a field in a disjoint region. Such an effect is alien to classical physics; indeed, it is a defining property of the quantum world. Numerous experiments have verified the effect, and recent novel techniques allow precise measurements of the shifts in electron interference patterns that demonstrate the phase (the AB phase) picked up by a charged particle moving around a solenoid. The AB phase is ubiquitous in modern physics—including cosmology, particle physics, non-abelian gauge theories, condensed matter chemical and molecular physics, and laser dynamics. Generalizations of the AB phase to non-abelian gauge theories, such as the Wilson and t'Hooft loops, are important tools for studying the issues of confinement and spontaneous symmetry breaking. The topological quantum phase explains charge quantization, the quantum Hall effect, the Josephson junction and many effects in the new field of mesoscopic physics where tiny electronic circuits exhibit quantum behavior. The AB phase plays a crucial role in electron microscope holography.
2. **Time-symmetry:** Aharonov, Bergmann and Lebowitz[4] suggested a two vector time symmetric formulation of quantum mechanics. Aharonov, Albert, and Vaidman[5] used ABL in conjunction with weak intermediate measurements performed on pre- and post-selected ensembles to introduce the notion of the "weak values." These values can be surprisingly large and have proven to be very useful tools for analyzing various physical phenomena, for constructing efficient devices for high precision measurements, etc. Phenomena which were thought to be unmeasureable have now been seen using this new approach. As a new paradigm for

[3] Y. Aharonov, D. Bohm, "Significance of Electromagnetic Potentials in the Quantum Theory," Physical Review, 115, 485 (1959).

[4] Y. Aharonov, P.G. Bergmann, and J.L. Lebowitz, Phys. Rev. 134, B1410 (1964).

[5] Y. Aharonov, D. Albert, L. Vaidman, Phys. Rev. Lett. 60 (1988).

the design of sensors, it is being broadly applied to precision Doppler frequency measurements, gravitational detectors, etc.[6] This also led to a new branch of mathematics, originally referred to as "Super-Fourier" by Sir Michael Berry, which manifests in super-oscillations and Quantum walks.[7]

These core themes of Yakir's life-work also impact perhaps the most controversial—yet the most important—aspect of his research which concerns the issue of time in quantum mechanics. As Nobel Laureate Sir Anthony Leggett said at the dedication of the Institute and library alcove at Chapman University:

> "... throughout all [previous scientific] revolutions in history, I think there's one assumption that has not really been seriously challenged and that is precisely that the past can affect the present and the present can affect the future and not vice versa. Personally, I believe if there is a really really major revolution in physics in the next 50 or 100 years, then it will involve the overthrow of that principle. If that happens, I think Yakir Aharonov will be seen to have played a major role in the preparatory work leading to that revolution."

A quick readers-note: whenever possible, we, the editors, have added footnotes to the first page of each chapter in order to refer the reader to relevant on-line videos of talks given by the respective chapter's author at the Aharonov-80 conference in 2012 at Chapman University. Finally, we have organized this book into six sections to allow the reader to more easily find particular subjects which were inspired by Yakir:

Part I: Quantum Mechanics and Reality
Part II: Building Blocks of Nature
Part III: Time and Cosmology
Part IV: Universe as a Wavefunction
Part V: Nonlocality
Part VI: Weak Values
Part VII: Mathematics of Weak Measurements
Part VIII: Weak Measurement Experiments
Part IX: Yakir Aharonov: Thinking Quantum

Acknowledgements

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[6] O. Hosten, P. Kwiat, Science, 319, 787 (2008).

[7] Y. Aharonov, L. Davidovich, N. Zagury, Phys. Rev. A, 48 (1993) 1687.

we wish to thank Yakir Aharonov for contributing two chapters to this Festschrift and for generally inspiring this entire project along with the novel research reported here and the contributors themselves. To this day, he continues to deepen and enrich his profound impact on the physics world, as David Albert so eloquently put it:

> "...I couldn't think of anybody ... in their twenties—who were even remotely as brave, or as open, or as creative, or as experimental, or as overcome with wonder, or as bursting with life, or as constantly and resolutely expecting the impossible, or (in brief) as young, as Yakir. But even I could not have imagined at the time that thirty years later he would turn out to be younger still."

Yakir, we dedicate this book to you with love and friendship and look forward to another 80 years.

Orange, California
April 26, 2013

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