VISIONS OF DISCOVERY

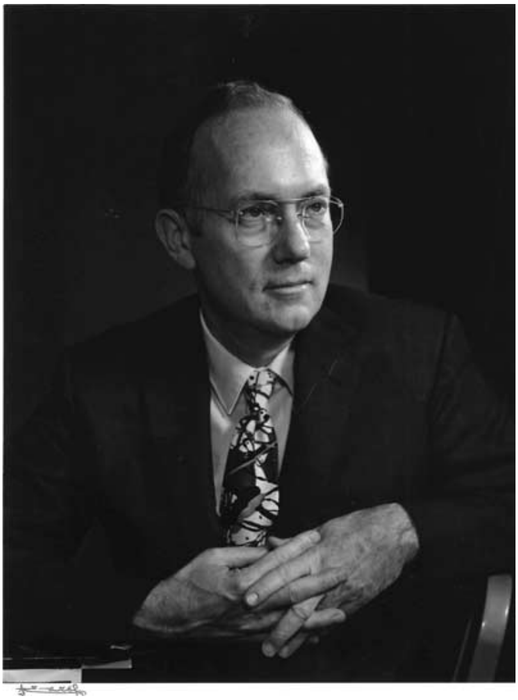
New Light on Physics, Cosmology, and Consciousness

The remarkable career of Charles H. Townes, the inventor of the maser and laser for which he shared the 1964 Nobel Prize in Physics, has spanned seven decades. His interests have ranged from the origin of the universe to the structure of molecules, always focusing on the nature of human life. Honoring his work, this book explores the most basic questions of science, philosophy, and the nature of existence: How did the Universe begin? Why do the fundamental constants of nature have the values they do? What is human consciousness, and do we have free will?

World-leading researchers, including Nobel Laureates and rising young stars, examine some of the most important and fundamental questions at the forefronts of modern science, philosophy, and theology, taking into account recent discoveries from a range of fields. This fascinating book is ideal for anyone seeking answers to deep questions about the universe and human life.

Charles Hard Townes is University Professor of Physics, Emeritus, in the Graduate School at the University of California, Berkeley. He has also served as Provost and Professor of Physics at the Massachusetts Institute of Technology and as Director of the Enrico Fermi International School of Physics. His development of the maser and laser changed the modern world, earning him one-half of the Nobel Prize in Physics (1964), which he shared with Nicolay Gennadiyevich Basov and Aleksandr Mikhailovich Prokhorov, "for fundamental work in quantum electronics which has led to the construction of oscillators and amplifiers based on the maser–laser principle."

Professor Townes has shown keen interest in many fields of inquiry, including quantum optics, astronomy, natural history, policies for controlling the influence of science and technology, and many more. In his work, he has raised important issues such as the question of human freedom, creativity, the great unknowns in science, the possibility of future discoveries, and the purposefulness of the universe. For his progress toward research or discoveries about spiritual realities, he was awarded the 2005 Templeton Prize.



Charles H. Townes
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VISIONS OF DISCOVERY

New Light on Physics, Cosmology, and Consciousness

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I do not know what I may appear to the world;
but to myself I seem to have been only like a boy
playing on the seashore, and diverting myself in now and then
finding a smoother pebble or a prettier shell than ordinary,
whilst the great ocean of truth lay all undiscovered before me.

(Sir Isaac Newton)

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Foreword

I am enormously appreciative of the conference organized to mark my ninetieth birthday in 2005 and of the many distinguished scientists and friends who came together at the University of California, Berkeley, that October to discuss a very broad range of basic scientific, philosophical, and human issues.[1] They have provided great depths of insight into what science has discovered and seems to understand, as well as into the basic and important problems we still face. This volume thus provides perceptive and careful discussions of present knowledge and understanding along with illuminating examinations of the puzzles yet before us to be solved through the science of the future. Although emphasis is placed on the physical sciences, the discussions within these pages are broad and cover important aspects of neurobiology, what might be called philosophical and religious questions, and the boundaries of science.

How did things begin and why? What is the nature of scientific laws? What do we know about the origin of life, consciousness, and free will? What is the future of science? The things we seem to know are fascinating. So also are the unknowns and the questions about what we might eventually understand more completely. To proceed, we need as clear a picture of present understanding as possible along with a clear view of the unknowns and of the important paths we need to follow to explore them. So many fascinating areas are carefully discussed here – our universe's beginnings, the nature of matter and of fundamental particles, examinations and tests of quantum mechanics, exquisite high-precision measurements, the interaction of science and religious viewpoints – plus our understanding (or lack of it) regarding consciousness and free will![2]

To address these important issues, it would be difficult to assemble a more perceptive, knowledgeable, or outstanding group of persons than those who have contributed to this volume. Of course, not all questions are answered – and some are perhaps not even asked. But it is important to define carefully what we don't currently know and to consider the possibility of developing further understanding in the future, and both the depth of current knowledge and the presentation and possibilities for future understanding are considered with expertise and insight.

[1] See *Amazing Light: Visions for Discovery:* http://www.metanexus.net/fqx/townes/.
[2] Editors' note: Charles Townes contributed a chapter to this volume on this topic; see Part V.

Discussions by such a wide variety of knowledgeable authors, of course, provide a broad range of ideas and approaches that advocate no simple overall view or recommended set of beliefs. The expertise of the authors, depth of discussions, broad coverage of so many important aspects of science, and insightful presentations of problems make this a very rich volume. I have no doubt it will be of long-lasting value. I hope many will enjoy and learn from it. Finally, I want to repeat my deep appreciation of the impressive authors and their contributions to this work.

Charles H. Townes
University of California, Berkeley

Editors' preface

The invention of the laser can be dated to 1958 with the publication of the scientific paper "Infrared and optical masers" by Arthur L. Schawlow, then a Bell Labs researcher, and Charles H. Townes, then a consultant to Bell Labs. That paper, published in *Physical Review*, a journal of the American Physical Society,[1] opened the door to a multibillion-dollar industry and launched a new scientific field – as well as many careers.

Visions of Discovery: New Light on Physics, Cosmology, and Consciousness is part of a program that was developed in 2005 to honor the leadership and vision of Townes in his ninetieth-birthday year. Beginning with the *Amazing Light: Visions for Discovery* symposium held at the University of California, Berkeley, in October 2005,[2] the program, including this volume, aims to honor and amplify Townes's vision and take it into the twenty-first century with new generations of researchers who continue to explore possibilities for investigating new, deep discoveries about the nature of the universe. To celebrate and extend these possibilities, the program also launched the Foundational Questions Institute (FQXi), whose mission is to catalyze, support, and disseminate research on questions at the foundations of physics and cosmology, particularly new frontiers and innovative ideas integral to a deep understanding of reality that are unlikely to be supported by conventional funding sources.[3]

Following Townes's example, this program emphasizes the role of technological innovations that accelerate scientific creativity and benefit human life. It focuses on the creative edges of the experimental (observational) aspects of physics, astrophysics, cosmology, and astronomy that may lead to new discoveries – and especially to powerful new scientific instruments – that may transform human capabilities to explore physical reality. The goal of developing cutting-edge tools is considered in the context of advancing the scientific quest for a fundamental, integrated understanding of the universe. A pre-eminent example is the fascinating, rich innovation made possible through the study of light and its quanta so successfully pioneered by Townes. His development of the maser and laser changed

[1] See http://www.bell-labs.com/history/laser/.
[2] The entire program was made possible by the John Templeton Foundation, the Metanexus Institute, and various partner organizations. See http://www.metanexus.net/fqx/townes/ for information on the symposium.
[3] See http://fqxi.org/. FQXi's Scientific Director, Max Tegmark of MIT, contributed a chapter to this volume; see Part VI.

the modern world and earned him one-half of the Nobel Prize in Physics, which he shared with Nicolay Gennadiyevich Basov and Aleksandr Mikhailovich Prokhorov in 1964.[4]

The ongoing study of light has huge potential for supporting technological innovation, as well as for leading to a new understanding of the workings of the universe. Illustrating the continued importance of this area of study, the Royal Swedish Academy of Sciences announced on October 6, 2009, that it had awarded the latest Nobel Prize in Physics jointly to the "Masters of Light," Charles K. Kao, Willard S. Boyle, and George E. Smith.[5] So 2010, the "Year of the Laser," as declared by the American Physical Society and the Optical Society of America, is a serendipitous opportunity to honor and celebrate the accomplishments of Townes and the generations of researchers he has inspired and guided.[6] Starting from some of the questions inspired by Townes's many areas of interest, as he expressed so eloquently in the foreword to this book and as echoed by the warm reflections of Freeman Dyson in the preface, the book's following chapters explore questions such as (1) Origins: What is the nature of the Big Bang? Why do the constants of nature have the values they do – and are they actually constants? What is the ultimate future of the universe? (2) Unknowns: What are dark matter and dark energy? Do zero-point electromagnetic fluctuations have anything to do with dark energy? What is the nature of black holes? What elementary particles are present but undetected? (3) The nature of life: How and when did it originate? How likely is life near other stars, particularly "intelligent life"? Do humans have free will? What is consciousness? What is the long-range future of humans?

While heavily based on the physical sciences, this volume also embraces the humanities, bringing together a large number of the world's greatest scientific and academic researchers in physics, astrophysics, astronomy, cosmology, neuroscience, philosophy, and theology who are concerned with the most fundamental questions posed by science, as well as with some of the big – and very important – questions that lie beyond the usual realm of the physical sciences. Many of these distinguished scholars have achieved international acclaim and earned many awards, including, like Townes himself, the Nobel Prize. Thus, this multidisciplinary volume attempts to address important questions in a manner that will appeal to fellow scientists and academics, as well as to interested others. It is broken down into six parts to allow easy access to specific areas of inquiry inspired by many of Townes's own pursuits and concerns:

Part I: Illumination: The History and Future of Physical Science and Technology
Part II: Fundamental Physics and Quantum Mechanics
Part III: Astrophysics and Astronomy
Part IV: New Approaches in Technology and Science
Part V: Consciousness and Free Will
Part VI: Reflections on the Big Questions: Mind, Matter, Mathematics, and Ultimate Reality

4 See http://nobelprize.org/nobel_prizes/physics/laureates/1964/index.html. Townes received one-half of the 1964 Nobel Prize in Physics "for fundamental work in quantum electronics which has led to the construction of oscillators and amplifiers based on the maser–laser principle."
5 See http://nobelprize.org/nobel_prizes/physics/laureates/2009/press.html.
6 See "LaserFest": http://www.aps.org/publications/capitolhillquarterly/200901/laserfest.cfm.

Providing rich personal perspectives on the scientific quest, as noted above, Townes himself wrote the foreword (and also a chapter for Part V), and Freeman Dyson supplied the preface (and also a chapter for Part I). Also included in this volume is a special "Laureates' preface" written by the three physicists who had just shared the 2005 Nobel Prize at the time of the *Amazing Light* symposium: Roy Glauber, Ted (Theodor) Hänsch, and Jan (John) Hall.[7] Joining them in contributing to this section is Wolfgang Ketterle, who won the Nobel Prize in Physics (which he shared with Eric Cornell and Carl Wieman) in 2001.[8]

In addition to bringing together an outstanding, select group of research leaders and scholars, the book also features contributions from four young scientists emerging as research innovators who were top winners at the Young Scholars Competition held at the symposium – Steven Gubser, Brian Keating, Marin Soljačić, and Jun Ye.[9]

We hope that this books meets its goals of exploring the deep questions and great unknowns in science, emphasizing the continuing potential and excitement of science and technology, considering promising domains for future research, and exploring questions on the boundaries of science and human life by bringing together highly esteemed contributors from many fields to share in an interdisciplinary exchanges of ideas. We hope that the book will inspire future scholars in many disciplines to generate new research projects and pursue answers to the ongoing human quest to understand the universe we inhabit.

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7 See http://nobelprize.org/nobel_prizes/physics/laureates/2005/press.html.
8 See http://nobelprize.org/nobel_prizes/physics/laureates/2001/press.html.
9 See http://www.metanexus.net/fqx/townes/pressroom.asp.

Preface

Thirty years ago, I visited Furman College in Greenville, South Carolina, where Charlie Townes had been a student forty years earlier. I have vivid memories of a long bus ride from Atlanta to Greenville, along country roads with frequent stops at little towns crowded with scrawny chickens and Baptist churches. When I arrived in Greenville, I was greeted at the bus stop by the students who had invited me, and they immediately began talking about Charlie Townes. Memories of Charlie were still alive at Furman after forty years, as no doubt they are still alive today after more than seventy.

Townes is remembered at Furman as the best student they ever had, a student who was outstanding not only as a scientist, but also as a character. Furman is a place where it is taken for granted that you say grace before meals, read the Bible, and don't take the name of the Lord in vain. I felt at home at Furman because it reminded me of my Yorkshire grandparents, who were Baptists and sang in the Baptist Chapel choir every Sunday. Charlie Townes was even more at home there. Townes left his mark on Furman, and Furman left its mark on Townes. For more than seventy-five years, he has maintained a close connection with Furman, and when he was awarded the Templeton Prize in 2005, he gave away a large chunk of it to that institution. Furman stands for the same qualities that Townes embodies: technical skill, hard work in the learning and teaching of science, joyful faith, and open-minded fellowship in the practice of religion. Townes and Furman both bear witness to the fact that science and religion can fit well together, either in an educational institution or in a human soul.

This book is a collection of essays celebrating Charles Townes's ninetieth birthday in 2005. Many of them, but not all, are expanded versions of talks given at a three-day birthday conference at the University of California, Berkeley in October 2005. The Berkeley meeting actually celebrated a double birthday: Charles's wife, Frances, reached the age of ninety in the same year, within a few days of the meeting. They have been married and have supported each other for more than seventy years. Both of them came to the meeting in good health and spirits. Together they have raised four daughters. Frances is not a scientist, but she shares all of Charles's interests, and her mind is as sharp as his.

Most of the authors, but not all, were students of Townes or students of students of Townes. Each chapter is a survey of some field of science or philosophy related to Townes's activities. The amazing breadth of his interests is reflected in the variety of subjects that are covered, from Jun Ye writing about the latest advances in the precise measurement of time to Bob Russell writing about theology. The precise measurement of time has opened the door to many recent advances, not only in physics, but also in astronomy and chemistry. The modern technique of measurement of time is a marriage of microwave technology and optical technology. Both these technologies have grown out of Townes's inventions of the maser and the laser forty years ago.

Bob Russell, Founder and Director of the Center for Theology and the Natural Sciences in Berkeley, has been for many years a friend and protégé of Townes. His Center is close to the UCB campus and maintains close contact with the scientific activities on campus. The Center comes second after Furman College in the list of institutions to which Townes gave substantial portions of his Templeton Prize. Its mission is to educate scientists who wish to learn about theology and theologians who wish to learn about science. Bob Russell has low tolerance for people who talk in glib and fuzzy words about the marriage of science and theology without understanding either field in detail. He is striving for a marriage based on professional competence in both fields. Townes shares his goal, namely to combine a warm faith with a sharp mind. Bob explores this in his contribution to this volume.

Many of the chapters here deal with astronomy and cosmology. This reflects the fact that Charlie Townes decided, after he had revolutionized the field of microwave spectroscopy with his discoveries in the 1960s, to leave the field for his students to explore further. He felt, rightly, that nothing he could do in that field in the future would be as exciting as what he had done in the past. He likes to be a pioneer, not a follower. So he decided to start a new career as an observational astronomer, using his technical mastery of optics to build new kinds of interferometers.

A few years ago, I was at the Mount Wilson Observatory in California in the middle of the night, visiting the Gilbert Clark Telescopes in Education project. Clark has a telescope on the mountain remotely controlled by a class of schoolchildren in a different time-zone thousands of miles away. To my surprise and delight, I bumped into Charlie Townes, who was also spending the night on the mountain, installing and trying out his newest infrared interferometer. At close to the age of ninety, he was not content to give orders to others, but enjoyed hauling the hardware and making the measurements himself. That is the way I will always remember him, up there on the mountain under God's sky, patiently coaxing his instruments until they finally worked, as close to Heaven as he could get.

Freeman J. Dyson
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Laureates' preface

Reflections from Four Physics Nobelists[1]

This book celebrates the vision of Charles Hard Townes, not by reviewing his specific legacy in detail, but by bringing to readers the visions of dozens of other important researchers – individuals who, like Townes, look to shed light on the scientific mysteries of the day and inspire both science and society with the power of their insights to explore and unveil the mysteries of the future.

This book includes chapters from established luminaries – including an impressive list of fellow Nobel Laureates – and also rising new stars representing the range of fields touched by Townes's research. In addition, four Nobel Laureates who were unable to develop chapters for the book because of other commitments nevertheless wished to be part of the project. This special preface includes their reflections – both professional and personal – on the legacy of the still vibrant Charles Townes.

Roy J. Glauber*, who was awarded half the 2005 Nobel Prize in Physics "for his contribution to the quantum theory of optical coherence," aptly introduces this section by speaking of Townes's vision, in particular his vision to "commit his efforts to an incomplete but persuasive insight," and how that vision accelerated and even spawned the work of so many others.*

John L. Hall *and* ***Theodor W. Hänsch****, who shared the remaining half of the 2005 prize "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique," reflect in their essays on how Townes's early insights transformed much of contemporary science and society. Hall speaks personally of Townes's "style and vigor in physics research," and Hänsch describes being inspired by Townes's ability to "combine elements and techniques known to people in different communities with his own brilliant ideas to do what no one had done before."*

Finally, **Wolfgang Ketterle***, who was awarded one-third of the Nobel Prize in 2001 "for the achievement of Bose–Einstein condensation in dilute gases of alkali atoms and for early fundamental studies of the properties of the condensates," remarks on how the discoveries made by Charles Townes would become the foundation for his own scientific work.*

[1] For further information, see http://nobelprize.org/nobel_prizes/physics/laureates/.

In their reflections, these four Nobelists illuminate how profoundly one man's vision can transform the world around us and our understanding of it.

Celebrating the vision of Charles Hard Townes

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Many of humankind's greatest occasions go uncelebrated. That is how it is with most of the inventions and discoveries that have shaped the lives we lead today. When the wheel was invented – for the first time, that is – no sculptors were there to record the event, and no historians were present to pass the word on to us by notching their stone tablets. So, whoever that putative "Mr. Wheeler" was, to whom we owe all of modern transport, his birthday passes unnoticed against the rolling background of our lives.

Things are different these days. The science that all of those innovations have spawned endows us with the power to foresee which inventions will be the formative ones for the ages ahead. The laser is unmistakably one of those, and we have now the unique opportunity of celebrating the birthday of its inventor, even while its era is still unfolding.

Dazzling realizations, such as the laser, can shine so brightly in the present that they even seem to cast a certain shadow over the past. Given the knowledge that light consists of electromagnetic waves, as well as the detailed understanding we had of electromagnetic theory fifty and even a hundred years ago, it becomes almost a shame to recall that the entire science of optics was developed from the observation of truly primitive sources of illumination, sources that were intrinsically chaotic in nature. The very essence of radio communication, by contrast, is the detailed control of electromagnetic oscillations. But in all available light sources preceding the laser, those higher-frequency oscillations were governed only by the hubbub of chaotic atomic collisions or the microscopically random happenings of thermal noise. It took the laser to tame the chaotic electrical oscillations of atoms and get them to march in step with one another.

It is interesting to note that the actual realization of the laser did not depend so much on the most recently developed equipment as it did on ideas that were some years in gestation. The laser was based, in fact, on laboratory techniques that could have been exploited years earlier. That they had not been bears some testimony to the importance of the conceptual route by which the essential ideas were established. Such a novel way of generating light depended on the development of the microwave maser, largely by Charles Townes and Arthur Schawlow, and that development did rest on the microwave technology developed in the 1940s. But it evidently took the development of the maser to provide Charlie with the vision and courage to contemplate making atoms radiate visible light by oscillating in unison, and accomplishing that didn't require any of the microwave hardware.

The development of both devices, the maser and the laser, was based, of course, on the quantum theory of atomic energy states and paid only crude attention to the light quanta that were to be generated. It is to Charlie's everlasting credit that he proceeded in this way, without a full description of the quantum fields he would be generating. The mathematics he used was soon supplemented by a theoretical treatment, credited to Willis Lamb, that included the electromagnetic field more explicitly, but only treated it classically, and thus was not fully consistent with the quantum theory. The fully quantum-mechanical theory of the laser was not easy to develop. It involved the efforts of many people and several years of further work. What we are now honoring is the vision that impelled Charlie to commit his efforts to an incomplete but persuasive insight – and how much that vision accelerated the work of all of us. Indeed, if the development of the laser had had to await the complete understanding provided by quantum field theory, we might be waiting for it still.

My own involvement in this work was not directly connected to the development of the laser. It started with analyses of the statistics of light quanta emitted from more ordinary kinds of light sources by the methods of quantum electrodynamics. It also included, however, a well-motivated guess about the quantum statistics of the laser output. So I was thrilled when Charlie invited me to come over to MIT and speak to his research group on several afternoons in 1963. That was the beginning of my association with the laser community, and the following years have given me many occasions to impress on it the mathematical conscience of the quantum theory. Those afternoons at MIT were, in fact, some of the last of Charlie's total devotion to lasers. After leaving MIT for Berkeley, he took up another relatively new field, radioastronomy, where he has also been responsible for a succession of seminal discoveries.

Adam, the Bible tells us, lived for 930 years. He must surely have been impressed by the size of the population he had spawned even within those years. While Charlie is still with us – and is only a tenth as old – he should be equally impressed that his invention is to be found almost everywhere, even in its early youth – and in one way or another gives employment to so many of us. In that sense, he too has become the father of us all.

Defining and measuring optical frequency

John L. Hall
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I was pleased to learn about the symposium *Amazing Light: Visions for Discovery* held at the University of California, Berkeley in October 2005 in honor of Charles Hard Townes's ninetieth birthday. Charles Townes is surely my all-time top personal hero, for his contributions in physics, in studying physics issues related to national defense, and especially for showing a style and vigor in physics research that serves as a great example to me and others considering the retirement issue. Indeed, when the symposium was held, my wife and I were just returning from a car trip visiting sites of notable US architecture – a first step in my attempting to make amends for many years of too many nights in the lab. In this choice I lost the chance to interact with some of the great minds in physics and to express my respects in person to this great man and great scientist. Still, I could take some comfort in my decision in that my protégée, Jun Ye, did participate in the symposium and illustrate just how powerfully Professor Townes's insights from long ago have helped shape the science and technology of today. Happily, Jun contributed a chapter to this volume.

As a graduate student learning about nuclear and electron spin resonance techniques, I made frequent use of a great new book, *Microwave Spectroscopy*[2] by Charlie and his brother-in-law Arthur Schawlow. When my Ph.D. thesis phase was winding up, there came the remarkable success by Ali Javan and his Bell Labs colleagues in using a "negative absorption" (amplification) regime in a He–Ne discharge to implement the coherent "optical maser" emission idea of the same two authors. I then joined the National Bureau of Standards (NBS)[3] as a postdoc under Peter Bender, and very soon the metrology community was attracted to the stable-laser work of the world leader, one Professor Charles Townes, now at MIT. Eventually, a differential laser-based speed-of-light measurement was planned at the NBS, which colleagues and I began to implement in an unused former gold mine near Boulder. Regrettably, the original color slide of Charlie wearing the miner's safety helmet for his underground visit almost instantly disappeared from my stack of slides during some lecture tour.

The extended (read thirty years!) development of frequency measurement tools at the NIST and JILA did eventually pave the way for the quick implementation of the optical comb idea, which was first studied in the late 1970s by Ted Hänsch, whose recollections follow mine below. For the ideal of single-step optical frequency measurement, the missing component was the method to generate bright white-light femtosecond pulses with a diffraction-limited spatial character. Eventually, this was supplied in 1999 by continuum generation at nondestructive, low power levels by organizing extended phase matching via microstructured optical-fiber design. After some months of intense collaboration/competition between the Boulder team and Ted Hänsch's group in Garching, a deluge of new results began flowing from the direct optical frequency synthesis enabled by the optical comb. For this work, as the team leaders, Ted and I shared half the Nobel Prize in Physics in 2005.[4]

At MIT, Charles Townes also continued his fundamental measurements of physical principles, beginning with atomic-beam and maser techniques and migrating to the optical domain. I was particularly struck by his application of stable lasers and optical heterodyne

[2] Townes, C.H. and Schawlow, A.L. (1955). *Microwave Spectroscopy.* New York: McGraw-Hill.
[3] Later known as the National Institute of Standards and Technology (NIST).
[4] Roy Glauber, whose perspectives appear earlier in this preface, won half of the total prize "for his contribution to the quantum theory of optical coherence." See http://nobelprize.org/nobel_prizes/physics/laureates/2005/.

measurements to the Michelson–Morley test of the spatial isotropy of the speed of light. After we had the methane-stabilized optical frequency reference laser working well at JILA, it was attractive to revisit Charlie's pioneering test of the isotropy of c. Our 1979 experiment was essentially an improved realization of his concept, but it gave a rewarding 4,000-fold accuracy gain. This idea, now called local Lorentz invariance, is a hot topic.

I was absolutely thrilled in 1984 when Veniamin Chebotayev and I jointly received the Charles Hard Townes Award of the Optical Society of America, presented by Professor Townes himself!

As well as being a disciple of Charles Townes, I was physically near him at a laser meeting in Arizona when the world nearly lost him, shortly after he, Nikolay Basov, and Aleksandr Prokhorov were announced as winners of the 1964 Nobel Prize in Physics for "oscillators and amplifiers based on the maser–laser principle."[5] Posing for photographs, the three were seated in a hay-filled wagon when a fire somehow got started. Luckily, they all escaped with no serious injuries.

My Nobel lecture "Defining and measuring optical frequencies,"[6] given in Stockholm on December 8, 2005, is my tribute to Charles Townes. Seldom in history have the ideas of one man had such a profound impact on science and society, including the explosion in optical physics of new results and laser capabilities that have transformed the world around us.

A passion for precision

Theodor W. Hänsch
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When I received an invitation to participate in the symposium *Amazing Light: Visions for Discovery* held at the University of California, Berkeley in October 2005 in honor of Charles Hard Townes's ninetieth birthday, I was thrilled and elated. The symposium would be a rare opportunity to meet some of the greatest minds in physics and cosmology and to pay tribute to a true giant of science, whose early insights have transformed much of contemporary science and technology.

When Charles Townes, Nikolay Basov, and Aleksandr Prokhorov were awarded the 1964 Nobel Prize in Physics for "the construction of oscillators and amplifiers based on the maser–laser principle,"[7] I was a first-year graduate student at the University of Heidelberg and had just decided to switch from nuclear physics to laser science. I found it incredibly encouraging and inspiring to see how Charlie Townes could combine elements

[5] Charles Townes won half of the total prize. See http://nobelprize.org/nobel_prizes/physics/laureates/1964/.
[6] Hall, J.L. (2006). Nobel lecture: Defining and measuring optical frequencies. *Reviews of Modern Physics*, **78**, 1279–95.
[7] Charles Townes won half of the total prize. See http://nobelprize.org/nobel_prizes/physics/laureates/1964/.

and techniques known to people in different communities with his own brilliant ideas to do what no one had done before. Avoiding mainstream research and following his own extraordinary instincts, he had invented first the maser and then the laser. With his invention of the laser, Charlie had introduced a revolutionary tool that has turned out to be both easier to realize and much more powerful and far-reaching in its applications than anybody could have imagined.

In his insightful book *How the Laser Happened*,[8] Charlie Townes writes "The steady improvement in technologies that afford higher and higher precision has been a regular source of excitement and challenge during my career. In science, as in most things, whenever one looks at something more closely, new aspects almost always come into view." Such passion for precision has long been a driving force in my own research revolving around lasers, coherence, interference, and precise laser spectroscopy. During the sixteen years I spent at Stanford University, I was privileged to work closely with my mentor, friend, and colleague Arthur L. Schawlow, who was married to Charlie Townes's youngest sister, Aurelia. Art would often recount fascinating stories about the early days of the laser. After Charlie and Art had written their textbook *Microwave Spectroscopy*,[9] which became a classic, Art came to the conclusion that microwave spectroscopy should be handed over to the chemists because to a physicist "a diatomic molecule is a molecule with one atom too many!" Following Art's strategy, for more than three decades I have focused much of my research on precision laser spectroscopy of the simple hydrogen atom. Hydrogen still provides unique opportunities for critical confrontations between fundamental theory and spectroscopic experiment. The goal of reaching the highest possible spectroscopic resolution and measurement accuracy for the simplest atom, together with the playful atmosphere encouraged by Art Schawlow at Stanford, inspired many advances in laser spectroscopy, from the first monochromatic tunable dye laser to powerful methods of nonlinear Doppler-free laser spectroscopy. Even the first proposal for laser cooling of atomic gases and the first experiments with laser-frequency combs date back to the exhilarating years at Stanford. Today, frequency-comb techniques make it possible to count the ripples of a light wave with incredible precision.

On October 4, 2005, the day I flew from Munich to the Townes Symposium at Berkeley, I learned that the Royal Swedish Academy of Sciences had decided that John L. Hall and I would each be awarded one-quarter of the 2005 Nobel Prize in Physics for "contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique."[10] The lecture, "A passion for precision," that I had prepared in honor of Charlie Townes naturally became the basis for the Nobel lecture that I gave in Stockholm on December 8, 2005.[11] This lecture adds to a large and growing bouquet of Nobel lectures that pay tribute to the seminal work of Charlie Townes.

[8] Townes, C.H. (1999). *How the Laser Happened: Adventures of a Scientist*. New York: Oxford University Press.
[9] Townes, C.H. and Schawlow, A.L. (1955). *Microwave Spectroscopy.* New York: McGraw-Hill.
[10] Roy Glauber, whose perspectives appear earlier in this preface, won half of the total prize "for his contribution to the quantum theory of optical coherence." See http://nobelprize.org/nobel_prizes/physics/laureates/2005/.
[11] Hänsch, T.W. (2006). Nobel lecture: A passion for precision. *Reviews of Modern Physics*, **78**, 1297–309.

From optical lasers to atom lasers and to superfluids

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When Charlie Townes received the Nobel Prize in 1964, I was a first-grader. Little did I know about lasers or science in general, but Lego started to fascinate me and gave me an early opportunity to design and build things. I was also unaware that the discoveries made by Charlie would become the foundation for my own scientific work, first in molecular spectroscopy, and then in the area of ultracold atoms.

Charlie realized the laser principle with microwaves and then extended it to the optical domain. I was privileged to extend the principle of coherence and stimulated emission from electromagnetic waves to matter waves.[12] The advent of Bose–Einstein condensation in atomic gases in 1995 gave us clouds of gases that behaved like waves; actually, they were one giant de Broglie wave. I soon became fascinated by the analogy with the optical laser. The Bose–Einstein condensate was supposed to be created by stimulated scattering, by a self-amplifying process, like the maser and laser. The idea of coherent amplification of matter was met with some reservation – it seemed to contradict the conservation of mass, whereas photons could be generated in an active medium. However, the correct analogy is that an ordinary laser extracts energy out of an active medium and converts it into coherent radiation. The atom laser takes atoms out of an active medium (an ultracold atom cloud) and converts them into coherent matter waves. Such a kind of matter-wave amplification occurs during the formation of a condensate, but it could be more directly demonstrated by sending a pulse of atoms through a Bose–Einstein condensate and observing its amplification.[13] After long, controversial discussions, it became clear that even fermionic matter waves could be amplified, although this requires a coherent preparation of the system.[14]

The atom laser (as a generator of coherent matter waves was dubbed) complemented many earlier developments in atom optics. The field of atom optics, pioneered by my mentor Dave Pritchard,[15] developed and characterized atom-optical elements such as mirrors and beam splitters for atomic beams, which eventually led to practical atom interferometers for sensing of gravitational and inertial forces. Finally, with Bose–Einstein condensates, the analog of the optical laser was added to the atom-optics catalog. Atom lasers are different from optical lasers because atoms interact, in contrast to photons. Therefore, nonlinear atom optics, such as four-wave mixing, frequency doubling (conversion of atoms to molecules), and parametric amplification, could be realized without any nonlinear medium – the atom laser itself shows nonlinear behavior.

[12] W. Ketterle. *Rev. Mod. Phys.*, **74** (2002), 1131.
[13] S. Inouye, T. Pfau, S. Gupta, *et al. Nature*, **402** (1999), 641; M. Kozuma, Y. Suzuki, Y. Torii, *et al. Science*, **286** (1999), 2309.
[14] W. Ketterle and S. Inouye. *Phys. Rev. Lett.*, **86** (2001), 4203; M.G. Moore and P. Meystre. *Phys. Rev. Lett.*, **86** (2001), 4199.
[15] D.E. Pritchard, A.D. Cronin, S. Gupta, *et al. Ann. Phys.*, **10** (2001), 35.

The interaction between atoms may limit the performance of atom lasers; for example, it may impose collisional limits on the maximum intensity or make atom-laser beams divergent because of mean-field repulsion. However, those interactions imply that ultracold atoms can do more than "marching in lockstep": they can show interesting correlations and turn into an interesting many-body system. Such interactions are responsible for many fascinating properties of these gaseous clouds, including phase transitions and superfluidity.

One of the most recent accomplishments is the observation of coherence and superfluidity of fermion pairs in a strongly interacting cloud of ultracold lithium atoms.[16] We now have not only photons, but also atoms, molecules, and correlated fermion pairs that show laser-like properties! Research on strongly interacting ultracold atoms has intensified links between quantum optics, atomic physics, and condensed matter physics, and rapid recent developments indicate that more excitement is yet to come.

[16] M.W. Zwierlein, J.R. Abo-Shaeer, A. Schirotzek, *et al. Nature*, **435** (2005), 1047.

Acknowledgments

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Thanks are due to Freeman J. Dyson for providing the preface to this volume, which gives affectionate personal insights into the life and times of Charlie Townes. He also contributed a fascinating chapter.

We are particularly grateful to Roy J. Glauber, John L. Hall, Theodore W. Hänsch, and Wolfgang Ketterle for contributing the special Laureates' preface. (The former three shared the Nobel Prize in Physics in 2005, the year the *Amazing Light* symposium was held.) Although their schedules would not permit them to submit full chapters, their personal and professional reminiscences pay homage to the influence Charlie Townes had on their lives and careers.

Also, we are much indebted to the Program Committee, many members of which are contributors to this volume, who played key roles in organizing the *Amazing Light* symposium at the University of California, Berkeley, in October 2005.

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Pamela M. (Bond) Contractor of Ellipsis Enterprises, working as a consultant to the John Templeton Foundation and the Metanexus Institute, helped to organize the 2005 *Amazing*

[1] Sir John passed away on July 8, 2008, at age 95. For further information, see http://www.templeton.org/.
[2] For further information, see http://www.ieee.org/organizations/foundation/index.html.