国家出版基金项目
NATIONAL PUBLICATION FOUNDATION

"十二五"国家重点图书出版规划项目

光物理研究前沿系列

总主编　张杰

精密激光光谱学研究前沿

高克林 等　编著

Advances in Precision Laser Spectroscopy

上海交通大学出版社
SHANGHAI JIAO TONG UNIVERSITY PRESS

国家出版基金项目
NATIONAL PUBLICATION FOUNDATION

"十二五"国家重点图书出版规划项目

光物理研究前沿系列

总主编 张杰

精密激光光谱学研究前沿

Advances in Precision Laser Spectroscopy

高克林 等 编著

上海交通大学出版社
SHANGHAI JIAO TONG UNIVERSITY PRESS

内容提要

本书是“十二五”国家重点图书出版规划项目“光物理研究前沿系列”之一，包括冷原子物理、冷分子物理、激光光谱、囚禁离子光频标、基于原子分子光物理的精密测量等前沿专题。

本书可供光学及物理专业的本科生、研究生及相关研究人员阅读参考。

图书在版编目(CIP)数据

精密激光光谱学研究前沿 / 高克林等编著. 一上海：
上海交通大学出版社，2014
(光物理研究前沿系列 / 张杰主编)
ISBN 978-7-313-11644-4

Ⅰ. ①精… Ⅱ. ①高… Ⅲ. ①激光光谱学一研究
Ⅳ. ①O433.5

中国版本图书馆 CIP 数据核字(2014)第 134680 号

精密激光光谱学研究前沿

编　　著：高克林　等
出版发行：上海交通大学出版社　　地　　址：上海市番禺路 951 号
邮政编码：200030　　电　　话：021-64071208
出 版 人：韩建民
印　　制：山东鸿杰印务集团有限公司　　经　　销：全国新华书店
开　　本：710 mm×1000 mm　1/16　　印　　张：32.25
字　　数：566 千字
版　　次：2014 年 10 月第 1 版　　印　　次：2014 年 10 月第 1 次印刷
书　　号：ISBN 978-7-313-11644-4/O
定　　价：135.00 元

光物理研究前沿系列
丛书编委会

分享光物理之美

经过三年时间的策划，在数十位活跃在光物理研究最前沿科学家的巨大努力和重量级资深科学家的倾情参与下，“光物理研究前沿系列”丛书中英文版终于同时面世了。

光物理是近代物理学中历史最悠久、同时也最具活力的领域之一，特别是激光问世以来，光学渗透到众多学科领域，光学自身的面貌不断发生着深刻的变化。与此同时，光物理的研究内容也从传统的光学与光谱学迅速扩展到光学与其他学科的交叉分支领域，逐渐形成了丰满的学科体系；层出不穷的光学诊断方法和技术发明推动了许多学科的快速发展，并进一步演化为新的科学前沿，这也是光物理研究中最美的景象。

近年来，随着我国科研实力的大幅增强，不少实验室都做出了国际水平的研究成果，我国科学家在 *Nature*，*Science*，*Physical Review Letters* 等国际顶级学术期刊上发表的论文数量已经在全世界占据了相当的份额，同时，国际顶级的综述类学术刊物也邀请我国科学家撰写了大批综述性论文。但是，令人遗憾的是，面向高年级大学生、研究生以及青年学者，介绍我国光物理科学前沿研究成果的专著还比较少，这也将成为制约我国光物理前沿研究未来发展的瓶颈。

出于这个原因，当上海交通大学出版社邀我作为主编，筹划组织编写一套“光物理研究前沿系列”丛书的时候，我欣然同意。我们的目标是编写一套给高年级大学生、研究生和青年学者阅读的中文入门读物，介绍国内外光物理前沿研究的最新进展。本丛书首批包括《强场激光物理研究前沿》《精密激光光谱学研究前沿》《非线性光学研究前沿》《纳米光子学研究前沿》《量子光学研究前沿》《超快光学研究前沿》《凝聚态光学研究前沿》《生物分子光子学研究前沿》等八个分册。每个分册包含了若干该领域的前沿研究专题，几十位活跃在光物理研究最前沿的作者均来自中国重要大学和科研院所。我们希望能以此为契机，汇集最有价值的研究资源，以供有建树的光物理科学家展示自身的研究成果；进而形成良好的学习和借鉴氛围，为高年级大学生、研究生以及青年学者提供学术交流的

平台。在每个分册的开始,我们都邀请了重量级资深科学家作序,介绍每个主题的精华,目的是想与大家一起分享光物理最前沿令人震撼的美。

强场激光物理对应的激光场强具有非常宽的范围,因而包含了极为丰富的非线性物理。强场激光物理及相关前沿新方向是现代物理学乃至现代科学中最重要的前沿之一,不仅有重大的科学意义,而且对国家战略高新技术与交叉学科领域也有重要的推动作用。

——摘自《强场激光物理研究前沿》的序

测量是物理科学的基础。在物理学中,原子、分子和光学物理领域比其他任何学科都能更加有力地说明这一点。精密测量是原子、分子和光物理的一个重要分支:它提供了深入了解物理基本定律的重要方法,激励了科学技术前沿的发展,并且推动了许多社会意义重大的革命性应用。

——摘自叶军院士为《精密激光光谱学研究前沿》所作的序

激光的发明,引导出很多新的学科,对我们今天的科学技术以及日常生活都产生了重大影响。其中最重要的学科之一就是非线性光学,它对半个世纪以来科技的发展起了十分重要的作用。

——摘自沈元壤院士为《非线性光学研究前沿》所作的序

纳米光子学融合了光子学和当代纳米技术,研究纳米尺度下光与物质相互作用的机理和效应,在高速信息传输和处理、新能源以及生物医学等领域都有重要的应用。因此,纳米光子学既是国家层面的重点科技战略,又为科技产业发展注入了新的源动力。

——摘自张翔院士为《纳米光子学研究前沿》所作的序

量子信息科学的重大意义在于它的发展不仅仅具有诱人的应用前景,还在于它使得我们意识到:量子其实是信息的载体,而且对某些应用来说也许是最好的载体。我们再次发现,在量子信息科学的发展中,量子光学仍然扮演了重要的角色。这包括人们对光子纠缠操纵能力的逐步提升,光子系统在光量子计算、量子通信和量子精密测量等诸多方面的应用。

——摘自潘建伟院士为《量子光学研究前沿》所作的序

超快光学是随着超短脉冲激光的出现而诞生，并随着飞秒激光技术的迅猛发展而快速发展起来的。它始终与超快现象研究相互促进、共同发展。超快现象研究的需求带动了超快光学的发展，超快光学的进步又促进了超快现象研究范围的扩展和深度的提升。

——摘自侯洵院士为《超快光学研究前沿》所作的序

光与凝聚态物质相互作用是光物理学科的重要研究内容之一。一般说来，凝聚态光学研究包括两个方面。一方面激光作为一种性能优异的探针，可用于研究凝聚态物质的结构和运动规律。另一方面，通过凝聚态光学研究可以发现新的物质状态和新的运动规律，这些新发现可用于产生新的光源、新的探测器和多种其他器件。

——摘自杨国桢院士为《凝聚态光学研究前沿》所作的序

光物理的研究领域包罗万象，但丛书规模有限，不可能面面俱到。作者和出版社已经尽了最大的努力，希望能从浩瀚广阔的光物理成就的海洋中选取最漂亮的“前沿浪花”结集成册。目前八个分册的阵容中，既有光物理研究领域的经典方向，也有近十年来发展迅猛的前沿方向；既有主要介绍科学进展的内容，也有主要介绍新技术的章节。然而，本丛书远不能代表光物理发展前沿的全部，更何况光物理研究前沿也处在日新月异的快速变化中，所以出版本丛书的目的就是抛砖引玉，希望能够吸引更多的年轻人走入光物理的科学殿堂，领略光物理之美。

当我掩上厚厚的书稿，准备送出付印之际，感慨万千。转眼间三年时间过去了，许多在三年前还认为只是个美好梦想的事情，现在变成了现实。作为主要策划者及丛书主编的我，对这套书有特殊的感情。可以说，本丛书凝聚了两代中国光物理学家多年来对世界科学发展的贡献和感情！为此，我要特别感谢丛书的所有作者，他们都是活跃在光物理研究最前沿的科学家。尽管他们每天的时间分配都是以分秒来计算的，但是，他们仍然抽出了大量的时间，撰写了各自前沿领域的进展。作为一个在光物理领域从业多年的科学家，我对他们非常了解，也非常敬佩他们的责任感与使命感。正是出于对科研和教育的强烈责任感和使命感，促使他们从繁忙的研究工作中抽出宝贵时间，甚至牺牲了很多与家人团聚的时间，撰写了各分册，对本丛书作出了至关重要的贡献。我还要感谢丛书的全部编委，他们不仅承担了写作的任务，还承担了策划组稿、审校稿件的繁重任务，是

他们的努力，构架了本丛书的有机结构和宏大涉猎，保证了本丛书的质量。感谢美国科学院院士沈元壤先生为本丛书策划所作的努力，沈先生早年写就的《非线性光学》已经成为非线性光学研究的经典之作，他在“非线性光学五十年”的序言中，更是深入浅出地回顾和展望了非线性光学的发展脉络。感谢中国科学院院士杨国桢先生给予本丛书策划和出版的帮助，多年来，杨先生引领、见证了凝聚态光学研究的发展。他为《凝聚态光学研究前沿》所作的序言见解精辟，同时为凝聚态光学研究指出了未来的新前沿。感谢中国科学院院士侯洵先生为《超快光学研究前沿》作序，侯先生为中国超快光学的发展作出了奠基性的贡献，二十多年前，他访问英国时对超快光学领域进展的精辟点评，我至今犹在耳边。他们三位都是我老师辈的先生，从我还是学生的时候起，就从他们撰写的论文和学术专著中向他们学习，从他们的言传身教中向他们学习，多年来，我向他们学到了很多很多，至今他们也还是我的老师。

感谢美国科学院院士叶军先生为《精密激光光谱学研究前沿》作序，他是上海交通大学的校友，也是我交往多年的好朋友。他在精密测量、冷分子物理和冷原子光钟等方面的开拓性研究工作，至今都是光物理领域的重要里程碑。感谢美国国家工程院院士张翔先生为《纳米光子学研究前沿》作序，他在光学超材料方面的杰出成果在国际上引起了很大反响。感谢中国科学院院士潘建伟先生为《量子光学研究前沿》作序，作为我国最年轻的院士之一，他在量子通信前沿和应用方面所做出的杰出成果，让量子通信不再神秘。在本丛书中，我与他们联袂作序，用我们的共同努力，用我们各自对光物理前沿的理解和积淀，努力向读者介绍本丛书试图展现的光物理之美，希望能成为各自分册的点睛之笔。

最后，我想感谢上海交通大学出版社韩建民社长及编辑团队，他们付出了巨大的努力，使梦想成为现实。令人欣喜的是，在上海交通大学出版社和德古意特出版社的合力打造下，这套丛书前两册的英文版将作为“中国学术出版走出去”的第一波，同步在海外发行。在此，我祝愿这套丛书成为“中国学术出版走出去”第一波中最美的一朵“浪花”！让我们一起分享光物理之美！

2014 年 10 月于飞越太平洋的飞机上

Preface

Measurement is the foundation of physical science. No other discipline in physics can illustrate this point more convincingly than the field of Atomic, Molecular, and Optical Physics. Precision measurement is one of the key branches in AMO physics: It provides important tests of and deep insights into fundamental laws of physics, stimulates the development of new frontiers in science and technology, and connects to a wide range of revolutionary applications that bring important benefits to our society.

In this book dedicated to the frontiers of research in precision laser spectroscopy, readers will be treated to a delicious course of lectures covering ultracold atoms and molecules, laser spectroscopy, trapped atoms and ions, frequency metrology and laser science, tests of basic physical principles as well as the determination of fundamental constants and development of quantum sensors. As one samples this smorgasbord of ideas, one may wonder why the specific title of "precision laser spectroscopy" was chosen for this book or even question whether an aged topic such as spectroscopy still represents a cutting-edge frontier of science. The answer is a resounding yes.

The relentless pursuit of spectroscopy resolution has been a driving force for many scientific and technological breakthroughs, including the foundations for relativity and quantum physics, over the course of the development of modern physics. A key motivation for the invention of the laser was spectroscopy. Indeed, laser spectroscopy completely revolutionized the field of spectroscopy, and it continues to drive present-day research on quantum matter and laser science. Spectroscopy now boasts many different subfields including ultraprecise measurement, ultracold matter, ultrastable lasers, and time-resolved ultrafast dynamics. Today, spectroscopy is at the heart of a powerful renaissance in AMO physics.

The laser allows us to produce and manipulate coherent optical fields for demanding measurement needs. In the early days of lasers, nonlinear optical physics advanced rapidly, providing new experimental techniques for spectroscopy and further improving the resolution of spectroscopy and its versatile applications. Laser stabilization was also relentlessly pursued, leading to the present state-of-the-art laser frequency control that achieves optical phase coherence over multiple seconds. In addition, the recent invention and development of optical frequency combs has allowed this optical phase coherence to be precisely transferred to other optical or microwave spectral domains.

The optical frequency comb was a result of the merger of continuous-wave—laser-based precision optical frequency metrology and mode-locked—laser-based ultrafast optical science. Since this merger in 2000, wide-bandwidth optical frequency combs have produced many unexpected and remarkable developments in precision spectroscopy, frequency metrology, and ultrafast science. A phase-stabilized optical frequency comb spanning an entire optical octave establishes millions of regularly spaced, precise frequency marks that are as stable and accurate as the best CW lasers. We have already implemented coherent phase connections among different parts of the electromagnetic spectrum, spanning the optical to radio frequencies.

The frequency comb has profoundly changed the optical frequency metrology, resulting in recent demonstrations of absolute optical frequency measurement, optical atomic clocks, and optical frequency synthesis. By combining these capabilities with the use of ultracold atoms and molecules, we can now perform optical spectroscopy, frequency metrology, and quantum control at the highest level of precision and resolution.

Parallel developments in the time-domain applications have been equally revolutionary, yielding simultaneous, precise control of the pulse repetition rate and the carrier-envelope phase. These developments have led to recent demonstrations of isolated attosecond pulse generation, coherent synthesis of optical pulses from independent lasers, coherent control in nonlinear spectroscopy, coherent pulse addition, and the generation of frequency combs in the extreme ultraviolet and mid-infrared spectral regions. Indeed, we now have the ability to perform completely arbitrary optical waveform synthesis that complements and rivals similar technologies developed in the radio frequency domain. This unified thrust in time- and frequency-domain control has made it possible to simultaneously pursue coherent control of quantum dynamics in the time domain and high-precision measurements of global atomic and molecular structure in the frequency domain.

The desire for better control of atomic motions for spectroscopy in the laboratory, together with the gradual mastery of laser-based control of matter, led to the development of laser cooling of atoms in the early 1980s. Today, we have the goal of preserving the longest possible coherence times between atomic states and an optical field. To accomplish this, we need to understand and control the atomic center-of-mass motion at the scale of an optical wavelength. Another challenge stems from the fact that the optical probing of internal atomic states creates an inevitable back-action on the atomic center-of-mass motion. Such back-action limits measurement precision and control. Meeting these challenges requires preparing atoms at ultralow temperatures and confining them in specially engineered optical, radio frequency, electric, or magnetic traps that decouple the atomic internal and external degrees of freedom for spectroscopy. Such a separation of internal and external dynamics is critical for precision measurement, frequency metrology, the coherent manipulation of quantum systems, and quantum information science.

Fortunately for the future prospects of precision measurement, there has been tremendous progress in research on ultracold atomic gases. Atoms can now be brought to a standstill in such a way that the gas exhibits striking quantum behaviors. Coherent matter waves in the form of quantum degenerate gases can now be routinely prepared, manipulated, and measured in laboratory. With important tools, such as the control of atomic interactions via Feshbach resonances and the introduction of optical lattices to regulate atomic motions, atomic physics and quantum gas experiments are now ready to take on challenging and outstanding problems from condensed matter physics via a powerful laboratory platform for studying strongly correlated quantum many-body systems and their dynamics.

With this development, we have come full circle. The birth of quantum information science was triggered by advances in the control of laser and atoms. These advances, in turn, have further stimulated developments in the AMO field. This is the beauty of AMO physics: Measurement science gives birth to new physical insights, and, in return, the new scientific frontier lays the foundation for further development in measurement technology. We are already dreaming about entangling a large number of quantum particles, engineering novel quantum states, establishing quantum networks for communication, advancing measurement precision beyond the standard quantum limit, and revealing deeper secrets of Nature.

One example is the development of atomic clocks. Atomic clock transitions are no longer confined to the microwave domain because the optical frequency comb provides a coherent bridge between optical and radio frequency spectral domains. This coherent bridge allows us to explore optical transitions that have orders-of-magnitude-higher line quality. The new capability in the control of light has also made it possible to create and probe novel quantum matter via the manipulation of dilute atomic and molecular gases at ultralow temperatures. Because we can localize atoms within a fraction of an optical wavelength inside a deeply bound trap, we can remove atomic motional effects from optical spectroscopy and state control. In addition, the quantized atomic motion and long interrogation times inside the trap permit high-resolution and precise investigations. Such capabilities have long been used in trapped-ion systems where charged ions are deeply bound with minimal perturbations to their electronic states. Optical atomic clocks based on single-trapped ions have achieved remarkably low uncertainties.

More recently, protocols for precision measurement and quantum information science have required large ensembles of neutral atoms to boost the measurement signal-to-noise ratio, explore the atomic collective effects, or create a massively entangled system. For neutral atoms, external-trapping potentials are created from spatially inhomogeneous energy shifts of the electronic states produced by an applied magnetic, electric, or optical field. It is thus crucial that we have recently constructed atom traps that do not perturb the *in-situ* precision spectroscopy of atomic transitions. For the first time, we can control the quantum states of more than 1,000 atoms so precisely that we achieve a more accurate and more precise atomic clock than any existing atomic clocks. With the clock accuracy and stability both reaching the 10^{-18} level, we have realized a single atomic clock with the top performance in both key ingredients necessary for a primary standard. This incredible measurement precision has also enabled researchers to study complex quantum many-body systems and integrate them into the frontiers of precision metrology, where we seek to advance measurement beyond the standard quantum limit. Such advanced clocks will allow us to test the fundamental laws of nature and find applications among a wide range of technological frontiers.

A second example is that molecules at ultralow temperatures represent an exciting new frontier for AMO physics The strong interdisciplinary character of this new topic facilitates powerful connections to other scientific fields, including chemistry, quantum information, condensed-matter physics, and astrophysics. These connections, and the many possibilities for technological advances, arise naturally as molecules constitute the ubiquitous building blocks of materials and embody common drives for everyday energy flow and dynamics. Control of molecular interactions has thus been an outstanding scientific quest for generations. For example, reaching the ultracold regime for molecules has been hindered by the presence of many internal degrees of freedom such as vibrational and rotational levels and fine or hyperfine states. Fortunately, we have recently witnessed rapid advances in producing molecules (mostly diatomic molecules) at low and ultralow temperatures. We have already performed the first set of experiments that demonstrate ultracold molecular collisions and chemical reactions in a regime where the collision must be described in terms of quantum wave functions. These efforts are serving as a staging ground for exploring collective quantum effects in an ultracold gas of molecules.

There are three key reasons for studying ultracold molecules. First, molecules represent a natural extension of precision experimental control and the on-going revolution of quantum-based measurement. The rich internal structure of molecules provides a unique experimental testing ground for fundamental laws of nature such as fundamental constants, symmetry and parity, as well as extensions of the Standard model. For example, at low temperatures, we can carefully control molecular motional effects, making it possible to perform high-resolution spectroscopy of molecular structure at an unprecedented level of precision; Such experiments are crucial in the search for symmetry violations.

Second, molecules provide new opportunities for the study of novel many-body quantum systems. It is the interactions between the particles that make the behavior of a many-body quantum system intriguing, and cold molecules, like cold atoms, will have the feature of tunable interparticle interactions. Molecules allow us to explore the long-range and anisotropic interparticle interactions between molecular dipoles—in contrast to the forces between atoms that are typically characterized by short-range potentials and contact interactions. The scientific opportunities available with quantum gases of ultracold molecules include (1) the creation of novel molecular superfluids that rely on the dipole-dipole interaction between ultracold fermionic molecules, (2) the study of quantum magnetism using the many internal degrees of freedom in molecules to engineer effective spin-spin interactions, and (3) the implementation of novel quantum matter with molecules confined in optical lattices.

Finally, molecular quantum gases provide us with an unprecedented opportunity to study chemical reactions in the ultralow energy domain. The recent discovery of bimolecular chemical reactions at ultralow temperatures already demonstrates that a molecular gas in the quantum regime can have a surprisingly large rate of chemical reaction, showing us that the ultracold reaction rate is dictated by the quantum statistics of the molecule and its long-range interactions. Interesting areas for future study include electric field-controlled collisions, resonance-mediated reactions, and collective many-body effects in chemistry.

We now stand on a broad scientific frontier where atoms, molecules, and their interactions are controlled at the quantum level. This control is allowing us to understand and probe many-body quantum systems. Such efforts have important consequences on the intellectual front for unraveling complexity and on the applied side for advancing quantum technology-based sensors. Quantum mechanics sets the ultimate limit in our ability to manipulate and measure matter. The cold atom and molecule-based measurement approach will allow us to push the quantum limits of precision measurement towards both fundamental tests of physical principles and advanced measurement tools and sensors for a range of practical applications. We are living in the golden age of AMO physics and precision measurement!

JILA, National Institute of Standards and Technology and
University of Colorado
September, 2014

序

测量是物理科学的基础。在物理学中，原子、分子和光学（AMO）物理领域比其他任何学科都能更加有力地说明这一点。精密测量是原子、分子和光物理的一个重要分支：它提供了深入了解物理基本定律的重要方法，激励了科学技术前沿的发展，并且推动了许多社会意义重大的革命性应用。

本书致力于研究最前沿的精密激光光谱学，读者将会享受一场精彩的讲座，其中包括超冷原子和分子、激光光谱学、原子和离子囚禁、频率测量和激光科学、基本物理定律的检测、基本常数的确定以及量子传感器的发展。当读者体会这些五彩缤纷的想法时，他们可能想知道为什么这本书会选"精密激光光谱学"这个特定的标题，甚至会提问："像光谱学这样陈旧的主题是否仍能代表一个尖端的科学前沿？"答案是完全肯定的。

在现代物理学的发展历程中，人们对光谱分辨率的不懈追求已经成为许多科学和技术突破的驱动力，包括相对论和量子物理的基础。发明激光的一个主要动因就是光谱学。实际上，激光光谱彻底地改变了光谱的研究领域，并且它将继续推动当今量子物质和激光科学的研究。光谱学现在拥有许多不同的分支学科，包括超精密测量、超冷物质、超稳激光和时间分辨的超快动力学。如今，光谱学在原子、分子和光物理蓬勃向上的复兴时期起到了核心作用。

为了满足高难度的测量需求，激光器让我们可以产生和操作相干光场。在早期的激光时代，非线性光学发展迅猛，这就为光谱学提供了新的实验技术，用于进一步提高光谱的分辨率，并将其应用在各个领域。同时，对激光稳定的不懈追求导致目前最先进的激光频率控制实现了达到数秒之久的光学相位相干。此外，光学频率梳的发明和发展使得这种光学相位相干性准确地转移到其他光学或微波光谱区域。

光学频率梳是以连续激光为基础的精密光学频率测量和以锁模激光为基础的超快光学相结合的产物。自从 2000 年发展以来，宽带光学频率梳在精密光谱学、频谱检测和超快科学中已经产生了许多意想不到和显著的发展。横跨整个光学频谱相位稳定的光学频率梳建立了数以百万计的均匀的频率间隔，用以精

确的频率标记。它们能够像最好的连续激光一样稳定和准确。我们已经实现了在电磁波谱从光频展开到射频的相干联系。

光学频率梳已经深刻地改变了光学频率计量，推动了关于绝对的光学频率测量、光学原子钟和光学频率合成的发展。利用光学频率梳、超冷原子和分子的实验结合，我们现在可以在最高水平的精度和分辨率来执行对光学光谱、频率的测量和量子控制。

与此同时，光学频率梳在时域应用中也带来了革命性的进展，例如脉冲重复率和载波包络相位的精确控制。这些发展带来了一些新兴产物，如：孤立阿秒脉冲的产生、独立激光相干合成的光脉冲、非线性光谱学中的相干控制、相干脉冲叠加以及扩展到深紫外线和中红外光谱区域内频率梳。实际上，现在我们有能力对任意光波形进行合成，如同在控制射频技术一样。在时域和频域控制的统一，使得同时追求在时域相干量子动力学的控制和在频域高精度测量整体原子和分子结构成为可能。

对实验光谱的发展使得我们渴望实现对原子运动的控制。随着激光技术的发展，在1980年代早期发展了原子的激光冷却。我们的目标是在原子状态和光场之间尽可能地保持最长的相干时间。为了达到这个目标，我们需要理解和控制原子质心在一个光学波长范围内运动。另一个挑战来自这样一个事实：光学探测原子的内部会产生一个不可避免的反向作用于原子质心的运动。这样的反向作用限制了测量的精度和控制。迎接这些挑战我们需要制备超低温度的原子，并且利用特制的光学、射频或电磁陷阱来囚禁它们，此时的原子内部和外部自由度在测量过程中可区分开来。这样的原子态制备对精密测量、频率计量学、量子系统的相干操纵和量子信息科学是至关重要的。

随着超冷原子气体研究的深入，精密测量展现出极好的发展前景。在超冷条件下，原子可以处于一种几乎"静止"的状态，气体便可呈现出显著的量子行为。现在，相干物质波和量子简并态原子气体可在实验室中随时制备、操纵、测量。利用一些新发展起来的重要工具，例如通过Feshbach共振控制原子的相互作用，引入光学晶格控制原子的质心运动，由此建立的利用原子物理及量子物理的实验平台，可以研究量子多体系统的特性及其动力学原理，它们如今已经承担解决凝聚态物理中诸多具有挑战性和突出性问题的研究。

回顾历史，实现可控的激光和原子触发了量子信息科学的产生和突飞猛进的发展。这些进展又反过来刺激了原子分子光学领域的发展。这恰恰就是原子分子光学物理的魅力所在。测量科学往往给予我们新的物理视角。反过来，新的科学前沿领域又为测量技术未来的发展奠定了基础。我们已经可以预见纠缠