Form: Course Syllabus		
	Form Number	EXC-01-02-02A
	Issue Number and Date	2/3/24/2022/2963 05/12/2022
	Number and Date of Revision or Modification	
	Deans Council Approval Decision Number	2/3/24/2023
	The Date of the Deans Council Approval Decision	23/01/2023
	Number of Pages	06

1.	**Course Title**	Atomic and Molecular Physics
2.	**Course Number**	0352762
3.	**Credit Hours (Theory, Practical)**	3 theory
	Contact Hours (Theory, Practical)	3 theory
4.	**Prerequisites/ Corequisites**	No prerequisites
5.	**Program Title**	M.Sc. in Physics
6.	**Program Code**	
7.	**School/ Center**	Faculty of Science
8.	**Department**	Department of Physics
9.	**Course Level**	Graduate
10.	**Year of Study and Semester (s)**	Fall semester ٢٠٢٢
11.	**Other Department(s) Involved in Teaching the Course**	
12.	**Main Learning Language**	English
13.	**Learning Types**	☐Face to face learning ☐Blended ☐Fully online
14.	**Online Platforms(s)**	☐Moodle ☐Microsoft Teams
15.	**Issuing Date**	October 202٢
16.	**Revision Date**	December 2024

17. Course Coordinator:

Name: Dr. Dia-Eddin Arafah Contact hours: (1٢:00-١٣:٣٠) Sunday, Tuesday

Office number: Math. R104 Phone number: 22052

Email: darafah@ju.edu.jo

18. Other Instructors:

Name: Office number: Phone number: Email: Contact hours: Name: Office number: Phone number: Email: Contact hours:

19. Course Description:

As stated in the approved study plan.

- **Review of Quantum Mechanics:** *The Schrodinger Equation; Resonance; Simple Harmonic Oscillator; Angular Momentum; Hydrogen Atom; Approximation Methods: (WKB, Variation and Perturbation).*
- **Interaction with External Electric and Magnetic Fields and Fine Structure:** *Stark Effect; Zeeman Effect; Fine Structure of Hydrogenic Atoms.*
- **Interaction with Electromagnetic Radiation:** *Electromagnetic Field; Transition Rate; Dipole Approximation; the Einstein Coefficients; Selection Rules.*
- **Two-Electron Atoms:** *The Schrödinger Equation for Two-Electron Atoms; Spin Wave functions and the Pauli Exclusion Principle; The Ground State of Two-Electron Atoms; The Excited State of Two-Electron Atoms.*
- **Many-Electron Atoms:** *The Central Field Approximation; the Periodic System of the Elements; the Thomas-Fermi Model.*
- **Molecular Structure and Spectra of Diatomic Molecules:** *The Born-Oppenheimer Approximation; The Electronic Structure; Rotational and Vibrational Energy Levels; Rotational-Vibrational Spectra; Effects of Nuclear Spin.*

20. Program Intended Learning Outcomes: (To be used in designing the matrix linking the intended learning outcomes of the course with the intended learning outcomes of the program)

1. To be able to identify, formulate, and solve broadly defined technical or scientific problems by applying knowledge of mathematics and science and/or technical topics to areas relevant to the discipline.
2. To be able to formulate or design a scientific system, process, procedure or program to contribute achieving scientific desired needs.

3. To be able to develop and conduct experiments or test hypotheses, analyze and interpret data and use scientific judgment to draw conclusions.
4. To be able to communicate his/her scientific contributions effectively with a range of audiences.
5. To be able to recognize and demonstrate social, ethical and professional responsibilities and the impact of technical and/or scientific solutions in global economic, environmental, and societal contexts.

6. To be able to function effectively independently and on teams for establishing goals, plan tasks, meet deadlines, and analyze risk and uncertainty.

21. Course Intended Learning Outcomes: (Upon completion of the course, the student will be able to achieve the following intended learning outcomes)

This graduate course, is to It is devoted to systematic of atomic spectra and radiative transitions, and starts by considering simple systems first, a one electron atom, a single molecule, a two level system in the presence of a monochromatic light source, etc. and then we will apply these basic concepts towards the understanding of some non-trivial quantum dynamics in realistic systems. Advanced techniques of the use of different levels to understand dynamics of atoms and molecules and the interaction processes and radiative transitions of two and many electron atoms study the molecular structure and spectra of diatomic molecules structure are illustrated.

- The student after completing this course on "Atomic and Molecular Physics", should be able to:
  - Understand the broad set of knowledge related to the quantum mechanics that governs the behavior of atoms and molecules with light and the interactions between them and the expected evolution.
  - Understand the nature of approximations made on the description of atomic and molecular systems.
  - Understand the dynamics of excited atomic and molecular states. ○ Use the knowledge and techniques of atomic and molecular physics.
  - Use the classical conservative approach (based on observation /experimentation, theoretical analysis and explanation, and the quantum mechanical approach to explore new aspects and concepts.
  - Apply the most common atomic and molecular spectroscopic methods and approximation techniques and obtain the atomic and molecular properties derived from them.
- The student after completing this course on "Atomic and Molecular Physics", should acquire the following skills and competencies: ○ Explore new concepts and insights combined with technology.

- ○ Search for analysis, synthesis of data explanation and link information. ○ Working independently in an interdisciplinary environment. ○ Production of free, creative and inductive thinking.
- ○ Modify and develop the domain space.

• The student after completing this course on "Atomic and Molecular Physics", should acquire the following interpersonal, communication skills responsibilities:
  - ○ Learn time management.
  - ○ Present a short report in written form and orally using appropriate scientific language.

Course ILOs	The learning levels to be achieved					
	Remembering	Understanding	Applying	Analysing	evaluating	Creating
1	✓	✓	✓	✓		
2	✓	✓	✓	✓		
3	✓	✓	✓	✓		
4		✓	✓	✓	✓	
5		✓	✓	✓	✓	✓
6		✓	✓	✓	✓	✓
٧		✓	✓	✓	✓	✓
٨		✓	✓	✓	✓	✓
٩			✓	✓	✓	✓
١٠			✓	✓	✓	✓
١١		✓	✓	✓	✓	✓
١٢			✓	✓	✓	
١٣		✓	✓	✓	✓	

2٢. The matrix linking the intended learning outcomes of the course with the intended learning outcomes of the program:

Course ILOs	ILO (1)	ILO (2)	ILO (3)	ILO (4)	ILO (5)	ILO (٦)
1. Understand the broad knowledge related to quantum mechanics and interactions.	✓	✓	✓			
2. Understand the nature of approximations made on atomic and molecular systems.	✓		✓			
3. Understand the dynamics of excited atomic and molecular states.	✓		✓			
4. Apply the knowledge and techniques of atomic and molecular physics.	✓	✓	✓			
5. Use the classical and quantum mechanical approaches to explore concepts.	✓	✓	✓			
6. Apply spectroscopic methods and obtain atomic and molecular properties.	✓	✓	✓			
7. Explore new concepts combined with technology.	✓	✓				
8. Search for analysis, synthesis, and link information.	✓		✓	✓		
9. Work independently in an interdisciplinary environment.						✓
10. Production of free, creative, and inductive thinking.					✓	✓
11. Modify and develop the domain space.	✓	✓	✓			
12. Learn time management.						✓
13. Present a short report in written form and orally using scientific language.				✓		

2٣. Topic Outline and Schedule:

Week	Lecture	Topic	ILO/s Linked to the Topic	Learning Types (Face to Face/ Blended/ Fully Online)	Platform Used	Synchronous / Asynchronous Lecturing	Evaluation Methods	Learning Resources
1	1.1	**Review of Quantum Mechanics:** *The Schrodinger Equation; Resonance; Simple Harmonic Oscillator; Angular Momentum;*	1,2,3,6,7	**Face to Face**	Lecture room Phys. 228	**Synchronous Lecturing**	Homework	Text, references and lecture notes and Internet
	1.2							
	1.3							
2	2.1							
	2.2							
	2.3							
3	3.1	*Hydrogen Atom; Approximation Methods: (WKB, Variation and Perturbation)*	1,2,3,6,7	**Face to Face**	Lecture room Phys. 228	**Synchronous Lecturing**	Homework	Text, references and lecture notes and Internet
	3.2							
	3.3							
4	4.1							
	4.2							
	4.3							
5	5.1	**Interaction with External Electric and Magnetic Fields and Fine Structure:** *Stark Effect; Zeeman Effect; Fine Structure of Hydrogenic Atoms.*	1,2,3,6,7	**Face to Face**	Lecture room Phys. 228	**Synchronous Lecturing**	Homework	Text, references and lecture notes
	5.2							
	5.3							
6	6.1	**Interaction with Electromagnetic Radiation:** *Electromagnetic Field; Transition Rate; Dipole Approximation; the Einstein Coefficients; Selection Rules.*	1,2,3,6,7	**Face to Face**	Lecture room Phys. 228	**Synchronous Lecturing**	Homework	Text, references and lecture notes
	6.2							
	6.3							
7	7.1							
	7.2							
	7.3							
8	8.1	**Two-Electron**		**Face to Face**				

	8.2	**Atoms:** *The Schrödinger Equation for Two-Electron Atoms; Spin Wave functions and the Pauli Exclusion Principle; The Ground State of Two-Electron Atoms; The Excited State of Two-Electron Atoms.*	1,2,3,6,7		Lecture room Phys. 228	**Synchronous Lecturing**	Homework	Text, references and lecture notes
	8.3							
9	9.1							
	9.2							
	9.3							
10	10.1	**Many-Electron Atoms:** *The Central Field Approximation; the Periodic System of the Elements; the Thomas-Fermi Model.*	1,2,3,6,7	**Face to Face**	Lecture room Phys. 228	**Synchronous Lecturing**	Homework	Text, references and lecture notes
	10.2							
	10.3							
11	11.1							
	11.2							
	11.3							
12	12.1	**Molecular Structure and Spectra of**						
	12.2							
	12.3	**Diatomic Molecules:** *The Born-Oppenheimer Approximation; The Electronic Structure; Rotational and Vibrational Energy Levels; RotationalVibrational Spectra; Effects of Nuclear Spin.*	1,2,3,6,7	**Face to Face**	Lecture room Phys. 228	**Synchronous Lecturing**	Homework	Text, references and lecture notes
13	13.1							
	13.2							
	13.3							
14	14.1							
	14.2							
	14.3							
15	15.1	**Tern paper & presentation**	2,3,5,6,7, 9	**Face to Face**	Lecture room Phys. 228			Text and references and Internet
	15.2							
	15.3							

2٤. Evaluation Methods:

Opportunities to demonstrate achievement of the ILOs are provided through the following assessment methods and requirements:

Evaluation Activity	Mark	Topic(s)	ILO/s Linked to the Evaluation activity	Period (Week)	Platform
Examinations	Exam 1: 20% Exam 2: 20% Final Exam: 35%	Topics and material included are announced in the lecture. However, the final exam includes all material.		Tentative, but adheres with University schedule: 5th. week 10th. Week Announced by the Registrar.	Students sit for written exams on University campus.
homework problems	15%			Every two weeks.	Submitted in lecture or online
Tern paper	10%			Tuesday, Jan 10 2023	

2٥. Course Requirements:

(e.g.: students should have a computer, internet connection, webcam, account on a specific software/platform…etc.):

Students must have previously completed a first semester of graduate-level Quantum Mechanics, an Advanced Mathematical Physics course and have taken at least undergraduate-level Electricity and Magnetism. Students should also have a computer, internet connection, webcam, and account on a specific software/platform…etc).

2٦. Course Policies:

A- A Attendance policies: Max. 15%, with accepted excuses.

B- Absences from exams and submitting assignments on time: Student should adhere to University of

Jordan's regulations

C- Health and safety procedures: N/A

D- Honesty policy regarding cheating, plagiarism, misbehavior: In accordance with the University of Jordan regulations E- Grading policy:

- Exams: There will be two in-class exams. There will also be a comprehensive Final Exam, scheduled by the Registrar and held during the Final Exam Period.
- Assessment: Examination + homework problems + Tern paper
- Grading: The final grade for the course will be based on the following:

  ○ Exam 1: 20% ; Exam 2: 20% & Final exam: 35% ○ Problem sets: 15%. ○ Term Paper 10%.

F- Available university services that support achievement in the course: Student academic counseling and support (three office hours/week).

2٧. References:

A- Required book(s), assigned reading and audio-visuals:

 The official course textbook is "**Physics of Atoms and Molecules",** by Bransden, B.H. and Joachain,

C.J., Second Edition (Prentice Hall, New York, 2003). However this book will only partially cover the material presented in class.

B- Recommended books, materials, and media:

- "**Atomic Physics**", by Christopher J. Foot, 1st Edition, (Oxford University Press, 2005).
- "**Atom—Photon Interactions: Basic Process and Applications",** by Claude Cohen-Tannoudji, Jacques Dupont-Roc, Gilbert Grynberg, (WILEY-VCH Verlag GmbH & Co. KGaA, 2004).
- "**Atoms, Molecules, and Photons**", Wolfgang Demtroder, (Springer, Berlin, Heidelberg, 2006). "**Modern Quantum Mechanics**",J.J. Sakuari, Revised Edition, (Addison-Weasley, Reading, Massachusetts, 1994).

"**The Physics of Atoms and Quanta**", Hermann Haken and Hans Christoph Wolf, (Springer, Berlin, Heidelberg, 2003).

2٨. Additional information:

Projects: The aim of this project is to give a clear and pedagogical presentation of a "problem" or "phenomenon" in quantum Physics. Everyone is required to give an oral and a written paper of an actual research topic in the field of atomic and molecular physics. A short paper on a topic related to or further explicate ideas or problems covered in the course, is expected. The paper should be written in the style and format of a brief journal article and should aim at an audience of students in the course.

Writing, editing and revising skills are an integral part of the project. The template should comply with the *Physical Review*) format. Your papers will be graded on the intellectual quality of your work, the effectiveness of your presentation and the success of your prose style.

A list of suggested topics is given below, but you are free to choose topics not on this list upon first obtaining approval.
Your **proposal** to choose a subject will be due on Tuesday November 15, in lecture. This must consist of: a title, a one paragraph description of what you plan to write about, an outline of your proposed tern paper. A hard copy of your final (8 - 15 pages), paper is due in lecture on Tuesday January 10.

• Oral Presentations: *The duration of your presentation will be between 10 and 15 minutes, depending on the number of presentations*

• List of some suggested topics:

1. Precision measurements: Atomic Clocks.
2. Coherent states.
3. Resonance: electron spin resonance & nuclear magnetic resonance.
4. Super cavities.
5. Magnetic monopoles, gauge invariance, and the Dirac quantization condition.
6. Bell's theorem - can classical mechanics imitate quantum mechanics?
7. The rotational and vibrational spectrum of diatomic molecules.
8. Super-symmetric quantum mechanics.
9. The Zeeman Effect in weak, intermediate and strong magnetic fields.
10. The Lamb-shift in hydrogen
11. The van der Waals force between hydrogen atoms in excited states.
12. Quantum computation.
13. Quantum teleportation and information.
14. Quantum cryptography.
15. Quantum beats.
16. Quantum dots.
17. Quantum entanglement.
18. Nano-materials
19. Bose Einstein condensate.
20. High resolution spectroscopy and the Frequency Comb.
21. Short pulse spectroscopy – Femto/Atto-second.
22. Photoelectron spectroscopy.
23. Laser cooling.
24. Ultra power lasers: Ti: Al_2O_3 (Ti-sapphos) lasers.
25. Ion and magnetic traps.

Name of the Instructor or the Course Coordinator: Dr. DIA-EDDIN ARAFAH	Signature:	Date: 10/2024
Name of the Head of Quality Assurance Committee/ Department …………………………………………………….	Signature: …………..……………….	Date: ……..…………
Name of the Head of Department …………………………………………………….	Signature: …………..……………….	Date: ……..…………
Name of the Head of Quality Assurance Committee/ School or Center …………………………………………………….	Signature: …………..……………….	Date: ……..…………
Name of the Dean or the Director …………………………………………………….	Signature: …………..……………….	Date: ……..…………

The University of Jordan

الجامعة الاردنية

Department of Physics

First Semester 2022/2023

Atomic and Molecular Physics PH 0302762

3 Credit Hours

Lecturer: **Dr. Dia-Eddin Arafah /** ***Room:*** Math. Building 104

E-mail: darafah@ju.edu.jo

Lectures: 15:30-17:00 Pm Sundays and Tuesdays ***Office Hours:*** 12:00-13:30 Pm (Sunday & Tuesdays)

Tentative Course Outline

- **Review of Quantum Mechanics:** *The Schrodinger Equation; Resonance; Simple Harmonic Oscillator; Angular Momentum; Hydrogen Atom; Approximation Methods: (WKB, Variation, and Perturbation).*
- **Interaction with External Electric and Magnetic Fields and Fine Structure:** *Stark Effect; Zeeman Effect; Fine Structure of Hydrogenic Atoms.*
- **Interaction with Electromagnetic Radiation:** *Electromagnetic Field; Transition Rate; Dipole Approximation; the Einstein Coefficients; Selection Rules.*
- **Two-Electron Atoms:** *The Schrödinger Equation for Two-Electron Atoms; Spin Wave functions and the Pauli Exclusion Principle; The Ground State of Two-Electron Atoms; The Excited State of Two-Electron Atoms.*
- **Many-Electron Atoms:** *The Central Field Approximation; the Periodic System of the Elements; the Thomas-Fermi Model.*
- **Molecular Structure and Spectra of Diatomic Molecules:** *The Born-Oppenheimer Approximation; The Electronic Structure; Rotational and Vibrational Energy Levels; Rotational-Vibrational Spectra; Effects of Nuclear Spin.*

Introduction and Motivation

- This "Atomic and Molecular Physics (AM) course is to introduce graduate students to the concepts of A&M and investigate the behavior of atoms and molecules and how they interact with light of. Prior to the late 20th. Century, AM (and Optical) science mainly focused on probing and understanding the structure of matter and light. In the early years of the 21st. the goals are more ambitious. Modern AM and Optical physics is actually revolutionizing our perspective of the quantum world.

- State-of-the-art A&M (and optical) – (AMO) physics wants to understand how to synthesize new states of matter, how to control them, and how to exploit atom-light interactions for broader purposes, both at the level of basic research and for numerous technological applications.
- All these developments have been possible through a deep understanding of the atomic/molecular structure, the coherent properties of light, and how atoms/ molecules interact with light. The latter has allowed us to use light to cool, trap and manipulate atoms and molecules with an exquisite degree of control.

Learning Outcomes

- This graduate course is to develop a theoretical understanding of the quantum mechanics that governs the behavior of atoms and light and the interactions between them by reviewing the fundamental aspects of atomic and molecular physics and. It is devoted to systematics of atomic spectra and radiative transitions and starts by considering simple systems first, a one-electron atom, a single molecule, a two-level system in the presence of a monochromatic light source, etc. and then we will apply these basic concepts towards the understanding of some non-trivial quantum dynamics in realistic systems. Advanced techniques of the use of different levels to understand the dynamics of atoms and molecules and the interaction processes and radiative transitions of two and many-electron atoms study the molecular structure and spectra of diatomic molecules structure are illustrated.

- The student after completing this course on "Atomic and Molecular Physics", should be able to use the knowledge and techniques of atomic and molecular physics and apply the most common atomic and molecular spectroscopic methods and obtain the atomic and molecular properties derived from them.

  Syllabus ***Text Book:***

- The official course textbook is "**Physics of Atoms and Molecules",** by Bransden, B.H., and Joachain, C.J., Second Edition (Prentice Hall, New York, 2003). However, this book will only partially cover the material presented in class. ***References:***
- **"Atomic Physics"**, by Christopher J. Foot, 1st Edition, (Oxford University Press, 2005).
- **"Atom—Photon Interactions: Basic Process and Applications",** by Claude Cohen-Tannoudji, Jacques Dupont-Roc, Gilbert Grynberg, (WILEY-VCH Verlag GmbH & Co. KGaA, 2004).
- **"Atoms, Molecules, and Photons"**, Wolfgang Demtroder, (Springer, Berlin, Heidelberg, 2006).
- **"Modern Quantum Mechanics"**,J.J. Sakurai, Revised Edition, (Addison-Weasley, Reading, Massachusetts, 1994).
- **"The Physics of Atoms and Quanta"**, Hermann Haken and Hans Christoph Wolf, (Springer, Berlin, Heidelberg, 2003). ***Course Prerequisites:***

Students must have previously completed the first semester of graduate-level Quantum Mechanics, an Advanced Mathematical Physics course and have taken at least undergraduatelevel Electricity and Magnetism. ***Problem Sets:***

Every Week or two, there will be problem sets which are an essential part of the course. Working through these problems is a mean to demonstrate how much various topics are understood, and is crucial to better understanding the material. After attempting each problem by yourself, your solutions should not be transcriptions or reproductions of someone else's work. Problem sets will generally be assigned on Tuesdays and will be due on the following Tuesday by 4:00 PM. For practical, not punitive reasons, late homework will not be graded. ***Projects:***

The aim of this project is to give a clear and pedagogical presentation of a "problem" or "phenomenon" in quantum Physics. Everyone is required to give an oral and a written paper of an actual research topic in the field of atomic and molecular physics. A short paper on a topic related to or further explicate ideas or problems covered in the course is expected. The paper should be written in the style and format of a brief journal article and should aim at an audience of students in the course.

Writing, editing, and revising skills are an integral part of the project. The template should comply with the *Physical Review*) format. Your papers will be graded on the intellectual quality of your work, the effectiveness of your presentation, and the success of your prose style. A list of suggested topics is given below, but you are free to choose topics not on this list upon first obtaining approval.

Your **proposal** to choose a subject will be due on Tuesday, November 15, in the lecture. This must consist of: a title, a one-paragraph description of what you plan to write about, and an outline of your proposed tern paper. A hard copy of your final (8 - 15 pages), paper is due in the lecture on Tuesday, January 10. ***Oral Presentations:***

The duration of your presentation will be between 10 and 15 minutes, depending on the number of presentations

List of some suggested topics:

1. Precision measurements: Atomic Clocks.
2. Coherent states.
3. Resonance: electron spin resonance & nuclear magnetic resonance.
4. Super cavities.
5. Magnetic monopoles, gauge invariance, and the Dirac quantization condition.
6. Bell's theorem - can classical mechanics imitate quantum mechanics?
7. The rotational and vibrational spectrum of diatomic molecules.
8. Super-symmetric quantum mechanics.
9. The Zeeman Effect in weak, intermediate and strong magnetic fields.
10. The Lamb-shift in hydrogen
11. The van der Waals force between hydrogen atoms in excited states.
12. Quantum computation.
13. Quantum teleportation and information.
14. Quantum cryptography.
15. Quantum beats.
16. Quantum dots.
17. Quantum entanglement.
18. Nano-materials
19. Bose-Einstein condensate.
20. High-resolution spectroscopy and the Frequency Comb.
21. Short pulse spectroscopy – Femto/Atto-second.
22. Photoelectron spectroscopy.
23. Laser cooling.

24.Ultra power lasers: Ti: Al_2O_3 (Ti-sapphos) lasers.

25.Ion and magnetic traps. ***Exams:***

There will be two in-class exams. There will also be a comprehensive Final Exam, scheduled by the Registrar and held during the Final Exam Period. ***Assessment:***

Examination + homework problems + Tern paper ***Grading:***

The final grade for the course will be based on the following: • Exam 1: 20% ; Exam 2: 20% & Final exam: 35%

- Problem sets 15%.
- Term Paper 10%.

Physics Today **52**, 4, 11 (1999); https://doi.org/10.1063/1.882619

REFERENCE FRAME

The Yin and Yang of Hydrogen

Daniel Kleppner

"To understand hydrogen is to understand all of physics!" an exuberant colleague once exclaimed, crediting the aphorism to Victor Weisskopf. I asked Viki, but he denied having coined it. Then, after a pause, he added, "But I wish I had." Most physicists understand Viki's sentiment for most physicists are reductionists who aim to understand nature in the simplest possible terms, and hydrogen is a reductionist's dream. For me, hydrogen holds an almost mystical attraction, possibly because I am among the small band of physicists who actually confront it more or less daily.

As an object of obsession, one could do worse than hydrogen. In its special role as the simplest of all atoms, hydrogen has starred in some great episodes in the history of science. Much of what we know about the universe has come from looking at hydrogen, and it cannot be denied that the universe itself is made almost entirely of hydrogen—at any rate, most of the universe that we can see. We might also note hydrogen's technological triumphs, which range from balloons to atomic clocks. One could call hydrogen an atom for all seasons. But the seasons include fall and winter as well as spring and summer, and hydrogen, too, has its dark side as well as its light side. In the timeless metaphor of the Chinese book of wisdom and philosophy known as the *I Ching*, hydrogen has its yin and hydrogen has its yang.

The concept of yin and yang celebrates the complementary nature of things: passive and active, earthbound and airborne, shadowy and luminous. Yin encompasses heavy, dark and earthborne qualities; yang encompasses light, luminous and ascendant qualities. Yin are the lakes, yang are the clouds. Together, yin and yang embody the principle of perpetual change and interchange. By reconciling opposites and extolling flux, the twin concept yin and yang provides a framework for viewing society, history, nature and life itself.

My colleague Thomas J. Greytak and I learned much about hydrogen's yin and yang during our search to see

it undergo Bose–Einstein condensation. We set out in that search, full of hope. Others also set out, and they, too, were full of hope. The search took much longer than any of us expected, more than 20 years, long enough to constitute a new chapter in the history of hydrogen. Knowing something of that history was good for the spirit when progress was slow.

The history of hydrogen unfolds in a world of yang, for hydrogen is the lightest of all gases and so luminous that the whole universe is suffused in its radiation. A good starting point is June 1783, when Charles Blagden, assistant to Henry Cavendish, visited Antoine-Laurent Lavoisier in Paris to describe how Cavendish had created water by burning "inflammable air." The facts were clear but Cavendish's explanation—dephlogistonization—was not. Lavoisier immediately repeated the experiment. The consequences were monumental, not because Lavoisier merely confirmed Cavendish's work but because the experiment inspired him to create the concept of a chemical reaction. "Inflammable air" and oxygen join to form water. The very next day, 24 June 1783, Lavoisier reported his results to the Royal Academy of Sciences. The name of hydrogen was born in that event, and so was modern chemistry.

June 1783 was a month of excitement for Paris. The reason, however, was not Lavoisier's discovery—like most important discoveries it was unremarked at the time—but because on 5 June the Montgolfier brothers had flown the first balloon. They filled their balloon with smoke and it floated away on a short flight that caused an absolute sensation throughout France. As to the reason why the balloon floated, however, there was confusion. The Montgolfiers' rationale for filling the balloon with smoke was merely that smoke was the most cloudlike vapor one could obtain.

Jacques-Alexandre-César Charles understood buoyancy, and after Lavoisier's report to the Royal Academy, hydrogen was, so to speak, in the air. Charles immediately set about constructing a hydrogen-filled balloon, raising a public subscription to pay the costs. On 27 August the balloon lifted from the Champs de Mars and ascended a thousand meters. So, barely two months after the news of hydrogen had been announced, it was put to practical use. Possibly this was the quickest case of spin-off from basic research in the history of science. In any case, in the 18th century, just as today, there was no better way to earn society's appreciation than by simply entertaining it.

Hydrogen's buoyant and ascendant nature has been evident ever since Charles's triumphant balloon flight. The optical spectrum of hydrogen first displayed itself imprinted on sunlight. In 1817, Joseph Fraunhofer discovered absorption lines in the sun's spectrum, and 50 years later the Swedish spectroscopist A. J. Ångström showed that Fraunhofer's C and F lines were due to hydrogen. In 1885, J. J. Balmer used Ångström's data to derive the empirical formula that provided the linchpin for Niels Bohr's 1913 paper on the structure of hydrogen. Bohr triggered the search for a new mechanics. Fifteen years later that search culminated in the work of P. A. M. Dirac. Once again hydrogen played a starring role, for the hydrogen spectrum provided the critical test of the Dirac theory. Two decades later, the spectroscopy of hydrogen was extended into the microwave regime by magnetic resonance techniques, and its precision was increased many-fold. The first microwave measurements of hydrogen's hyperfine and fine structure revealed that things were amiss with the Dirac theory. That dilemma was resolved by the creation of relativistic quantum electrodynamics, now the paradigm of field theories, the most precise and precisely tested theory in all of physics.

Hydrogen seems almost aware of its illustrious history for the atom behaves in a regal fashion. Just as monarchs

DANIEL KLEPPNER *is the Lester Wolfe Professor of Physics and associate director of the Research Laboratory of Electronics at the Massachusetts Institute of Technology.*