Physics 240/250: Einstein's Century

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I'll give a conceptual introduction to three theories that revolutionized physics in the 20th century: statistical physics, quantum theory, and the theory of relativity. This is one of the most exciting detective stories in all of Western intellectual history. Many of the themes were laid out by Einstein in three incredible papers, all published the year 1905, whose anniversary we are now celebrating. We'll see how these very abstruse theories have led to a wealth of technological and fundamental advances, leading right up to the present.

Of course we can't possibly treat all these topics in detail. But actually, all of these advances rest on a small kernel of simple, universal ideas. Unfortunately "simple" does not mean "easy"; our common sense rebels against these ideas, and physicists have had to retool common sense considerably in order to accommodate them. Physicists are not philosophers, but there is something beautiful about how the human mind has been able to discover the crazy laws which really do govern the world of the very small, and then find so many new, correct, and even *practical* consequences from them.

Announcements: `http://courseweb.library.upenn.edu/`
Time: Lecture: Tuesday-Thursday 1:30–3:00pm in DRL room A4. Recitation: Wednesdays 2:00–3:00pm in DRL room A2.
Lab (250 only): Fridays (not every week) 1:00–3:00pm or 3:00–5:00pm.
General Policies: see "Policies" handout.
Office Hours: We'll arrange these to suit the class.
Assignments: Weekly problem sets, two midterm exams, final exam.

General prerequisites:
Physics 150–151 or 170–171. First-year calculus. Concurrent second-year calculus. Physics 230 is helpful but not required. Some background in chemistry is helpful but not required.

Books:
Required:
• Main text: Bernstein, Fishbane, and Gasiorowicz, *Modern Physics*.
• Supplementary text: R. Feynman, *QED, the strange theory of light and matter* (Princeton, 1985).
• Lab manual: *Experiments in modern physics* (at the bookstore).

Other books you may find helpful (available on reserve):
• *Feynman Lectures on Physics*, vols. 1–3.
• D. Halliday, R. Resnick, and J. Walker, *Fundamentals of physics*, 6th ed. (Wiley, 2002).
• R. Shankar, *Basic training in mathematics* (Plenum 1995).
• E. Taylor and J. Wheeler, *Spacetime physics,* second edition (Freeman, 1992).

More advanced stuff:
• *The collected papers of Albert Einstein*, vol. 2 (1900–1909), Anna Beck, translator (Princeton University Press, 1989); A. Einstein, *Theory of the Brownian movement.*
• R. Feynman and A. Hibbs, *Quantum mechanics and path integrals* (McGraw-Hill, 1965).
• M. Horbatsch, *Quantum mechanics using Maple* (Springer 1995).
• P. Landshoff, A. Metherell and G. Rees, *Essential quantum physics* (CUP, 1997).
• N. D. Mermin, *Space and time in special relativity.*
• E. Wichman, *Quantum physics* (Berkeley Physics Series vol. 4).

Semipopular/Historical:
• B. Cathcart, *Fly in the cathedral: How a small group of Cambridge scientists won the race to split the atom* (Viking, 2004).
• R. P. Crease and C. C. Mann, *The second creation* (Macmillan, 1986).
• R. Feynman, *The character of physical law.*
• P. Galison, *Einstein's clocks, Poincaré's maps: Empires of time.*
• W. Moore, *Schrodinger: Life and thought* (Cambridge,1989).
• A. Pais, *Subtle is the Lord.*
• A. Pais, *Niels Bohr's times.*
• A. Pais, *Inward bound.*
• S. Quinn, *Marie Curie: A life.*
• R. Rhodes, *The making of the atomic bomb.*
• Tony Rothman, *Everything's relative and other fables from science and technology.*
• A. Sakharov, *Memoirs.*
• R. L. Sime, *Lise Meitner: A life in physics.*
• S. Weinberg, *The first three minutes.*

Outline

See the weekly Assignments for reading and homework assignments.

Part one: Before 1905

Prologue

"Good prophesy is always given in riddles, for the gods do not reveal their every secret to men. They only open a way and wait for mortal nobility or depravity to take its normal course." — Loren Eiseley, *The Night Country*

1. Big themes in 20th century physics. Three branches of modern physics, three decisive papers, three fundamental universal constants of Nature — one year, one author.
2. Some high points of first-year physics and mathematics.
3. Some key ideas from chemistry.
4. The discovery of electrons, X-rays, the atomic nucleus, and radioactivity.
5. Eve of the revolution: Something is very wrong in the world of the very small. Why don't we fall through the floor? Why are atoms stable? Why are hydrogen atoms all the same? Where does all that energy come from in radioactive decay?

Probability

"The primary task of a useful teacher is to teach his students to recognize 'inconvenient' facts — I mean facts that are inconvenient for their party opinions.... I believe the teacher accomplishes more than a mere intellectual task if he compels his audience to accustom itself to the existence of such facts." — Max Weber, 1918

6. Sometimes physics only gives statistical predictions.
7. Kinetic theory: Why doesn't the air in this room all fall on the floor?
8. Distributions. The variance. Maxwell's distribution.
9. Diffusion equation. Restoration of predictive power, but only for *distributions*.
10. Diffusion to equilibrium and the full Boltzmann distribution. Equipartition. The puzzle of specific heats of gases and solids.

Classical particles and waves

"You boil it in sawdust, you salt it in glue, you condense it with locusts and tape,
Still keeping the principal object in view: to preserve its symmetrical shape."
— Lewis Carroll, *The hunting of the snark*

11. Action formulation of Newton's laws.
12. The wave equation in electrodynamics, and in acoustics.
13. Fourier synthesis. Phase velocity. Quantization in organ pipes.
14. Diffraction. Our first uncertainty relation. X-rays and the structure of DNA.

Part two: Big ideas

Relativity

"Einstein explained his theory to me every day, and on my arrival I was fully convinced that he understood it" — Chaim Weizmann, 1921, on his crossing the Atlantic with Einstein.

15. Invariance. Good frames. Galileo's principle of relativity.
16. The problem with electromagnetic waves.
17. A bold idea: time is not sacred. A pictorial solution.

18. Addition of velocities. The speed of light in flowing water.
19. Decay of elementary particles. Doppler effect. Mossbauer spectroscopy. Supernova 1987A: c really is universal.
20. Evolution, not revolution. Tweaking the great conservation laws. $E = mc^2$. PET scans and the fingerprints of positrons.
21. The amazing secret of spacetime geometry. On knowing when to shut up.
22. Recent experiments. Vistas: Relativistic effects in technology: klystrons, medical electron accelerators. Combine relativity with quantum theory: Pair production.

Quanta

"The heresies we should fear are those which can be confused with orthodoxy." — J. L. Borges

23. Dimensional analysis. Police sketch of the fugitive $\hbar$. Bohr's crazy idea. A very suspicious coincidence.
24. When light acts like a particle. PE effect, Compton effect.
25. When electrons act like waves.
26. Bohr's idea and deBroglie's interpretation.
27. A new kind of statistical prediction. The wavefunction. The key role of complex numbers. Uncertainty. The sizes of atoms.
28. Feynman's absurdly simple proposal. The link to classical mechanics. The deep reason why $\hbar$ is universal.

Wave mechanics

"Erwin wrote to 'an old girlfriend in Vienna' to join him in Arosa.... Efforts to establish the identity of this woman have so far been unsuccessful, since Erwin's personal diary for 1925 has disappeared.... Whoever may have been his inspiration, the increase in Erwin's powers was dramatic." — W. Moore, *Schrödinger*

29. Schrödinger's law. How to get it from Feynman's.
30. Seven key examples. Degeneracy, superposition, separation of variables, symmetry, tunneling, quantization of energy and of angular momentum.
31. Our first spectral series. The simplest hydrogen-atom states.
32. Uncertainty: precise ideas vs. pop philosophy. Quantum indeterminacy versus chaos.

Part three: Big Consequences

The nature of atoms and molecules

"In any case, [physics] is too difficult for me, and I wish I had been a movie comedian or something of the sort and had never heard of physics." — Wolfgang Pauli

33. About atoms and their spectra.
34. The hydrogen atom in wave mechanics. Angular momentum in 3d.
35. The spin hypothesis. Stern–Gerlach: seeing is believing. Bohr's train ride. Spin cannot be explained by electron substructure.
36. Many electrons; Pauli's proposal; Dirac's interpretation; bosons and fermions.
37. Why some atoms are bigger than others. Filled shells. The periodic table. X-ray and visible spectra.
38. Ionic bonds. Covalent bonds. Bonding and antibonding.
39. Stereochemistry, or, why methane is tetrahedral.

The Nucleus

"Everybody was conscious in 1939 of the imminence of a war of annihilation. There was well founded fear that the tremendous military potentialities that were latent in the new scientific developments might be reduced to practice first by the Nazis." — Enrico Fermi, 1945

40. Radioactivity. What Marie Curie found.

41. Nuclear reactions. Curve of binding energy; liquid drop model; Weiszacker formula.
42. How the Sun works.
43. When good stars go bad: Supernovae and neutron stars.

Quarks and All That

"If I could remember the names of all those particles I would have been a botanist." — Enrico Fermi

44. Creation of particles. Yukawa hypothesis and pions.
45. Feynman diagrams. Weak interactions.
46. Order out of chaos: the standard model of particles and forces. A mysterious repetition.

Back to Statistics

47. The puzzle of specific heats at low temperatures. Einstein's explanation for solids. Freezing out of modes; the gas puzzle resolved.
48. How to count. Identical particles.
49. A crowd of photons. Thermal radiation; photons as a gas.
50. A crowd of atoms. Bose–Einstein condensation.
51. A crowd of electrons. The Fermi edge.

Electrons in solids

52. The puzzle of conduction: the Fermi sea.
53. The puzzle of positive charge carriers: holes.
54. Band theory: semiconductor devices.

The Universe

"Don't let me catch anyone talking about the Universe in my department." — Ernest Rutherford

55. Einstein's big idea about gravitation.
56. First facts about the Universe. Hubble law. Friedmann equation. Birth and death of a universe.
57. The cosmic microwave background. Primordial nucleosynthesis. Alpher, Bethe, Gamow.
58. The First Three Minutes.

Epilogue

"Never prophesy — especially about the future." — Sam Goldwyn

59. Something is lurking at the Planck scale.
60. What is physics anyway? Truth, Beauty, and All That.
61. Ten pillars of wisdom. Is fundamental physics finished?