

Atoms

The discrete unit and the uncertain viewpoint

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Is Nature Discrete or Continuous?

- Is the ultimate reality of nature granular—made up of distinct little bits of matter, like grains of sand?
 - This was the view of the ancient atomists, such as Democritus, but it was not popular then.
- Or is nature continuous—smoothly shading from one kind of reality into another with no sharp divisions?
 - This was the view of Parmenides and Aristotle, and in general won out in antiquity.
- Both views have continued to have supporters up to the present. Both have explanatory power.

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The Discrete Viewpoint

- Explains change well
- The Mechanist model:
 - Discrete bits of matter knock into each other and produce motion by impact or stick together (as in chemical reactions) and produce apparent qualitative change due to structural differences.

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[The Continuous Viewpoint]

- Explains stability well
- Does not have the problem of the “existence of nothing.” E.g., empty space.
- Explains action at a distance. (There is never empty space between.)
- Electricity, magnetism, light, gravity reach out beyond matter. How is this possible?
- In the continuous model, the boundary between matter and space is apparent but not real.

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[The confused scene at the end of the 19th century]

- Conflicting views at the end of the 19th century that support either the Discrete or the Continuous viewpoint:
 - Discrete Continuous
 - Mechanism Thermodynamics
 - Astronomy Electromagnetism
 - Chemistry Biology
 - Statistical Mechanics Relativity
 - Radiation? or Radiation?

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[Cathode Rays]

- William Crookes in the 1870s invented a vacuum tube in which when electricity was pumped into a metal plate at one end (the *cathode*) it caused a glow in the direction of a metal plate the *anode* at the other end.
- This glow could be deflected by a magnet.
- He called these emanations, *cathode rays*.



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X-Rays



- Wilhelm Röntgen discovered in 1895 that a cathode ray tube also caused illumination of a coated paper screen up to 2 metres away.
- Röntgen concluded he had found a new form of electromagnetic radiation
- He called these *x-rays*.

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X-Rays, 2

- The property of x-rays of taking pictures of hard material, such as bones, looking right through soft material, like flesh, was quickly noticed by scientists.
- X-rays became a tool of medicine almost immediately.



Röntgen's wife's hand

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Radioactivity

- Radiation: transmission outward in all directions of some emanation
 - e.g. electromagnetic waves, or, more simply, light
- Henri Becquerel (1896)
 - measured fluorescence of materials after being in the sun
 - found that *uranium* salts glow even when they have not been in the light
- Marie Curie refined and purified these salts producing purer uranium, polonium, and radium
 - She called them *radioactive*.
- But is radioactivity a continuous emanation? If so, of what? And where does it come from?

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[Atoms: what are they?]

- Ultimately just a theory of discreteness
 - *a - tom* = not cut = indivisible
- Chemistry pointed to the existence of some smallest units in combination
 - Were these units atoms?
- If so, how do these units account for the structure of matter?
- Another question: Why is the Periodic Table periodic?

[Electrons]



- J. J. Thomson in 1897 at the Cavendish Laboratories at Cambridge:
 - Tried to measure effects of cathode ray tubes
 - Found that cathode rays could be generated from any element and that they behaved like a stream of particles.
- Thomson believed the particles came out of chemical atoms.
- He called cathode rays *electrons*.

["Atoms" are not atomic]

- Therefore, the "atom" had parts and was not an indivisible ultimate unit.
- Thomson's model of the atom had electrons stuck within a spherical atom.
 - Cathode rays were the result of forcing atoms to spit out a stream of electrons.



Rutherford's Rays

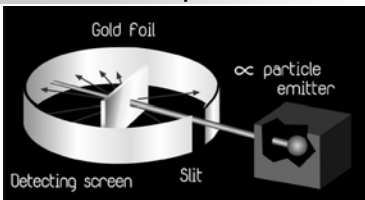


- Ernest Rutherford – 1911
 - from New Zealand
 - student of J. J. Thomson at Cambridge
 - later taught at McGill University
 - ultimately set up a laboratory at the University of Manchester
- Set out to analyze the different “rays” that could be produced. Gave them names from the Greek alphabet:
 - alpha rays – later found to be the nucleus of helium atoms
 - beta rays – turned out to be the same as cathode rays or electrons
 - gamma rays – light of a small wave length, something like x-rays

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Rutherford's Experiment



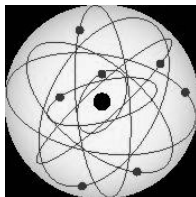
- To explore the structure of the atom, Rutherford set up an experiment to bombard thin foils of metal with (heavy) alpha particles and see what happens.
- Though most passed through the foil, some were deflected back.

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Rutherford's model of the atom

- Rutherford concluded that almost all of the mass of an atom must be concentrated in a very small nucleus, surrounded by a large space where the electrons orbit, like planets around the sun.



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[From Thomson to Rutherford]

- An animation of Rutherford's experiment, with a narrative:
 - <http://www.mhhe.com/physsci/chemistry/essentialchemistry/flash/ruther14.swf>

[Black body radiation]

- When metal is heated, it tends to change colour.
 - As it heats it begins to radiate energy, some of which is in the form of light.
 - Consider a red hot piece of iron, for example.
 - Different colours correspond to different temperatures.
 - Why? What is going on?

[Black body radiation, 2]

- To study this phenomenon, scientists tried to create a perfect radiator of energy – one that would not give confusing information in an experiment.
- Such a perfect radiator is called a “black body.”
 - True black is the colour that absorbs all light, reflecting none.
 - Any light emitted from a “black body” would depend entirely on its temperature.

[Black body radiation, 3]

- What is the theoretical relationship between electromagnetic radiation (e.g., light) and temperature?
 - According to (continuous) electromagnetic wave theory (Maxwell's equations), a black body, when heated, emits energy at every possible wave length.
 - The smaller the wavelength, the more energy is emitted.

[The ultraviolet catastrophe]

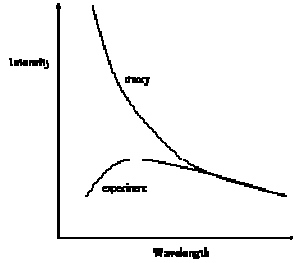
- According to theory, when a black body radiates waves of extremely short wave length (e.g., ultraviolet light), it radiates an *infinite amount of energy* – more than all the energy in the universe.
- This violates the first law of thermodynamics and, if true, would be ruinous to much of 19th century physical theory.

[The cavity radiator]

- A “black body” is a theoretical notion, but scientists could approximate the ideal with a piece of equipment for laboratory tests, called a cavity radiator.
- Contrary to theoretical expectations, the cavity radiator did *not* emit an infinite amount of energy.
 - In fact, at very short wave lengths, it emitted no energy at all.

[The cavity radiator, 2]

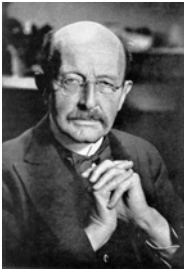
- The graph shows the theoretical expectation of energy emissions at different wave lengths, compared with the actual measured emissions from the cavity radiator.



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[Max Planck to the rescue]



- German physicist, lived 1858-1947.
- In 1899-1900, Planck realized that Maxwell's (*continuous*) wave equations led to the "ultraviolet catastrophe" because it allowed for infinitely small amounts of energy.
 - A quantity divided by an infinitely small amount = an infinitely large quantity.
- If Planck used *discrete* equations, he could get around the division by zero problem.

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[h – the quantum of energy]

- Planck found that energy could not be radiated at all in units smaller than an amount he called h – the quantum of energy.
- When he introduced the restriction h into his equations, the ultraviolet catastrophe disappeared.
- But what was the physical meaning of a smallest amount of energy?

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Einstein and the Photoelectric Effect

- Einstein took Planck's constant, h , to have serious physical meaning.
- He suggested that light comes in discrete bits, which he called *light quanta* (now called *photons*).
- This would explain how light can produce an electric current in a sheet of metal.
 - Einstein's Nobel Prize was for this work (not for relativity).



Planck and Einstein

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Niels Bohr

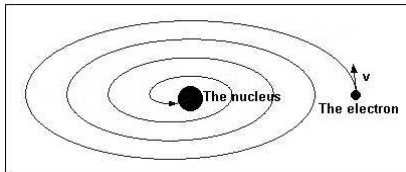


- 1885-1962
- Danish physicist, worked in Rutherford's laboratory in Manchester in 1913
- Was trying to understand how electrons were arranged in the atom, using Rutherford's basic model

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Inherent problem with the Rutherford model



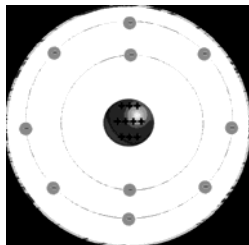
- Rutherford had thought of the atom as a *miniature solar system* with the nucleus as the "sun" and the electrons as "planets."
- Problem: If so, why did the electrons not all spiral into the nucleus and radiate energy continuously?

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The Bohr Atom

- Atoms do radiate energy, but only intermittently.
- Bohr postulated that electrons are fixed in *discrete orbits*, each representing an energy level.

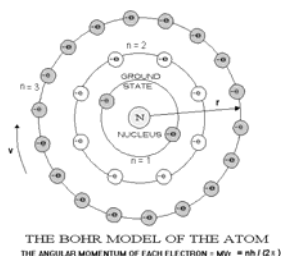


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The Bohr Atom

- When an electron jumped from one orbit to another, it gave off a burst of energy (light) at a particular wavelength (colour).
 - These were specific to different elements.
- Bohr found that each "orbit" or "shell" had room for a fixed maximum number of electrons.
 - 2 in the first, 8 in the second, 18 in the third, 32 in the fourth, etc.



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The Bohr Atom and the Periodic Table

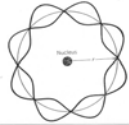
	Group								Number of occupied shells	
	1	2	3	4	5	6	7	8		
Period 1									2	1
									He	
Period 2	3	4	5	6	7	8	9	10		2
	Li	Be	B	C	N	O	F	Ne		
Period 3	11	12	13	14	15	16	17	18		3
	Na	Mg	Al	Si	P	S	Cl	Ar		
Period 4	19	20								4
	K	Ca								
	2,8,1	2,8,8,2								
	Number of electrons in outer shell (except for helium)									

- The number of electrons in the outer shell accounted for properties revealed by the Periodic Table.
 - Each Group in the Periodic Table corresponds to elements with the same number of electrons in their outer shell.

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Matter Waves

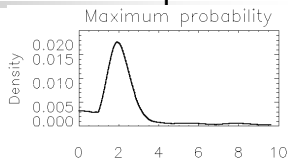


- Louis de Broglie (1924) suggested that if waves can behave like particles, maybe particles can behave like waves.
- He proposed that electrons are waves of matter. The reason for the size and number of electrons in a Bohr electron shell is the number of wave periods that exactly fit.

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Schrödinger's Wave Equations



- In 1926, Erwin Schrödinger published a general theory of "matter waves."
- Schrödinger's equations describe 3-dimensional waves using *probability functions*
- Gives the probability of an electron being in a given place at a given time, instead of being in an orbit
- The probability space is the electron cloud.

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Heisenberg's Uncertainty Principle

- Werner Heisenberg
 - German physicist, 1901-1976
- Schrödinger's equations give the probability of an electron being in a certain place and having a certain momentum.
- Heisenberg wished to be able to determine precisely what the position and momentum were.



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Heisenberg's Uncertainty Principle, 2

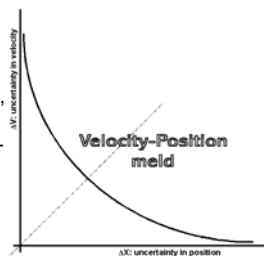
- To "see" an electron and determine its position it has to be hit with a photon having more energy than the electron – which would knock it out of position.
- To determine momentum, a photon of low energy could be used, but this would give only a vague idea of position.
- Note: the act of observing alters the thing observed.

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Heisenberg's Uncertainty Principle, 3

- Using any means we know to determine position and momentum, the uncertainty of position, Δq , and the uncertainty of momentum, Δp , are trade-offs.
- $\Delta q \Delta p \geq h/2\pi$, where h is Planck's constant



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Particles or Waves?

- Question: Are the fundamental constituents of the universe
 - Particles – which have a position and momentum, but we just can't know it,or
 - Waves (of probability) – which do not completely determine the future, only make some outcome more likely than others?

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The Copenhagen Interpretation

- Niels Bohr and Werner Heisenberg:
 - The underlying reality is more complex than either waves or particles.
- We can *think* of nature in terms of either waves or particles when it is convenient to do so.
- The two views *complement* each other.
 - *Neither is complete* in itself and a complete description of nature is unavailable to us.



Heisenberg & Bohr

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The uncertainty principle outside of physics

- The ramifications of uncertainty in physics, has prompted many “applications” in everyday life.

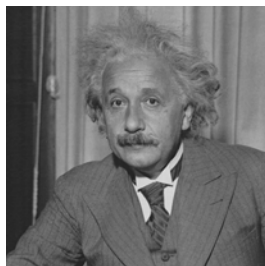


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Does Quantum Mechanics describe Nature fully?

- Einstein said no.
- “God does not play dice.”



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Making a science of uncertainty

- Is there no reality until we look?
 - In the Copenhagen interpretation of the world, events that are only determined probabilistically in quantum mechanics are settled once and for all when we examine them and determine which outcome happened.
- If quantum mechanics is a complete description of the physical world, then an unpredictable event, such as radioactive decay, doesn't actually happen or not happen until we measure it.
 - Until then, both happening and not happening are possible.

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Schrödinger's Cat Paradox

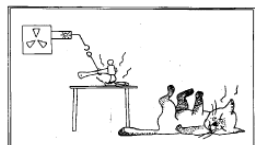
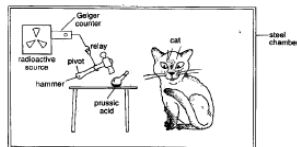
- Erwin Schrödinger set out to show the absurdity of this with his cat paradox.
- A cat is placed in a closed chamber with a radioactive substance and a device to release poisonous fumes if the radioactive matter decays.
- The cat is left in the chamber for a period of time, during which the *probability* of radioactive decay of the substance is known.

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Schrödinger's Cat Paradox, 2

- According to quantum mechanical theory, all we know is what the chance is of the radioactive matter having decayed – not whether it has or not.
- The cat is therefore neither alive nor dead until we open the chamber!



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[Schrödinger's Cat Paradox, 3]

- Schrödinger's point was to show the absurdity of the notion that quantum mechanics is complete.
- His macabre example has led to many jokes.
 - Here, the SPCA call on Schrödinger to investigate his treatment of his cat.

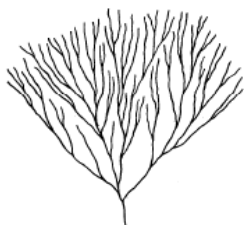


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[Many Universes Interpretation]

- And yet even more bizarre interpretations to the meaning of it all.
- Hugh Everett (1950s), came up with a logically consistent interpretation of quantum probability.
- Every outcome that is possible happens, in different universes.



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