Atoms

The discrete unit and the uncertain viewpoint

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.

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.

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.

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?

Cathode Rays

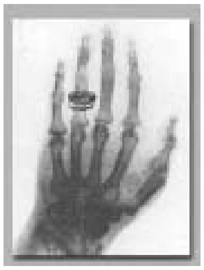
- William Crookes in the 1870s invented a vacuum tube in which when electricity was pumped into a metal plate at one end (the *cathode*) it caused a glow in the direction of a metal plate the *anode*) at the other end.
- This glow could be deflected by a magnet.
- He called these emanations, *cathode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

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*.

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

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?

Atoms: what are they?

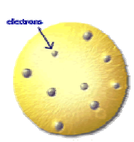
- Ultimately just a theory of discreteness
  - *a – tom* = not cut = indivisible
- Chemistry pointed to the existence of some smallest units in combination
  - Were these units atoms?
- If so, how do these units account for the structure of matter?
- Another question: Why is the Periodic Table periodic?

Electrons

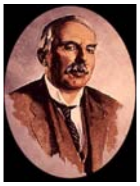
- J. J. Thomson in 1897 at the Cavendish Laboratories at Cambridge:
  - Tried to measure effects of cathode ray tubes
  - Found that cathode rays could be generated from any element and that they behaved like a stream of particles.
- Thomson believed the particles came out of chemical atoms.
- He called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

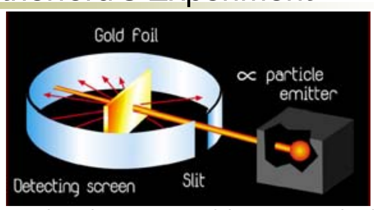


Rutherford's Rays



- 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

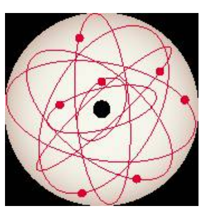
Rutherford's Experiment



- 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.

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.



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 termperatures.
    - 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

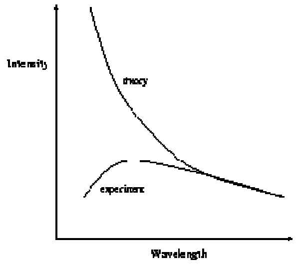
- According to theory, when a black body radiates waves of extremely short wave length (e.g., ultraviolet light), it radiates an *infinite amount of energy* – more than all the energy in the universe.
- This violates the first law of thermodynamics and, if true, would be ruinous to much of 19th century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

The cavity radiator

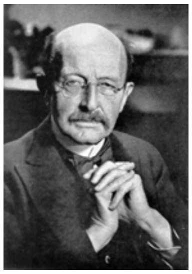
- A "black body" is a theoretical notion, but scientists could approximate the ideal with a piece of equipment for laboratory tests, called a cavity radiator.
- Contrary to theoretical expectations, the cavity radiator did *not* emit an infinite amount of energy.
  - In fact, at very short wave lengths, 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.



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.

***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?

Einstein and the Photoelectric Effect

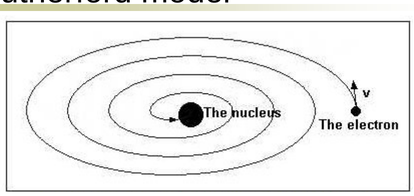
- Einstein took Planck's constant, *h*, to have serious physical meaning.
- He suggested that light comes in discrete bits, which he called *light quanta* (now called *photons*).
- This would explain how light can produce an electric current in a sheet of metal.
  - Einstein's Nobel Prize was for this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

Planck and Einstein

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

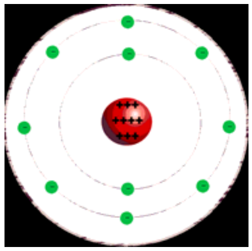
Inherent problem with the Rutherford model



- 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?

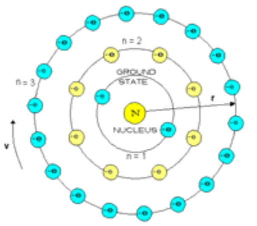
The Bohr Atom

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



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.

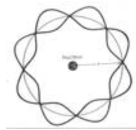


The Bohr Atom and the Periodic Table

	Group 1	2	3	4	5	6	7	0	Number of occupied shells
Period 1								2 He 2	1
Period 2	3 Li 2,1	4 Be 2,2	5 B 2,3	6 C 2,4	7 N 2,5	8 O 2,6	9 F 2,7	10 Ne 2,8	2
Period 3	11 Na 2,8,1	12 Mg 2,8,2	13 Al 2,8,3	14 Si 2,8,4	15 P 2,8,5	16 S 2,8,6	17 Cl 2,8,7	18 Ar 2,8,8	3
Period 4	19 K 2,8,8,1	20 Ca 2,8,8,2							4
Number of electrons in outer shell	1	2	3	4	5	6	7	8 (except for helium)	

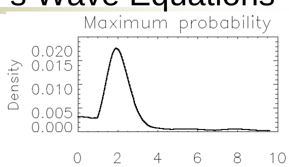
- The number of electrons in the outer shell accounted for properties revealed by the Periodic Table.
  - Each Group in the Periodic Table corresponds to elements with the same number of electrons in their outer shell.

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.

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.

Heisenberg's Uncertainty Principle

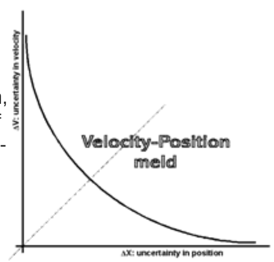
- Werner Heisenberg
  - German physicist, 1901-1976
- Schrödinger's equations give the probability of an electron being in a certain place and having a certain momentum.
- Heisenberg wished to be able to determine precisely what the position and momentum were.

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.

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



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?

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.

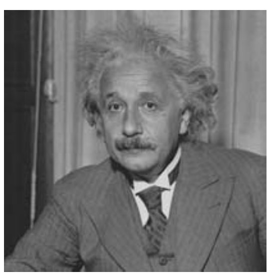
Heisenberg & Bohr

The uncertainty principle outside of physics

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

Does Quantum Mechanics describe Nature fully?

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



Making a science of uncertainty

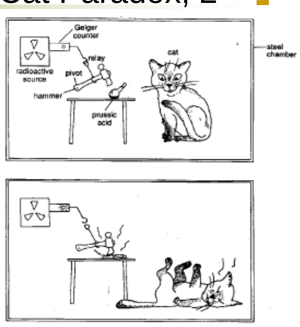
- Is there no reality until we look?
  - In the Copenhagen interpretation of the world, events that are only determined probabilistically in quantum mechanics are settled once and for all when we examine them and determine which outcome happened.
- If quantum mechanics is a complete description of the 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.

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.

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!



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.

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.