Historical introduction to Elementary Particles: Particles in atoms and nuclei

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• Griffiths, 2nd ed., 1.1-1.2,1.4
Historical introduction to elementary particles

• Griffiths “Introduction of Elementary Particles”
  – Chapter 1: a rush through the history of particle physics without any in depth discussion
  – Following chapters elaborate on many points
  – We will try to follow this approach.

• Knowing history is important:
  – Naming conventions or even concepts are difficult to understand without historical context
  – Amazing developments spanning only a bit more than a centaury: the oldest living person is 116 years old and was born 3 years after the first elementary particle was identified!

• Please read the textbook:
  – It contains more information and stories that we can cover in class time (even though I also sometimes go beyond the textbook)
Ancient atomic theory

- Ancient Greek philosophers (Leucippus and especially his pupil Democritus) speculated about matter consisting of imperishable, indivisible small parts – “atoms”.
  - Different geometrical shapes of atoms and how they connect to each other, responsible for properties of materials (more like contemporary molecules than contemporary atoms)
  - Represented philosophical point of view as well: world which can be understood as interacting parts as opposed to continuous divine intervention
    - Epicurus 341-270 BC was one of ancient Greek philosophers who propagated atomic philosophy
- One of many ancient hypotheses. They could not be sorted out experimentally at that time.
- This philosophical thought was revived by European philosophers in 17th century as corpuscularianism (Pierre Gassendi 1592-1655, France; John Locke 1632-1704, England) and physicists (Robert Boyle 1627-1691, Ireland; Isaac Newton 1842-1727, England)
Beginnings of modern theory of atoms. Ions.

- In early 1800’s John Dalton explained patterns he observed in chemical reactions (“law of multiple proportions”) by atomic hypothesis.
- Charged atoms – ions
  - Michael Faraday experimented (~1820-30) with substances flowing between electrically charged plates (anode and cathode):
    - His observations were soon explained as electrically charged atoms (ions).
    - Both positive and negative ions were observed.
- Mass-to-charge ratio was measured for several ionized substances.
Periodic Table of Elements

- In mid 1800's a lot of new chemical elements were being discovered.
- Chemists were attempting to tabulate them according to their chemical properties.
- Periodicity with atomic weight was noticed.
- The first one to recognize full pattern was Dmitri Mendeleev in 1869 who also predicted existence of a few yet unknown elements at that time.
Discovery of radioactivity - 1886

- Henri Becquerel discovered that uranium salt can fog photographic plate 1886
- Soon later, Maria Sklodowska (Marie Curie) showed that uranium was emitting charged particles and suggested it was not a chemical reaction but spontaneous disintegration (i.e. decay) of atoms: **atoms are not indestructible!**
- Together with Pierre Curie they identified more radioactive substances (Polonium, Radium).
- All three shared Nobel Prize in Physics in 1903
Discovery of electron - 1897

- Even before work of Curies, some scientists (Prout, Lockyer) speculated that atoms were not elementary but built up from more fundamental units, like the smallest atom (i.e. hydrogen)

- **J.J. Thomson** experimented with “cathode rays” deflected in electric and magnetic fields [Do related Problem 1.1]

- Thomson showed that:
  - Cathode rays were negatively charged particles
  - **Mass-to-charge ratio was ~1000 times smaller than for ionized atoms**
  - Same cathode rays were emitted by cathodes made out of different materials

- Anode rays were also observed (Eugen Goldstein 1896): positive charge, but mass-to-charge ratio changed from material-to-material

- **Discovery of electron** (means “elementary charge” – the name comes from Goerge Stoney) by Thomson marks beginning of elementary particle physics
  - Electrons are indivisible, identical to each other, don’t decay, contained in all atoms

- Thomson’s “plum pudding” model of atoms:
  - Electrons embedded in the positive charge like plums in a plum pudding
Alpha, Beta, Gamma radiation

- **Ernst Rutherford** (student of J.J. Thomson) working at McGill University classified various rays from radioactive decays according to their charge and how well they penetrated materials:
  - **Alpha**: stopped easily (e.g. sheet of paper), positively charged
    - Later understood as nucleus of helium (2 protons + 2 neutrons)
  - **Beta**: more penetrating (need aluminum plate to stop), either positive or negative
    - Later understood as electrons and positrons
  - **Gamma**: highly penetrating (need a lead brick to stop), neutral
    - Later understood as highly energetic photons

This terminology is still in use, especially in radiation safety.

**Ernest Rutherford**
1871-1937
New Zealand, England

Nobel Prize is Chemistry
1908
Discovery of nucleus - 1909

- Ernest Rutherford, with his students Hans Geiger and Ernest Marsden, scattered beam of alpha particles on the gold foil (Manchester University, 1909)
- The plum model predicted only small deflections from the original beam direction:
  - electrons are too light to knock heavy alpha particle off their path
  - positively charged “pudding” has low density and also can’t deflect alphas much
- Scattering at even very large angles (backwards!) was observed:
  - Hard (dense) scattering centers exists in atoms

(usually called the Rutherford Gold Foil Experiment)
Rutherford model of atom

• Motivated by the results of their experiment, Rutherford introduced in 1911 correct model of atom:
  – Almost entire atomic mass is concentrated in a tiny positively charged nucleus, located at the center of atom
  – Electrons orbit around nucleus, being attracted by electromagnetic force
  – Most of space in atom is empty!
    • Size of a nucleus ~ 1 fm = 10^{-15} m
    • Size of an atom ~ 1 Angstrom = 100,000 fm
    • If nucleus was twice my size, then atom would have been the size of Moon’s orbit

• Rutherford experiment and model sparked theoretical developments:
  – dynamics of hydrogen atom was understood via Bohr’s planetary model (1913) which lead to development of quantum mechanics (Schrodinger 1926) which, including Pauli exclusion principle for electrons, eventually lead to full understanding of the mechanism behind the period table of elements
Identification of proton - 1919

- Rutherford observed (1917) that alpha particles bombarding nitrogen gas produced ionized hydrogen
  - Previously (1815) William Prout speculated that all atoms are built from hydrogen atoms (called it “protyle”)
  - After his observation, Rutherford proposed (1919) that nucleus of hydrogen was an elementary building block of all nuclei
  - He called it “proton” in reference to Prout’s idea and a Greek word (πρωτον)
  - Modern interpretation of Rutherford’s proton discovery:
    - the first reported inelastic nuclear collision reaction:
      - \(^{14}\text{N} + \alpha \rightarrow ^{17}\text{O} + p\)
Neutron discovery - 1932

• Bohr’s model of hydrogen (quantized electron + proton bound system) described its excitation energies very well.

• However, helium (two electron atom) was 2 times as heavy as two protons together. All heavier atoms were about factor of 2 too heavy compared to number of protons needed to compensate charge of electrons (extra protons and electrons inside nucleus were considered as a possibility).

• Rutherford proposed in 1920 that nuclei also contained neutral version of proton.

• In 1931 Walther Bothe and Herbert Becker in Germany found that if the very energetic alpha particles emitted from polonium fell on certain light elements (beryllium, boron, or lithium, an unusually penetrating neutral radiation was produced); initially assumed to be gamma rays.

• In 1932 James Chadwick (Rutherford’s student) studied this radiation and proved that it could not be gamma rays but neutral particle with mass nearly equal to proton. He received Nobel Prize in 1935.

• Nuclei contain both protons and neutrons. They clamp together by means of strong force (which also needs to overcome electrostatic repulsion of protons).

• Quantitative understanding of nuclei can be achieved by applying quantum mechanics to bound states of protons and neutrons (a subject in Nuclear Physics).
Photon – light as wave

- **Wave theory of light** was founded by Dutch physicist **Christian Huygens** in 1678:
  - every point which a luminous disturbance reaches becomes a source of a spherical wave; the sum of these secondary waves determines the form of the wave at any subsequent time
- In **1704** Newton put forward corpuscular theory of light based on his experienced with geometrical optics
- In **1818** French physicist Augustin-Jean Fresnel showed that Huygens’ principle, together with interference effect, can explain light diffraction which the corpuscular theory couldn’t
- **Maxwell** unified theory of electric and magnetic interactions in 1864, and showed that his equations predicted electromagnetic wave propagating with speed (~300,000 km/s) which was consistent with the measured speed of light (first determined by Danish astronomer Ole Romer in 1676)
- Particle theory of light seemed to be definitely ruled out
Photon – black body radiation

- In 1900 theoretical physicist Max Planck demonstrated that power of black body radiation (light emitted and absorbed by material in thermal equilibrium) would be infinite unless emitted in quanta, each with energy:
  - \( E = h \nu \)
  - \( \nu \) – frequency of light;
  - \( h \) – Planck’s constant determined from experimentally observed frequency spectrum
- Initially it was thought that quantization was due to unknown mechanism in the emitting material
Photon – photoelectric effect

- In **1905 Albert Einstein** proposed that the light itself is quantized and predicted that electrons knocked off metals by light would have energies dependent on light frequency but not intensity:
  - $E_e < h \nu - W$
  - $W$ – amount of energy lost by electron in metal before getting out

- Einstein’s prediction confirmed experimentally in **1919** by **Robert Millikan**

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- **Einstein**
  - 1858-1947
  - Germany, Switzerland, US
  - Nobel Prize in Physics 1921 (for photoelectric effect!)

- **Millikan**
  - 1868-1953
  - US
  - Nobel Prize in Physics 1923 (also for the measurement of electron charge in 1913)
Photon – an elementary particle!

- Some physicist remained skeptical until Compton experiment in 1923 scattering light off electrons, which proved that light behaved like a massless particle carrying both energy and momentum \((E=pc)\).

- Unlike for electrons, protons and neutrons, Pauli’s exclusion principle does not apply to photons (photon is spin 1 boson, while others are spin \(\frac{1}{2}\) fermions).

- It was also realized that gamma rays were very high frequency (i.e. energy) photons – particle nature of gamma radiation is apparent in the experiments.

- Meanwhile quantum mechanics was developed, describing all particles with waves of probability. Wave-particle duality is property of all matter!
Photon – a force carrier

- In mid 1900’s quantum field theory of electromagnetic interactions was developed (QED) which cast a photon as mediator of any electromagnetic force:
  - Any particle with electric charge can emit or absorb photons. Manifestation of such exchanges are electric and magnetic forces.
  - Photons are neutral thus they do not interact with each other
- More on this later in the semester

This is not quite like passing a ball between people – electric force can be attractive!

Many photons can be exchanged at the same time
Discovery of positron - 1932

• Electrons with “negative energies” predicted by Paul Dirac in 1928 from relativistic quantum theory of electrons:
  – non-relativistic $E = p^2/2m$ (only one solution: $E > 0$); $E, p$ become operators in quantum physics
  – relativistic $E^2 = m^2c^4 + p^2c^2$ (two solutions: $E > 0, E < 0$)
  – interpretation was a puzzle

• After discussions with Robert Oppenheimer, Dirac published a paper in 1931 predicting anti-electron (same mass, opposite charge, annihilate with electron when in contact)

• Carl Anderson (Millikan’s student) discovered positrons in 1932
  – positively charged electron like particles detected in cosmic rays passing through a cloud chamber immersed in a magnetic field
  – Later he demonstrated the same effect with gamma rays produced in a lab

• This was the first discovery of antimatter
Yukawa’s prediction of a meson

• Protons and neutrons are held together in nuclei by a force much stronger than electrostatic repulsions of protons

• Yukawa in 1934:
  – Strong interactions must be mediated by a particle
  – Since strong forces drop quickly to zero outside the nucleus, the strong force carrier must have a large mass
  – From the size of a nucleus he estimated the mass of the particle exchanged by nucleons to be between the electron and proton masses. As middle-weight it got labeled “meson”.

• We will talk about mesons next time. Do related problem 1.2 before Thursday.