NASA Space Radiation Summer School
June 3 - 26, 2015
Brookhaven National Laboratory
Upton, New York

RADIATION PHYSICS

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Friday June 5, 2015

OUTLINE

DISCOVERY OF X RAYS

RÖNTGEN, 1895

1895, William Röntgen

(German, 1845-1923)

- Received first physics Nobel prize in 1901
- Not a dentist!

[Wikipedia, 2014]

DISCOVERY OF X RAYS

- Late C19 people fascinated with electricity
- One way of investigating electricity was to examine what happens when it passes through all manner of substances, including gases
- Earlier people had observed the beautiful glow that appears when electric current flows through gas at low pressure

- Basic equipment consisted of a thin glass tube with metal electrodes & pump to remove air (vacuum pump)
  - the end was often coated with fluorescent material
- Became known as Crookes tubes
- British physicist William Crookes (1832-1919) began systematic study of the electrical glows in 1879

[Wikipedia, 2014]

DISCOVERY OF X RAYS

RÖNTGEN, 1895

Fluorescence

- Atom excited by UV - emits visible light as it returns to ground state
- Typical lifetime of an atomic state $\approx 10^{-8}$ sec
- Process appear to occur instantaneously

DISCOVERY OF X RAYS RÖNTGEN, 1895

Phosphorescence

- Light emitted long after original excitation
- Minutes to hours
- Due to metastable states

[Wikipedia, 2014]

DISCOVERY OF X RAYS RÖNTGEN, 1895

- Two other people who studied glows in Crookes tubes were William Röntgen & J.J. Thomson
- In 1895, Röntgen accidentally left some unexposed, tightly wrapped photographic plates near his tube
- Later wanted to use the plates but found they were fogged
- Repeated this (did not ignore) & always found plates were fogged

DISCOVERY OF X RAYS

RÖNTGEN, 1895

- One night he left the lab but after dinner remembered he forgot to turn off his Crookes tube
- Returned to lab, in dark
- Noticed a glow coming from a sheet of paper on nearby table
- Paper was coated with barium paltinocyanide (known to give off a glow in a strong light)
- But there was no light!
- And the Crookes tube was covered by thin black cardboard!

DISCOVERY OF X RAYS RÖNTGEN, 1895

- Röntgen realized cause of glow must be same as cause of fogged plates
- Invisible rays of an unknown type were coming from Crookes tube
- He called them x-rays
- He soon discovered their most remarkable properties
  - Able to penetrate many objects as easily as light penetrates glass

[Wikipedia, 2014]

DISCOVERY OF RADIOACTIVITY BECQUEREL, 1896

1896, Henri Becquerel (French, 1852-1908)

- Less than a month later in early 1896 Becquerel noticed his photographic materials being fogged and discovered radioactivity!

[http://faculty.randolphcollege.edu/tmichalik/becquerel.htm, 2014]

- 1897 J.J. Thomson discovered the electron
- 1898 Marie Curie isolated radium
- 1911 Rutherford discovered atomic nucleus

DISCOVERY OF RADIOACTIVITY BECQUEREL, 1896

- 20 Jan, 1896 Henri Poincare put forward his ideas on origin of x rays
- X rays appeared to come from the fluorescent spot where cathode rays hit wall of Crookes tube
- Poincare speculated that x rays were not unique to Crookes tubes but emitted by all fluorescent bodies

  (i.e. materials that glow on exposure to strong source of light, e.g. Sun)
- Within days people did experiments
- Easy! Wrap photographic plate in black paper
  - Put fluorescent substance on top
  - Lay it in sunlight
  - Develop plate

DISCOVERY OF RADIOACTIVITY BECQUEREL, 1896

- Becquerel had same idea

- 44 years old and came from family of scientists

- Several years earlier had helped father with experiment involving a uranium salt & noticed the crystals would glow for some time after removed from sunlight

- He decided to use same salt in his x ray experiments, hoping it would be a powerful source of x rays & leave clear imprint on photo plates

- 26 Feb, 1896 he began
  - But cloudy day!
  - Therefore put his whole experiment in a closed drawer

DISCOVERY OF RADIOACTIVITY BECQUEREL, 1896

- Experiment: metal cut-out between uranium salt & photo plate so as to leave no doubt as to origin of x rays

- But cloudy for 3 days!

- Becquerel decided to develop the plate anyway to prove that no image was formed when sunlight not present

- But very clear image!

- Uranium salt gave out invisible rays even in pitch darkness

- He found these rays very different to x rays
  - Did not penetrate materials
  - Emitted spontaneously (always)

DISCOVERY OF RADIOACTIVITY BECQUEREL, 1896

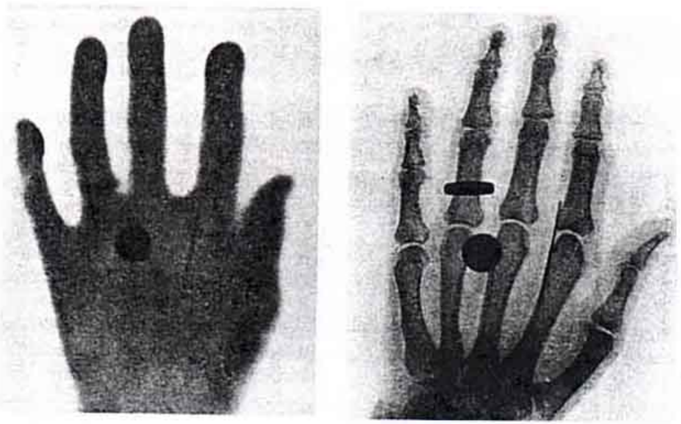


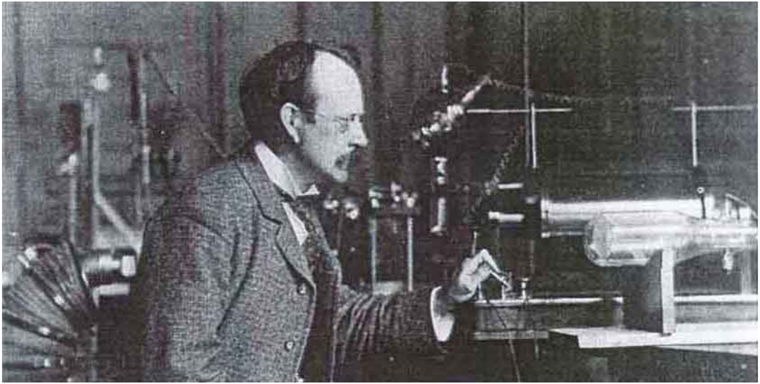
Image of a hand made with emissions from radioactive substances (Left) is not nearly as sharp as that made with x rays (Right). Becquerel's discovery of radioactivity thus attracted far less attention than the discovery of x rays made by Röntgen the previous year.

[Badash, The discovery of radioactivity, Physics Today, February 1996]

DISCOVERY OF ELECTRON J.J. THOMSON, 1897

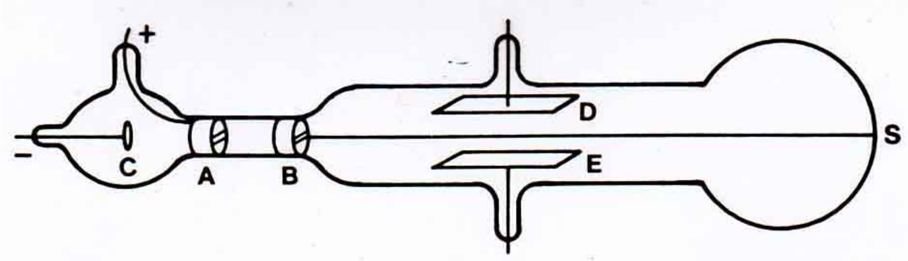
1897, J.J. Thomson (English, 1856-1940)

- Cavendish Lab
- Birth of Particle Physics



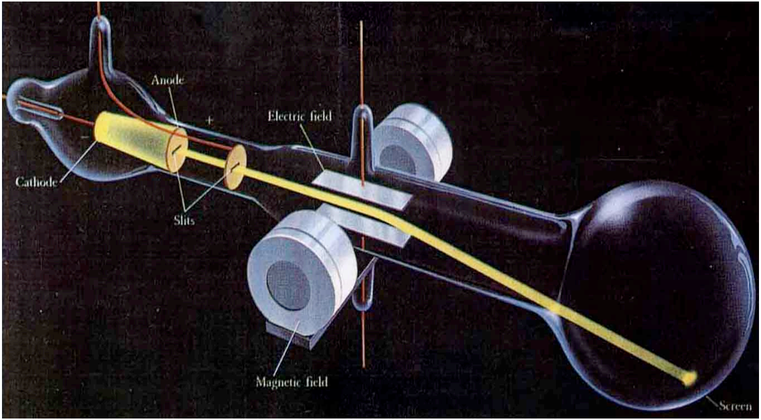
J.J. Thomson in his Cavendish laboratory with the apparatus he used to find the mass of the electron. [Lederman & Schramm, From quarks to the cosmos, Freeman, New York, 1989]

DISCOVERY OF ELECTRON J.J. THOMSON, 1897



J.J. Thomson's cathode ray tube. The negative terminal of the high voltage supply is connected to the cathode (C), and the positive terminal to the anode (A). Accelerated electrons pass through slits in the anode and another screen (B) and travel until they strike the end of the tube (S), which is coated with a fluorescent material. The cathode beam can be deflected by application of a suitable voltage across the additional plates (D and E) or by using a magnet. [Wikipedia, 2014]

DISCOVERY OF ELECTRON J.J. THOMSON, 1897



The cathode ray tube of J.J. Thomson. A heated wire at the cathode emits free negative electrons, which are accelerated toward the positively charged slits. A narrow stream continues out of the slits toward the plates. The field of the plates can deflect the stream, which may move up or down depending on the polarity of the field.

[Lederman & Schramm, From quarks to the cosmos, Freeman, New York, 1989]

DISCOVERY OF ELECTRON J.J. THOMSON, 1897

Crookes tubes

- In 1870s people found as gas pressure lowered, gas ceased glowing
- Instead luminous spot appeared opposite cathode

- Objects placed in tube would cast shadows
  (showing that a stream of rays must emanate from cathode)
- Called cathode rays

- By mid 1890s there were 2 opinions as to nature of cathode rays
  i) Wave-like vibrations
  ii) Energetic charged particles

- 1895 in Paris, Jean Perrin showed rays carried negative charge
  & he could deflect fluorescent spot (& hence rays themselves)
  with magnet

DISCOVERY OF ELECTRON J.J. THOMSON, 1897

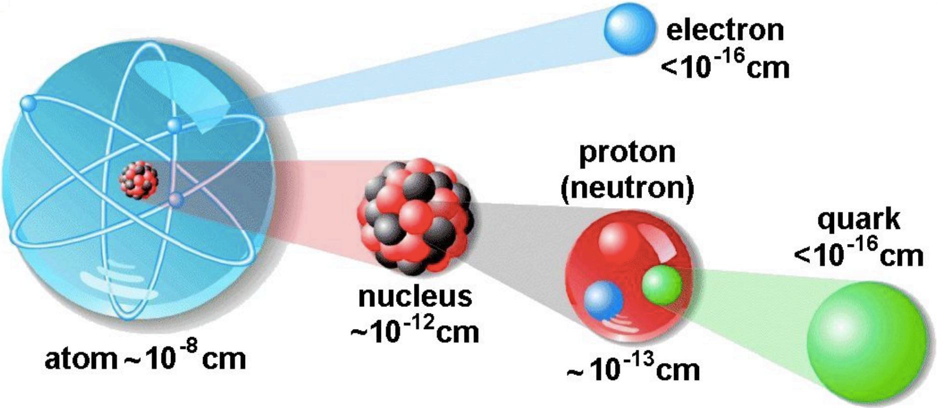
- But general reluctance to believe in new type of particle
- 1897, J.J. Thomson performed series of experiments proving conclusively that cathode rays are indeed streams of particles
- Thomson found he could deflect rays with electric as well as magnetic fields (Possible because he had the best vacuum pump! Residual gas in poor vacuum conducts electricity and so static electric field could not be maintained before)
- By measuring both E and B fields, Thomson concluded the particles had mass $< \frac{1}{2000} \times$ H atom
- Got same results irrespective of cathode material or gas

DISCOVERY OF ELECTRON J.J. THOMSON, 1897

- 1897 discovery of electron
  - Birth of particle physics
  - First elementary particle

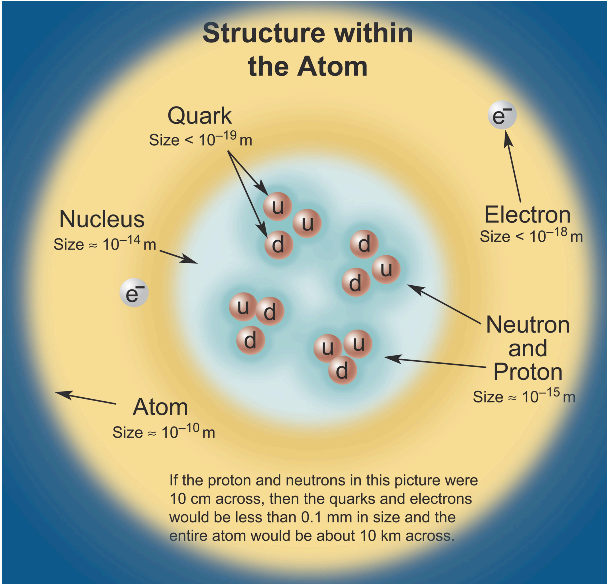
- Today
  - Cannot explain $m_e = 9 \times 10^{-31}\mathrm{kg} = 0.511\mathrm{MeV}/c^2$
  - 3 “electrons” (e, μ, τ) Why ???
  - Anything inside electron?
  - Point or String?

ELEMENTARY PARTICLES



[http://www.ehs.utoronto.ca/services/radiation/radtraining/module1.htm, 2014]

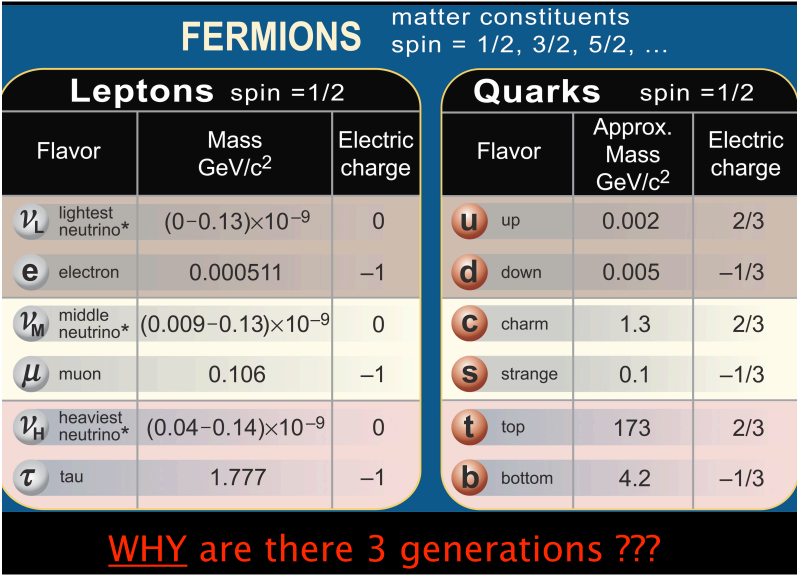
ELEMENTARY PARTICLES



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

[http://education.web.cern.ch, 2014]

ELEMENTARY PARTICLES



FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

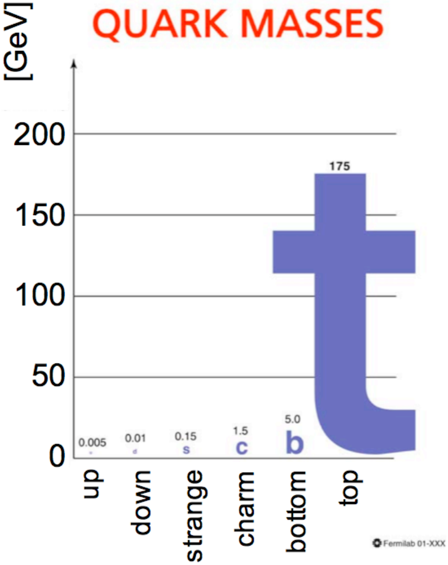
Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

WHY are there 3 generations ???

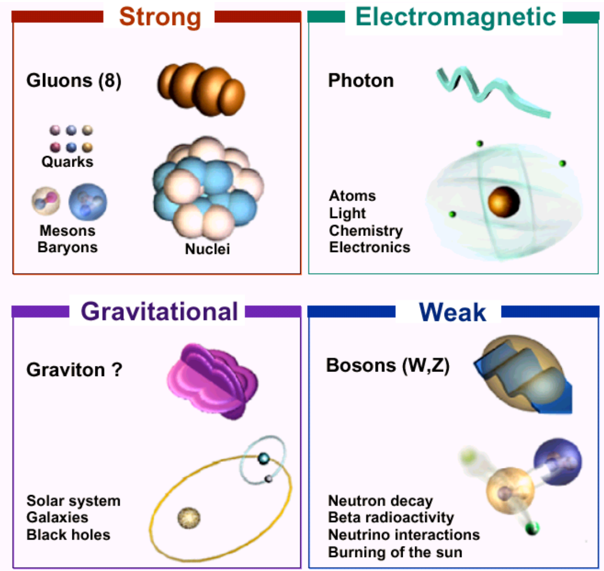
[http://education.web.cern.ch, 2014]

ELEMENTARY PARTICLES



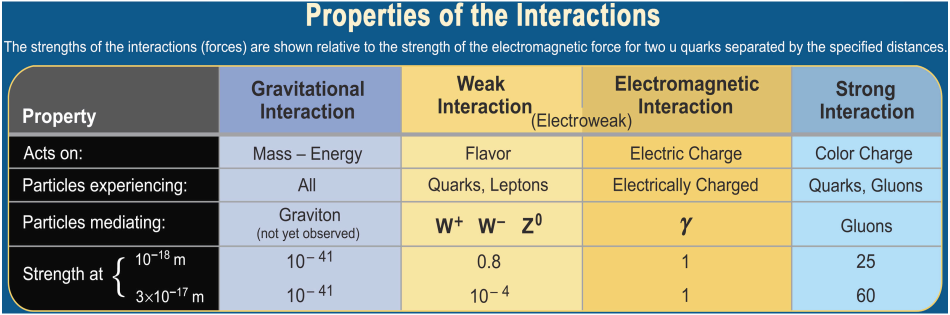
[http://www-d0.fnal.gov/Run2Physics/top/public/fall06/singletop/figures]

ELEMENTARY PARTICLES



[http://education.web.cern.ch, 2014]

ELEMENTARY PARTICLES



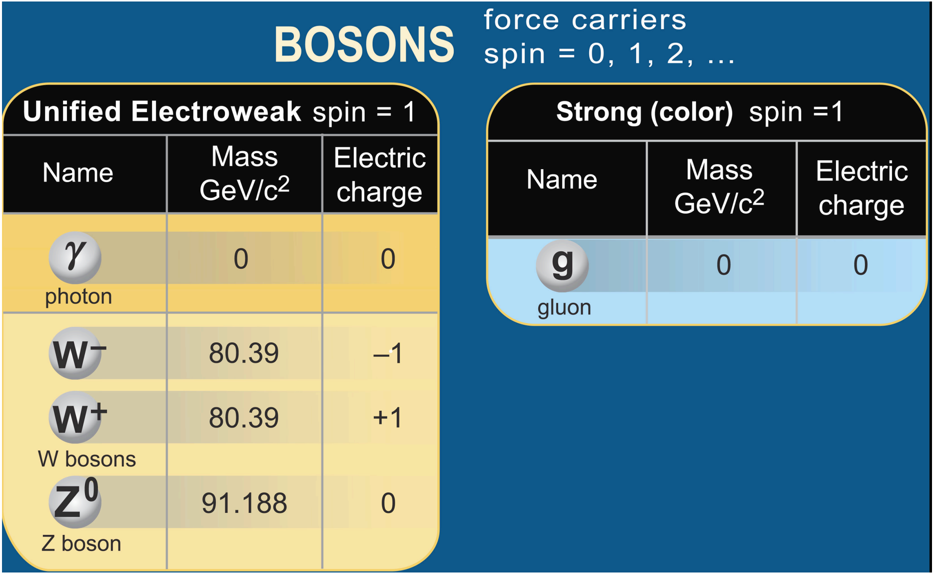
Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	**Gravitational Interaction**	**Weak Interaction**	**Electromagnetic Interaction**	**Strong Interaction**
		(Electroweak)		
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

[http://education.web.cern.ch, 2014]

ELEMENTARY PARTICLES



BOSONS force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

[http://education.web.cern.ch, 2014]

ELEMENTARY PARTICLES

- Standard Model of particle physics describes universe in terms of fundamental particles, called quarks and leptons, which interact via electromagnetic, strong, or weak force

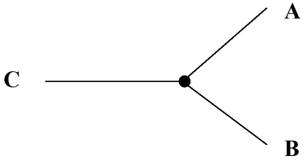
- Theories of these forces are quantum electrodynamics (QED), quantum chromodynamics (QCD), and quantum flavordynamics (QFD), mediated by particles called photons (γ), gluons, and $W^{\pm}, Z^0$ bosons respectively

- These force mediating particles are called gauge bosons

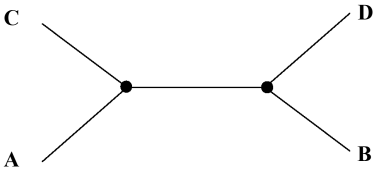
- Gravity is not included in Standard Model

ELEMENTARY PARTICLES
FEYNMAN DIAGRAMS

Decay
$C \to A + B$



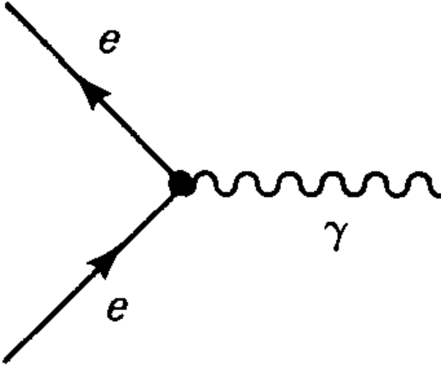
Scattering
$A + B \to C + D$



[Griffiths, Introduction to elementary particles, Wiley, New York, 1987]

ELEMENTARY PARTICLES

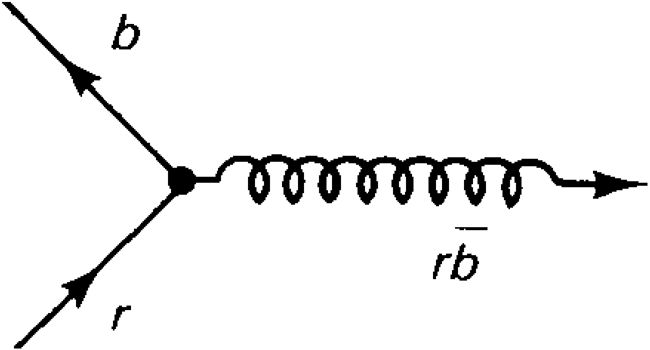
ELECTROMAGNETIC INTERACTION



[Griffiths, Introduction to elementary particles, Wiley, New York, 1987]

ELEMENTARY PARTICLES

STRONG INTERACTIONS CHANGE COLOR



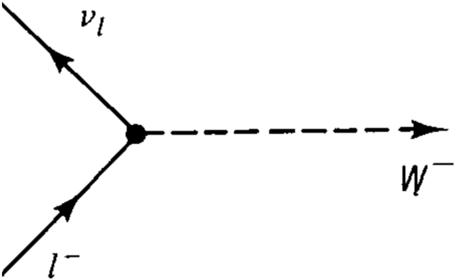
[Griffiths, Introduction to elementary particles, Wiley, New York, 1987]

ELEMENTARY PARTICLES

WEAK INTERACTIONS CHANGE FLAVOR (WEAK ISOSPIN)

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}, \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$



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ELEMENTARY PARTICLES

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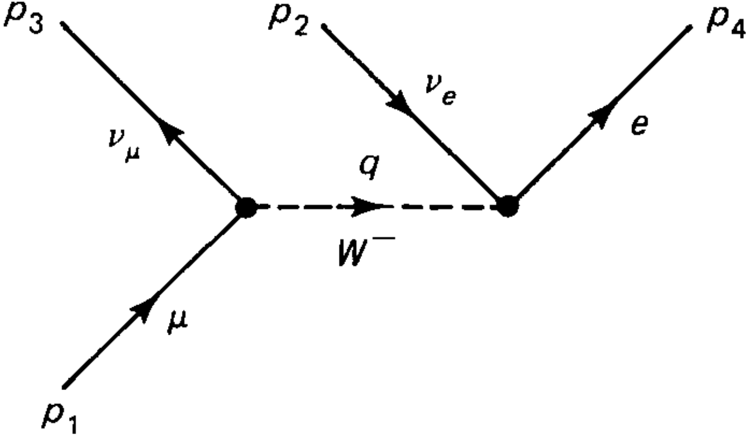


Muon decay

[Griffiths, Introduction to elementary particles, Wiley, New York, 1987]

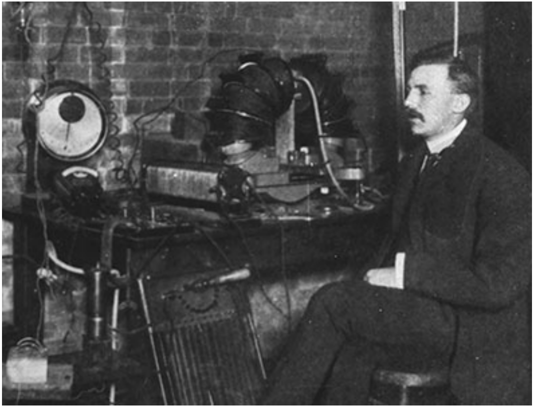
DISCOVERY OF NUCLEUS

RUTHERFORD, 1911

1911, Ernest Rutherford

(New Zealand, 1871-1937)

- Univ. Manchester
- Cavendish Lab
- Birth of Nuclear Physics



[http://www.nrc-cnrc.gc.ca/eng/dimensions/issue6/flashback.html, 2014]

DISCOVERY OF NUCLEUS RUTHERFORD, 1911

- Rutherford was student at Cambridge when Thomson discovered e^-
  - then went to McGill
  - then Manchester - scattering experiments & discovery of nucleus
  - 1919 became director of Cavendish lab

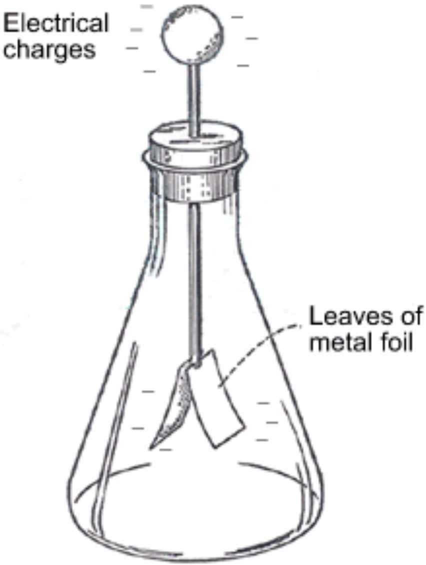
- Radioactivity was intensively studied by Marie Curie (1867-1934) and Pierre Curie (1859-1906).
  - Marie isolated Radium & Polonium in 1898

- While Rutherford was student at Cambridge he studied radioactivity

- 1897-98 he discovered two components of radioactivity: α and β rays

- He used an electrometer!

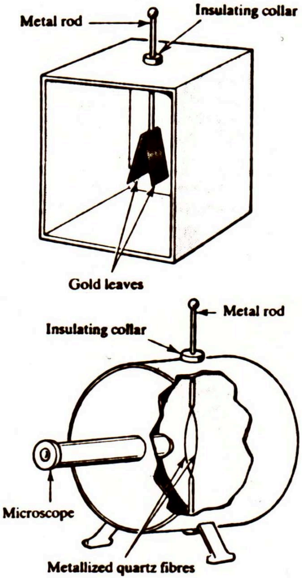
DISCOVERY OF NUCLEUS RUTHERFORD, 1911



[http://www.school-for-champions.com/experiments/]

DISCOVERY OF NUCLEUS RUTHERFORD, 1911

- In early days electroscopes & electrometers also used to study x-rays, radioactivity, etc.
- x-rays & radioactive emanations ionize gases
- Strong sources of radiation cause leaves in electroscope to come together (after electroscope initially charged)
- Strength of radiation can be measured by how quickly leaves come together



[Close et al., The particle explosion, Oxford Univ. Press, Oxford, 1994]

DISCOVERY OF NUCLEUS

RUTHERFORD, 1911

Electrometer

- Charge it up
  - Leaves repel

- Send in radiation
  - Air around leaves becomes ionized & charge leaks away

- Rutherford could measure rate of leakage,
  & hence amount of ionization, by timing the movement

  - The faster the leakage rate, the more the ionization & the stronger the radiation

Discovery of α, β, γ

- Rutherford covered sample of uranium with sheets of aluminum foil
  - Noticed radiation dropped as foil thickness increased - expected

- But as thickness increased further radiation maintained its intensity
  - Concluded two types of radiation α, β
    (α easily absorbed, β more penetrating)

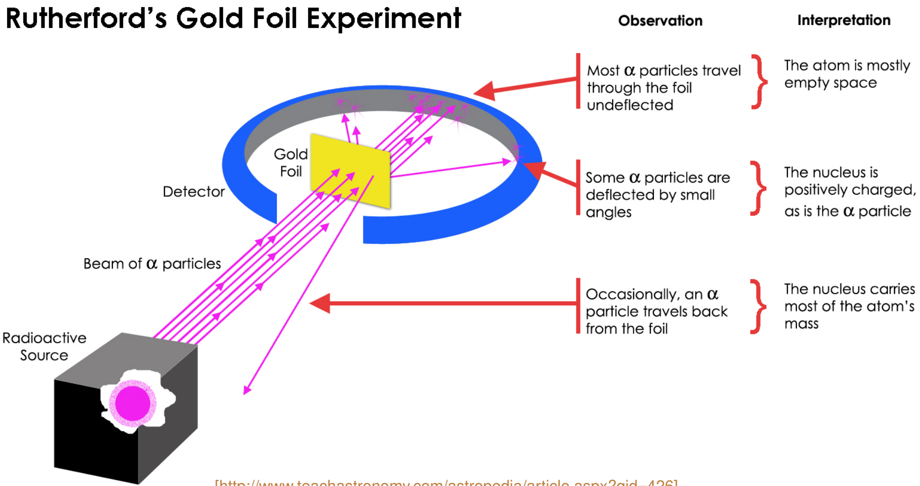
- Later studied thorium
  - Also found α, β
  - But also found 3rd type much more penetrating than either α or β
  - He called it γ

- 1898 Rutherford moved to McGill Univ. in Canada
- Other researchers used E & B fields to show that β rays are negatively charged - later identified as electrons
- But α rays did not deflect
- Rutherford used stronger E & B fields and showed that α rays were positively charged particles (1902)
- 1903 Thomson put forward "plum pudding" model of atom (Rutherford "*not worth a damn*")

DISCOVERY OF NUCLEUS RUTHERFORD, 1911

- 1907 Rutherford moved from McGill to professor at Manchester U.
  - Bohr also came to Manchester
  - At Manchester, Rutherford set up famous scattering experiment

DISCOVERY OF NUCLEUS RUTHERFORD, 1911



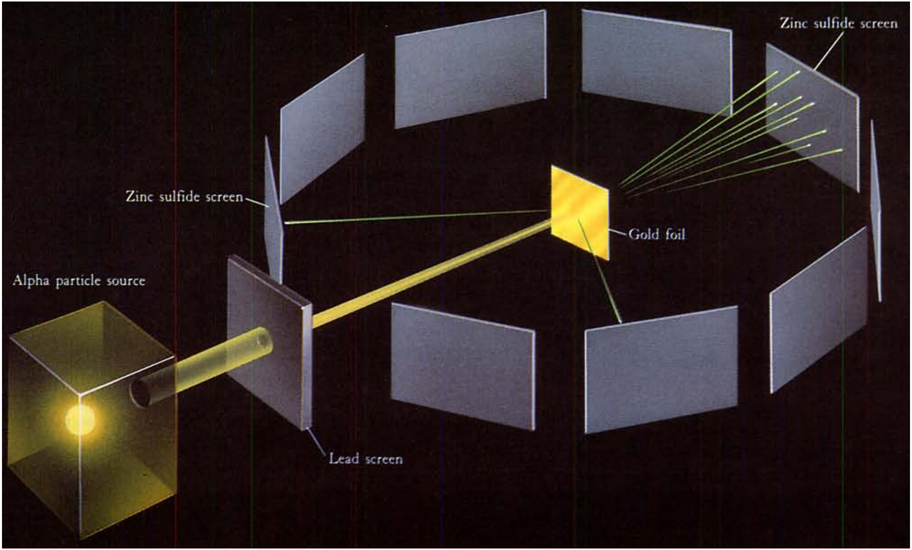
Rutherford's Gold Foil Experiment

Observation	Interpretation
Most α particles travel through the foil undeflected	The atom is mostly empty space
Some α particles are deflected by small angles	The nucleus is positively charged, as is the α particle
Occasionally, an α particle travels back from the foil	The nucleus carries most of the atom's mass

[http://www.teachastronomy.com/astropedia/article.aspx?qid=426]

Source = Radon, Energy of α particle $\sim$ 5 MeV $\approx$ 1 MeV/n

DISCOVERY OF NUCLEUS RUTHERFORD, 1911



Source = Radon, Energy of α particle $\sim$ 5 MeV $\approx$ 1 MeV/n

[Lederman & Schramm, From quarks to the cosmos, Freeman, New York, 1989]

NUCLEAR CONSTITUENTS

- Nucleus made up protons & neutrons
- Generically both called nucleons
- Proton carries same charge as electron, but opposite sign
- Neutrons are neutral
- Whereas electron mass is 0.511 $\mathrm{MeV}/\mathrm{c}^2$, mass of proton and neutron are 938.27 $\mathrm{MeV}/\mathrm{c}^2$ and 939.57 $\mathrm{MeV}/\mathrm{c}^2$ respectively
- We often write MeV instead of $\mathrm{MeV}/\mathrm{c}^2$

NUCLEAR CONSTITUENTS

Particle	Charge	Mass (MeV)
electron	- e	0.511
proton	+ e	938
neutron	0	940

- Sometimes mass given in kg or atomic mass units, u
- Atomic mass unit is defined so that mass of neutral $^{12}\mathrm{C}$ atom is exactly 12 u

$$\text{mass of } {}^{12}\mathrm{C} \text{ atom} \equiv 12.000000 \text{ u}$$

Modern physics books list atomic masses of many atoms

- Conversion factors

$$\text{amu} \equiv \text{u} \quad = \quad 931.49432\,\mathrm{MeV}/\mathrm{c}^2 = 1.6605402 \times 10^{-27}\,\mathrm{kg}$$

NUCLEAR CONSTITUENTS

- Notation for denoting a nucleus is ^{A}Z
  Z = # of protons
  A = # of nucleons = total # of protons + neutrons
  N= # of neutrons, $\Rightarrow$ N = A - Z
- Chemical properties of element determined by # of electrons
- In neutral atom, # of electrons = # of protons
- $\Rightarrow$ # of protons determines chemical properties of neutral atoms.
- Thus, each different element labelled by # of protons
- Thus, element Carbon (chemical symbol C) is defined to be element with 6 protons in its nucleus
- Element Iron (chemical symbol Fe) is defined to be element with 26 protons in its nucleus
- Element Hydrogen (chemical symbol H) is defined to be element with only 1 proton in its nucleus

NUCLEAR CONSTITUENTS

- Nucleus need not have same # of protons & neutrons
- Single element can exist in a variety of forms, called isotopes in which # neutrons is different
- The most stable isotope of Carbon happens to be ^{12}C, has 6 protons (Z=6) & also 6 neutrons (N = 12 - 6 = 6)
- However, less stable isotope ^{13}C is also found in nature, has 6 protons and 7 neutrons
- ^{14}C has 6 protons and 8 neutrons

NUCLEAR FORCE

- Gravitational and electromagnetic (EM) forces are the forces most experienced in everyday life
- Inside nucleus ignore gravity because it is so weak
- Now all nuclei, except Hydrogen, have more than one proton and protons being positively charged repel each other via their mutual electrical repulsion
- Thus, if EM force was only one operating inside the nucleus, then nuclei should not exist becuase they would fall apart due to mutual electrical repulsions of protons
- There must be another fundamental force of nature holding nucleus together
  - We call this nuclear force

NUCLEAR FORCE

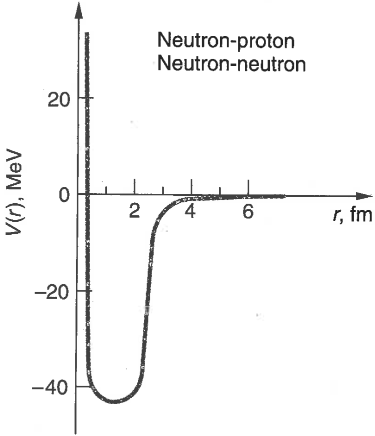
- Nuclear force
  1. must be attractive
  2. between nucleons
  3. is very strong
  4. acts over very short distance (1 fm)
  5. for larger distances force is negligible
  6. at very short distances force is repulsive, which means that nucleons cannot be squeezed together very much

Forces inside nucleus

Force	Sign	Strength	Range	Particles
EM	repulsive	not strong	long	acts between protons
Nuclear	attractive	strong	short	acts equally between protons & neutrons

NUCLEAR FORCE

- Nuclear force has approximate shape of finite square well of width 1 fm, with a repulsive hard core shown in figure

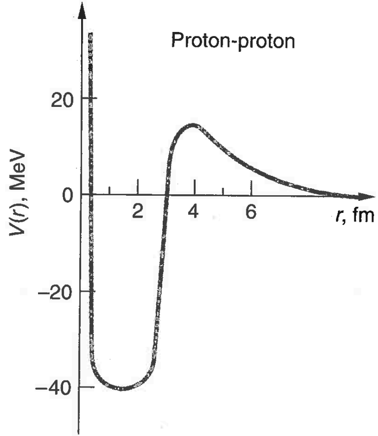


Nuclear potential energy between nucleons (nn or np)

[Tipler & Llewellyn, Modern physics, 3rd ed., Freeman, New York, 1999]

NUCLEAR FORCE

- This is combined with repulsive EM force in figure below



Nuclear potential energy between nucleons plus Coulomb potential energy between protons (pp)

[Tipler & Llewellyn, Modern physics, 3rd ed., Freeman, New York, 1999]

NUCLEAR STABILITY

- If we have a small nucleus, such as ^{4}He then all nucleons are closely packed together and feel strong nuclear force from all other nucleons
- Because this force is so strong, the EM force is negligible
- However, consider a very big nucleus such as ^{208}Pb
  - Consider a specific nucleon:
  - It will feel a strong attraction to its nearest neighbours, but will not feel strong attractions from nucleons much further away because nuclear force is short range and drops to zero at large distances

NUCLEAR FORCE

- However, EM force will be important for those nucleons at large distances and they will provide a repulsive effect
- Thus, for our specific nucleon, it feels a strong attractive force from its nearest neighbours and a smaller repulsive force from nucleons further away
- Thus, small nucleus more tightly bound than big nucleus, because in small nucleus only strong attraction important, whereas for big nucleus, repulsive EM force acts
- A small tightly bound nucleus is more stable than a large loosely bound nucleus
- An unstable nucleus will tend to break apart or decay into smaller pieces all by itself
  - We call this radioactive decay

NUCLEAR STABILITY: PROTONS VS. NEUTRONS

- Small tightly bound nuclei tend to have equal number of protons and neutrons because only nuclear force is important and it acts equally between protons and neutrons

- Big nuclei have more neutrons - provides more of attractive force & prevents break up

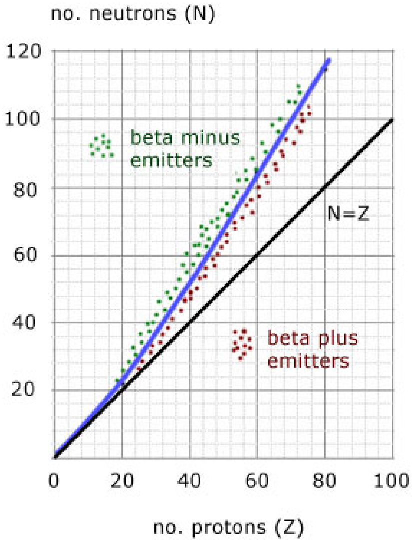
- When neutrons added, only strong nuclear force contributes, but if protons are added then repulsive EM force comes into play

NUCLEAR STABILITY: PROTONS VS. NEUTRONS

- See Figure (next page), which is plot of number of neutrons vs. number of protons for stable nuclei

- Whereas stable isotope ^{12}C has 6 protons and 6 neutrons, stable isotope ^{208}Pb has 82 protons and 126 neutrons

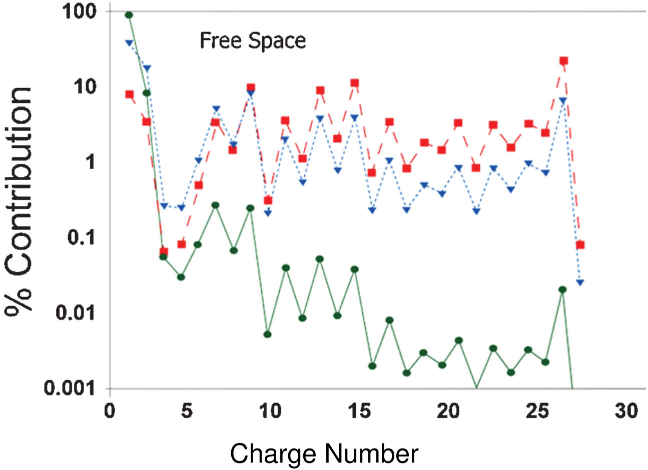
NUCLEAR STABILITY: PROTONS VS. NEUTRONS



Plot of N vs. Z for the known nuclides. Blue line through stable nuclides is called line of stability.

[http://www.a-levelphysicstutor.com/nucphys-NZ-curve.php]

NUCLEAR STABILITY: BINDING ENERGY



Relative contribution in fluence, dose and dose equivalent of different elements in the GCR spectrum. Calculation is an average over 1 year in solar minimum behind 5 g/cm^2 Al shielding.

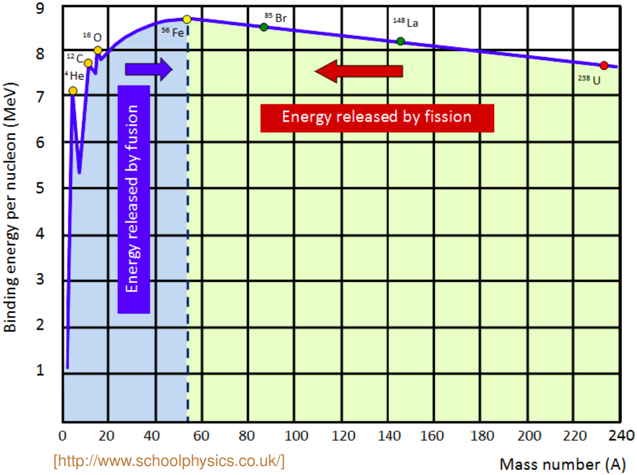
[Durante & Cucinotta, Rev. Mod. Phys. 83, 1245, 2011]

NUCLEAR STABILITY: BINDING ENERGY

- Small nucleus is tightly bound whereas big nucleus is more loosely bound
- But how does binding energy change?
- For example is ^{12}C more or less tightly bound than ^{4}He?
- Turns out that ^{12}C more tightly bound than ^{4}He because it has more nucleons which feel strong mutual attractive force, and yet ^{12}C is still small enough that electrostatic repulsion between protons not important
- Thus, for small nuclei, binding energy increases as more nucleons are added
- However expect binding energy to reach maximum & then start decreasing as more nucleons are added because electrostatic repulsion between protons comes into play
- Thus expect binding energy to increase as a function of Z, reach a maximum, and then start decreasing

NUCLEAR STABILITY: BINDING ENERGY

- Binding energy reaches maximum for nucleus ^{56}Fe
  - Most tightly bound nucleus found in nature
  - Explains why so many ^{56}Fe nuclei are found in GCR



[http://www.schoolphysics.co.uk/]

BINDING ENERGY

- To reproduce Fig (previous page) need to calculate binding energy
- For sake of clarity, first consider how to calculate atomic binding energies before we turn to nuclear case
- Consider neutral atom ^{12}C, which has 6 protons and 6 neutrons in its nucleus and 6 electrons
- One would think that to calculate mass of atom, you just multiply electron mass by 6 and add mass of nucleus
- If you do that you get a mass slightly larger than the observed atomic mass
- Where did missing mass go?
- It was converted to pure energy (via $E = mc^2$) which is called binding energy
- Thus, atomic binding energy is defined as

$$\mathrm{BE}_{\mathrm{atomic}} \equiv -(m_{\mathrm{nucleus}} + Zm_{\mathrm{electron}} - m_{\mathrm{atom}})c^2$$

The masses are measured experimentally

BINDING ENERGY

- For Hydrogen-like atoms (with only one electron in orbit), we have calculated this theoretically as

  $$\mathrm{BE}_{\text{atomic}} \equiv -(m_{\text{nucleus}} + m_{\text{electron}} - m_{\text{atom}})c^2 = -\mathrm{Z} \times 13.6\,\mathrm{eV}$$

  Thus, theoretical calculations of atomic & nuclear binding energies very important area of research because they can be compared to experimental values by measuring masses

- This will be very important in nuclear physics

- However, not so important in atomic physics because binding energies so small & masses not determined accurately

BINDING ENERGY

- The nuclear binding energy is defined as

$$\begin{aligned}\mathrm{BE}_{\mathrm{nuclear}} &\equiv -(\mathrm{Z}m_{\mathrm{proton}} + \mathrm{N}m_{\mathrm{neutron}} - m_{\mathrm{nucleus}})c^2 \\ &= -[\mathrm{Z}(m_{\mathrm{proton}} + m_{\mathrm{electron}}) + \mathrm{N}m_{\mathrm{neutron}} \\ &\quad -(m_{\mathrm{nucleus}} + Zm_{\mathrm{electron}})]c^2 \\ &= -(\mathrm{Z}m_{\mathrm{Hydrogen\ atom}} + \mathrm{N}m_{\mathrm{neutron}} - m_{\mathrm{atomic}})c^2\end{aligned}$$

  where Z = # of protons and N = # of neutrons
- 1st line in this equation makes perfect sense
- However, it is 2nd line usually used in calculations because one generally knows values of atomic masses (tabulated App. A Tipler) rather than nuclear masses
- Note that in 2nd line electron mass cancels out
- That is, there are Z electron masses included in term $\mathrm{Z}\, m_{\mathrm{Hydrogen\ atom}}$ but these get cancelled from electron masses in m_{atomic} term
- 2nd line tiny effects from atomic binding energy neglected

NUCLEAR SIZE

- Electron is truly elementary particle - no one has ever found any other particles inside
- Obviously, nuclei are not elementary because they are made from neutrons and protons
- Neutrons & protons are not elementary either - made of more fundamental elementary particles called quarks
- As far as we know quarks and electrons are elementary particles, in that there is no structure inside
- In modern particle theories they are therefore considered as point particles, which are zero dimensional objects
- Actually, some of the latest theories consider them as tiny strings, or one dimensional objects

NUCLEAR SIZE

- Thus, electrons and quarks have no size
- But protons, neutrons and nuclei do have finite sizes of order of $10^{-15}\,\mathrm{m}$ which is extremely small compared to size of atoms which are about $10^{-10}\,\mathrm{m}$
- Thus nucleons are about 100,000 times smaller than atoms
- Atoms are mostly empty space
- Useful to remember:
  Atomic sizes $\approx \mathrm{\AA} \equiv 10^{-10}\,\mathrm{m}$, Nuclear sizes $\approx \mathrm{fm} \equiv 10^{-15}\,\mathrm{m}$

NUCLEAR SIZE

$$R \approx 1.2\mathrm{A}^{1/3}\,\mathrm{fm}$$

- Nuclei in periodic table have sizes $\approx$ 1 fm - 10 fm

RADIOACTIVITY

- $>$ 3000 nuclides known but only 266 are stable
- All others decay with the emssion of radiation
- Nuclei can decay by emitting alpha (α), beta (β) or gamma (γ) radiation or many other types of decay mechanisms such as fission, proton decay, neutron decay etc
- The most characteristic feature of nuclear radioactivity is that it follows exponential decay law
- This was discovered by Rutherford in 1900
- That is, number of parent nuclei (i.e. the nuclei undergoing decay) drops off exponentially as a function of time according to radioactive decay law,

$$N(t) = N_0 e^{-\lambda t} \tag{1}$$

The form of this equation is due nuclear radioactivity being a purely statistical process

EXAMPLE

Derive exponential decay law by assuming that nuclear radioactive decay is a purely statistical process

For statistical process # nuclei undergoing decay *dN* in a time interval *dt* is just proportional to *dt* and number of nuclei N present. Thus,

$$-dN = \lambda N dt$$

where λ is constant of proportionality. A minus sign is put in front of *dN* because it decreases. Rearranging gives

$$-\frac{dN}{N} = \lambda dt$$

and integration gives

$$\log N = -\lambda t + \text{constant}$$

or

$$N = N_0 e^{-\lambda t}$$

which is equation (1). N_0 is number of nuclei present at time $t = 0$.

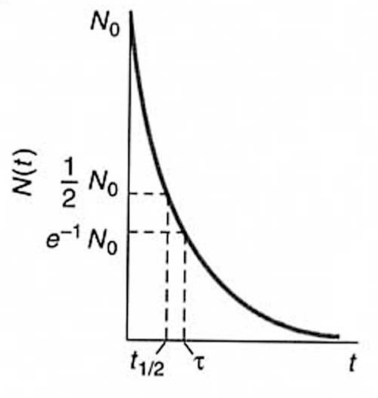
RADIOACTIVITY

$$N = N_0 e^{-\lambda t}$$

- $N(t)$ = # of parent nuclei remaining at time t
- N_0 = # of original parent nuclei, i.e. # at time $t = 0$
- Some nuclei decay very quickly & some decay very slowly
- Good question to ask is how long does it take for a sample of radioactive nuclei to decay away completely, so that there are none of original parent nuclei left
- Thus, we want $N(t) = 0$ which corresponds to $t = \infty$
- Now even though this is correct it is not very helpful
- Tells us that no matter whether nuclear sample decays quickly or slowly, it will always take an infinite time for quick or slow sample to disappear completely

RADIOACTIVITY

- Reason we get this is due to exponential nature of decay
- Figure - takes infinite time for nuclei to completely disappear



Exponential radioactive decay law. Number of nuclei remaining at time t decreases exponentially with time t. Half-life $t_{1/2}$ and mean life or lifetime $\tau = 1/\lambda$ are indicated.

[Tipler & Llewellyn, Modern physics, 3rd ed., Freeman, New York, 1999]

RADIOACTIVITY

- More useful question to ask is how long does it take for half of original parent nuclei to disappear?
- Reason this is better is because answer is different depending on whether nuclei decay quickly or slowly
- *Half life* $t_{1/2}$ *of a radioactive sample is time it takes for half of sample to decay*
- So far proportionality constant λ is left unspecified, but it can be written in terms of the half life
- Instead of using 1/2 life could use any other fractional life
- Another common one is the time it takes for number of nuclei to drop to $1/e$ of original number
- The lifetime or mean life τ of a radioactive sample is time it takes for $1/e$ of sample to decay

EXAMPLE

Express proportionality constant λ in terms of the half life

When $t = t_{1/2}$ we have

$$N(t = t_{1/2}) = \frac{1}{2}N_0$$

Thus,

$$N(t = t_{1/2}) = \frac{1}{2}N_0 = N_0 e^{-\lambda t_{1/2}}$$

giving

$$\begin{aligned} \log\frac{1}{2} &= -\lambda t_{1/2} \\ = & \quad -0.693 \end{aligned}$$

Thus,

$$\lambda = \frac{0.693}{t_{1/2}}$$

EXAMPLE

Express proportionality constant λ in terms of the mean life ($\equiv$ lifetime)

When $t = \tau$ we have

$$\begin{aligned} N(t=\tau) &= \frac{1}{e} N_0 \\ \Rightarrow \quad N(t=\tau) &= e^{-1} N_0 = N_0 e^{-\lambda\tau} \\ \Rightarrow \quad 1 &= \lambda\tau \\ \Rightarrow \quad \lambda &= 1/\tau \end{aligned}$$

Thus, another way to write radioactive decay law is

RADIOACTIVE DECAY LAW

$$N(t) = N_0 e^{-\lambda t} = N_0 e^{-0.693 \frac{t}{t_{1/2}}} = N_0 e^{-t/\tau}$$

RADIOACTIVITY: COUNTING RATE

- Suppose one wants to measure half life or lifetime of a radioactive sample
- One could measure number of parent nuclei present at a particular time and then calculate the half life or lifetime
- However, number of nuclei present as a function of time is rather difficult to measure
- What is much easier to measure is counting rate $R(t)$ as a function of time
- Counting rate defined as

$$R(t) \equiv -\frac{dN}{dt}$$

which is number of atoms dN decaying in a time dt

RADIOACTIVITY: COUNTING RATE

- One can easily show that counting rate follows same exponential decay law as encountered previously

COUNTING RATE

$$R(t) \;=\; R_0 e^{-\lambda t} = R_0 e^{-0.693 \frac{t}{t_{1/2}}} = R_0 e^{-t/\tau}$$

- To get half life just hold radiation counting detector next to radioactive sample & plot number of counts as function of time
- From graph, you can get half life
- Counting rate has some special units
- *curie* (Ci) is defined as disintegration rate of 1g of radium;
  1 Ci = 3.7 × 10^{10} decays/s
  The SI unit of activity is *becquerel* (Bq) defined as
  1 Bq = 1 decay/s $\Rightarrow$ 1 Ci = 3.7 × 10^{10} Bq

ALPHA, BETA & GAMMA DECAY

- About 3000 different nuclides have been produced in laboratory and only 266 of these are stable
- It is estimated that there are about 2000 more unstable nuclei that can be produced
- Many different decay modes available to unstable nuclei such as α, β, γ decay and also p emission, n emission, fission and double beta decay (not yet observed)
- We concentrate on decay modes α, β, γ
- First noticed by Rutherford, who characterized them by their *range* in passing through matter
- He found three groups of decays; ptcles in α decay were least penetrating & γ decay was most penetrating
- It was later found that α particles are actually He nuclei, and β particles are actually electrons
- γ particles were found to be very energetic photons

ALPHA, BETA & GAMMA DECAY

- These three types of radiation correspond to three fundamental forces of nature, excluding gravitation

- α decay is due to Strong nuclear force
  β decay is due to Weak force
  γ decay is due to EM force

- All of this was discovered much later

- It is possible to theoretically predict that about 5,000 nuclei can be created in laboratory

- So far 3,000 have been created and 266 occur naturally

SUMMARY

- Discoveries
  - X rays - Röntgen, 1895
  - Discovery of Radioactivity - Becquerel, 1896
  - Discovery of Electron - J.J. Thomson, 1897
  - Discovery of Nucleus - Rutherford, 1911

- Radiation α, β, γ

$\alpha \equiv {}^4\text{He}$	easily absorbed
$\beta \equiv \text{e}^-$	more penetrating
γ	very penetrating

- Radioactive Decay Law

$$N(t) = N_0 e^{-\lambda t} = N_0 e^{-0.693 \frac{t}{t_{1/2}}} = N_0 e^{-t/\tau}$$

THE END

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