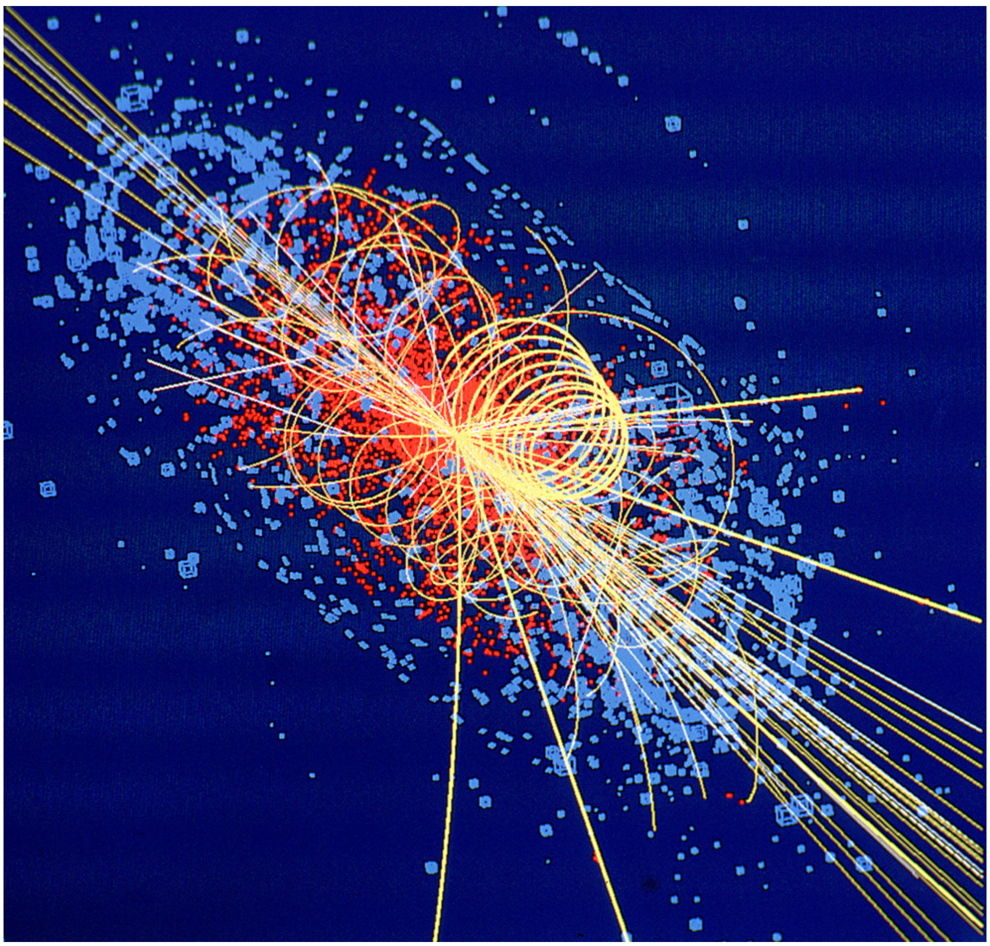
Module 8: From the Universe to the Atom

Part 5: Deep inside the atom



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Contents

Cover photo credit: Computer simulation of particle traces from an LHC collision in which a Higgs Boson is produced. CERN. Image credit: Lucas Taylor

Syllabus content: From the Universe to the Atom

Structure of the Atom

Inquiry question: How is it known that human understanding of matter is still incomplete?

Students:

- analyse the evidence that suggests:
  - that protons and neutrons are not fundamental particles
  - the existence of subatomic particles other than protons, neutrons and electrons
- investigate the Standard Model of matter, including:
  - quarks, and the quark composition hadrons
  - leptons
  - fundamental forces (ACSPH141, ACSPH142)
- investigate the operation and role of particle accelerators in obtaining evidence that tests and/or validates aspects of theories, including the Standard Model of matter

Evidence for particles other than protons, neutrons and electrons

Evidence for the existence of particles other than protons and electrons came rapidly from the 1930s onwards. We have already examined Chadwick's discovery of the neutron in 1932.

Discovery of the positron

In 1930 a British theoretical physicist, P.A.M. Dirac, developed an equation which unified special relativity and quantum theory. The problem (as was the initial view among physicists) was that Dirac's equation predicted the existence of electrons with positive charge. The situation at the time was elegant and simple, two known fundamental particles, protons and electrons were the building blocks of matter (the discovery of the neutron was to come two years later). However, in 1931 Anderson discovered a positive electron in an image from a cloud chamber, identified because its curvature in a magnetic field was in the opposite direction to an electron.

Yukawa's pion

In 1934, Japanese physicist Hideki Yukawa predicted the existence of a new particle, in addition to the neutron, proton, electron and positron that were known at the time. Yukawa's idea was that we can describe the force that acts between particles in terms of the exchange of another particle, (now) called a gauge boson. Yukawa proposed that the strong force was only short range as it is mediated by the exchange of a particle with mass (now called a pion), whereas the electromagnetic force was infinite in range as it is mediated by the exchange of a massless particle, the photon[1].

[1] Pais, A. (1986). Inward Bound: Of matter and Forces in the Physical World. (New York: Oxford University Press).

By studying the collisions of cosmic ray particles (high energy particles from the solar wind which collide with the atmosphere of earth), scientists found a new particle in the tracks left in a cloud chamber in 1937. It was soon realised, however, that the particle observed did not have the expected properties of Yukawa's pion (the tracks were much too long for a particle that interacted with matter via the strong nuclear force), and remained a mystery for some time. We now call this particle a muon, and know that it belongs to the same family as electrons and neutrinos in the standard model.

In 1946 a new technique using photographic plates was developed by Occhialini and Powell in Bristol which allowed much more sensitive detection of particles present in cosmic rays, and this group found evidence for Yukawa's pion[2].

[2] Segré, E. (1980) From X-rays to Quarks: Modern Physicists and Their Discoveries (Mineola, New York: Dover Publications)

Discoveries of many more exotic particles followed, such as K^0 and $K^{\pm}$. The technique had the advantage that it was very cheap, but it required painstaking work (usually done by young women) using a microscope to find events of interest on the photographic plate. In post-war Europe labour was cheap and the technique was widely used. The disadvantage of relying on cosmic rays was that it was a matter of serendipity what one was able to detect, and often interesting events were not able to be duplicated.

More reliable sources of high energy particles were obtained with the development of accelerators in the late 1940's.

Evidence that protons and neutrons are not fundamental particles

Once the atom was found to be constituted of electrons and protons (and later neutrons in 1932) the natural question to ask was whether these particles were themselves fundamental?

Evidence from theoretical considerations

As the number of new particles discovered continued to increase in the 1940s and 1950s, from a theoretical view is seemed very unlikely that all these particles were fundamental. Physicists began to catalogue particles to find similarities or patterns in their properties, identifying "families" of particles including *baryons*, such as protons and neutrons, *mesons* such as the pion, and *leptons*, such as electrons and muons.

In 1964 Murray Gell-Mann and George Zweig postulated that all mesons and baryons consisted of either three (for baryons) or two (for mesons) of a more fundamental type of particle they called 'quarks'. Initially it was thought that only three types of quarks could account for all particles, but as more particles were discovered it was realised that six quarks (and their antiparticles) were required.

Evidence from experiment

One predicted property of quarks is that they are never found in isolation, but only confined inside baryons or mesons, so that they are not able to be observed individually. Nonetheless, experimental evidence for the existence of quarks (and so for the proposal that protons and neutrons are not fundamental) was obtained in the late 1960s through high-energy electron collisions with hydrogen and deuterium at the Stanford Linear Accelerator Center[3]. In a very similar way that Geiger and Marsden probed the structure of the atom through the use of high energy alpha particles, in these experiments high energy electrons were deflected in collisions with protons with scattering angles that were consistent with their interaction with

[3] A brief overview is given by CERN here: `https://home.cern/news/news/physics/fifty-years-quarks`, a full-text version of the paper "The discovery of Quarks" *Science*, Vol 256, pg. 1287 (1992) by Michael Riodan is available here `https://s3.cern.ch/inspire-prod-files-9/90ba9674ad34bb45f161327cb8cbf442` (preprint) and here: `https://www.jstor.org/stable/2877300` (JSTOR)

point-like particles within the proton - providing support for the suggestion that the proton is composed of quarks.

The standard model

Murray Gell-Mann and George Zweig's original theory contained three new fundamental particles called 'quarks'[4]. The three quarks, named 'up', 'down' and 'strange', were sufficient to explain all types of particles then discovered. Later, in 1974, simultaneous discoveries at the Brookhaven National Laboratory (BNL) and the Stanford Linear accelerator center (SLAC) of a new type of particle required the addition of a forth quark, the 'charm' quark, and since then an additional two have been discovered, the 'top' and 'bottom' quarks.

The standard model of matter proposes that there are three types of fundamental particles that comprise all matter, leptons, quarks and gauge bosons (which mediate interactions between particles).

[4] Gell-Mann called named them after a nonsense rhyme from a James Joyce novel, "three quarks for Muster Mark".

Leptons

There are six leptons "flavors", grouped in three "generations", the electron, the electron neutrino, the muon, the muon neutrino and the tau (discovered at the SLAC in 1977) and the tau neutrino, as well as six corresponding antiparticles.

Leptons spin =1/2

Flavor		Mass GeV/c^2	Electric charge
ν_L	lightest neutrino*	$(0-2)\times10^{-9}$	0
e	electron	0.000511	–1
ν_M	middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ	muon	0.106	–1
ν_H	heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ	tau	1.777	–1

Figure 1: Leptons in the standard model. Image credit: Contemporary Physics Education Project (CPEP). CPEP grants permission for copyright images to be used in the classroom.

Quarks

There are six quark flavors, also grouped in three generations, 'up', 'down', 'strange', 'charm', 'top' and 'bottom', as well as corresponding antiparticles. These fundamental particles are the building blocks of hadrons (baryons and mesons) and have fractional electric charge.

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

Figure 2: Quarks in the standard model. Image credit: Contemporary Physics Education Project (CPEP).

Gauge bosons

In addition to six quarks (and six anti-quarks) and six leptons (and six anti-leptons), the standard model predicts the existence of four types of gauge bosons, particles that mediate interactions between particles (that is, produce forces). For the strong force, responsible for holding quarks together inside baryons and mesons, this force carrier is known as a gluon. For the weak force, there are three, W^+, W^- and Z^0, discovered at CERN in 1983. For the electromagnetic force there is the photon. For the force of gravity, it is predicted that there exists a force carrier called a graviton, but this has not yet been detected experimentally.

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

Higgs Boson spin = 0		
Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Figure 3: Gauge bosons in the standard model. Image credit: Contemporary Physics Education Project (CPEP).

Higg's boson

The Higgs field (of which the Higgs boson is an 'excitation'), was discovered in 2013 at CERN in both the ATLAS and CMS experiments. It is predicted by the standard model as the mechanism by which all fundamental particles gain mass. Its successful detection was a major experimental confirmation of the predictions of the standard model.

Baryons

Baryons are composite particles composed of three quarks, each with a different color charge. The combination of three quarks with different colors (known as 'red', 'blue' and 'green', but not at all related to actual colour) can combine to make a colour neutral particle (in analogy to the way three colours of light can combine to give white light). All known composite particles are colour neutral. Examples of baryons are protons (composed of two 'up' quarks and one 'down' quark) and neutrons (composed of two 'down' quarks and one 'up' quark).

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Figure 4: A few types of baryons. Image credit: Contemporary Physics Education Project (CPEP).

Mesons

Mesons are also composite particles, are composed of a quark-antiquark pair. The combination of a color of a given colour and an antiquark carrying the corresponding anti-colour is also color neutral. An example of a meson is Yukawa's pion, discussed earlier, which consists of an 'up' quark and an 'anti-down' quark.

Mesons $q\bar{q}$
Mesons are bosonic hadrons
There are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Figure 5: A few types of mesons. Image credit: Contemporary Physics Education Project (CPEP).

Summary of the fundamental particles in the standard model: CERN

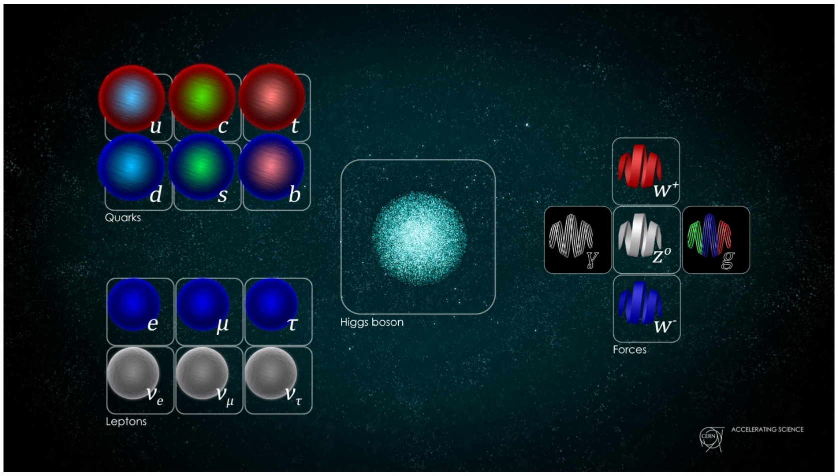

Figure 6: Particles of the Standard Model. Image credit: Daniel Dominguez/CERN

Particle accelerators

Definitions

An accelerator is a machine used to accelerate particles to high speeds (and thus high energy). A collider is an accelerator in which two beams traveling in opposite directions are steered together to provide high-energy collisions between the particles in one beam and those in another. The basic elements of an accelerator, a beam in an evacuated tube, a target and a detector, have been used since Geiger and Marsden's famous 'gold-foil' experiment, the pattern of scatterings from which Rutherford could interpret as evidence of a small, dense nucleus. In that experiment, the beam was produced by the natural alpha decay which produced relatively low-energy helium nuclei. To gain more evidence about the internal structure of the nucleus and the forces holding it together, it was necessary to turn to particles with more energy. The reason is two-fold. Firstly, particles with higher energies have the potential to produce particles with larger mass in collisions (as $E = mc^2$). Secondly, higher energy particles have a smaller de Broglie wavelength, and so can be used like a microscope to probe on a smaller scale (as resolution is proportional to wavelength), they can also approach the nucleus more closely before being deflected[5].

[5] Barnett, R. Michael., MÃijhry, Henry., Quinn, Helen R., (2000). The charm of strange quarks (Springer-Verlag, New York).

Approach to detecting particles

Detectors in particle accelerators work on the principle of observing an ionisation path of a charged particle (a tracking chamber), or on the principle of detecting the transfer of energy to another material (calorimeters). Using the tracks they can see (produced by charged particles), magnetic fields to deflect charged particles in an arc with a radius that depends upon their speed and mass, and the principles of conservation of momentum, conservation of (mass-)energy and other conservation laws that have been discovered over the past few decades (conservation of lepton number and baryon number) physicists can determine what particles must have been made in any collision (called an event), and so discover new particles.

Types of particle accelerators

In accelerators it is always electric fields which are used to increase the speed of charged particles, and magnetic fields which are used to focus and guide the beams.

Electrostatic accelerators

The earliest and simplest accelerators were cathode ray tubes[6], where an electric field is used to accelerate electrons to a speed of around 20% the speed of light.

[6] Barnett, R. Michael., MÃijhry, Henry., Quinn, Helen R., (2000). The charm of strange quarks (Springer-Verlag, New York).

Linear accelerators (LINACs)

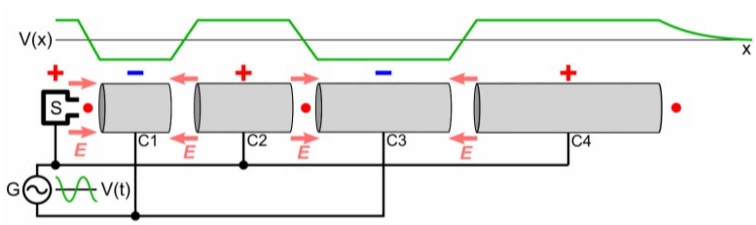

Figure 7: Accelerator tube animation for a LINAC. Image credit: Wikipedia `https://commons.wikimedia.org/wiki/File:Linear_accelerator_animation_16frames_1.6sec.gif`

To achieve higher particle energies a sequence of electrostatic accelerators can be used. The usual structure is a series of cylinders separated by a disk with a hole to allow the beam to pass through. The electric field from a pulse of microwave radiation is timed to accelerate particles at the right place in each cavity (see figure 7). Particles arriving early receive less than average acceleration and those arriving late receive higher than average acceleration, so that particles are maintained in "bunches". In the SLAC (stanford linear accelerator, figure 8) electrons or positrons can be accelerated to an energy of $50 GeV$ (so they are travelling at 90% the speed of light).

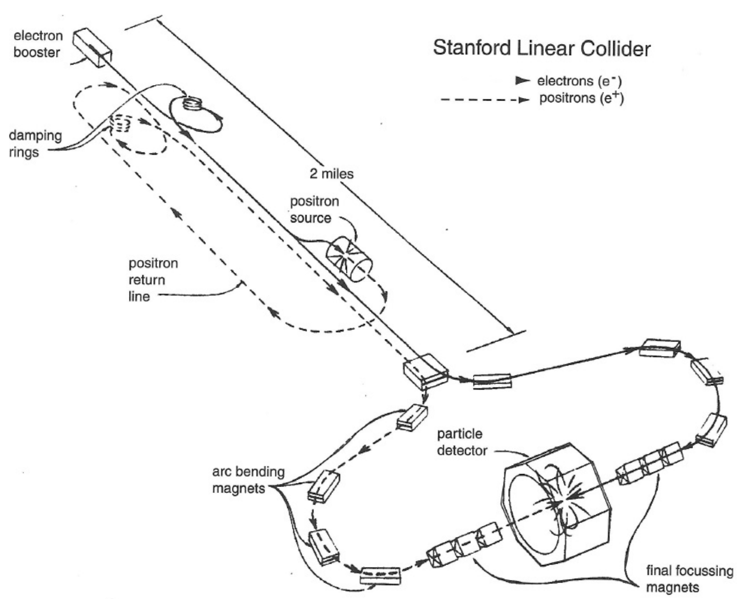

Figure 8: Stanford Linear Accelerator. Image credit: Wikipedia

Cyclotrons

In cyclotrons, charged particles in the center of the machine are accelerated across an electric field which is produced between two hollow metal plates (called 'dees' as their shape resembles the letter 'D'). A vertical magnetic field then steers the particle in a semicircle until it again passes between the dees, where the electric field direction has been switched so that it is again accelerated. This process continues until the particles, now travelling at very high speeds, emerge as a beam.

Cyclotrons can produce continuous beams of particles by using the fact that the period for a charged particle circling in a magnetic field is independent of its speed (for non-relativistic speeds), which means that the frequency used for switching the electric field across the dees can be the same for particles travelling slowly in the center of the dee as well as those travelling very fast towards the perimeter of the dees. The independence of the period and the speed of the particles follows from

$$\frac{mv^2}{r} = qvB$$

and

$$v = \frac{2\pi r}{T}$$

By eliminating the velocity of the particle from the two expressions, an expression can be obtained for the period of the particle in the cyclotron that is independent of the speed of the particles, as long as the speed is not relativistic (i.e. that the mass is independent of the speed).

$$T = \frac{2\pi m}{qB}$$

Cyclotrons can be used to accelerate particles to around $40MeV$, but for higher energies (where speeds are relativistic), a different type of accelerator, called a *synchotron* is required.

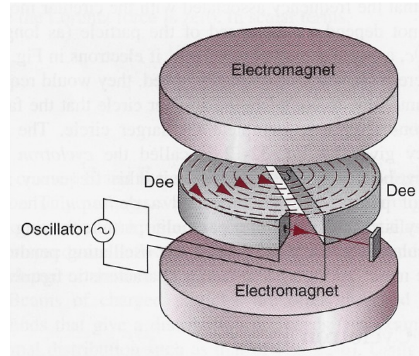

Figure 9: Diagram of a cyclotron. Image credit: Halliday, D., Resnick, R. Krane, K.S., (1960). Physics: Volume 2 (5th Ed. New York: John Wiley Sons, Inc.)

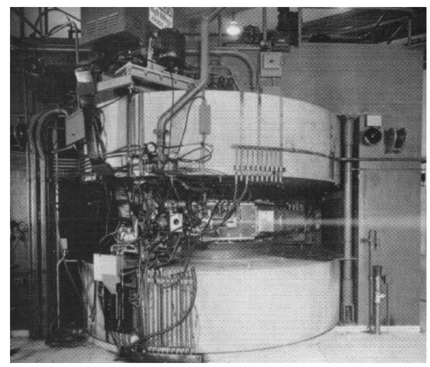

Figure 10: A cyclotron in which the emerging beam of particles is visible as it ionises the air molecules. Image credit: Halliday, D., Resnick, R. Krane, K.S., (1960). Physics: Volume 2 (5th Ed. New York: John Wiley Sons, Inc.)

Synchotrons

Synchrotrons are circular accelerators. The beam travels in an evacuated pipe and is steered and kept focused by the magnetic field of electromagnets placed around the ring. The increase in speed of the particles is produced by pulses of microwaves (RF frequency radiation) in cavities, in a similar way to Linacs[7]. The charged particles in a synchrotron traverse the ring millions of times and are accelerated by the RF cavities each time, unlike a linear accelerator where they pass through the sequence of cavities only once. Synchrotrons can be used to accelerate and store high energy particles for use in "colliding beam" experiments or extracted for use in "fixed-target" experiments.

[7] Barnett, R. Michael., M uhry, Henry., Quinn, Helen R., (2000). The charm of strange quarks (Springer-Verlag, New York).

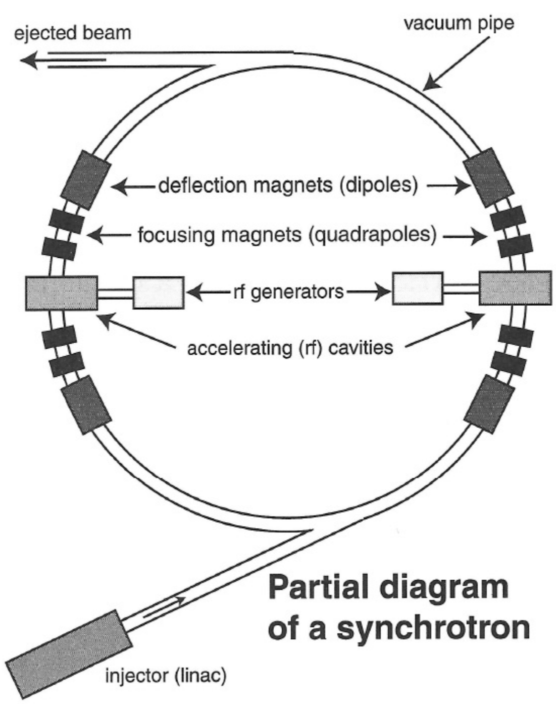

Figure 11: Synchotron. Image credit: Barnett, R. Michael., MÃijhry, Henry., Quinn, Helen R., (2000). The charm of strange quarks (Springer-Verlag, New York).

Two effects limit the energies achievable with a synchrotron of a given radius.

- All charged particles emit electromagnetic radiation when they accelerate. When travelling in a circle they are continuously accelerated towards the center of the circle and so are continually emitting radiation as a result (known as 'synchrotron radiation'). This limits the energy that particles can attain for a given radius (a larger radius mean less acceleration is required for a given speed, $a_c = \frac{v^2}{r}$). The problem is more serious for electron/positron synchrotrons than proton synchrotrons as the much larger mass of the protons means they can carry higher energies for any given speed.

- There is a limit to the magnetic field strengths that can be achieved with superconducting magnets, as running too high currents through them can raise the magnetic field beyond the critical value and send the material into its normal state (causing sudden massive ohmic heating as the resistance becomes high, and so a sudden boiling of the liquid helium used to cool the magnet and potentially a large explosion!). This limit on magnetic field strength means a limit on the radius of curvature that can be achieved (as the centripetal force to bend the beam of charged particles is supplied by the magnetic force).

Some synchrotrons are specifically designed to be a source of sychrotron radiation, such as the Australian synchroton in Melbourne, Victoria. In this facility, intense beams of X-rays are produced by electrons accelerated around the sychrotron, which are used for generating images and elemental, structural and chemical information from diverse sample types ranging from biological to industrial materials. The broad range of available wavelengths allow scientists to look at the size and shape of macromolecules and voids in bulk materials, peer into the biochemistry of single cells and delve all the way down to the bonds between atoms[8].

[8] From: Australian Synchrotron Light Source fact sheet. Downloaded from: `www.synchrotron.org.au/images/stories/aboutus/machine-factsheet_23oct08_final.pdf`

The role of particle accelerators in testing theories

How accelerators (and colliders) test theories

During a collision, the kinetic energy of the particles in the accelerator or collider can be converted to mass. In the case of particle-antiparticle collisions in which the particles annihilate, the entire energy of the particles is available for conversion to mass.

Accelerators and colliders are therefore able to test theoretical predictions of the existence of massive unstable particles that are not able to be otherwise observed due to their rapid decay into smaller particles. The energy of particles in the accelerator or collider is adjusted to the particular energy required to make a particle of the predicted mass.

The properties of the particles created during the collision, such as their path, energy and momentum are recorded in detectors surrounding the collision chamber [9]. If the particles are highly unstable any immediately decay into other particles, then conservation laws such as conservation of momentum, conservation of energy (mass-energy), conservation of lepton and baryon number are used to "work backwards" to deduce the particle originally created in the collision.

For example, the Higgs boson (an excitation of the Higgs field) was identified in 2013 in collisions in the LHC at CERN at an energy of $125 GeV$ [10]. Theoretical predictions for the decay products of the Higgs boson had been made (which depended upon its mass). When decay products characteristic of the Higgs boson were observed independently in two different detectors (CMS and ATLAS) scientists were able to confirm its discovery. Aspects of the behaviour of the Higgs continue to be predicted and then tested and verified at CERN. It had been predicted to decay into two bottom quarks with a probability of 60%. This has been confirmed in recent (2018) observations of the decay of the Higgs at CERN[11].

[9] e.g. `https://home.cern/science/experiments/atlas`

[10] `https://atlas.cern/updates/atlas-feature/higgs-boson`

[11] `https://atlas.cern/updates/press-statement/observation-higgs-boson-decay-pair-bottom-quarks`

A brief history of particle accelerators

After the end of the second world war and the Manhattan project a new respect for physics facilitated the development of new, 'big' nuclear physics research projects[12].

[12] Pais, A. (1986). Inward Bound: Of matter and Forces in the Physical World. (New York: Oxford University Press).

- Several cyclotrons were commissioned in the US, including one at Berkeley in 1946 which produced deuterons with energies of 190MeV and a particles with energies of 380MeV.
- In Europe, the first accelerator at CERN was commissioned in 1957 with an energy of 600MeV. The first observations of antinuclei (antprotons and anti-neurtons combined to form an anti-deuterium nucleus) were made here and in the AGS at Brookhaven lab simultaneously.
- The cosmotron was a proton synchrotron built at Brookhaven National Labs (BNL) in 1953 which was the first accelerator to reach GeV. In 1960 it was replaced by the alternative gradient synchrotron (AGS) reaching 33GeV, just higher than the proton synchrotron at CERN at the time.
- The Stanford Linear Accelerator Center (SLAC) was commissioned in 1966 with an energy of 17GeV, which was gradually increased to 50GeV by the 1980's. Responsible for the discovery of the J/Psi particle and the tau lepton.
- CERN - development of the Super Proton Synchrotron with an energy of 400GeV in 1976. In 1983 this was converted into a proton-antiproton collider, which was responsible for the discovery of the $Z^{\pm}$ and Z^0 particles.
- CERN - In 2000 work on the Large Hadron collider commenced, and was only finished in 2008. This was eventually used to discover the Higgs boson in 2013.