Class Notes for Modern Physics, Part 4
Some topics in Modern, Modern Physics

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Introduction

Everything we have talked about at any depth so far was part of the development of physics roughly pre-1930 or so. But, of course a lot has happened since then.

1. There was ever increasing understanding of statistical physics based on bose and fermi statistics for integer and half integer spin objects.

2. Increased understanding of molecular structures, bonding and dynamics was rapidly developed.

3. Solid state physics developed rapidly. Much was and still is being learned about how metals form, have quantum mechanically determined energy "bands", and so forth.

   Especially important was the development of a thorough understanding of semiconductors and related devices as well as the discovery and eventual (at least partial) understanding of superconductivity.

4. **Lasers are based upon coherent wave phenomena as well as semiconductor physics and have become a part of everyday life.**

5. **Nuclear physics was developed, eventually leading to the fission and fusion bombs and nuclear energy, which, although we may not like it, is likely to be an energy source to which we must increasingly turn.**

6. **And, finally, there are the areas of cosmology and elementary particle physics in which we work on understanding the inner structure of matter, e.g. what is inside a proton, what are the actual carriers of forces, what is dark energy, what is dark matter.**

It is the last two items that I will try to say a few words about in these final two lectures.

Nuclear Structure and Reactions

Recall that Rutherford's α scattering experiments showed that the nucleus is very small despite the fact that there is Coulomb repulsion of the protons inside the nucleus (I will try to avoid the bushisms of nuculous and nucular).

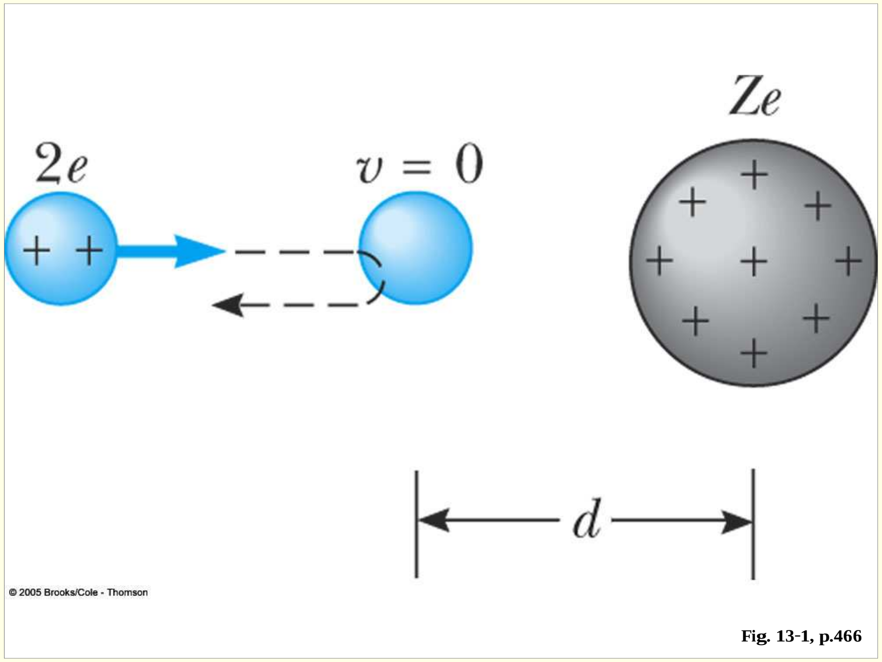


Figure 1: The Rutherford experiment establishing the size of the nucleus by when the alpha particle penetrates into the nucleus and its scattering no longer obeys the simple formula.

This means that there has to be a new force, the nuclear force which holds the protons (and the neutrons) together to form the nucleus. It turns out that this nuclear force is a remnant of an even stronger force that I will discus next lecture called the strong force.

Standard nuclear notation is ${}^{A}_{Z}X$ where $Z =$ number of protons, $A = Z + N$ is the atomic number, N is the number of neutrons. For example, ${}^{56}_{26}Fe$ denotes the isotope of iron with 26 protons, 30 neutrons.

Often a so-called unified mass unit u is employed and is defined by

$$M({}^{12}C) = 12\ u\,, \quad exactly! \tag{1}$$

The conversion is

$$1\ u = 1.66 \times 10^{-27}\ kg = 931.5\ MeV/c^2\,. \tag{2}$$

We have

$$m_p = 1.007276\ u, \quad m_n = 1.008665\ u\,. \tag{3}$$

Note that the neutron is heavier than the proton.

Recall the Rutherford experiment that looked for deviations from Coulomb scattering to determine the nuclear size. A typical result for silver or gold is

$$r \sim 10\ fm = 10^{-14}\ m\,. \tag{4}$$

Further experimentation reveals that larger nuclei are typically quite spherical and have a radius given by

$$r = r_0 A^{1/3}\,, \quad r_0 = 1.2 \times 10^{-15}\ m\,. \tag{5}$$

The $A^{1/3}$ makes sense since it implies that the density given by

$$\rho_n \equiv \frac{A}{V} = \frac{A}{\frac{4}{3}\pi r^3} \simeq 2.3 \times 10^{17}\ kg/m^3 \tag{6}$$

(which, by the way, is *a very big number***) is roughly independent of the type of nucleus.**

Because of the $A^{1/3}$, nuclear radii only increase slowly with A:

$$\frac{R(^{238}U)}{R(^{4}He)} = \frac{(238)^{1/3}}{(4)^{1/3}} \sim 4\,. \tag{7}$$

So, the picture is that the nuclear force produces a kind of tight-packed spherical collection of protons and neutrons that do not easily penetrate into one another's territory but are held very close to one another.

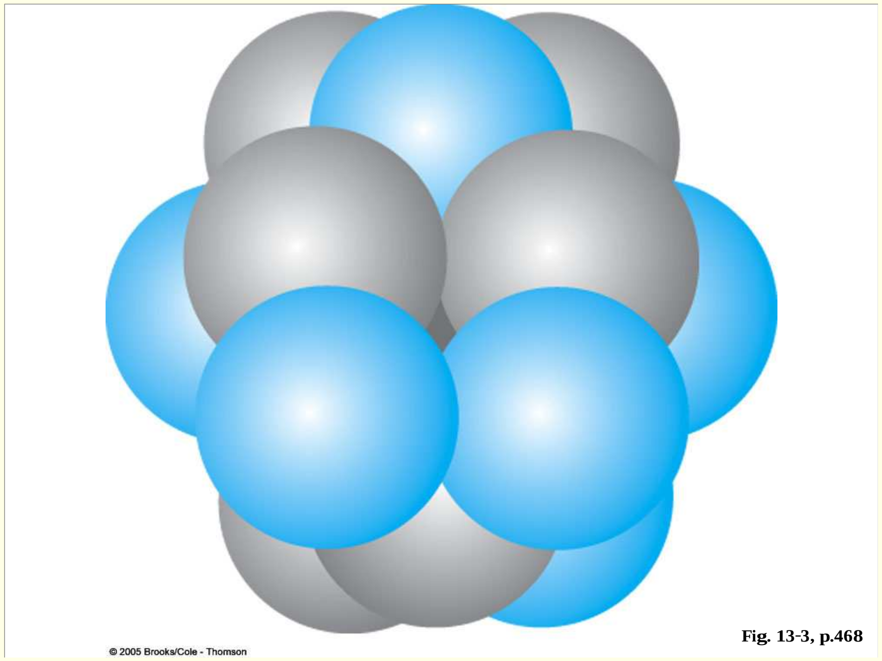


Figure 2: A picture of the nucleus.

At this point, you might ask the question: "are the neutrons and protons themselves truly elementary". After all, the neutron and proton each seems to have a size of order $r_0 \sim 1\ fm$. If they are truly elementary, why should we see an observable size?

So, you will not be surprised to learn in the next lecture that the proton and neutron are both composite objects consisting of **quarks** orbiting

around one another and held together by a force coming from gluons. The result is a kind of mini-atom-like formation, a situation that comes with a certain amount of separation.

Notes on Nuclear Stability

- **There are more than 400 stable nuclei.**
- **They are all held together by the nuclear force that acts between neutrons and protons and that has a range of about $2\ fm$.**
- **Light nuclei are most stable for $N \simeq Z$.**
- **Heavy nuclei are most stable for $N > Z$.**
- **The reason for the above is that as you add protons, you increase the repulsive Coulomb interactions.**

  As you add neutrons, there is no increase in Coulomb repulsion but the extra nuclear force between the additional neutrons and protons yields more binding.

  However, for $Z > 83$, no amount of neutrons can stabilize the nucleus.
- **The most stable nuclei have $A = even$. All but eight have $Z = even$ and $A = even$.**

- **The most stable nuclei have**

$$Z\ or\ A = 2, 8, 20, 28, 50, 82, 126 \tag{8}$$

This comes from the fact that the p's and n's have spin-$1/2$ and obey the Pauli Exclusion principle and thus fit into nuclear shells

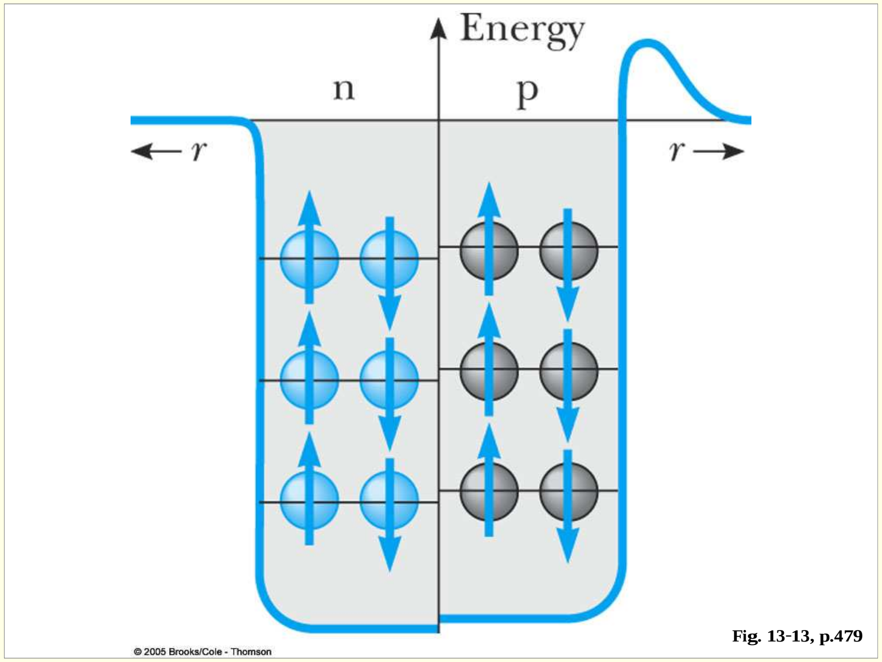


Figure 3: The nuclear shell picture.

Each shell can contain a proton with spin up, a proton with spin down, a neutron with spin up, and a neutron with spin down, which is to say 4 nucleons.

The proton energy levels are slightly above the neutron shell energy levels because of the extra Coulomb repulsion.
Helium with $2p$ and $2n$ is very stable because the lowest proton shell and lowest neutron shell are both filled and maximal advantage can be taken of the very strong binding of the nuclear force when a bunch of nucleons are together *without going to the next shell level*.
Another example is to compare ${}^{12}_{5}B$ to ${}^{12}_{6}C$ (*i.e.* same A, but different Z). The latter is a much more stable nucleus because in ${}^{12}_{5}B$ the extra neutron must move to the next shell whereas in ${}^{12}_{6}C$ the extra proton fits into the remaining slot in the 3rd shell very nicely.

- So, just when is a nucleus stable or unstable?
  Stability requires (at the very least)

$$M_{nucleus} < Zm_p + Nm_n \,. \tag{9}$$

Binding energy is defined by

$$\Delta mc^2 = (Zm_p + Nm_n - M_{nucleus})c^2 \,. \tag{10}$$

Unless Δm is positive, the nucleus would find it energetically favorable to split into separate protons and neutrons.

And, in quantum mechanics, tunneling implies that if something is energetically favored, it will eventually happen, even if there is some barrier temporarily restraining the ultimate decay.

Example The binding energy of the deuteron.

The deuteron is a stable nucleus consisting of one proton and one neutron. We have

$$m_D = 2.014102\ u, \quad m_p = 1.007276\ u, \quad m_n = 1.008665\ u \tag{11}$$

which leads to

$$\Delta m = (m_p + m_n) - m_D = 0.002388\ u \simeq 2.224\ MeV/c^2\,. \tag{12}$$

To split a nucleus apart, you must supply

$$E_b(MeV) = [Zm_p + Nm_n - M({}^A_Z X)] \times 931\ MeV/u \tag{13}$$

- A plot of binding energy per nucleon as a function of A is below.

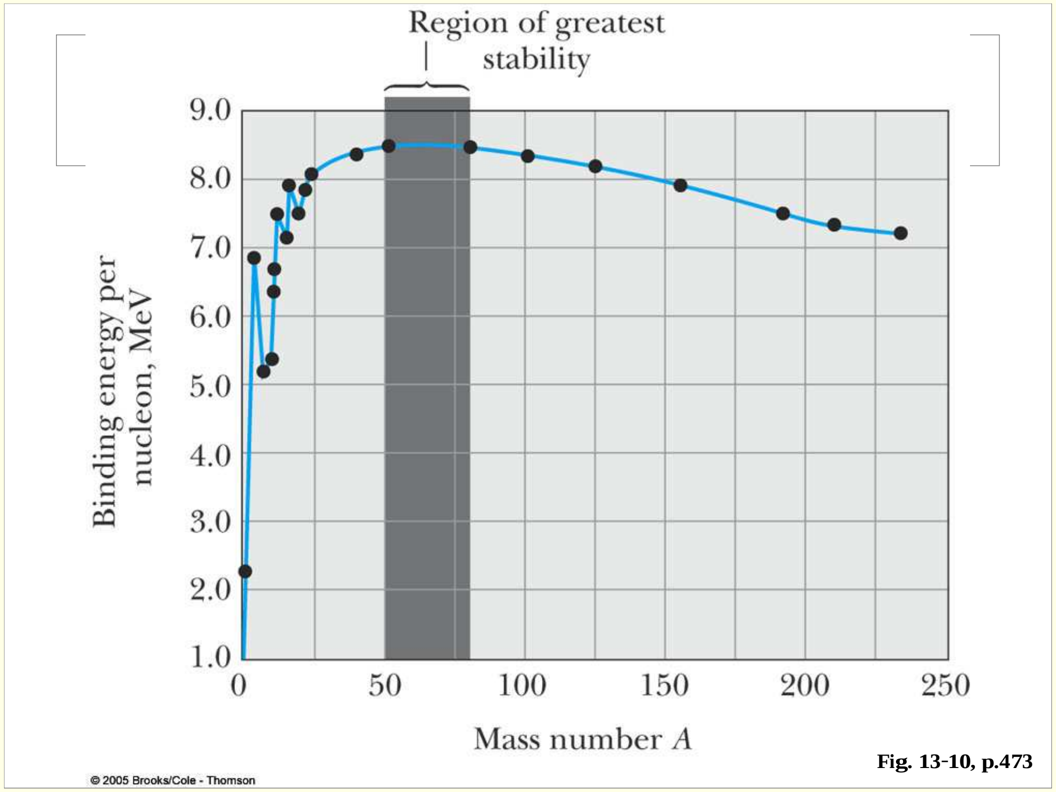


Figure 4: Binding energy per nucleon.

There are two things to observe:

(a) The fairly flat nature of the curve at large A.

This is known as saturation. Each additional nucleon can only interact with its closest neighbors and so the binding energy added when adding a nucleon is always about the same.

Also, the nuclear force and binding, aside from the shell issues described earlier, is more or less the same for neutrons and protons (as depicted in the earlier shell picture). This is called charge-independence of the nuclear force.

(b) The slow decrease at large A is because of increasing Coulomb repulsion among the protons.

This is what makes fission reactions possible. See later example.

Another Example

You may recall the question asked in class concerning why a nucleus would decay to an α particle (i.e. the He nucleus) rather than to just a proton or neutron.

The answer is in the above figure and the descriptive discussion above. In particular, note the huge peak in the binding energy curve associated with $A = 4$ at $7\ MeV$ per nucleon. The first shell of the nuclear shell model is just completed and the 4 nucleons are able to benefit maximally from their nuclear/strong attraction to one another. Thus, something like ^{226}Ra with binding energy per nucleon of around $7.3\ MeV$ likes to decay to ^{222}Rn which (see curve) has higher binding energy per nucleon and ^{4}He which has binding energy per nucleon of nearly $7\ MeV$. The actual Q for this decay is

$$\begin{aligned} Q &= (M_{Ra} - M_{Rn} - M_{\alpha})c^2 \\ &= (226.025406 - 222.017574 - 4.002603)\ u \times 931.494\ \frac{MeV}{u} \\ &= 0.005229\ u \times 931.494\ \frac{MeV}{u} = 4.87\ MeV\,, \end{aligned} \tag{14}$$

a rather substantial Q value.

Let us compare that to what is the case if ${}^{226}_{88}Ra$ tries to decay to a single proton instead, which would give ${}^{225}_{87}Fr$. We would have a Q value of

$$\begin{aligned} Q &= (226.025406 - 225.02561 - 1.0072675)\ u \times 931.494\ \frac{MeV}{u} \\ &= (-7.48 \times 10^{-3})\ u \times 931.494\ \frac{MeV}{u} \\ &= -6.97\ MeV < 0\,. \end{aligned} \tag{15}$$

Thus, this decay is simply not possible. Not only is there the usual barrier, but the final height of the potential step is such that the wave function would continue exponential decay, meaning the supposed final particles could never actually propagate as waves.

Nuclear Reactions

Here, the critical issue is whether the reaction is exothermic (energy is released) or endothermic (energy must be supplied).

Typically, one thinks of two particles colliding and making two particles in the final state: $a+X \to Y+b$. The colliding particles must have enough kinetic energy to overcome the Coulomb repulsion to the extent that a can enter into the nuclear interior of X. This creates a highly excited state of some kind that can then turn into the final $Y+b$ particles.

(Note that if $a=n$, a neutron, then there is no Coulomb barrier. Thus, neutrons are a good particle to use to initiate a nuclear reaction.)

A reaction that is exothermic has the potential to make a bomb. Since the mass energy of the two colliding particles is greater than the mass of the two particles appearing in the final state, the energy available in the final state for further reactions will be even larger than the kinetic energy initially supplied. Typically, this will come in the form of several a type particles ($b = few \times a$) such as neutrons. These neutrons can then initiate further $a+X$ reactions, and the chain reaction is under way.

For a reaction $a + X \rightarrow Y + b$, we define

$$Q = (M_a + M_X - M_Y - M_b)c^2\,. \tag{16}$$

Exothermic implies $Q > 0$.

Example

$${}^1_1H + {}^7_3 Li \rightarrow {}^4_2 He + {}^4_2 He \tag{17}$$

has $Q = 17.3\ MeV$.

Application 1: Fission

One important application is to the fission reaction.

$${}^1_0n + {}^{235}_{92} U \rightarrow {}^{236}_{92} U^* \rightarrow X + Y + neutrons \tag{18}$$

for instance

$${}^1_0n + {}^{235}_{92} U \rightarrow {}^{236}_{92} U^* \rightarrow {}^{141}_{56} Ba + {}^{92}_{36} Kr + 3{}^1_0n\,. \tag{19}$$

The U^* notation means a highly excited and distorted nucleus that is throbbing with impatience to break apart. We call this kind of intermediate state a virtual state.

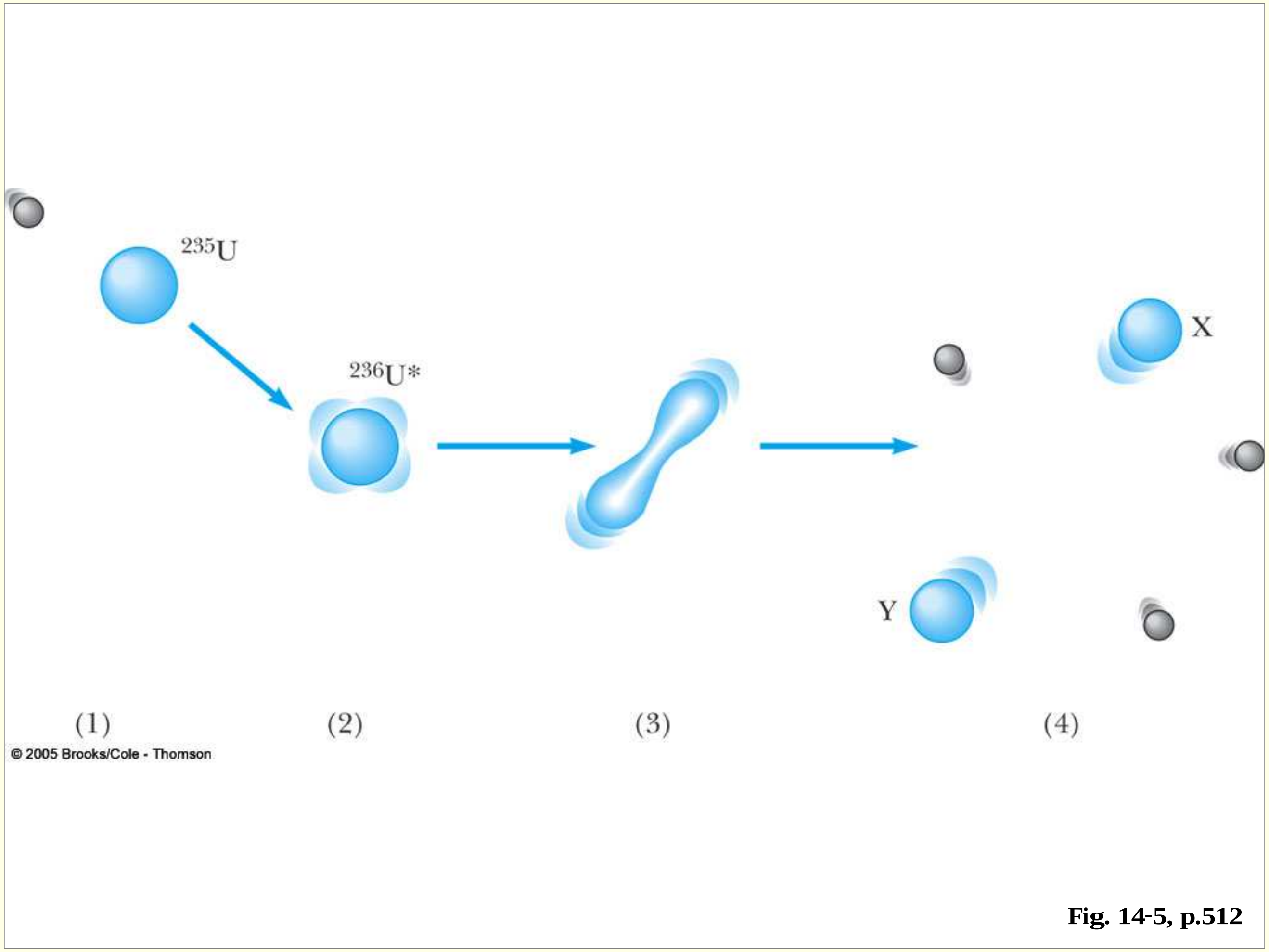


Figure 5: Fission reaction example.

A crude Q estimate for these reactions is

$$Q \sim 240\ nucleons \left(8.5\ \frac{MeV}{nucleon} - 7.6\ \frac{MeV}{nucleon}\right) \sim 220\ MeV\,, \tag{20}$$

where the two numbers are taken from the binding energy graph — the first being near the mid area and the 2nd being a large A type of number.

This is a lot of energy! For example, take $1\ kg$ of ^{235}U. There are

$$\#\ of\ U\ nuclei = \left(\frac{6 \times 10^{23}\ nuclei/mole}{235\ g/mole}\right) \times 10^3\ g = 2.56 \times 10^{24} \tag{21}$$

in the $1\ kg$. If each of these undergoes a fission reaction ($Q = 208\ MeV$ to be precise for this case), you get out

$$E = NQ \sim 5.32 \times 10^{26}\ MeV \sim 2.37 \times 10^7\ kWh\,. \tag{22}$$

That is, you have a power plant.

In practice, you must supply kinetic energy to get the fission reaction to proceed. This kinetic energy does not disappear; it goes into the kinetic energy of the final products.

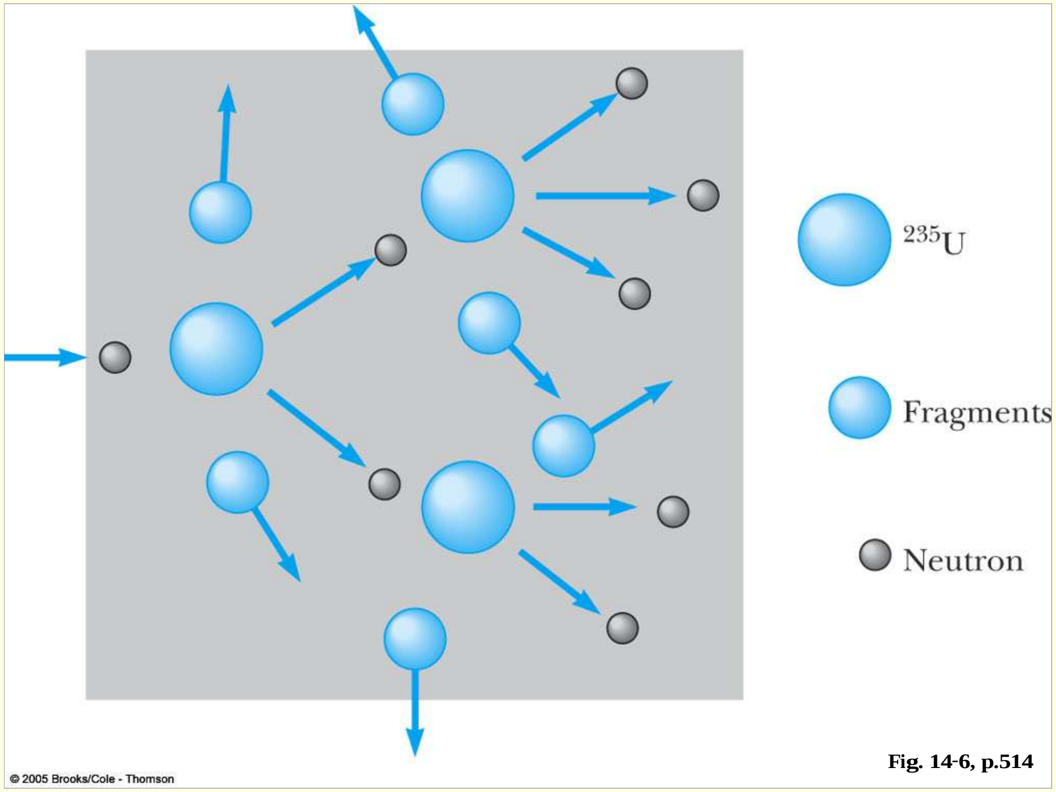


Figure 6: Picture of a chain reaction.

In a bomb or power plant, it is the extra neutrons released with their high kinetic energy that go looking for other U nuclei.

Since more than one neutron is emitted in each reaction, once you get a

few reactions to take place, the neutron numbers can grow exponentially rapidly by initiating more and more fission reactions. The result is a very sudden energy release, i.e. a bomb.

In a nuclear reactor, most of these extra neutrons are absorbed by a regulator material adjusted in amount and location so that the chain reaction proceeds at a constant pace.

Application 2: Fusion

The Sun

The prime example of fusion (other than the fusion-based Hydrogen bomb) is the sun. Fusion is the source of the sun's energy.

The basic reactions are the following:

$$\begin{array}{ccc} {}^1_1H + {}^1_1H & \rightarrow & {}^2_1H + {}^0_1e + \nu \\ {}^1_1H + {}^2_1H & \rightarrow & {}^3_2He + \gamma \\ & \text{followed by} & \\ {}^1_1H + {}^3_2He & \rightarrow & {}^4_2He + {}^0_1e + \nu \\ & \text{or} & \end{array}$$

$$ {}_2^3He + {}_2^3He \quad \rightarrow \quad {}_2^4He + {}_1^1H + {}_1^1H \tag{23} $$

This sequence is called the proton-proton cycle. The net result is that 4 protons combine to yield an α particle (2 protons + 2 neutrons) and 2 positrons (the antiparticle of the electron —*also predicted by the Dirac wave equation mentioned earlier*) and several neutrinos and a photon.

The net energy release is $Q = 25\ MeV$. However, a high temperature of $T \sim 1.5 \times 10^7\ K^\circ$ is required to initiate this fusion sequence.

This high T is needed to overcome Coulomb barriers for protons or proton and nucleus to get closer together than the $10^{-14}\ m$ range where the nuclear binding force takes over.

The sun's energy budget

Since $1\ MeV \sim 1.6 \times 10^{-13}\ J$, we have $25\ MeV \sim 4 \times 10^{-12}\ J$.

The sun puts out $\sim 4 \times 10^{26}\ W$ ($1.4\ kW$ arrives per m^2 at the earth which is $150 \times 10^6\ km$ away from the sun, so that $4\pi r^2 \times 1.4\ kW/m^2 = 4 \times 10^{26}\ W$).

This means that the sun has

$$\frac{4 \times 10^{26}\ W}{4 \times 10^{-12}\ J} = 10^{38}\ \text{fusion cycles}/s\,. \tag{24}$$

The sun's mass is $2 \times 10^{30}\ kg = 1.2 \times 10^{57}\ protons$, 4 of which are used for each fusion cycle.

Thus, we expect the lifetime of the sun to be

$$\begin{aligned} \text{sun's lifetime} \ &\sim\ \frac{1.2 \times 10^{57}}{(4)(10^{38}/s)} = 3 \times 10^{18}\ s \\ &\sim\ 100\ \text{billion years}\,. \end{aligned} \tag{25}$$

We have some time left.

A Fusion Reactor for Power Generation

The focus is currently on the $D - T$ (deuterium-tritium) possibility:

$${}^2_1H +{}^3_1 H \rightarrow{}^4_2 He +{}^1_0 n + 17.6\ MeV\,. \tag{26}$$

This is a big yield.

One problem is that tritium is not easy to get hold of since it decays — still there is enough to make this a viable possibility.

The main obstacle is that you need a temperature of roughly $4\ keV \sim 4.5 \times 10^7\ K$ to get the reaction going given the Coulomb barrier.

Such a high temperature means you will have trouble confining the plasma, and, in particular, must input power to achieve the magnetic confinement needed and to overcome the energy losses due to radiation of photons from rapidly moving charged particles that are bent/confined by the magnetic fields.

Thus, achieving breakeven (where power in equals power out) for a fusion reactor has proved a very daunting task.

Perhaps the ITER project that may soon get under way will achieve the breakeven point.

High Energy Theory / Elementary Particles

The most fundamental advances of recent years have been in the area of what is called high energy theory or elementary particle physics.

This is a very big subject and we will only have time for a very global glimpse of it.

There has been a long series of experiments at high energy accelerators that have led to our current picture.

Especially important were the recent experiments at e^+e^- colliders (such as LEP at CERN) where collisions take place in the center-of-mass (equal but opposite momenta) and the reactions are of the type

$$e^+e^- \to \gamma^*, Z^* \to \textbf{various pairs of particles + secondary particles}\,. \tag{27}$$

Here, the γ^* is a virtual version of the photon that rapidly decays to the stuff in the final state. A picture of a typical collision event is below.

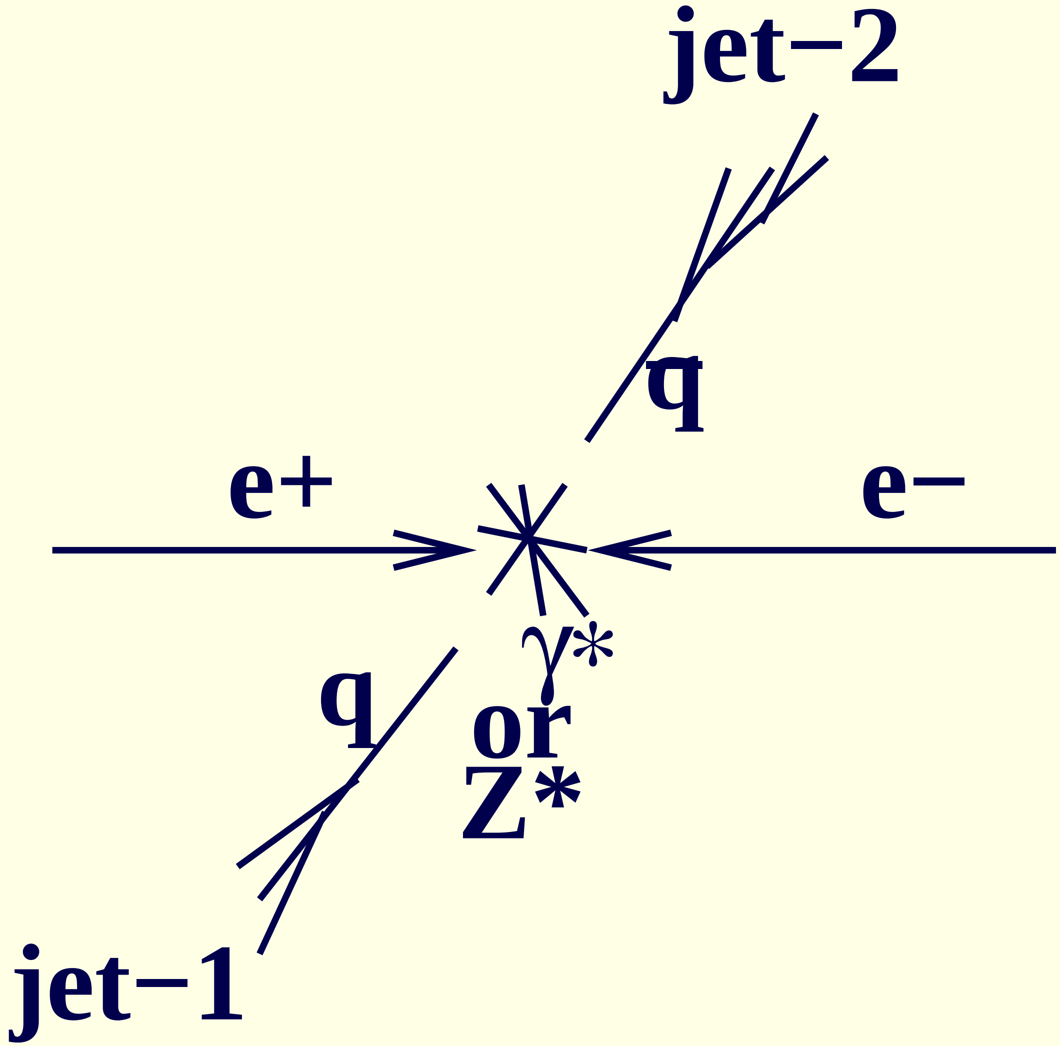


Figure 7: A picture of an e^+e^- collision in the com, yielding two quark jets.

The γ^* (or Z^*, where the Z will be discussed) has 4-momentum Q with Q^2 large and positive. Since this does not correspond to a real photon, the γ^* is not something we can see in the normal way. We see it only as an intermediary for the above type of process.

It is (what else) the Heisenberg uncertainty principle that allows this situation. We can have a virtual particle so long as it does not last very long or travel very far:

$$\Delta t \sim \frac{\hbar}{\Delta E} \sim \frac{\hbar}{Q}. \tag{28}$$

This $e^+e^- \to \gamma^* \to$ anything type of process is particularly useful as the photon couples to any charged object (and in particular most directly to the elementary charged objects) and so this process will reveal any elementary particles that are charged and have mass such that

$$E_{e^+e^-}^{\text{center of mass}} > \text{net mass of final state}\,. \tag{29}$$

In this way, we have directly observed nearly all the elementary particles of which we are currently aware. You will see a list shortly.

Another very crucial reason for doing experiments at very high Q, *i.e.* very high energy, can be understood based on the heisenberg uncertainty principle. In this context, Q corresponds roughly to Δp, the amount of momentum you use to disturb something and attempt to see it. Then, the HUP says

$$\Delta x \Delta p \sim \Delta x\, Q \geq \frac{1}{2}\hbar\,. \tag{30}$$

This means that you cannot expose structure at distance scales any smaller than

$$\Delta x \geq \frac{1}{2}\hbar\left(\frac{1}{Q}\right). \tag{31}$$

Thus, the smaller the spatial scale we want to probe, the larger the Q required.

The experimental apparati needed to analyze the final state of the γ^* and other types of high energy collisions is quite large and remarkably sophisticated, as are the acclerators themselves that produce the collisions. The following pictures show some accelerator laboratories, accelerators and detectors. Note the huge scale needed for very high energy collisions and detection of the resulting "collision events".

Figure 8: The LEP/LHC Accelerator Complex at CERN, Geneva

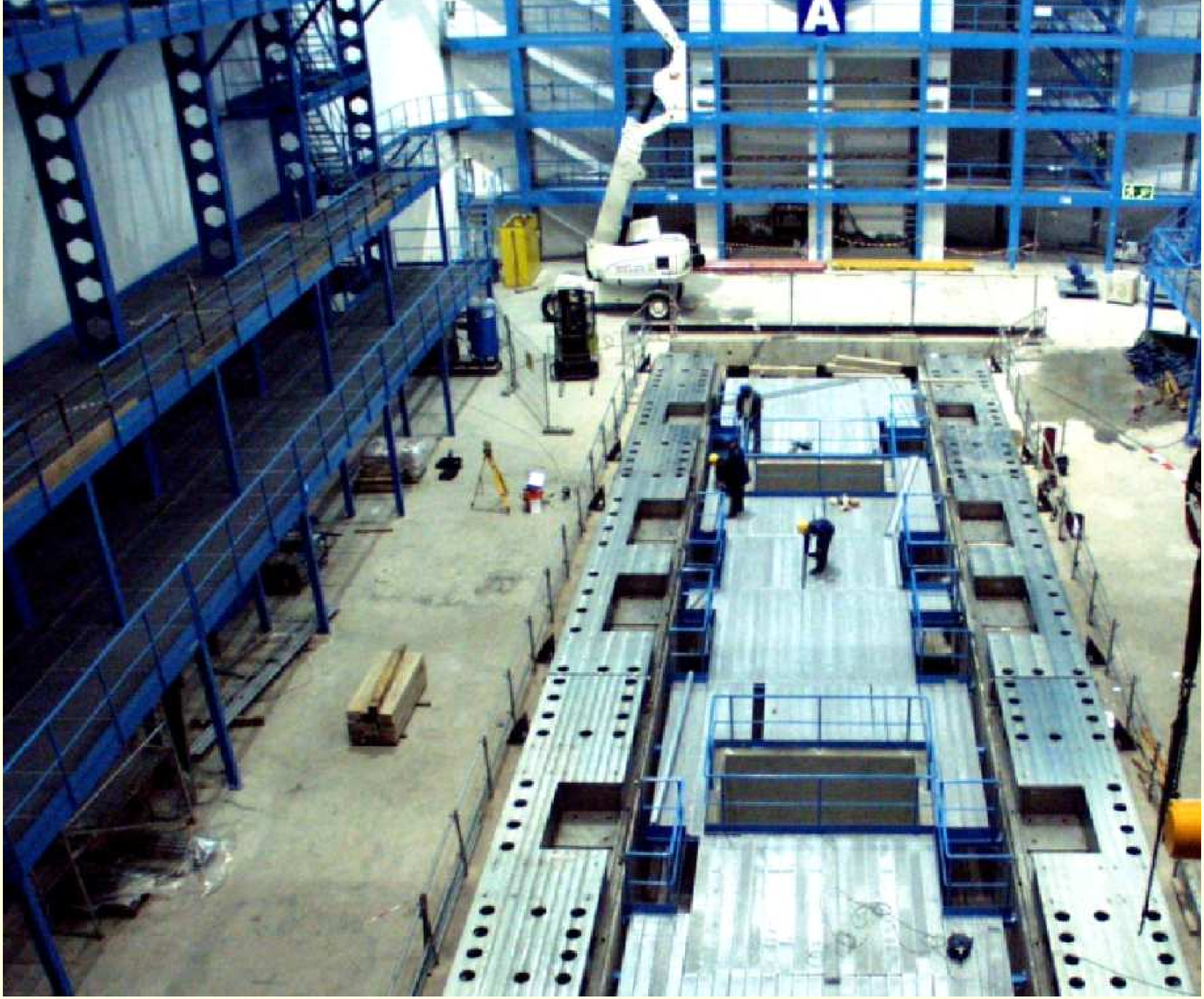


Figure 9: An underground cavity for one of the detectors being built for the LHC

Figure 10: Accelerator magnets and such that guide and accelerate the proton beams at the Fermilab Tevatron. Similar things will be installed at the LHC

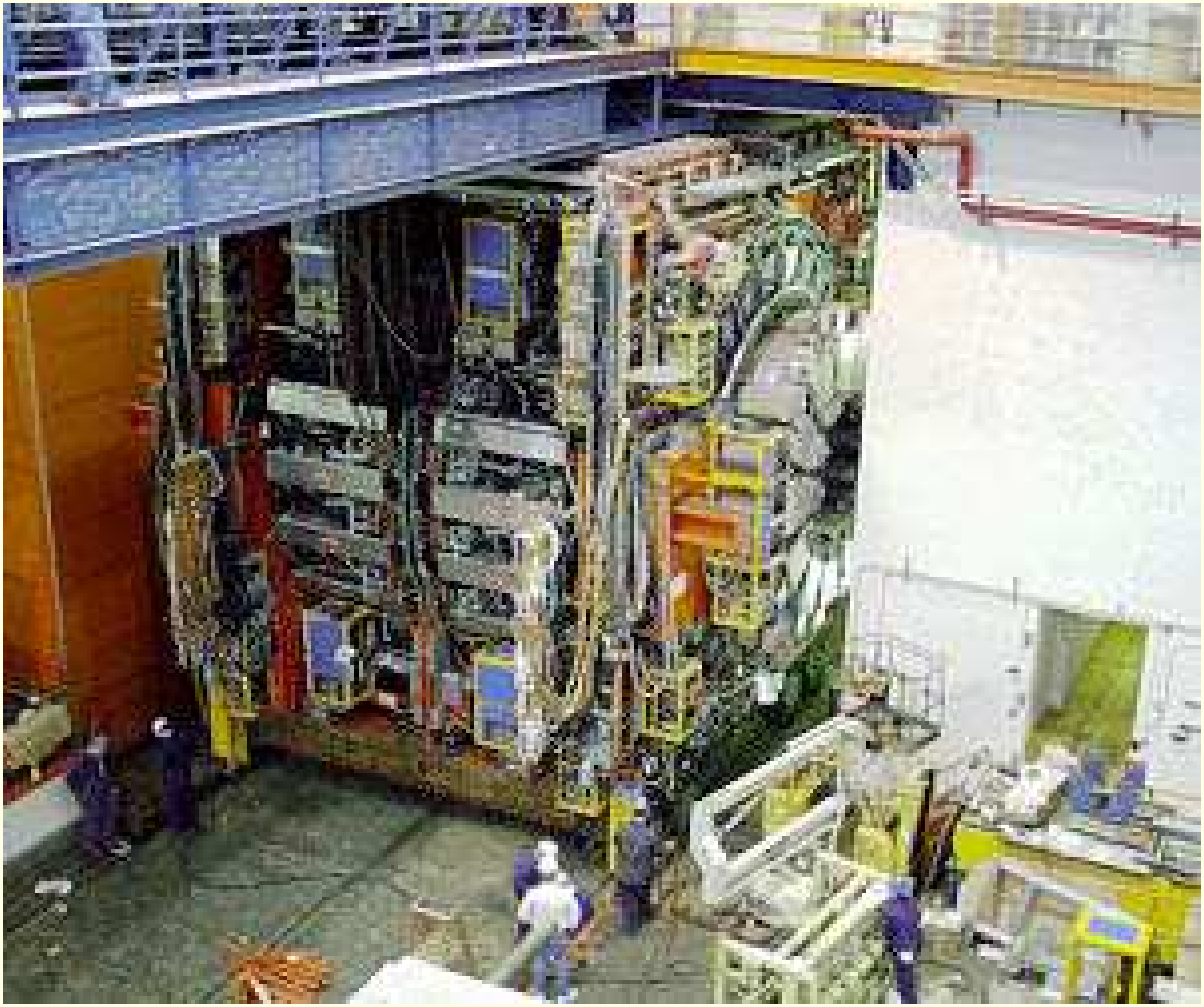


Figure 11: The CDF Tevatron detector. LHC detectors will be roughly 3 times as large once completed.

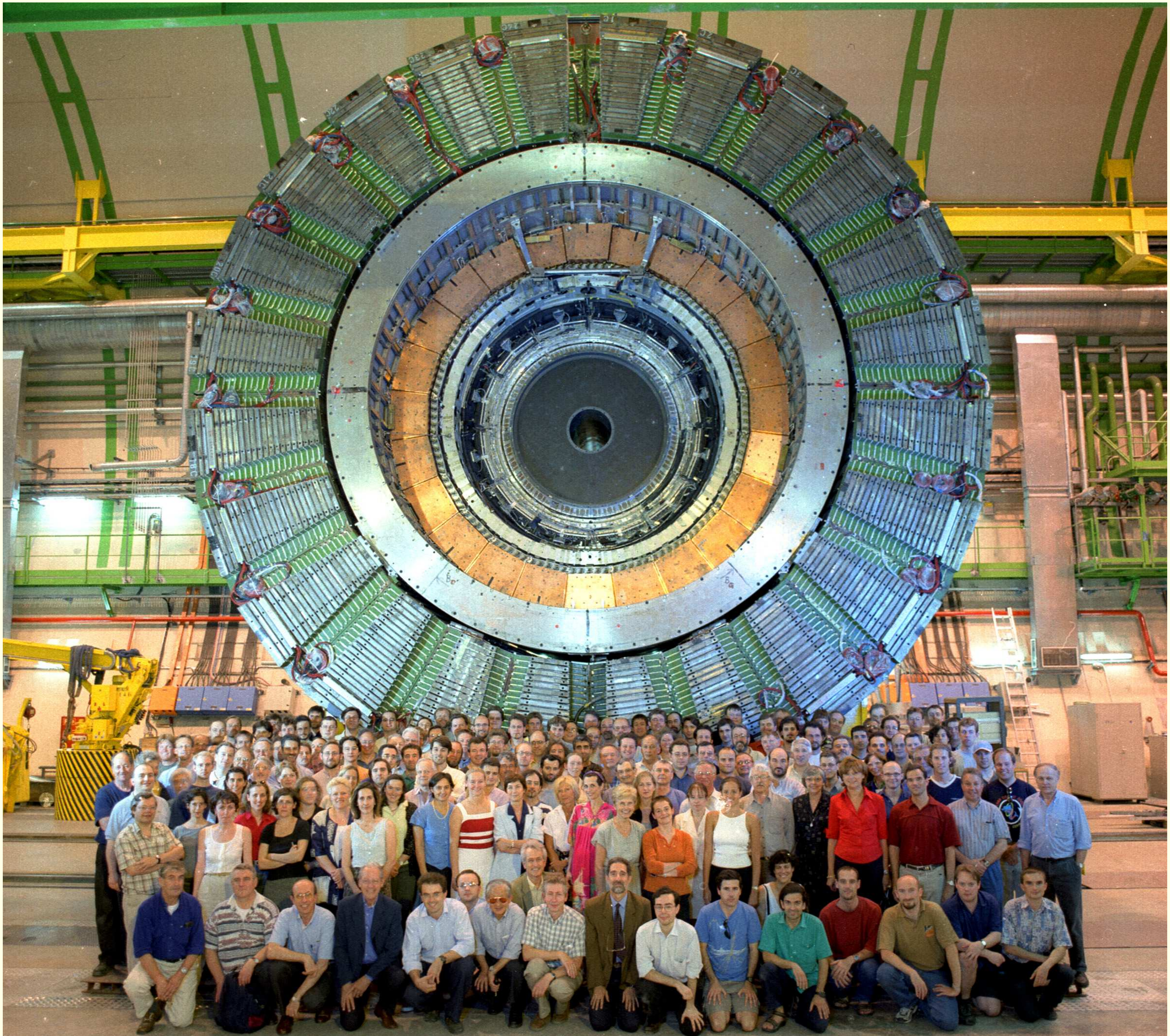
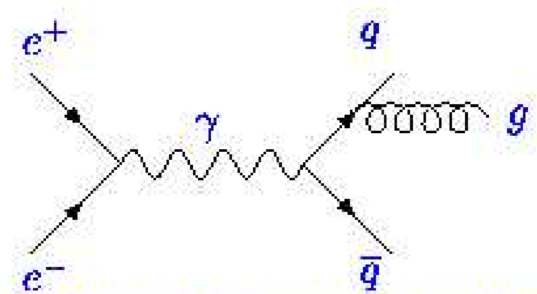


Figure 12: The DELPHI detector at LEP.

Let us illustrate using the process $e^+e^- \to \gamma^* + Z^* \to q\overline{q}g$, where q stands for one of the **quarks** (the things that bind together to form a proton, or similar), $\overline{q}$ stands for an anti-quark (just like the e^+, predicted by the Dirac equation and observed long ago, is the antiparticle of the e^-) and g stands for the **gluon** that is responsible for this binding. The q or $\overline{q}$ **radiates** the extra g which couples strongly to them (as necessary if the g is responsible for the strong force that binds quarks together to form the proton). A **Feynman Diagram** depicting this process is given below:



electron-positron annihilation to quark + antiquark + gluon
via virtual photon exchange

What the diagram depicts is the e^+e^- pair coming in and at a specific point (in 4-d space time) they annihilate via the coupling of their charge to a photon (the photon couples to charge). This photon is the highly virtual photon which then is depicted as turning into a $q\overline{q}$ pair at another space-time point, using the coupling of the photon to the charge of the quarks. These quarks then propagate until (for this diagram) at a 3rd space-time point the q emits a gluon. Then, the final q, g and $\overline{q}$ continue propagating and emerge into the final state in some particular directions.

There are specific calculation rules for writing down the probability amplitude for this diagram. Another diagram gives a 2nd contribution. These amplitudes are summed and the absolute square of this sum gives the net probability for the process to occur.

The size of this probability increases with the strength of the couplings as $[(-1e)(e_q e)(g_{strong})]^2$, where e_q is the charge of the quark in units of e and g_{strong} is the much larger strength of the $q\overline{q}g$ coupling.

A typical experimental set up is that for the detector depicted earlier and the reaction discussed gives rise to a collision event which could be described as follows:

- The e^- and e^+ beams enter in opposite direction along the small circular (beam) pipe at the center of the detector, which defines the z axis.
- The conversion to the γ^* occurs near the center of the detector.
- The γ^* decays immediately into the $q\overline{q}$ and the g is emitted also almost immediately, all extremely close to the center of the detector.

- **The q, $\overline{q}$ and g then pass outside the beam pipe with large x and y momenta and go into the detector where they turn into three separate energetic cascades of secondary particles.**
- **These narrow cascades are known as jets. The jets are then detected by a variety of very clever means.**
- **Different types of quarks can be identified by the secondary particles that appear in the jets.**

  In this way, we know that we have all the different quarks that I shall shortly discuss: u and d (both already needed to make up the proton, $p = uud$), c (charm) and s (strange), b (bottom) and (not at LEP because of limited energy) t (top).
- **Also made, in other collision events, are various different charged leptons. The e^- is one type we know about. But, there are also two other distinguishable leptons: μ^- and τ^-.**
- **In still other events, using the Z^* exchange, where Z is a heavy version of the photon, we make neutrinos ($e^+e^- \to Z^* \to \nu\overline{\nu}$) which come in the same three types as the leptons: ν_e, ν_μ and ν_τ.**

So, if you see this kind of process and its many cousins, you really know all these objects are there. An actual $q\overline{q}g$ event at LEP is depicted in the following figure. What is shown is a real-time computer display of where the q, $\overline{q}$ and g jets went and how they evolved.

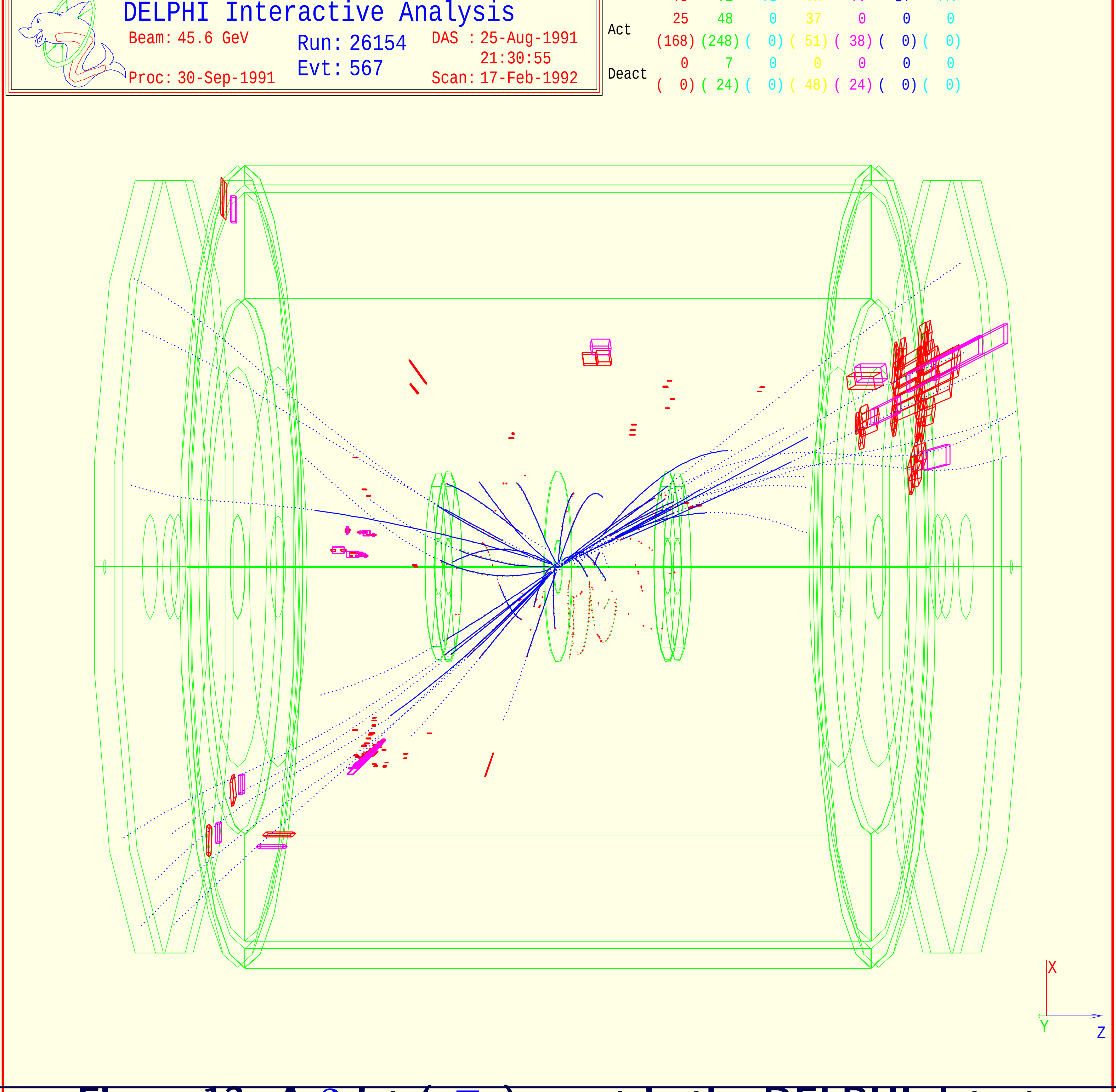


Figure 13: A 3-jet ($q\bar{q}g$) event in the DELPHI detector.

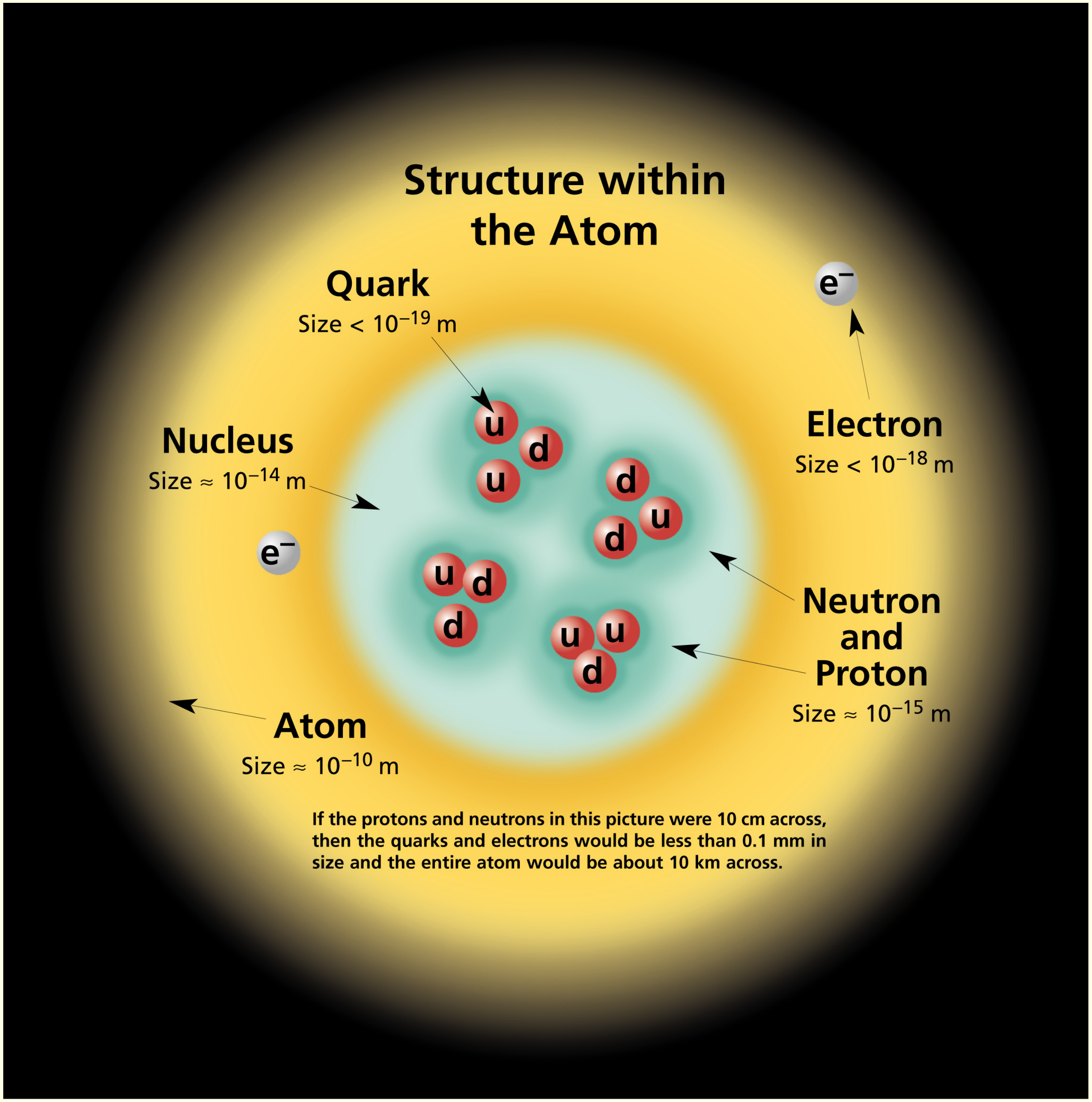


Figure 14: A picture of the atomic, nuclear and nucleon structures.

The preceding picture shows all the different matter particles involved in our full picture of the atom: from electrons and the nucleus, to protons and neutrons, to quarks. The relative sizes of these objects are also indicated. As far as we know the e^- and quarks have zero size.

What the picture does not show is the photons being exchanged between the e^-'s and the protons that causes the electromagnetic attraction that binds the electrons and protons together to make the atom.

Also not shown are the gluons that are exchanged $within$ the $p = uud$ or $n = udd$ quark composites. These cause the strong force that binds the quarks together to make the proton or neutron.

The exchanges responsible for the nuclear force can roughly be thought of as 2-gluon exchanges between the protons and/or neutrons, dominated by a meson call the pion or π. These exchanges that bind the neutrons and protons together to form the nucleus are also not shown.

Regarding the quarks, the u has charge $+2/3$, the d charge $-1/3$. Together, uud has charge 1 and udd has charge 0. Exotic baryons such as $\Omega^- = sss$ can be made at low-energy accelerators, where s is another kind of quark. All quarks have baryon number of $1/3$. Then $p = uud$ has baryon number 1 as does $n = udd$.

Altogether there is much evidence for fractional quark charge and fraction quark baryon number.

There are also mesons such as $\pi^+ = u\overline{d}, \pi^0 = \frac{1}{\sqrt{2}}(u\overline{u} - d\overline{d})$, $K^+ = u\overline{s}$.

All of these quarks carry other quantum numbers, referred to by such names as strangeness (the s quark carries strangeness $= 1$), or charm (for the c quark), bottomness for the b and topness for the heaviest of the quarks, the t quark. It is the fact that an s quark has very tiny probability for turning into a d or b quark (all of which have the same baryon number and charge), and vice versa, that identifies these quarks as all being different.

Altogether, we actually have 3 families of quarks and leptons.

- family 1: u, d, ν_e, e^-.
- family 2: c, s, ν_μ, μ^-.
- family 3: t, b, ν_τ, τ^-.

Just like the u, c, t are identifiably separate quarks, and the d, s, b are distinguishable, so are the different leptons, e, μ, τ. They have extremely tiny probability for turning into one another.

A full summary of all the forces and matter particles is given in the following table. You will see there the weak force mediated by exchange of the massive W and Z vector bosons. We have not yet discussed it.

Matter	Name	Mass	Charge	"Color"	Forces "felt"
ν_e	e-type neutrino	~ 0	0	$none$	$Z, W^{\pm}$
e^-	electron	$\sim 0.5\ MeV$	-1	$none$	$Z, W^{\pm}, \gamma$
u	up quark	$\sim 3\ MeV$	$+\frac{2}{3}$	r,g,b	$Z, W^{\pm}, \gamma, g$
d	down quark	$\sim 5\ MeV$	$-\frac{1}{3}$	r,g,b	$Z, W^{\pm}, \gamma, g$
ν_μ	μ-type neutrino	~ 0	0	$none$	$Z, W^{\pm}$
μ^-	muon	$\sim 100\ MeV$	-1	$none$	$Z, W^{\pm}, \gamma$
c	charm quark	$\sim 1.5\ GeV$	$+\frac{2}{3}$	r,g,b	$Z, W^{\pm}, \gamma, g$
s	strange quark	$\sim 100\ MeV$	$-\frac{1}{3}$	r,g,b	$Z, W^{\pm}, \gamma, g$
ν_τ	τ-type neutrino	~ 0	0	$none$	$Z, W^{\pm}$
τ^-	tau	$\sim 1.78\ GeV$	-1	$none$	$Z, W^{\pm}, \gamma$
t	top quark	$\sim 175\ GeV$	$+\frac{2}{3}$	r,g,b	$Z, W^{\pm}, \gamma, g$
b	bottom quark	$\sim 4.5\ GeV$	$-\frac{1}{3}$	r,g,b	$Z, W^{\pm}, \gamma, g$

List of "matter" particles. All have spin-$1/2$ ($i.e.$ are fermions) with $m_s = \pm 1/2$ possible. All have anti-particle brothers.

Force	Name	Mass	charge	"color"	Nature of Force
g	gluon	0	0	$r\overline{r}, r\overline{g}, r\overline{b}, \ldots$	strong force sees color
γ	photon	0	0	none	$E\&M$ force sees charge
$W^{\pm}$	weak charged VB	$\sim 80\ GeV$	± 1	none	weak force $\nu_\ell \rightarrow \ell$, $u \rightarrow d$
Z	weak neutral VB	$\sim 91\ GeV$	0	none	weak force couples to $f\overline{f}$

List of particle that mediate Standard Model (SM) forces. All are spin-1 vector bosons (VB). f=any matter fermion.

Particles

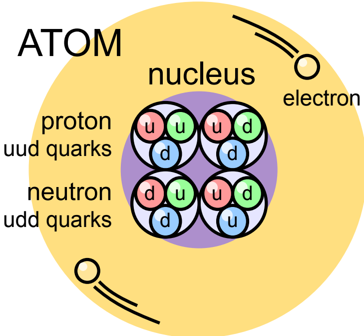
What is the universe made of?

It is made of particles.
Atoms are made of particles,
light is made of particles,
and even gravity is
made of particles.

There are two fundamental types of particles: fermions and bosons.

Fermions
Spin 1/2, 3/2, 5/2, ...
Matter is made of fermions. Fermions obey the exclusion principle: they cannot be in the same place at the same time.

Bosons
Spin 0, 1, 2, ...
Forces are carried by bosons. Bosons do not obey the exclusion principle: they can pass right through each other.



Fundamental Particles

These are all the fundamental particles, according to the standard model of particle physics.

Fundamental Fermions

Quarks
spin 1/2

family	symbol	flavor	electric charge	mass (MeV/c^2)
1	d	down	-1/3	6
	u	up	+2/3	3
2	s	strange	-1/3	100
	c	charm	+2/3	1300
3	b	bottom	-1/3	4300
	t	top	+2/3	175000

Each "flavor" comes in three "color" charges: red, green, & blue.

Leptons
spin 1/2

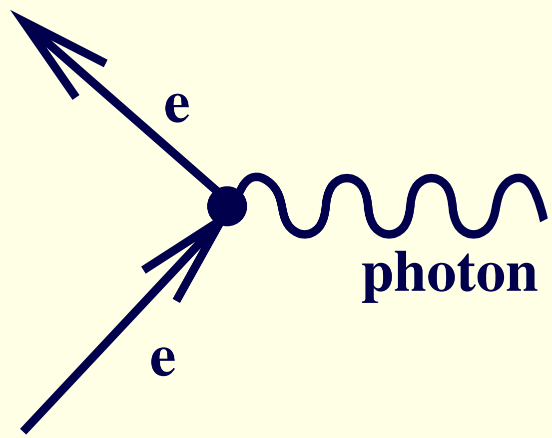
family	symbol	name	electric charge	mass (MeV/c^2)
1	e	electron	-1	0.51
	ν_e	electron neutrino	0	<0.00000022
2	μ	muon	-1	106
	ν_μ	muon neutrino	0	<0.2
3	τ	tau	-1	1780
	ν_τ	tau neutrino	0	<20

Fundamental Bosons

symbol	name	field or force carried by boson	spin	electric charge	mass (MeV/c^2)
γ	photon	electromagnetism *(light)*	1	0	0
W^+ W^- Z^0	W Z	weak force *(radioactivity)*	1	+1,-1 0	80400 91200
g	gluon	strong force *(nuclear force or color force)*	1	0	0
G	graviton *[predicted]*	gravity	2	0	0
H^+ H^0 H^-	higgs *[predicted]*	higgs field *[predicted]*	0	+1,0,-1	>114000

Figure 15: Note the Higgs and Gravity additions to force particles.

More on Feynman diagrams, forces and particles



arrow lines indicate electron in and electron out
wavy line is photon emitted or absorbed
solid circle indicates vertex where photon is emitted or absorbed
the vertex comes with a certain coupling strength, in this case e

Figure 16: Prototype Feynman vertex diagram.

There are actually 3 different forces as illustrated by the vertex diagrams that follow. The last two are both weak force examples.

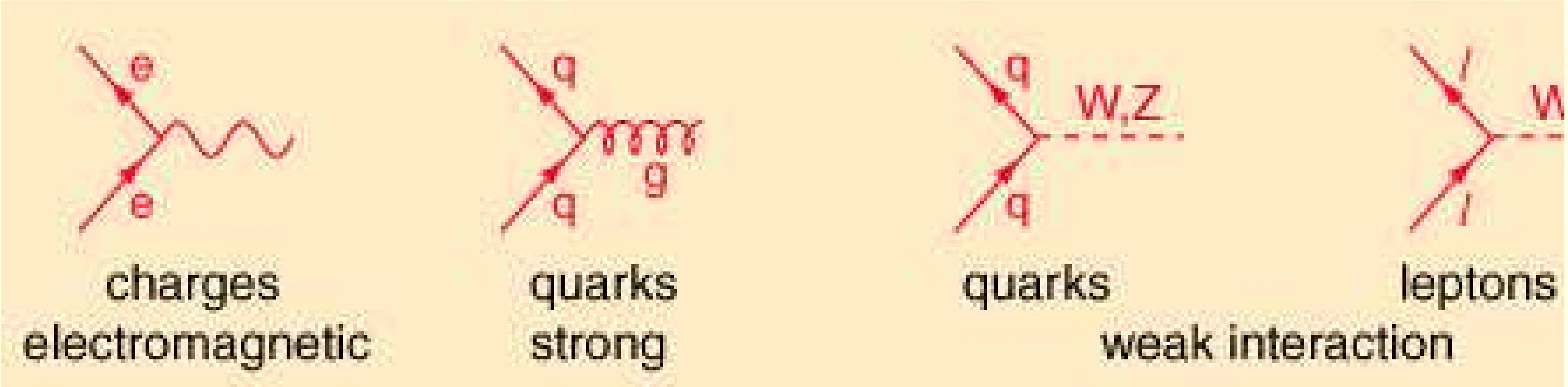


Figure 17: The electromagnetic, strong and weak force vertices.

These vertices can be used to construct many different types of processes involving virtual exchange of the force mediating particle (gluon, photon, or weak vector boson).

An analogy you might think of for the vertices and interactions they can cause is based on an old Budweiser advertisement. In that ad there was this frog that sent out his tongue that then seized something it encountered (a beer truck). Here the source particle (e.g. electron) sends out its (virtual) photon tongue and looks for another charged particle to either attract or repel (depending upon relative sign of charges).

If the tongue finds nothing then the frog simply withdraws his tongue and tries again. If the tongue finds something then the interaction becomes "real" and the frog influences the object his tongue encounters.

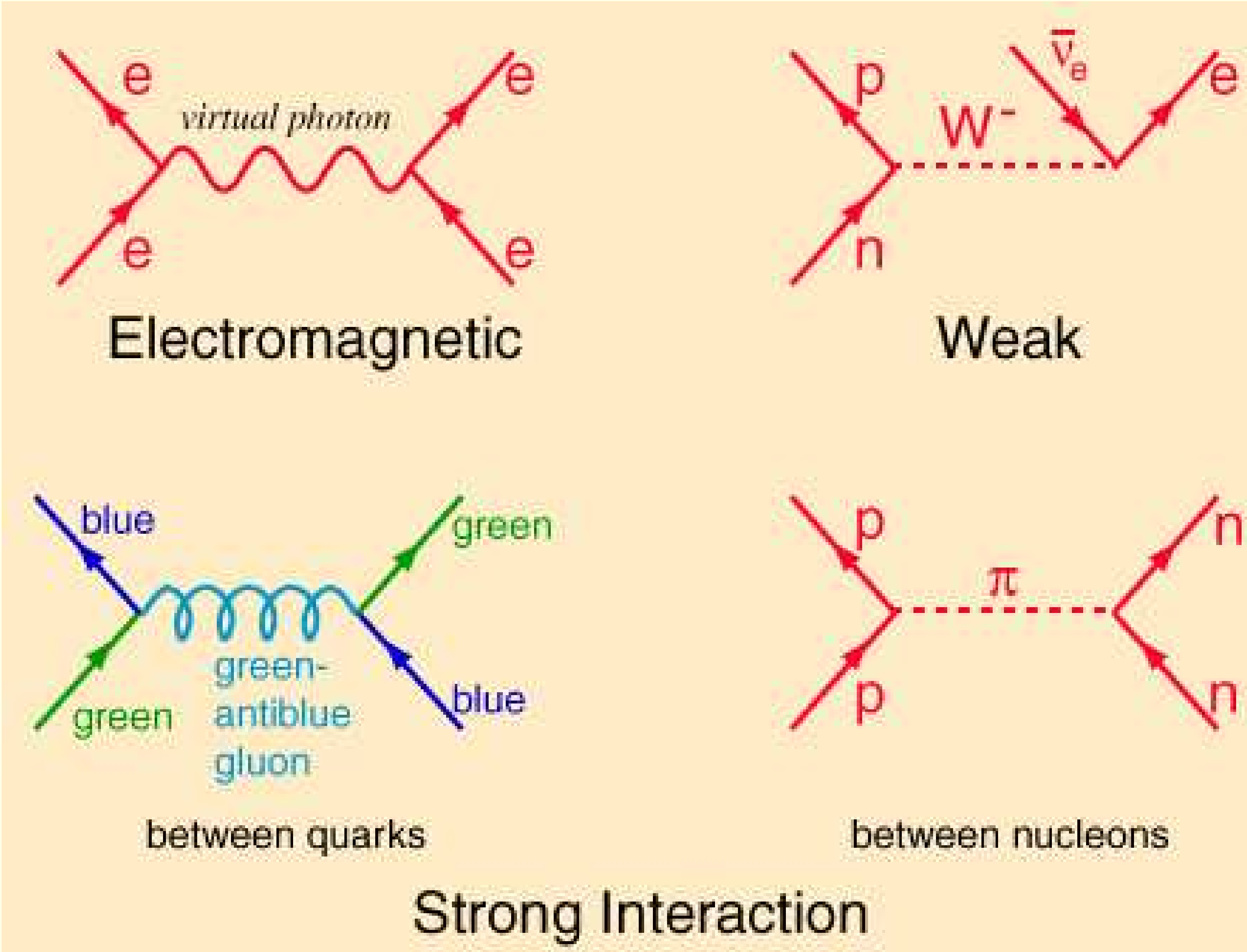


Figure 18: Typical processes mediated by the electromagnetic, strong and weak forces.

Another part of the analogy is that the tongue might be very light and could have a long range. This would be the photon for example. Or it could be very heavy and would not go far. This is the case for the weak massive vector bosons with range $d \sim \hbar/m_W$ or $\hbar/m_Z$. (The large values of m_W and m_Z make this force weak, not because the coupling is small (see below), but because the range of the force is very short.)

Also, if the frog is well-connected to his tongue (coupling constant) he can send it out more frequently.

And the more strongly his tongue couples to the object it encounters, the stronger will be the interaction.

Unification of Forces

We have seen that each interaction appears at energies where we perform our measurements to have a different coupling strength:

- e for electromagnetism and the photon;
- g_s for the strong interactions and the gluon;
- g_W for the coupling of Z and $W^{\pm}$ to leptons and quarks.

However, it turns out that coupling constants are not actually constant.

They change with the energy scale at which the interaction takes place.

This is a relativistic quantum effect.

Let's take the photon coupling to an electron as an example.

According to the uncertainty principle there is nothing wrong with the photon temporarily turning into a virtual electron-positron pair (which means a big excursion in ΔE from a situation that can be "real"), so long as this pair lasts an appropriately short time: $\Delta t \sim \hbar / \Delta E$.

This kind of virtual pair creation and reannihilation stuff is happening all the time. This room is filled with virtual $e^+ e^-$ bubbles that come and go.

The result is that all these virtual pairs form a kind of quantum dielectric medium which can be polarized. The consequence is that the farther away the electron is from another electron (which corresponds to smaller momentum scales) the weaker the coupling of one electron to another.

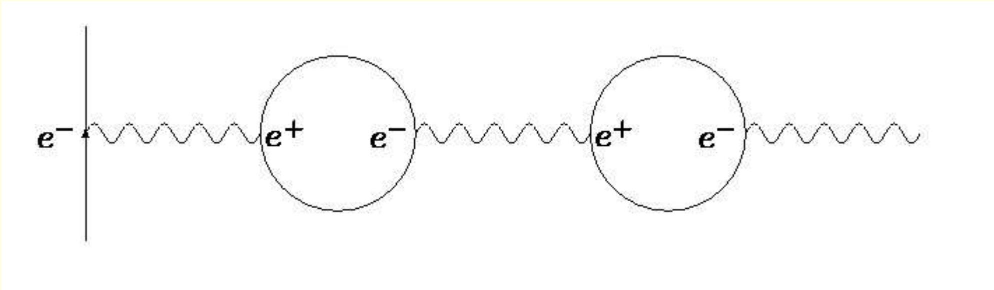


Figure 19: Polarization of the e^+e^--pair bubbles for photon coupling to e^-.

The way the couplings move

- The effective electromagnetic coupling decreases with increasing distance and increases with decreasing distance, *i.e.* with increasing Q.
- The strong force does just the opposite (because the force carriers themselves carry the color "charge" in contrast to the photon that is chargeless): The strong force decreases with increasing Q.
- For the weak force, these effects are quite closely balanced and the weak charge changes quite slowly with increasing Q.

To quantify the couplings strengths of the different forces and the momentum dependence of these couplings, it is convenient to employ the "α"'s of the different forces.

You may recall a problem you did regarding the electromagnetic Coulomb force. You constructed

$$\alpha_{E\&M} = \frac{ke^2}{\hbar c} \simeq \frac{1}{137}. \tag{32}$$

As we have just said, this number depends upon the momentum scale at which it is determined. The number $1/137$ is for very low momentum scales and large distances (as in the original Coulomb experiment). More generally one writes $\alpha_{E\&M}(Q)$.

There are exactly analogous "α" constructions for the other forces, each of which has an analogue of k and e. If we determine all of them at the scale $Q = m_Z$ (the mass of the Z boson produced at LEP), one finds

$$\alpha_s(m_Z) \sim 0.118, \quad \alpha_{E\&M}(m_Z) \sim \frac{1}{128}, \quad \alpha_W(m_Z) \sim 0.04 \tag{33}$$

where the subscript W stands for "weak".

Note that the weak force is actually somewhat stronger than the $E\&M$ force in terms of coupling.

- At lower energies it is weaker because the exchange W and Z particles are very heavy, which suppresses the net strength of the weak interactions.

- At the high energies we are about to discuss, the masses of the exchange particles are no longer relevant.

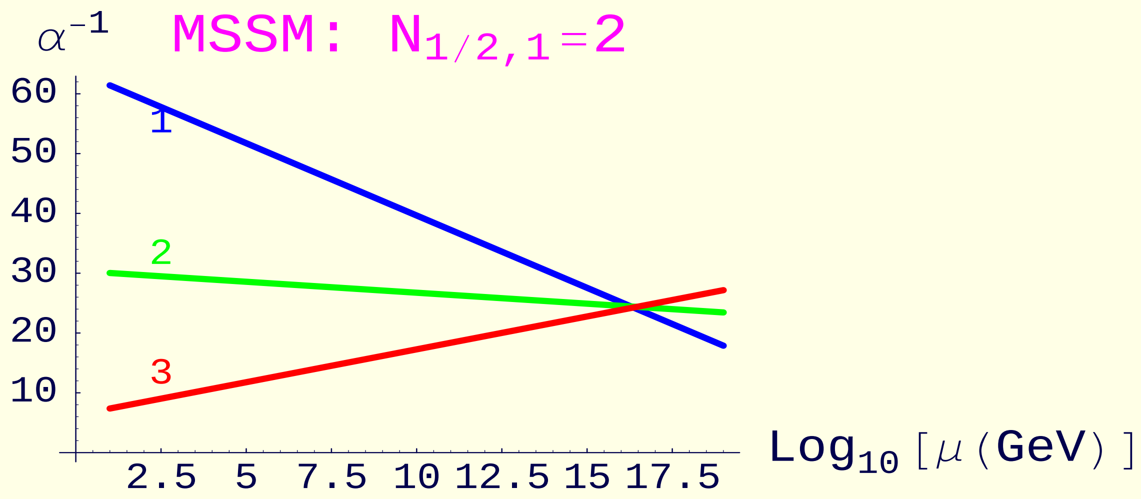
With these α's in hand, any given theory of particles and forces will predict how they change as a function of Q. The question is whether there is a theory in which they all become equal at exactly the same Q value, called the unification scale M_U.

The answer is yes. The theory is one in which every Standard Model particle (those elementary matter and force particles we listed earlier in our tabulation) has a spartner which differs by $1/2$ unit of spin.

For example, each spin-$1/2$ quark of definite S_z should have a spin-0 squark spartner.

Another important example is that the γ should have a spin-$1/2$ partner, called the photino and denoted by $\widetilde{\gamma}$.

The theory we are talking about is called Supersymmetry (SUSY). The behavior of the couplings as a function of the measurement energy Q and their unification appears below, where we plot α^{-1} for the different forces as a function of $\log_{10}(Q)$.



The scale Q is called μ in the figure. Unification occurs at $Q = \mu = M_U \sim 1.9 \times 10^{16}\ GeV$, *i.e.* at an energy equivalent to the rest mass of more than 10^{16} protons.

The very high value of this scale is fortunate. This is because where the forces unify, new vector bosons are present and their interactions cause protons to decay. However, since they are so massive, these decays are very improbable. $M_U \sim 1.9 \times 10^{16}\ GeV$ implies a lifetime for the proton of $\sim 10^{32}$ years. We have some time. The sun will burn out long before a significant fraction of the protons and neutrons here on earth and in the stars of the galaxies will have decayed away (to electrons and other light particles).

Dark Matter

In the most attractive version of the Supersymmetry theory, it turns out that the $\widetilde{\gamma}$ (actually a combination of it and the $\widetilde{Z}$) is absolutely stable.

It will be created in the early universe and will never decay. It is an excellent candidate for the dark matter of the universe that has likely been the reason behind the clustering of matter and the formation of galaxies and stars.

The LHC

The LHC, operating at $Q \sim 14000~\mathrm{GeV}$ is the next big step in checking our ideas regarding the fundamental interactions and particles.

If SUSY is correct, then we will observe the dark matter particle as well as all the spartners of the SM particles.

And we will also observe the HIGGS boson. It provides a new fundamental force that is responsible for giving all the elementary particles their mass. We have no time to discuss it, but it is a fascinating and very elusive object.

There is even a chance that we will see extra spatial dimensions that are small in size, $e.g.$ $\boldsymbol{\Delta x < \hbar/(10^{12}\ eV)}$**.**

Final Announcements

- There will be two discussion sessions. I can hold them at 6pm on Sunday and 6pm on Monday in Rm 416 phys/geo (the usual place).

  Another possibility is to have a session tomorrow at 6pm (as usual) and the 2nd one Monday at 6pm. Which is better?

- The final grade sheet including all regrades is now posted with abbreviated student ID's.

- Solutions to all problems of all chapters are now posted.

- The grade distribution for Quiz 5 is now posted.

- I will post by Friday evening the list of things I expect you to memorize for the final.

- Please fill out an evaluation and place it in the quiz boxes at the back.