Physics 228, Lecture 21
Thursday, April 14, 2005

Fusion; Effects of Radiation. Ch. 43.8 (Plus more)

1 Fusion

We now turn to the light nuclei and notice that the nucleons in a few light nuclei could gain binding energy if they could get together into a heavier nucleus. Of course they need to get close enough together to feel the strong interaction attraction, and to do this they need to overcome the coulomb repulsion. We will see that this has important consequences, both for the way the sun works and for power generation.

An important example of this occurs in the Sun. The major source of energy generation in the sun is the *proton-proton cycle*, which consists of the four reactions

$$\begin{aligned}
{}^1_1\mathrm{H} + {}^1_1\mathrm{H} &\longrightarrow {}^2_1\mathrm{H} + \mathrm{e}^+ + \nu \qquad (+0.420\mathrm{MeV}) && (1)\\
{}^1_1\mathrm{H} + {}^2_1\mathrm{H} &\longrightarrow {}^3_2\mathrm{He} + \gamma \qquad (+5.494\mathrm{MeV}) && (2)\\
{}^1_1\mathrm{H} + {}^3_2\mathrm{He} &\longrightarrow {}^4_2\mathrm{He} + \mathrm{e}^+ + \nu \qquad (+18.772\mathrm{MeV}) && (3)\\
{}^3_2\mathrm{He} + {}^3_2\mathrm{He} &\longrightarrow {}^4_2\mathrm{He} + {}^1_1\mathrm{H} + {}^1_1\mathrm{H} \qquad (+12.858\mathrm{MeV}) && (4)
\end{aligned}$$

Notice that in the first and third interactions, one proton in converted to a neutron, a positron and a neutrino. So the total number of neutrons + protons, or baryon number, is conserved, and so is the total charge, but the number of protons decreases.

Note that the net result of one each of (1), (2), and (3) is to convert four hydrogen atoms into a helium atom, two positrons, two neutrinos, two leftover spectator electrons from the hydrogens not needed by the helium atom, and a lot of energy. 24.686 MeV. In fact, the electrons and positrons will annihilate as well, producing another $4 \times 0.511 = 2.044$ MeV. This is the basic way the sun burns hydrogen, converting 0.7% of its rest energy into heat, and leaving helium. The same result comes from two (1), two (2), and one (4).

Notice that several of these reactions have more than two particles in the final state, one reason why I don't like the $X(a,b)Y$ notation.

Similar reactions occur in a deuterium-rich environment, and with tritium. Deuterium ${}^2_1\mathrm{H}$ and tritium ${}^3_1\mathrm{H}$ are isotopes of hydrogen, though tritium is unstable with a half life of 12 years, and so does not occur naturally on Earth. The reactions

$$\begin{aligned} {}^2_1\mathrm{H} + {}^2_1\mathrm{H} &\longrightarrow {}^3_2\mathrm{He} + {}^1_0\mathrm{n} \qquad (+3.27\mathrm{MeV}) \quad (5) \\ {}^2_1\mathrm{H} + {}^2_1\mathrm{H} &\longrightarrow {}^3_1\mathrm{H} + {}^1_1\mathrm{H} \qquad (+4.03\mathrm{MeV}) \quad (6) \\ {}^2_1\mathrm{H} + {}^3_1\mathrm{H} &\longrightarrow {}^4_2\mathrm{He} + {}^1_0\mathrm{n} \qquad (+17.59\mathrm{MeV}) \quad (7) \end{aligned}$$

convert these weakly bound (2.1 MeV for ${}^2_1\mathrm{H}$ and 8.5 MeV for ${}^3_1\mathrm{H}$) isotopes into more strongly bound helium isotopes, releasing a lot of energy. This is what provides the energy of a hydrogen bomb, and also a promising source of energy in the future, if we ever manage to perfect controlled fusion.

All of these reactions require that the nuclei in the initial state overcome their coulomb repulsion, which can only occur if they are headed towards each other with sufficient kinetic energy. While the reactions can be easily generated in small numbers using particle beams, energy will be generated in large amounts only if the thermal energy is high enough. In the sun, fusion only takes place deep in the sun's interior, where the temperature is $\sim 1.5 \times 10^7$ K, and not near the cool surface where it is only ~ 6000 K.

For two deuterium nuclei, the coulomb barrier might reach its peak at about $r = 10^{-14}$ m, where the potential energy $k_e e^2/r \approx 0.14$ MeV, which is $2 \times \frac{3}{2} k_B T$ for $T = 5.4 \times 10^8$ K. Actually fusion can occur at somewhat lower temperatures, because

- in a thermal distribution $\frac{3}{2}k_B T$ is only the average energy, and there is a distribution of particles with higher energy, given by the Boltzmann distribution[1] $n \propto e^{-E/k_B T}$.

- there is a chance of quantum tunnelling, where a collision with not quite enough energy to surmount the barrier classically still has a small chance of getting in. Actually this is not a very important effect in this context.

Both of these effects fall off exponentially in the amount by which the available energy falls short of the barrier height. In the sun, with $T \sim 1.5 \times 10^7$ K, the probability that any two deuterium atoms fuse in any one attempted

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[1] Look back at S&B Chap. 21.

collision is exceedingly small, but the sun has an awful lot of deuterium nuclei densely packed, and there is no escape for the deuterium nuclei. As a consequence, the sun consumes 600 million tons a second of hydrogen, converting it into 596 million tons of helium.

In a fusion reactor one needs much greater efficiency, because we have less material and there is an unavoidable loss of energy and of deuterium atoms from the reactor. The temperature at which the rate of power generation exceeeds loss is called the **critical ignition temperature**. For the deuterium–deutermium reaction this is about 4×10^8 K, equivalent to 35 keV, while for deuterium–tritium it is 4.5×10^7 K, equivalent to 4 keV. Power is lost due to X-ray emissions when these particles collide without fusing.

Of course the collision rate depends not only on T but also on the density of nuclei n. To get more energy out than you used to heat the stuff up in the first place, there needs to be a certain probability that any one nucleus will fuse before it escapes. Of course that will depend on the **confinement time** τ. Lawson showed that the product of ion density and confinement time needs to be big enough:

$$\begin{aligned} n\tau &\geq 10^{14}\text{s/cm}^3 \qquad\qquad (D-T)\\ n\tau &\geq 10^{16}\text{s/cm}^3 \qquad\qquad (D-D) \end{aligned}$$

where $n\tau$ is known as the **Lawson number**.

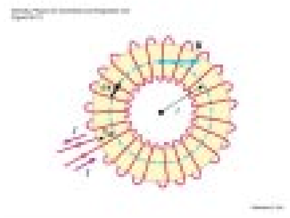
2 Magnetic Confinement

If you go to your local Pottery Barn and try to buy a vessel to hold a **deuterium plasma** hotter than 10^7 K, they will not be able to satisfy your needs. How do we contain the nuclei we wish to fuse?

Firstly, I said plasma rather than gas, because at temperatures much greater than 13.6 eV$/k_B$, the probability the electrons will be attached to the nuclei in atoms is very slim. We essentially have a gas of uncoupled nuclei and electrons. Needless to say, at temperatures at which atoms dissociate you certainly don't get solids, so the confinement cannot be with material vessels. There are currently two ways do try to confine the plasma, magnetic confinement and inertial confinement.

The basic ideas of magnetic confinement were discussed in section 27.4. You will recall that charged particles move in orbits which circle around magnetic field lines while simultaneously moving along the field lines. We discussed a magnetic bottle in which the particles not only wrap around the field lines, and thus are confined transverse to the lines, but also mostly bounce back from regions where the field gets stronger. But there is always leakage out of the ends of the magnetic bottle.

One way to avoid loss from the ends is to have no ends. So we can curve the field lines around into circles, and get a **toroidal field**. This is what we get from a current through a toroidal winding (around a donut), which we considered in Ex. 28.11. Then the field lines are circles which go around the hole in the donut and come back on themselves. If a particle wraps around a field line it will never get to the icing of the donut.



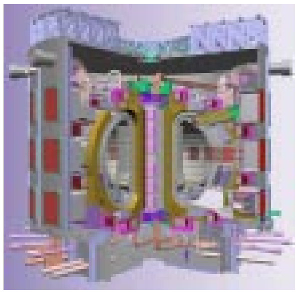
Actually we also induce a toroidal current in the plasma itself, which causes a magnetic field wrapping around the short direction of the donut, up through the hole and down on the outside. This is called a **poloidal field**. Adding this field to the toroidal field, we get field lines which wind in curved helices around the donut. In addition to creating the poloidal field, the current passing through the plasma helps to heat the plasma. Other means are also used to heat the plasma, including shooting high energy neutral beams and rf electromagnetic beams into it.

S&B 45.10a
poloidal field

An example of such a reactor is the tokamak fusion test reactor (TFTR) which was the leading fusion energy experiment in the '80s and early 90's, down the road at the Princeton Plasma lab. This facility reached temperatures of more than 5×10^8 K and Lawson values of $10^{13}\mathrm{s/cm}^3$ in a 50-50 mixture of deuterium and tritium, producing over 10^7 W. It has, however, been shut down since 1997. In its place they have now the National Spherical Torus Experiment.

TFTR: PPL's tokamak, 1982–1997

National Spherical Torus Experiment, PPL



A newer tokamak project by Canada, Europe, Japan and Russia is called ITER, the International Thermonuclear Experimental Reactor. In February 2003, the US announced it would join the project, 10 days after China did the same. The proposed sites are in France, Canada, Japan, and Spain. Here is what its reactor will look like. Notice the person at the bottom!

There is also an American project called FIRE, or Fusion Ignition Research Experiment.

The history of projects promising to bring cheap fusion energy in abundance has been long and disappointing. Deuterium is plentiful and cheap, free to get and you get about 3 grams per dollar in extraction costs. 3 grams could produce about 7×10^{11} J, or 200,000 kwh. It also seems like the possible processes are cleaner than with fission energy, as the products of the reaction itself are harmless. From the 1950's on, people have been saying that while a great deal of development will be necessary before fusion energy is a practical, economic way to produce energy, these problems should be resolvable, and we should have fusion power plants in about thirty years. Unfortunately the thirty year figure has not changed since the 1950's, so one may be a bit skeptical. But there really is promise, in the long run, for fusion energy.

Inertial Confinement

In a hydrogen bomb confining the plasma is not much of a problem. The creation of the plasma and the fusion takes place so quickly that the nuclei simply can't get out of the way fast enough. So another approach to controlled fusion is to make little hydrogen bombs.

In real hydrogen bombs the plasma is created by exploding an atomic (fission) bomb, and this has a minimum size rather too large for *controlled* fusion. Another way to try to get the deuterium dense and hot enough is to squeeze a little pellet of frozen deuterium. At the National Ignition Facility at the Lawrence Livermore National Laboratory, 192 huge laser beams will fire 1.8 MJ of light from all sides on a tiny pellet of deuterium and tritium. These beams will vaporize the surface of the pellet and compress the insides to 1000 times the density of water, and incredibly hot temperatures. This will be enough to trigger the reaction (7), Here are some pictures.

Containment Vessel for the pellets.

Cables from capacitors to excite laser amplifiers.

Assuming we can make the pellets explode and give off more energy than was used to fire at the pellets in the first place, how can we make practical use of such a device? Or if we can produce fusion in a magnetically confined region, the same question arises. There are two problems. One is capturing the energy. Most of the energy released is in the kinetic energy of the neutrons, which will escape the reaction region. The other is that we need tritium as well as deuterium. One proposed solution to both problems is to surround the reaction region with liquid lithium, used as a heat exchanger. The lithium will absorb the energy of the neutrons, and some of the neutrons will react with the lithium

$$ {}^1_0\mathrm{n} + {}^6_3\mathrm{Li} \longrightarrow {}^3_1\mathrm{H} + {}^4_2\mathrm{He}. $$

S&B 45.15
fusion reactor,
Li→T
9 3/4" × 6 1/4"

This makes new tritium which can be used to mix with new deuterium to make more fuel.

We have just given a brief overview of two approaches to nuclear power, fission and fusion. Fission currently plays a major role in worldwide energy supply, but nuclear energy will be required even more in the future, with fusion a very promising long range prospect.

3 Radiation Damage

We have been thinking of radiation in terms of the good it can do, but of course everyone knows that radiation is dangerous stuff. We mean, of course, not infrared or microwave or visible or EMF radiation, but radiation at X-ray and gamma ray energies.

Materials that are irradiated can be damaged in several ways. An energetic charged particle can destroy molecular bonds, and even a nonenergetic charged particle, lodged in an insulating substance, can produce weakness in the material. Of course of the greatest concern is when the damaged molecular structure is in someone's DNA. Within a general cell in the body this is **somatic damage**, and can cause the death of the cell, or even worse, cause the cell to become cancerous. The word somatic is in contrast to **genetic damage**, which refers to damage to cells involved in reproduction, where any damage may be inherited by offspring.

The units of radiation are rather confused. There are **roentgen** and **rad**s and **rem** which are supposed to be increasing relevant measures of biological damage rather than only numbers of charged particles per unit area. I am not going to discuss this.

4 Detectors

We mentioned earlier a **Geiger counter**, which is a device to measure charged particle rays by means of an ionization chamber. A strong electric field is set up between two plates, in a region with neutral gas — when an ionizing particle passes through the gas, it knocks some electrons out of atoms, leaving seperated positively and negatively charged particles which are accelerated in opposite directions by the electric field. They gain energy and can produce further ionization, so that a significant current can flow momentarily between the plates. This can be set up either to click, as we saw last week, or to read average current off a meter, as here.

show Geiger counter

There are also *semiconductor devices*, in particular diodes, which work on the increase in charged carriers when ionizing radiation knocks electrons out of their usual states.

Scintillation counters are transparent media which have atoms which are excited when a charged particle passes through them, and which then emit light when the atom returns to its ground state. Usually these are attached to a photomultiplier tube by means of a light pipe.

show light pipe and photomultiplier tube

The photomultiplier tube works by photoemission of an electron from a "photocathode", which is in the presence of a sequence of plates at increasing positive voltages, say 200 V apart. The electrons are accelerated to significant energies by these voltages, so when they strike the plate they knock out several electrons each, which then do the same in the next stage. Thus a large current will flow from the highest voltage plate triggered by a single optical photon.

There are a number of track detectors, which not only detect the charged ray but record the track in some way. The simplest is **photographic emulsion**, for a charged particle can disrupt the sensitive atoms just as photons do, and after development there will be a track in the emulsion where the particle passed. In **cloud chambers** a supercooled gas can be triggered to condense into a fog when a charged particle passes though — we have one here which may or may not work. **Bubble chambers** do exactly the reverse — hydrogen in liquid form at its boiling point is exposed to charged particles and the pressure immediately dropped. The hydrogen will then boil, but it will do so first along the path of disturbed atoms where the charged particles passed. Finally we mention a **spark chamber**, which is like a geiger counter in that it works on ionization in an intense electric field, but with a method of determining where the discharge took place. This may be by photographing the visible sparks or by measuring time delays in electrical signals, determining where along a wire the current flowed.

Neutral beams are harder to detect. Fast neutrons do interact with nuclei and so will ionize hydrogen gas. High energy gamma rays will interact with matter and produce showers of electrons and positrons