PGH136: Nuclear Fusion

Script to Screencast on Nuclear Fusion

[Fig 34.11]
We've talked about nuclear fission, where the nucleus of heavy atoms such as uranium split into smaller and lighter nuclei. And, how energy is liberated in the fission process.
[Fig 34.21 top]
Now we talk of the opposite process, where the nuclei of light atoms combine to form heavier nuclei—and, also with the release of much energy.
[photo fission reactor]
Initiating nuclear fusion turns out to be a difficult thing to achieve. All nuclear power plants in the world today are fission power plants. Initiating fission is relatively easy if you have an ample supply of fissionable isotopes. Initiating fusion is another story.
[photos of particle accelerators]
All atomic nuclei are positively charged. How do you push a proton against another, for example, against the enormous electric force of repulsion between them? In an accelerator it's easy. You just accelerate a proton to high energy and fire it at a target that may contain other protons. But that involves just a few protons and releases very little energy. In fact, you put more energy in than you get out. Achieving fusion in bulk matter in order to release considerable energy is a much bigger challenge.
[close-up photo Sun]
Fusion occurs in the Sun's interior due to its environment of enormous heat and gravitational contraction. Fusion in the Sun is called *thermonuclear fusion*, because it is initiated by thermal means. At very high temperatures, some protons move against others so fast that they get close enough to fuse. You may be surprised to learn, that even in the solar interior thermonuclear fusion is rare. If it weren't, the Sun would have expired long ago.
[photo Earth]How about fusion in bulk matter here on Earth?

Prior to the development of the fission bomb, the temperatures required to overcome mutual proton repulsion and initiate nuclear fusion on Earth were unattainable. When it was found that the temperatures inside an exploding fission bomb would be appreciably greater than the temperature at the center of the Sun, the thermonuclear bomb was but a step away.

[2 H-bomb blast photos]

This first hydrogen bomb was detonated in 1952. Whereas the critical mass of fissionable material limits the size of a fission bomb, no such limit is imposed on a fusion bomb, which is to say a thermonuclear, or hydrogen, bomb. Just as there is no limit to the size of an oil-storage depot, there is no theoretical limit to the size of a fusion bomb. Like the oil in a storage depot, any amount of fusion fuel can be stored with safety until it is ignited.

[Fig 34.22 cartoon of bombs]

Although a mere match can ignite an oil depot, nothing less energetic than a fission bomb can ignite a thermonuclear bomb. We can see that there is no such thing as a "baby" hydrogen bomb. It cannot be less energetic than its fuse, which is a fission bomb.

The hydrogen bomb is another example of a discovery applied to destructive rather than constructive purposes. The potential constructive side of the picture is the controlled release of vast amounts of clean energy.

[Fig 34.16 ‘empty graph’]

To understand the vast energy release in nuclear fusion, let’s return to what I consider the most important graph in my treatment of Conceptual Physics, the plot of mass-per-nucleon versus atomic number. We can look at the graph as a sort of “energy valley.”

It applies very nicely to the nuclear process of fusion.

[Fig 34.19 curve with data]

Here we see a pair of hydrogen nuclei that fuse to become helium. The nuclei are those of the heavy isotope hydrogen-2, called deuterium. On this graph, the element helium is lower on the curve. The nucleons in helium have less mass than they did as hydrogen, as if they trimmed their mass to form a helium nucleus.

It’s easy to see that the steepest side of the energy valley on the left side, where the lower atomic numbers are. Average mass per nucleon decreases along the elements from hydrogen to iron.

[$E = mc^2$]

Decreased mass, in accord with $E = mc^2$, means energy is released. So when two small nuclei fuse, the mass of the fused nucleus is less than the total mass of the two single nuclei before fusion. Hence, energy is released.

Recall this graph illustrating fission.

[Fig 34.17 fission part]

In fission reactions, the amount of matter that is converted to energy is about 0.1%; in fusion, it can be as much as 0.7%. These numbers apply whether the process takes place in bombs, in reactors, or in stars. The decrease in mass is transformed into energy, chiefly in the kinetic energy of the product nuclei.

[back to Fig 34.19 curve with fusion data]

Interestingly, most of the energy of nuclear fusion is *also* in the kinetic energy of its products.

[Fig 34.21 reactions (top only)]

Here’s an actual fusion reaction that involves isotopes of hydrogen, or deuterium. We see that the two identical isotopes fuse to become an isotope of helium, helium-3, and a free neutron. The energy release is 3.26 MeV, that’s million electron volts, a considerable amount of energy for so little mass.

[Fig 34.21 reactions (+ bottom)]

Here’s another typical fusion reaction. This one involves another isotope of hydrogen, tritium, that has two neutrons along with its single proton. We see the deuterium and the tritium fuse to become the common isotope of helium, helium-4, plus a free neutron. This is a more energetic reaction, yielding 17.6 MeV of energy.

Notice in these two reactions, the result is not a sole helium isotope, but one with a free neutron. Here’s the interesting thing: The reaction wouldn’t occur without the neutron to carry the energy away! A lone-nucleus product is not in accord with the conservation of momentum and energy. If a lone helium nucleus flies away after the reaction, it adds momentum that wasn’t there initially.

Or if it remains motionless, there’s no mechanism for energy release. So, because a single product particle can’t move and it can’t sit still, it isn’t formed. That’s why the fusion of two deuterons to form an alpha particle—that is, a helium-4 nucleus—doesn’t take place in a single step. Fusion normally occurs in intermediate steps and requires the creation of at least two particles to share the released energy.

Yum physics! Now here's an important statement:

Both fission and fusion reactions can occur only if there are two or more products of the reaction to carry away energy.

Physics rules, whether at the nuclear level or otherwise.

In the next lesson we'll contemplate controlled fusion.

For now, I want to leave you with a question.

Nuclear energy is released when atoms split apart. Now we learn that nuclear energy is released when atoms combine. Is this a contradiction? How can energy be released by opposite processes?

Until next time, good fusion energy.

[Answer: Energy is released in any nuclear reaction in which the mass of the nuclei after the reaction is less than the mass of the nuclei before. When light nuclei, such as those of hydrogen, fuse to form heavier nuclei, total nuclear mass decreases. When heavy nuclei, such as those of uranium, split to become lighter nuclei, total nuclear mass also decreases. So in both processes decreased mass transforms to energy.]