Chapter 7:
The Fires of Nuclear Fission

Nuclear Fuel

A nuclear fuel pellet contains about 4 grams of fuel

It produces the same amount of energy as a ton of coal or 150 gallons of gasoline

It's fairly cheap - $3 per pellet (compare to 150 gallons of gasoline!)

It produces no greenhouse gases, nor VOCs, nor NO, nor SO_2

It does not rely on petroleum

So why isn't it the primary fuel used in the U.S.?

Nuclear Fuel

The answer: radioactivity

Spent fuel pellets emit radioactive particles (we’ll learn what this means later)

“Radioactivity” carries with it images of Nagasaki, Hiroshima, Chernobyl

But these catastrophes are NOT typical of nuclear fuel

The leftover residue is “toxic” ...

... but is that so different than gasoline and coal?

Nuclear Power

Consider This 7.1:

A) Given a choice between your town building a nuclear power plant and a coal-burning power plant, which would you choose?

B) Under what circumstances, if any, would you be willing to change your mind?

Nuclear Power

In the U.S., 20% of electricity is generated by nuclear plants

But **no** new nuclear plants have been constructed since 1978

In 1979, Three Mile Island (Harrisburg, PA) experienced a partial meltdown

Since then, 9 nuclear plants have closed:

- Couldn’t compete with natural gas

Recent demands for energy have slowed the decommissioning – will new plants be built?

Nuclear Power

What **is** nuclear power?

Nuclear power plants run on the principle of **nuclear fission**:

The process of splitting a large **nucleus** into smaller ones, usually by bombarding the target nucleus with neutrons

Why does this produce energy?

The products of this reaction actually possess **slightly** less **mass** than the reactants

Nuclear Fission

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"But wait", you say...

Table 1.8 Characteristics of Chemical Equations

Always Conserved

Identity of atoms in reactants = Identity of atoms in products
Number of atoms in reactants = Number of atoms in products
Mass of all reactants = Mass of all products

May Change

Number of molecules in reactants may differ from number of molecules in products
Physical states (*s*, *l*, or *g*) of reactants may differ from physical states of products

Nuclear Fission

The products of this reaction actually possess **slightly** less **mass** than the reactants

“But wait”, you say...

In earlier chapters, we said that mass was conserved (Ch. 1) and that energy was conserved (Ch. 4).

This is, strictly speaking, not true.

Neither property is conserved *independently of the other*

In ALL “normal” reactions, the assumption that they are independently conserved is valid

Nuclear Fission

Recall that we said that the total energy of a system must be conserved, but that energy could be transformed from one “type” of energy to another

This is what takes place in nuclear reactions – the mass of the nucleus itself is converted into energy

Nuclear reactions are NOT “normal” – they involve **tremendous** amounts of energy

Nuclear Fission

In fact, we will see that **none** of these "conserved" properties must be conserved in a nuclear ("abnormal"?) reaction

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Nuclear Fission

If we accept that mass can be converted into energy – which is to say that mass is just another form of energy – there must be a way to express that conversion

The ***Einstein Equation***:

$$E = mc^2$$

$$\text{Energy} = \text{mass x (speed of light)}^2$$

Note the units here... c is a large number!

$(3.0 \times 10^8\ m/s)^2 = 9.0 \times 10^{16}\ m^2/s^2$

1 Joule = 1 kg m^2/s^2

Small changes in mass make for HUGE changes in energy

Nuclear Fission

Let’s take a specific example:

The fission of Uranium-235

Recall from Chapter 2 that atoms can exist as different **isotopes**, each of which must contain the same number of protons as each other, but which contain a different number of neutrons

Protons = atomic number, this **defines** the element

Neutrons, together with protons, make up the mass of the nucleus

Nuclear Fission

We write the symbol for these isotopes differently, to reflect the different number of neutrons *and thus the different atomic masses*

Table 2.3 Isotopes of Hydrogen

Isotope	Isotopic Symbol	Number of Protons	Number of Neutrons	Sum of Protons and Neutrons
hydrogen, H-1	$^{1}_{1}H$	1	0	1
deuterium, H-2	$^{2}_{1}H$	1	1	2
tritium, H-3	$^{3}_{1}H$	1	2	3

Nuclear Fission

Similarly, Uranium (element number 92) has several isotopes, and U-235 has a mass number of 235, written:

$$^{235}_{92}U$$

In order for Uranium-235 to undergo fission, it must be struck by a neutron

A bare neutron has no protons, but a mass number of one, and can thus be written:

$$^{1}_{0}n$$

Nuclear Fission

So, if we want to write down our reaction, we would begin by writing our reactants:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow$$

But what are our products? It is true that we *could* produce a different isotope of Uranium here by adding a neutron:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U$$

But that's not what happens. What happens is more complicated.

Nuclear Fission

Rather than simply adding a new neutron, the Uranium nucleus undergoes **fission**, breaking apart into smaller nuclei. One such reaction is:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

Note that rules of balancing DO still apply to nuclear equations:

Protons on the left = 92

Protons on the right = 56 + 36 =92

Mass numbers on the left = 235 + 1 = 236

Mass numbers on the right = 141+ 92+ 3 = 236

Nuclear Fission

$$ {}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n $$

But two things should worry you about this analysis:

- Why do neutrons appear on both sides? Shouldn't they cancel?
- If the mass numbers on both sides are equal, where is the energy coming from?

Nuclear Fission

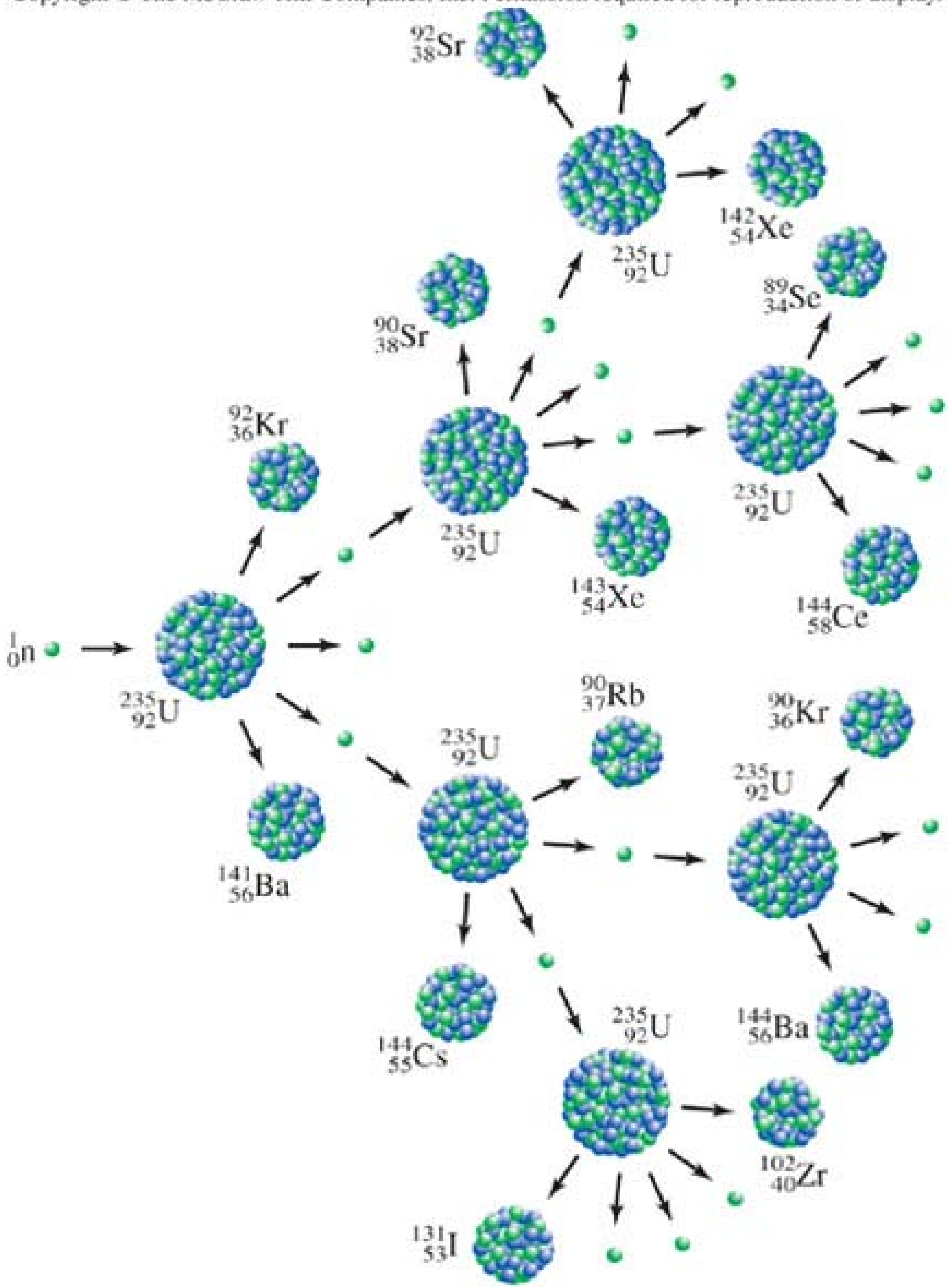
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

Why do neutrons appear on both sides? Normally, we would cancel them out. But here, they play a crucial role in *describing* the reaction

It’s true that we’re left with a **net** increase of only 2 neutrons

But it’s also true that we put one neutron in, and got three out – and those three are important!

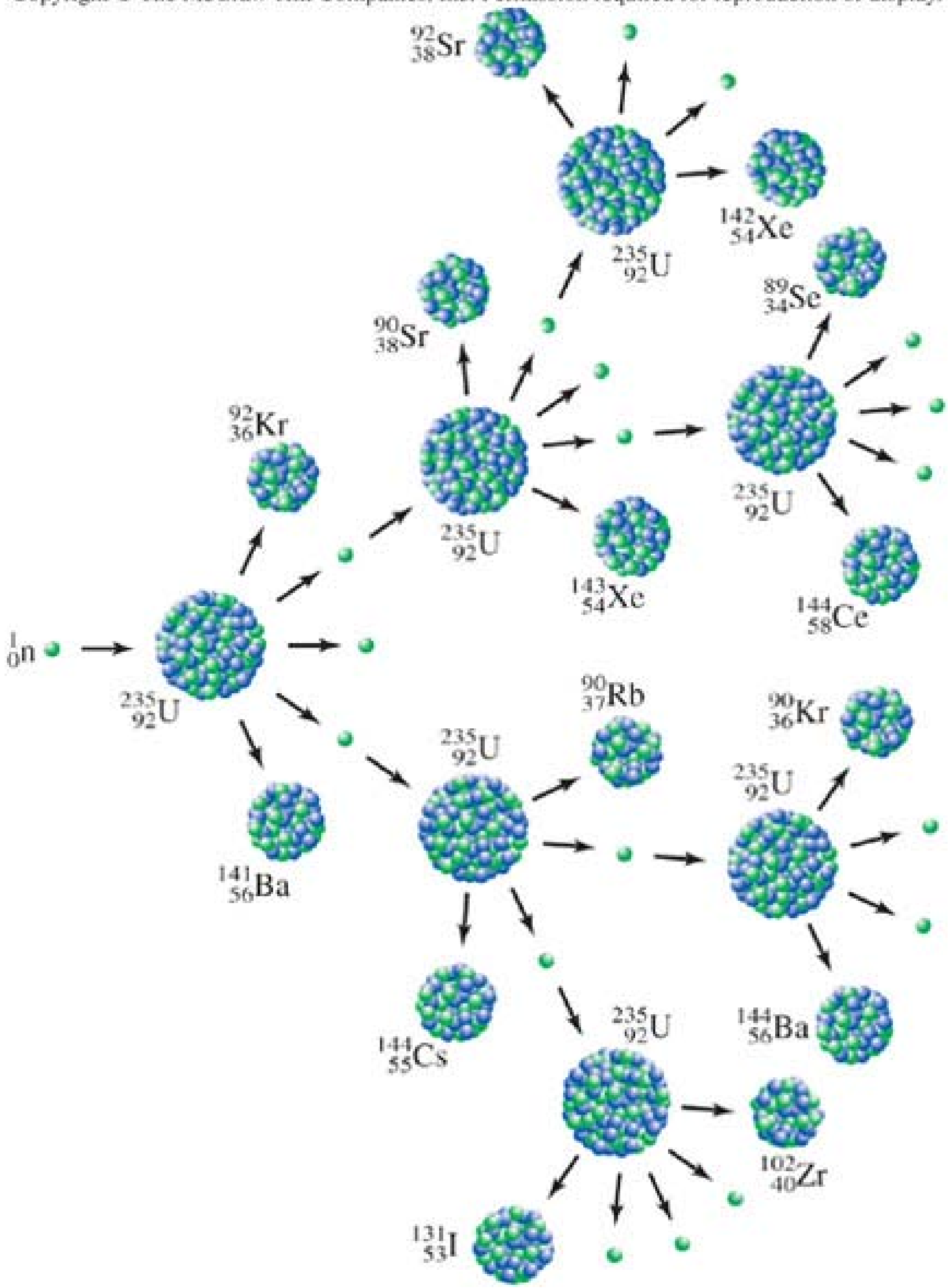
They initiate a **chain reaction**



A chain reaction is one in which the **products** of an initial step undergo further reaction

Here, the three neutrons emitted by the fission process can strike **other** nearby U-235 atoms, and induce fission in them

... Producing **more** neutrons, which can go on to strike **more** nearby U-235 atoms...



An important concept with regard to chain reactions is that of **critical mass**:

The amount of fissionable material which is necessary to sustain the chain reaction

For U-235, this is 15 kg:

If 15 kg of U-235 is contained in the same place, it will undergo **spontaneous** fission

This is the principle behind nuclear bombs

Nuclear Fission

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

If the mass numbers on both sides are equal, where is the energy coming from?

Recall that the **actual** mass of a nucleus is not simply the mass number:

In order to define the mass number, we declared that protons and neutrons weigh exactly the same amount, and that electrons don’t weigh anything

Neither of these statements is true, although both are good approximations

Nuclear Fission

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

In fact, an atom of U-235 weighs 235.043924 amu

An atom of Kr-92 weighs 91.926156 amu

An atom of Ba-141 weighs 140.914412 amu

A neutron weighs 1.00866 amu

So, the reactants weigh 236.052584 amu

The products weigh 235.866548 amu

Over the course of this reaction, 0.186036 amu of matter is converted into energy

Nuclear Fission

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

Over the course of this reaction, 0.186036 amu of matter is converted into energy

That's about 1/1000th of the total mass

How much energy is produced from the fission of 1 kg of U-235?

$E = mc^2 = [(1/1000)(1\ kg)](9.0x10^{16}\ m^2/s^2)$

$= 9.0\ x\ 10^{13}$ Joules!

This is the same amount of energy as from 33,000 tons of TNT, or 3300 tons of coal

Change of Pace:
Your Letters Assignment

<u>Letter</u>: The Letter is worth **20%** of your final grade.

It is due on April 26th – there will be no quiz and no homework that week to ensure that you have the time to complete the assignment

As a large part of the job of an environmental scientist is that of communicating to the masses, I would like you to show your proficiency in describing the science we've covered in class to a lay-person.

You will write a letter to your fictional great aunt, who is 85 years old and lives in Nebraska.

Your aunt has found out you were taking this course. She is so thrilled because she watches CNN and hears all about environmental issues, but since she hasn’t taken a science class in 70 years and has spent her whole life working on her farm, she doesn’t quite understand what the problems and solutions are.

Could you please explain to her **(*in no more than two pages*)** what is the big deal about ONE of the following issues, **and** *what can she do to make a difference*:

Global Warming
The Ozone Hole
Alternative fuels to replace petroleum

Write this assignment **as a personal letter**

Do not attempt to persuade your aunt with math and chemical equations – it's all gobbledygook to her.

Use everyday language to explain the issues and the possible solutions

You can't explain everything in two pages – you'll have to decide what is important enough to include

If your aunt is really confused by your letter, she may write back and ask for some clarification. If you're going to write her a second letter, it will be due on the last day of classes.