Energy
on this world and elsewhere

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Course web site available at www.phys.virginia.edu,
click on classes and find Physics 1110.
or at http://people.virginia.edu/~gdc4k/phys111/fall11

Lecture 22, November 10, 2011
Announcements

• Homework will be due on Tuesday November 15th, by 6pm.
• Problem sessions, Monday the 14th and Tuesday the 15th, from 4-5:30, in room 313.
• Midterm will be on November 17th.
• Review on Tuesday in class, office hours on Wednesday.
• Read Capter 13 of Richter’s book
Nuclear Power
The relative abundance of nuclear fuel

- U.S. Reserves @ $100/lb or less: 1,227 million pounds uranium oxide (557 thousand metric tons)
- U.S. Reserves plus estimated additional resources @ $100/lb. or less: 6,077 million pounds (2.76 million metric tons).
- Loaded into U.S. reactors in 2008 51.3 million pounds.
- Reserves at this rate would last 23.9 years.
- Reserves and resources at this rate would last 118.5 years.
- Most uranium ore is presently imported.
- The above times estimates are based on a “once-through” fuel cycle.
The relative abundance of nuclear fuel

Note the number reported in this pie chart for the U.S. (342 thousand metric tons at roughly $60/lb) is from the 2006 numbers from the World Energy Council.
Price is VERY important in determining the size of available resources.
Isotopes
The structure of atoms

- The atomic nucleus contains protons and neutrons. Collectively they are referred to as "nucleons".
- The nucleus is surrounded by a cloud of electrons.
- Whereas the nucleus has a diameter of a few "femptometers", or $10^{-15}$ meters, an atom has a diameter of around $10^{-10}$ meters, or an Ångstrom.
- If the atom were the size of a football field, the nucleus would be around one millimeter, or the size of a grain of sand.
The number of protons in the nucleus determines the element associated with the atom

- 1 proton: hydrogen
- 2 protons: helium
- 3 protons: lithium
- 4 protons: beryllium
- 5 protons: boron
- 6 protons: carbon

Why is it that the number of protons determines the number of electrons?

Because atoms are usually neutral, so the number of protons also determines the number of electrons, and the number of electrons determines the atom's chemical properties.
The number of protons in the nucleus determines what element the atom is.

This atom has two protons and two neutrons in its nucleus, making it an isotope of helium (He-4).

This atom has three protons and four neutrons in its nucleus, making it an isotope of lithium (Li-7).
The number of protons in the nucleus determines what element the atom is.
So when we speak of isotopes, we are generally referring to a specific element.
Isotopes

• If two nuclei have the same number of protons but different numbers of neutrons, we say that they are two isotopes of a particular element.
• A nucleus is always a particular isotope of an element.
• A nucleus is uniquely identified when you identify both the element and the “mass number”, the total number of neutrons plus protons.
• Two nuclei with the same mass number but different numbers of protons are not the same isotope, they are two particular isotopes of two different elements.
Two isotopes of helium

- Both isotopes have two protons, as they must to be the same element.
- One isotope has two neutrons, the other isotope has one neutron.
Two isotopes of the same element have the same chemical properties, but different nuclear properties.

\[ ^{133}_{55}\text{cesium (stable)} \]
\[ ^{137}_{55}\text{cesium (unstable or radioactive)} \]

78 neutrons
55 protons

82 neutrons
55 protons
Identifying a particular isotope

The “mass number”, equal to the total number of protons plus the total number of neutrons.

Sometimes one would also just refer to this as U-235

The “atomic number”, which is equal to the number of protons. This number is sometimes left out since it is essentially redundant with the chemical symbol.

The “chemical symbol” (here U for uranium) identifying the element.
Uranium comes in two isotopes: one is fissionable, one is not (at least not with slow neutrons).

99.28% of all uranium is U-238
U-238
When hit by a neutron it will sometimes undergo fission, but most of the time the neutron is just absorbed.

0.72% of all uranium is U-235
U-235
When hit by a neutron it will almost always undergo fission.
Isotopic enrichment

It is very difficult to separate out different isotopes of a given element.

• Chemical technique cannot be used because different isotopes have the same chemical properties.
• It is necessary to take advantage of the slightly different mass of the two isotopes.
• Something called gas-diffusion separation, combined with mass spectrometers were used during WWII.
• The more modern technique involves vacuum ultracentrifuges, invented by Jesse Beams right here at UVa.

\[
\begin{align*}
\text{238} & \quad \text{U} \\
\text{235} & \quad \text{U}
\end{align*}
\]
Secret efforts to develop the bomb

Article from NY Times the day after the bombing of Hiroshima (August 7th, 1945) describing the “hidden cities” where the materials to make the bombs, and the bombs themselves, were produced.
Making a bomb out of uranium.

Gas Centrifuge

The use of centrifugal fields for isotope separation was first suggested in 1919; but efforts in this direction were unsuccessful until 1934, when J.W. Beams and co-workers at the University of Virginia applied a vacuum ultracentrifuge to the separation of chlorine isotopes. Although abandoned midway through the Manhattan Project, the gas centrifuge uranium-enrichment process has been highly developed and used to produce both HEU and LEU. It is likely to be the preferred technology of the future due to its relatively low-energy consumption, short equilibrium time, and modular design features.
The vacuum ultracentrifuge

Invented by Jesse Beams at UVa, the ultracentrifuge spins incredibly fast, separating things according to their weight. For uranium, the compound uranium hexafluoride (UF₆) is used.

Above, Jesse Beams receives the Nation Medal of Science from President Johnson in 1967.
Clicker question

What is the designation of the isotope shown at right?

\[
\begin{align*}
\frac{2}{1}\text{He} & \quad \frac{2}{3}\text{He} & \quad \frac{1}{2}\text{He} & \quad \frac{3}{2}\text{He} & \quad \frac{3}{1}\text{He} \\
\text{A.} & \quad \text{B.} & \quad \text{C.} & \quad \text{D.} & \quad \text{E.}
\end{align*}
\]
Fission reactions in uranium

An example of a fission reaction.

$$^{235}\text{U} + n \rightarrow ^{236}\text{U} \rightarrow ^{140}\text{Xe} + ^{94}\text{Sr} + 2\text{n} + 200\text{ MeV}$$
Uranium-235 can undergo “fission”

While both isotopes of uranium can undergo fission, only $^{235}\text{U}$ will undergo fission after absorbing a slow neutron.

Note that after fissioning, the resulting nuclei are in a size range where a lower neutron to proton ratio is favored.
In a very real sense, a chain reaction is the same thing as the phenomena of burning when considered in the context of chemistry.
Notice that on average, every mousetrap must release more than one ball or the chain reaction will not grow in size.
Nuclear reactors

- Pellets of uranium oxide are combined into what are called fuel rods.
- The fuel rods are arranged into a matrix.
- The space between the fuel rods is filled with a “moderator” that slows down the neutrons after they emerge from a fission reaction.
- Control rods, that are very good at absorbing neutrons, are inserted and withdrawn to control the rate at which reactions take place.