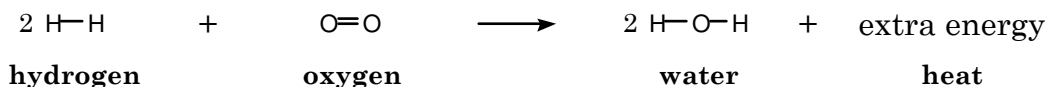


## ENERGY II

### NUCLEAR ENERGY

#### NUCLEAR ENERGY

The last form of energy to be considered is nuclear energy, which is in a class by itself. While all forms of energy have a mass equivalence, this equivalence is, except for nuclear reactions, insignificantly small and cannot be detected. For example, we do believe that in the chemical reaction of hydrogen with oxygen to give water, the mass of water formed will be less than that of the sum of the masses of hydrogen and oxygen that have been used.



The difference, however, the “mass equivalence” of the extra energy, will be so small as to be undetectable, being on the order of 1 part in a million million.

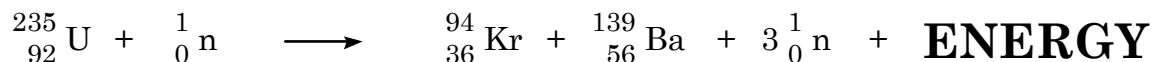
It is important to remember that all *chemical* reactions involve only a *recombination* of the original atoms. No atom is either created or destroyed. Indeed the word “atom” is derived from the Greek word “atomos”, which means “uncuttable”.

#### *Nuclear reactions*

In contrast, *nuclear* reactions involve a change of one type of atom into another type of atom. The energies involved in nuclear changes are vastly greater than those involved in chemical changes. The possibility of cutting, or “splitting”, an atom was unsuspected until 1938.

#### *A nuclear reaction*

The reaction of a neutron with a uranium atom is probably the most famous nuclear reaction.



The most significant thing about this reaction is the huge amount of energy that is produced. The second most significant thing about this reaction is the fact that while *one* neutron is consumed, *three* neutrons are produced.

### *A nuclear reactor*

Under some conditions the nuclear reaction will take place at a low and constant rate; these are the conditions of a nuclear reactor. The energy from the nuclear reaction is typically used to produce steam at a high pressure and high temperature. The steam then rotates a turbine, which turns a generator, which produces electricity.

### *A nuclear bomb*

Under other conditions the nuclear reaction can take place at a high and accelerating rate, bursting its container, and destroying everything in the neighborhood; these are the conditions of a nuclear bomb.

These two possibilities are analogous to those for the chemical reaction of hydrogen with oxygen. Under some conditions the reaction will push the spaceship into orbit; under other conditions the reaction can destroy the spaceship.

## **The structure of the atom**

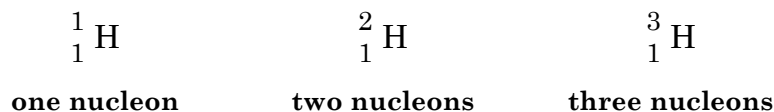
Atoms, we now know, have parts. There are the *electrons*, negatively charged, that surround the nucleus and give the atom its size. Then there are the *protons*, positively charged, in the middle, in the nucleus. The number of protons in the nucleus, the “proton number” determines the chemical identity of the element. For a neutral atom the number of electrons equals the number of protons. The protons, however, are much heavier than the electrons. The “proton number” is usually called the *atomic number*.

### *Isotopes*

There is a third component of an atom, an uncharged particle called a *neutron*, about as massive as a proton and also found in the nucleus. It turns out that the atoms of many elements can differ in neutron number even though, to be the same element, they have the same proton number. These different versions of the same element are called *isotopes* (*same place*, in the periodic table of the elements). The isotopes of hydrogen provide an illustration.

### *The isotopes of hydrogen*

There are three known isotopes of hydrogen, and we can represent them in this way.



one proton	one proton	one proton
one electron	one electron	one electron
no neutrons	one neutron	two neutrons
hydrogen	deuterium	tritium
stable	stable	unstable
99.985%	0.015%	0

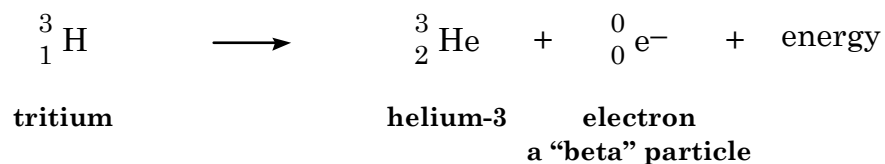
**the three isotopes of hydrogen**

The subscript indicates the *proton number*; for all isotopes of hydrogen the proton number is, by definition, 1. The superscript indicates the total number of nucleons, protons plus neutrons. The superscript is also the *mass number*. Since both the proton and the neutron have a nominal mass of 1, the number of nucleons and the mass number of the isotope are the same. The electrons are so much less massive than the nucleons that they can be ignored in this approximation. The neutron number is not explicitly indicated; it is the difference between the mass number and the proton number. Thus “ordinary” hydrogen has no neutrons in its nucleus, “heavy” hydrogen, deuterium, has one neutron in addition to the proton, and tritium has two neutrons in the nucleus in addition to the proton.

The “hydrogen” found in Nature is almost entirely “ordinary” hydrogen (99.85% is “ordinary”), but there is also a little “heavy hydrogen”, or deuterium present (0.15%). Thus in a random sample of 10,000 “hydrogen” atoms there will be 9,985 atoms of ordinary hydrogen and 15 atoms of deuterium. There will be no tritium.

### *Unstable isotopes*

The reason no tritium is to be found in Nature is that the tritium nucleus is unstable; it spontaneously turns into something else. This change can be represented by the following equation.



In effect, one of the two neutrons of tritium turns into a proton and an electron, and the electron is ejected from the nucleus, a process called *beta decay*. The nucleus still has three nucleons, but now there is only *one* neutron and *two protons*. The nucleus of the original hydrogen atom has become the nucleus of one of the isotopes of helium, “Helium-3”. Helium-3, of atomic number 2, is stable, and has an abundance such that of 10,000,000 “helium”

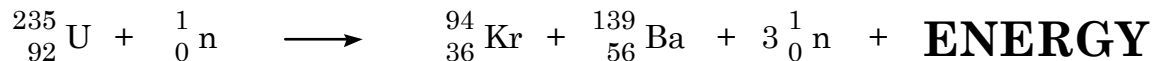
atoms, there will be only 15 atoms of helium-3, all the rest being helium-4, the other stable isotope of helium.

### *Half-time; half-life*

How unstable is tritium? How fast does tritium “decay”? How fast does tritium turn into helium-3? In 12.3 years only half of the original amount of tritium will remain; the other half will have turned into helium-3. In another 12.3 years only a quarter of the original tritium will be left, three-quarters of the original tritium having turned into helium-3. And so on. The time of 12.3 years is called the *half-time*, or *half-life* of tritium. This short half-life is the reason that the natural abundance of tritium is essentially zero; it changes into helium-3, and the helium-3 accumulates.

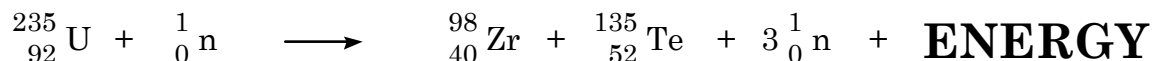
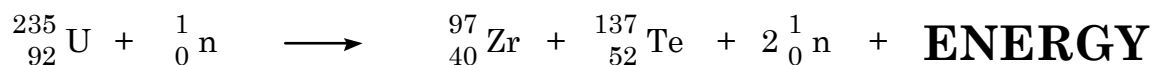
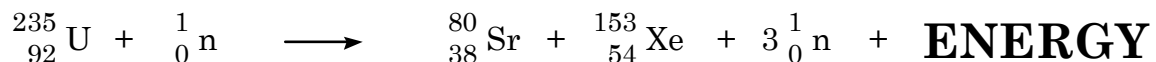
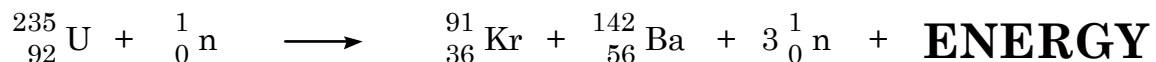
### *More about the fission of uranium*

A little earlier we considered the nuclear reaction of uranium-235 with a neutron to give krypton-94, barium-139, three neutrons, and an enormous amount of energy. We represented the reaction in this way.



As the equation indicates, the reaction involves the neutron-induced *splitting*, or *fission*, of the nucleus of the uranium atom into the nuclei of two lighter elements.

It turns out that a uranium atom can split in several different ways, and some of the other possibilities are shown here.



Many of the fission reactions produce three neutrons, but others give only two. The average yield of neutrons from the fission of uranium is slightly less than 2.5 per fission event.

### *Nuclear power stations*

The *neutron-induced* fission of uranium-235 provides the energy for the generation of about 8% of the electrical energy produced in this country. Although uranium-235 will undergo *spontaneous* fission, the rate of spontaneous fission is extremely low. That is, uranium-235 has a very long half-life. Nevertheless, even though uranium-235 has a half-life of more than 700 million years the natural abundance of uranium-235 is only 0.7%, with the remainder being uranium-238. That is, out of every 1000 atoms of “uranium” only 7 are uranium-235.

### *Enrichment of uranium-235*

A concentration of 7 atoms per thousand is too dilute to sustain a neutron-induced fission of uranium-235. The concentration of uranium-235 atoms must be increased. The natural mixture of uranium isotopes must be enriched to at least 4% (40 per thousand) U-235 for use in a nuclear power station.

Similar considerations apply to the burning of hydrogen. Two million molecules of air contain 420,000 molecules of oxygen but only 1 molecule of hydrogen. The hydrogen content of air must be enriched to about 5% (100,000 molecules per 2,000,000 molecules of air) to sustain combustion of hydrogen in air, and to about 20% (400,000 molecules of hydrogen per 2,000,000 molecules of air) for an explosive reaction.

### *Thermal neutrons*

There is yet another factor that must be taken into account in designing a nuclear reactor. Not all neutrons are created equal, and the “right” kind is in the minority. The neutrons created by fission differ in speed, and the fast neutrons don’t even notice the uranium-235 nuclei. The neutrons must be slowed down.

Since temperature is a measure of the average kinetic energy of a material substance, we can say that neutrons that move very fast, the “hot” neutrons, must be slowed down to the average kinetic energy of the interior of the reactor. The “hot” neutrons must be converted to *thermal* neutrons. Thermal neutrons react very readily with uranium-235 nuclei.

The mechanism for “thermalization” can be compared to the “break” in pool. The cue ball, the “hot” ball, hits the massed balls, transferring the cue ball’s excess energy to the massed balls. The cue ball is thus “thermalized”, and the massed balls are somewhat energized.

In the nuclear reactor the uranium-containing fuel elements are suspended

in water. As the “hot” neutrons exit the fuel element and enter the water they collide with the protons of the water molecules. After 15 or so such collisions the hot neutrons have been thermalized and the water has been warmed. We will consider later how the thermal energy of the hot water, *extremely* hot water, is converted to electricity. In these reactors, in which water thermalizes the “hot” neutrons, water is called the *moderator*.

### *Neutron cross-section*

The nuclei of U-235 atoms look small to fast neutrons. In contrast, the nuclei of U-235 nuclei look big to thermal neutrons. Earlier we said that under some circumstances light acts as a particle, and that under other circumstances light acts as a wave. We do not ask what light “is”. Here we say that under some circumstances the U-235 nucleus looks small (to “hot” neutrons) but that under other circumstances the same nucleus looks big (to thermal neutrons). We do not ask how big the nucleus *is*. We say that for “hot” neutrons the U-235 nucleus has a small “cross-section”, while for thermal neutrons the U-235 nucleus has a large “cross-section”. The nuclear *cross-section* is an expression of the probability that a particular reaction will take place under the specified conditions. The cross-section of U-235 for thermal neutrons is about 580 barns. Yes, “barn” as in “as big as a barn”. A *barn* is  $1 \times 10^{-24}$  square centimeters.

### *Control rods*

There is yet another consideration in the design of a nuclear power reactor. As we said earlier the average fission event for U-235 produces about 2.5 neutrons. There is therefore the possibility that the first fission event will cause a second, and the second will cause a third, and so on. That is, there is the possibility for a *chain* reaction.

However, since more than one neutron is formed in each fission event, it is also possible for one fission event to cause two or even three additional fission events. Thus there is also the possibility for a *branching chain* reaction. A branching chain reaction would be extraordinarily dangerous as it would cause the nuclear reaction to accelerate out of control. Mechanisms are therefore needed that will stabilize the neutron flux at an appropriate level.

One of these mechanisms is the insertion into the reactor of materials that will absorb neutrons, the so-called *control rods*. These control rods typically contain compounds of either boron or cadmium, since these elements have isotopes that are strong absorbers of thermal neutrons.

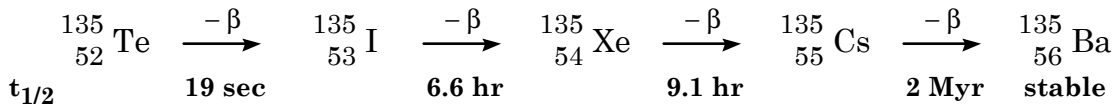
Cadmium-113, 12% natural abundance, for example, has a thermal neutron

cross-section of about 20,000 barns, and it was cadmium control rods that were used to control the first sustained nuclear reaction, which took place in the squash court at the University of Chicago on December 2, 1942. Since this experiment had never been done before, there were, in addition to the last control rod which was automatically controlled, three young men, the “suicide squad” perched on top of the pile, under the ceiling, ready to pour on buckets of a cadmium solution in case something “unexpected” were to happen.

### *Xenon poisoning*

When the first Hanford reactor was started it had run for only a few hours at a rate of 100 megawatts when it unexpectedly slowed down and stopped. It was restarted the next day, but after a few hours it again stopped.

The presence of xenon-135 was found to be the cause. Although xenon-135 is only a minor product of the direct fission of U-235, xenon-135 is also formed indirectly by beta decay of tellurium-135 by way of iodine-135.



The yield of tellurium-52 from the direct fission of U-235 is about 6%, and it, with a half-life for beta emission of only 19 seconds, immediately turns into iodine-135. Iodine-135, with a half-life of 6.6 hours for beta emission then more slowly turns into xenon-135.

The “problem” with xenon-135 is that it has the “highest neutron absorbing ability of any known material”. For thermal neutrons its cross-section is two million (yes, 2,000,000) barns. To thermal neutrons the nucleus of xenon-135 looks two million times bigger than it “really” is. After absorbing a neutron xenon-135 has become xenon-136, which, having a cross-section for thermal neutrons of only 280 barns, has almost no attraction for another neutron. Thus if the formation of xenon-135 is not anticipated, the neutron flux of the reactor can fall below the level needed to sustain the nuclear chain reaction. However, if one waits for a while, the concentration of xenon-135, with a half-time of 9.1 hours for beta-decay, will decrease as the xenon-135 turns into cesium-135. The reactor can then be restarted; cesium-135 has no interest in neutrons. Over a period of a few million years cesium-135 turns into barium-135, which is stable.

### *Chernobyl*

One of the explanations proposed to account for the nuclear accident at Chernobyl on April 25-26, 1986, is that the operators at the time did not fully understand “xenon poisoning”. Here is a simplified version of the story. When the power of the reactor began to drop because the increase in the concentration of xenon-135 was reducing the neutron flux the operators pulled out the control rods beyond the specified limit in an attempt to compensate. As the xenon-135 was “burned” into xenon-136 by the increasing neutron flux caused by withdrawal of the control rods the power of the reactor surged to more than 100 times the operating level because the control rods could not be reinserted fast enough.

### *Nuclear power reactors worldwide*

As of June, 2006, according to the International Atomic Energy Agency, there were 446 nuclear power plants in operation worldwide, one in long-term shutdown, and 27 under construction. Nuclear power currently generates more than 80% of the electricity in France, and more than 35% of the electricity in Japan.

### *Nuclear power reactors in the United States*

As of June, 2006, there were 104 nuclear power reactors in the United States, which generate, as we said, about 8% of the electricity used in this country. The last nuclear power plant constructed, Watts Bar #1, in Tennessee, was started in 1973, completed in 1996, and came on line in 1997. Watts Bar #2 remains partly completed.

Of the 104 power reactors in the United States, 69 are boiling water reactors, and 35 are pressurized water reactors. There are also 36 research and test reactors in the US, and the US Navy has, as of 2004, 105 reactors that power 11 aircraft carriers, 9 cruisers, and many smaller vessels.

### *Boiling water reactors*

In a boiling water reactor, *BWR*, the water that surrounds the fuel elements, the reactor *core*, is partially converted to steam (the water *boils*). The water is under pressure, however, and so the boiling temperature is higher than the 100 °C boiling point of water under a pressure of 1 atmosphere. At the typical pressure of a BWR of about 75 atmospheres the boiling temperature, and thus the temperature of the steam that is produced, is about 285 °C. This high temperature, high pressure steam is then passed to the turbines that run the generators that produce the electricity.

### *The Duane Arnold nuclear plant*



The Duane Arnold nuclear generating plant, the only nuclear generating plant in Iowa, is a boiling water reactor. It came on line in February, 1975, and is one of only 8 US nuclear generating stations of less than 600 net Megawatts electric in capacity. Of the 31 states with nuclear capacity Iowa ranks number 30. In Iowa in 2003, 85% of the electricity was generated from coal, and 10% was generated from nuclear energy.

### *Pressurized water reactors*

Pressurized water reactors, PWR, differ from BWR in that the containment pressure is higher for PWR, about 150 atmospheres rather than only 75 atmospheres for BWR. The temperature of the water in a PWR is allowed to reach only about 320 °C, and under these conditions the water does *not* boil. The 320 °C water from the reactor core is circulated to a heat exchanger where the 320 °C water boils water in a separate loop at lower pressure to provide the steam for the turbines that generate the electricity.

The significant difference between a BWR and a PWR is that in a BWR the steam for the generators is produced *directly* from the water that cools the core, and in a PWR the steam for the generators is produced *indirectly* from water separate from the water that cools the core. In a PRW the generators are isolated from the slight radioactive contamination of the cooling water.

### *Radioactivity*

Originally radioactivity referred to a mysterious process whereby photographic plates became “exposed” even though they were wrapped in black paper and kept in the dark. The darkening of the plates appeared to be caused by “emanations” from the potassium uranyl sulfate that had been stored next to the plates. While it was Henri Becquerel who made these observations, it was Marie Curie who named the phenomenon *radioactivity*.

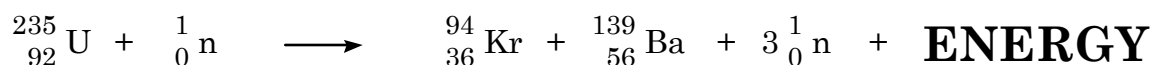
We now know of three types of “emanation”: the  $\alpha$  type, the  $\beta$  type, and the  $\gamma$  type. The  $\alpha$  and  $\beta$  types are material in nature, but the  $\gamma$  type is high-energy electromagnetic radiation. The  $\alpha$  type is the combination of 2 protons and 2 neutrons, and is known as an  $\alpha$  particle. The  $\alpha$  particle is the nucleus of a helium atom, and every helium atom on earth originated as an  $\alpha$  particle. The  $\beta$  particle, as we have mentioned, is an electron.

Materials that spontaneously emit  $\alpha$  particles,  $\beta$  particles, or  $\gamma$  rays are said to be *radioactive*. All three of these “emanations” carry enough energy to dislodge electrons from other atoms, and this is the property by which they are detected: exposure of film, a Geiger counter (a sort of photoelectric effect), a scintillation counter, and many others.

The ability to dislodge electrons is also the reason that radioactivity is bad for your health, as explained earlier when we talked about ultraviolet light.

### *The source of nuclear energy*

Although we imply in the equation for the neutron-induced fission of U-235 that the mass of the product nucleons ( $94 + 139 + 1 + 1 + 1 = 236$ ) is the same as the mass of the reactant nucleons ( $235 + 1 = 236$ ), the truth is that the product nucleons are just slightly lighter than the starting nucleons. The enormous energy produced by the reaction is the energy equivalent to the loss of mass during the reaction.



### *Comparison of chemical and nuclear energy*

The concept here applies just as well for chemical reactions, as we have said, as it does for nuclear reactions. The difference is a *difference in scale*. The mass differences in nuclear reactions (rearrangement of nucleons) is very much larger than the mass differences in chemical reactions (rearrangement of electrons only). The difference in scale is about 7 orders of magnitude. The mass loss and energy production in a nuclear reaction is 10,000,000 times larger than the mass loss and energy production in a chemical reaction.

### *Rates of nuclear reactions*

Nuclear reactions, just like chemical reactions, can take place at a constant rate, as we have just seen. Nuclear reactions can also take place at an accelerating rate in which all the energy is released in a very short period of time, as an *explosion*. It is possible for the chemical reaction of hydrogen with oxygen to take place in an explosive manner, as can the decomposition of trinitrotoluene (TNT), or nitroglycerine (dynamite).

In order to understand the conditions that can lead to a nuclear explosion we need to consider the concepts of critical concentration and criticality.

### *Critical concentration*

For the neutron-induced fission of U-235 in a power reactor a certain minimum concentration of U-235, or *critical concentration*, is needed so as to have a sustained, or “steady state” nuclear chain reaction and production of nuclear energy. The natural level, or natural abundance, of 0.7% U-235 in uranium is too low, and “enriched” material is required. At the natural

concentration of fissile U-235 nuclei too many neutrons escape, and not enough meet another U-235 nucleus and cause another fission event.

Since total size and weight considerations are unimportant in a stationary nuclear power generating station, nuclear power plants can be made to work with 3 to 5% U-235, making up for the low concentration of U-235 with large size and other factors.

Greater degrees of enrichment of uranium with respect to U-235 allow the construction of smaller reactors. All navy reactors and some research reactors, for example, use highly enriched uranium, *HEU*, uranium whose U-235 content is greater than 20%. The leftovers from enrichment are called *depleted uranium*.

### *Critical mass*

Even more highly enriched uranium, or *weapons grade*, uranium contains at least 93.5% U-235. At this concentration almost all of a sample of uranium is fissile, and its measure can now be *mass*. The minimum mass that will sustain a fission reaction is called the *critical mass*. The critical mass of uranium-235, for example, is a sphere of the metal about 7 inches in diameter and weighing about 25 pounds. Here is the way a critical mass of U-235 has been described. “The critical mass for an unreflected sphere of U-235 is about 50 kilograms.” A sphere is the most favorable shape for retaining neutrons, and “unreflected” means that nothing but air surrounds the sphere.

If something more substantial than air surrounds the sphere, a *neutron reflector*, the sphere could be as small as 6 inches in diameter. A neutron reflector, water or graphite, for example, is analogous to a moderator. The reflector randomizes the direction of the escaping neutrons, and some that would otherwise escape are redirected toward the uranium sphere.

### *Criticality*

When a nuclear reactor reaches the steady state of a *sustained* nuclear chain reaction and constant production of energy it is in the *critical* state. This is the desirable operating state of a nuclear reactor.

Before the reactor reaches criticality the reactor is *subcritical*. In a subcritical state the chain reaction cannot be sustained because as the U-235 is consumed the neutron flux will decrease. Increasing the neutron flux by withdrawing control rods will compensate, and further withdrawal of control rods will lead in a linear manner to a new subcritical state with a higher rate of reaction and greater rate of production of energy.

Once the critical state has been reached, however, any increase in the neutron flux will lead to a *supercritical* state and an extremely rapid, exponential, increase in rate and energy production.

### *Prompt and delayed neutrons*

As we have said, each neutron-induced fission event of U-235 results, on the average, in the release of about 2.5 neutrons. More exactly, for every 100 fission events 242 neutrons are released immediately (the *prompt* neutrons), and 1.58 neutrons are released later (the *delayed* neutrons) by neutron-emitting fission products. Or, for 200 fission events there will be 484 prompt neutrons and 3 delayed neutrons.

The key to success in nuclear power generation, first recognized by Enrico Fermi, is to reach a state of criticality that relies on *both prompt and delayed* neutrons. Such a critical state is called a *delayed critical* state. The reactor is subcritical with respect to prompt neutrons, and goes supercritical only with the contribution of delayed neutrons. This is the desired and controllable state of a nuclear power reactor. It is controllable because the “lifetime” of a delayed neutron, the time between the fission event in which its emitter was formed and the time at which the neutron initiates another fission event, can be as long as 10 seconds; time enough for a control rod to move.

A state to be absolutely avoided is a state of criticality that is supported by prompt neutrons alone, the *prompt critical* state, a supercritical state. The lifetime of a prompt neutron is on the order of 0.0001 second; not nearly time enough for a control rod to make an effective adjustment.

### *Nuclear accidents*

At this time there have been only two accidents in which it has been suspected that a prompt critical state might have been reached. One was the case of Chernobyl #4, a power reactor in Russia, and the other the case of SL-1, a research reactor in Idaho. “At 9:01 p. m. on January 3, 1961, ... the SL-1 went prompt critical.” In 0.004 seconds the power surge had caused the cooling water to be explosively vaporized, an event that destroyed the reactor and killed the operator and two observers. The explosion in this case, and in the Chernobyl case, was a steam explosion, not a nuclear explosion. Although prompt criticality might have been reached, certainly in the SL-1 case, there was no confinement, and a nuclear explosion was not possible.

The evidence for prompt criticality in the SL-1 case was the recovery of radioactive gold-198 from a gold watch band and copper-64 from a screw in a cigarette lighter. These unnatural isotopes contain an extra neutron.

### *Nuclear explosions*

The first requirement for a nuclear explosion is a supercritical mass, not merely a multiplying factor for successive generations of neutrons of just barely larger than 1 but at least as large as 2.

Then, in order that the result not be a “supercritical fizzle”, the supercritical mass must be confined. *Confinement* is largely inertial, achieved by surrounding the critical mass with thousands of pounds of metal, some of which also acts as a neutron reflector.

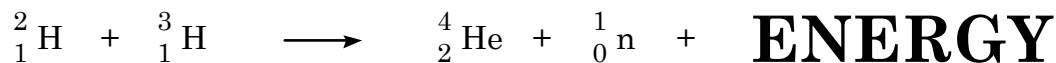
### *Formation of a superprompt critical mass*

A supercritical mass can be assembled by pushing together two subcritical masses. One approach is to “shoot” one subcritical mass from a “gun” into the other subcritical mass. This will work for an explosive device based on U-235 because the spontaneous fission rate for this isotope of uranium is only about 0.2 to 0.3 disintegrations per second per kilogram (U-235 has a half-life of more than 700 million years). The gun-type assembly method has a “critical insertion time” of about 0.001 second and so there is only a small probability for the spontaneous production of two or three neutrons during insertion. To ensure rapid multiplication after insertion a neutron source is placed where the moving subcritical mass will stop.

### *Nuclear fusion*

We have seen that energy can be produced by splitting certain large atoms; energy from nuclear *fission*. Energy can also be produced by forcing together two small nuclei to make the nucleus of a helium atom; energy from nuclear *fusion*.

The most promising possibility appears to be the fusion of the nucleus of a deuterium atom with the nucleus of a tritium atom, the D-T fusion, to give a helium nucleus, a neutron, and about four times the energy of a fission process from comparable masses of starting materials.



While fission will occur spontaneously, fusion requires the investment of a huge amount of energy.

Although the energy produced by the sun is due to fusion of hydrogen to form helium, with 5 million metric tons of mass being converted to energy per second, no practical method for the net production of energy from a fusion

reaction has yet been developed on earth.

### **Summary of Energy II; nuclear energy**

- Nuclear reactions; fission of uranium
- Structure of the atom; isotopes; isotopes of hydrogen
- Unstable isotopes; half-life
- Nuclear power stations: enrichment of uranium; thermal neutrons; neutron cross-section; control rods; xenon poisoning; Chernobyl; nuclear power reactors worldwide; nuclear power reactors in the United States; boiling water reactors; pressurized water reactors
- Radioactivity
- Source of nuclear energy; comparison of chemical and nuclear energy
- Rates of nuclear reactions; critical concentration; critical mass; criticality; prompt and delayed neutrons; nuclear accidents
- Nuclear explosions; superprompt critical mass; confinement
- Nuclear fusion