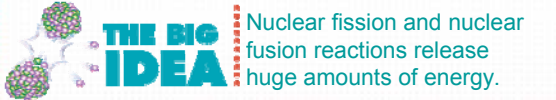



40 Nuclear Fission and Fusion Conceptual Physics



THE BIG IDEA Nuclear fission and nuclear fusion reactions release huge amounts of energy.

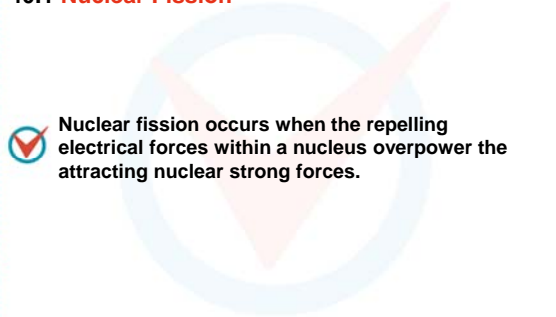
40 Nuclear Fission and Fusion Conceptual Physics

In 1939, just at the beginning of World War II, a nuclear reaction was discovered that released much more energy per atom than radioactivity, and had the potential to be used for both explosions and power production. This was the splitting of the atom, or *nuclear fission*.



40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission



Nuclear fission occurs when the repelling electrical forces within a nucleus overpower the attracting nuclear strong forces.

40 Nuclear Fission and Fusion Conceptual Physics

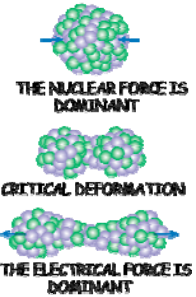
40.1 Nuclear Fission

The splitting of atomic nuclei is called **nuclear fission**. Nuclear fission involves the balance between the nuclear strong forces and the electrical forces within the nucleus. In all known nuclei, the nuclear strong forces dominate. In uranium, however, this domination is tenuous. If the uranium nucleus is stretched into an elongated shape, electrical forces may push it into an even more elongated shape.

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

Nuclear deformation leads to fission when repelling electrical forces dominate over attracting nuclear forces.



40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

The absorption of a neutron by a uranium nucleus supplies enough energy to cause such an elongation. The resulting fission process may produce many different combinations of smaller nuclei. The fission of one U-235 atom releases about seven million times the energy released by the explosion of one TNT molecule. This energy is mainly in the form of kinetic energy of the fission fragments.

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

In a typical example of nuclear fission, one neutron starts the fission of the uranium atom and three more neutrons are produced when the uranium fissions.

$${}^1_0\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3({}^1_0\text{n})$$

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

Chain Reaction

Note that one neutron starts the fission of the uranium atom, and, in the example shown, three more neutrons are produced.

- Most nuclear fission reactions produce two or three neutrons.
- These neutrons can, in turn, cause the fissioning of two or three other nuclei, releasing from four to nine more neutrons.
- If each of these succeeds in splitting an atom, the next step will produce between 8 and 27 neutrons, and so on.

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

A **chain reaction** is a self-sustaining reaction. A reaction event stimulates additional reaction events to keep the process going.

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

Chain reactions do not occur in uranium ore deposits. Fission occurs mainly for the rare isotope U-235. Only 0.7% or 1 part in 140 of uranium is U-235. The prevalent isotope, U-238, absorbs neutrons but does not undergo fission. A chain reaction stops as the U-238 absorbs neutrons.

U-235 U-238

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

If a chain reaction occurred in a chunk of pure U-235 the size of a baseball, an enormous explosion would likely result. In a smaller chunk of pure U-235, however, no explosion would occur.

- A neutron ejected by a fission event travels a certain average distance before encountering another uranium nucleus.
- If the piece of uranium is too small, a neutron is likely to escape through the surface before it "finds" another nucleus.
- Fewer than one neutron per fission will be available to trigger more fission, and the chain reaction will die out.

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

An exaggerated view of a chain reaction is shown here.

- In a small piece of pure U-235, the chain reaction dies out.

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

An exaggerated view of a chain reaction is shown here.

- In a small piece of pure U-235, the chain reaction dies out.
- In a larger piece, a chain reaction builds up.

PHASION

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

Critical Mass

The **critical mass** is the amount of mass for which each fission event produces, on the average, one additional fission event.

A *subcritical* mass is one in which the chain reaction dies out. A *supercritical* mass is one in which the chain reaction builds up explosively.

PHASION

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

Two pieces of pure U-235 are stable if each of them is subcritical.

If the pieces are joined together and the combined mass is supercritical, we have a nuclear fission bomb.

PHASION

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

Each piece is subcritical because a neutron is likely to escape. When the pieces are combined, there is less chance that a neutron will escape. The combination may be supercritical.

PHASION

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

A simplified diagram of a uranium fission bomb is shown here.

TNT TO DRIVE URANIUM PIECES QUICKLY TOGETHER

SUBCRITICAL PIECES OF URANIUM

RADIOACTIVE SOURCE THAT SUPPLIES FREE NEUTRONS

PHASION

40 Nuclear Fission and Fusion Conceptual Physics

40.1 Nuclear Fission

Building a uranium fission bomb is not a formidable task. The difficulty is separating enough U-235 from the more abundant U-238.

It took more than two years to extract enough U-235 from uranium ore to make the bomb that was detonated over Hiroshima in 1945.

Uranium isotope separation is still a difficult, expensive process today.

PHASION

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.1 Nuclear Fission

think!

Five kilograms of U-235 broken up into small separated chunks is subcritical, but if the chunks are put together in a ball shape, it is supercritical. Why?

PEARSON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.1 Nuclear Fission

think!

Five kilograms of U-235 broken up into small separated chunks is subcritical, but if the chunks are put together in a ball shape, it is supercritical. Why?

Answer:

Five kilograms of U-235 in small chunks will not support a sustained reaction because the path for a neutron in each chunk is so short that the neutron is likely to escape through the surface without causing fission. When the chunks are brought together there is sufficient material that the neutron is likely to hit a nucleus and to cause fission rather than escape.

PEARSON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics


40.1 Nuclear Fission

CONCEPT CHECK: What causes nuclear fission?

PEARSON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.2 Uranium Enrichment

 In order to sustain a chain reaction in uranium, the sample used must contain a higher percentage of U-235 than occurs naturally.

PEARSON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.2 Uranium Enrichment

Uranium-235 undergoes fission when it absorbs a neutron, but uranium-238 normally doesn't.

To sustain a chain reaction in uranium, the sample must contain a higher percentage of U-235 than occurs naturally. Since atoms U-235 and U-238 are virtually identical chemically, they cannot be separated by a chemical reaction. They must be separated by physical means.

PEARSON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.2 Uranium Enrichment

Gaseous diffusion takes advantage of the difference in their masses.

- For a given temperature, heavier molecules move more slowly on average than lighter ones.
- Gaseous diffusion uses uranium hexafluoride (UF_6) gas.
- Molecules of the gas with U-235 move faster than molecules with U-238.
- Lighter molecules containing U-235 hit a diffusion membrane on average 0.4% more often than a molecule with U-238.

PEARSON

40 Nuclear Fission and Fusion Conceptual Physics

40.2 Uranium Enrichment

Gas leaving the chamber is slightly enriched in the U-235 isotope.

The gas is passed through thousands of interconnected stages to enrich uranium sufficiently in the U-235 isotope for it to be used in a power reactor (3% U-235) or a bomb (U-235 > 90%).

A newer method of isotope separation involves gas centrifuges. The uranium hexafluoride gas is spun at high speed. The lighter molecules with U-235 tend toward the center of the centrifuge.


40 Nuclear Fission and Fusion Conceptual Physics

40.2 Uranium Enrichment

CONCEPT CHECK: What is necessary to sustain a chain reaction?

40 Nuclear Fission and Fusion Conceptual Physics

40.3 The Nuclear Fission Reactor

 A nuclear fission reactor generates energy through a controlled nuclear fission reaction.

40 Nuclear Fission and Fusion Conceptual Physics

40.3 The Nuclear Fission Reactor

A liter of gasoline can be used to make a violent explosion. Or it can be burned slowly to power an automobile.

Similarly, uranium can be used for bombs or in the controlled environment of a power reactor.

About 19% of electrical energy in the United States is generated by nuclear fission reactors.

40 Nuclear Fission and Fusion Conceptual Physics

40.3 The Nuclear Fission Reactor

A nuclear fission reactor generates energy through a controlled nuclear fission reaction.

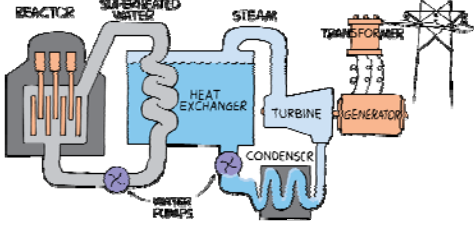
These reactors are nuclear furnaces, which boil water to produce steam for a turbine.

One kilogram of uranium fuel, less than the size of a baseball, yields more energy than 30 freight-car loads of coal.

40 Nuclear Fission and Fusion Conceptual Physics

40.3 The Nuclear Fission Reactor

A nuclear fission power plant converts nuclear energy to electrical energy.



40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics x

40.3 The Nuclear Fission Reactor

Components of a Fission Reactor

A reactor contains three main components:

- the nuclear fuel combined with a moderator,
- the control rods, and
- water.

PEARSON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics x

40.3 The Nuclear Fission Reactor

The nuclear fuel is uranium, with its fissionable isotope U-235 enriched to about 3%. Because the U-235 is so highly diluted with U-238, an explosion like that of a nuclear bomb is not possible.

The moderator may be graphite or it may be water.

PEARSON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics x

40.3 The Nuclear Fission Reactor

Control rods that can be moved in and out of the reactor control how many neutrons are available to trigger additional fission events.

The control rods are made of a material (usually cadmium or boron) that readily absorbs neutrons.

Heated water around the nuclear fuel is kept under high pressure and is thus brought to a high temperature without boiling.

It transfers heat to a second, lower-pressure water system, which operates the electric generator in a conventional fashion.

PEARSON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics x

40.3 The Nuclear Fission Reactor

Waste Products of Fission

A major drawback to fission power is the generation of radioactive waste products of fission.

When uranium fissions into two smaller elements, the ratio of neutrons to protons in the product is too great to be stable.

These fission products are radioactive.

Safely disposing of these waste products requires special storage casks and procedures, and is subject to a developing technology.

PEARSON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics x

40.3 The Nuclear Fission Reactor

American policy has been to look for ways to deeply bury radioactive wastes.

Many scientists argue that "spent" nuclear fuel should first be treated in ways to derive value from it or make it less hazardous.

If these wastes are kept where they are accessible, it may turn out that they can be modified to be less of a danger to future generations than is thought at present.

PEARSON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics x

40.3 The Nuclear Fission Reactor

think!

What would happen if a nuclear reactor had no control rods?

PEARSON

40 Nuclear Fission and Fusion Conceptual Physics

40.3 The Nuclear Fission Reactor

think!

What would happen if a nuclear reactor had no control rods?

Answer:

Control rods control the number of neutrons that participate in a chain reaction. They thereby keep the reactor in its critical state. Without the control rods, the reactor could become subcritical or supercritical.


40 Nuclear Fission and Fusion Conceptual Physics

40.3 The Nuclear Fission Reactor

CONCEPT CHECK: How does a nuclear fission reactor generate energy?

40 Nuclear Fission and Fusion Conceptual Physics

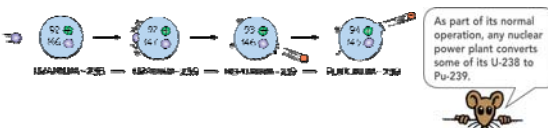
40.4 Plutonium

 Pu-239, like U-235, will undergo fission when it captures a neutron.

40 Nuclear Fission and Fusion Conceptual Physics

40.4 Plutonium

When a neutron is absorbed by a U-238 nucleus, no fission results. The nucleus that is created, U-239, emits a beta particle instead and becomes an isotope of the element *neptunium*. This isotope, Np-239, soon emits a beta particle and becomes an isotope of *plutonium*. This isotope, Pu-239, like U-235, will undergo fission when it captures a neutron.



40 Nuclear Fission and Fusion Conceptual Physics

40.4 Plutonium

The half-life of neptunium-239 is only 2.3 days, while the half-life of plutonium-239 is about 24,000 years. Plutonium can be separated from uranium by ordinary chemical methods. It is relatively easy to separate plutonium from uranium.

40 Nuclear Fission and Fusion Conceptual Physics

40.4 Plutonium

The element plutonium is chemically a poison in the same sense as are lead and arsenic. It attacks the nervous system and can cause paralysis. Death can follow if the dose is sufficiently large. Fortunately, plutonium rapidly combines with oxygen to form three compounds, PuO, PuO₂, and Pu₂O₃. These plutonium compounds do not attack the nervous system and have been found to be biologically harmless.

40 Nuclear Fission and Fusion Conceptual Physics

40.4 Plutonium

Plutonium in any form, however, is radioactively toxic. It is more toxic than uranium, although less toxic than radium.

Pu-239 emits high-energy alpha particles, which kill cells rather than simply disrupting them and leading to mutations.

The greatest danger that plutonium presents is its potential for use in nuclear fission bombs. Its usefulness is in breeder reactors.


40 Nuclear Fission and Fusion Conceptual Physics

40.4 Plutonium

CONCEPT CHECK: What happens when Pu-239 captures a neutron?

40 Nuclear Fission and Fusion Conceptual Physics

40.5 The Breeder Reactor

 A breeder reactor converts a non-fissionable uranium isotope into a fissionable plutonium isotope.

40 Nuclear Fission and Fusion Conceptual Physics

40.5 The Breeder Reactor

When small amounts of Pu-239 are mixed with U-238 in a reactor, the plutonium liberates neutrons that convert non-fissionable U-238 into more of the fissionable Pu-239.

This process not only produces useful energy, it also “breeds” more fission fuel. A reactor with this fuel is a breeder reactor.

A **breeder reactor** is a nuclear fission reactor that produces more nuclear fuel than it consumes.

40 Nuclear Fission and Fusion Conceptual Physics

40.5 The Breeder Reactor

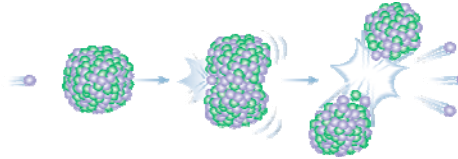
After the initial high costs of building such a device, this is an economical method of producing vast amounts of energy.

After a few years of operation, breeder-reactor power utilities breed twice as much fuel as they start with.

40 Nuclear Fission and Fusion Conceptual Physics

40.5 The Breeder Reactor

Pu-239, like U-235, undergoes fission when it captures a neutron.



40 Nuclear Fission and Fusion Conceptual Physics

40.5 The Breeder Reactor

Fission power has several benefits.

- It supplies plentiful electricity.
- It conserves the many billions of tons of coal, oil, and natural gas every year.
- It eliminates the megatons of sulfur oxides and other poisons that are put into the air each year by the burning of these fuels.
- It produces no carbon dioxide or other greenhouse gases.

40 Nuclear Fission and Fusion Conceptual Physics

40.5 The Breeder Reactor

The drawbacks of fission power include:


- the problems of storing radioactive wastes,
- the production of plutonium,
- the danger of nuclear weapons proliferation, and
- low-level release of radioactive materials into the air and groundwater, and the risk of an accidental (or terrorist-caused) release of large amounts of radioactivity.

40 Nuclear Fission and Fusion Conceptual Physics

40.5 The Breeder Reactor

Reasoned judgment is not made by considering only the benefits or the drawbacks of fission power. You must also compare nuclear fission to alternate power sources. Fission power is a subject of much debate.

Know nukes before you say "No nukes!"



40 Nuclear Fission and Fusion Conceptual Physics

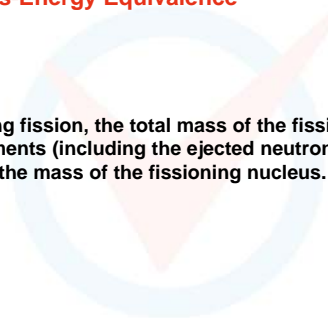
40.5 The Breeder Reactor

CONCEPT CHECK What is the function of a breeder reactor?

40 Nuclear Fission and Fusion Conceptual Physics

40.6 Mass-Energy Equivalence

✓ During fission, the total mass of the fission fragments (including the ejected neutrons) is less than the mass of the fissioning nucleus.

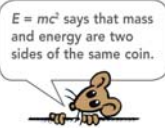


40 Nuclear Fission and Fusion Conceptual Physics

40.6 Mass-Energy Equivalence

The key to understanding why a great deal of energy is released in nuclear reactions is the equivalence of mass and energy. Mass and energy are essentially the same—they are two sides of the same coin. Mass is like a super storage battery. It stores energy that can be released if and when the mass decreases.

$E = mc^2$ says that mass and energy are two sides of the same coin.



40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

Mass Energy

If you stacked up 238 bricks, the mass of the stack would be equal to the sum of the masses of the bricks.

Is the mass of a U-238 nucleus equal to the sum of the masses of the 238 nucleons that make it up?

Consider the work that would be required to separate all the nucleons from a nucleus.

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

Recall that work, which transfers energy, is equal to the product of force and distance.

Imagine that you can reach into a U-238 nucleus and, pulling with a force, remove one nucleon.

That would require considerable work.

Then keep repeating the process until you end up with 238 nucleons, stationary and well separated.

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics


40.6 Mass-Energy Equivalence

You started with one stationary nucleus containing 238 particles and ended with 238 separate stationary particles.

Work is required to pull a nucleon from an atomic nucleus. This work goes into *mass* energy.

The separated nucleons have a total mass greater than the mass of the original nucleus.

The extra mass, multiplied by the square of the speed of light, is exactly equal to your energy input: $\Delta E = \Delta mc^2$.



40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics


40.6 Mass-Energy Equivalence

Binding Energy

One way to interpret this mass change is that a nucleon inside a nucleus has less mass than its rest mass outside the nucleus.

How much less depends on which nucleus.

The mass difference is related to the “binding energy” of the nucleus.



40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

For uranium, the mass difference is about 0.7%, or 7 parts in a thousand.

The 0.7% reduced nucleon mass in uranium indicates the binding energy of the nucleus.

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

The masses of the pieces that make up the carbon atom—6 protons, 6 neutrons, and 6 electrons—add up to about 0.8% more than the mass of a C-12 atom.

That difference indicates the binding energy of the C-12 nucleus.

We will see shortly that binding energy per nucleon is greatest in the nucleus of iron.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

Measuring Nuclear Mass

The masses of ions of isotopes of various elements can be accurately measured with a *mass spectrometer*.

This device uses a magnetic field to deflect ions into circular arcs.

The ions entering the device all have the same speed.

The greater the inertia (mass) of the ion, the more it resists deflection, and the greater the radius of its curved path.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

In a mass spectrometer, ions of a fixed speed are directed into the semicircular "drum," where they are swept into semicircular paths by a strong magnetic field.

Heavier ions are swept into curves of larger radii than lighter ions.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

A graph of the nuclear masses for the elements from hydrogen through uranium shows how nuclear mass increases with increasing atomic number.

The slope curves slightly because there are proportionally more neutrons in the more massive atoms.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

Nuclear Mass per Nucleon

A more important graph plots nuclear mass *per nucleon* from hydrogen through uranium.

This graph indicates the different average effective masses of nucleons in atomic nuclei.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

Nuclear Mass per Nucleon

A proton has the greatest mass when it is the nucleus of a hydrogen atom. None of the proton's mass is binding energy.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

Nuclear Mass per Nucleon

The low point of the graph occurs at the element iron. This means that pulling apart an iron nucleus would take more work per nucleon than pulling apart any other nucleus.

Iron holds its nucleons more tightly than any other nucleus does.

Beyond iron, the average effective mass of nucleons increases.

40 Nuclear Fission and Fusion Conceptual Physics

40.6 Mass-Energy Equivalence

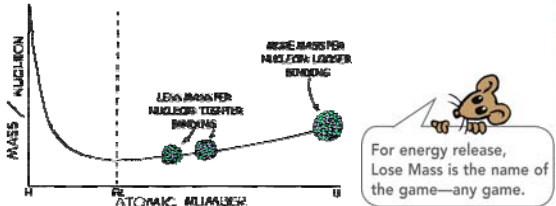
Nuclear Mass per Nucleon

For elements lighter than iron and heavier than iron, the binding energy per nucleon is less than it is in iron.

40 Nuclear Fission and Fusion Conceptual Physics

40.6 Mass-Energy Equivalence


If a uranium nucleus splits in two, the masses of the fission fragments lie about halfway between uranium and hydrogen. The mass per nucleon in the fission fragments is *less than* the mass per nucleon in the uranium nucleus.



40 Nuclear Fission and Fusion Conceptual Physics

40.6 Mass-Energy Equivalence

When this decrease in mass is multiplied by the speed of light squared, it is equal to the energy yielded by each uranium nucleus that undergoes fission. The missing mass is equivalent to the energy released.



40 Nuclear Fission and Fusion Conceptual Physics

40.6 Mass-Energy Equivalence

The mass-per-nucleon graph is an energy valley that starts at hydrogen, drops to the lowest point (iron), and then rises gradually to uranium. Iron is at the bottom of the energy valley, which is the place with the greatest binding energy per nucleon.

40 Nuclear Fission and Fusion Conceptual Physics

40.6 Mass-Energy Equivalence

Any nuclear transformation that moves nuclei toward iron releases energy. Heavier nuclei move toward iron by dividing—nuclear fission. A drawback is that the fission fragments are radioactive because of their greater-than-normal number of neutrons. A more promising source of energy is to be found when lighter-than-iron nuclei move toward iron by *combining*.

40 Nuclear Fission and Fusion Conceptual Physics

40.6 Mass-Energy Equivalence

think!

If you know the mass of a particular nucleus, how do you calculate the mass per nucleon?

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

think!

If you know the mass of a particular nucleus, how do you calculate the mass per nucleon?

Answer:

You divide the mass of the nucleus by the number of nucleons in it.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.6 Mass-Energy Equivalence

CONCEPT CHECK

How does the total mass of the fission fragments compare to the mass of the fissioning nucleus?

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.7 Nuclear Fusion

After fusion, the total mass of the light nuclei formed in the fusion process is less than the total mass of the nuclei that fused.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.7 Nuclear Fusion

The steepest part of the energy hill is from hydrogen to iron.

Energy is released as light nuclei *fuse*, or combine, rather than split apart. This process is **nuclear fusion**.

Energy is released when heavy nuclei split apart in the fission process.

In nuclear fusion, energy is released when light nuclei fuse together.

A proton has more mass by itself than it does inside a helium nucleus.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.7 Nuclear Fusion

a. The mass of a single proton is more than the mass per nucleon in a helium-4 nucleus.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.7 Nuclear Fusion

a. The mass of a single proton is more than the mass per nucleon in a helium-4 nucleus.

b. Two protons and two neutrons have more total mass when they are free than when they are combined in a helium nucleus.

40 Nuclear Fission and Fusion Conceptual Physics

40.7 Nuclear Fusion

Atomic nuclei are positively charged. For fusion to occur, they must collide at very high speeds to overcome electrical repulsion. Fusion brought about by high temperatures is called **thermonuclear fusion**.

40 Nuclear Fission and Fusion Conceptual Physics

40.7 Nuclear Fusion

In the central part of the sun, about 657 million tons of hydrogen are converted into 653 million tons of helium each second. The missing 4 million tons of mass is discharged as radiant energy.

40 Nuclear Fission and Fusion Conceptual Physics

40.7 Nuclear Fusion

In both chemical and nuclear burning, a high temperature starts the reaction.

- The release of energy by the reaction maintains a high enough temperature to spread the reaction.
- The result of the chemical reaction is a combination of atoms into more tightly bound molecules.
- In nuclear reactions, the result is more tightly bound nuclei.
- The difference between chemical and nuclear burning is essentially one of scale.

40 Nuclear Fission and Fusion Conceptual Physics

40.7 Nuclear Fusion

think!
First it was stated that nuclear energy is released when atoms split apart. Now it is stated that nuclear energy is released when atoms combine. Is this a contradiction?

40 Nuclear Fission and Fusion Conceptual Physics

40.7 Nuclear Fusion

think!
First it was stated that nuclear energy is released when atoms split apart. Now it is stated that nuclear energy is released when atoms combine. Is this a contradiction?

Answer:
This is contradictory only if the same element is said to release energy by both the processes of fission and fusion. Only the fusion of light elements and the fission of heavy elements result in a decrease in nucleon mass and a release of energy.

40 Nuclear Fission and Fusion Conceptual Physics

40.7 Nuclear Fusion

CONCEPT CHECK: How does the total mass of the products of fusion compare to the mass of the nuclei that fused?

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

Producing thermonuclear fusion reactions under controlled conditions requires temperatures of hundreds of millions of degrees.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

Producing and sustaining such high temperatures along with reasonable densities is the goal of much current research.

No matter how the temperature is produced, a problem is that all materials melt and vaporize at the temperatures required for fusion.

One solution to this problem is to confine the reaction in a nonmaterial container, such as a magnetic field.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

A magnetic bottle is used for containing plasmas for fusion research.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

A magnetic field is nonmaterial, can exist at any temperature, and can exert powerful forces on charged particles in motion.

“Magnetic walls” of sufficient strength can hold hot ionized gases called *plasmas*.

Magnetic compression heats the plasma to fusion temperatures.

Fusing hydrogen releases less energy per nucleus than fissioning uranium. But since there are more atoms in a gram of hydrogen than in a gram of uranium, gram for gram, fusion releases more energy.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

At about a million degrees, some nuclei are moving fast enough to overcome electrical repulsion and slam together, but the energy output is much smaller than the energy used to heat the plasma.

At about 350 million degrees, the fusion reactions will produce enough energy to be self-sustaining.

At this *ignition temperature*, nuclear burning yields a sustained power output without further input of energy.

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

The State of Fusion Research

Fusion has already been achieved in several devices, but instabilities in the plasma have prevented a sustained reaction.

A big problem is devising a field system that will hold the plasma in a stable and sustained position while a number of nuclei fuse.

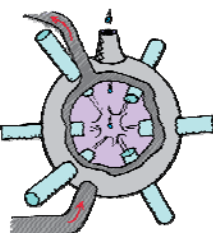
40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

Another promising approach uses high-energy lasers.

One technique is to aim laser beams at a common point and drop solid pellets of frozen hydrogen isotopes through the crossfire.

The resulting heat will be carried off by molten lithium to produce steam.

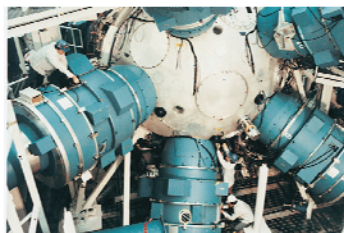


40.8 Controlling Nuclear Fusion

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

In the pellet chamber at Lawrence Livermore Laboratory, the laser source is Nova, the most powerful laser in the world, which directs 10 beams into the target region.



40.8 Controlling Nuclear Fusion

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

A Potential Energy Source

Fusion power is nearly ideal.

- Fusion reactors cannot become “supercritical” and get out of control because fusion requires no critical mass.
- There is no air pollution because the only product of the thermonuclear combustion is helium.
- Disposal of radioactive waste is not a major problem.

40.8 Controlling Nuclear Fusion

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

The fuel for nuclear fusion is hydrogen—in particular, its heavier isotopes, deuterium (H-2) and tritium (H-3).

Hydrogen is the most plentiful element in the universe. Deuterium and tritium are found in ordinary water.

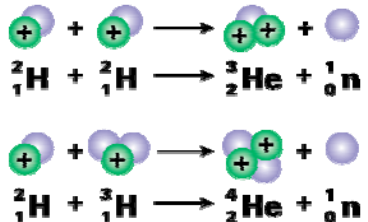
Because of the abundance of fusion fuel, the amount of energy that can be released in a controlled manner is virtually unlimited.

40.8 Controlling Nuclear Fusion

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

In the fusion reactions of hydrogen isotopes, most of the energy released is carried by the lighter-weight particles, protons and neutrons, which fly off at high speeds.



$${}^2_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_2\text{He} + {}^1_0\text{n}$$

$${}^2_1\text{H} + {}^3_1\text{H} \rightarrow {}^4_2\text{He} + {}^1_0\text{n}$$

40.8 Controlling Nuclear Fusion

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

The development of fusion power has been slow and difficult, already extending over 50 years.

It is one of the biggest scientific and engineering challenges that we face.

Our hope is that it will be achieved and will be a primary energy source for future generations.

40.8 Controlling Nuclear Fusion

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

40.8 Controlling Nuclear Fusion

CONCEPT CHECK: Why are thermonuclear fusion reactions so difficult to carry out?

PEARSON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

Assessment Questions

- Which of the following statements is true?
 - The greater the surface area of a piece of fission material, the less likely an explosion will occur.
 - The greater the surface area of a piece of fission material, the more likely an explosion will occur.
 - The greater the mass of a piece of fission material, the more likely an explosion will occur.
 - The greater the mass of a piece of fission material, the less likely an explosion will occur.

PEARSON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

Assessment Questions

- Which of the following statements is true?
 - The greater the surface area of a piece of fission material, the less likely an explosion will occur.
 - The greater the surface area of a piece of fission material, the more likely an explosion will occur.
 - The greater the mass of a piece of fission material, the more likely an explosion will occur.
 - The greater the mass of a piece of fission material, the less likely an explosion will occur.

Answer: A

PEARSON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

Assessment Questions

- A major problem in chemically separating uranium-235 from the more abundant uranium-238 stems from the fact that
 - both are isotopes of the same element.
 - both have nearly the same mass.
 - the lighter isotope moves slightly faster than the heavier one.
 - both are radioactive.

PEARSON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

Assessment Questions

- A major problem in chemically separating uranium-235 from the more abundant uranium-238 stems from the fact that
 - both are isotopes of the same element.
 - both have nearly the same mass.
 - the lighter isotope moves slightly faster than the heavier one.
 - both are radioactive.

Answer: A

PEARSON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics

Assessment Questions

- A nuclear fission reactor
 - is a major contributor to pollution in the atmosphere.
 - can be used to produce energy from nothing.
 - uses coal to heat water and generate energy.
 - uses uranium to heat water and generate energy.

PEARSON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics X

Assessment Questions

3. A nuclear fission reactor

- is a major contributor to pollution in the atmosphere.
- can be used to produce energy from nothing.
- uses coal to heat water and generate energy.
- uses uranium to heat water and generate energy.

Answer: D

PRESON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics X

Assessment Questions

4. Plutonium is an element that

- cannot be used in nuclear power plants.
- fissions like uranium.
- ranks high as a cancer-producing substance.
- poses no danger to humans.

PRESON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics X

Assessment Questions

4. Plutonium is an element that

- cannot be used in nuclear power plants.
- fissions like uranium.
- ranks high as a cancer-producing substance.
- poses no danger to humans.

Answer: B

PRESON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics X

Assessment Questions

5. A breeder reactor

- converts uranium-238 into plutonium.
- produces greenhouse gases.
- in time produces less fission fuel than it starts with.
- produces little electricity.

PRESON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics X

Assessment Questions

5. A breeder reactor

- converts uranium-238 into plutonium.
- produces greenhouse gases.
- in time produces less fission fuel than it starts with.
- produces little electricity.

Answer: A

PRESON

40 Nuclear Fission and Fusion Presentation EXPRESS Conceptual Physics X

Assessment Questions

6. Hydrogen is a lighter element than iron, which is a lighter element than uranium. Which of these three elements has the least mass *per* nucleon, that is, which has the least massive nucleons in its nucleus?

- hydrogen
- iron
- uranium
- The mass per nucleon is equal in each.

PRESON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics X

Assessment Questions

6. Hydrogen is a lighter element than iron, which is a lighter element than uranium. Which of these three elements has the least mass *per* nucleon, that is, which has the least massive nucleons in its nucleus?

- a. hydrogen
- b. iron
- c. uranium
- d. The mass per nucleon is equal in each.

Answer: B

REASON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics X

Assessment Questions

7. When the process of fission releases energy, the total mass of the material after the event is

- a. less.
- b. the same.
- c. doubled.
- d. tripled.

REASON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics X

Assessment Questions

7. When the process of fission releases energy, the total mass of the material after the event is

- a. less.
- b. the same.
- c. doubled.
- d. tripled.

Answer: A

REASON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics X

Assessment Questions

8. What remains unchanged in a fusion event?

- a. energy
- b. the mass of nucleons
- c. the number of nucleons
- d. temperature

REASON

40 Nuclear Fission and Fusion PresentationEXPRESS Conceptual Physics X

Assessment Questions

8. What remains unchanged in a fusion event?

- a. energy
- b. the mass of nucleons
- c. the number of nucleons
- d. temperature

Answer: C

REASON