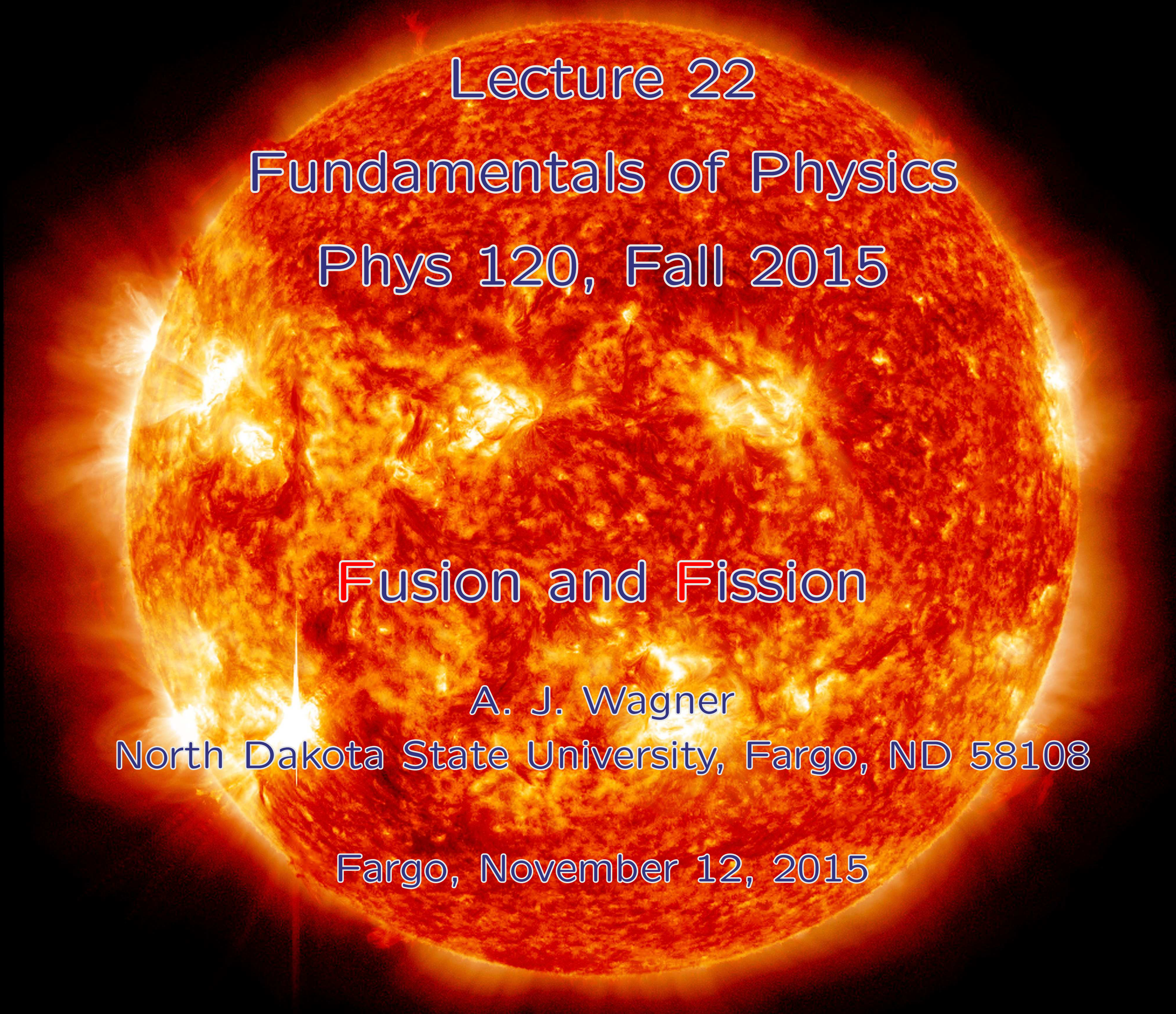

Lecture 22
Fundamentals of Physics
Phys 120, Fall 2015

Fusion and Fission

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Overview

- Fusion and the sun
- The Nuclear Energy curve
- The origin of elements
- Discovery of fission

Why does the sun shine?

Most everything on earth, from the weather to plant and animal life, depends on the sunlight we receive on earth *. But what is the sun, and how does it shine?

A related question is: how old is the sun?

Remember the question from last lecture: how old is the earth? William Thompson (Lord Kelvin) tried to answer it with an energy argument: how long has the earth been cooling? And he came up with an answer of between 20 and 400 million years.

The sun also radiates energy, only much more than the earth. But what is the source of that energy? It radiates so much energy that it can't be just a hot body cooling down.

*This part of the lecture is a condensation of this website on fusion.

Helmholtz's energy argument

Remember Hermann Helmholtz (1821 – 1894), the person that discovered Energy conservation?

He asked the question: What kind of energy could be transformed into radiative energy?

Think about what he might possibly have come up with!

Helmholtz' energy argument

There were only a few known kinds of energy: heat energy, electrical, chemical and gravitational energy.

Helmholtz argued that the gravitational energy from a contracting body could be sufficient to radiate enough energy. The idea is that as the star is falling into itself a lot of gravitational energy becomes available.

Think about it this way: if you drop a stone, it will convert its gravitational energy to heat energy as it hits the ground. That does not generate a lot of heat, but if a whole star is falling into itself the amount of gravitational energy is significant enough the heat up a star so that it would shine.

Darvin's age of the earth

At the same time Charles Darvin [1809 – 1882] considered the are of the earth.

In the first edition of *On The Origin of the Species by Natural Selection*, made a crude calculation of the age of the earth by estimating how long it would take erosion occurring at the current observed rate to wash away the Weald, a great valley that stretches between the North and South Downs across the south of England. He obtained a number for the "denudation of the Weald" in the range of 300 million years, apparently long enough for natural selection to have produced the astounding range of species that exist on earth.

Lord Kelvin's estimate

William Thompson (Lord Kelvin), whom we already know as the person who formulated the second law of Thermodynamics and set up the absolute temperature scale was an opponent of Darwin's evolutionary theory and delighted in concluding:

That some form of the meteoric theory is certainly the true and complete explanation of solar heat can scarcely be doubted, when the following reasons are considered: (1) No other natural explanation, except by chemical action, can be conceived. (2) The chemical theory is quite insufficient, because the most energetic chemical action we know, taking place between substances amounting to the whole sun's mass, would only generate about 3,000 years' heat. (3) There is no difficulty in accounting for 20,000,000 years' heat by the meteoric theory.
What then are we to think of such geological estimates as [Darwin's] 300,000,000 years for the "denudation of the Weald"?

A new energy

The two arguments stood irreconcilable, until the discovery of radioactivity brought a new kind of energy into play. This led Lord Rutherford to declare:

The discovery of the radio-active elements, which in their disintegration liberate enormous amounts of energy, thus increases the possible limit of the duration of life on this planet, and allows the time claimed by the geologist and biologist for the process of evolution.

But there was no evidence that radioactive elements existed on the sun.

Hydrogen and Helium

In 1920 Francis William Aston $(1877 - 1945)$ discovered a weight difference between four Hydrogen atoms (6.693 10^{-27} kg) and one Helium atom (6.945 10^{-27} kg).

He knew from Einstein that $E = mc^2$ so there was a difference in energy. When you fuse four atoms of Hydrogen to one atom of Helium you would gain an energy per atom of

$$\Delta E = \Delta mc^2 = 0.048\ 10^{-27}(3\ 10^8)^2 J = 4.32\ 10^{-12} J \quad (1)$$

So how much energy will be released per kg helium generated?

Energy released per kg of Helium

$$E = \frac{1.44\ 10^{-12} J}{6.945\ 10^{-27} kg} \approx 6\ 10^{14} \frac{J}{kg} \tag{2}$$

which is an enormous amount of energy.

This allows for a much longer estimate of the age of the sun: we arrive at an age of 5 billion years, very similar to the age of the earth.

Three forms of energy revisited

In the macroscopic world we experience the effect of gravity is the most noticeable, next come electric forces and nuclear forces are least noticeable.

In the microscopic world the order of importance is reversed: between two protons the gravitational interaction is a trillion trillion times smaller (10^{-24}) than the electric interaction.

To generate 1000 MW powerplant you need (approximately):
60,000 tonnes of water per second for hydroelectric power
0.1 tonne of coal every second for coal powered plant
0.000003 tonnes of uranium every second for a nuclear power plant

Fusion and Fission

Fusion to unite: in nuclear fusion two nuclei are brought together to form a larger nucleus.

Fission to split: in nuclear fission one nucleus is split roughly in half to form two smaller nuclei.

Nuclear energy

We saw that nucleotides in an atomic nucleus are kept together by the strong nuclear force.

Consider the nucleus ${}^{2}_{1}H$. If you wanted to separate the neutron and proton in this nucleus this would not be easy because you would have to overcome the strong nuclear force holding them together.

Concept Check

Compared with the ${}_{1}^{2}H$ nucleus before separation, a separated proton and neutron have

a) more energy;

b) less energy;

c) the same energy.

Concept Check

Compared with the force exerted by the proton an neutron on each other before the ${}^2_1H$ nucleus is separated, the force between them after separation is

a) greater;

b) less;

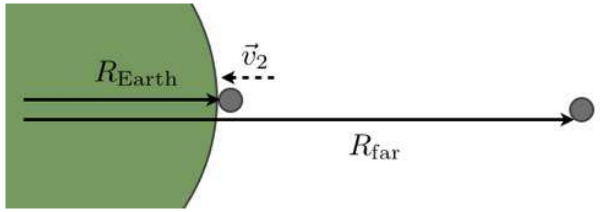
c) the same.

Fusion reaction

The combined nucleus ${}^2_1H$ has more energy than the separated n and p. This excess is a form of **nuclear energy**. (Think of the example of a rock and the earth which works similarly.)

Now consider putting a neutron and a proton together:

$$n + p \rightarrow {}^2_1 H$$



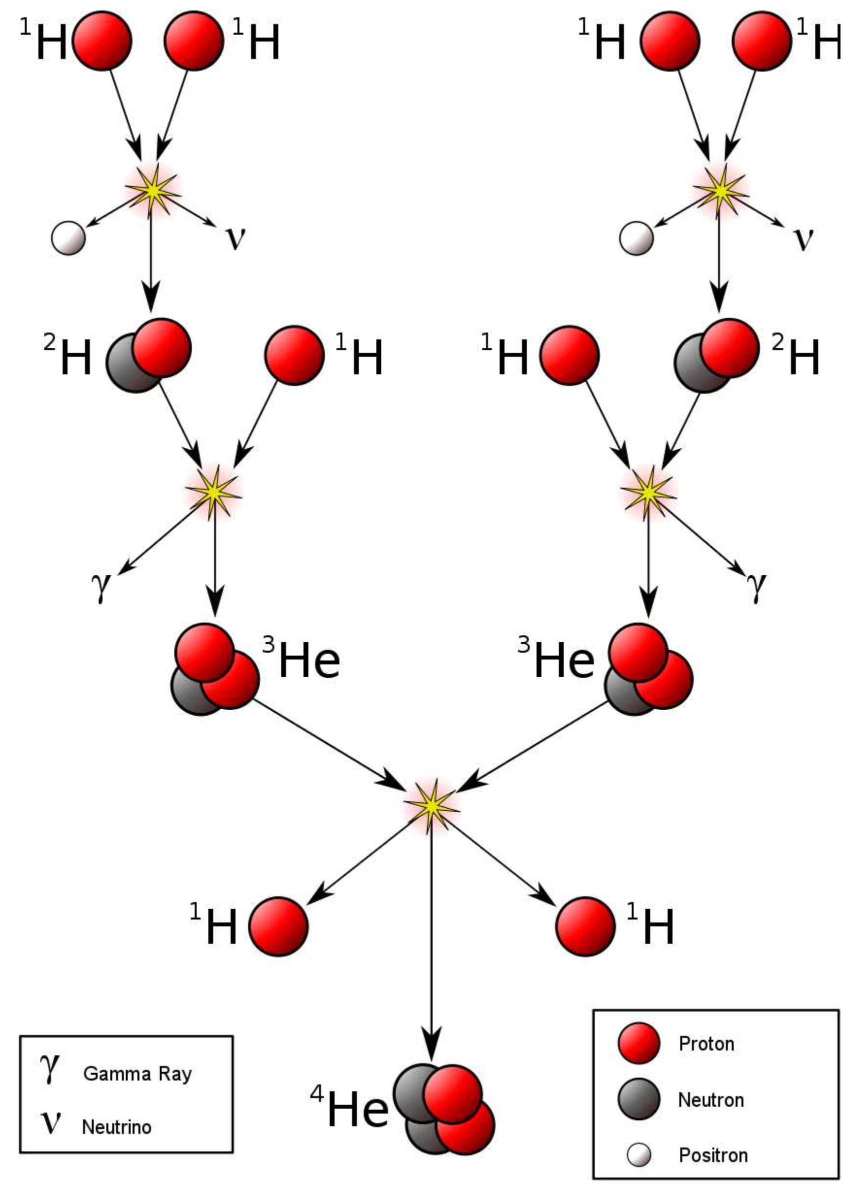
When large masses of neutrons and protons fuse together like this we get heating and emission of gamma radiation:

$$\text{NuclE} \rightarrow \text{ThermE} + \text{RadE}$$

We call this a **release of nuclear energy**.

Creation of ${}^2_1H$ and the sun

Almost all of the ${}^2_1H$ in existence today was formed during the first few minutes of the big bang. Today this reaction occurs during supernovae explosions.
More important today is the fusion reaction in the sun: the protons of the hydrogen that makes up the original material of the sun fuse to form Helium.



Concept Check

The isotope created by the fusion of ${}^{1}_{1}H$ with ${}^{2}_{1}H$ is

a) ${}^{3}_{1}H$;
b) ${}^{3}_{2}H$;
c) ${}^{2}_{2}He$;
d) ${}^{3}_{1}He$;
e) ${}^{3}_{2}He$;
f) ${}^{4}_{2}He$.

Thermonuclear reactions

There is a problem in fusing ^1H and ^2H because the nuclei are both charged. Electric forces prevent the nuclei to get too close.

Only if they are very hot do they manage to overcome this barrier. If they are hot (and therefore fast) they break through each others barriers*. The fusion energy generates radient and thermal energy. We can summarize this as

$$\text{ThermE}_{in} + \text{NuclE} \rightarrow \text{ThermE}_{out} + \text{RadE}$$

If the thermal output is much larger than the thermal input (as is the case for this fusion reaction) then the reaction sustains itself.

Think of this as a campfire: you have to light it (add initial thermal energy) and after that the heat it generates is sufficient to continue to ignite more wood. The only difference is that we release chemical (i.e. electrical) energy in a fire whereas we use nuclear energy in fusion.

Such reactions are called **thermonuclear reactions**.

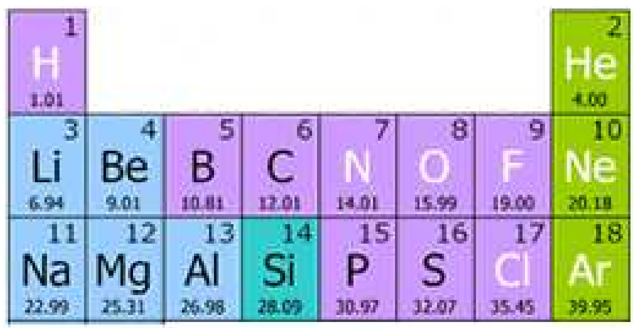
*But even that is not classically possible. We require a quantum phenomenon called tunneling, first proposed by George Gamow (1904 – 1968).

Fusion reactions/Concept Check

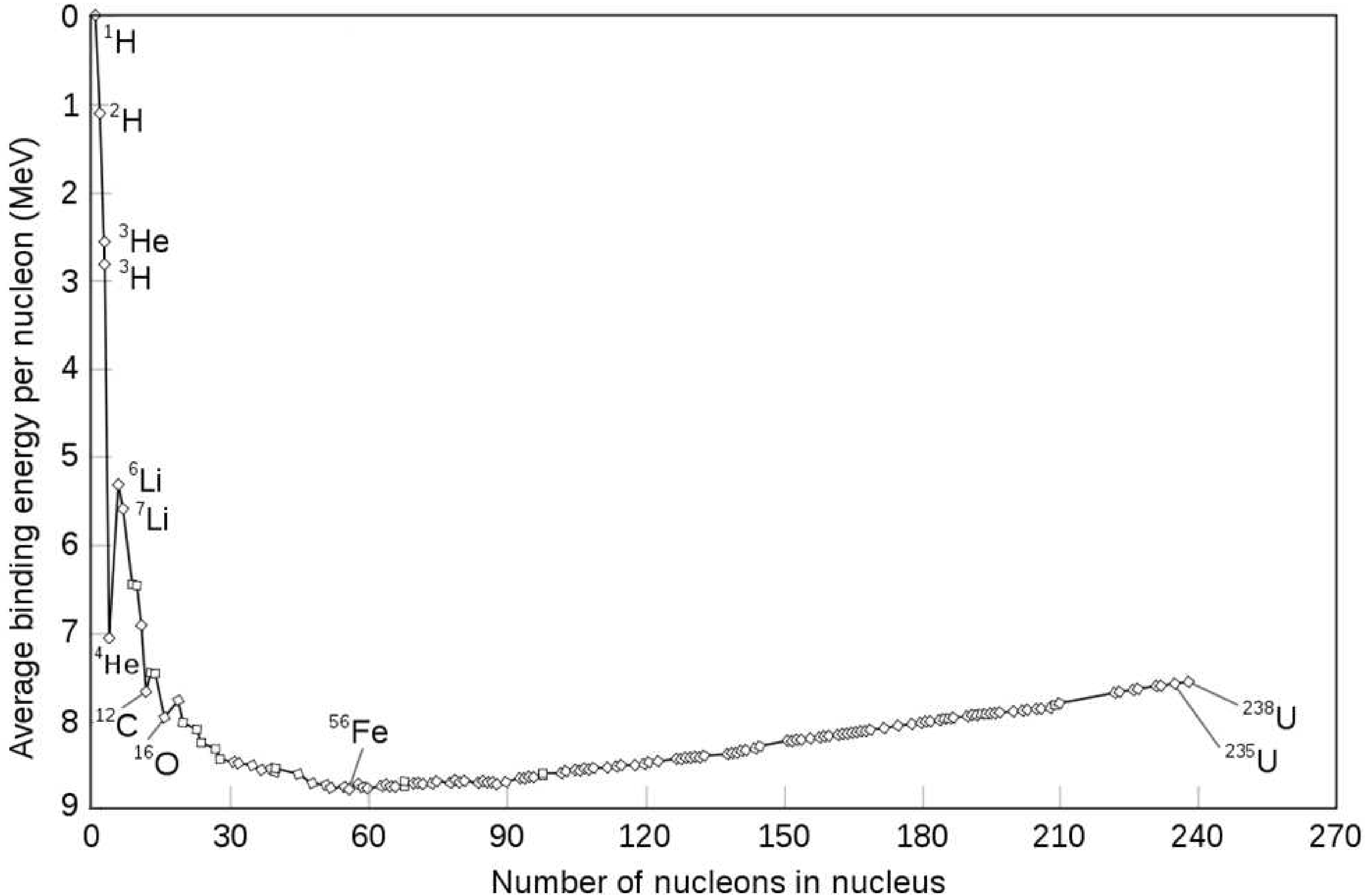
Many other nuclei can fuse to form larger nuclei.

Concept Check: When two ^4_2He nuclei fuse, they form an isotope of the element

a) helium;
b) beryllium;
c) lithium;
d) boron.



The nuclear energy curve



Average binding energy per nucleon. Note the special place for ^4_2He, the minimuim at iron and the rise to Uranium.

The origin of elements

During the big bang only three elements were formed: hydrogen, helium and traces of lithium. They still form 99% of the ordinary matter in the universe. Where do the other elements come from?

They are made in stars: once the hydrogen is burned out, the stars collapse, and in the process heats up. This additional heat allows for further fusion reactions like

$$ {}^4_2He +^4_2 He \rightarrow^8_4 Be $$

$$ {}^4_2He +^4_2 Be \rightarrow^{12}_4 C $$

These reactions can create all the atoms up to iron (mass number 56). But not elements beyond this mass number because further fusion reactions would use up thermal energy and stop the fusion process.

Where do all the heavy elements come from?

Since we can find heavier elements here on earth the question arises: how can these heavier elements be formed?

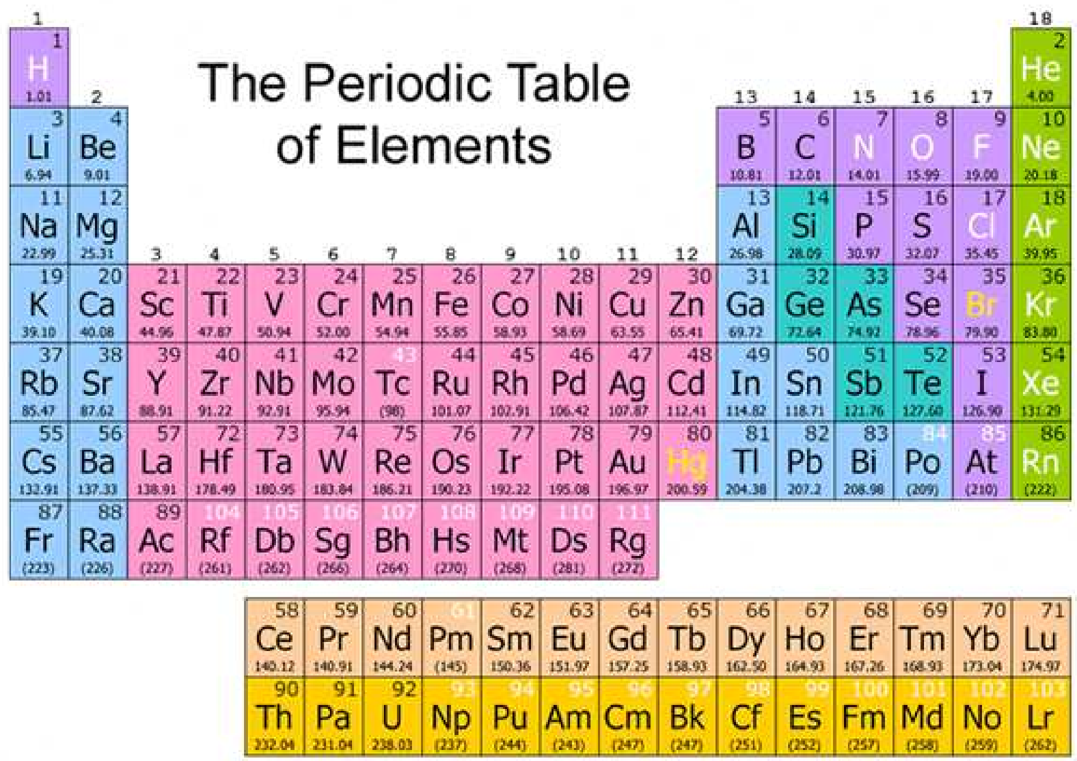
Normal stars may cool down, collapse and form a heavy core of iron through these fusion reactions. But if the stars are heavier they will collapse further into a neutron star or a black hole. This collapse is causes a supernova explosion where about 80% to 90% of the original mass of the sun is blasted off. Scientists suspect that during this violent explosion some nuclei get fused further forming the heavier elements that are then dispersed throughout space.

Concept Check

During a supernova, if an iron nucleus captured three neutrons and then beta-decayed twice, it would be transformed into

a) chromium;
b) manganese;
c) cobalt;
d) nickel;
e) zinc.

This kind of process can create the elements heavier than iron.



Discovery of fission

1933: Irene Joliot-Curie bombarded aluminum foil with alpha particles and generated a new form of radioactive potassium

About the same time Scientists bombarded beryllium with alpha particles and detected the previously unknown neutron.

1934: Enrico Fermi started bombarding nuclei with the newly discovered neutrons. He built up larger and larger atoms. But in the neighborhood of uranium the recipe strangely failed

Ida Noddack suggested that the nucleus could be thought of as a drop and might break up during the capture of neutrons

Hahn and Meitner show that uranium can be broken up in this way (fissioned) and more neutrons are released allowing for a **chain reaction**

${}^{235}_{92}U$ and ${}^{238}_{92}U$

We find that ${}^{235}_{92}U$ has a high chance of fissioning when bombarded with a neutron where as ${}^{238}_{92}U$ is more likely to absorb the neutron.

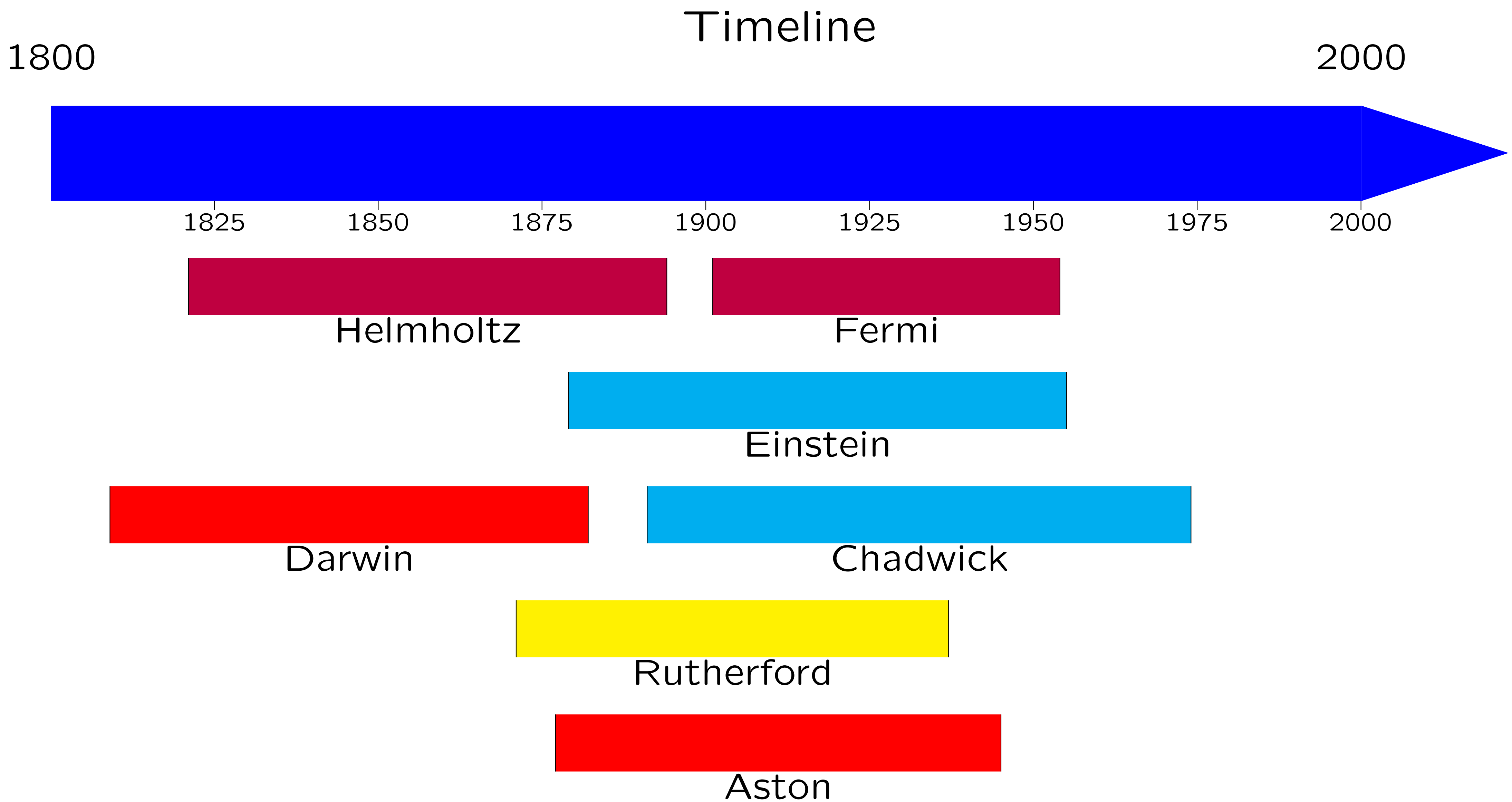
But naturally found uranium consists to 99% of ${}^{238}_{92}U$, so it is hard to generate a chain reaction using this isotope.

Concept check

If you want to build a uranium bomb, you can use an ultracentrifuge to separate heavier from lighter elements. If you use a gas molecule containing uranium and you put it in an ultracentrifuge, which part of the centrifuge do you want to siphon off to get the “good stuff”?

a) the heavy part at the bottom

b) the light stuff at the top.


Timeline
1800
2000
1825
1850
1875
1900
1925
1950
1975
2000
Helmholtz
Fermi
Einstein
Darwin
Chadwick
Rutherford
Aston

Summary

- Fusion and Fission
- Nuclear energy (and energy curve)
- How the sun works
- The origin of heavier elements from sun (up to Fe)
- Neutron capture in supernova generate heavier elements
- The miracle of fission of $^{235}_{92}U$ (only 1% of U found naturally)