Elements, Fusion and The Sun

Elements and the Periodic Table

Here are the essentials about elements and the periodic table:

(1) An atom has a **nucleus** and the nucleus is surrounded by **electrons**.

(2) The nucleus itself contains **protons** and **neutrons**. Together, these are called **nucleons**.

(3) An electron has negative electrical charge, the proton has positive electrical charge, and a neutron has no electrical charge. The amount of charge in any reaction, including a nuclear reaction, cannot be changed.

(4) Advanced stuff for completeness, you can ignore if you want: I need to mention another particle that shows up in nuclear reactions, called the positron, which is a great deal like the electron except with positive charge. There is also a neutral particle called the photon, which is a particle of light. To be completely complete, there is yet another particle called the neutrino. On my questions and exams, you just need pay attention to the protons, neutrons and electrons.

(5) When we make diagrams of nuclear reactions, we label the protons “p”, the neutrons “n”, the electrons “e”. (More advanced stuff for completeness: on the nuclear reaction diagrams the positrons are labeled “β” (that’s the Greek letter beta that we are using because we’ve already used “p”), the photons are labeled “γ” (that’s the Greek letter gamma), and the neutrinos are labeled “ν” (that looks like a “v”, but it is the Greek letter nu).)

(6) If an atom is stripped of some of the electrons, we have a **positive ion** but of the same element. If it gets extra electrons, we have a **negative ion** but of the same element.

As an example, Sodium (written Na) with one electron removed is called a sodium ion and is written Na^+. As another example, Chlorine (written Cl) with one extra electron is called a chlorine ion and is written Cl^-. *So you may have been taught in high school that the number of electrons defines an element, but as you can see from the examples just given that is not right.*

(6) Furthermore, the number of neutrons isn’t part of the definition of an element either.

For example we can have Uranium with 146 neutrons and 92 protons written ^{238}U or uranium with 143 neutrons and 92 neutrons written ^{235}U and both are considered uranium.

They are different **isotopes** of uranium.

(7) So what does that leave?? **An element is defined by the number of protons.** Here is the periodic table showing all the known kinds of atoms. It is numbered by the number of protons. The columns are stacked in a very special way so that elements with similar chemical properties are near each other. We only care about nuclear properties right now, not chemical properties, so you don't have to contemplate the meaning of the columns.

Group→ ↓Period	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

The Periodic Table of the Elements

(8) To summarize, what is shown in each box is the name of an **element (abbreviated), and the number is the number of protons.** For example, Iron has the abbreviation Fe and its box says it is element 26, so iron has 26 protons. If you are wondering why Iron didn't get the abbreviation Ir, well, that's Iridium, element 77.

Question 1: If an Iron atom is neutral, how many electrons does it have?

Question 2: Iron often loses two electrons. How many electrons would it then have?

Question 3: The symbol for an Iron atom having lost two electrons is Fe^{++} or sometimes Fe^{+2}. What would be two fine symbols for an Iron atom that has lost three electrons?

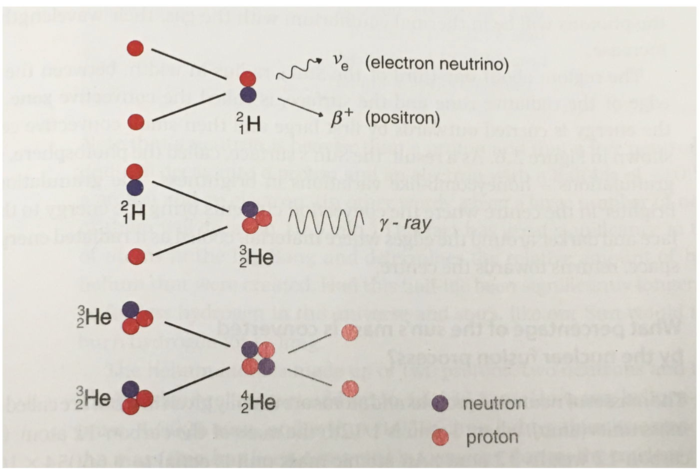
Question 4: Iron most commonly has 30 neutrons. This would be written ^{56}Fe. What would be the symbol for the isotope of iron that has 28 neutrons?

Note: Many websites don’t have the right typography to do the isotopes the way I have with superscripts. Instead, they’ll just write Fe-56 or Fe-54.

Fusion in the Sun

The oversimplified version, which is enough for you to know, is that four hydrogens can fuse to make one helium.

If you want to see all the reactions, then here is a diagram from a textbook:



The top reaction above shows **deuterium** being produced. You don’t need to memorize the name. The second reaction above shows **^{3}He** being produced.

To summarize, it is sufficient to know that 4 Hydrogens make 1 Helium. The mass of hydrogen has been measured to be 1.6737236 x 10^{-27} kg. The mass of a Helium atom has been measured to be 6.6464764 x 10^{-27}kg.

Question 5: How much mass disappears when four hydrogens make one Helium?

$E = mc^2$

In 1905, Einstein realized that matter could be turned into energy. It’s extraordinarily difficult to make this happen on Earth or it would have been discovered experimentally before it was discovered theoretically.

The first nuclear reactor based on these ideas was called Chicago Pile-1. It was set up under the stadium seats in the University of Chicago because the scientists were in the middle of a war and in a dreadful hurry to get it done. Enrico Fermi is famous for this project. The reactor was started on December 2, 1942.

The first bomb exploded based on these ideas was called Trinity. It was detonated on July 16, 1945 in the desert in New Mexico. Robert Oppenheimer is famous for leading this project. It was called “The Manhattan Project” and worked under extreme secrecy and urgency with all the resources it needed because there was grave concern that the Germans might be making their own atomic bomb. We will have a short unit on ethics toward the end of the course. We will discuss the Manhattan Project seminar-style.

Question 6: Suppose there is a small town called “Outback Junction” with 100 houses each using 5000W. Maybe Outback Junction is tired of trucking in a truckload of coal every day to run their coal plant, and they want to go nuclear. Using the $E = mc^2$ formula, how much mass would have to be converted to energy to meet Outback Junction’s energy needs for one day. HINT: First you need to figure out how many Joules of energy Outback Junction needs for one day. Then you solve the $E = mc^2$ for m. You’ll need that $c = 3 \times 10^8$ m/s.

How Long can the Sun Last? If it is made of Hydrogen!

Let's get back to a calculation we just got started on at the end of class on Wednesday, which was figuring out how long the Sun can last if it is made entirely of hydrogen, and it is going to fuse all that Hydrogen into Helium. We already figured out that the Sun is made out of hydrogen then it has:

$$\frac{1.989 \times 10^{30}\ \text{kg}}{1.67 \times 10^{-27}\ \text{kg/Hydogen atom}} = 1.2 \times 10^{57}\ \text{Hydrogen atoms}$$

That means we have enough Hydrogen atoms to do the reaction 4 Hydrogen → 1 Helium,

0.3×10^{57} reactions

In question 6 above you discovered that each time we make a Helium atom from four Hydrogen atoms, about $0.048\ \text{x}10^{-27}$ kg of mass disappears.

So if the Sun turns all its Hydrogen into Helium, it will release make

$0.3 \text{ x } 10^{57} \text{x } 0.048 \text{ x } 10^{-27} \text{ kg x } \left(3 \text{ x} 10^{8} \, \frac{\text{m}}{\text{s}}\right)^{2} = ...$

Don't just shove all this into the calculator! It's too easy to mess up. First we take care of the powers of 10. That's 57-27+16=46. Then do the rest 0.3 *0.048 * 9 = 0.13. So our answer is 0.13×10^{46} J.

The Sun is producing energy at a rate of $3.85 \text{ x} 10^{26}$ Watts.

$$\frac{0.13 \times 10^{46} \text{ J}}{3.85 \times 10^{26} \text{ W}} = 3.4 \times 10^{18} \text{ s}$$

If you convert from seconds to years, you'll find that that is 10^{11} years. That's 100 billion years!

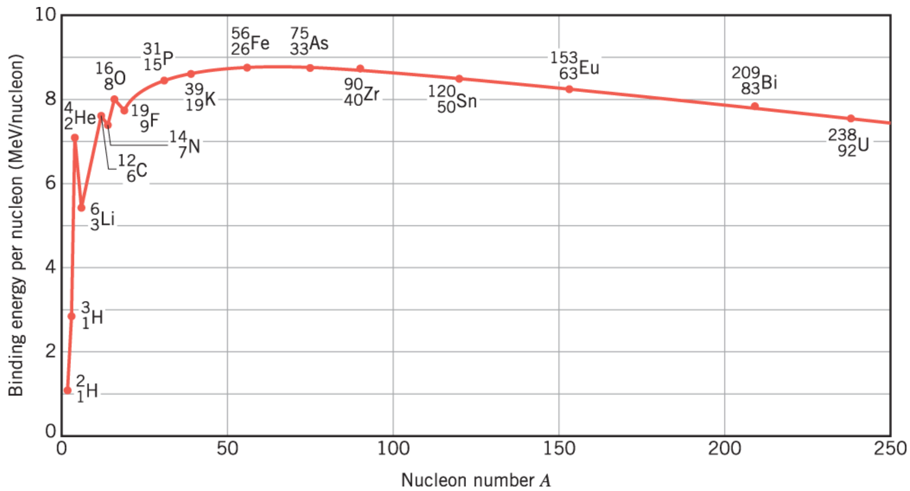
However, it turns out the Sun is only going to be able to turn about 10% of its Hydrogen into Helium :(. Then it balloons up into a Red Giant (like Betelgeuse but not as big). That's jumping ahead, but I didn't want to finish our first calculation about the life of the Sun by leaving you with the idea that we have 100 billion years left on Earth to peacefully orbit it.

In fact, our Sun will only last 10 billion years and it has already lasted over 4 billion of those. So we have less than 6 billion to go.

Energy in Nuclei

Light elements can be fused (releasing energy) to form heavier elements. Also, heavy elements can have their nuclei split (also releasing energy) to make lighter elements. When they fuse it is called **fusion**. When they split it is called **fission**.

Here is a table that shows much more precisely which elements can be fused to get energy and which elements can be split to get energy. The one at the very top of this table is ^{56}Fe. What this table is showing is that if all you have is Iron, you can’t get energy by splitting it or by fusing it.

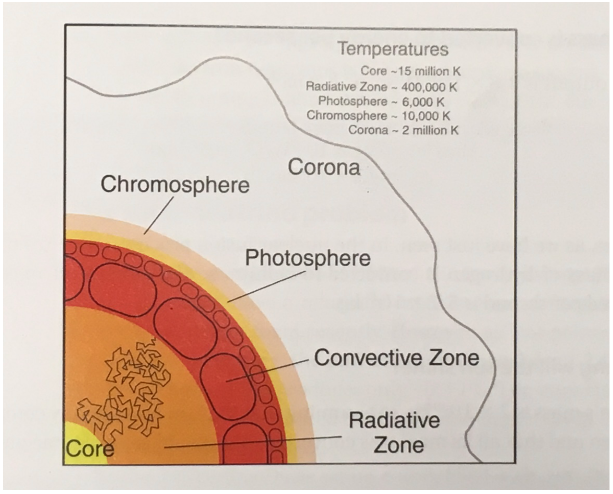


Binding Energy per Nucleon

So to be more precise, you can fuse light elements (ones lighter than Iron) until you get Iron, or you can split heavy elements (ones heavier than Iron) until you get Iron. Once you have Iron, you're done getting energy out.

Structure of the Sun

This is a pretty good diagram from a textbook. It is only slightly oversimplified.



(1) The **core** is where is the only place where the sun is hot enough to do fusion. The other layers are just transporting the heat outward.

(2) The Sun has a layer where the heat is getting out via conduction, called the “**radiative zone**,” and it has a layer where the heat is getting out via convection, called the “**convection zone**.”

(3) Exactly like at the edge of a fog bank, the energy made by the Sun gets free of the material of the sun at some point. The layer where the light gets free is called “the **photosphere**.” The surface of our Sun’s photosphere is 5777 K (or in round numbers 6000 K).

(5) Above the photosphere is a layer called “the **chromosphere**.” It is thin and hot and glows red due to a particular Hydrogen emission. You can’t see it except with special instruments.

(6) Above the chromosphere is “the **corona**.” It is millions of degrees and apparently the math is still too hard for anybody to have definitively calculated why it is this hot. You can only see the corona during total eclipses during which a lovely halo around the Moo is created. In photos taken during eclipses, you can see that it extends millions of miles.