PhyzGuide: The Ties That Bind...

Reduce The Mass

The mass of two magnets is smaller when the magnets are bound together by their attraction. When they are bound, they are in their lowest energy configuration. (Likewise a marble rolling around inside a teacup is in its lowest energy configuration when it settles at the bottom of the cup.) Since the magnets gave up energy to get to this low energy situation, and since mass and energy are two different versions of the same thing, the magnets have the lowest mass when bound.

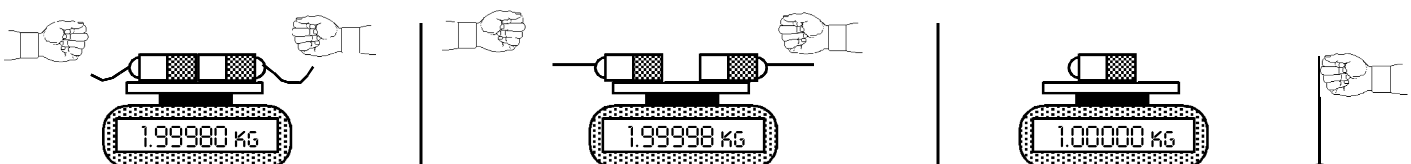
We begin with two magnets far away from each other. Since they are so distant, there is not much attraction. This is a high (potential) energy situation--like a bowling ball high above the earth. The mass of each is greatest here: 1.00000kg each.

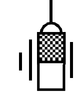
Closer together, they are slightly more stable (lower energy configuration). Each has a mass of 0.99999kg.

When completely bound, energy is lowest; each has a mass of 0.99990kg.

We can express this reduction of mass in terms of "binding energy" as well. Binding energy is the energy that must be added to break a bond. When the magnets are far apart, there is nearly no binding energy: the magnets are not bound and can be moved away from each other with ease. When the magnets are tightly bound, there is a considerable binding energy: pulling the magnets apart would require a certain amount of work (energy!).

Guess what happens to the mass of the magnets as we add the energy needed to pull them apart? Let's see now... we're *adding* energy... energy and mass are equivalent... You guessed it! The mass goes right back up!





With a high binding energy (i.e. when they're tough to pull apart), the magnets have the least mass.

As energy is added, the bond loosens, and the binding energy goes down. The mass of the magnets increases proportionally to the energy added ($m=E/c^2$).

With the bond completely broken, binding energy is back down to zero; mass is back up to its original value.

So if you wish to reduce your mass, simply form a bond with someone you share an attractive force with. This process also adds years to your life ("time dilation" in relativistic terms). But keep in mind: if the bond is broken, your mass goes right back up!

THE BOTTOM LINE

To summarize, the mass of objects held together by an attractive force is less than when those objects are apart. The reduction in mass of the objects is proportional to the strength of the bond they form. The strength of this bond is measured as the binding energy. Binding energy can be viewed as the amount of energy given up by the objects when they formed the bond. It can also be thought of as the amount of energy required to break the bond. If the binding energy is added to the objects to break the bond, the energy will manifest itself as increased mass in the objects. The mass of the objects after the bond is broken is equivalent to the mass of the objects before the bond formed.

Actually, we would have a most difficult time measuring the difference in mass of magnets when they come together. The amount of mass that "leaves" upon bonding—called *mass defect* —is infinitesimal. The difference is important, however, when we consider the bonding of nucleons. For instance, the mass of a Helium atom is *not* equal to the mass of two protons plus two neutrons plus two electrons.

Rest masses of subatomic particles

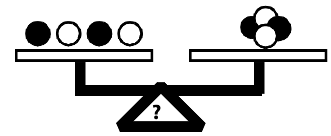
	kg	u	MeV/c^2*
Electron	9.1095¥10^{-31}	0.000549	0.511
Proton	1.67265¥10^{-27}	1.007276	938.28
Neutron	1.67356¥10^{-27}	1.007825	938.79
H atom	1.67500¥10^{-27}	1.008665	939.57

*MeV/c^2 gives the mass in terms of the energy it represents via $m=E/c^2$. An MeV is a mega-electron volt; an electron volt is a small unit of energy (the work needed to move an electron through one volt of electric potential).

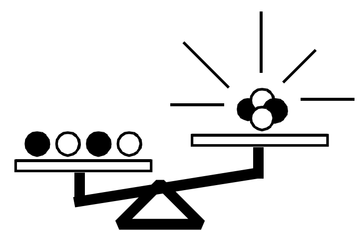
The mass of the particles $2p^+ + 2n^o + 2e^-$ (or, more accurately, 2H + 2n, since H is one proton and one electron) taken individually is

$$
\begin{array}{rl}
2m(n^o) & = 2.017330 \text{ u} \\
+2m(H) & = 2.015650 \text{ u} \\
\hline
\text{Total} & = 4.032980 \text{ u}
\end{array}
$$

Yet, when the nucleons are bound through the highly attractive nuclear strong force to create the very stable Helium nucleus, the mass is different! (Do you expect it to be higher or lower? Answer this in your head before you move on) No, you can't proceed until you've answered the question back there in the parentheses... Hey, I'm not kidding about this--go back and answer that question first! The mass of the neutral helium atom, which consists of $2p^+ + 2n^o + 2e^-$, is actually 4.002603 u! Some of the mass has defected! The helium atom is 0.030377 u short of the mass it "should" have. The mass that has defected did so as *energy*. A great deal of energy is given off when a helium nucleus is formed from its constituents. Converting to the energy units (via $E = mc^2$), 0.030377 u = 28.30 MeV.



What weighs more, 4 nucleons apart or 4 nucleons together?



Energy is given off when the nucleons bond; the He nucleus weighs less than its constituent particles.

And guess what 28.30 MeV represents? Hmmm... the energy given off when the bond formed... I wonder how much energy it would take to break that bond... probably about 28.30 MeV!... so 28.30 MeV is the *binding energy* of the helium nucleus! If you want to pull a nucleus apart, you must overcome its binding energy to do so.

If we consider the mass *per nucleon* of a hydrogen nucleus and a helium nucleus, we see that a nucleon has less mass in the helium nucleus. (4.002603 u/4 nucleons < 1.007825 u/1 nucleon—calculate it yourself, don't take *my* word for it!) So although the mass of progressively larger nuclei increases (which we expect since they have progressively more nucleons), **the mass per nucleon decreases for larger nuclei**—for a certain interval, anyhow. This is simply stating that larger nuclei are more tightly bound together (more strong force interaction). However, this effect does not persist through the entire periodic table. Past $Z = 26$ (iron), nuclei become less tightly bound.