University Lowbrow Astronomers
Ann Arbor, Michigan

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University Lowbrow Astronomers

OCTOBER 2013
VOLUME 37, ISSUE 10

Rho Ophiuci

by Brian Ottum

This is a shot of the Antares and Rho Ophiuchus region. It's got to be one of the most naturally colorful areas of the sky. You can see rivers of dark dust clouds obscuring the stars behind. You can see the red star-forming nebula regions. In fact, this is one of the closest star-forming regions to Earth. Closer than the Orion Nebula. Antares is a red giant, enveloped in a yellowish glowing nebula. Near Antares is the large M4 globular cluster. It's so big because it's the closest globular to Earth – 7,000 light years. Another Messier globular, M80, is on the lower right (very small because it's 4 times further away than M4). The small globular right next to Antares is NGC 6144 (also 4 times further away than M4). Since most globulars are well above or below the plane of the galaxy, and this view is near the center of the galaxy, does this mean that M4 is located just above the disk of the Milky Way and the other two are well above the disk but on the other side of the central bulge?

TECHNICAL DETAILS: Page 2

TECHNICAL DETAILS

Taken early Sunday morning, June 16 (Father's Day), from Midnight until 1:45 A.M.. I was volunteering that night at the Bryce Canyon National Park, having just finished up an evening showing big dob views to a couple hundred visitors. Bryce sets up half a dozen telescopes in employee parking lot behind the Visitors Center on Tuesday, Thursday and Saturday nights. I set up my tripod, Losmandy StarLapse motor drive, 12V battery, Canon 5D Mark III (modified), and 200mm f/2.8 Canon telephoto lens prior to the start of the viewing. The StarLapse has a polar alignment scope, but I only took a few minutes to get Polaris in roughly the right spot in the reticle. I stopped the 200mm lens down to f/3.2 to get slightly sharper corner stars and the pretty starburst effect. A $20 Chinese intervalometer was programmed to take 105 separate 60 second exposures. The tracking accuracy was not good enough for longer exposures which would have allowed an even better picture (oh well, next time). I checked a test exposure, re-set the composition, and let it run for an hour and a half. During that time, I biked over to a cabin where other "AstroVIP" volunteers and rangers were enjoying post-observing snacks. The Canon 5D has a sensor that is over 50% bigger than the usual consumer DSLR (it is the size of the old 35mm film – 24mm x 36mm). I had the infrared-blocking filter that covers the sensor removed, and replaced with a filter that allows more of the deep red end of the spectrum. Without the modification, the reds in the image would be more muted. However, this is still a very colorful area of the sky. Not a lot of Photoshop tricks were applied. Nearly every major color is in there. ImagesPlus software was used to convert from Raw to Fits, and then align and stack into one Tif file. Photoshop 5.5 then was used to do a lens correction to remove vignetting, and several rounds of Curves tweaking. The final image represents about 90% of the original frame.

LOWBROW CALENDAR

Saturday, October 5, 2013--*Open House at Peach Mountain--*Begins at sunset. May be cancelled if cloudy.

Saturday, October 12, 2013--*Public Observing at Scio Farm Estates--*7:00 P.M. May be cancelled if cloudy.

Friday, October 18, 2013--*Monthly Club Meeting--*7:30 P.M. Room 130, Dennison Hall, U.M. Central Campus. Speaker: Jay Strader, Professor at Michigan State: "Black Holes and Globular Clusters; Sparkling Hosts of Frozen Stars"

Friday, October 25, 2013--***Public Observing at Emerson School--***6:00 P.M. Located at the corner of Scio Church and Zeeb Roads. May be cancelled if cloudy.

Saturday, October 26, 2013--*Open House at Peach Mountain--*Begins at sunset. May be cancelled if cloudy.

Saturday, November 2, 2013--*Open House at Peach Mountain--*Begins at sunset. May be cancelled if cloudy.

Nucleosynthesis

Part Three

by Dave Snyder

In parts 1 and 2 of this series I introduced the topic of nucleosynthesis, the study of how chemical elements like carbon, oxygen, silicon, iron and so on were created (see Dave Snyder, “Nucleosynthesis,” March, 2012 and Dave Snyder, “Nucleosynthesis, Part 2,” August, 2012). To continue the story, I need to go further into the topic of nuclear physics. I will do this through a series of steps:

1) Billiard Balls. The simplest models of the nucleus assume that protons and neutrons are hard spheres (you will see “billiard ball” used as an adjective where this assumption is used). Such models sometimes produce the correct answer, but sometimes not. But they are not taken very seriously, since there are much better models.

2) A first attempt at a better model assumes that the nucleus is a drop of liquid, and protons and neutrons are constantly moving within that drop. In “Nucleosynthesis, Part 2,” I presented a simple model of binding energy based on a liquid drop model. I plotted binding energy as a three dimensional surface. Nuclei can transform over time, generally from lower to higher binding energy along this surface.

3) Energy. Physicists use the concept of energy to understand many phenomena. For example the motion of a roller coaster can be understood by examining two types of energy (namely kinetic and potential energy). In the same way, energy can be used to study the nucleus. Both steps 1 and 2 suggested that nuclei can change over time. Step 1 does not constrain which transformations are possible and which are not; step 2 only has the mild constraint that binding energy generally increases. The concept of energy adds a new constraint on which transformations are possible. In addition, this concept is useful in studying radioactive decay: some isotopes decay quickly and others slowly. It is possible to predict the lifetime (or half-life) of radioactive isotopes if you know the available energy.

4) Linear Momentum. Linear momentum is another concept that physicists use. This adds another constraint (though energy is more helpful in this respect than linear momentum).

5) The simple model of binding energy described in step 2 is incomplete. A better model can be constructed. Measurements show that nuclei with an even number of protons are more stable (and have higher binding energy) than nuclei with an odd number of protons. Similarly nuclei with an even number of neutrons are more stable than nuclei with an odd number of neutrons. Models that take this into account are slightly more difficult to visualize than the model in step 2, but still fairly easy to deal with.

6) The model in step 5 is inaccurate in certain respects. There are other models called “shell models.” They are more complicated, harder to understand, but more accurate than the model described in step 5. While they vary, all these models assume that nuclei with a certain number of protons (or a certain number of neutrons) have a higher binding energy than would be expected from the model in step 5. These are known as “magic numbers.” For example 2 is a magic number, and helium-4 has 2 protons and 2 neutrons. Shell models correctly predict that helium-4 should be exceptionally stable (which the model in step 5 does not). In addition, the following numbers are considered magic numbers: 8, 20, 28, 50, 82, and 126.

7) Angular Momentum. Another concept from physics. Applying angular momentum to the nucleus gets complicated for several reasons (which I’m not going to explain here). It doesn’t add constraints (unlike steps 3 and 4), but is important for the following reason: The lifetime predictions made in step 3 are not very accurate (especially if the number of protons, neutrons or both are odd), taking angular momentum into account helps improve the accuracy.

8) Excited States. In the previous steps, we assumed that all nuclei with a specific number of protons or neutrons are identical. So all carbon-12 nuclei should be the same. This isn’t completely true. Carbon-12 has several variations,

a “ground state” and a group of “exited states.” This is true of many other isotopes as well. Most excited nuclei rapidly decay into ground state nuclei; and thus virtually all the atoms found in normal environments contain nuclei in the ground state. However excited states are common during certain nucleosynthesis processes (and occasionally other situations as well). To properly understand these processes you must take excited states into account.

9) Nuclear physics has many applications: weapons, power production, radioisotopes to diagnose or treat disease, study of biological processes, health effects of radioactive materials, tracing movement of atoms in the environment, determining the age of materials, studying how stars generate energy and nucleosynthesis. In pure nuclear physics, you generally work with one reaction at a time, but the applications of nuclear physics often involve many reactions occurring simultaneously which adds a new level of complexity.

10) Much of what I described above are theoretical models, there are a number of ways these models can be compared to experimental data.

Billiard Balls

Let’s start with a possible billiard ball model: protons and neutrons are considered to be hard spheres (“billard balls”) and they are “glued” together in fixed positions to form a nucleus. Over time, a nucleus might remain unchanged, it might split (or “decay”) into two or more pieces, or two nuclei might merge (or “fuse”) into a larger nucleus. Now, some reactions follow this model (at least partially) and other reactions do not. We will call the former “billiard ball reactions.” What happens if we work with this model? Glue a proton and a neutron to form a hydrogen-2 nucleus (also known as deuterium). The mass of the proton, neutron and deuterium nucleus are known. It might seem that the mass of two billiard balls glued together would be the same as the sum of its parts. This is not the case. The mass of the deuterium nucleus is less than the sum of the mass of the proton and the mass of the neutron; the difference in mass is exactly equal to the binding energy. Similar statements can be made for heavier nuclei. While it may be counterintuitive, during the process of binding a nucleus together, some of the proton and neutron mass disappears and goes into binding the nucleus together.

If protons and neutrons are in fixed locations, it should be possible to take a heavy nucleus, say uranium-238, and create different versions. Some versions have the protons close together and others have the protons further apart. Based on the discussion in “Nucleosynthesis, Part 2,” we should expect these nuclei to have different binding energies. (Protons repel each other and placing them close together causes a larger repulsion than if they are spread out). However experiments do not show this, all uranium-238 nuclei have the same binding energy.
So our billiard ball model doesn’t work very well. An alternative is to assume that protons and neutrons are constantly in motion within the nucleus. This was done in “Nucleosynthesis, Part 2” to produce a simple model of binding energy. While it is much better than the billiard ball model, it is not complete.

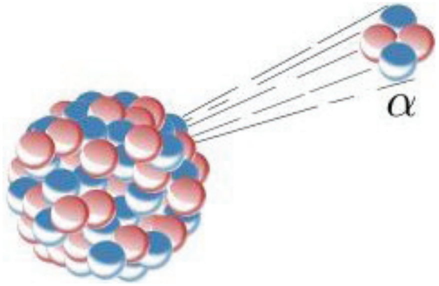
Energy

Nuclei undergo transformations and move through the binding energy landscape one step at a time. It might seem like there are a wide variety of transformations that could take place. However there are constraints and many transformations are not allowed. I will now explain why (and in the process improve on the model used in “Nucleosynthesis, Part 2”). Suppose I suggest a possible decay route for radioactive radon-222: radon-222 → technetium-111 + technetium-111 ?

This reaction splits the nucleus into two equal pieces. Proton and neutron numbers balance out so it seems to be possible, but the question mark means we don’t know (yet) whether this is viable.
To use the concept of energy to test viability, calculate a quantity called Q (see the notes for details on how this is done). Q is the energy left over after a specific decay (such as the one proposed above). If Q is greater than zero the decay is allowed to take place, if it is less than zero it is not allowed. For the decay above, Q is less than zero, and radon-222 does not decay into technetium-111.

However, there many other possible decay routes. Let’s try this one:
radon-222 → polonium-218 + helium-4

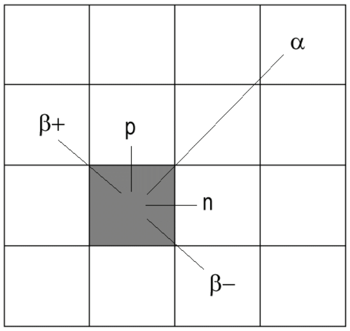
In this case, Q is greater than zero, and radon-222 will decay via this route. Decays that have helium-4 on the right side of the reaction are known as alpha decay. Alpha decay is the most common billiard ball decay, but not the only one. Other billiard ball decay modes go by the names cluster decay, spontaneous fission, neutron emission and proton emission (neutron and proton emission are rarely observed outside of research facilities, but are known to occur during nucleosynthesis).



alpha decay

Not all decays are billiard ball decays. There are non-billiard ball decays called "beta decays" and they fall into one of three categories: 1) Beta plus where one of the protons in the nucleus is converted to a neutron or 2) Beta minus where one of the neutrons in the nucleus is converted to a proton. 3) Double beta where two beta decays occur simultaneously (the last type is very rare). All types of beta decay result in emission of neutrinos and all involve some type of electron (normal electrons or anti-electrons, the later known as positrons).

The various types of decays (billiard ball and beta), can be viewed as "moves" within the binding energy landscape described in "Nucleosynthesis, Part 2" (recall that proton number increases from bottom to top, and neutron number increases from left to right).



Alpha decay (α) moves a nucleus down and to the left two squares (only occurs for heavy atoms, that's the only way to get Q>0; cluster decay and spontaneous fission are not shown).

Beta plus decay (β+) moves down and to the right one square. Beta minus decay (β-) moves up and to the left one square (beta decays always move from lower to higher binding energy, this is true of all types of beta decays; double beta decay is not shown).

Proton emission (p) moves down one square. Neutron emission (n) moves left one square (both only occur far from peak binding energy, that's the only way to get Q>0; some nuclei emit two, three or four protons/neutrons at a time. In the later case move two, three or four squares).

Note: there are no decays that move nuclei directly up, directly to the right, or up and to the right. Such decays would increase the number of protons, neutrons or both and cannot occur.

Q not only tells us the viability of a decay process, it is also the energy left over after decay. Generally speaking if Q is small, the decay takes a long time and if Q is large, the decay takes place quickly. This should make sense (intuitively a lot of energy means things happen quickly, and less energy means things happen slowly). However, this relationship is only approximately correct.

That's enough for now. In future articles I will go further into nuclear physics and eventually we will be ready to work through the various reactions of nucleosynthesis. For further reading, there is a separate document with notes on the topics discussed in this article.

NOTES to the first three parts of Dave's Nucleosynthsis article are posted <u>online</u> with this issue of ***Reflections****.*

A New Dark Sky Preserve at the Tip of the Thumb

by Brian Ottum

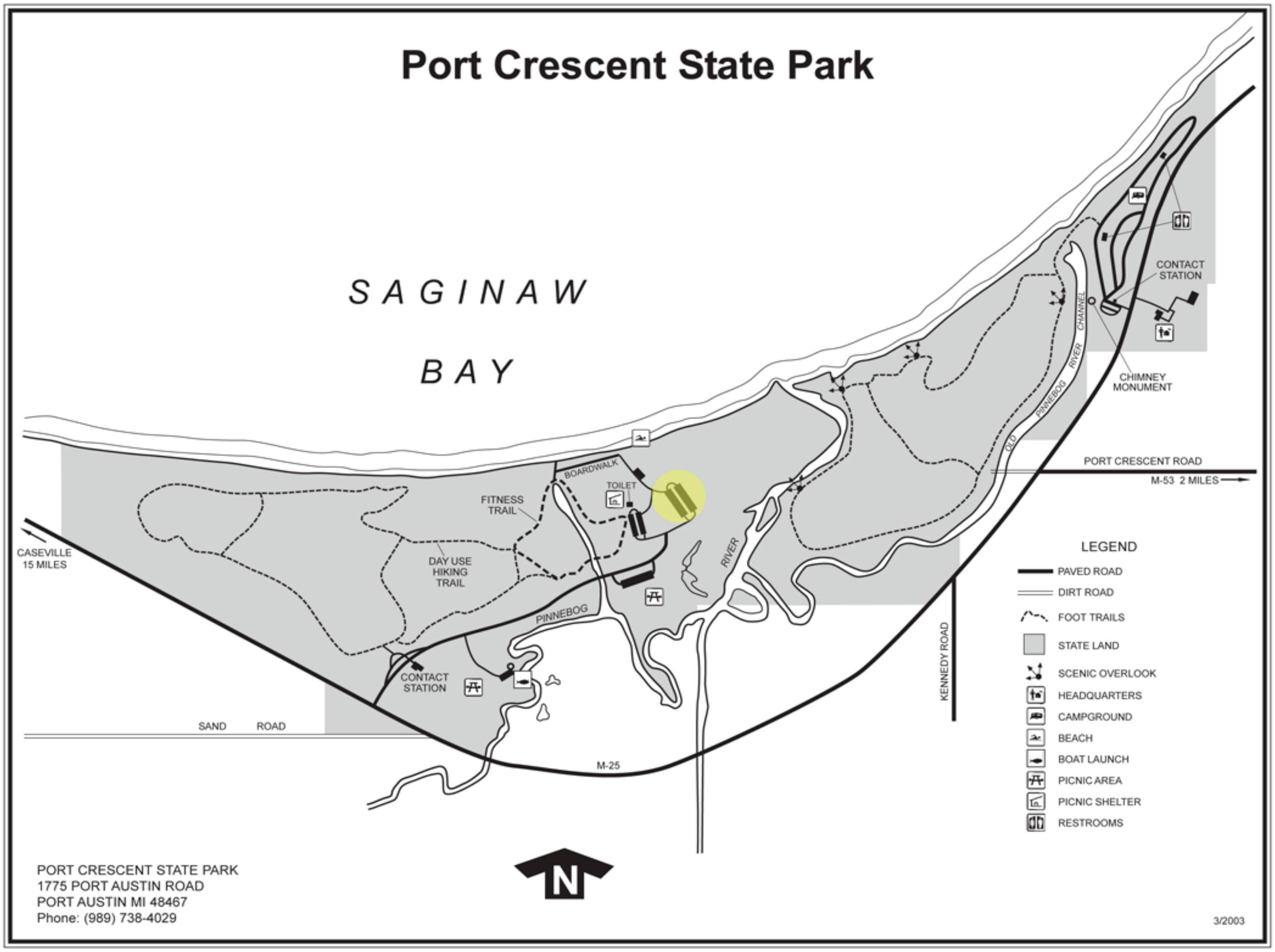
The International Dark Sky Association has granted the third state park in Michigan as a "Dark Sky Preserve." It is Port Crescent State Park. On Friday, September 6, Bill Nigg and I helped with a celebration of this new designation. The DNR rolled out the red carpet for 140 attendees, with talks by the state senator sponsor and regional leadership. Bill and I did a presentation that covered a tour of the universe and light pollution issues. We then adjourned to the telescopes. Thankfully, we had Jack Brisbin helping, along with two observers (Jeff and Greg) from Toledo. Jeff and Greg love the observing site so much that they had come up three straight months! We were able to dodge clouds to show the public some objects. By midnight, it was clear (though not highly transparent) and we switched over to the more esoteric stuff.

The night before was totally cloudless and highly transparent, so I could really see what the site could offer. It is an excellent observing site. The Milky Way was obvious all the way from the NE to overhead to setting in the NW. A 10" dob showed Barnard's Galaxy, which is quite a feat. We tracked down dozens of planetaries that I had never seen before in my 14.5" dob (including "the fetus"). The Veil in the binoviewer with OIII filter was simply amazing. We also easily spotted Triton, largest moon of Neptune. Jeff took many excellent widefield images with his Canon DSLR on a Celestron CG-5 mount, piggybacked on an 80mm refractor.

Here are the specifics of the observing site. It is in the "Day Use" area of the park, which is separated by 2 miles from the campground. Rangers have promised that it will not be locked up with a gate. The parking lot is located just 100 yards south of the beach, but there are dunes in between that block some wind and coastal lights. In fact, there are no lights whatsoever. Horizons are great all around, with just a couple large trees many yards off of the pavement. There is lots of room to spread out on pavement, or to set up on the grass in the middle. There was a bit of a breeze on my first evening, but it died down as usual at sunset. But I could imagine that this site could be quite cold with a north wind. Dew was present but no more than we have around here. The only negative to the site, which is the same as Lake Hudson State Park (the 1st Dark Sky Preserve in the state, the second being Headlands). Vehicles can roll into the parking area and can blast you with their headlights. So using your vehicle to block incoming lights could be recommended. However, this only happened to us once

.

See the park map on the next page, which highlights the observing area in yellow. The Day Use Area is clearly marked off of highway M-25. The campground is 2 miles NE off of M-25. It is a very nice campground near the beach, so it is full on summer weekends. Bonnie is their enthusiastic camp host, who offers coffee each morning.



The town of Port Austin is just 5 miles to the NE, and offers many affordable motels, restaurants and touristy things to do. In the summer, many come to canoe and kayak the scenic coastline.
In fact, there is canoe & kayak rentals across the highway from the entrance to the park – for navigating the Pinnebog River down to where it empties into Lake Huron. I saw one low-priced motel+restaurant right near the park, but most are the 4-6 miles away. Caseville is about 11 miles along the coast to the SW, and seems to bill itself as the “Key West of Michigan.” They host the huge “Cheeseburger in Caseville” drunkfest in early August every year. Lots of interesting stores and restaurants. Driving along the coast is a great daytime activity.

GETTING THERE

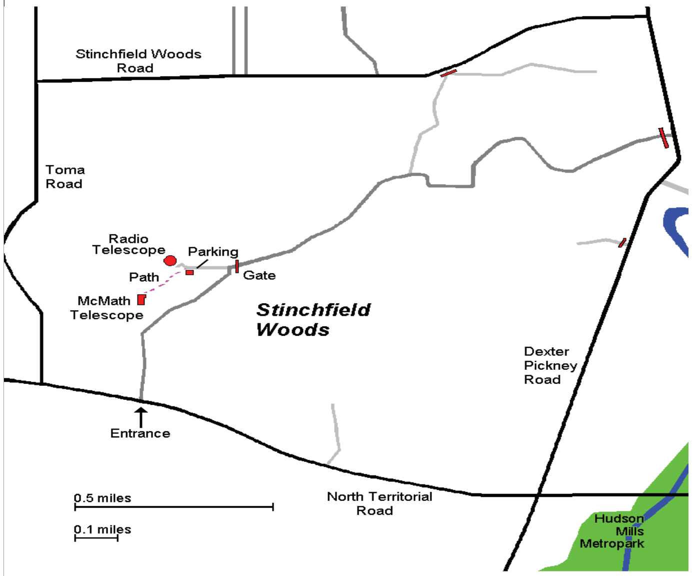
Unfortunately, there are no divided highways in the Thumb. I drove up following my GPS (through Imlay City), but it lead me on a different route back (through Lapeer). Both contained too way many stoplights and stop signs. So I say use the Google maps recommended route from Ann Arbor: go north on 23 then 75 to Saginaw. Exit 151 east to highway 81 (Washington Rd). Then zigzag as recommended to avoid towns, until you reach 25, which follows the coast. Three hours from Ann Arbor.
The average high temperature there for the October 4-6 weekend is a high of 63 and low of 47. For the dark-moon first weekend of November, the average high is 47 and low is 39. Frost is likely on clear nights in early November.

Photographs by the author

Places & Times

Dennison Hall, also known as The University of Michigan's Physics & Astronomy building, is the site of the monthly meeting of the University Lowbrow Astronomers. Dennison Hall can be found on Church Street about one block north of South University Avenue in Ann Arbor, MI. The meetings are usually held in room 130, and on the 3rd Friday of each month at 7:30 pm. During the summer months and when weather permits, a club observing session at the Peach Mountain Observatory will follow the meeting.

Peach Mountain Observatory is the home of the University of Michigan's 25 meter radio telescope as well as the University's McMath 24" telescope which is maintained and operated by the Lowbrows. The observatory is located northwest of Dexter, MI; the entrance is on North Territorial Rd. 1.1 miles west of Dexter-Pinckney Rd. A small maize & blue sign on the north side of the road marks the gate. Follow the gravel road to the top of the hill and a parking area near the radio telescopes, then walk along the path between the two fenced in areas (about 300 feet) to reach the McMath telescope building.



Public Open House / Star Parties

Public Open Houses / Star Parties are generally held on the Saturdays before and after the New Moon at the Peach Mountain observatory, but are usually cancelled if the sky is cloudy at sunset or the temperature is below 10 degrees F. For the most up to date info on the Open House / Star Party status call: (734)332-9132. Many members bring their telescope to share with the public and visitors are welcome to do the same. Peach Mountain is home to millions of hungry mosquitoes, so apply bug repellent, and it can get rather cold at night, please dress accordingly.

Membership

Membership dues in the University Lowbrow Astronomers are $20 per year for individuals or families, $12 per year for students and seniors (age 55+) and $5 if you live outside of the Lower Peninsula of Michigan.

This entitles you to the access to our monthly Newsletters on-line at our website and use of the 24" McMath telescope (after some training).

A hard copy of the Newsletter can be obtained with an additional $12 annual fee to cover printing and postage. Dues can be paid at the monthly meetings or by check made out to University Lowbrow Astronomers and mailed to:

The University Lowbrow Astronomers

P.O. 131446

Ann Arbor, MI 48113

Membership in the Lowbrows can also get you a discount on these magazine subscriptions:

Sky & Telescope - $32.95 / year $62.95/2 years

Astronomy - $34.00 / year or $60.00 for 2 years

For more information contact the club Treasurer at:

lowbrowdoug@gmail.com

Newsletter Contributions

Members and (non-members) are encouraged to write about any astronomy related topic of interest.

Call or Email the Newsletter Editor: **Jim Forrester (734) 663-1638 or jim_forrester@hotmail.com** to discuss length and format. Announcements, articles and images are due by the 1st day of the month as publication is the 7th.

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Reflections & Refractions

Website
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Charlie Nielsen at the telescope with some help. The rig is a 180 mm F10 Intes Maksutov-Cassegrain, tricked out with a 50 mm Stellarvue illuminated correct image finderscope, Rigel viewfinder, William Optics rotating two speed Crayford focuser and 2" dielectric diagonal. It is sitting on an Orion Sirius EQ mount with GOTO and GPS. But the star of the picture is the Chihuahua. Britta, aka "B" dog is inspecting the list of objects to view from the hand controller to see if they meet with her standards. It helps if I include the "Dog" star, but hard to slew to in the Summer

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Notes for Nucleosynthesis (Parts 1 through 3)

Dave Snyder

Billiard Balls

Note that when we call something a billiard ball reaction, we only mean that the proton and neutron numbers add up as you'd expect. We don't expect that protons and neutrons are really acting like hard spheres.

Notation

I use this notation to represent billiard ball decays:

$$A \rightarrow B + C$$

(A decays into nucleus B and nucleus C). Since the order doesn't matter, we generally assume that B is heavier than C. In some cases a lower case letter will appear instead of or in addition to the letter C.

- n – a neutron or a small number of neutrons
- p – a proton or a small number of protons

You can assume two things.

- If you add up the number of protons on the left of the arrow (→), it will equal the number of protons to the right of the arrow.
- If you add up the number of neutrons on the left of the arrow, it will equal the number of neutrons to the right of the arrow.

This will allow you to figure out the exact results of any of these decays or reactions (with the exception of fission reactions, which have too many unknowns). You should know how to go from an isotope name (like carbon-12) to values for N, Z and A. And you should know how to go from to values for N, Z and A to an isotope name.

For beta decays, I use the symbols N_* and N_*' with subscripts and superscripts to represent two different nuclei. Each nucleus appears in this form: $^{A}_{Z}N_*$. This indicates a nucleus with Z protons and total mass number of A. ($A = Z + N$ where N is the number of neutrons). Given Z and A, we can calculate N using $N = A - Z$. This notation allows the numbers of protons and neutrons to be followed. In addition the following symbols may appear:

- e^- – an electron
- e^+ – a positron
- ν_e – either a neutrino or anti-neutrino

Binding Energy

Why do transformations tend to move nuclei from low binding energy to higher binding energy? To understand this, let's look at how gravity works.

Suppose we have an apple falling near the Earth. The Earth has a gravitational field, and you can define a value V (potential energy). V is smaller near the Earth's surface, larger farther away. The apple will tend to move to locations with lower V. This continues until a force is encountered that stops or reverses this process. So apples and other objects usually move to locations with lower V, but not always.

Potential energy also applies to other situations, including the nucleus of atoms. To see this, make the following translations:

BE (total binding energy) = -V (note the minus sign, if you forget it, the results will come out wrong).
Moving to a location with lower V = a nucleus changing to one with higher binding energy.

Therefore nuclei will tend to change into nuclei with higher binding energy. However there can be forces that cause nuclei to change into nuclei with lower binding energy. This can occur with some fusion reactions, some proton absorption reactions and some neutron absorption reactions. It is also possible that nuclei will remain unchanged even though there are higher binding energy nuclei they could change into. There are many examples of the later situation.

Conservation of Energy

Suppose we want to know if a decay route A → B +C for a billiard ball reaction is viable. Simply look up the mass of A, the mass of B and the mass of C (which can found from many sources). Make the following calculation:

$$Q = (\text{mass of A}) - (\text{mass of B}) - (\text{mass of C})$$

If $Q>0$, the decay is viable. If $Q<0$, the decay is forbidden. (The calculation works for billiard ball decays only. It is possible to calculate Q for beta decay, photon emission and internal conversion, but equation above doesn't apply in these cases, you need to use different equations).

Why does the calculation of Q work? This calculation is a consequence of conservation of energy. In any transformation A → B, Energy(A)=Energy(B) or $\Delta E = 0$. This works in classical mechanics as well as many other situations including nuclear physics.

In classical mechanics

$$E = T + V$$

Where E is total energy, T is kinetic energy and V is potential energy.

If we use conservation of energy outside of classical mechanics, there may be additional forms of energy. In the case of the nucleus,

$$E = T + V + m_{pn}c^2$$

Where m_{pn} is the mass of the protons and neutrons.

As before $BE = -V$

(The trickiest part of this is remembering when to include minus signs and when not to).

$$\Delta E = 0 \text{ (conservation of energy)}$$

$$\Delta E = \Delta T + \Delta V + \Delta m_{pn}c^2$$

For the case of radioactive decay, $\Delta T \geq 0$ (T is initially zero and $T = \frac{1}{2}mv^2$ so T can never be negative).

For a nucleus, $m = m_{pn} - BE/c^2$

This can be rewritten $m = m_{pn} + V/c^2$

We define $Q = -(\Delta m)\, c^2$

So $Q = (-\Delta m_{pn} - \Delta V/c^2)\, c^2 = -\Delta m_{pn}\, c^2 - \Delta V$

$\Delta m_{pn}c^2 = 0$ (for billiard ball reactions the number of protons and neutrons don't change)

$$Q = -\Delta V$$

$$\Delta E = 0 = \Delta T + \Delta V + \Delta m_{pn}c^2$$

So, $\Delta T + \Delta V = 0$ and $Q = \Delta T$

But in a realistic decay, $\Delta T \geq 0$, so $Q \geq 0$.

In conclusion, if we calculate Q for a billiard ball decay, and get a negative value, this is not a physically realistic decay. If Q is zero or positive, it satisfies conservation of energy.

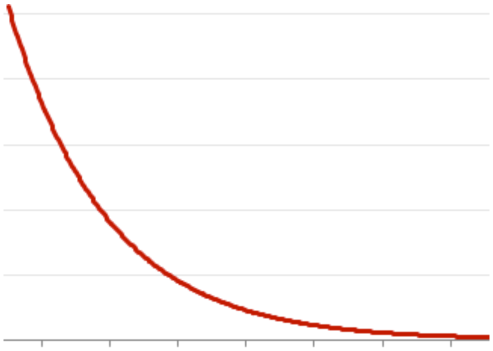
Decay Half-lives

It is possible to use the Schrödinger Equation to model radioactive decay. Modeling billiard ball decays is easier than modeling beta decay, so let's start with billiard balls. Using the Schrodinger Equation to create a realistic model of a radioactive nucleus is extremely difficult (no one has been able to successfully do this). Instead we use an approximation. The details involve some calculus which I will gloss over quickly (see Krane's Introductory Nuclear Physics for the full details).

We pretend that a fully formed alpha particle is located within the nucleus and is bouncing back and forth from one side of the nucleus to the other. The surface of the nucleus is a barrier that prevents the escape of the alpha particle. Quantum mechanics suggests that sometimes the alpha particle will penetrate the barrier and escape, and sometimes not. This leads to a second order differential equation, and the solution to this equation is an exponential curve; a curve satisfying an equation of the form

$$y = e^{-at}$$

y can be interpreted as the probability that the alpha particle is still inside the nucleus at time t (or in other words, the probability that the nucleus has not decayed yet). While this approach involves a simplification, it matches the observed behavior of both billiard ball decays and beta decays. Note that "a" is a parameter that is small for decays that occur slowly and large for decays that occur quickly. The following diagram shows the result of plotting this curve.



The speed of the decay is usually measured by the value half-life which is related to "a" by the following relationship

$t_{1/2} = \ln(2)/a$, where ln is the natural logarithm and $t_{1/2}$ is the half-life

In many cases you can measure the half-life of an isotope by counting how many decays occur in a given time and converting that into a half-life. However that is difficult or impossible to do in two cases: If the half-life is very short or if the half-life is very long.

First very long half-lives: As half-life increases, the number of decays observed per second for a given amount of radioactive material decreases. For extremely long half-lives, the number of decays can be so small they are essentially impossible to detect.

There are a number of examples of isotopes where the Q value for alpha decay is positive; suggesting the isotope should be unstable against alpha decay, but no such decay has been observed. The best known example of this is gold-197, but there other examples. No radioactive decay of gold-197 has ever been observed (it has long been believed to be stable), but Q>0 for gold-197 alpha decay. Naturally occurring gold is entirely gold-197. Hence if the theory is correct, gold-197 is unstable and there are no stable isotopes of gold. This begs to be explained.

There are two possibilities: 1) Some physics, yet to be determined, prevents some or all of these isotopes from decay. 2) These isotopes are in fact radioactive, but have a very long half-life.

Case 1: There are possible theories, but they are all difficult to prove experimentally.

Case 2: it would be very difficult to detect the radioactivity. It is entirely possible that Gold-197 is radioactive but with a half-life so long that it is extremely difficult to detect, perhaps impossible to detect with present technology. So the fact that no radioactivity has been detected simply means we failed so far to detect the radioactivity, not that no radioactivity exists.

Even if this is true and Gold-197 is radioactive, Gold-197 can be safely handled (since the rate of radioactivity, if it exists, is extremely low).

Long half-lives are hard to measure. Short half-lives are also difficult to measure. If you observe the decay of an isotope with a short half-life all the decays will occur over a very short period. In extreme cases, directly counting decays is impossible. But there are other ways. There is a relationship between the life of a system and the energy available (this is based on the Heisenberg Uncertainty Principle) so measuring the energy can be used to estimate the half-life.

Excited States

With a few exceptions, most nuclei come in two or more energy states. The state with the highest binding energy and lowest total energy (remember that binding energy always has a negative sign compared to other forms of energy) is called the ground state. Other states are called excited states.

With one possible exception, all excited states are unstable and will eventually decay into a ground state (usually, but not necessarily, the corresponding ground state of the same isotope). Excited states normally have very short half-lives (less than one nanosecond). In some cases an excited state may have a longer half-life. If an excited state has a half-life more than one nanosecond it is called a metastable isotope. The best known example is Tc99m (metastable isotopes are denoted by an m after the mass number). Excited states with shorter half-lives are denoted with an asterisk (such as carbon12*).

The “one possible exception” mentioned above is tantalum-180m. It is believed to be stable. If it is unstable, the half-life must be very long (over a million trillion years). Oddly enough tantalum-180 (the corresponding ground state) is unstable with a half-life of about 8 hours.

So if excited states are usually highly unstable, how are they created? Fusion reactions that occur in nucleosynthesis often result in excited states. Some beta decays result in excited states.

Most isotopes have at least one excited state. There are a few notable exceptions. Neither the neutron nor the proton (also known as hydrogen-1) have any excited states (since neither is a bound state). In addition, some isotopes with very low binding energy have no excited states. The best example is hydrogen-2 (deuterium). Adding a small amount of energy to a deuterium nucleus causes it to split into a proton and neutron, and thus no excited state is possible.

Conservation of Energy (Billiard Ball Decay Modes)

Cluster Decay

Cluster decay was briefly mentioned. It is a billiard ball decay of the form:

A → B +C

where C is a lightweight atom heavier than helium. In observed examples of cluster decay, C is one of carbon-12, carbon-14, oxygen-20, neon-22, neon-24, neon-26, magnesium-28 or silicon-34.

Cluster decays are rare compared to the much more common alpha decay.

Spontaneous Fission

Spontaneous Fission was briefly mentioned. It is a billiard ball decay of the form:

A → B + C + n

Where the identity of B and C are random, but if a large number of fissions are observed, a statistical pattern arises. n represents a small number of neutrons (the exact number varies).

For example uranium-235 will spontaneously fission. If A is uranium-235 and if we assume C is lighter than B, the most likely possibility is for C to have about 70% the weight of B. B and C with the same weight is very unlikely.

Spontaneous fission is rare compared to the much more common alpha decay. They are observed in isotopes involved in weapons and/or power plants (such as certain isotopes of Uranium and Plutonium) as well as a number of other heavy isotopes. In theory spontaneous fission can occur in selected isotopes of tin as well as selected isotopes heavier than tin, but it is never been observed for anything lighter than thorium.

Proton Emission

Proton emission is a billiard ball decay of the form:

A → B + p

where p is either a proton or a small number of protons. Unlike most other billiard ball reactions, proton emission can occur with either lightweight or heavy isotopes. However it is rarely seen outside of research facilities specifically designed to observe these decays. It only occurs with isotopes with an extreme excess number of protons, isotopes that lie far from the stability line.

Neutron Emission

Neutron emission is a billiard ball decay of the form:

A → B + n

where n is either a neutron or a small number of neutrons. Unlike most other billiard ball reactions, neutron emission can occur with either lightweight or heavy isotopes. However it is rarely seen outside of research facilities specifically designed to observe these decays. It only occurs with isotopes with an extreme excess number of neutrons, isotopes that lie far from the stability line.

Oddball Decays

In addition to the billiard ball decay modes described in the main text, others are possible. Most billiard ball decays only occur for heavy atoms. We saw that proton and neutron emission were exceptions. There are a few other exceptions as well.

Beryllium-8 decays by the path

Beryllium-8 → Helium-4+Helium-4

There is no generally agreed name for this decay. Some authors use the term fission for this decay and other similar decays of lightweight nuclei. Don't confuse this type of fission with spontaneous fission, as there is no emission of neutrons and the decay products are fixed, not random.

Excited states can have any of the billiard ball decays that ground state atoms do, but they sometimes use modes that are never seen in ground state decays. For example, Carbon-12* will sometimes fission into three Helium-4 atoms. This is not the only possibility, other oddball decays are known.

Conservation of Energy (Beta Decay Modes)

There are several types of beta decay.

Single beta decays change a proton within the nucleus into a neutron or vice-versa, but also involve two additional particles. These particles might be electrons, anti-electrons (positrons) and neutrinos. Unlike most billiard ball reactions, beta decay can occur for either low mass or high mass isotopes.

Double beta decays change two protons within the nucleus into two neutrons or vice-versa. It is believed that these decays always involve four additional particles. These particles might be electrons, anti-electrons (positrons) and neutrinos.

First let's go over the different types of single beta decay:

Beta Minus Decay

$^{A}_{Z}N_{*} \rightarrow {}^{A}_{Z+1}N_{*}' + e^{-} + \nu_{e}$

If the atom is heavily ionized (which can occur within the atmospheres of stars), the electron might get incorporated into the atom and not released into the environment. This is rare, but has been observed. Also the decay rate can be affected by the ionization state of the atom in some cases.

Beta Plus Decay

$^{A}_{Z}N_{*} \rightarrow {}^{A}_{Z-1}N_{*}' + e^{+} + \nu_{e}$

This cannot occur when Z=1 and A=1 (because this would change a proton into a neutron, and protons are lighter than neutrons). In real environments, the positron will quickly encounter an electron, annihilate and in turn release photons.

Nuclei with multiple modes that include both beta plus decay and electron capture are common (multiple modes are described below). In some cases beta plus is not allowed, but electron capture is. The reverse is never true. If electron-capture is not allowed, neither is beta plus.

Some data sources group both beta-plus and electron capture into a single decay mode (often without explaining this). If you see a data source that includes electron capture, but beta-plus is not mentioned at all, it is very likely this grouping has occurred. You can assume that some of the isotopes that decay with electron-capture actually have a multiple mode decay of both electron capture and beta-plus decay.

Note the main text refers to beta plus, but not electron capture. For simplicity, electron capture was grouped into the category of “beta-plus.”

Electron Capture (K-capture)

$^{A}_{Z}N_{*} + e^{-} \rightarrow {}^{A}_{Z-1}N_{*}' + \nu_e$

Note this is an exception to the rule that radioactive decays always have a single item to the left of the arrow. In this decay two items are to the left (namely $^{A}_{Z}N_{*}$ and e^{-}).

This decay requires an atom with at least one electron. This is an exception to the idea that we can ignore electrons. Atoms without electrons are not uncommon within astronomical contexts. For example, stars can strip all the electrons off from atoms. An atom with no electrons cannot participate in electron capture.

Electron capture results in electronic transitions which in turn release X-rays. In some cases so called Auger electrons are also released.

Note that in most cases a nuclei will either decay by a negative decay (beta minus) or a positive decay (beta plus and/or electron capture) but not both. Whether a decay is positive or negative depends on which side of the stability line a nuclei lies. A handful of nuclei, all along the stability line and all with odd N and odd Z have multiple modes that include both negative and positive decays.

Double Beta Decay

It is possible that two beta decays will occur simultaneously within the same nucleus. Valid combinations include

- Beta-Minus and Beta-Minus
- Beta-Plus and Beta-Plus
- Beta-Plus and Electron-Capture

- Electron-Capture and Electron-Capture

This is known as a double beta-decay. They decays are rare. If an isotope has a multiple mode that includes both single and double beta-decay modes, the single beta decay will be more common. In this case it is almost impossible to separate the common single beta from the rare double beta, and hence the double beta decay is almost impossible to detect in these cases. However in other cases double beta-decays occur when single beta decays are impossible. In these cases the decay will have a long half-life that is hard, but not necessarily impossible to detect.

While in theory double beta decay should be possible wherever two single beta decays can occur as a decay chain, double beta decays have only been observed for nuclei with even *N a*nd even *Z* (even/even) near the stability line. For such nuclei, single beta decay is impossible if the nucleus has higher binding energy than any of the nearby nuclei (which is often the case near the stability line). However a double beta decay would push the nuclei to another even/even nucleus. If this even/even nucleus has a higher binding energy than the first, double beta decay is possible.

Since all single beta decays involve emission of a neutrino, it would follow that all double beta decays should involve emission of two neutrinos. While this is likely to be true, there is some theoretical reason to believe that double-beta decays can occur without emission of any neutrinos. So far no neutrino-less beta decays have been detected, and they may or may not exist. Detection of such decays is a current research project, but so far has been very difficult to do.

Combinations of Decays

Multiple Modes

A given isotope might be stable (in which case it has no decay modes), it might decay by one of the billiard ball decays mentioned above or one of the beta decay modes described above. Or it might decay by two or more such decay modes. This later is known as an isotope with multiple decay modes.

In a multiple decay mode isotope, a nucleus will have a certain probability of decaying by decay mode 1, a certain probability of decaying by decay mode 2 and so on through all the modes. The probabilities will add up to 1. They might be just billiard ball decays, just beta decays or a mixture of the two.

Decay Chains

Suppose we have the following case: isotope 1 decays into isotope 2. Isotope 2 is unstable and it decays into isotope 3. This is known as a decay chain. A chain might include just 3 isotopes. Or it might continue for 4, 5 or even more isotopes.

Decay chains can include just billiard ball decays, just beta decays or a combination of both. Decay chains always move nuclei one step at a time toward higher binding energy. Long chains always start with a nucleus some distance from peak binding energy.

Interaction Types

There are three types of reactions and decays.

- Strong Interaction – describes what I have been calling "billiard ball" decays and reactions.
- Electromagnetic Interaction –either absorption or emission of photons.
- Weak Interaction –includes includes all of the beta decays as well as a number of reactions. In the context of nuclear physics, weak interactions have several characteristics:
    1. Proton number and neutron number both change, but the total number of protons and neutrons remain the same.
    2. The reaction will always involve either an electron or anti-electron (positron).
    3. The reaction will always involve a neutrino.

(Note the characteristics are not true for all weak interactions, but are true of weak interactions that are covered in nuclear physics).

Excited State Decays

Some possible excited state decays were discussed above. However the most common decay mode is for an excited state to emit a photon, and decay into the corresponding ground state. Another common decay is for the excited state atom to eject an electron. This is called internal conversion, and should not be confused with beta decay. The number of protons do not change, nor do the number of neutrons. And there is no emission of neutrinos. The excited state decays into the corresponding ground state.

Beta decays of ground state nuclei sometimes result in excited states. Alpha decays of ground states are much less likely to do this. (Explaining why requires going into angular momentum, which I will not do here). In some of the situations where a beta decay results in an excited state, we consider both decays as if it were a single decay. This combination is known as delayed-beta decay.

Excited states always have lower binding energy than the corresponding ground state. Excited states usually, but not always, have shorter half-lives than ground states. This is because the decay of an excited state has a larger Q than the same decay with the ground state. Larger Q usually, but not always, implies shorter half-life. Note that excited states frequently have decay modes that the corresponding ground state does not have, and based on what I've said so far, we cannot say anything about the half-life of these decay modes.

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Wikipedia, http://en.wikipedia.org/ There are many articles within Wikipedia, but these articles are most relevant:

- http://en.wikipedia.org/wiki/Angular_momentum
- http://en.wikipedia.org/wiki/Beta_decay
- http://en.wikipedia.org/wiki/Double_beta_decay
- http://en.wikipedia.org/wiki/Electron_capture
- http://en.wikipedia.org/wiki/Nuclear_binding_energy
- http://en.wikipedia.org/wiki/Nuclear_fission_product
- http://en.wikipedia.org/wiki/Nuclear_isomer
- http://en.wikipedia.org/wiki/Positron_emission
- http://en.wikipedia.org/wiki/Segre_chart
- http://en.wikipedia.org/wiki/Semi-empirical_mass_formula
- http://en.wikipedia.org/wiki/Spontaneous_fission

Tools Used

Wolfram Alpha (http://www.wolframalpha.com) was used a source for BE values in “Nucleosynthesis part 2.”

Some of the diagrams in “Nucleosynthesis part 2” were produced by the author using Mathematica.