Michael J. Ruiz, "Astronomy and the Weak Interaction," in AstroNotes, Column Editor Joe Heafner, *The Physics Teacher* **54**, 122 (February 2016).

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The link to the VOR is below.
https://aapt.scitation.org/doi/full/10.1119/1.4940183

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Astronomy and the weak interaction

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An introductory astronomy course provides an excellent vehicle to explore applications of the weak interaction from elementary particle physics. When the topic of the proton-proton cycle appears in my astronomy course, I teach the rules of the weak interaction. In this way, the students not only understand the first step in the proton-proton cycle, but can write down the other three reactions where the weak interaction arises naturally in astronomy: neutronization, neutrino detection, and carbon-14 dating. This exercise encourages critical thinking as students need to apply conservation laws to arrive at the correct reactions.

The weak interaction is one of the four fundamental forces in the Standard Model of elementary particle physics. The other three forces are the gravitational, the electromagnetic, and strong forces. It is common today for astronomy texts to include a discussion of the four fundamental forces in nature and the goal to unify them into a theory of everything (TOE), superstring theory being the leading candidate.[1] The birth of the universe provides for a "laboratory" to investigate TOE due to the incredibly hot temperatures of the Big Bang. The four forces were unified at the initial instant of the Big Bang and these forces quickly separated within an instant as the universe cooled.

Gravity, the electromagnetic force, and the strong force can be pictured in terms of pushes or pulls. The gravitational force pulls us downward. Electrical and magnetic forces can be attractive or repulsive. The strong force supplies the "nuclear glue" that holds the nucleus together. The weak force cannot be easily pictured, which makes the weak force the most challenging to explain to the general student. However, as students learn about the rules of the weak interaction described in this paper, they gain a deeper understanding of this fundamental mysterious force of nature.

I first ask my students what they know about the alchemical dream to change one element into another. After they respond "to change lead into gold," I explain that in nuclear physics you actually get changes of elements. They know that in the world of chemistry, atoms rearrange and you obtain transformations of molecules. With the "strong interaction" of nuclear physics, the protons and neutrons rearrange and you get transformations of elements ("real alchemy"). Turning to the weak interaction, you find a conversion of the most fundamental kind: a proton or neutron undergoes a "transmutation"–the most marvelous transformation of them all.

I list the characters in the "play" of the weak interactions (see Table I). The students know about the first three from physical science courses in middle school. They also know about the positron from my earlier treatment of special relativity and the conversion of matter into pure energy.

Table I. The particles for our weak interactions in astronomy.

Particle	Symbol	Charge	Lepton Number
proton	p	+1	0
neutron	n	0	0
electron	e^-	–1	+1
positron	e^+	+1	–1
neutrino	ν	0	+1
antineutrino	$\bar{\nu}$	0	–1

So at this point I need to introduce just two particles, the neutrino and antineutrino.[2] I tell students to think of the electron as having a little "pet cat"—the neutrino. As they already know about antimatter, they don't wince when I mention the associated antineutrino. Later, when I talk more about the Standard Model, I explain that this neutrino is the electron neutrino as the electron has bigger sisters—the muon and tau particle with their "pet neutrinos."

I proceed with three rules from which we can arrive at all four weak interactions we encounter in astronomy. Rule 1 is the "Transformation Rule"—a proton transforms into a neutron or vice versa. Rule 2 is "Conservation of Charge"—you pick either the electron or antielectron to insure that the total charge is the same before and after the interaction. Rule 3 is "Conservation of Lepton Number."

I explain that the leptons are the lightweight particles: your electron, positron, and associated neutrinos. The conservation of lepton number can be thought of like this: you have to balance matter and antimatter when you introduce the leptons into the picture. The regular leptons (electron and neutrino) have positive lepton number while the antileptons have negative lepton number. We assign zero lepton number for the proton and neutron since they are not leptons. After seeing an example or two, I tell students they will get the hang of it.

A. The first step in the proton-proton cycle. The net effect here is that a single proton undergoes a weak transformation as it collides with another proton. The reaction for the proton that transforms is given below.

Step 1 – Transformation: $p \rightarrow n + ?$
Step 2 – Charge Conservation: $p \rightarrow n + e^+ + ?$
Step 3 – Lepton Conservation: $p \rightarrow n + e^+ + \nu$

In Step 1, since we start with a proton, we must end up with a neutron. For Step 2 we pick the positron so that the charge stays balanced on each side of the reaction. Considering Step 3, since we create antimatter via the positron, we need to balance this with "regular" matter, the regular neutrino.

B. Neutronization. In the formation of a neutron star, protons and electrons get squeezed together: $p + e^- \rightarrow ?$

Step 1 – Transformation: $p + e^- \rightarrow n + ?$
Step 2 – Charge Conservation: $p + e^- \rightarrow n + ?$
We are already balanced.
Step 3 – Lepton Conservation: $p + e^- \rightarrow n + \nu$

For Step 1 we start with a proton, so need to end up with a neutron. For Step 2 we are good since charge is already balanced. For Step 3, since we start with regular lepton matter (lepton number of +1), we must end up with the neutrino (again a regular lepton with lepton number +1). The following analysis reveals the conservation laws in action.

	$p + e^- \rightarrow n + \nu$
Charge:	$1 - 1 = 0 + 0$
Lepton No.:	$0 + 1 = 0 + 1$

C. Neutrino detection. In the 1960s scientists set up a large tank of 380,000 liters (100,000 gallons) of dry cleaning fluid (tetrachloroethylene, or perchloroethylene) nearly a mile (1.6 km) below ground (at the Homestake Gold Mine in South Dakota) in search of the elusive neutrino.[2] Which particle of the nucleus can capture a neutrino, the proton or neutron? Let's try the proton first.

Step 1 – Transformation: $p + \nu \rightarrow n + ?$
Step 2 – Charge Conservation: $p + \nu \rightarrow n + e^+$
Step 3 – Lepton Conservation fails as seen below.

	$p + \nu \rightarrow n + e^+$
Lepton No.:	$0 + 1 = 0 + (-1)$

However with the neutron doing the capture, we can obtain a valid weak interaction.

Step 1 – Transformation: $n + \nu \rightarrow p + ?$
Step 2 – Charge Conservation: $n + \nu \rightarrow p + e^-$
Step 3 – Lepton Conservation now works.

	$n + \nu \rightarrow p + e^-$
Lepton No.:	$0 + 1 = 0 + 1$

Note that this reaction is the reverse of neutronization. When this capture occurs in a chlorine atom of the cleaning fluid, we get the "alchemical transformation" where a chlorine atom transforms into an argon atom since our proton number increases by 1. Argon is next in line after chlorine in the periodic table.

$$^{37}_{17}Cl + \nu \rightarrow {}^{37}_{18}Ar + e^-.$$

The total number of nucleons, i.e., protons plus neutrons in the nucleus, stays the same at 37.

D. Carbon-14 dating. Here a neutron transforms into a proton and we have an "alchemical transformation" taking us from carbon to nitrogen. The reaction for one of the neutrons can be determined from our rules.

Step 1 – Transformation: $n \rightarrow p + ?$
Step 2 – Charge Conservation: $n \rightarrow p + e^- + ?$
Step 3 – Lepton Conservation: $n \rightarrow p + e^- + \bar{\nu}$

The carbon-14 reaction has a half-life of nearly 6000 years.

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + e^- + \bar{\nu}.$$

Note again that the number of nucleons in the nucleus remains the same at 14. However, we have an "alchemical change" as the number of protons increases by 1. Since nitrogen is next in line after carbon in the periodic chart, nitrogen appears on the right side of the reaction.

A single free neutron undergoes the weak interaction $n \rightarrow p + e^- + \bar{\nu}$ since the neutron is slightly heavier than the proton. The half-life for the free neutron decay is about 10 minutes. Since the proton has less mass than the neutron, you don't see the proton decay. By the way, the current lower limit on proton decay via other means is over 10^{33} years! Note that in the weak interaction of the proton-proton cycle, two protons collide adding the necessary energy to enable the proton to transform.

I praise my students when we work out these reactions together in class. They are completing reactions in nuclear physics. We are well beyond chemistry here, doing analyses aligned with "rocket science." We are doing astrophysics!

References

1. Laura Kay, Stacy Palen, Brad Smith, and George Blumenthal, *21st Century Astronomy*, 4th ed. (W. W. Norton & Company, New York, 2013), see Chap. 22, "Modern Cosmology," for an excellent discussion of the four fundamental forces of the Standard Model and their unification.
2. Don Lincoln and Tia Miceli, "The enigmatic neutrino," *Phys. Teach.* **53**, 331–338 (Sept. 2015).