Duane's Science Enrichment Series

Challenge: Why Do Protons and Neutrons Have Spin 1/2?

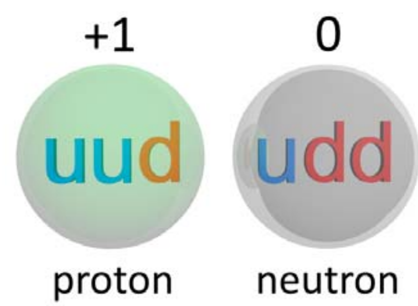
Keywords: Physics, Chemistry
Target: General Chemistry

By now, you've learned everything you need to know about electrons for general chemistry: orbitals, the Pauli Exclusion Principle, the Aufbau Principle, and so on. You also know that they have a spin of ±½. What general chemistry typically doesn't teach is that particles such as electrons are called *fermions* (after physicist Enrico Fermi, after whom the element fermium is also named). The behaviors you learned about electrons are true for fermions in general.

Incidentally, fermions have an antisymmetrical wavefunction, and it is the antisymmetrical transform of the wavefunction under the exchange of two electrons that leads to the Pauli Exclusion Principle. But don't worry; we're not going to go there.

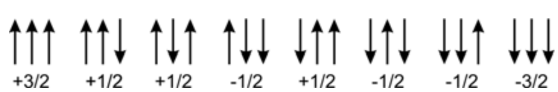
Another thing that General Chemistry doesn't talk much about is nucleons, i.e., protons and neutrons. You know that protons have an electrical charge of +1 and neutrons a charge of 0, and you know that together they make up atomic nuclei. What general chemistry also doesn't teach you about them is that they are fermions too, having a spin of ±½.

Ah, but it doesn't stop there. Protons and neutrons are not elementary particles as once believed, but are made up of other fermions called quarks. Protons consist of two up quarks and a down quark, and neutrons consist of one up quark and two down quarks. The terms *up* and *down* have nothing to do with any literal up and down; they just needed something to call them and picked those as words.



Challenge to get you ready: figure out what electrical charges the up and down quarks must have in order to add up to +1 and 0.

Being fermions, quarks must have half-integer spins, and in particular, like electrons, their spin is ±½. Since there are three of them per nucleon, there are eight ways that their spins could add up:



The only problem is that there are no nucleons with spins of ±3/2.

Here's the Challenge: Why do quarks in nucleons always combine to form spins of ±½?

Hint: Not all the combinations adding up to ±½ are possible, either.

During the semester when I presented this question in class, two students out of 150 came up with the answer, but that's not to say that others wouldn't have if someone hadn't beaten them to it. There is enough information on this page to solve the challenge.

Do no turn the page until you've given it some thought.

Solution:

Remember at the beginning how I said that the rules for electrons apply generally to all fermions. Well, here's the answer:

The Pauli Exclusion Principle.

No two electrons (or fermions) in a system can have the same two quantum numbers. Therefore, in the ground state, a pair of quarks of the same kind must have opposite spins. This is why you never find nucleons with a spin of ±3/2 and why some of the combinations totaling ±½ are impossible.

But it's cooler than that. Notice that I said, "in the ground state." Quarks are bound fermions just as electrons in an atom are bound fermions, and so they, too, have orbitals with fixed energy states. If one of the paired quarks is elevated to an excited state, then you can get previously impossible spin states, but then they are no longer called protons and neutrons. They're called *delta particles*, and you can find one with, for example, three up quarks, a spin of 3/2, and an electrical charge of +2. You don't find delta particles in nuclei because the energy levels we are talking about here are much, much greater than the ones between atomic energy levels, so they don't exist on Earth outside of particle accelerators.

The cool stuff doesn't stop here. Protons and neutrons, though not elementary particles, are still fermions, so they have similar orbitals and energy levels within the atomic nucleus. There are different sets of shells for protons and neutrons. Just as atoms are more stable when they have complete shells, nuclei are the most stable when either the proton shell or the neutron shell is full, and doubly stable when they both are. Did you talk about "magic numbers" when you covered isotopes in nuclear chemistry?

Also, just as when atoms emit a photon when an electron drops to a lower-energy orbital, so do nucleons in the nucleus. You learned about this when you discussed nuclear decay. That's precisely where the gamma particle comes from; it's the photon released when an excited atomic nucleus drops to a lower energy state. They generally get excited as the result of some other nuclear decay.

Remember the big picture: physics is physics. The laws that apply in Chicago apply everywhere.