On the instability of free neutrons compared to neutrons in nuclei: An analogy from experience in the classroom

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Abstract

Free neutrons are radioactive. On the other hand, a number of neutron-containing atomic nuclei are stable. An analogy is offered for better explaining/understanding these seemingly contradictory facts.

The analogy

During classes of the basic course in radiochemistry I was explaining the types of radioactive decay. I explained that one might understand the β decay as resulting from a transformation of a single neutron into a proton, electron and antineutrino. I also mentioned that, unlike the proton, the free neutron is unstable with a half-life of approximately 10 minutes.[1] At the end of the lesson, when we usually discuss issues that are not completely understood, a student posed the following question.

"Why are many nuclei stable? After all, they all contain neutrons, and the neutrons are unstable."

I first intended to explain that a free neutron is not the same thing as a neutron in a nucleus, but I realized soon that was exactly the question: why are the two different? One possible answer, based on the mass-defect and the binding energy of the nuclei, was offered, but did not seem to fully convince the students. Fortunately, I got an idea to make an analogy with something they are really familiar with. Here's how I presented it.

"Let us consider sodium metal. As you all remember, it reacts vigorously with water; when exposed to air, for even a short period of time, it loses its metallic luster. Altogether, it is very, very reactive — a typical metal as chemists say. But let us compare a sodium atom and a sodium ion. They are the same element, right? And the atom may be taken as a representative of the properties of the sodium metal. It is the sodium atoms in the metal that are responsible for its reactivity. That reactivity is lost in the sodium ions. This is, in a way, understandable: sodium ions are products of the reaction of sodium atoms (sodium metal) with some oxidant (water, air, halogens etc.). The loss of one electron converts the atom into ion and the released energy accounts for the loss of reactivity.

"In a way, it is similar with neutrons. Free neutrons are radioactive due to an excess of energy. The free neutron mass is larger than the sum of masses of the proton, electron and the antineutrino (the difference being Δm), and the excess energy is $\Delta E = c^2 \Delta m$. In the language of ordinary chemistry, we could say that neutrons behave as though they are very reactive. However, when Z protons and N neutrons combine (a fusion reaction), a huge amount of energy is released and a nucleus is formed. It is thus the release of energy that stabilizes the neutrons in the nuclei, similar to the above redox reaction where sodium atoms lose electrons and turn into stable ions."

This seemed to work very well. The students got the point. After that we discussed the necessary cautions when one uses analogies. We also pointed to an important difference: there is no one-to-one correspondence in the processes

$$\mathrm{Na} \rightarrow \mathrm{Na}^{+} + \mathrm{e}^{-}$$

and

$$\mathrm{p} + \mathrm{n} \rightarrow {}^{2}\mathrm{D}.$$

There is nothing in the latter process that could be compared with a loss of a particle (electron) in the first one.

This analogy may be useful to instructors who teach radiochemistry. It may also motivate them to think of other analogies, which enrich the 'set of tools' that teachers have at their disposal.

Reference

1. The first person to identify the proton as a decay product of neutron decay was the Canadian researcher, J.M. Robson, then working at the Chalk River nuclear establishment in Ontario. See *Physical Reviews*, volume 78, pages 311-312, 1950. He estimated that the neutron half-life is in the range 9-25 minutes. The currently accepted half-life is 10.3 min (or a lifetime of 14.8 min, http://prola.aps.org/abstract/PRL/v72/i21/p3309_1).