EXAMPLES OF FINE TUNING 2 - THE STRONG NUCLEAR FORCE

Parts of the text set in a smaller font size and in a box are longer quotations from the source literature. They help to fill in the background, but you can safely skip them if you just want the main thread of the argument.

In everyday life we're only aware of two fundamental forces: gravity and electromagnetism. Physicists know about two more forces, which only work at very short range (inside atoms): the strong nuclear force and the weak nuclear force.

This article is about the strong nuclear force – the force that holds protons and neutrons together in the nucleus of atoms. It is about ten thousand billion billion billion billion times (10^{40}) times more powerful than the force of gravity.

> 'The amount of energy released when simple atoms undergo nuclear fusion depends on the strength of the force that 'glues' together the ingredients in an atomic nucleus. This force is different from the two forces I have discussed so far, namely gravity and electricity, because it acts only at very short range, and is only effective on the scale of an atomic nucleus. We don't directly experience it, in contrast to the way that we can 'feel' electrical and gravitational forces. Within an atomic nucleus, however, this force grips the protons and neutrons together strongly enough to combat the electrical repulsion that would otherwise make the (positively charged) protons fly apart. Physicists call this force the 'strong interaction.'[1]

Picture two protons. They are pulled together by the strong nuclear force (as long as they are within range to start with.) But the electromagnetic force pushes them away from each other, because they both have the same positive electric charge.

The electromagnetic repulsion wins over the strong nuclear force attraction, and you can't get two protons to stick together. So a nucleus made of just two protons (called a 'diproton') isn't stable.

But if you add a neutron the balance of the forces shifts: neutrons feel the strong nuclear force, but they don't feel the electromagnetic force, because they're electrically neutral. So adding a neutron is enough to tip the balance: a nucleus made of two protons and one neutron is stable.

So the balance between the strong nuclear force and the electromagnetic force affects the way protons and neutrons can combine to make stable atomic nuclei. This balance has to be fine-tuned for life to be possible.

What would happen if the strong nuclear force were a bit weaker?

If the strong force were a bit weaker, it would not be able to hold atomic nuclei together against the repulsion of the electromagnetic force. According to Barrow and Tipler:

> 'A 50% decrease in the strength of the nuclear force… would adversely affect the stability of all the elements essential to living organisms and biological systems.'[2]

A bit more of a decrease, and there wouldn't be any stable elements except hydrogen.

‘The crucial first link in the chain [the making of the elements] – the build-up of helium from hydrogen – depends rather sensitively on the strength of the nuclear ‘strong interaction’ force. A helium nucleus contains two protons, but it also contains two neutrons. Rather than the four particles being assembled in one go, a helium nucleus is built up in stages, via deuterium (heavy hydrogen), which comprises a proton plus a neutron. If the nuclear ‘glue’ were weaker… a proton could not be bonded to a neutron and deuterium would not be stable. Then the path to helium formation would be closed off. We would have a simple universe composed of hydrogen, whose atom consists of one proton orbited by a single electron, and no chemistry. Stars could still form in such a universe (if everything else were kept unchanged) but they would have no nuclear fuel. They would deflate and cool, ending up as dead remnants.’[3]

‘Slight *de*creases [in the strong nuclear force] could be equally ruinous. The deuteron, a combination of a neutron and a proton which is essential to stellar nucleosynthesis, is only just bound: weakening the strong force by ‘about five percent’ would unbind it, leading to a universe of hydrogen only. And even a weakening of 1 percent could destroy ‘a particular resonance in the carbon nucleus which allows carbon to form from ^{4}He plus ^{8}Be despite the instability of ^{8}Be’ (which is however stable enough to have a lifetime ‘anomalously long’ in a way itself suggesting fine tuning). ‘A 50% decrease would adversely affect the stability of all the elements essential to living organisms:’ any carbon, for example, which somehow managed to form would soon disintegrate.

I L Rozental estimates that the strong force had to be within 0.8 and 1.2 times its actual strength for there to be deuterons and all elements of atomic weight greater than four.’[4]

What would happen if the strong nuclear force were a bit stronger?

If the strong nuclear force was just a bit stronger compared to the electromagnetic force, two protons could stick together in spite of their electromagnetic repulsion (forming a diproton).

If this happened, all the hydrogen in the universe would have been burned to helium in the big bang. It’s very difficult to imagine how a universe with no hydrogen could produce the complicated chemistry needed for life – there would be no water, for a start, and there would be no long-lived stars like the sun. (Stars made from helium burn up much more quickly than stars made from hydrogen.) Barrow and Tipler again:

> ‘All the hydrogen in the Universe would be burned to He^2 during the early stages of the big bang and no hydrogen compounds or long-lived stable stars would exist today.’[5]

‘In our actual universe, two protons repel each other so strongly that the nuclear ‘strong interaction’ force can’t bind them together without the addition of one or two neutrons (which add to the nuclear ‘glue,’ but being uncharged, exert no extra electrical repulsion). If… [the strong nuclear force was fractionally stronger] then two protons would have been able to bind directly together. This would have happened readily in the early universe, so that no hydrogen would remain to provide the fuel in ordinary stars, and water could never have existed.’ [6]

> ‘The *nuclear strong force*, too, must be neither over-strong not over-weak, for stars to operate life-encouragingly. ‘As small an increase as 2 percent’ in its strength ‘would block the formation of protons out of quarks,’ preventing the existence even of hydrogen atoms, let alone others. If this argument fails then the same small increase could still spell disaster by binding protons into diprotons: all the hydrogen would now become helium early in the Big Bang, and stars would burn by the strong interaction which, as noted above, proceeds 10^{18} times faster than the weak interaction which controls our sun. A yet tinier increase, perhaps of 1 percent, would so change nuclear resonance levels that almost all carbon would be burned to oxygen. A somewhat greater increase, of about 10 percent, would again ruin stellar carbon synthesis, this time changing resonance levels so that there would be little burning beyond carbon’s predecessor, helium. One a trifle greater than this would lead to ‘nuclei of almost unlimited size,’ even small bodies becoming ‘mini neutron stars.’ All which is true despite the very short range of the strong force. Were it long-range then the universe would be ‘wound down into a single blob.’’[7]

Conclusion
If the strong nuclear force was weaker than it is, the chemical elements needed for life would not be stable, and we would not be here. If it were stronger, all the hydrogen in the universe would have been burned to helium in the Big Bang. As a result, there would be no long-lived stars like the sun, and no water. There would probably be no complicated chemistry in the universe, and we would not be here. (But even if this argument fails – see below - the production of carbon and oxygen in stars would be greatly reduced if the strong nuclear force was stronger, so we would probably not be here.)

> ‘The existence of deuterium and the non-existence of the diproton therefore hinge precariously on the precise strength of the nuclear force. If the strong interaction were a little stronger the diproton would be a stable bound state with catastrophic consequences – all the hydrogen in the Universe would have been burned to He^2 during the early stages of the Big Bang and no hydrogen compounds or long-lived stable stars would exist today. If the di-proton existed, *we* would not! Also, if the nuclear force were a little weaker the deuteron would be unbound with other adverse consequences for the nucleosynthesis of biological elements because a key link in the chain of nucleosynthesis would be removed. Elements heavier than hydrogen would not form.[8]

A footnote: the above argument about a stronger strong nuclear force may not work

According to Robin Collins, the argument that a stronger strong nuclear force would lead to a universe without hydrogen may not work. He says that:

> ‘^{2}He [that is, the diproton] is unstable, and would decay relatively quickly to deuterium (heavy hydrogen) via the weak force. So, the binding of the diproton would not have resulted in an all-^{2}He universe.’

On the other hand…
However, even if the argument that a stronger strong nuclear force would result in a universe without any hydrogen isn’t right, Collins points out[9] that a stronger strong nuclear force would still affect the way carbon and oxygen are formed by nuclear burning in stars. Scientists modelled the way the formation of carbon and oxygen would change if the strong nuclear force were varied. They found that:

> ….a change of more than 0.5% in the strength of the strong interaction or more than 4% in the strength of the Coulomb [electromagnetic] force would destroy either nearly all C or all O in every star. This implies that irrespective of stellar evolution the contribution of each star to the abundance of C or O in the ISM [interstellar medium] would be negligible. Therefore, for the above cases the creation of carbon-based life in our universe would be strongly disfavored.[10]

So the case for fine tuning of the relative strengths of the strong nuclear force and the electromagnetic force still stands, even if the specific argument about all the hydrogen in the universe being turned into helium does not work.

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[1] Rees, M, 'Just Six Numbers: the deep forces that shape the universe' Basic Books, 2000 p. 53-54
[2] Barrow, J D and Tipler, F J, 'The Anthropic Cosmological Principle' Oxford University Press 1986, p. 327
[3] Rees, p. 54-55
[4] Leslie, J 'Universes' Routledge 1989, p. 35-36
[5] Barrow and Tipler, p. 322
[6] Rees, p. 55.
[7] Leslie p. 35
[8] Barrow and Tipler, p. 322
[9] Collins, R, 'The Evidence of Fine Tuning,' at http://home.messiah.edu/~rcollins/Fine-tuning/FT.HTM, accessed 25th August 2010, p. 18ff
[10] Oberhummer, H, Csótó, A, and Schlattl, H: 'Stellar Production Rates of Carbon and Its Abundance in the Universe,' Science, vol. 289, p. 90 (2000)