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Anthropic Argument for Three Generations

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ABSTRACT

The standard model of particle physics contains $N_{\rm gen} = 3$ generations of quarks and leptons, i.e., two sets of three particles in each sector, with the two sets differing by 1 unit of charge in each. All 12 "predicted" particles are now experimentally accounted for, and there are strong (though not air-tight) arguments that there are no more than three generations. The question is: why exactly $N_{\rm gen} = 3$? I argue that three generations is a natural prediction of the multiverse theory, provided one adds the additional, quite reasonable assumption that $N_{\rm gen}$ in a randomly realized universe is a steeply falling function of number. In this case $N_{\rm gen} > 2$ to permit CP violation (and so baryogenesis and thus physicists) and $N_{\rm gen} < 4$ to avoid highly improbable outcomes. I thereby make a testable anthropic-principle prediction: that when a theory of randomly realized $N_{\rm gen}$ is developed, the probability will turn out to be steeply falling in $N_{\rm gen}$.

1. Introduction

After Anderson and Neddermeyer's 1936 discovery of the muon was confirmed by Street & Stevenson (1937), I. I. Rabi famously quipped "who ordered that?", i.e., why was there a second "electron"? No sensible answer to this question could even be attempted until the general pattern of "multiplicity" of "fundamental" particles was established.

The emergence of a standard particle physics model does allow this question to be at least properly framed. In this model, there are exactly three "electrons" (electron, muon, tau), and each is associated with its corresponding neutrino, with identical quantum numbers except 1 extra unit of charge. In parallel, there are exactly three "lower quarks" (down, strange, bottom), each with its corresponding "upper quark" (up, charm, top), also with identical quantum numbers except 1 extra unit of charge. The standard model has demonstrated at least some predictive power (as opposed to being merely a post-facto classification scheme) because the top quark was firmly established in the model well before its experimental confirmation.

With four classes of particles in each of three "generations", there are 12 predicted particles. All 12 members of these three generations have been confirmed experimentally (so $N_{\rm gen} \geq 3$), and there is a powerful piece of evidence that there are no more than three generations. The Z particle can decay into particle/anti-particle pairs of any of these 12 particles, except for the top quark, since two tops have more mass than the Z. The rate of decay would increase (and so the width of the Z resonance would decrease) beyond its measured value if there were particles in a fourth generation. The only caveat is that if all four particles in this putative generation were heavier than half the Z mass, these decay channels would be blocked (as they are for the top quark).

Hence, there is excellent, though not absolutely secure evidence that there are exactly three generations ($N_{\rm gen} = 3$). And so, Rabi's question can now be made more precise: "why exactly three generations"?

2. In Defense of the Anthropic Principle

There is a broad class of answers to such questions that is subsumed under the lofty slogan "anthropic principle". The core idea of this principle is that our "universe" is only one of many universes, each with its own "fundamental constants", such as the electron mass, the fine structure constant, etc. These constants appear as "fundamental" (i.e., without any further explanation – or perhaps "explained" by mathematical derivation from other constants that are themselves unexplained), but they actually are just realizations of fields whose symmetries are broken as the universe cools, leaving them at some random value. Then there are a huge number of universes that have various values for these constants that are incompatible with intelligent life, and so do not contain physicists to ponder the values of these constants. Our universe is among the others. Hence, if we see that certain constants (or combinations of constants) "happen" to be compatible with life, the reason is the same as why the Earth "happens" to have water: our planet may well be in a minority that are so endowed, but the others do not have people on them to worry about this issue.

Of course, the full conditions for intelligent life are not known, but we can conservatively identify at least some conditions. For example, if big bang nucleosynthesis had ended with $> 99\%$ helium, then stars would not live long enough for intelligent life to evolve, even supposing that such life could form without hydrogen. And I think that few would argue that a universe without baryons (protons and neutrons – made of quarks) could contain life, intelligent or otherwise.

Now, before continuing, I must take note of the fact that many people object to the "anthropic principle" on the grounds that it is "not a scientific theory" in that it "does not make testable predictions". Such arguments reflect a deep misunderstanding of the nature of scientific inquiry. Of course, the anthropic principle is not a scientific theory and obviously in itself makes no testable predictions. Rather it is a framework for theoretical speculation. Any profoundly new theory will be preceded by theoretical speculation, or even groping, before it can be properly formulated. Such full formulations may require additional universes and at the same time make predictions about our universe. If there are one or two such predictions that are verified, and these are minimally entangled with the hypothesis of other universes, one might maintain the hope that a new theory will emerge that predicts the same things about our universe but avoids the "embarrassment" of other universes. But if these correct predictions multiply, and if they become deeply entangled with the existence other universes, then the other universes will come to be accepted, in the same way that we currently accept the "reality" of the magnetic vector potential, despite the fact that it was originally introduced as a mathematical convenience. Of course, it is also possible that nothing will come of the anthropic-principle speculation, in which case it would join the ranks of the vast majority of such speculations in the waste bin of theoretical physics.

In this context, it is useful to catalog physical constants that would be (post-facto) explained by the anthropic principle, assuming that many universes with very different physical constants do exist.

3. The Anthropic Explanation of Three Generations

In 1967, the great Soviet physicist Andrei Sakharov identified three conditions for baryogenesis. In the early universe, there were exactly equal numbers of baryons and anti-baryons, and these both approximately equaled the number of photons. Today, the number of photons is roughly unchanged, but essentially all of the anti-baryons have annihilated with baryons. From the presently observed baryon/photon ratio, we therefore learn that somehow during those early times, about one in a billion anti-baryons was converted into a baryon. Sakharov's (1967) three necessary conditions were 1) baryon-number violating process, 2) violation of charge-parity (CP) symmetry, 3) out-of-equilibrium thermodynamics.

The first condition is obvious. The third is also obvious, since in thermodynamic equilibrium detailed balance ensures that every baryon-violating process will be countered by baryon violation going in the other direction. The second is less obvious. Under the CP symmetry, a given particle's anti-particle will behave exactly as the particle does, provided we consider anti-particles of the opposite parity. In quantum mechanics, CPT symmetry is essentially a mathematical identity. That is, the above symmetry must hold if, in addition, the anti-particle is going backwards through time. Hence, breaking the CP symmetry is essential to breaking symmetry in time, which is required to move from a state of 0 baryon number to positive baryon number at a later time.

Sakharov was inspired to consider this problem by Cronin and Fitch's discovery of CP violation in the neutral kaon system (Christenson et al. 1964). Neutral kaons are composed of quarks from the first two generations, down and strange. But, if there were only two generations, CP violation would be mathematically impossible: the matrix linking the mass states and the flavor states of these particles could always be "rotated" so that the CP violating terms were zero. Realizing this, Kobayashi & Maskawa (1973) introduced a third generation of quarks (and the Cabbibo-Kobayashi-Maskawa matrix to link them) to explain CP violation, even though no such third generation had yet been isolated. Hence, it was immediately clear that three generations were needed for baryogenesis.

And so, from our present perspective, if the number of generations is a random field that "freezes out" in the early universe, the "selection requirement" that our universe contain physicists strictly imposes $N_{\rm gen} > 2$.

4. A Testable Anthropic Prediction

Why then are there only three generations? Within the anthropic-principle framework, the answer is clear: the random "generation number" field has a steeply falling probability of freezing out with increasing value of $N_{\rm gen}$. Hence, my prediction is that when the theory of these fields is developed, it will be found that the probability of high $N_{\rm gen}$ is small, perhaps because extra generations require the mediation of a high-mass (therefore heavily suppressed) particle.

Although Sakharov's 3 conditions for baryogenesis were inspired by the discovery of CP violation in the quark sector, the actual channel for baryogenesis is not yet established and therefore may involve other particle sectors. For example, one possibility is that the earliest particle asymmetry is leptogenesis through the neutrino sector (rather than baryogenesis directly through the quark sector), and this indirectly induces baryogenesis by processes that conserve $B-L$ (baryon minus lepton number) but violate each separately, by converting anti-leptons into baryons. If neutrinos are Majorana particles, and so their own anti-particles, then it would be possible to have CP violation with only two generations. In this case, the appearance of a third generation would be superfluous from the standpoint of human existence, so that no such anthropic argument could be made. This serves to underline that anthropic arguments in general must be based on a thorough understanding of the physics of our universe.

5. A Quantitative Example

Let us suppose that, some time in the future, it is firmly established that baryogenesis is due to quark-sector CP violation. And further, that continuing searches for heavy quarks and leptons at LHC fail to find a fourth generation, thus tending to confirm the present conclusion that $N_{\rm gen} = 3$. And finally, that physicists converge on a theory of generation-number "freeze out" with probability $P \propto N_{\rm gen}^{-\alpha}$, where α is established to be some definite number.

If $\alpha = 1.05$, then the probability of our universe having exactly $N_{\rm gen} = 3$ (versus $N_{\rm gen} > 3$) would be $\sim 1/60$. This would not, by itself, rule out the multiverse, because events of this level of improbability do happen. But it would by itself be reason for extreme caution. And if the multiverse failed a few such tests, it would be ruled out.

On the other hand, if $\alpha = 10$, then the prior probability of the observed $N_{\rm gen} = 3$ would be 94%, which would be consistent with the multiverse. Of course, scientific hypotheses can never be finally "proved", but if the multiverse passed many such tests, it would come to be accepted by the same process as other theories.

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