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Review

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# Anthropic considerations in nuclear physics

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**Abstract** In this short review, I discuss the sensitivity of the generation of the light and the life-relevant elements such as carbon and oxygen under changes of the parameters of the Standard Model pertinent to nuclear physics. Chiral effective field theory allows for a systematic and precise description of the forces between two, three and four nucleons. In this framework, variations under the light quark masses and the electromagnetic fine-structure constant can also be consistently calculated. Combining chiral nuclear effective field theory with Monte Carlo simulations allows to further calculate the properties of nuclei, in particular of the Hoyle state in carbon, that plays a crucial role in the generation of the life-relevant elements in hot, old stars. The dependence of the triple-alpha process on the fundamental constants of nature is calculated, and some implications for our anthropic view of the Universe are discussed.

**Keywords** Anthropic principle · Nuclear physics · Effective field theory

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## 1 A brief guide through this short review

In this review, I discuss certain fine-tunings in nuclear physics that are relevant to the formation of life-relevant elements in the Big Bang and in stars. To set the stage, in Sect. 2, I give a brief discussion of the so-called anthropic principle and argue that one can indeed perform physics tests of this rather abstract statement for specific processes such as element generation. This can be done with the help of high-performance computers that allow us to simulate worlds in which the fundamental parameters underlying nuclear physics take values different from the ones in nature. In Sect. 3, I define the specific physics problems we want to address, namely how sensitive the generation of the light elements in the Big Bang is to changes in the light quark mass $m_q$[1] and also how robust the resonance condition in the triple-alpha process, i.e., the closeness of the so-called Hoyle state to the energy of $^4$He+$^8$Be, is under variations in $m_q$ and the electromagnetic fine-structure constant $\alpha_{EM}$. The theoretical framework to perform such calculations is laid out in Sects. 4 and 5. First, I briefly discuss how the forces between nucleons can be systematically and accurately derived from the chiral Lagrangian of QCD. Second, I show how combining these forces with computational methods allows for truly *ab initio* calculations of nuclei. In this framework, the decades old problem of computing the so-called Hoyle state, a particular resonance in the spectrum of the $^{12}$C nucleus, and its properties can be solved. This is a necessary ingredient to tackle the

[1] Throughout this review, we work in two-flavor QCD with up and down quarks with masses $m_u$ and $m_d$, respectively. In most cases, it suffices to work in the isospin limit $m_u = m_d \equiv m_q$, but at one instance we also have to consider strong isospin breaking with $m_u \neq m_d$.

problem of the fine-tuning mentioned before. In Sect. 6, I show how the quark mass dependence of the nuclear forces can be consistently calculated within chiral nuclear effective field theory (EFT). Constraints on such variations can be derived from Big Bang nucleosynthesis, as outlined in Sect. 7. Here, we will encounter the first fine-tuning relevant to life on Earth. This, however, requires also heavier elements such as carbon and oxygen. The viability of the generation of these elements under changes in the light quark mass and the fine structure constant is discussed in Sect. 8. I summarize the implications of these findings for the anthropic principle in Sect. 9 and give a short summary and outlook in Sect. 10. I note that much more work has been done on the topics discussed here, for recent works and reviews, the reader is referred to Refs. [1–3], and the papers quoted therein.

## 2 The anthropic principle

The Universe we live in is characterized by certain parameters that take specific values so that life on Earth is possible. For example, the age of the Universe must be large enough to allow for the formation of galaxies, stars and planets. On more microscopic scales, certain fundamental parameters of the Standard Model of the strong and electroweak interactions like the light quark masses or the electromagnetic fine-structure constant must take values that allow for the formation of neutrons, protons and atomic nuclei. At present, we do not have a viable theory to predict the precise values of these constants, although string theory promises to do so in some distant future. Clearly, one can think of many universes, the multiverse, in which various fundamental parameters take different values leading to environments very different from ours. In that sense, our Universe has a preferred status, and this was the basis of the so-called *anthropic principle* (AP) invented by Carter [4]. The AP states that "the observed values of all physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirements that the Universe be old enough for it to have already done so". There are many variants of the AP, but this definition serves our purpose quite well. At first sight, one might think that it is a triviality, as the statement seems to be a tautology. However, we can move away from the philosophical level and ask whether the AP can have physical consequences that can be tested? This is indeed the case particularly in nuclear physics, as I will argue in this review. But it is worth mentioning that anthropic reasoning has been used in some well-cited papers, I name here Weinberg's work on the cosmological constant [5] and Susskind's exploration of the string theory landscape [6]. The influence of the AP on string theory and particle physics has been reviewed recently in Ref. [3]. But let us return to nuclear physics. A prime example of the AP is the so-called Hoyle state. In 1954, Hoyle [7] made the prediction of an excited level in carbon-12 to allow for a sufficient production of heavy elements ($^{12}$C, $^{16}$O, $\cdots$) in stars. As the Hoyle state is crucial to the formation of the elements essential to life as we know it, this state has been nicknamed the "level of life" [8]. See, however, Ref. [9] for a thorough historical discussion of the Hoyle state in view of the anthropic principle. Independent of these historical issues, the anthropic view of the Universe can be nicely shown using the example of the Hoyle state; more precisely, one can understand how the abstract principle can be turned into a physics question. The central issue is the closeness of the Hoyle state to the threshold of $^4$He+$^8$Be that determines the resonance enhancement of carbon production. In Fig. 1, I show the possible response of this resonance condition to the change of some fundamental parameter, here called $g$. If for a wide range of this parameter, the resonance condition stays intact (Fig. 1a), more precisely, the absolute energies might shift, but the Hoyle state stays close to the energy of $^4$He+$^8$Be. In such a case, one can hardly speak of an anthropic selection. If on the other hand, the two levels split markedly for small changes in $g$ as shown in Fig. 1b, this would correspond to a truly anthropic fine-tuning. In nature, we cannot investigate which of these scenarios are indeed fulfilled as all fundamental constants take specific values. However, with the powerful tool of computer simulations, this has become possible and this issue will be discussed in the remaining part of the review.

## 3 Definition of the physics problem

In this section, I will more precisely define the nuclear physics problems that have implications for our anthropic or non-anthropic view of the Universe. As it is well known, the elements that are pertinent to life on Earth are generated in the Big Bang and in stars through the fusion of protons, neutrons and nuclei. In Big Bang nucleosynthesis (BBN), alpha particles ($^4$He nuclei) and some other light elements are generated. Life-essential elements such as $^{12}$C and $^{16}$O are generated in hot, old stars, where the so-called triple-alpha reaction plays an important role. Here, two alphas fuse to produce the unstable, but long-lived $^8$Be nucleus. As the density of $^4$He nuclei in such stars is high, a third alpha fuses with this nucleus before it decays. However, to generate a sufficient amount of $^{12}$C, an excited state in $^{12}$C at an excitation energy of 7.65 MeV with spin zero and positive parity is required [7], and this is the