Nuclei with an Extra Quark, Stellar Burning, and the Solar Neutrino Problem

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Possible modes of nucleosynthesis involving nuclei with an extra quark have been considered. It is found that such nuclei can contribute significantly to stellar burning even at an abundance level of less than 1 nucleus with an extra quark in 10^{15} nuclei. Consideration of the beta-decay properties of nuclei with an extra quark also suggests that their contribution could solve the solar neutrino problem.

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Our present understanding of the stellar processes which generate energy in stars and synthesize nuclei has developed over the past few decades. While the resulting description[1] of these processes has been quite successful, one difficulty, the solar neutrino (SN) problem, has persisted over the past decade. The number of detected SN's predicted[2] by the "standard solar model" (SSM) is 7.5 ±1.5 SNU.[3] The experimental value[4] is 1.8 ±0.2 SNU, thus creating a serious conflict between theory and experiment.

If the sun's core, usually taken[2] to be at 15.5×10^6 K, were at a somewhat lower temperature, the predicted and observed rates could be brought into agreement. However, this would also result in a significant reduction in the energy, or, equivalently, the number of α particles, produced in the sun. Numerous suggestions have been offered to explain the discrepancy. One, that of uncertainties in the nuclear cross sections, does not appear to be able to resolve the difficulty.[5] Another, ν oscillations, could explain the SN problem, but the several searches[6] for them have not yet proven their existence. Dynamical stellar processes, e.g., mixing and rotation, are also thought not to resolve the problem; they have recently been reviewed by Rood.[7]

In this Letter we show that quarked nuclei (Q-nuclei), i.e., single quarks combined with nuclei, could solve the SN problem. They need to be of sufficient density in stars to contribute appreciably to the burning, but must, in their reactions, emit few ν's which could be detected by the Davis SN detector. Then a lower core temperature of the sun could produce both the observed luminosity and SN flux. Possible contributions of quarks to stellar burning were discussed previously,[8] but that model was subsequently shown to be incorrect.[9] It also differs fundamentally from the present one, as the quark-nucleus interactions were assumed to be leptonic instead of hadronic as in the present case.

Several questions arise from our proposed explanation. First, would the abundance of Q-nuclei necessary to generate the required amount of stellar energy be consistent with experimental evidence for free fractional charges? Second, are their properties consistent with our knowledge of QCD and of nuclear physics? Third, would Q-nuclei produce any catastrophic consequences for stars, such as a reduced lifetime or increased high-energy ν production?

The question of Q-nuclear abundance can be determined, at present, only from the experiments of LaRue, Phillips, and Fairbank.[10] Numerous other experiments,[11] all different from theirs, have tested various hypotheses regarding the fractional charges claimed by that group; none has been able to confirm their result. However, all such experiments had inherent caveats which could have precluded observation of Q-nuclei. The 6×10^{17} atoms on each of the spheres used by LaRue, Phillips, and Fairbank imply an abundance of Q-nuclei of 2 in 10^{18} nuclei. However, the actual abundance could differ[11] by orders of magnitude in either direction, depending on their chemical properties. Thus Q-nuclei may exist in nature, albeit at a very low level.

In a model studied by De Rújula, Giles, and Jaffe,[12] it was concluded that a quark left deconfined from the "big bang" would accrete nucleons. Presumably the resulting Q-nuclei would also undergo β decay to achieve their minimum-energy configuration. The term of the nuclear mass formula[13] which represents the energy of the charge distribution should also apply for β decays of Q-nuclei: Those formed by adding an up (down) quark to a nucleus will have more (less) energy to give to β decay than would the corresponding nuclei. Since the color polarization force increases the binding of the nucleons of Q-nuclei over that of nuclei,[14] the size of a Q-nucleus would be expected to be smaller than that of the corresponding nucleus, and the Q-nucleus β-decay energy, therefore, greater than the nuclear value.

A wide range of values exists[12,14] for the enhancement of the Q-nuclear potential over that of nuclei. For the present mode of Q-nucleosynthesis to occur, it must be greater than the 0.4 MeV/nucleon necessary to make $^{5}\mathrm{He}^{u}$ ($^{5}\mathrm{He}$ + an up quark) and $^{5}\mathrm{Li}^{u}$ stable to baryon emission, but less than about 4 MeV/nucleon so that the binding energy of $^{7}\mathrm{Li}^{u}$ does not become large enough to inhibit or prohibit a (p, α) reaction. Both of these requirements fall[12,14] within the theoretical limits. Since the Q-nuclear and nuclear potentials might differ in both shape and strength, those limits seem to allow the required values with ease. Thus Q-nuclei appear capable of undergoing proton-radiative-capture reactions and, when their structures are favorable, particle-transfer reactions. Both are necessary for them to participate in nucleosynthesis cycles.

We assume that the Q-nuclei of interest are based only on up quarks. Considerations of β-decay rates of Q-nuclei based on down quarks, to be discussed in a subsequent paper, suggest that they would achieve a large nuclear charge, and so would not be relevant to nucleosynthesis with protons. This conclusion is consistent with that of Salpeter,[9] although for different reasons. We will also assume that Q-nuclei do not progress past seven nucleons in their nucleosynthesis; the present study suggests that they would undergo a (p, α) reaction and reinitiate a cycle, rather than continue to accrete nucleons.

Tabulations of many stellar reaction rates, based on measured nuclear reaction information, have been given[1] as a function of stellar temperature. A formalism which uses a statistical description of nuclear cross sections has been developed[15] to describe rates for reactions which have not been measured. We shall use it to describe reactions involving Q-nuclei. While this approach does not provide as good a description of such processes as might be desired, a better one would require considerably more knowledge of Q-nuclei than is presently available. However, even this description will allow determination of important features about Q-nuclear participation in stellar nucleosynthesis.

Our calculations suggest that $^{4}\mathrm{He}^{u}$ could catalyze the $4p \rightarrow \alpha$ process much as $^{12}\mathrm{C}$ does in the CNO cycle, thereby producing the same resulting energy per α particle as does the CNO cycle or the p-p chain. The resulting cycle is indicated in Fig. 1: It is simply not possible without Q-nuclei, since no stable nuclei exist at mass 5 u. As in the CNO cycle, this Q-nuclear cycle requires two β decays. And, just as the structure of $^{15}\mathrm{N}$ favors reinitiation of the CNO cycle, the Q-nuclear cycle would be expected to terminate with $^{7}\mathrm{Li}^{u}$ which, because of its structure, would be expected to undergo a (p, α) reaction and reinitiate that cycle rather than to continue to capture protons. The slowest rate for this cycle is that of the reaction $^{6}\mathrm{Li}^{u}(p, \gamma)$. But it is many orders of magnitude larger than that of the p-p chain over a wide range of temperature.

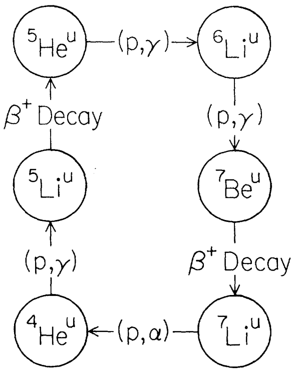

FIG. 1. The Q-nucleosynthesis cycle suggested by the results of our calculations. Details of the nuclear reactions and β decays are discussed in the text.

This cycle requires that the β decay of $^{5}\mathrm{Li}^{u}$ to $^{5}\mathrm{He}^{u}$ (see Fig. 1) proceed rapidly enough that little of the $^{5}\mathrm{Li}^{u}$ can proceed on, via a (p, γ) reaction, to $^{6}\mathrm{Be}^{u}$, and that the $^{7}\mathrm{Be}^{u}$ decay rapidly enough that very little $^{8}\mathrm{B}^{u}$ can be formed. The ν's produced in the β decay of $^{6}\mathrm{Be}^{u}$ would have a maximum energy of around 4.0 MeV, well above the threshold of the Davis detector, and so would produce some observable SN's. The Q value for the decay of $^{5}\mathrm{Li}^{u}$ would be expected[13] to be appreciably larger than that for $^{5}\mathrm{Li}$, i.e., around 0.8 MeV instead of 0.29 MeV. Comparison of the lifetime[16] for β decay to an analog nucleus with this Q value under stellar conditions to the reaction rate predicted[15] for $^{5}\mathrm{Li}^{u}$ (p, γ) suggests that few of the $^{5}\mathrm{Li}^{u}$ decays would occur. However, as noted above, the expected Q-nuclear size decrease could boost this Q value above the e^{+} emission threshold. Then the lifetime would decrease rapidly with decay energy, most of the $^{5}\mathrm{Li}^{u}$ decays could occur, and the detectable ν flux would be small.

The decay of $^{8}\mathrm{B}^{u}$ to $^{8}\mathrm{Be}^{u}$ would produce ν's of essentially the same energy as those from the p-p chain to which the Davis detector is sensitive. Thus the relative rates of α and ν production in the Q-nuclear cycle indicated in Fig. 1 must be considered. The ratio of the Q-nuclear rate of α production $R_\alpha{}^Q$ to that for the p-p chain $R_\alpha{}^{\rm SSM}$ can be shown to be

$$\frac{R_\alpha{}^Q}{R_\alpha{}^{\rm SSM}}=\frac{[^1\mathrm{H}][^6\mathrm{Li}^Q]\langle\sigma v\rangle_{16}{}^Q}{[^3\mathrm{He}]^2\langle\sigma v\rangle_{33}/2+[^3\mathrm{He}][^4\mathrm{He}]\langle\sigma v\rangle_{34}}. \tag{1}$$

In this expression, the reaction rate between nuclei of masses A and B is denoted by $\langle\sigma v\rangle_{AB}$. The ^{3}He density, [^{3}He], was taken from Ref. 2. The ratio of Q-nuclear ν production $R_\nu{}^{\rm SSM}$ is

$$\frac{R_\nu{}^Q}{R_\nu{}^{\rm SSM}}=\frac{[^1\mathrm{H}][^6\mathrm{Li}^Q]\langle\sigma v\rangle_{16}{}^Q\tau_Q\langle\sigma v\rangle_{17}{}^Q(1+\tau[^1\mathrm{H}]\langle\sigma v\rangle_{17}{}^{\rm SSM})}{[^3\mathrm{He}][^4\mathrm{He}]\langle\sigma v\rangle_{34}{}^{\rm SSM}\tau\langle\sigma v\rangle_{17}{}^{\rm SSM}(1+\tau_Q[^1\mathrm{H}]\langle\sigma v\rangle_{17}{}^Q)}. \tag{2}$$

The lifetime for the β decay of $^7\mathrm{Be}^u$ τ_Q (τ is the lifetime of ^{7}Be) is critical: For reasons noted above, it is likely that $\tau_Q \ll \tau$. The combined effect of the increased Q-nuclear charge and the decreased radius from those of ^{7}Be boosts the available energy from the 0.86 MeV value of ^{7}Be to well over the threshold for e^+ decay. (The increase is 0.5 MeV as a result of the increased charge alone.) With use of β-decay ft values[17] typical of analog transitions, τ_Q can be calculated[18] as a function of Q value. For example, for a Q value of 1.5 MeV, τ_Q is 6.5×10^3 sec, more than three orders of magnitude less than typical values for τ under stellar conditions.

The above equations show that the α production rate of the SSM can be achieved by the Q-nuclear cycle at any temperature by an appropriate Q-nuclear density, essentially that of $^6\mathrm{Li}^u$. Then the SN rate predicted for the Q-nuclear cycle at any temperature will be significantly less than that predicted by the SSM if τ_Q is small enough. The Q-nuclear densities and τ_Q values required to give both the solar energy (or α) production and the SSM SN production as a function of temperature are shown in Fig. 2.

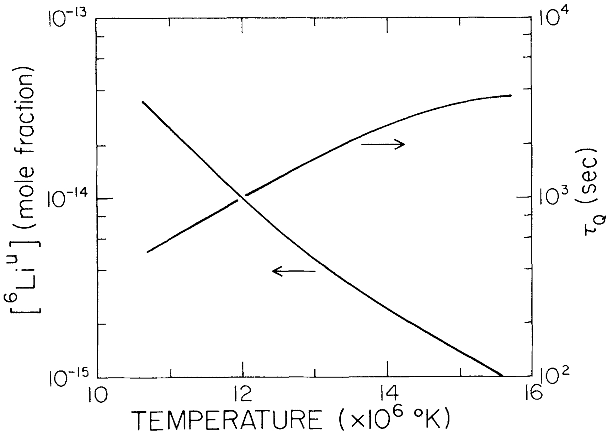

FIG. 2. Mole fraction of $^6\mathrm{Li}^u$ for which α-particle production of the Q-nucleosynthesis cycle equals that of the SSM (curve with left-pointing arrow), and lifetime of $^7\mathrm{Be}^u$ for which the high-energy SN production of the Q-nucleosynthesis cycle equals that of the SSM (curve with right-pointing arrow), as a function of stellar temperature.

For a given Q-nuclear density, a combination of normal nuclear and Q-nuclear burning would give the sun's total energy and SN output. Most of the SN's are produced[2] near the sun's center, in a region where the temperature is about 14.4×10^6 K. If this region were instead at 13.4×10^6 K, the SN production would be reduced fourfold and the energy production by 22%. The Q-nuclear density required to produce that amount of energy is 1.0×10^{15} Q-nuclei per nucleus. If the lifetime of $^7\mathrm{Be}^u$ is sufficiently short, i.e., appreciably less than 2.5×10^3 sec, the predicted SN flux from the sun would agree with that observed.

Q-nuclear burning does not appear to produce nonphysical consequences on the size, luminosity, or time evolution of the sun, as preliminary solar model calculations[19] have shown. Nor would it be expected to have much impact on other important types of nucleosynthesis, e.g., helium burning, the triple-α process, or synthesis of heavy nuclei. Elaboration of these points will be given in an expanded version of this Letter.

Thus with plausible assumptions about Q-nuclear densities and β-decay lifetimes, it is found that Q-nucleosynthesis can compete with that via the SSM, and even solve the SN problem. Further experiments on the existence of Q-nuclei thus become crucial to determining their importance. Additional Sn experiments, e.g., that with Ga, should also provide information as to the existence of stellar burning processes other than those of the SSM. If the existence of Q-nuclei is confirmed, studies of their properties then become essential for a detailed understanding of the stellar burning which they would produce.

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