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July 1968

P-3884

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ABSTRACT

It is suggested that negatively charged quarks and antiquarks may catalyze fusion in light elements. In build-up of the elements by quark catalysis the well known difficulty at atomic number 5 does not occur. About 10^{-26} quarks per proton could have produced the observed 1/10% abundance of light elements on stellar sufaces by fusion catalysis. The sun's energy output could be provided by 10^{-25} quarks per proton catalyzing fusion in a mixture of hydrogen isotopes and helium.

[†] Supported in part by the U. S. Atomic Energy Commission, Contract AT-(11-1) 1537.

In a continuing study[1] of quark chemistry we have made some estimates of the capabilities of quarks to catalyze fusion reactions of the light elements. Our analysis is analogous to that of F.C. Frank[2] for interactions of bound (negative) pions with nuclei in photographic emulsions, causing various possible induced reactions, including induced fusion, i.e. nuclear build-up.

Nuclear build-up has been observed by Luis Alvarez and his collaborators[3] in muon catalyzed reactions in a liquid hydrogen bubble chamber containing an admixture of deuterium, as follows:

$$\begin{array}{l} \text{p-muon-p} + \text{d-p} \dashrightarrow \text{p-muon-d} + \text{p-p} \\ \text{p-muon-d} \dashrightarrow \text{He}^3 + \text{muon} + 5.4\ \text{MeV} \end{array} \qquad (1)$$

Here the bound muon exchanges a proton for deuteron because of the 5% larger reduced mass, the process being exothermic by 135 eV. The muon, recoiling in the fusion process with energy sufficient to free it, (about 5 Mev) would be able to catalyze more fusion reactions except that it is too short lived. The authors point out "the practical importance of this process if a sufficiently heavy, negatively charged, weakly interacting particle more long lived than the muon is ever found." We propose that single negatively charged quarks and antiquarks fit these requirements and may catalyze fusion.

Quarks slowing to rest in matter should live forever without being captured by strong forces in nuclei, owing to the restriction that nuclei may not carry non-integral charge. Although there is no theoretical understanding of this property of quarks,[4] strong force binding of clusters of quarks, Q_N, saturates at $N \approx 3$. By hypothesis,[5] nucleons consist of 3 quarks each, Q_3, and thus nuclei consist of clusters, Q_{3A}, where A is the atomic number. Single quarks apparently do not bind to nucleons to form Q_4 and may even experience repulsion by nucleons. If Q_4 existed in a strongly bound form, its mass would be close to the mass of the proton, Q_3, thus pairs of Q_4 should be created more easily than pairs of the more massive Q, (mass $\geq$ 5 GeV). So presumably Q_4 would already have been observed among particles created at the targets of the high energy accelerators.[6] One would expect the Q_4

production cross section to depend on a strong coupling constant similar to production of proton-antiproton pairs which are abundantly produced at present accelerator energies. Thus in principle quarks would live forever and so would be able to catalyze fusion reactions more or less indefinitely.

Our purpose in the present paper is to describe some general features of fusion catalysis by quarks in reactions similar to that already observed for muons (1).

A negatively charged quark or antiquark, (-e/3, -2e/3, -4e/3, -5e/3,...) both hereafter referred to as quarks, slowing to rest, is captured by the Coulomb field of a nucleus and de-excites to the K orbit in a time of about 10^{-12} sec, estimated using considerations of Fermi and Teller[7] for capture of negative muons. In a time determined by density and temperature a quarko-nucleus, $(A_i^{Z_i})$-Q, collides with another nucleus, $(A_i^{Z_i})$, and captures it into a three body entity, $(A_i^{Z_i})$-Q-$(A_i^{Z_i})$, which exists until fusion occurs. In matter of 300°K and density about 1 gram/cm^3, this time is about 4 microseconds.

Assuming a quark to have mass $\sim$ 5 GeV and radius $\sim$ 1 Fermi, we compute binding energies of these three body entities assuming them to be linear. The quark, in contact with both nuclei and separating them, mitigates the Coulomb repulsion of the two nuclei for each other. With this picture we find that $Q^{-1/3}$ binds and thus catalyzes fusion of the isotopes of hydrogen, while $Q^{-2/3}$, $Q^{-4/3}$, $Q^{-5/3}$,... catalyze build-up of heavier elements. Figure 1 summarizes our main conclusions on the abilities of quarks to catalyze fusion.

In the three body entity the two bound nuclei continue to collide with each other until fusion occurs. Thus in spite of the Gamow barrier, fusion may occur in a short time because of the high frequency of collision. After fusion the quark and the newly formed fused nucleus recoil from each other sharing the energy released by fusion, usually several MeV of kinetic energy, a large part of which goes to the quark.

Build-up of elements induced by cosmic ray quarks occurs most directly through such reactions as the following:

$$\begin{aligned}
&pQp \longrightarrow d + e^{+} + \nu + Q + 1.4\ \mathrm{MeV}\\
&dQd \longrightarrow He^{4} + Q + 23.8\ \mathrm{MeV}\\
&pQd \longrightarrow He^{3} + Q + 5.4\ \mathrm{MeV}\\
&He^{3} - Q - He^{4} \longrightarrow {}_{4}Be^{7}\ (55d) + Q\\
&d\text{-}Q\text{-}He^{4} \longrightarrow {}_{3}Li^{6} + Q + 1.5\ \mathrm{MeV}.
\end{aligned}$$

We may take into consideration, in nuclear build-up, radioactive elements having half lives as short as 1 millisecond, if the collision time is short compared with this. The rate of induced fusion of deuterium with emission of a beta particle occurs at about 1 $\sec^{-1}$ for two protons bound to a quark with about 72 keV,[8] and may be thus the slowest of these reactions, the others going at rates given by the collision times.

We note that in build-up of the elements by quark catalysis, the well known difficulty at atomic number 5 does not occur. Instead quarks $Q^{-2/3}$ are able to produce ${}_{4}Be^{7}$ and ${}_{3}Li^{6}$ directly, and from these, heavier nuclei may be built as follows:

$$\begin{aligned}
&{}_{3}Li^{6} - Q - p \longrightarrow {}_{4}Be^{7} + Q + 5.6\ \mathrm{MeV}\\
&{}_{3}Li^{6} - Q - He^{4} \longrightarrow {}_{5}B^{10} + Q + 4.4\ \mathrm{MeV}\\
&{}_{3}Li^{6} - Q - {}_{3}Li^{6} \longrightarrow {}_{6}C^{12} + Q\\
&{}_{4}Be^{7} - Q - He^{3,4} \longrightarrow {}_{6}C^{10,11} + Q\\
&{}_{3}Li^{6} - Q - {}_{4}Be^{7} \longrightarrow {}_{7}N^{13} + Q\\
&{}_{4}Be^{7} - Q - Be^{7} \longrightarrow {}_{8}O^{14} + Q\ .
\end{aligned}$$

At beryllium, the Bohr radius of the quarko-beryllium estimated for spherical beryllium would be approximately equal to the radius of the beryllium nucleus itself, and more sophisticated considerations must be introduced to find out whether quarks will bind protons to nuclei heavier than beryllium in the ground state. However fusion catalysis might continue with nuclei heavier than beryllium for at least two reasons. First, the time for deexcitation is long enough that penetration of the Gamow barrier and fusion can occur before the three body entity reaches a ground state. For example, if a quarko-proton is captured by a carbon nucleus, the proton and carbon collide about 10^6 times with a barrier factor of about 10^{-3} in the time lapse of 10^{-12} seconds for deexcitation of the three body molecule. Thus fusion is overwhelmingly probable for a proton to C, provided that the quark first captures a proton and later a carbon. Secondly, the presence of the quark strongly polarizes both bound nuclei, deforming them so that their Gamow barriers are reduced. Furthermore since the quark velocity is no faster than the nucleon velocities, the polarized deformations of the two nuclei follow the quark motion. One expects a linearly elongated three body entity, with the charges concentrated near the center of gravity[9] and the neutrons concentrated at the two ends of the prolate system so that the effective nuclear charge radii are reduced. Naive estimates of these effects lead us to believe that binding might occur even for such heavy systems as, for example, Fe-Q-P and C-Q-C. We estimate that $Q^{-2/3}$ in fact catalyzes fusion of protons to elements of mass slightly past iron.

In the life of a star of $\sim 4 \times 10^9$ years, each cosmic ray quark can build about 5×10^{22} nuclei on the star's surface. For a limiting quark density, N_Q quarks per proton, the total number of fused nuclei, other than helium, relative to hydrogen is $\sim 5 \times 10^{22}\, N_Q$, and this number may be related to the abundance of the naturally occurring elements on the surface of stars. According to Suess and Urey[10] the ratio of elements other than helium, to hydrogen, is $\sim 10^{-3}$. Thus we may set a limit on the quark density needed to produce this abundance of light elements in stellar surfaces from the following relation:

$$5 \times 10^{22}\, N_Q \sim 10^{-3}$$

$$N_Q \sim 2 \times 10^{-26} \text{ quarks per nucleon.}$$

Catalysis of element synthesis by cosmic ray quarks offers an appealing explanation for elements other than hydrogen and helium on stellar surfaces. There would be no need to postulate complicated phenomena such as mixing of surface material with the interior, nor of cycling stellar matter through super-novae, nor of a sequence of widely different stellar reactions in nuclear synthesis.[11]

If the energy output of the entire sun, 3.9×10^{33} ergs/sec, were caused mainly by fusion catalysis by primordial quarks, we estimate that the density required would be $\sim 3 \times 10^{-19}$ quarks per proton, assuming that the sun contains little helium internally and the energy is coming mainly from the relatively slow proton-proton fusion involving beta emission. If,instead, the energy is coming mainly from the relatively fast fusions involving He the required primordial quark density is $\sim 10^{-25}$ quarks per proton.

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9. We are indebted to W. F. Libby for suggesting and clarifying the significance of nuclear polarization in decreasing the effective charge radius.
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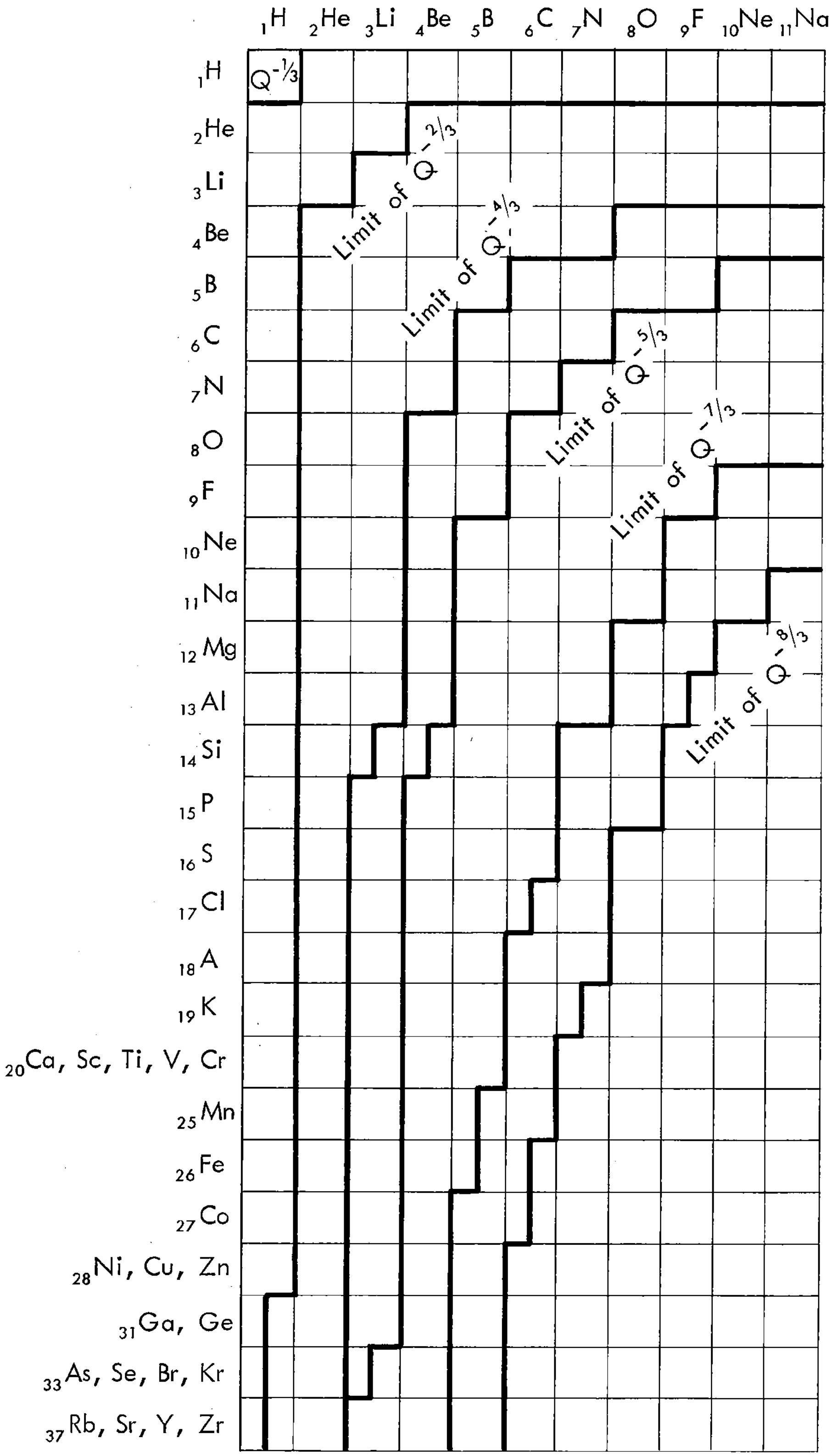
FIGURE CAPTION

Map showing synthesis reactions able to be catalyzed by quarks and antiquarks of charges - 1/3, - 2/3, - 4/3 ...



Note:
Partial square
indicates binding
for only some
of the isotopes