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Quark Catalysis of Exothermal Nuclear Reactions

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The idea that all strongly interacting particles are in some sense composed of a simpler set of fractionally charged objects, now called quarks, was first proposed in 1964 (*1*). Quarks provided a heuristic description of the hadronic particle spectrum and specified relationships between the lifetimes of its members. Subsequent experimental information has led to both confirmation and expansion of the original quark hypothesis. Electron scattering off protons and neutrons suggested that nucleons behave as if they were composed of more elementary pointlike scattering centers (*2*). The introduction of additional quarks not only has given us a greater understanding of the structure of the weak interactions (*3*), but has provided a description of the recently discovered high-mass resonances and their striking decay characteristics (*4*). With one exception (*5*), however, the experimental evidence for the existence of free fractionally charged particles is negative (*6*). The single outstanding experiment yielding positive results has been completed only recently; it is too early to evaluate fully or to receive confirmation of this finding.

In this article the word quark means any particle of fractional charge $\pm e/3$, $\pm 2e/3$, $\pm 4e/3$, . . . , where $-e$ is the electron charge; combinations of quarks whose net charge is fractional are therefore also referred to as quarks. Quarks of baryon number 1/3 and charge 2/3 or $-$ 1/3 are written as u (up) or d (down), respectively. Their antiparticles are $\bar{u}$ and $\bar{d}$.

If quarks exist in a free state, then at least one kind of quark is stable, since charge is conserved in particle reactions. Conservation of charge requires that a quark either be stable or decay into one or more other quarks, each lighter than the first. Any given quark therefore leads to at least one sequence of quarks, decreasing in mass, the sequence terminating at a stable quark. Each stable quark has a corresponding stable antiquark of opposite electric charge and baryon number.

This article explores ways in which stable quarks might be used to convert nuclear mass into energy. First I will discuss the simplest case in which the stable quark is heavy (much more massive than a proton) and binds with protons through electromagnetic interactions. Under these circumstances quarks are catalysts for exothermal nuclear reactions (*7*). The effects of strong interactions between quarks and nuclei and the catalytic properties of light quarks are examined in the discussion section.

Simple Catalysis

Fusion. In principle, the two deuterons in a deuterium molecule can fuse to form tritium plus a proton or helium plus a neutron, liberating several million electron volts in the process. The two electrons in the deuterium molecule act as a catalyst, keeping the deuterons together so that they can interact. In practice, the rate of reaction is very small, primarily because the electrostatic repulsion between the deuterons keeps them from coming close enough to fuse. According to classical mechanics fusion could never occur, but according to quantum mechanics the deuterons may tunnel toward each other through the classically forbidden region of repulsion until they get so close that the strong interaction forces become dominant and fusion occurs. Fusion is extremely unlikely because of the large distance through which the deuterons must tunnel. This distance is of the order of the Bohr radius a_e of the electron

$$a_e = \hbar^2/m_e e^2 \approx 5 \times 10^{-9} \text{ cm}$$

which is much larger than the range of the strong interactions given by the Compton wavelength $\lambda\!\!\!^{-}_\pi$ of the pi meson

$$\lambda\!\!\!^{-}_\pi = \hbar/m_\pi c \approx 1.4 \times 10^{-13} \text{ cm}$$

where $\hbar$, c, and m_e and m_π are Planck's constant divided by 2π, the speed of light, and the masses of the electron and pi meson, respectively. If an electron is replaced by a heavier negatively charged particle, such as a muon (of mass $m_\mu \approx 207\ m_e$), this distance decreases by a factor equal to the ratio of the electron mass to the muon mass and penetration of the barrier is much more likely. Fusion catalyzed by muons (*8*) was in fact observed (*9*) in 1957, but since the lifetime of the muon is only $\sim 10^{-6}$ second, muon catalysis is not a practical way of producing energy (*10–13*).

If one of the electrons is replaced by a stable quark q, of charge $-4/3$ (for example, $\bar{u}\bar{u}$), the deuterons are separated by approximately the Bohr radius of the deuteron

$$a_d = \hbar^2/m_d e^2 \approx 1.4 \times 10^{-12} \text{ cm}$$

and fusion is rapid, freeing the quark to catalyze another reaction. Quarks of charge $-1/3$ (d) or $-2/3$ ($\bar{u}$) are also catalysts, but at least three or two such quarks, respectively, are necessary to bind two deuterons together.

The physical picture of the bound state prior to fusion depends on the charge of

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the quark. If the quark has charge $-4/3$ it forms the center of a bound state with the two deuterons distributed around it, much like a proton surrounded by two electrons in a H^- ion. In a system of two quarks of charge $-2/3$ and two deuterons, the two quarks are at separate centers bound together by sharing the deuterons, much as two protons in a hydrogen molecule are bound together by sharing the electrons (covalent bonding).

The most prominent fusion reactions involving the isotopes of hydrogen and helium are listed in Table 1 together with the total energies released. The symbol dQt, for example, stands for a bound state consisting of a deuteron d, triton t, and one or more quarks Q. Fusion of nuclei, such as helium, with charge greater than 1 requires either more quarks or quarks that are more negatively charged.

The expected cycle of events during catalytic fusion is illustrated in the following example. A stable quark of charge $-4/3$ is introduced into a pressurized container of H_2, D_2, or some mixture of these gases. After coming to rest, it captures a molecule, the quark-molecule system being in a highly excited state. During the process of deexcitation, the molecule breaks up with a single nucleus finally orbiting the quark at a Bohr radius $a = 3\hbar^2/4me^2$, where m is the mass of the nucleus. This system with charge $-1/3$ attracts another nucleus and fusion occurs. The quark is then free to start the process over again (*14*). In most reactions (Table 1) the rate at which energy is released is limited by the time it takes a free quark to form a bound state with two nuclei since the rate of fusion, once a bound state is formed, is generally quite rapid. In this example where the quark has charge $-4/3$, the reaction rate for the formation of a bound state will be at least of the order of 1 sec^{-1} (*15*) at a pressure of 2000 pounds per square inch (*16*). If the gas is deuterium, the mean energy release per fusion is 3.65 MeV, and at least 10^{16} Btu's per year can be catalzyed by one mole of quarks (*17*).

Fission. A heavy element such as U^{235} undergoes fission while capturing a quark. Fission occurs in U^{235} if enough energy (~6 MeV) is supplied to the nucleus to raise it over the fission barrier. This energy becomes available when the quark cascades to the nuclear surface (the electric potential energy of a quark at the surface of U^{235} is $-18Z_q$ MeV, where Z_q is the absolute value of the quark charge). Fission induced by muons has been studied both experimentally and theoretically (*12*).

Cyclic Catalysis

General case. By cyclic catalysis of nuclear reactions I refer to a system of plural reactions which successively involve transfer of charge to and from catalytic particles. Catalysis results because in the overall system the net transfer of charge to the particles used as catalysts is zero. Consider a series of reactions in which a catalyst A mediates a reaction which results in the formation of a more positively charged particle B. If particle B in turn catalyzes a further reaction with the result that A is re-formed, then in the aggregate no charge transfer has occurred between A and B and the regeneration of A makes the overall system catalytic. For such cyclic catalysis to succeed, particles A and B must be close in mass so that the energy liberated by the nuclei, less the mass difference of the particles, will be positive.

An isotopic spin multiplet is a family of differently charged particles similar in mass, the mass differences between them attributable to their respective charge differences. For example, the proton and neutron belong to an isotopic spin doublet called the nucleon. The stable quark will also be a member of an isotopic spin multiplet [for instance, the doublet ($\bar{u}$, $\bar{d}$) or triplet ($\bar{u}\bar{u}$, $(\bar{u}\bar{d} + \bar{d}\bar{u})/\sqrt{2}$, $\bar{d}\bar{d}$)]. If the multiplet is not a singlet, then nuclear reactions can be catalyzed cyclically. Thus, nuclear matter will either lose or gain charge during a reaction, and the charge lost or gained will be transferred to the final-state quark. That quark is transformable back to its original state by (i) catalyzing another charge-changing nuclear reaction, (ii) beta decay if the final-state quark is unstable, or (iii) electron capture. Some of the simpler charge-changing reactions, along with the energies released, are listed in Table 2. The mass difference of the quarks is Δm MeV, $q^{(+1)}$ is an isobar of q whose charge is one greater than the charge of q, and $Q^{(+1)}$ is the same collection of one or more quarks as Q, save that one of the latter's quarks has been replaced by $q^{(+1)}$.

In general, one proceeds by choosing from among the reactions of Table 2 a first reaction involving the transfer of charge of a first sign to the quark, and a second reaction involving the transfer of charge of opposite sign to the quark. Of course, where the first reaction chosen involves transfer of charge of, say, -2, then two different remaining reactions may be selected, each involving transfer of charge $+1$ to the quark.

The selection of reactions from Table 2 will be guided by considerations involving the comparison of the nuclear energy liberated to the mass difference between the original and final-state catalytic particle, and the availability of one or more quarks close in mass to the stable quark. The mass difference between the stable quark and a corresponding final-state quark may be assumed to be on the order of other isotopic mass differences, which range from 1.3 MeV for the nucleon doublet to a maximum of 6.5 MeV for the Ξ doublet.

As an example of cyclic catalysis, suppose that the lowest-mass stable quark q has charge $-4/3$, baryon number $-2/3$, and is a member of an isotopic spin triplet (for instance, q = $\bar{u}\bar{u}$). The charges of the members (q, $q^{(+1)}$, $q^{(+2)}$) of the multiplet are then ($-4/3$, $-1/3$, $2/3$). If the mass difference Δm between q and $q^{(+1)}$ is less than the mass of an electron, $q^{(+1)}$ will also be stable. In this case any of the fusion reactions with a charge transfer of $+1$ to the quark can form the first part of the cycle. The cycle can be completed by using $q^{(+1)}$ as a catalyst in any of the fusion reactions with charge transfer -1 to the quark, by electron capture $e^-q^{(+1)} \rightarrow q + \nu$, or by the isobaric transformation $tq^{(+1)} \rightarrow He^3 + q$. The fission reaction $dq^{(+1)} \rightarrow 2p + q$ and the beta decay $q^{(+1)} \rightarrow q + e^+ + \nu$ are not energetically possible because Δm is not large enough. The availability of the isobaric transformation $Li^7q^{(+1)} \rightarrow Be^7 + q$ and the fission reaction $Be^9q^{(+1)} \rightarrow 2He^4 + p + q$ depends on the actual value of Δm.

If Δm is greater than the mass of an electron—for instance, Δm = 3 MeV—then certain reactions that were allowed

Table 1. Simple catalysis of nuclear reactions.*

Reaction	Energy released (MeV)
pQp → d + e^+ + ν + Q	0.4
pQd → He^3 + Q	5.5
pQt → He^4 + Q	19.8
dQd → t + p + Q	4.0
→ He^3 + n + Q	3.3
→ He^4 + Q	23.9
dQt → He^4 + n + Q	17.6
tQt → He^4 + 2n + Q	11.3
→ He^6 + Q	12.3
He^3Qd → He^4 + p + Q	18.4
He^3Qt → Li^6 + Q	15.8
→ He^4 + d + Q	14.3
→ He^4 + p + n + Q	12.1
He^3QHe^3 → He^4 + p + p + Q	12.9
He^3QHe^4 → Be^7 + Q	1.6

*Radiative reactions are not listed in Tables 1 to 3. Symbols: Q stands for one or more quarks q, where Q contains enough quarks to bind the two fusing nuclei; p, n, d, t, e^+, and ν stand for proton, neutron, deuteron, triton, positron, and neutrino, respectively.

in the previous example are now energetically forbidden; that is $pqp \rightarrow d + q^{(+1)}$, $dqd \rightarrow t + n + q^{(+1)}$, and $He^3qqHe^4 \rightarrow Li^7 + q + q^{(+1)}$ in the first half of the cycle. Other reactions, such as the beta decay of $q^{(+1)}$ or the fission reaction $dq^{(+1)} \rightarrow 2p + q$, however, become energetically possible in the second half of the cycle.

Paired isobaric transformations. The isobaric transformations illustrated in Table 2 must be used in conjunction with reactions of other kinds in order that the catalyst be regenerated. Are there permissible pairs of isobaric transformations such that, in the aggregate, net charge transfer to the quark is zero? Consider the following pair of isobaric transformation wherein (A, Z) is a nucleus of atomic number A and charge Z, and q is a stable quark

$$(A, Z)q \rightarrow (A, Z + 1) + q^{(-1)}$$

followed by

$$(A, Z)q^{(-1)} \rightarrow (A, Z - 1) + q$$

Although each reaction involves the transfer of charge to the quark, the overall system utilizes catalysis because the net transfer of charge to the quark is zero. If the nucleus (A, Z) is additionally selected such that its mass is greater than the masses of both of the neighboring isobars $(A, Z + 1)$ and $(A, Z - 1)$, then it will be seen that the second reaction given above will always be energetically allowable. The first reaction will also be energetically allowable if a further condition is satisfied—that is, that the diminution of nuclear mass is greater than the augmentation of quark mass. As discussed above, the augmentation of quark mass arising from the addition of one unit of charge may be expected to be of the order of magnitude of other known hadronic electromagnetic mass differences.

Table 3 depicts in succession four pairs of isobaric transformations, where each nucleus in the starting reaction is selected such that its mass is greater than those of the neighboring isobars. The quark ceases to shuttle back and forth between neighboring isobars when it is captured by an isobar in a radiative reaction.

Sequestered Quarks

The central problem in maintaining catalysis is to free quarks sequestered by nuclear reaction products. In fusion reactions such as $dqd \rightarrow He^3 + n + q$, the quark will be removed from the catalytic chain when it is captured by the helium nucleus (*18*). The energy required to separate quarks from He^3 is small compared to the energy liberated in the fusion reaction, but large compared to chemical binding energies. The quark may be liberated either by ionizing or transmuting the binding nucleus.

Ionization may be effected either by heating or "stripping." Heating (for example, by high-intensity lasers) is most practical for quarks of low charge whose ionization energies are small (it takes 33 keV to ionize a He^3 nucleus from a heavy quark of charge $-1/3$). The process of stripping is most efficient for light quarks and is referred to in (*19*).

Some binding nuclei are easily transmuted when bombarded with thermal neutrons. The term thermal neutron connotes a slow-moving neutron of low energy, comparable to that of a neutron at room temperature. Thermal neutrons currently are used to induce fission and they are obtained by moderating (slowing down) the neutron by-product of fission itself. The likelihood that a particular neutron will react with a particular nucleus may be referred to as the neutron capture cross section of that nucleus. The capture cross section of a particular nucleus is inversely proportional to the velocity of the neutron. Thus, in the case of thermal neutrons, capture cross sections tend to be high.

Binding nuclei are transmuted—that is, altered in charge and velocity—by their reaction with thermal neutrons. For example, the isotope He^3 has an unusually large neutron capture cross section when compared to the fusion fuels deuterium and tritium (*20*). The reaction between He^3 and a thermal neutron yields energetic triton and proton products. The interaction of thermal neutrons and quark-bearing He^3 will leave the majority of the quarks free from the resulting nuclei. Accordingly, the transmutation of quark-bearing He^3 in the presence of nuclear fuel will result in catalysis of energy-yielding nuclear reactions. To the extent that the triton or proton by-product of transmutation itself captures a quark, the product of that capture will itself be available as fusion fuel. Thermal neutrons can be obtained by moderating neutrons released in catalyzed fusion reactions or from conventional fission reactors.

Discussion

To simplify the preceding presentation, quarks were assumed to be heavy and to bind with protons through electro-

Table 2. Cyclic catalysis of nuclear reactions.

Type of reaction	Reaction	Energy released (MeV)
	Positive charge transfer to quarks	
Fusion	$pQp \rightarrow d + Q^{(+1)}$	$0.9 - \Delta m$
	$pQd \rightarrow t + Q^{(+1)}$	$5.0 - \Delta m$
	$dQd \rightarrow t + n + Q^{(+1)}$	$2.7 - \Delta m$
	$pQHe^3 \rightarrow He^4 + Q^{(+1)}$	$19.3 - \Delta m$
	$\rightarrow He^4 + n + Q^{(+1)}$	$17.1 - \Delta m$
	$tQHe^3 \rightarrow He^6 + Q^{(+1)}$	$11.8 - \Delta m$
	$\rightarrow He^4 + n + n + Q^{(+1)}$	$10.8 - \Delta m$
	$He^3QHe^3 \rightarrow Li^6 + Q^{(+1)}$	$15.3 - \Delta m$
	$\rightarrow He^4 + d + Q^{(+1)}$	$13.8 - \Delta m$
	$\rightarrow He^4 + p + n + Q^{(+1)}$	$11.6 - \Delta m$
	$\rightarrow He^4 + n + n + Q^{(+2)}$	$10.3 - \Delta m$
	$He^3QHe^4 \rightarrow Li^7 + Q^{(+1)}$	$1.9 - \Delta m$
Beta decay	$q^{(-1)} \rightarrow q + e^- + \nu$	$-0.5 + \Delta m$
Isobaric transformation	$He^3q^{(-1)} \rightarrow t + q$	$-0.5 + \Delta m$
Fission	$dq^{(-1)} \rightarrow 2n + q$	$-3.5 + \Delta m$
	Negative charge transfer to quarks	
Fusion	$dQd \rightarrow He^3 + p + Q^{(-1)}$	$4.6 - \Delta m$
	$dQt \rightarrow He^4 + p + Q^{(-1)}$	$18.9 - \Delta m$
	$tQt \rightarrow Li^6 + Q^{(-1)}$	$16.3 - \Delta m$
	$\rightarrow He^4 + 2p + Q^{(-2)}$	$13.9 - \Delta m$
	$\rightarrow He^4 + d + Q^{(-1)}$	$14.9 - \Delta m$
	$\rightarrow He^4 + p + n + Q^{(-1)}$	$12.6 - \Delta m$
	$tQHe^3 \rightarrow He^4 + p + p + Q^{(-1)}$	$13.4 - \Delta m$
	$tQHe^4 \rightarrow He^3 + He^4 + Q^{(-1)}$	$0.5 - \Delta m$
Beta decay	$q^{(+1)} \rightarrow q + e^+ + \nu$	$-0.5 + \Delta m$
Electron capture	$e^-q \rightarrow q^{(-1)} + \nu$	$0.5 - \Delta m$
Isobaric transformation	$tq \rightarrow He^3 + q^{(-1)}$	$0.5 - \Delta m$
	$Li^7q^{(+1)} \rightarrow Be^7 + q$	$-0.4 + \Delta m$
Fission	$dq^{(+1)} \rightarrow 2p + q$	$-0.9 + \Delta m$
	$Be^9q^{(+1)} \rightarrow 2He^4 + p + q$	$-0.3 + \Delta m$

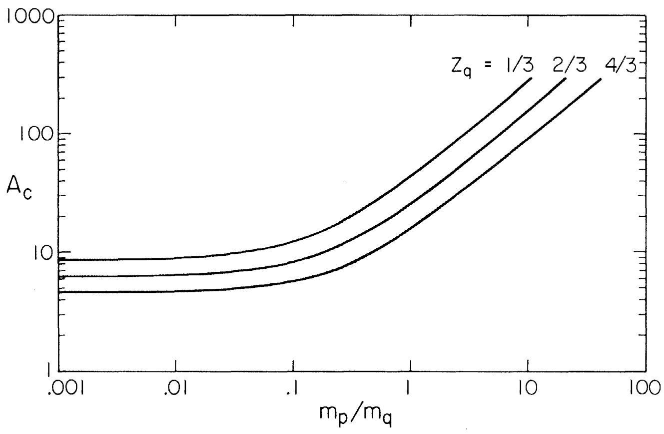

Fig. 1. The atomic number A_c for which a quark in its Bohr orbit just grazes the nuclear surface is shown as a function of the ratio of proton mass to the quark mass. The three curves correspond to three possible quark charges $-Z_q$. Note that both axes are logarithmic.

magnetic interactions. What problems arise if quarks are light, and what are the effects of possible strong interactions between quarks and nucleons?

Quark mass. The quark mass is important for three reasons. First, it must be substantially greater than an electron mass if rapid fusion or fission is to occur. Quarks with baryon number $\pm 1/3$ have a mass greater than one-third the proton mass; otherwise the proton would decay into three quarks. This quark mass is greater than the muon mass, and muons are massive enough to rapidly fuse nuclei.

Second, when two or more quarks bind nuclei, the quarks may react before the nuclei fuse; for instance, $d + d \rightarrow ddu + \bar{u}$, where ddu is a neutron. Two very heavy quarks ($m_d \gg m_p$) are not likely to react for the same reason that the two deuterons in a deuterium molecule rarely fuse; their low relative velocity makes Coulomb barrier penetration highly unlikely. Two light quarks ($m_d < m_p$) cannot react because of constraints coming from the conservation of energy.

Third, light negatively charged quarks which are stable in isolation may be transformed into positively charged quarks by nucleons; for instance, $duu + \bar{u} \rightarrow d + u + u\bar{u}$, where duu is a proton and $u\bar{u}$ a meson or photon. If d is unstable and undergoes beta decay into u ($d \rightarrow u + e^- + \nu$), there may be no negatively charged quark that is stable in the presence of matter. The reaction above only occurs when quarks are light ($1/3\, m_p < m_q < m_p$).

Note that if more than one kind of quark is stable in isolation, a nucleon may transform one quark into another, such as $duu + \bar{u} \rightarrow du + u\bar{u}$. This reaction is energetically possible only if the du mass is less than the sum of the proton and $\bar{u}$ masses (in which case du or one of its isotopic spin partners is stable in isolation).

Effects of strong interactions. The nature of the strong interaction between quark and nucleus is unknown. When the nucleus is weakly charged, the quark orbits far outside the nucleus and effects of strong interactions are minimized. Nuclei with charges greater than the "critical" charge Z_c at which the Bohr radius of the quark is equal to the nuclear radius have the quark inside them, and strong interactions between the quark and the nuclear matter presumably dominate. Strong interactions may either enhance or suppress a reaction. The critical charge Z_c depends on both the mass and the charge $-Z_q$ of the quark. This dependence is found by equating the quark Bohr radius to the nuclear radius

$$\hbar^2/MZ_qZ_ce^2 = R_0A_c^{1/3}$$

where the atomic number A_c is related to Z_c by the empirical relation

$$Z_c = A_c/(1.98 + 0.015A_c^{2/3})$$

the reduced mass M is related to the quark mass m_q and nuclear mass m_c by

$$M = m_qm_c/(m_q + m_c)$$

with

$$m_c = A_cm_p$$

and R_0 is an empirical constant equal to 1.2×10^{-13} cm. The atomic number A_c is shown as a function of the ratio m_p/m_q for quarks of charge $-4/3$, $-2/3$, and $-1/3$ in Fig. 1. Note that no matter how heavy the quark is, its Bohr radius is always larger than the radii of the isotopes of hydrogen and helium (*19*). Since the strong interactions between quarks and nuclei are poorly understood, it is especially difficult to estimate their effects on reactions involving heavy nuclei in fission or paired isobaric transformations.

1) *Strong repulsive forces.* A strong short-range force between quark and nucleus, such as the nuclear force, if it is also repulsive, is a perturbation on the electromagnetic interaction if the quark Bohr radius is much greater than the nuclear radius. This force keeps the quark outside the nucleus. It does not influence the formation of quark-nucleus bound states or the covalent bonding between these bound states if the quark-quark interaction is not strongly attractive.

2) *Strong attractive forces.* If the quark-nucleus force is strong and attractive, quarks enter nuclei and the situation is poorly understood. In this case, however, quarks may induce alpha-particle decays of radioactive nuclei, or isotopic and isotonic transformations.

i) *Facilitation of alpha decay.* The alpha decay of a nucleus is hindered by the Coulomb barrier through which an alpha particle must tunnel. The transparency of this barrier depends on both the charge and mass of the alpha particle. Quarks that bind with alpha particles, and reduce their charge without greatly increasing their mass, reduce the electric barrier which holds the alpha particle inside the nucleus. These quarks facilitate alpha decay (*21*), and if the quarks are subsequently freed from the alpha particles, they may enter other nuclei and repeat the process (*22*). Among the isotopes whose alpha decay could be stimulated in this fashion may be mentioned Th^{232} and U^{238}. For example, introducing a quark of charge $-4/3$ and mass one-third that of the proton into a thorium nucleus reduces its half-life by a factor of $10^{O(36)}$ [O(36) is a number of the order of 36], changing it from 10^{10} years to $10^{-O(18)}$ second (*23*). Each decay liberates 4 MeV.

ii) *Isotopic and isotonic transformations.* If quarks bind strongly to nuclei as nucleons do, a different class of cyclically catalyzed reactions may be possible in which quarks shuttle baryons from one reaction to another; examples are $\bar{u}\bar{u} + d \rightarrow \bar{u}\bar{u}n + p$ followed by $\bar{u}\bar{u}n + He^3 \rightarrow \bar{u}\bar{u} + He^4$ or $\bar{u}\bar{u} + d \rightarrow \bar{u}\bar{u}p + n$ followed by $\bar{u}\bar{u}p + t \rightarrow \bar{u}\bar{u} + He^4$. Here uun is an isotope and $\bar{u}\bar{u}$p an isotone of $\bar{u}\bar{u}$. The first half of each of these reactions is energetically favored because the nucleons in a deuteron are very weakly bound and may therefore prefer to bind with quarks. The second half of each reaction is favored because of the exceptionally strong binding between He^3 and n or t and p, tending to remove the nucleon from the quark to form the highly stable He^4.

From the foregoing, it becomes apparent that a stable strongly interacting quark $\bar{u}\bar{u}$, whose mass lies in the range

$$m_p < m_{\bar{u}\bar{u}} < m_{\bar{u}} - m_p$$

should cyclically catalyze nuclear reactions if its strong interactions with nuclei are similar to those of other hadrons.

Summary

This article discusses circumstances under which free quarks catalyze exothermal nuclear reactions. It also presents possible methods for removing quarks sequestered by nuclear reaction products.

Stable quarks that are negatively charged and significantly heavier than electrons attract positively charged nuclei to form new states of matter. The nuclei and quarks are closely bound, and presumably interact through both electromagnetic and nuclear forces. Nuclear fusion and fission are possible, as well as a new class of plural reactions in which either a quark isobar, isotope, or isotone is created in each individual reaction, with catalysis resulting in the overall system because the net transfer of charge, neutrons, or protons to the quarks is zero. The quark with quantum numbers of $\bar{u}\bar{u}$ is a promising catalytic candidate. A satisfactory understanding of which reactions are or are not possible awaits the isolation of free quarks and a description of their strong interactions with matter.

Finally, other kinds of stable negatively charged particles (such as heavy leptons), if discovered, can catalyze deuterium fusion reactions if thermal neutrons are used to liberate He^3-bound catalytic particles.

Appendix: Some Practical Matters

How can free quarks found in association with nuclear matter be concentrated, separated from the nuclei to which they are bound, and made available for catalyzing nuclear reactions?

Enrichment. Quark-bearing nuclei differ from their normal neighbors in mass, total charge, and the number of electrons that surround them. Separation may therefore be effected by, for instance, mass spectrography, gaseous diffusion, electrolysis, and differences in chemical properties arising from differing electron shell configurations or energies of solvation. Differences in the energy of solvation make separation possible by differential evaporation. As an example of enrichment, differential evaporation is next discussed.

A charged particle in solution in a polar solvent (that is, one having a high dielectric constant) resists evaporation by reason of the attraction between the charged particle itself and dipoles characteristic of the polar solvent. One common example is the low vapor pressure of ordinary table salt dissolved in water, which arises from attractions between solvent water molecules on the one hand and the salt ions on the other. Advantage may be taken of this same phenomenon to enrich the free quark content of a quark-containing material, because that portion of the material containing the free quarks will exhibit fractional charge unshared by its non-quark-containing neighbors, which latter can accordingly be more or less selectively distilled off. Resorting to this technique requires that a compound of the quark-containing element be dissolved to an appreciable extent in a solvent exhibiting a relatively high dielectric constant that does not ordinarily dissociate the compound in the course of solvation.

Table 3. Paired isobaric transformations.

Reaction	Energy released (MeV)
$K^{40}q \rightarrow Ca^{40} + q^{(-1)}$	$1.8 - \Delta m$
$K^{40}q^{(-1)} \rightarrow Ar^{40} + q$	$1.0 + \Delta m$
$V^{50}q \rightarrow Cr^{50} + q^{(-1)}$	$1.6 - \Delta m$
$V^{50}q^{(-1)} \rightarrow Ti^{50} + q$	$1.7 + \Delta m$
$La^{138}q \rightarrow Ce^{138} + q^{(-1)}$	$1.6 - \Delta m$
$La^{138}q^{(-1)} \rightarrow Ba^{138} + q$	$1.3 + \Delta m$
$Ta^{180}q \rightarrow W^{180} + q^{(-1)}$	$1.3 - \Delta m$
$Ta^{180}q^{(-1)} \rightarrow Hf^{180} + q$	$0.4 + \Delta m$

For example, the free quark content of tungsten may be increased by converting the tungsten to tungsten hexafluoride and dissolving the latter in anhydrous hydrogen fluoride (*24*). Tungsten hexafluoride dissolves without reaction or dissociation in anhydrous hydrogen fluoride (*25*), and of course hydrogen fluoride is a highly polar solvent, exhibiting a dielectric constant approximately equal to that of water itself. Because quark-containing tungsten hexafluoride will exhibit fractional charge, then, distillation from anhydrous hydrogen fluoride will enrich the quark-containing component of the dissolved solute relative to the more readily evaporable, non-quark-containing molecules.

As the process of enrichment proceeds, a point will be reached at which individual quark-containing moieties will associate in clusters which permit charge neutralization, and the properties of these clusters will be markedly different from those of the individual particles and may be exploited to further the refining process. Consider, for example, an assembly of fractionally charged quark-containing molecules which contain a statistical distribution of individual particles lacking one or more electrons. Two molecules with their normal complement of electrons and each containing a quark of charge $-1/3$ will, under these circumstances, tend to associate with another such molecule if the latter, because it lacks one electron, exhibits a net charge of $+2/3$.

Transformation to the carrier state. Once the quark content of material has been enriched to a suitable degree by any of the foregoing methods, the nuclei of the enriched material are next reduced in size by processes of fragmentation (discussed below) to the point at which the quark is found in association with a "carrier" nucleus. The carrier fixes the quark for convenience in transportation, and is chosen such that the quark can be simply freed for catalysis after the quark-bearing carrier has been introduced into the nuclear fuel whose energy-yielding reaction is to be catalyzed.

The enriched sample of quark-bearing material may be fragmented either by bombarding it with intense radiation (consisting of, for example, protons, neutrons, or alpha particles) or by accelerating it and allowing it to irradiate a target material (such as helium). In either case, the final quark-bearing nuclei are separated from other reaction products by employing techniques such as those mentioned in the discussion of enrichment. These successive processes of fragmentation and enrichment are continued until the quarks become bound to the carrier nuclei. The process of nuclear fragmentation will, of course, not be necessary if quarks are naturally bound to the lightest elements (p, d, and so on).

The optimal carrier state for a quark of any particular charge requires, among other things, that the carrier nucleus be sufficiently charged to prevent the overall charge of the quark-nucleus system from being negative. To assure transportability of the quark-carrier system, one relies on the electrically repulsive character of a positive system to discourage strong binding of the quark-containing carrier to surrounding matter. For example, a quark of charge $-4/3$ in association with a helium nucleus will confer a net charge of $+2/3$. Again, the combination of a quark with charge $-1/3$ or $-2/3$ in association with a proton or deuteron carrier will yield a net positive charge for the quark-nucleus system. Ordinarily, plural fractionally charged carrier-quark systems will charge neutralize by electron sharing, forming "molecules," all without affecting the later step in which quarks are freed from their respective carriers. Thus, for example, where quarks are to be stripped from carriers (*19*), the charged systems are first simply reconstituted by heating.

As one example of all of the foregoing, consider the case in which the quark is found in association with lithium, either innately or by reason of fragmentation from some larger element with lithium as its intermediate product. Bombardment of the stable lithium isotope Li^6 with thermal neutrons yields a mixture of the free quark with tritium and He^4. Most preferably, a gaseous compound of quark-containing lithium will be bombarded in a sea of He^3, such that the majority of quarks resulting from bombardment will become bound to He^3, a useful carrier. The various manners in which the quark may be removed from the carrier for catalytic employment are next discussed.

Removal of the quark from the carrier. The optimal choice of carrier depends on the particular charge and mass of the quark used for catalysis. The carrier chosen will vary according to both the characteristics of the quark and the method chosen for its removal from the carrier. In the main, two techniques of removal can be utilized, ionization and carrier transmutation. As discussed in the section on sequestered quarks and in (*19*), ionization may involve either heating or stripping and, in either case, preferably involves a proton or deuteron carrier.

Quarks of low charge ($-1/3$ or $-2/3$) may be liberated from proton or deuteron carriers by heating to temperatures within the reach of present-day technology. Thus, for example, in an inertial confinement system a pellet comprising fuel and the quark-containing carrier may be laser-heated, freeing the quarks for catalytic interaction with the fuel (*26*).

A light quark associated with a proton or deuteron carrier can be stripped from the carrier for catalytic interaction by electrically accelerating the fractionally charged quark-carrier system through a stripping medium. Ordinarily, the stripping medium will be nuclear fuel itself (as in the case of isobaric transformations) or some nuclear fuel precursor (in the precursor case a material such as deuterium is employed to strip quarks from carriers, yielding an intermediate product dQ whose later fusion is catalyzed by an additional quark).

Carrier transmutation, like the transmutation of a binding nucleus discussed in the section on sequestered quarks, involves the reaction between a thermal neutron and the carrier nucleus. The isotopes He^3, Li^6, and B^{10} have unusually large neutron capture cross sections when compared to the fusion fuels deuterium and tritium and therefore are convenient carriers. The transmutation of a quark-bearing carrier in the presence of nuclear fuel will result in catalysis of energy-yielding nuclear reactions, and the transmutation itself may be regarded as a form of ignition. Where ignition is to be had by resort to thermal neutron reaction, carriers may be employed without reference to quark mass or charge, so long as the quark-carrier system has a net nonnegative charge.

Nuclear reaction management. The energy released by quark-catalyzed nuclear reactions may be extracted in the form of heat by conventional means, such as heating water or converting it to steam, and this requires no elaboration. In this section I discuss other considerations involved in the management of catalytic nuclear reactions in various modes, referring by way of example to the case in which He^3 is the final-state reaction product.

Choice of reaction environment and mode principally involves attention to quark capture by reaction products that would tend to diminish the rate of overall catalysis pending return of the sequestered quark to the free state. Reactions whose final-state product is He^3 are preferred because that product itself is suitable as a carrier from which sequestered quarks may be readily removed in the manners previously discussed.

Further in this vein, it may prove useful to line the reactor environs with Li^6 or B^{10}, both of which have high thermal neutron capture cross sections. Thus, in any reactive mode quarks that are liberated from carriers or produced in the nuclear reaction adjacent to the reactor walls will bind to a lithium or boron carrier, from which they can in due course be freed through thermal neutron capture.

The reaction can be run in an explosive or supercritical mode, as by successively exploding minute, discrete mixtures of fuel and catalyst. Thereafter, quark-bearing He^3 is separated from non-quark-containing He^3 in the manners previously discussed for enrichment. Again the reaction can be operated on a sustained or critical basis within a closed system if the production of neutrons outweighs that of by-product He^3, as occurs in the case of catalysis and cyclic catalysis of fusion, one of whose reactions is $dQd \rightarrow t + n + Q^{(+1)}$. More conventionally, however, the reactions can be run in one or another subcritical mode, as next discussed.

1) Continuous operation in the subcritical mode. In this case the reactor contains fuel (such as deuterium), carrier-bound quark (such as He^3q), and a graphite or heavy-water moderator. Following ignition, neutrons are continuously fed to the reactor from a satellite reactor to replace others which escape from the reaction environment. The moderator thermalizes neutrons created in the course of the nuclear reaction, making them continuously available to free quarks sequestered by by-product He^3 through the transmutation reaction previously discussed.

2) Semicontinuous operation in the subcritical mode. In this case, the reaction vessel itself contains no moderator. Instead, the vessel is surrounded by a combination of moderator and a material such as Li^6, U^{238}, or Th^{232}, such that high-velocity neutrons emanating from the reactor are thermalized and reacted to breed radioactive fuel. In particular cases, the fuel can be used as a source of the neutrons which, as in the previous case, are continuously admitted to the reaction chamber to liberate sequestered quarks. In the case of this unmoderated reaction, few quarks engage in catalysis at any given time. When the quark-free He^3 waste content of the reactor reaches the same order of magnitude as the number of quark-bearing carriers, the reactor contents are flushed to an enrichment station where He^3 and He^3q are separated by the techniques previously discussed.

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13. It is commonly believed that catalysis of fusion by μ^- mesons cannot profitably produce energy because the μ^- is (i) short-lived and (ii) eventually captured by a helium nucleus formed in a fusion reaction (*10*, *11*). Accordingly, for example, even if long-lived heavy leptons were discovered they could not profitably produce energy (*11*). This view is incorrect. It will be shown that by proper choice of fusion fuel—that is, deuterium—the catalyst will bind to He^3, from which it may be liberated by thermal neutrons originating either in the fusion reaction itself, or in a conventional fission reactor using fuel, for example, bred with neutrons from the fusion reaction.
14. The occasional capture of the quark by one of the final-state reaction products will be considered in the section on sequestered quarks.
15. An upper limit to the time it takes the quark to form a bound state with two deuterons may be found by assuming that the deuterons behave as classically radiating particles while spiraling the quark. The second deuteron reaches its Bohr or-

bit more slowly than the first, since the first deuteron screens the charge of the quark. The time it takes the second deuteron to move from the initial radius r_i to the final radius r_f about the quark-deuteron system is given by $m_d{}^3c^3(r_i{}^3 - r_f{}^3)/4(Z_q - Z_d)$, where $Z_q = 4/3$ is the absolute value of the quark charge. Taking r_i as the mean separation between deuterium molecules in the quark-containing gas and $r_f \ll r_i$ results in the number given in the text. This is an upper limit because it ignores the energy the deuteron loses in scattering off bound electrons.

16. The fusion rate once the second nucleus has been added is, for comparison, $10^{O(16)}$ sec^{-1}, where O(16) stands for a number that is of the order of 16.
17. The U.S. energy consumption is about 10^{17} Btu's per year.
18. The probability w that the quark ($Z_q = 4/3$) is captured by the He^3 nucleus can be estimated by "sudden perturbation theory," assuming that the He^3, when formed, is distributed around the quark like one of the deuterons. In this case

$$w = a_g{}^6/a_a{}^6\,[1 + (ka_g{}^2/2a_a)^2]^4 \approx 1.7 \times 10^{-2}$$

where $a_g = (a_i a_f)^{1/2}$ and $a_a = (a_i + a_f)/2$ are the geometric and arithmetic means of the initial and final Bohr radii

$$a_i = \hbar^2/m_d Z_q' Z_d e^2$$
$$a_f = \hbar^2/m_{He^3} Z_q Z_{He^3} e^2$$

$Z_q' \approx Z_q - 5/16$ is the screened quark charge, and k is the He^3 wave number (momentum/$\hbar$). Since two fusing deuterons will yield t + p about as often as He^3 + n, the quark catalyzes approximately 100 reactions before binding with He^3.

19. Light sequestered quarks that do not have strong attractive forces with nuclei have large Bohr radii and are therefore readily ionized from isotopes of hydrogen or helium either by heating or by a process of electromagnetic stripping. Electrons are stripped from ionized materials by, for example, accelerating the ionized material through a gas. Electrons are stripped from the electron cloud surrounding the moving charged particle by interactions with electrons or nuclei of the relatively stationary uncharged gaseous component [N. Bohr, *K. Dan. Vidensk. Selsk. Mat. Fys. Medd.* **18** (No. 8) (1948)]. In like manner, a relatively light quark (for example, mass about one-third of the proton mass) associated with a binding nucleus can be stripped from the nucleus by employing the fractionally charged nature of the quark-containing material to accelerate it through a stripping medium (such as the nuclear fuel).
20. The thermal neutron capture cross sections for He^3, deuterium, and tritium are 5×10^3, 5×10^{-4}, and $< 6 \times 10^{-6}$ barn, respectively. Therefore thermal neutrons pass through the deuterium fuel and tritium fusion by-product to their He^3 targets.
21. Interactions between the quark and the entire nucleus are ignored. This is justified if the strong quark-nucleon force has a short range like other nuclear forces.
22. Methods for efficiently freeing quarks strongly bound to alpha particles are not presently available.
23. The probability per unit time, $1/\tau$, of alpha particle escape is approximately the product of the rate r of hitting the barrier times the barrier transparency e^{-G}

$$1/\tau \approx re^{-G}$$

where r = velocity of the alpha particle inside the nucleus divided by the nuclear radius $\approx 10^9$ cm/sec/10^{-12} cm = 10^{21} sec^{-1} and

$$G \approx 8e[MZ(Z_\alpha - Z_q)R/Z_\alpha]^{1/2}/\hbar - 4\pi e^2 M^{1/2} Z(Z_\alpha - Z_q)/Z_\alpha \hbar (2E)^{1/2}$$

where E is the energy liberated in the decay, Z and R are the charge and radius of the final-state nucleus, and M is the mass of the quark–alpha particle system [R. B. Leighton, *Principles of Modern Physics* (McGraw-Hill, New York, 1959), p. 527].
24. Tungsten hexafluoride is 11.2 percent by weight soluble in anhydrous hydrogen fluoride at −50°C [N. S. Nikolaev, S. V. Vlasov, Y. A. Buslaev, A. A. Opalovskii, *Izv. Sib. Otd. Akad. Nauk SSSR* (1960), p. 47].
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27. I thank Murray Gell-Mann, who asked if a quark of charge −2/3, like a μ^-, could make nuclei fuse. I am also grateful to Thomas Kiley for his interest and penchant for the practical.

Nothomyrmecia macrops: A Living-Fossil Ant Rediscovered

The most primitive living ant, previously an enigma, rediscovered and the subject of international study.

Robert W. Taylor

The Australian ant *Nothomyrmecia macrops* was described by Clark in 1934 (*1*) from two worker specimens in the National Museum of Victoria, Melbourne. The species was classified in a new monotypic higher taxon, now tribe Nothomyrméciini of subfamily Myrmeciinae (*1–3*). Other myrmeciine genera are *Myrmecia* (Australia, about 65 species; New Caledonia, 1 species), *Prionomyrmex* (Oligocene, Baltic Amber, 1 species), and *Ameghinoa* (early Tertiary, Argentina, 1 species) (*4*). The myrmeciines are considered the most structurally generalized of all ants, apart from the North American Cretaceous fossil *Sphecomyrma freyi* (subfamily Sphecomyrminae) (*5*). *Myrmecia*, while fully eusocial, has significantly primitive behavior (*6, 7*). *Nothomyrmecia* has been recognized as the most generalized of these insects and hence the most primitive known living ant, the descendent of a group important in formicid phylogeny (*5, 7*), and a likely near facsimile of species extant perhaps 60 million years ago or more. There has been speculation on the outside possibility that its behavior, when known, might represent an early stage in formicid social evolution (*3, 7, 8*). Study of the Melbourne specimens has been limited by their being dry-mounted, while the developmental stages and adult sexual forms have remained unknown. In the absence of further collections, *N. macrops* has become, naturally enough, a "holy grail" to ant specialists, and its "rediscovery in the living condition" has been stated as "one of the principal challenges of modern Australian entomology" (*8*).

Clark's specimens were probably collected near the western end of the Great Australian Bight by an excursion party that traveled, in December 1931, southward from near Balladonia through mallee-type *Eucalyptus* woodland and forest and set up camp for several weeks at the Thomas River mouth, east of Esperance, in the extensive sand plain heath present there. Insects were collected, without precise data, for a local naturalist, Mrs. A. E. Crocker, who sent them to Clark. Many Australian and American collectors and expeditions have since unsuccessfully sought *Nothomyrmecia* in this area, especially in the sand plain heath, where a guild of similarly pale colored, large-eyed, nocturnally foraging ants is well represented (*8*).

Nothomyrmecia was rediscovered on 22 October 1977 southeast of Ceduna on the Eyre Peninsula of South Australia by a CSIRO field party that had camped overnight en route from Canberra to Western Australia (*9*). Workers and dealate queens were collected while foraging nocturnally on the ground and tree trunks in disturbed roadside mallee woodland, but colonies were not lo-

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