Searching for strange matter by heavy-ion activation

Edward Farhi and R. L. Jaffe
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
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Stable, superdense quark matter may be a rare impurity in materials found on Earth today. We propose an experiment, using a conventional low-energy beam of heavy ions, to search for these strange-matter impurities.

It is possible that quark matter with roughly equal numbers of up, down, and strange quarks is absolutely stable; i.e., it has a separation energy (dE/dA) below 930 MeV and, therefore, cannot emit α particles.[1] This substance, "strange matter," has a density comparable to that of nuclei but could exist in lumps ranging in size from a few fermis to kilometers. Lumps with baryon numbers less than $\sim 10^{16}$ are possibly light enough to be materially bound to ordinary matter at the surface of the Earth. In this paper, we propose a method to search for small impurities of strange matter which may be found in materials which can be examined in the laboratory.

Strange matter was originally proposed as the missing dark matter of the Universe.[1] In this case, strange matter permeates the Universe and may be raining on the Earth today.[2] However, it has been shown that lumps of strange matter with baryon numbers less than $\sim 10^{52}$ would have evaporated before the Universe was one second old.[3] This makes the original dark-matter scenario implausible. Still, the interiors of neutron stars could be stable strange[1] matter and there may be astrophysical sources of the substance.[4] Regardless of any cosmological or astrophysical discussions, strange matter may be a stable substance waiting to be discovered on the Earth today.

Our proposal is to expose a sample of material which may contain strange matter to a low-energy beam of heavy ions. The beam energy is adjusted to be just below the Coloumb barrier of the nuclei in the sample. If there is no strange-matter impurity (essentially) no nuclear reactions will occur. However, the Coulomb barrier of strange matter is typically lower than that of ordinary nuclei, so the beam may interact with whatever strange matter is in the sample. Each interaction would characteristically result in a high-multiplicity, isotropic burst of photons, which should present an unmistakable signature to the experimentalist. Even at beam energies somewhat above the Coulomb barrier of ordinary matter, we know of no conventional nuclear process capable of mimicking this striking signature. In this paper, for the sake of simplicity, we consider only beam energies below ordinary Coulomb barriers. Similar considerations apply at higher energies, but a more detailed analysis of background processes would be necessary to determine the sensitivity of such an experiment.

Our proposal is based on the observation that strange matter has a much lower net charge density carried by its quarks than ordinary nuclei. Strange matter can be modeled[5] as a Fermi gas of up, down, and strange quarks with the equilibrium between the flavors maintained by the weak interactions. At the chemical potentials of interest, ~ 300 MeV, the up- and down-quark masses can be neglected, but the strange-quark mass m_s cannot. If m_s were zero, then the equilibrium configuration would consist of equal numbers of up, down, and strange quarks, which has zero net charge $(\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0)$ and zero Coulomb energy. The mass of the strange quark cannot be precisely determined, but it is roughly between 100 and 300 MeV. So, strange matter has relatively fewer strange quarks and a small net positive charge is carried by the quarks. For large lumps (but still small enough so electrons reside in Bohr orbitals outside the lumps), this charge grows like $A^{1/3}$ where A is the baryon number[5] (one-third the number of quarks), whereas in stable nuclei the charge grows roughly linearly with A.

Lumps of strange matter are neutralized by electons. For small lumps, $A < 10^6$, the electrons form a cloud around the lump much like an ordinary atom (we call these small lumps strangelets). For large lumps, the electrons form a degenerate Fermi gas inside the lump. However, in this case the electrons still extend a little beyond the edge of the hadronic material, since the quarks are bound by the short-range strong interaction while the electrons are only electromagnetically bound.

Consider what happens when a nucleus encounters a lump of strange matter. First, imagine that a single low-energy neutron strikes a lump. The neutron sees no Coulomb barrier, falls in, breaks apart, and releases its quarks. The quarks are now in a lower-energy state and their excess energy is shared by the other quarks. The lump has increased its baryon number by one, and will eventually radiate the excess energy in photons.

A charged nucleus incident on a lump first passes through a layer of electrons and then sees a positive charge. If the nucleus has sufficient kinetic energy, it can penetrate the Coulomb barrier; otherwise, it is repelled and usually does not interact. If it penetrates, its individual nucleons will suffer the same fate as the single neutron just considered. The lump increases its baryon number and then radiates the excess energy.

For a wide range of the parameters which go into modeling strange matter, and for all very small lumps, strange matter presents a lower Coulomb barrier than ordinary nuclei. If so, an incident nucleus requires less energy to interact with strange matter than it does to interact (strongly) with ordinary matter. If the incident nucleus does interact, the energy released will be IA_B+K, where I is the binding energy per nucleon of strange matter, relative to the binding energy per nucleon of the beam nucleus, A_B is the atomic number of the beam nucleus, and K is the kinetic energy of the beam. We expect I to be a few tens of MeV. By choosing a beam nucleus with a high atomic number, a few GeV of energy can be released per event.

I. THE COULOMB BARRIER

Consider a beam particle with charge Z_B and mass M_B incident on a target particle, at rest, with charge Z_T and mass M_T. In order to overcome the Coulomb barrier, the center-of-mass energy should exceed the potential energy when the two particles are just touching. The required kinetic energy of the beam is

$$K_c = \alpha \frac{Z_B Z_T}{R} \left[\frac{M_B + M_T}{M_T} \right] , \tag{1}$$

where $R = r_T + r_B$ is the sum of the beam and target radii. For ordinary nuclei, $r = (1.2\ \mathrm{f}) A^{1/3}$ and M is proportional to A:

$$\frac{K_c}{Z_B} = \frac{Z_T}{A_T} \left[\frac{A_B + A_T}{A_B{}^{1/3} + A_T{}^{1/3}} \right] (1.2\ \mathrm{MeV}) . \tag{2}$$

If the target consists of ordinary nuclei, Z_T is roughly $A_T/2$, and if A_B is large, the Coulomb barrier is insensitive to A_T. For a gold beam ($A_B = 197$), K_c/Z_B varies from 14 to 17 MeV over all target nuclei. If K_c/Z_B is below 14 MeV, no ordinary nuclear reactions occur. [Actually formula (1) overestimates the Coulomb barrier by roughly 15%. This is because we used the nuclear charge radius, which is slightly smaller than the nuclear-matter radius. We will also not distinguish between the two radii for strange matter, and therefore make a small overestimate of the strange-matter Coulomb barrier.]

A strange-matter target will have a much larger mass than the beam nucleus, so on strange matter,

$$\frac{K_s}{Z_B} = \alpha \frac{Z_T}{R} , \tag{3}$$

which is simply the Coulomb potential at a distance R from the center of the lump.

We will first discuss the charge on a lump of strange matter which is too small to contain electrons within itself, a "strangelet." The equilibrium distributions of the different quark flavors are established through weak interactions like $d \leftrightarrow u + e + \bar{\nu}$, $s \leftrightarrow u + e + \bar{\nu}$, and $d + u \leftrightarrow s + u$. Using a Fermi-gas model including the effect of the Coulomb energy, we have shown[5] that the charge Z on a strangelet with baryon number A has the form

$$Z = f(A) A^{1/3} , \tag{4}$$

where $f(A)$ goes from zero at very low A to a constant value for large A:

$$f(A) \cong \frac{5}{8\pi} \left[\frac{4\pi}{3} \right]^{2/3} \frac{1}{\alpha} \left[\frac{\mu - \mu_u}{n_A^{1/3}} \right] \quad \text{for } A > 10^6 . \tag{5}$$

Here, μ_u is the up-quark chemical potential, μ is the down-quark chemical potential (equal to the strange-quark chemical potential), and n_A is the baryon-number density of neutral bulk matter without electrons.

The potential at the surface of a strangelet is

$$\phi = \alpha \left[\frac{4\pi}{3} \right]^{1/3} n_A^{1/3} f(A) , \tag{6}$$

which for large A approaches

$$\phi = \tfrac{5}{6}(\mu - \mu_u) \quad \text{for } A > 10^6 . \tag{7}$$

The difference in chemical potentials depends on the parameters in our Fermi-gas model, such as the strange-quark mass and the color fine-structure constant α_c. For zero strange-quark mass the difference vanishes and it has its maximum value when the strange-quark mass is so large that there are no strange quarks in the system. For $\mu = 300$ MeV, $m_s = 150$ MeV, and $\alpha_c = 0$, ϕ approaches 15 MeV. If m_s is below 150 MeV, all strangelets will have a potential at the surface below 15 MeV, while if m_s is larger than 150 MeV only small strangelets will have a potential below 15 MeV. In Fig. 1, we plot the potential at the surface of a strangelet as a function of A for various choices of m_s and α_c.

For large lumps, the electron cloud which neutralizes the lump is mostly within the lump, but it extends slightly beyond the hadronic material. Deep within the lump the electron density is uniform and characterized by a constant chemical potential μ_e. Using a Thomas-Fermi model for the electron distribution and assuming a uniform quark-charge distribution up to the edge of the lump, it can be shown that the electron chemical potential at the edge is $\frac{3}{4}\mu_e$. (This assumes massless electrons, a good approximation.) The energy required to liberate the electron from the

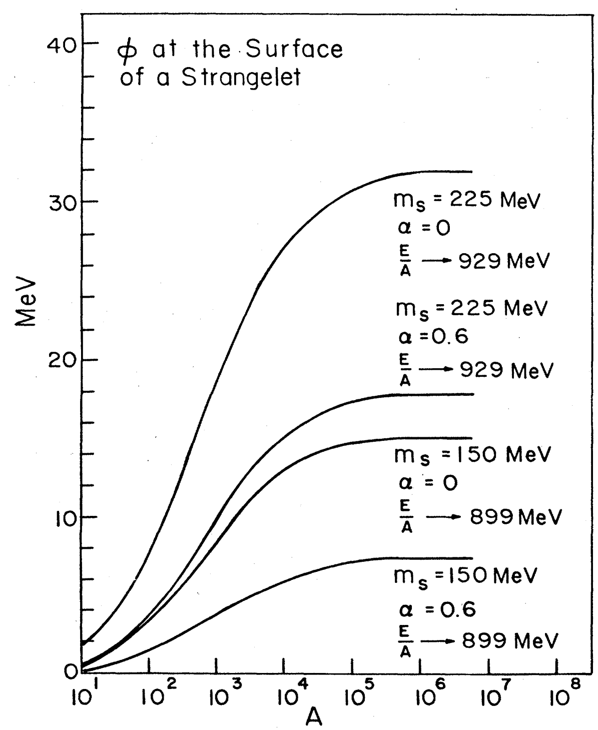

FIG. 1. The electrostatic potential at the surface of a strangelet for various choices of α_c, m_s, and the binding energy of bulk strange matter (E/A).

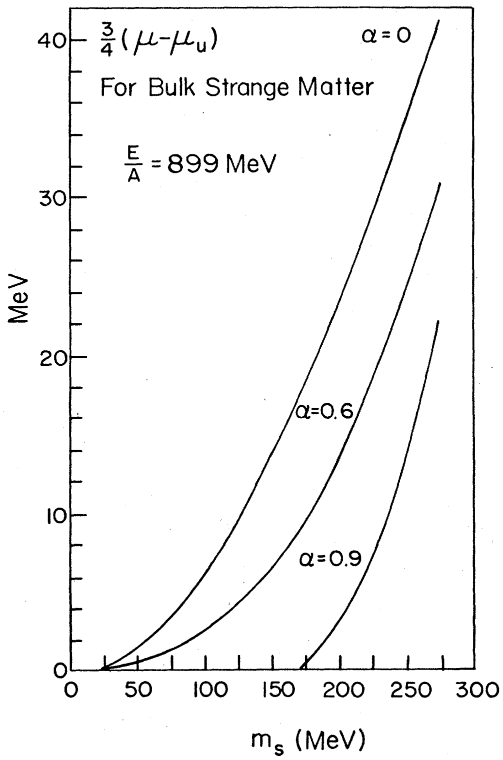

FIG. 2. The Coulomb barrier at the surface of bulk strange matter as a function of m_s for various choices of α_c. Below $m_s \approx 170$ MeV for $\alpha_c = 0.9$, strange matter would have a negative Coulomb barrier, i.e., an attraction for ordinary charged matter.

edge is $\frac{3}{4}\mu_e$, which is also the energy needed to bring a positive charge to the surface of a lump, i.e., the Coulomb barrier. Because of weak interactions like $d \leftrightarrow u+e+v$ and the fact that the density of neutrinos is negligible, we have $\mu_e = \mu - \mu_u$. The inclusion of electrons lowers the Coulomb barrier from $\frac{5}{6}(\mu-\mu_u)$ to $\frac{3}{4}(\mu-\mu_u)$. (The inclusion of electrons also changed μ and μ_u, but only by amounts of order $\mu_e{}^3/\mu^2$, which can be neglected.) In Fig. 2 we display the Coulomb barrier $\frac{3}{4}(\mu-\mu_u)$ for bulk strange matter as a function of m_s, where the calculations have been done using the model of Ref. 5. It may appear surprising that the Coulomb barrier of strange matter is not smaller relative to nuclei, given the very low charge-to-mass ratio typical of strange matter. The reason lies in the fact that the Coulomb barriers of strange matter and of nuclei grow with A. For a fixed A the Coulomb barrier of a strangelet is much lower than that of a nucleus. However, it is not necessarily true that the Coulomb barrier of strange matter for *all* A is below that of *all* nuclei.

In summary, a lump of strange matter with baryon number larger than 10^6 has a Coulomb barrier, independent of size, close to $\mu-\mu_u$. For smaller strangelets, the Coulomb barrier decreases monotonically with size. $\mu-\mu_u$ is typically a few tens of MeV. For m_s below 150 MeV, it is always below 15 MeV. Thus, for a wide range of parameters, strange matter presents a lower Coulomb barrier than ordinary nuclei.

II. THE SIGNAL

Consider a single neutron slowly entering a lump of strange matter. The energy per baryon number of strange matter is not precisely known but it is expected to be a few tens of MeV below the neutron mass. When the neutron falls in, its quarks go to the top of the Fermi sea of quark matter. These quarks interact through gluon exchange and the excess is quickly shared by other quarks. One may worry that the neutron consisting of two downs and an up is far from the equilibrium configuration of strange matter, which consists of roughly equal numbers of up, down, and strange quarks. However, the addition of a nucleon, or even a nucleus, to a *large* lump of strange matter makes only a very small change in the densities of each quark flavor. The strange matter can reestablish its equilibrium distributions through a weak-interaction process at any time. One might also worry that since entering quarks are "blocked" by the exclusion principle from entering occupied orbits, the nucleon might experience a repulsive force at the surface of the strange-matter lump. In fact, this is unlikely, because the typical energies of the quarks bound in the entering hadron are $\sim M_N/3$, at or above the chemical potential of the nonstrange quarks in strange matter.

The binding energy per baryon, I, added to the strange matter is not enough to make a pion, so it must be radiated by photons. The fastest this could conceivably occur is in a time $\sim 1/\alpha I$. In this time the energy moving at the speed of sound, $\sim c/\sqrt{3}$, through the quark matter would have gone a distance of order $1/\alpha I$. For I equal to 10 MeV this distance is 2700 fm. Even for the largest lumps we consider, which are 50 times this size, only a small fraction of the energy is radiated before the energy is distributed throughout the lump. We will therefore model an excited lump, with an excess energy ΔE, by assuming that it has a uniform temperature T. In the free Fermi-gas model this temperature is

$$T = \left(\frac{2\mu\Delta E}{\pi^2 A} \right)^{1/2}, \tag{8}$$

where A is the baryon number of the lump and μ is the quark chemical potential, roughly 300 MeV. Even a very large lump of quark matter is not opaque to photons with energies characteristic of this temperature, so the radiation will not display the Planck spectrum of a cooling blackbody. Nevertheless, we expect the spectrum to be characterized by T, modulated by an energy-dependent emissivity. For large A, $T \ll \Delta E$ so the lump radiates many low-energy photons.

Now consider a large nucleus, with just enough energy to overcome the Coulomb barrier, entering a lump of strange matter. Perhaps a few hard photons or occasionally a pion may be produced at the point of entry, but for the most part the nucleus can be regarded as a collection of individual nucleons, each of which breaks apart. If the total-binding energy plus kinetic energy is ΔE, the system can then be characterized by the temperature given by Eq. (8).

For an incident gold beam with $K_c/Z_B = 10$ MeV and a binding energy of strange matter, relative to gold, of 20 MeV, we have $\Delta E = 4730$ MeV. The effective temperature reached by a lump with $A = 10^6$ is 0.5 MeV and for a lump with $A = 10^{12}$ it is 0.5 keV. In the first case, we expect around 10 000 photons with energy of order 0.5 MeV, in the second case, around 10^7 photons with energy of order 0.5

keV. They are produced by the lump as it deexcites, so we expect a nearly isotropic distribution.

In addition to the photons produced with energies characteristic of T, there may be other hard photons emitted, for example, at the point of impact. The introduction of a nucleus into a lump of strange matter may also excite modes characteristic of the lump as a whole. Some thermally excited nuclei, for example, emit dominantly a single sharp line, the giant dipole resonance, which lies at an energy of ~ 79 MeV/$A^{1/3}$. The analogous mode in strange matter should have considerably higher excitation energy. The wave number of the dipole charge-density mode is $\sim 2.08/R$ in both systems [2.08 is the first zero of $j_1'(x)$], but the velocity of a charge-density wave in a relativistic Fermi gas is $c_s = 1/\sqrt{3}$ and is much greater than that of the nonrelativistic Fermi gas. The excitation energy is therefore $E_{\text{dipole}} \sim 2.08/\sqrt{3}R \sim 250$ MeV/$A^{1/3}$. For all cases of interest $E_{\text{dipole}} >> T$ (e.g., for $\Delta E = 4$ GeV, $\mu = 300$ MeV, and $A = 10^9$, $T \cong 16$ keV, but $E_{\text{dipole}} = 250$ keV), so we do not expect the giant dipole resonance to appear prominantly in the emission spectrum of a cooling lump of strange matter.

III. THE SAMPLE

The mass of a lump of strange matter is proportional to its baryon number $M = \epsilon A$, where ϵ is expected to be around 900 MeV. A lump with a baryon number of 7×10^{15} would exert a gravitational force per unit area at the surface of Earth of 10^{10} erg/cm^3 [assuming a density of (125 MeV)^3]. This is a typical structural energy density of ordinary material so a lump more massive than this would sink to the center of the Earth.[2] Only lumps of strange matter with a lower baryon number may be found in ordinary materials. However, if the material has undergone any type of processing, chemical or physical, it is likely that it would have lost its strange matter. Strange matter should be looked for in unprocessed materials like meteorites, moon rocks, or other objects which may never have been melted in the presence of a strong gravitational field. Alternatively, it may be found in places where materials accumulate, such as sludge, sea-floor nodules, ooze, or the waste of chemical-processing plants.

IV. THE SENSITIVITY

We estimate the counting rate for a beam with current i (particles per second) incident on a sample with a mass concentration c of strange matter. For simplicity, we assume that all lumps of strange matter have the same baryon number A and a mass $M = \epsilon A$ with ϵ near 900 MeV. We also assume that any incoming nucleus which overcomes the Coulomb barrier has a 100% chance of interacting so the cross section is geometric: $\sigma = \sigma_0 A^{2/3}$ where $\sigma_0 = 7.8 \times 10^{-5}$ MeV^{-2} comes from a baryon-number density of (125 MeV)^3. The beam only penetrates a short distance into the sample before it is dissipated and no longer useful as a probe. We need to know the surface density S of the sample, which is the mass density times the penetration length. The number of interactions per second is then

$$\text{counting rate} = \frac{iS\sigma_0 c}{\epsilon A^{1/3}} .$$

A 100-nA beam striking a target with a surface density of 10 mg/cm^2 would produce a counting rate of $(1 \times 10^{13})c/A^{1/3}$ events per day. For lumps with baryon number 10^6 this experiment could reasonably search for impurities of strange matter down to concentrations of 10^{-11} by mass (one event per day). Recently, an experiment of the type we have described was carried out[6] at the LBL Super HILAC. The target consisted of a piece of the Murchison meterorite and the beam was ^{197}Au at an energy of 903 MeV and an average current of 85 nA. The data have not yet been fully analyzed, but preliminary indications are that no prominant signal was seen.

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