The strangelet saga

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Abstract. A strangelet is a small piece of strange quark matter, which consists of roughly equal numbers of u, d, and s quarks. Some have said that strange quark matter could be more stable than ordinary nuclear matter for which the quarks are collected into groups of three as neutrons and protons. At a time when our understanding was largely qualitative it was suggested that a single strangelet could grow without limit by absorbing ordinary nuclei. This raised fears that making a single strangelet in a high energy accelerator could result in the destruction of the earth. Improved theory supplemented with additional experiments, have removed all justification for such catastrophic scenarios. Calculations of color-flavor locking allow for a number of variations of strange quark matter, some of which have a lower energy than any other arrangement of quarks. Such material might be found inside of neutron stars for which the necessary pressure and low temperature are available. Those calculations that predict a density larger than that of compressed neutrons have been ruled out by the recent observation of a neutron star with a mass 2.0 times the mass of the sun.

1. Introduction
The term “strange quark matter” refers to a theorized state of matter containing a large number of delocalized quarks (u, d, s) in multiquark droplets. Small pieces of strange quark matter are called strangelets. The smallest strangelet would be the six quark H particle with the quarks of two lambdas in one bag. It has been suggested that the center of neutron stars consists of strange quark matter.

The Alpha Magnetic Spectrometer (AMS-02) was launched and attached to the International Space Station in May, 2011. It will use the unique environment of space to study the universe and its origin by searching for antimatter, dark matter, and strangelets while performing precision measurements of cosmic ray composition and flux [1]. We predict that they will not find strangelets, but nature provides no end of surprises. The papers associated with this project may provide much information about the history and theoretical predictions for strangelets.

Strangelets got into the popular press with the conjecture that a single strangelet could grow and consume the entire earth. There were some who tried to prevent the start of RHIC and LHC because of concerns about this possibility. A search with www.google.com will bring up a number of notes about the alleged danger. In the early days of quark matter studies, there was room for imaginative theorists to formulate disastrous strangelet events, but they are certainly ruled out now by both theory and experiment.

Hypermolecules, consisting mostly of protons, neutrons, and lambdas, can have the same quark content as a strangelet. They can be stable to strong interactions, but the strange baryons in them will decay by
weak interactions with lifetimes of the order of 100 ps. It could be difficult to distinguish between strangelets and hypernuclei in measurements made at high altitudes.

The transition between quark matter and hadronic matter takes place by strong interactions and is rapid. It requires only a small rearrangement of the quarks. From this it would follow that all nuclear wave functions have a quark matter component, and that a strangelet and a hypernucleus with the same quark content are different names for the same object.

2. The beginning
As soon as quarks became considered as real particles, people started asking why baryons are limited to three quarks. In a system with many quarks the lowering of the Fermi energy by changing some of the u and d quarks to s quarks could, under some circumstances, more than make up for the larger mass of the s quark. Such considerations led to many papers about the possibility of strange quark matter. In 1971 Bodmer [2] suggested that a “collapsed state” of matter would have a lower energy than ordinary nuclei, but that the time required for the transition to the lower energy state could be longer than the age of the universe. As an analogy he noted that the D-D molecule requires a very long time to go into the lower energy state of a He atom.

There were people who wanted to prevent heavy ion studies at RHIC and at the LHC. They claimed that the production of a single piece of such quark matter, if it were neutral or slightly negative, could swallow the earth. Early on, knowledgeable people showed this need not be a concern. E. Whitten, in 1984 [3], pointed out that such an object would have to be positive. “To ensure beta equilibrium, quark matter will have a degenerate electron gas with \( \mu_e = \mu_d - \mu_u \). Since this is much more than the electron mass \( m_e \), the electron gas is bound only if there is a large electrostatic potential, equal to

\[ \mu_d - \mu_u - m_e = 50 \text{ MeV}. \]

As time went on the calculations became more quantitative. In 1991 Greiner and Stöcker, using the MIT bag model, found that stable quark matter required a small bag constant, \( B_{1/4} < 150 \text{ MeV} \), which would give a very small transition temperature to a quark gluon plasma (QGP), \( T_c \sim 100 \text{ MeV} \) [4]. Experiments indicate \( T_c > 160 \text{ MeV} \).

3. Possible danger
The logic behind alleged danger was that if a strangelet were the lowest energy state of nuclear matter and had a negative or neutral electric charge it would absorb nearby nuclei and convert them into additional strange quark matter. Once inside the strangelet its quarks would adjust their flavor by weak decays. Since each flavor change would be energetically allowed they could proceed sequentially. The absorption of ordinary nuclei would continue as long as additional nuclei are available—until the entire earth is consumed.

Ordinary nuclear matter does not decay sequentially into strangelets because the initial conversions of u or d quarks to s quarks are not energetically allowed. If the overall energies were such that a bismuth nucleus, for example, would release energy by converting to a strangelet, the time required for the conversion would be extremely long because the decay would require over 60 simultaneous weak decays.

The overlap region in collisions of energetic heavy ion can be considered as an extremely hot strangelet. The quarks are not confined to hadrons and the fraction of strange quarks is large. Many of the anti strange quarks are removed by the process of strangeness distillation [4]. If, but only if, some of this material could cool without forming into hadrons, would it become a strangelet that could be a matter of concern.
4. Ice cube from a hot furnace

Ellis has shown that no object even as large as a carbon nucleus could come out of such a hot system [5]. This would include strangelets as well as ordinary nuclei. It has been compared to making ice cubes in a furnace. Andronic et al. [6] make predictions for specific nuclei and hypernuclei and show that their model provides good fits to available data for nucleon-nucleon center of mass energies from 5 to 200 GeV. The maximum production occurs at 5 GeV, and the production of masses larger than 4 falls off rapidly with increasing energy. They find the production ratio for $\Lambda\Lambda\Xi^-$He/$\Lambda$ at 5 GeV to be only $5 \times 10^{-12}$. Note that these considerations apply only to production from the hot quark gluon plasma (QGP) and not to the much cooler spectators.

To date there have been no confirmed observations of strangelets. The smallest strangelet would be the H particle (H for hexaquark). This particle was first proposed by Jaffe [7] who noted that the special symmetry of two u, two d, and two s quarks should lead to a stable particle (stable with respect to the strong interactions) with the quark content of two lamdas. He estimated that the mass should be about 80 MeV below the sum of the masses of two lambda particles. Subsequent calculations using a wide variety of models have given mass estimates ranging from values less than the deuteron to unbound states. The H has not been seen in any experiments. The driving interest in the particle lies in its being a new state of matter (six quarks in one bag). In addition, if the mass is near the deuteron mass, it could have a lifetime sufficiently long to have cosmological significance.

The Facility for Antiproton and Ion Research (FAIR) [8] experiment at GSI Darmstadt will study heavy ion reactions with high luminosity at the optimum energy for producing hypernuclei [9]. These studies will provide a more quantitative understanding of multi-hypernuclear systems and possibly strange quark matter. FAIR is projected to deliver its first beams in 2017/2018.

The QGP present in the early universe, shortly after the big bang, is thought to have been a hot soup of delocalized quarks (with roughly equal numbers of u, d, and s quarks) and gluons that is similar to the QGP formed in the interaction region of heavy ion collisions. So for the reasons given above we should not expect to find strangelets, or even medium weight nuclei, left over from the big bang. These considerations do not rule out the possibility of the appearance of strangelets in cosmic rays. We certainly do not understand all possible productions mechanisms by stellar processes. If stable strangelets are possible, nature will find some way to make them. If strange quark matter is stable at zero pressure then compact stars are strange stars, not neutron stars. In that case collisions between strange stars and their partners in binary systems would cause tidal forces that could lead to the ejection of appreciable amount of strange quark matter into the cosmos [1].

5. CFL

Recent calculations involving color-flavor locking (CFL) [10] have shown that strange quark matter may be the lowest energy state of matter and that it also could be neutral or even slightly negative. Because of asymptotic freedom, at sufficiently high densities and low temperatures matter can be a Fermi sea of essentially free quarks. The behavior is dominated by quarks near Fermi surface. With an attractive force between them they can form pairs of a bosonic nature that reduces the free energy. Many such pairs will form a bosonic condensate. This is a standard recipe for the BCS type of superconductivity. With color, flavor and spin, many pairing patterns are possible resulting in many varieties of “Cooper pairs” and “color superconductivity” and many different predictions for the density of the resulting strange quark matter. The necessary extreme pressures and adequate cooling times may be found in neutron stars. Pressures near the center are huge, and millions of years are available for cooling, but the pressures may not be sufficient for color-flavor locking even in neutron stars.
6. Neutron Stars

There has been considerable interest in the question of strangeness in compact star interiors. For a review and many references, see [11]. Most of the calculations, including CFL calculations, predict that strange quark matter would have a density larger than that of hadronic matter. Those calculations that predict an average density for a star that is much larger than that of compressed neutrons have been ruled out by the recent observation of a neutron star with a mass 2.0 times the mass of the sun. This star, PSR J1614-2230, is a pulsar emitting a radio signal every 3.15 ms [12]. The best calculation of the equation of state for compressed neutrons predicts a radius for the star that is only slightly larger than the Schwarzschild radius. If the average density were larger, the star would be a black hole that could not emit a radio signal. The stellar measurements are compatible with any model of strange quark matter that predicts an equation of state similar to that of compressed neutrons. It is also possible that cold strange quark matter is not the lowest energy state of matter or that the pressure required for the CFL states is more than is found even in neutron stars.

7. Hypernuclei from spectators

The only sizable nuclear objects that can be made by high energy heavy ion collisions are the spectators in collisions in which the overlap between the two nuclei is small. For collisions with a larger region of overlap the spectator part disintegrates into individual neutrons and protons. It is suggested that particles from the hot interaction region could get into a spectator and make it into a hypernucleus.

Figure 1 shows how strange quarks could develop in a spectator. The figure shows the interacting system in the rest frame of the nucleus that will produce the spectator. The Lorentz contracted incoming nucleus is just making contact. As it passes through the edge of the target nucleus, nucleon-nucleon collisions will produce energetic particles, some of which will pass into the spectator part of the target. PYTHIA version 8.145 was used to calculate the number and type of particles that leave a proton-proton reaction at angles greater than 5°. Reactions involving neutrons should produce particles similar to those from the p-p reactions With Pb-Pb reactions at the LHC in mind, the calculations were done for nucleon-nucleon center of mass energies of 5.5 TeV and 2.75 TeV and then at 0.2 TeV (RHIC energy) to determine the energy dependence. In the center of mass of one nucleus this required the incoming Pb nuclei to have energies of 16000 TeV/nucleon (for 5.5 TeV) and 4000 TeV/nucleon (for 2.75 TeV). For each energy, 30 p-p reactions were calculated and the number of reaction products summed. This is an approximation to the number of nucleon-nucleon reactions that would occur during a semiperipheral Pb-Pb reaction.

There are two types of reaction products of interest. There are particles containing strange quarks and the much larger number of pions. The pions mostly have energies suitable for initiating reactions that result in strange quarks. The neutral pions are included along with the charged pions. The lifetime of a $\pi^0$ is much too long for it to decay into gammas during its passage through the spectator nucleus. Also included in the pion counts are a small number of $\eta$, $\rho$, and $\omega$ mesons. There were also a few neutrons and protons with angles greater than 5°; these were not included in the count. In order of decreasing energy the pion counts (for 30 pp reactions) are 148, 141, and 115, which shows an increase with
energy. The numbers for particles carrying strangeness are smaller, 1 \( K^- \), 2 \( \Lambda^0 \), 3 anti\( K^0 \), and 2 \( K^0 \) for the highest energy and 1 \( K^- \), 1 \( \Lambda^0 \), 2 anti\( K^0 \), and 2 \( K^0 \) for 2.74 TeV. For 0.2 TeV the numbers are larger, 3 \( K^- \), 4 \( \Lambda^0 \), 4 anti\( K^0 \), and 5 \( K^0 \). The larger numbers at the lowest energy reflects the peak in the production cross section not far above threshold.

With these numbers one could expect that LHC experiments would produce some spectators with one \( \Lambda^0 \) but few with more than one. It would have been useful to have extended these calculations to the much higher energies available in cosmic rays, but there was doubt that Pythia would give reliable results at such energies.

We speculate that at sufficiently high energies a large number of strange quarks would reach the spectators and produce multi-hypernuclei. A large nucleus, Fe or Pb, colliding with an atmospheric nitrogen nucleus would always leave considerable spectator matter.

It would be good to make a thorough study of spectators from Pb-Pb reactions at LHC energies to see how well the “universal” distribution function [13] works at the much larger energy. A careful study would also determine the fraction of the spectators that are hypernuclei. The experiments would be difficult, and so far no one has accepted the challenge.

8. All nuclei have a quark matter component

There is generally assumed dichotomy between matter that is composed of nucleons and quark matter for which the quarks are not localized in nucleons. However, in an ordinary nucleus the force binding the nucleons is the result of quarks and gluons being somewhat delocalized. A good place to look for a quark matter component in the wave function is in the \(^4\)He nucleus. With two flavors, two spin states, and three colors, up to 12 quarks, 6 \( u \) and 6 \( d \), can all be in the ground state. A detailed calculation shows that 12 quarks do indeed provide an energy minimum as a function of quark number [14]. Mosallem and Uzhinskii [15] found that it was impossible to describe simultaneously the p-\(^4\)He and d-\(^4\)He elastic scattering cross sections using the same set of N-N amplitude parameters. The data was fitted well using a \(^4\)He wave function of which 10.5% was a 12 quark bag. For \( _\Lambda 6\)He it could be expected that the delocalized quark component would be an even larger part of the wave function. This would be an extremely tightly bound nucleus, but with a mass still larger than normal \(^6\)He so that it would decay by weak interactions.

From this point of view the nature of the ground state of a nuclear object depends only on the number of \( u \), \( d \), and \( s \) quarks. The terms hyper nucleus and strangelet refer to the endpoints of a continuum. Starting from the other end of this continuum, consider a large box containing quarks. The forces between the quarks will ensure no concentrations of color charge. The quarks will be associated in color-neutral triplets. Only a small amount of motion of the quarks, or a reduction in temperature, is required for the triplets to become normal baryons.

Returning to the H particle, Jaffe [7] contrasted a particle with 6 quarks in one bag with two bags with 3 quarks each. Nature does not make such a distinction. The H particle could be expected to be mostly a deuteron like object consisting of two \( \Lambda^0 \)’s. While the two \( s \) quarks in the six quark component could, in principle, allow two \( \Lambda^0 \)’s to be bound when two neutrons are not, this appears to not happen.

It might be expected that in neutron stars there is a delocalized quark component and that some of the quarks are strange. The magnitude of these components would depend on the pressure (depth). The question is not whether there is strange quark matter or not in a neutron star, but rather the relative numbers of \( u \), \( d \), and \( s \) quarks and the extent of delocalization. In neutron stars there is the additional feature that a CFL phase would require some of all of the quarks to be combined as Cooper pairs [10].
9. CASTOR and ZDC

Many unusual cosmic-ray events have been recorded at high altitude observatories [16]. Some of these may have been caused by strangelets [17]. The AMS-02 experiment will see such objects if they are part of the primary cosmic rays. If they are produced by reactions of heavy ions with the upper atmosphere, it is likely that they would also be formed by Pb-Pb reactions at the LHC and may be seen by the CASTOR (Centauro And STrange Object Research) detector [18]. CASTOR is a small angle detector covering the angles from 0.7º down to 0.08º (5.2<η<6.6) from the beam direction that has sufficient granularity to identify and characterize unusual nuclear objects. It is divided into two parts, a short electromagnetic part (EM) and a long part (HAD) for studying objects with the penetrating potential of hadrons. Its total length provides 10.3 nuclear interaction lengths. The showers are sampled by observing Čerenkov light from thin quartz plates between tungsten plates. It is divided into 14 longitudinal sections, each with 16 azimuthal divisions, for a total of 224 analog signals. Figure 2 shows the structure. There have been no reports yet from CASTOR about strange objects. The detailed calibration has been difficult because CASTOR, with 224 photomultiplier tubes (PMTs), is located in a part of CMS [19] that has a large and irregular magnetic field.

![Figure 2. Details of the structure of CASTOR](image)

CASTOR cannot see spectator matter because it follows the outgoing beam through the middle of CASTOR. It is not expected that strangelets will come from the hot quark gluon plasma at LHC energies. However it is likely that detailed small angle studies with CASTOR will lead to a better understand of the unusual cosmic ray events.

For detailed studies of reaction products at even smaller angles there are only the Zero Degree Calorimeters (ZDCs). These are located at the closest point for which the incoming and outgoing beams are in separate beam pipes. This is 140 m from the interaction point for CMS. A ZDC must be small because the distance between the beam pipes is only 10 cm. Figure 3 shows the design of a ZDC for CMS [20]. With heavy ion reactions a ZDC sees mostly spectator neutrons. A spectator hypernucleus would get out of the beam pipe and into the ZDC only if it had a Z/A ratio less than 0.2. The Pythia calculations, present earlier, appear to rule out this possibility.
Figure 3. Design of ZDC. Both the EM and the HAD section consist of tungsten plates as the absorbing material. The Čerenkov light from quartz fibers between the metal plates is collected by PMTs at the top.

From the experimental point of view, a ZDC should see any nearly neutral heavy object that leaves the interaction point in the same direction as the original beam and has a cross section for producing charged particles in tungsten metal that is within an order of magnitude of that of hadrons. Figure 4 shows the energy spectrum from one of the CMS ZDCs gated on a signal from elsewhere in CMS for Pb-Pb at 2.75 TeV/nucleon. The sharp peak on the left is from single neutrons released from a Pb nucleus by the intense Coulomb field of the other Pb nucleus. The broad peak is from spectator neutrons from actual Pb-Pb collisions. The number of spectator neutrons is a function of the impact parameter (the distance of closest approach of the centers of the two nuclei), which can be determined from the total number of particles in CASTOR or other parts of CMS. Heavy, nearly neutral objects would appear as deviations from the predicted number.

Figure 4. ZDC energy spectrum gated on other CMS signals showing the single (and small double) neutron peaks from ultra-peripheral collisions and a broad peak of spectator neutrons from actual Pb-Pb collisions at a center of mass energy of 2.75 TeV/nucleon.
The interacting Coulomb fields can produce particles with masses up to about 200 GeV. Perhaps some of the unusual objects seen in high altitude cosmic rays studies will be produced by this process. They should be seen in CASTOR or other parts of CMS in coincidence with the one neutron peak. All of the single neutrons in figure 4 are in coincidence with other objects seen by CMS. If the ZDC had supplied the gate, the area under the single neutron peak would have been an order of magnitude larger than the area under the broad multi-neutron peak.

10. Conclusions
- There is no longer any reason to be concerned that strangelet production at an accelerator could destroy the earth.
- To date no strangelets have been observed.
- The distinction between quark matter and hadronic matter may be spurious. All nuclear matter may be a mixture of both.
- High energy, heavy ion cosmic rays may produce multi-hyper nuclear objects by the spectator part of the heavy ion being infiltrated with strange quarks from the hot quark gluon plasma.

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