The Stranglet Saga

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For the 27th Winter Workshop on Nuclear Dynamics

Winter Park, CO   12 February 2011

Early Days

As soon as quarks became considered a real particles, people started asking why are baryons limited to three quarks?

Consider a single particle with 6 quarks, all in ground state.
d d u d d u
↑ ↓ ↑ ↑ ↓ ↓
R Y B Y R B

With three quarks u, d, and s, there can be 12 quarks, all in the ground state.

Possibilities

Why not have millions of quarks all in one big bag?
Define “quark matter” as a Fermi gas of 3A quarks which together are a single color-singular baryon with baryon number A.

If macroscopic it must be electrically neutral.
With u and d quarks the Fermi energy is $\sim$ 300 MeV
Replacing a u or d with a different quark would lower the energy if the mass were less than 300 MeV (assuming the u and d masses are tiny).

Early on it was suggested that the most stable form of matter might be quark matter with equal numbers of u, d, and s.
Energetically, one chunk of such matter could grow indefinitely by absorbing nucleons.

Problems

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, 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 $\mu_d - \mu_u – m_e = 50$ MeV.”

Not really a problem

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 $B_{1/4} < 150$ MeV, which would give a very small transition temperature to a QGP, $T_c \sim 100$ MeV.

Experiments indicate $T_c > 160$ MeV.

Short lived stranglets

Objects thought to be strangelets are seen in cosmic rays.

Cannot be formed from hot quark-gluon plasma.

Nucleons (P, N, Λ_o) from hot QGP do not stick together to form nuclei.

[J. Ellis *et al* J. Phys. G **35** (2008) 115004]

These strangelets need not be stable. Need only long enough lifetime for identification.

STAR made an extensive search for such strangelets from QGP and found none.

Even less likely at LHC.

Lower energies would be better. The Compresses Baryonic Matter (CMB) experiment at FAIR, GSI Darmstadt should look for strangelets.

Recent developments, CFL phase

Recent CFL (color-flavor locked phase) calculations 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.

Do we need to rethink the issue of a strangelet catastrophy?

The CFL phase

Because of asymptotic freedom:
At sufficiently **high densities** and **low temperatures**
matter can be a Fermi sea of essentially free quarks.

Behavior is dominated by quarks near Fermi surface.
With an attractive force between them they can form a pairs of a bosonic nature thereby reducing the free energy.
Many such pairs will form a bosonic condensate.

This is a standard recipe for BCS type of superconductivity.

With color, flavor and spin, many pairing patterns are possible.
Many varieties of “Cooper pairs” and “color superconductivity”

Where can one find high pressures and adequate cooling times?

In neutron stars.

Pressure near center is huge with millions of years for cooling.

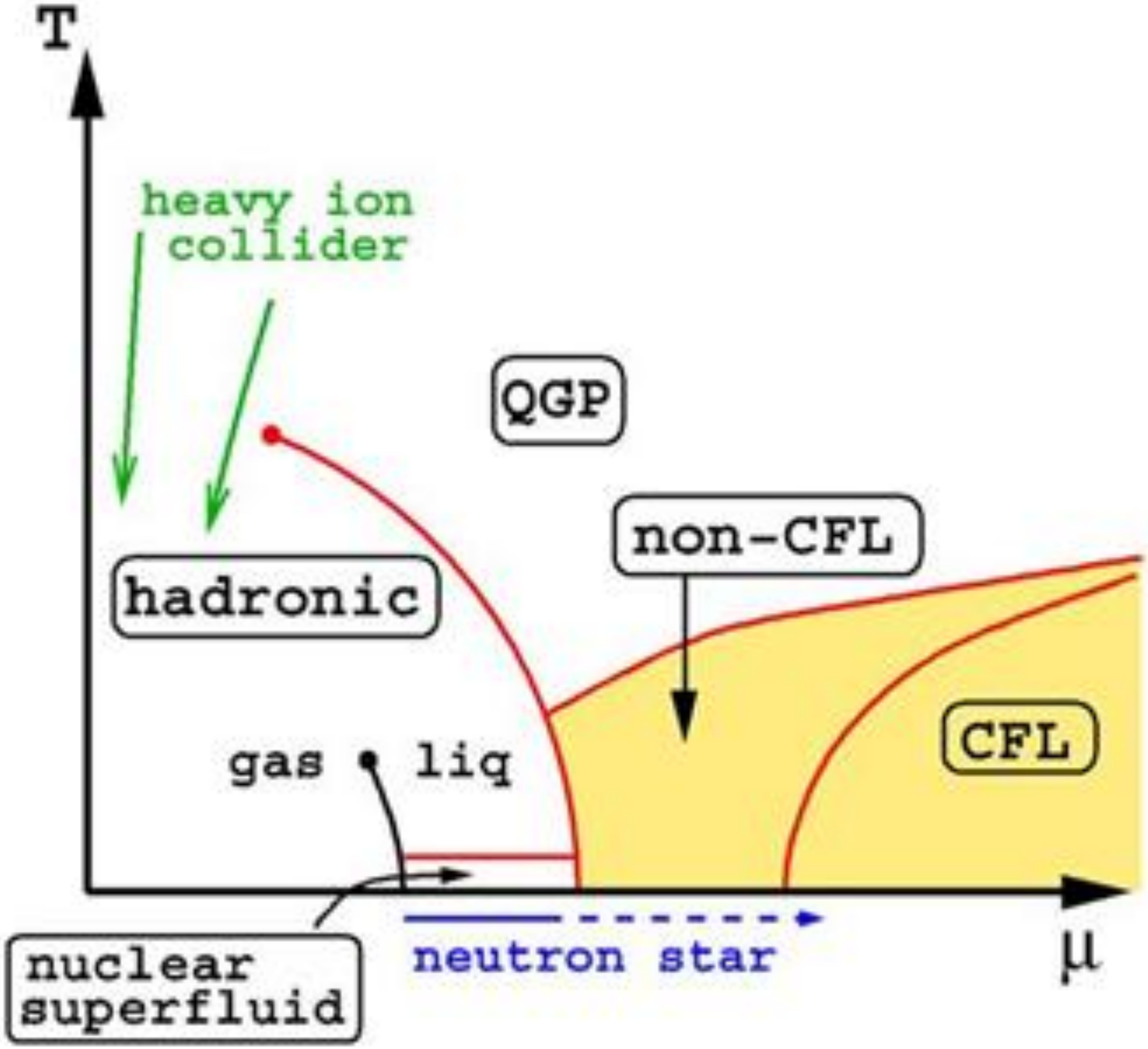
But pressure may not be sufficient even in neutron stars.

Experiments inside of neutron stars

PSR J1614-2230, is a pulsar emitting a radio signal every 3.15 ms.
It is a neutron star rotating at 317 Hz.
Demorest, P.B.; Pennucci, T.; Ransom, S.M.; Roberts, M.S. & Hessels, J.W.T.
A Two-Solar-Mass Neutron Star Measured Using Shapiro Delay
Nature: **467** (7319): 1081 (28 October 2010) [Previous limit ~1.6 $M_\odot$]

A 2.0 $M_\odot$ star composed of ordinary neutrons has a radius is only slightly larger than the Schwarzschild radius. If the density in increased, by having a quark matter core, the 2.0 $M_\odot$ star becomes a black hole and the 3.15 ms radio signals could not get out to be observed.

This suggests that cold quark matter may not be the lowest energy state of matter or that the pressure required is more than is found even in a neutron star.


T
heavy ion
collider
QGP
hadronic
non-CFL
CFL
gas
liq
nuclear
superfluid
neutron star
μ

Any experimental result can be explained by some theorist

There are many models of strange quark matter.
One paper said any neutron star with > 1.8 $M_\odot$ would rule out stable strange quark matter.

Some models predict an EOS at least as stiff as for neutron matter in which case mass-radius measurements alone can not rule out the possibility of quark matter in a neutron star.

Strangelets vs hypernuclei

At this meeting a year ago I defined a strangelet as any nuclear object with a number of strange quarks. It is better to limit the term strangelet to deconfined quarks in a single bag and use the term hypernucleus if the quarks are present in groups of three as nucleons.

Some of the unusual cosmic-ray objects may be hypernuclei from spectator matter infiltrated with negative kaons from the fireball.

Hypernuclei are well bound by strong and EM interactions but are subject to weak decay.

Lifetime of a hypernucleus

Consider a hypernucleus with one Λ_o
The lifetime of a free Λ_o is **263 ps**
Moving at the velocity of a spectator at the LHC the mean travel distance would be 84 m (the ZDC is at 140 m).
Is the lifetime of a Λ_o in a nucleus longer or shorter?
The answer is shorter, but why is it not longer?

$\Lambda_{o\ (\mathrm{free})} \rightarrow p + \pi^- + 37.8$ MeV (64.8 %) (momentum ~ 70 MeV/c)
$\rightarrow n + \pi^0 + 41.1$ MeV (35.8 %)

The reaction is suppressed by the Pauli principle.
The nuclear Fermi momentum is ~ 270 MeV/c.

Lifetime of a hypernucleus (2)

In a nucleus other modes become possible.

Λ_o n → nn

A virtual meson (both π^0 and heavier mesons) is transferred.

Here the energy of the reaction is the Λ_o n mass difference, 176 MeV

The emitted neutrons have momenta of ~ 420 MeV/c, well above the Fermi momentum of ~ 270 MeV/c.

Λ_o p → np also occurs.

Another mode is Λ_o NN → nNN (~340 MeV/c for each of the three)

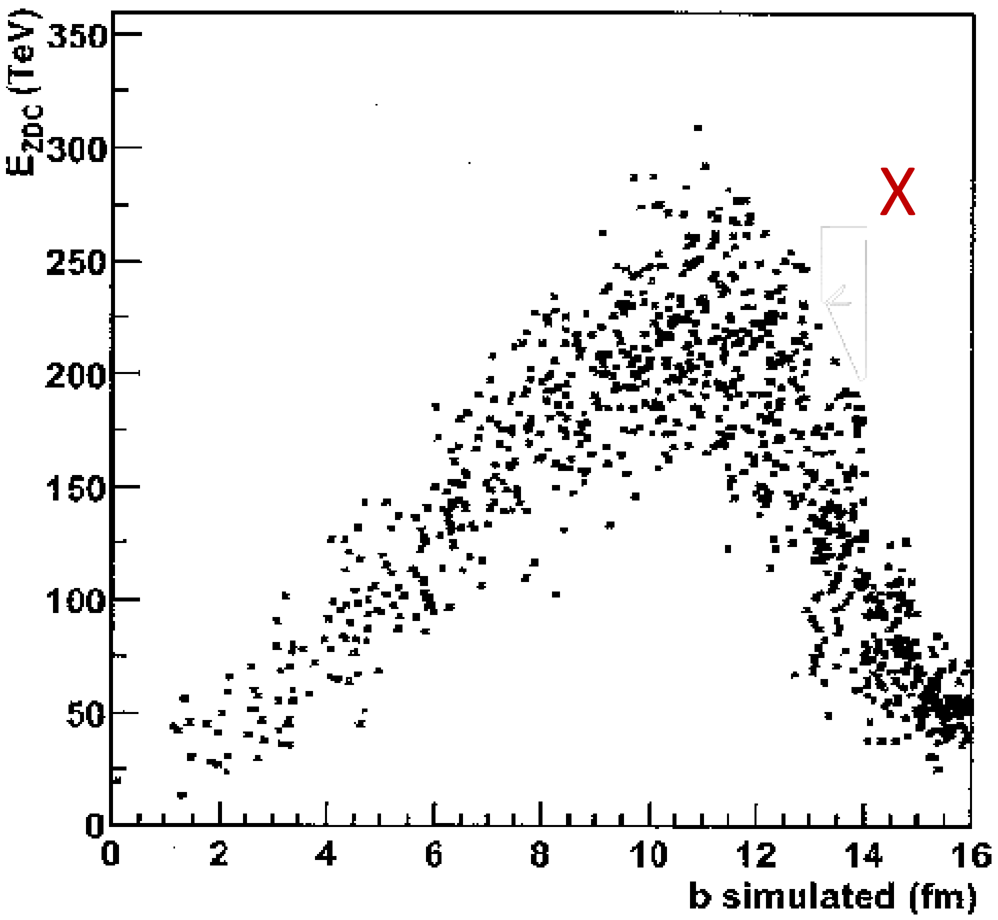
The measured lifetime is only~ **200 ps**, shorter than 263 ps .

Moving at the velocity of a spectator at the LHC the mean travel distance for each Λ_o would now be only 64 m. (The hypernucleus loses half of its strange quarks in 44 m and each strange quark takes out two nucleons.)

Nucl. Phys. News. Int. **20** (2010 Issue 4) 13

Cosmic ray stranglets

- Cannot be formed from hot quark-gluon plasma.
- Suggest formed by Ks, etc. from QGP getting into the spectators.
- For Fe on N there is always much spectator matter.
- Would like to make them with Pb-Pb and see them in the Zero Degree Calorimeter (ZDC).
- To get into ZDC would need $Z/A < 0.2$, compared with the beam with $Z/A = 82/208 = 0.4$


E_{ZDC} (TeV)
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
b simulated (fm)
X

Spectators from Pb-Pb

Methods for gently heating nuclear matter

Gentle heating that leave the hot, disintegrating nucleus almost at rest

- Slow antiproton (a limited energy range)
- Relativistic light ions

With small overlap of Pb ions, large spectators are heated on one side.

With larger overlap, spectators are smaller and completely disintegrated into protons and neutrons with almost no added tranverse momentum.

Study breakup of spectators by looking at multiply charged particles close to the beam direction.

Spectators from Pb-Pb
What is known?

Detailed predictions in ALICE ZDC TDR.

The key parameter is Z_{bound}

Z_{bound} is the sum of the atomic numbers of all projectile fragments with $Z > 1$

Parameters such as:

Mean number of intermediate mass fragments

Charge distributions of the produced fragments

are unique functions of Z_{bound} over a **“wide” energy range!** projectile energies form **0.1 to 160 A GeV (on stationary targets)**.

At the LHC the equivalent energy is 16400 A TeV

An energy larger by a factor of 10^5.

Conclusions

- You need not lose sleep about the danger from strangelets
- Still need good explanation for strange cosmic ray events.
- Need data about spectators from high energy collisions.