Overview

The Strongly Interacting Quark Gluon Plasma and Future Physics

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May 15, 2004 (RBRC / BNL)

QED

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Coulomb Interaction + Schroedinger Eq.

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- atomic and molecular physics
- condensed matter physics (superfluidity, superconductivity, quantum Hall effect, ..)
- chemistry
- biology

Superconductivity and Superfluidity

1911 Kamerlingh Onnes : Superconductivity

1924 " " & Boks : λ transition of He

1924 Bose - Einstein transition

1938 Two Fluid Model of liquid He (F. London)

1957 BCS Theory

late 1980's High T_c Superconductivity

- Knowing the Eq'n ≠ Knowing the Solutions

QCD

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quarks, gluons and the strongly interacting QGP

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- QGP Physics and Dark Energy
- " " at LHC and beyond

QGP Physics and Dark Energy

TDL astro-ph/040-4601

Λ = cosmological constant :

its energy density is "negative," with

$$|\rho_\Lambda| \sim 3 - 7 \times 10^{-6} \ \text{Gev}/\text{cm}^3$$

vs

the critical density ρ_c,

$$\rho_c \sim 1 \times 10^{-5} \ \text{Gev}/\text{cm}^3$$

Questions : 1. origin of ρ_Λ

2. Why should ρ_Λ & ρ_c be the same order of magnitude ?

THE MEANING OF RELATIVITY

Third edition, revised, including
THE GENERALIZED THEORY OF GRAVITATION

By ALBERT EINSTEIN

INSTITUTE FOR ADVANCED STUDY

PRINCETON UNIVERSITY PRESS · 1950
PRINCETON NEW JERSEY

from First Edition

...eton U. Press (1922), based on 4 Lectures

... in May 1921.

follows. Matter consists of electrically charged particles. On the basis of Maxwell's theory these cannot be conceived of as electromagnetic fields free from singularities. In order to be consistent with the facts, it is necessary to introduce energy terms, not contained in Maxwell's theory, so that the single electric particles may hold together in spite of the mutual repulsions between their elements, charged with electricity of one sign. For the sake of consistency with this fact, Poincaré has assumed a pressure to exist inside these particles which balances the electrostatic repulsion. It cannot, however, be asserted that this pressure vanishes outside the particles. We shall be consistent with this circumstance if, in our phenomenological presentation, we add a pressure term. This must not, however, be confused with a hydrodynamical pressure, as it serves only for the energetic presentation of the dynamical relations inside matter. In this sense we put

$$T_{\mu\nu} = g_{\mu\alpha} g_{\nu\beta} \sigma \frac{dx_\alpha}{ds} \frac{dx_\beta}{ds} - g_{\mu\nu} p. \tag{122}$$

In our special case we have, therefore, to put

$$T_{\mu\nu} = \gamma_{\mu\nu} p \text{ (for } \mu \text{ and } \nu \text{ from 1 to 3)}$$
$$T_{44} = \sigma - p$$
$$T = -\gamma^{\mu\nu}\gamma_{\mu\nu} p + \sigma - p = \sigma - 4p.$$

Observing that the field equation (96) may be written in the form

$$R_{\mu\nu} = -\kappa(T_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} T)$$

we get from (96) the equations,

$$+\frac{2}{a^2}\gamma_{\mu\nu} = \kappa\left(\frac{\sigma}{2} - p\right)\gamma_{\mu\nu}$$
$$0 = -\kappa\left(\frac{\sigma}{2} + p\right).$$

motion of the stars. One can arrange it so that the mean velocity of matter relative to this system shall vanish in all directions. There remain the (almost random) motions of the individual stars, similar to the motions of the molecules of a gas. It is essential that the velocities of the stars are known by experience to be very small as compared to the velocity of light. It is therefore feasible for the moment to neglect this relative motion completely, and to consider the stars replaced by material dust without (random) motion of the particles against each other.

The above conditions are by no means sufficient to make the problem a definite one. The simplest and most radical specialization would be the condition: The (naturally measured) density, ρ of matter is the same everywhere in (four-dimensional) space, the metric is, for a suitable choice of coordinates, independent of x_4 and homogeneous and isotropic with respect to x_1, x_2, x_3.

It is this case which I at first considered the most natural idealized description of physical space in the large; it is treated on pages 103–108 of this book. The objection to this solution is that one has to introduce a negative pressure, for which there exists no physical justification. In order to make that solution possible I originally introduced a new member into the equation instead of the above mentioned pressure, which is permissible from the point of view of relativity. The equations of gravitation thus enlarged were:

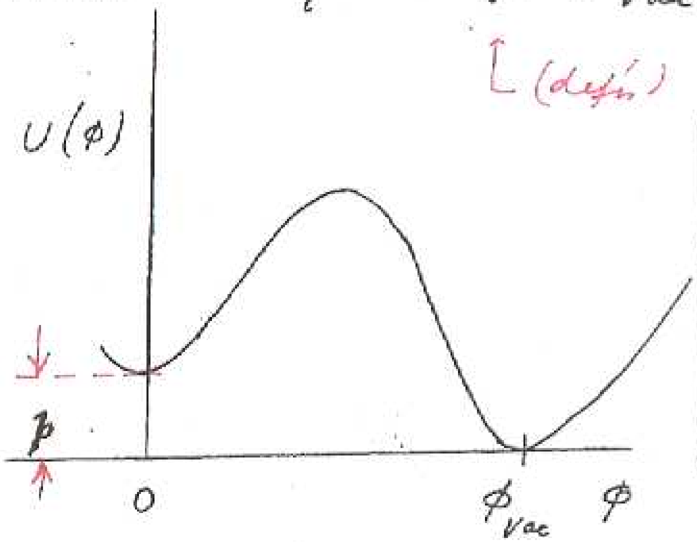
$$(R_{ik} - \tfrac{1}{2} g_{ik} R) + \Lambda g_{ik} + \kappa T_{ik} = 0 \tag{1}$$

where Λ is a universal constant ("cosmologic constant"). The introduction of this second member constitutes a complication of the theory, which seriously reduces its logical simplicity. Its introduction can only be justified

Any spin 0 field, fundamental or composite (σ-model, Higgs, QGP-component;) is coupled to vacuum; therefore it is always connected to the <u>inertia</u> of <u>any particle i</u>

T.D.L. & G. Wick, Phys. Rev. D9, 2291 (1974)

Write $m_i \equiv g_i \phi_{vac}$ (defn), $\phi = \phi(x)$ spin 0 field, g_i = coupling to i



<u>transformation</u>:

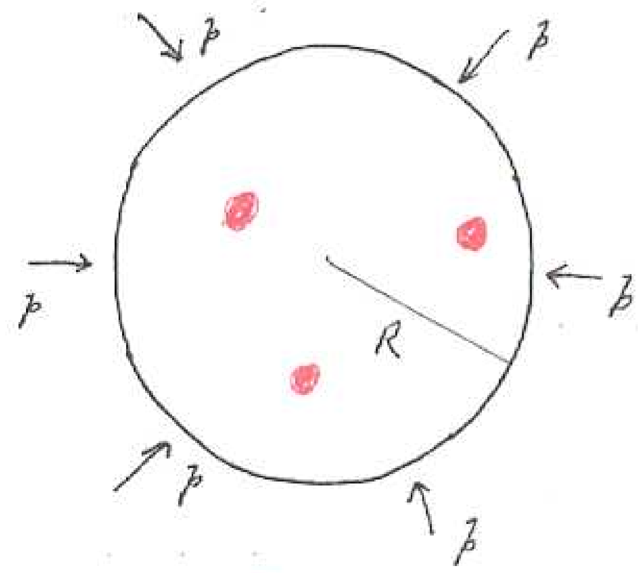
$\phi(x)$ from $\phi_{vac} \to 0$,

mass of i at x: $m_i \to 0$.

MIT / Dirac bag

model of a

"negative pressure"



$N_Q = 3$

$$E - \frac{4\pi}{3} R^3 p = N_Q \frac{2.0428}{R}$$

$$\therefore \quad 4\pi R^2 p = \frac{1}{R} \quad ''$$

$$\rho_E \equiv \frac{E}{4\pi R^3/3} = 4p$$

$$\rho_Q \equiv N_Q \frac{2.0428}{4\pi R^4/3} = 3p$$

Dirac Proc. R. Soc. A268, 57 (1962)

Chodos et al Phys Rev D9, 3471 (1974)

Date: Tue, 23 Mar 2004 13:47:40 -0400 (EDT)
From: charles.baltay@yale.edu
Subject: Message to TD
To: rae@bnl.gov
X-yahMAIL: YAHMAIL AXP-1.6.4 (MIME) (PMDF) (CGILIB AXP-1.6.5/OBJ)
X-BNL-MailScanner-Information: Please contact the ISP for more information
X-BNL-MailScanner: Found to be clean
X-MailScanner-From: charles.baltay@yale.edu

Dear Rae

Would you please pass on this message to TD Lee for me.For Omega Lambda=0.7 and the Hubble constant=65 km/sec/Mparsec,the currently preferred values,the energy density associated with the Cosmological Constant is

ρ_Λ = rho(lambda)=3 E-6 Gev per cubic cm = $3 \cdot 10^{-6}$ Gev/cm^3

I would be happy to talk to him in more detail if that were useful.

with Best Regards

Charlie

Assume our Universe to be a large bag

$$\mathcal{E} - \frac{4\pi}{3} R^3 \rho_\Lambda \cong \frac{\text{const}}{R} \quad \left(\equiv \frac{4\pi}{3} R^3 \rho_M \right)$$

$\frac{\partial \mathcal{E}}{\partial R} = 0$ gives

$$\rho_M \cong 3 \rho_\Lambda \cong 9 \times 10^{-6} \text{ Gev/cm}^3$$

$$\rho_{\mathcal{E}} = \mathcal{E} / \tfrac{4\pi}{3} R^3 \cong 4 \rho_\Lambda \cong 1.2 \times 10^{-5} \frac{\text{Gev}}{\text{cm}^3}$$

Both are same order as

critical density $= \rho_c \cong 1 \times 10^{-5}$ Gev/cm^3

2. ASTROPHYSICAL CONSTANTS

Table 2.1. Revised 2001 by D.E. Groom (LBNL). The figures in parentheses after some values give the one-standard deviation uncertainties the last digit(s). Physical constants are from Ref. 1. While every effort has been made to obtain the most accurate current values of the list quantities, the table does not represent a critical review or adjustment of the constants, and is not intended as a primary reference.

Quantity	Symbol, equation	Value	Reference, footnote
speed of light	c	$299\,792\,458$ m s^{-1}	defined[2]
Newtonian gravitational constant	G_N	$6.673(10) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	[3]
astronomical unit (mean ⊕–⊙ distance)	au	$149\,597\,870\,660(20)$ m	[4, 5]
tropical year (equinox to equinox) (2001.0)	yr	$31\,556\,925.2$ s	[4]
sidereal year (fixed star to fixed star) (2001.0)		$31\,558\,149.8$ s	[4]
mean sidereal day (2001.0)		$23^h\,56^m\,04\overset{s}{.}090\,53$	[4]
Jansky	Jy	10^{-26} W m^{-2} Hz^{-1}	
Planck mass	$\sqrt{\hbar c/G_N}$	$1.2210(9) \times 10^{19}$ GeV$/c^2$ $= 2.1767(16) \times 10^{-8}$ kg	[1]
parsec (1 AU/1 arc sec)	pc	$3.085\,677\,580\,7(4) \times 10^{16}$ m $= 3.262\ldots$ ly	[6]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,1\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,08$ km	[7]
solar mass	$M_\odot$	$1.988\,9(30) \times 10^{30}$ kg	[8]
solar equatorial radius	$R_\odot$	6.961×10^8 m	[4]
solar luminosity	$L_\odot$	$(3.846 \pm 0.008) \times 10^{26}$ W	[9]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	$8.870\,056\,22$ mm	[10]
Earth mass	$M_\oplus$	$5.974(9) \times 10^{24}$ kg	[11]
Earth mean equatorial radius	$R_\oplus$	$6.378\,140 \times 10^6$ m	[4]
luminosity conversion	L	$3.02 \times 10^{28} \times 10^{-0.4\,M_{bol}}$ W (M_{bol} = absolute bolometric magnitude = bolometric magnitude at 10 pc)	[12]
flux conversion	$\mathcal{F}$	$2.52 \times 10^{-8} \times 10^{-0.4\,m_{bol}}$ W m^{-2} (m_{bol} = apparent bolometric magnitude)	from above
$v_\odot$ around center of Galaxy	$\Theta_\circ$	$220(20)$ km s^{-1}	[13]
solar distance from galactic center	$R_\circ$	$8.0(5)$ kpc	[14]
Hubble expansion rate†	H_0	$100\,h$ km s^{-1} Mpc^{-1} $= h \times (9.778\,13$ Gyr$)^{-1}$	[15]
normalized Hubble expansion rate†	h	$(0.71 \pm 0.07) \times {}^{1.15}_{0.95}$	[16, 17]
critical density of the universe†	$\rho_c = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\,h^2\,M_\odot$Mpc^{-3} $= 1.879(3) \times 10^{-29}\,h^2$ g cm^{-3} $= 1.053\,9(16) \times 10^{-5}\,h^2$ GeV cm^{-3}	
local disk density	ρ_{disk}	$3–12 \times 10^{-24}$ g cm^{-3} $\approx$ 2–7 GeV$/c^2$ cm^{-3}	[18]
local halo density	ρ_{halo}	$2–13 \times 10^{-25}$ g cm^{-3} $\approx$ 0.1–0.7 GeV$/c^2$cm^{-3}	[19]
pressureless matter density of the universe†	$\Omega_M \equiv \rho_M/\rho_c$	$0.15 \lesssim \Omega_M \lesssim 0.45$	[16, 20]
baryon density of the universe	$\Omega_B \equiv \rho_B/\rho_c$	$0.0095 \lesssim \Omega_B h^2 \lesssim 0.023$	[21]
scaled cosmological constant†	$\Omega_\Lambda = \Lambda c^2/3H_0^2$	$0.6 \lesssim \Omega_\Lambda \lesssim 0.8$	[16]
scale factor for cosmological constant†	$c^2/3H_0^2$	$2.853 \times 10^{51}\,h^{-2}$ m^2	
$\Omega_M + \Omega_\Lambda + \ldots$ [22]	Ω_{tot} [22]	see footnote [23]	
age of the universe†	t_0	12–18 Gyr	[16]
cosmic background radiation (CBR) temperature†	T_0	2.725 ± 0.001 K	[24, 25]
solar velocity with respect to CBR		371 ± 0.5 km s^{-1} towards $(\alpha, \delta) = (11.20^h \pm 0.01^h, -7.22^\circ \pm 0.08^\circ)$ or $(\ell, b) = (264.31^\circ \pm 0.17^\circ, 48.05^\circ \pm 0.10^\circ)$	[25]
Local group velocity with respect to CBR	v_{LG}	627 ± 22 km s^{-1} towards $(\ell, b) = (276^\circ \pm 3^\circ, 30^\circ \pm 3^\circ)$	[25]
energy density of CBR	ρ_γ	$4.641\,7 \times 10^{-34}\,(T/2.725)^4$ g cm^{-3} $= 0.260\,38\,(T/2.725)^4$ eV cm^{-3}	[12, 25]
energy density of relativistic particles (CBR + ν)	ρ_{rel}	$7.804\,2 \times 10^{-34}\,(T/2.725)^4$ g cm^{-3} $= 0.437\,78\,(T/2.725)^4$ eV cm^{-3}	[12, 25]
	$\Omega_{rel} = \rho_{rel}/\rho_c$	$4.153\,4 \times 10^{-5} h^{-2} (T/2.725)^4$	
number density of baryons	n_B	$2.6 \times 10^{-10} < n_B/n_\gamma < 6.2 \times 10^{-10}$	[21]
entropy density/Boltzmann constant	s/k	$2\,889.2\,(T/2.725)^3$ cm^{-3}	[12]

† Subscript 0 indicates present-day values.

Crude Approximation

1. no non-Euclidean geometry
2. no short wave length matter energy
3. no expansion

Yet, order of magnitude agreement.

So the nucleon is a tiny bag
" nucleus is a little bag
our universe is a larger bag!

Implications

1. Through RHIC expt. p and $\partial p/\partial \rho$ of the Quark - Gluon - Plasma can be measured.

2. In the bag model, p is exerted by the space outside. Likewise, Λ may also be due to the space outside the radius of our Universe.

3. Λ, like p, is not a constant, but space-time dependent. Its variation can also be measured.

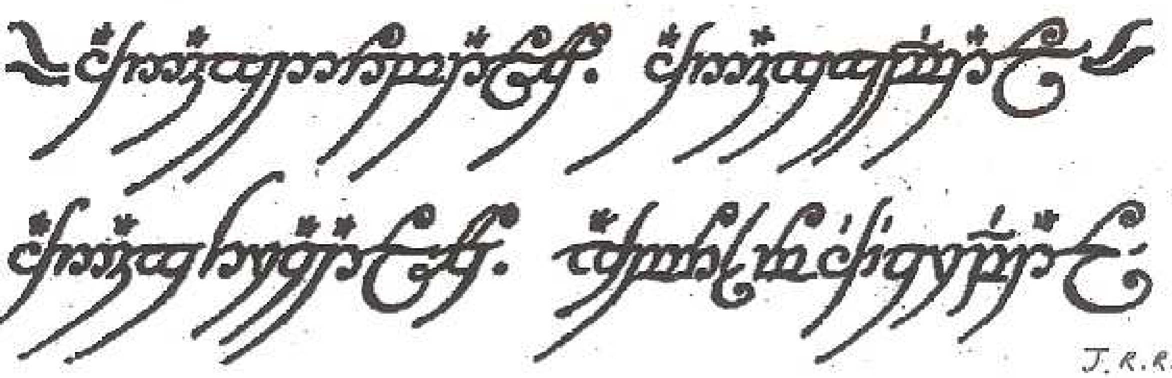
QGP Physics at LHC and beyond

- QGP is contained within each nucleon
  and " " nucleus
- QGP will be produced at LHC
  abundantly, and will dominate LHC physics
  ∵ its strong interaction.
- At small distance r, $g(r)$ is weak
  but QCD is non linear; one expects
  soliton solutions with amplitude $\sim \frac{1}{g(r)}$
  to exist.
- These soliton-like QGP excitations
  can be high energy, depending on r,
  and may be described approximately
  by a phenomenological super-symmetrical
  field, with sym. violations.
- Need early RHIC II to supplement LHC

Also, e-RHIC to differentiate QED vs QCD

Eight Gluons for the Universe,
To set her gauge.
Six Quarks for Humankind,
Searching for the truth.
One Plasma with superstrength,
One Plasma to bind them.
Through Dark Energy,
One Plasma to quench them.
And from the Big Bang,
One Plasma to shape them all.

TOL



J.R.R. Tolkien