#### SONOLUMINESCENCE IN NEUTRON STARS

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#### Abstract

After a brief discussion of a possible relationship between the electroweak phase transition in highly compressed matter and gravitational collapse, we examine the speculative possibility that the electroweak phase transition might be contemporarily occurring in processes in neutron stars. We conjecture that adiabatic compression of neutron star matter due to focusing of the energy from a supernova bounce into a very small volume could result in extreme densities, and Fermi levels or temperature above  $\mathcal{O}$  (100 GeV). We propose a qualitative scenario for sonoluminescence in neutron stars and discuss possible observable consequences.

#### 1 Introduction

In the past few decades, a description of all fundamental processes, except gravity, has emerged and is referred to as the Standard Model of particle physics[1]. According to be the Model, baryon number and lepton number non-conservation occur, but are extremely strongly suppressed except in processes which take place at very high temperature or under conditions of very high density. The suppression is so strong that for practical purposes baryon and lepton number may be regarded as conserved. The theory engenders a phase transition, the electro-weak phase transition, which takes place when the characteristic temperature exceeds the Higgs vacuum expectation value

$$v \sim [\sqrt{2}G_F]^{-\frac{1}{2}} \sim 250 \text{ GeV}$$

where  $G_F$  is the Fermi constant. For temperatures in this range and above, baryon and lepton number non-conservation become important. At still higher temperature, above the sphaleron energy, which is,

$$E = \frac{2M_W}{\alpha_W} B(\lambda/g^2) \sim 8 - 15 \ TeV,$$

(where  $M_W$  is the W boson mass, and the function B depends upon the Higgs mass via the Higgs self coupling  $\lambda$  and g the gauge coupling constant, and  $\alpha_W = g^2/4\pi$ ), the Model predicts that baryon and lepton number violation is completely unsuppressed[2].

These processes, which violate conservation laws normally observed to hold very precisely in the laboratory, are experimentally inaccessible because they are expected to occur only at temperature[3] or fermion densities[4] inaccessible at laboratory scales. Nor are these processes thought to be available for study in any contemporary astrophysical situations. Within the standard Big Bang model, the electroweak phase transition from the state where electroweak symmetry is exact and the weak bosons are massless to the spontaneously broken ground state that we see today occurred early, when the universe was extremely hot and dense. Here, we address whether such extremes of temperature and/or densities can lead to this phase transition in contemporary processes.

In the next section we examine the relationship between the electroweak phase transition[4] in highly compressed matter and the formation of black holes during gravitational collapse. We shall show that the densities and temperatures achieved in gravitational collapse of stellar size masses do not approach those needed for the electroweak phase transition.

In view of the potential importance of finding an experimental system in which the electroweak phase transition might be observed today, we examine a speculative possibility. Sonoluminescence[5] in water is an acoustical process which focuses mechanical energy from macroscopic dimensions down to nearly atomic dimensions. (The most likely mechanism is cavitation followed by forced collapse of the bubble. The speed of the collapsing bubble wall exceeds the speed of sound in the water vapor within the bubble and a shock wave is formed, which focuses a great deal of energy at a point. In a subsequent section of this paper we suggest an alternative scenario applicable to sonoluminescence in neutron stars.) If sonoluminescence should somehow occur in a neutron star as a result, say, of a star quake or supernova core bounce, we could have focusing of energy over a stellar volume, down, perhaps, to nearly nuclear dimensions; a volume scale factor of the order of  $10^{30}$  over the laboratory scale sonoluminescence, (as well as a large scale up in energy). We calculate the minimum energy needed to overcome lepton cooling and to compress matter to the electroweak scale. We find that energy required is small compared to that available in a star quake. We shall also note that sonoluminescence does not seem to have the potential to form black holes in neutron stars.

The electroweak phase transition can be reached by way of high temperature or high fermion density (which is to say, high Fermi level) but the characteristic energy of the transition and the rate of baryon and lepton violation can only be determined by means of detailed modeling. Several authors[6] report that the characteristic energy, either temperature or Fermi level, is in the range 100 to 200 GeV. Based upon those results, we shall assume that baryon number and lepton number violation is important above 100 GeV.

# 2 Electroweak Transition in Gravitational Collapse

Gravitational collapse often proceeds through a low temperature compression of material bodies of stellar mass scale, as when mass is accreted on a neutron star. In this case, the conditions for the electroweak transition will not be reached for several reasons.

If we set the Fermi level of a degenerate fermion core (T = 0) equal to  $E_c$ , we obtain a fermion density which is typical of that at the phase transition. If  $E_c = 100 \text{ GeV}$ ,  $(\frac{n}{V})_c = 4 \times 10^6 / \text{fm}^3$ ,  $\rho_c = 5 \times 10^{23} \text{ gm/cm}^3$ . If we draw this density as a line on a curve which portrays density vs radius for astronomical objects[7], we find that the electroweak density line intersects the black hole line where the radius of the object equals its Schwarzschild radius, when

$$\frac{E_c^4}{(3\pi^2)} = \frac{1}{2\pi G R^2} \tag{1}$$

This corresponds to a mass of  $M_c \sim 3 \times 10^{26} \text{kg} \sim 10^{-4} M_{sun}$  and a radius of  $R_c \sim 50$  cm. An object with such a low mass has few natural processes via which to achieve such high densities.

Moreover, the critical density cannot be reached in isothermal compression since compression leads to copious W boson production at a threshold equal to the W mass, which prevents the Fermi level from reaching electroweak scale because of lepton cooling; energy expended in further compression is radiated away into the body of the neutron star by the leptons deriving from the boson decay.

## 3 Sonoluminescence in Neutron Stars

Since sonoluminescence in water only partly understood[5] at this time, we cannot build a convincing model of the same phenomenon in a neutron star. However, while the occurrence of a phenomenon analogous to sonoluminescence in a neutron star is strictly speculative, such a phenomenon may be *the only (contemporary) process* which yields any chance of achieving electroweak phase transitions. In the next section, we propose a qualitative scenario to argue that it may be possible to achieve sonoluminescence in a neutron star under some circumstances.

In neutron stars, interparticle energies are negligible compared to the thermodynamic energy of the Fermi gas as well as compared to the gravitational energy. Waves can therefore propagate without loss until the energy is very high. Possible driving forces might be infalling matter, star quakes[7] (which have equatorial symmetry and release on the order of  $10^{42}$  ergs), and, most importantly, residual energy from supernova explosions[8] (the approximately spherically symmetric 'bounce' energy following the collapse with an release of the order  $10^{52}$  ergs). We conjecture that the focusing of this energy into a very small volume at the center of a neutron star may result in compression heating of the material.

We have already noted that isothermal, T = 0, compression cannot achieve the critical density. We shall next argue that adiabatic compression can, in principle achieve temperatures as high as  $E_c$ . If the temperature of the fermions exceeds 100 GeV, W bosons are formed producing prompt leptons. The absorption length of leptons of energy ~ 100 GeV is approximately

$$\Lambda_W \simeq \frac{1}{(\frac{n}{V})_W \sigma(100 \ GeV)} \simeq 10^{-9} m$$

where  $(\frac{n}{V})_W \simeq 5.10^6/fm^3$  is the density of relativistic fermions at temperature  $\geq 100$  GeV. Assuming a spherical volume being compressed, the radius must be very large compared to  $\Lambda_W$  in order that the lepton cooling be suppressed. That is

$$R_W \gg \Lambda_W. \tag{2}$$

The condition 2 implies that a minimum acoustical energy input, E, is needed to achieve adiabatic compression beyond the W threshold;  $E \gg E_W$ , where  $E_W$  is the order of magnitude energy of a sphere of quarks at the W threshold (with  $N_W$ = the number of fermions in the sphere ).

$$E_W \simeq \frac{4\pi}{3} (\frac{n}{V}) \Lambda_W^3 (100 \ GeV) \sim 10^{24} erg.$$

Beyond the W phase transition there are several species of particles present. We assume thermodynamic equilibrium and equal populations of all quarks and leptons produced below 100 GeV, implying that  $N_s \sim 28$  (We count all leptons and quarks with lifetimes long compared to  $10^{-10}$  seconds.) The density of each species will be the same as given above. The absorption length

$$\Lambda_c = \frac{1}{N_s(\frac{n}{V})_c \sigma(\frac{1}{2}E_c)}$$

will be smaller than  $\Lambda_W$ , both because the cross section is rising with energy and because the number density is higher. Therefore, lepton cooling decreases with increasing compression beyond the W threshold. We thus conclude that via adiabatic compression, temperatures as high as ~ 100 GeV may possibly be achieved; the minimum energy required should substantially exceed  $E_{\min}$ given by,

$$E_{\rm min} \simeq 10^{23} - 10^{25} erg, \tag{3}$$

which is very small compared to the star quake[6] and supernova[8] energies mentioned above. We conclude from these dimensional arguments that the adiabatic conditions can be met.

Since the ratio of energy released by changing the initial population of neutrons into leptons to the electroweak ignition energy is small,  $m_n/E_c \simeq$ 1/100, sustained burning is not possible. Therefore, once the threshold for the electroweak phase transition has been exceeded, the sphere contains mainly high energy leptons which escape into the body of the star in a time of the order of  $R_W/c$ . The neutrinos diffuse out of the star when they have degraded in energy such that  $\Lambda \sim R_{star} = 10 km$ . Setting

$$\Lambda \approx 10 km = \frac{1}{\left(\frac{n}{V}\right)_{ns} \sigma}$$

where  $(\frac{n}{V})_{ns} \simeq 6 \times 10^{37}/cm^3$  is the number density in a typical neutron star and  $\sigma \sim 9 \times 10^{-42} \ cm^2 \left(\frac{E}{10 \ MeV}\right)^2$  is the low energy neutrino - nucleon cross section,  $E_{esc}$  is found to be of the order of 1 MeV. We note that the energy radiated from the star as neutrinos will be large compared to  $E_{\min}$  in eq.(3) but, of course, smaller than the driving energy.<sup>1</sup>

Finally, we ask whether the compression due to sonoluminescence could result in the formation of a blackhole. The order of magnitude of the energy required to achieve the electroweak threshold and the black hole threshold is ~  $M_c \cdot A_0 \cdot (100 GeV) \sim 10^{52} erg$  ( $A_0$  is Avogadro's number). Consistent with the lepton cooling arguments, above, we could scale the radius down by no more than about  $10^{-5}$ , but to achieve the black hole condition the density would scale up by  $10^{10}$ , and black hole formation would still require of the order of  $10^{47} erg$ . Therefore, we conclude that black hole production by sonoluminescence is unlikely.

#### 4 A Scenario for Sonoluminescence

In the previous sections we treated sonoluminescence in a neutron star as a speculation. In this section, we introduce a scenario which serves to make our speculation somewhat plausible. We suppose that the energy of the bounce

<sup>&</sup>lt;sup>1</sup> Poplitz[9] has shown that magnetic fields of the order of 10<sup>33</sup>Gauss are required for the electroweak transition. Therefore, typical neutron star magnetic fields will not affect our results.

from neutronizaton in a supernova explosion is deposited in an acoustic field in the neutron star (or proto-neutron star) and is propagating centrally inward carrying a kinetic energy of the order of[8]

$$E_{Bounce} = 10^{52} \ ergs$$

When the energy density of the acoustic field at some radius,  $R \ll R_{star}$ , exceeds the threshold for the production of a new species of particle, there is a brief period of time during which the energy is used to create new species of particles; during this interval, the medium becomes "soft", and the disturbance cannot propogate as rapidly. After this brief interval, the local Fermi levels of all fermion final states fill up to the threshold energy, the particle production process saturates, the speed of sound (at R) resumes its nominal value,  $c_s = c/\sqrt{3}$ , and the active region of particle production moves inward to a smaller radius. Thus, a spherical discontinuity forms and propagates inward, driven by the acoustic field impinging from the body of the star. The front edge of this discontinuity travels at a velocity lower than that of sound and can, therefore accumulate energy from the acoustic wave. The acoustic energy absorbed in a thin shell at R goes partly into production of particles and we propose, partly into increased energy of the discontinuity. Assuming that the acoustic wave is not *all* reflected back at the discontinuity, it is plausible that the inward focusing discontinuity continues to increase in energy density while encountering a series of higher and higher thresholds for particle production at smaller and smaller radii. The density increases due to compression of the initial material present in the star, plus the compression of newly formed Fermi seas.

The issue then is whether the acoustic wave can drive the discontinuity to the centre of the star, where by adiabatic compression, a temperature above 100 GeV, and the accompanying effects discussed previously might result. Since an acoustic wave would take  $\sim 10^{-5}s$  to traverse a star of radius  $\sim 1km$ , we believe that it is reasonable to suppose that the discontinuity gets driven to the center provided that the initial disturbance (perhaps the energy of the bounce from neutronization) that causes the energy to be deposited into the acoustic field lasts substantially longer. Here we remark that the typical time scale for the initial neutrinos produced dynamically in supernova collapse is  $\sim 10ms \gg 10^{-5}s$  mentioned above. Finally, we remark that the energy  $E_{Bounce}$  is truly enormous, so that even if the bulk of it is reflected at the discontinuity, the mechanism that we propose would be energetically possible. Of course, whether or not it will actually occur will depend on many detailed issues beyond the scope of the present analysis.

#### 5 Concluding Remarks

We have noted that on a black hole phase diagram, the line portraying the density of matter at the electro-weak transition intersects the black hole curve at a point, eq(1). The right hand side this equation depends only upon gravity while the left hand side depends only upon electroweak physics, so that this provides an intriguing connection between these areas of physics which have no common fundamental theoretical basis at the present time.

We have shown that in the normal course of gravitational collapse, the electroweak density will not be reached. However, we have suggested a mechanism, sonoluminescence in a neutron star, which might achieve the electroweak phase transition. While this mechanism is only a speculation on our part, it is of some interest since this may well be the only contemporary process where the electroweak phase transition would be of relevance. We have also presented a very simple hydrodynamic scenario to support the plausibility of our speculation of sonoluminescence. Should the sonoluminescence process occur during star quake or supernova, (with or without attainment of the electroweak threshold), the result is a pulse of low energy neutrinos (E  $\sim$ MeV) of all flavors which diffuse from the star. The neutrino flux from such a process at 10 kpc would not register any events with even the low-threshold solar neutrino detectors such as Borexino<sup>[10]</sup> under construction at Grand Sasso and Hellaz<sup>[11]</sup> in the design stage at present. If such an event occurs as close as 1 kiloparsec, then it may be possible to see 10 to 20 neutrino events of a time scale  $10^{-3}$  sec due to sonoluminescence in a detector such as Borexino. The events would stand out above backgrounds (due to solar neutrinos) and be distinguished from the neutronization burst events by being lower in energy (average energy being close to 1 MeV rather than 10 MeV for neutronization  $\nu's$ ) and being later in time. The secondary thermal neutrinos are expected to be emitted as usual; these were observed from SN1987A but due to the high thresholds of the detectors no conclusion can be drawn about possible low energy neutrinos from sonolominescence. Future low threshold  $(E_{th} < 1 \text{ MeV})$  high volume detectors would be able to study this question in detail. We have shown that the electro-weak phase transition can only occur if the energy of the sonoluminescence discontinuity is large compared

to  $10^{25} ergs$ , which is necessary to overcome cooling by prompt leptons when the energy per particle rises above the W boson production threshold. The additional energy released in the phase transition is expected to be less than about 1 GeV for each 100 GeV of sonoluminescence input energy. Expansion of the electroweak phase to consume a large part of the star is impossible; a spherical detonation wave cools faster by adiabatic expansion than it can heat up by burning nucleons at neutron star densities.

In summary, sonoluminescence in a neutron star appears possible and has interesting consequences, but the details depend upon many factors beyond the scope of our analysis.

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