RMP Colloquia

This section, offered as an experiment beginning in January 1992, contains short articles intended to describe recent research of interest to a broad audience of physicsts. It will concentrate on research at the frontiers of physics, especially on concepts able to link many different subfields of physics. Responsibility for its contents and readability rests with the Advisory Committee on Colloquia, U. Fano, chair, Robert Cahn, S. Freedman, P. Parker, C. J. Pethick, and D. L. Stein. Prospective authors are encouraged to communicate with Professor Fano or one of the members of this committee.

Cooling of neutron stars

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On the basis of current physical understanding, it is impossible to predict with confidence the interior constitution of neutron stars. Cooling of neutron stars provides a possible way of discriminating among possible states of matter within them. In the standard picture of cooling by neutrino emission developed over the past quarter of a century, neutron stars are expected to cool relatively slowly if their cores are made up of nucleons, and to cool faster if matter is in an exotic state, such as a pion condensate, a kaon condensate, or quark matter. This view has recently been called into question by the discovery of a number of other processes that could lead to copious neutrino emission and rapid cooling.

CONTENTS

I. NEUTRON STARS AND THE PROPERTIES OF DENSE MATTER

In the later stages of evolution, massive stars develop dense cores in which the gravitational forces become strong enough to overwhelm the pressure of the matter and thereby cause the core to collapse. Neutron stars, which have masses of about a solar mass and densities a few times that of matter in atomic nuclei, are one possible product of such collapses. They are observed as radio pulsars, whose emissions are powered by the rotational energy of the neutron star, and as accretion-powered x-ray sources, in which a neutron star accretes matter from a companion star.

Just before core collapse, the fraction of nucleons in the core that are protons is comparable to the value in the most neutron-rich terrestrial matter, about 0.4. (For ^{238}U, the proton fraction is $92/238 \approx 0.387$.) This value is significantly greater than one expects for matter in neutron stars. As collapse proceeds, protons are converted into neutrons by capture of electrons. However, this process does not proceed very far during the collapse itself, which lasts only a fraction of a second, because the stellar core very rapidly becomes opaque to neutrinos emitted in electron captures. Neutrinos are unable to escape from the core during the collapse, and their density builds up. By virtue of the Pauli principle, final neutrino states are blocked, further electron captures are inhibited, and the proton fraction only falls to about 0.3 during the collapse. Immediately following the collapse, neutrinos diffuse out of the core on a time scale of order seconds. This allows further electron captures to take place, and the proton fraction falls to the lower values characteristic of neutron stars, of order 0.1. At this stage, the temperature T of the newborn neutron star exceeds 10^{11} K, which corresponds to thermal energies $k_B T$ of some tens of MeV. Subsequently the neutron star cools, and in its early life the chief mechanism for energy loss is emission of neutrinos and antineutrinos. Later, when the temperature has fallen, neutrino processes become less effective, and emission of electromagnetic radiation from the surface of the neutron star takes over as the dominant process.

On the basis of theory, together with empirical input from laboratory studies, it is at present impossible to predict with confidence the interior constitution of neutron stars. The density of matter ranges up to 3 or more times the density of matter in nuclei, and our knowledge of the basic interactions at such densities is uncertain. Effects that are minor at nuclear densities can be major at such densities. One way in which it is hoped observationally to obtain information about neutron star interiors is by studying thermal radiation from their surfaces. Neutrino emission rates, and hence the temperature of the central part of a neutron star, depend on the properties of dense matter. The surface temperature of the star depends on the interior temperature, and therefore measurements of photons emitted from the surface hold out the promise of enabling one to distinguish among a number of possible states of dense matter.

The simplest neutrino-emitting processes one can envisage are beta decay of the neutron,

$$n \to p + e^- + \bar{\nu}_e \ , \tag{1}$$

and electron capture on protons,

$$p + e^- \to n + \nu_e \ . \tag{2}$$

If either of these processes were to proceed alone, reaction products would build up and choke off the reaction. When both processes take place, a steady state can be reached if the reactions proceed at the same rate, with neutrinos and antineutrinos being emitted in equal numbers. The successive neutron decays and electron captures lead to the emission of a neutrino and an antineutrino for every cycle completed, and thereby lead to energy loss from the star.

Pairs of reactions such as (1) and (2) were first considered by Gamow and Schoenberg (1941) as a mechanism for causing stellar collapse and supernova explosions. In their paper they state that for brevity they refer to such processes as urca processes. This is an example of one of George Gamow's many jokes in physics, since the name was in fact that of a casino in Rio de Janeiro, which was closed down by the Brazilian government in 1955. As Gamow (1970) recounted, "We called it the Urca Process, partially to commemorate the casino in which we first met, and partially because the Urca Process results in a rapid disappearance of thermal energy from the interior of a star, similar to the rapid disappearance of money from the pockets of the gamblers on [*sic*] the Casino da Urca." In case *Physical Review* asked for an explanation of the origin of the name, the authors had an alternative version of its derivation available—an abbreviation of "unrecordable cooling agent"—but they were never asked. This may, however, account for the word being spelled "URCA" in some places, presumably because it is thought to be an acronym. Returning to the subject of the present colloquium, we shall refer to reactions (1) and (2) collectively as the *direct* Urca process, to distinguish it from the *modified* Urca process (see below), which for the past quarter of a century has been regarded as the "standard" process for neutron star cooling. A decade ago, Boguta (1981) drew attention to the possible importance of the direct Urca process, but his work was un-noticed. Recently the process has been studied by Lattimer *et al.* (1991), whose discussion we shall follow closely.

Let us now consider the conditions under which these processes can take place. Temperatures in neutron stars are much less than the Fermi temperatures of the constituents, typically of order 100 MeV in energy units, which corresponds to a temperature of order 10^{12} K. Matter is thus degenerate. In addition, after loss of the initial neutrino pulse, during which the proton fraction of matter falls to the values characteristic of neutron stars, matter is close to beta equilibrium. This corresponds physically to the requirement that it cost no energy to convert a neutron into a proton plus an electron, or vice versa; that is, the neutron, proton, and electron chemical potentials μ_n, μ_p, and μ_e must satisfy the condition

$$\mu_n = \mu_p + \mu_e \ . \tag{3}$$

Since the chemical potential is the energy of a particle at the Fermi surface, there is, at zero temperature, no phase space for neutrinos and antineutrinos in the final states of reactions (1) and (2). However, at nonzero temperature, fermions are excited above their respective Fermi surfaces by energies of order $k_B T$, and, for example, a neutron just above its Fermi surface can decay into a proton and a neutron at their Fermi surfaces with the emission of an antineutrino of energy $\sim k_B T$. Particles participating in reactions (1) and (2) must therefore have energies that lie within $\sim k_B T$ of their respective Fermi energies.

In the mid 1960s, when cooling of neutron stars was first studied in detail, it was argued that reactions (1) and (2) could not occur. The reasoning was that neutrons, protons, and electrons participating in these processes must have momenta close to their respective Fermi momenta, which we denote by p_{F_n}, p_{F_p}, and p_{F_e}. Since the neutrino momentum is of order $k_B T/c$, which is small compared with the Fermi momenta of the other participating particles, for momentum to be conserved it must be possible to construct a triangle with sides whose lengths are the electron, proton, and neutron Fermi momenta. Since the sum of the lengths of any two sides of a triangle must exceed the length of the third side, it therefore follows that

$$p_{F_e} + p_{F_p} \geq p_{F_n} \ . \tag{4}$$

Since the density of particles of species i is given by

$$n_i = p_{F_i}^3 / 3\pi^2 \hbar^3 \ , \tag{5}$$

and in dense matter the proton fraction is typically of order of a few percent, it was argued that momentum could not be conserved. We now reexamine this conclusion in the light of our current knowledge of nuclear physics.

II. NEW INSIGHTS

Let us now estimate the minimum proton fraction for reactions (1) and (2) to proceed. If matter consists only of neutrons, protons, and electrons, the condition for charge neutrality is $n_p = n_e$ or $p_{F_p} = p_{F_e}$. Thus the threshold condition (4) becomes

$$p_{F_p} \geq p_{F_n} / 2 \ , \tag{6}$$

or

$$n_p \geq n_n / 8 \ . \tag{7}$$

The proton fraction $x = n_p/n$, where $n = (n_n + n_p)$ is the total baryon density, is then given by

$$x \geq \tfrac{1}{9} \approx 11.1\% \ .$$

If the electron chemical potential exceeds the muon rest mass, $m_\mu c^2 \approx 105.7$ MeV, muons will also be present in dense matter, and this will increase the threshold proton concentration. If $\mu_e \gg m_\mu c^2$, the threshold proton concentration is ≈ 0.148; for smaller values of μ_e, the threshold concentration lies between $\frac{1}{9}$ and this value. At densities typical of the central regions of neutron stars, the calculated proton concentration of matter is very sensitive to the choice of physical model, and in reality it might exceed the threshold value, as Lattimer *et al.* (1991) discuss. Estimates of proton fractions as a function of baryon density for a number of different equations of state indicate, first, that estimated proton concentrations depend sensitively on the assumptions made about the microscopic interactions, which are poorly known, and, second, that it is quite possible that proton concentrations are large enough to allow the direct Urca process to occur. As calculations by Wiringa, Fiks, and Fabrocini (1988) demonstrate, the form of the three-body interaction, especially its isospin dependence, has a large influence on the proton fraction.

Why was the direct Urca process neglected for so long? Part of the reason is probably that in the mid 1960s studies of neutron star matter were in their infancy. Estimates of proton fractions were based on simple models like the free-particle model, and the density was taken to be close to nuclear matter density. Modern estimates of proton fractions tend to be higher than the old ones because particle interactions tend to increase the proton fraction and because current estimates of central densities of neutron stars are a few times greater than nuclear density.

Let us now estimate the rate at which antineutrino energy is emitted per unit volume by reaction (1). This may be done using Fermi's "golden rule." Neglecting for the moment the effects of possible superfluidity of neutrons and superconductivity of protons, to which we shall return later, one finds

$$\dot{E}_\beta = -\frac{2\pi}{\hbar} 2 \sum G_F^2 \cos^2\theta_C (1+3g_A^2) n_1(1-n_2)(1-n_3) \times \epsilon_4 \delta^{(4)}(p_1 - p_2 - p_3 - p_4) \ , \quad (8)$$

where n_i is the Fermi function and the subscripts $i=1$ to 4 refer to the neutron, proton, electron, and antineutrino, respectively. The p_i are four-momenta, and ϵ_4 is the antineutrino energy. The sum over states is to be performed only over possible three-momenta $\mathbf{p}_i$ in unit volume, and the prefactor 2 takes into account the initial spin states of the neutron. The beta-decay matrix element, squared and summed over spins of final particles and averaged over angles, is $G_F^2 \cos^2\theta_C (1+3g_A^2)$, where $G_F \approx 1.436 \times 10^{-49}$ erg cm^3 is the weak-coupling constant, θ_C is the Cabibbo angle, and $g_A \approx -1.261$ is the axial-vector coupling constant. Final electron and proton states must be vacant if the reaction is to occur, and this accounts for the blocking factors $1-n_2$ and $1-n_3$. The electron-capture process (2) gives the same energy-loss rate as process (1), but in neutrinos, and therefore the total luminosity per unit volume of the direct Urca process is twice Eq. (8). The integrals may be calculated straightforwardly, since the neutrons, protons, and electrons are very degenerate, and one finds

$$\dot{E}_{\rm Urca} = \frac{457\pi}{10\,080} \frac{G_F^2 \cos^2\theta_C (1+3g_A^2)}{\hbar^{10} c^5} m_n m_p \mu_e (k_B T)^6 \Theta_t \ . \quad (9)$$

Here Θ_t is the threshold factor $\Theta(p_e + p_p - p_n)$, which is $+1$ if the argument exceeds 0, and is 0 otherwise.

Particle interactions change this result in a number of ways. First, the neutron and proton densities of states are determined by effective masses rather than bare masses. Second, the effective weak-interaction matrix elements can be modified by the medium. These effects are expected to reduce the luminosity, but probably by less than a factor of 10.

The temperature dependence of the direct Urca emissivity may easily be understood from phase-space considerations. The neutrino or antineutrino momentum is $\sim k_B T/c$, and thus the phase space available in final states is a three-dimensional sphere of this radius, whose volume is proportional to $(k_B T/c)^3$. The participating neutrinos, protons, and electrons are degenerate. Therefore, for the reaction to occur, they must have energies that lie within $\sim k_B T$ of the energies at the Fermi surfaces, and thus each degenerate particle contributes a factor $\sim k_B T$. (The fact that only three of the four particle energies are independent might be expected to reduce the powers of T by 1, but this effect is compensated for by the fact that we are interested in the rate of emission of neutrino energy.)

Whether or not the direct Urca process occurs in reality, the above calculation is an instructive one, since neutrino emissivities from other neutrino emission processes may be understood in terms of it.

How fast do neutron stars cool by the direct Urca process? During the phase when cooling is primarily by neutrino emission, a characteristic time τ for cooling may be estimated by equating the energy loss per unit volume to the rate of change of the thermal energy per unit volume, or $\tau = -T/\dot{T} = c_V T/\dot{E}$. If for simplicity we approximate the heat capacity by that for degenerate neutrons alone, $c_V = (\pi^2/3) N_n(0) k_B^2 T$, where $N_n(0) = m_n p_{Fn}/(\pi^2 \hbar^3)$, we find

$$\frac{1}{\tau_{\rm Urca}} = \frac{457}{3360\pi} \frac{G_F^2 \cos^2\theta_C (1+3g_A^2)}{\hbar^7 c^6} \frac{m_n c}{p_{Fn}} \mu_e (k_B T)^4 \ . \quad (10)$$

This time may be compared with the lifetime of the neutron *in vacuo,* given by

$$\frac{1}{\tau_n}=\frac{1}{60\pi^3}\frac{G_F^2\cos^2\theta_C(1+3g_A^2)}{\hbar^7c^6}\kappa\Delta^5 , \tag{11}$$

where $\Delta\approx 0.8$ MeV is the maximum antineutrino energy in the decay, and $\kappa\approx 0.47$ is a factor that takes into account the reduction of phase space due to the fact that electrons in final states are not extremely relativistic. Thus

$$\frac{1}{\tau_{\rm Urca}}=\frac{457\pi^4}{28\kappa}\frac{c}{v_n}\frac{\mu_e(k_BT)^4}{\Delta^5}\frac{1}{\tau_n} , \tag{12}$$

where $v_n=p_{Fn}/c$ is the neutron Fermi velocity. As remarked earlier, effects of interaction in the nuclear medium reduce the rate of the Urca process compared to our simple golden rule estimate by as much as a factor of about 10, and thus, since the neutron lifetime is about 900 s, we find that the characteristic cooling time is typically

$$\tau_{\rm Urca}\sim\frac{1\ {\rm min}}{T_9^4} , \tag{13}$$

where, using a notation standard in astrophysics, we denote by T_9 the temperature measured in units of 10^9 K. In other words, the neutron star cools to 10^9 K in minutes and to 10^8 K in weeks.

III. RECEIVED WISDOM

Until 1990, it was tacitly assumed by most people (except Boguta) that proton concentrations in dense matter lie below the threshold for the direct Urca process. In this case, the simplest allowed weak-interaction processes for nucleons are

$$n+n\rightarrow n+p+e+\bar{\nu}_e \tag{14}$$

and

$$n+p+e\rightarrow n+n+\nu_e . \tag{15}$$

These processes are related to processes (1) and (2) by the addition in initial and final states of a nucleon, whose sole purpose is to enable momentum to be conserved. They were first discussed by Chiu and Salpeter (1964), and detailed estimates of their rates were made by Finzi (1964), Bahcall and Wolf (1965a, 1965b), and Friman and Maxwell (1979). The process is basically the processes (1) and (2), with the modification that a nucleon in an initial or final state interacts, via the nucleon-nucleon strong interaction, with a bystander nucleon. The perturbation-theory diagram for one such process is shown in Fig. 1. A total of five degenerate particles participate in these processes, and therefore, on the basis of the phase-space arguments given above, one would expect the emissivity to vary as T^8, a conclusion borne out by the detailed calculations.

The modified Urca luminosity may be estimated in terms of that for the direct Urca process. The lowest-order matrix element for the modified Urca process has

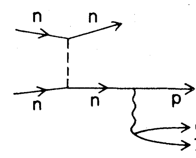

FIG. 1. Perturbation-theory diagram for a typical contribution to the modified Urca process. The wavy line represents a weak interaction, while the dashed line represents a strong interaction.

an extra strong-interaction matrix element V and an extra energy denominator (typically of the order of a Fermi energy) compared with the usual weak-interaction matrix element; their ratio is thus $\sim V/E_F$. The additional neutrons in the initial and final states each contribute a factor proportional to the number of states accessible, of the order of the density of states at the Fermi energy, $\sim n_n/E_F$, times the thermal energy. Thus the modified Urca luminosity is of order $(V/E_F)^2(n_nk_BT/E_F)^2$ times that of the direct process. Because neutron matter is a strongly interacting system, a typical neutron potential energy n_nV is comparable to the Fermi energy, and therefore the modified Urca rate is of order $(k_BT/E_F)^2$ times the characteristic direct rate. Since Fermi energies are of the order of 100 MeV, which corresponds to temperatures $\sim 10^{12}$ K, this factor is of the order of $10^{-6}T_9^2$. The characteristic time for cooling by the modified Urca process is thus greater than that for the direct Urca process by a factor $\sim 10^6/T_9^2$, or

$$\tau_{\rm mod\ Urca}\sim\frac{1\ {\rm yr}}{T_9^6} . \tag{16}$$

Thus, if the direct Urca process cannot occur, the core temperature will exceed $\sim 10^8$ K for $\sim 10^6$ yr, while if the direct Urca process can occur, the temperature will be that high only for about a week.

IV. EXOTICA

Since the mid 1960s it has been proposed that the state of dense matter may be completely different from the mixture of normal neutron, proton, and electron Fermi liquids we have assumed in our discussion up to now. Among the possibilities are Bose condensations of pions or kaons, and quark matter, which are usually referred to collectively as "exotic" states. All of these could give rise to neutrino emission comparable to that from the direct Urca process for nucleons, if the latter were allowed. In fact, neutrino emission processes for exotic states may be regarded as variants of the direct Urca process for nucleons, although historically the processes for exotic states were considered before the nucleon process.

In 1965 Bahcall and Wolf considered the possibility that the energy of a pion in matter could be low enough for a Bose condensation of pions to arise. They argued that this could lead to enhanced neutrino emission compared with the modified Urca process. The condensed pions (or more properly, the macroscopic condensed pion field) give rise to an isospin-dependent potential, which results in the nucleon excitations' becoming a superposition of neutrons and protons, which we denote by f. The basic physics is similar to that for electrons in a metal with a spin-density wave: excitations are then coherent superpositions of electrons with different spins. In the case of a pion condensate, which carries isospin as well as spin, the basic excitations may have components with different spin components and different isospin components. It is therefore possible for the processes

$$f \rightarrow f + e^- + \bar{\nu}_e \tag{17}$$

and

$$f + e^- \rightarrow f + \nu_e \tag{18}$$

to occur. The first reaction is basically the decay of the neutron part of one f excitation into the proton part of another, and the second may be interpreted in a similar way. As in the case of nucleons, excitations that have energies within $\sim k_B T$ of the neutron and proton Fermi energies can participate in the reactions. Since the two f quasiparticles in the initial and final states may have momenta close to the neutron Fermi momentum, these reactions are not inhibited by momentum conservation considerations, unlike what may happen for the direct Urca process for nucleons [Eqs. (1) and (2)]. More detailed studies of pion condensation carried out in the 1970's indicate that it will occur, if it does at all, at a finite wavelength. However, the finite momentum imparted to nucleons by scattering from the pion condensate is not expected to be so large that reactions (17) and (18) would be prohibited by the impossibility of conserving momentum for particles near the Fermi surface.

The rate of the process (17) and (18) may be calculated by arguments similar to those for the nucleon direct Urca process, except that the weak-interaction matrix element that enters is that between two f quasiparticles, rather than between a neutron and a proton, and the phase space is different because the momentum of the condensate k enters the momentum conservation condition (Maxwell *et al.*, 1977). The strength of the pion condensate is measured by an angle θ_π, and for small θ_π one finds that the square of the beta-decay matrix element summed over spins is $(\theta_\pi^2/4)[1+(g_A k/p_{F_e})^2]$ times the result for nucleons. Since $k > p_{F_e}$, the phase space is reduced by a factor p_{F_e}/k compared with the rate for the direct Urca process for nucleons, and therefore

$$\dot{E}_\pi = \dot{E}_{\rm Urca}(\theta_\pi^2/4)[1+(g_A k/p_{F_e})^2] p_{F_e}/k \ . \tag{19}$$

For plausible parameter values, one finds that the rate of emission of neutrino energy from a pion condensate is more than an order of magnitude less than the direct Urca rate for nucleons. Unlike the nucleon direct Urca process, the process for a pion condensate will occur for arbitrary proton concentrations. However, more recent studies indicate that, because of the strong repulsion between nucleons and nucleon holes in the spin-isospin channel, pion condensation is unlikely in neutron stars.

Another possible exotic ground state of dense matter is a kaon condensate (Kaplan and Nelson, 1986; Nelson and Kaplan, 1987). The approximate $SU(3)\times SU(3)$ chiral symmetry of the strong interactions leads to an attractive interaction between kaons and nucleons proportional to the baryon density, and therefore at sufficiently high density there is the possibility that the kaon energy would become so low that a Bose condensate of kaons would appear. Such a state is analogous to a pion condensate. The basic neutronlike excitations are coherent superpositions of neutrons and Σ^- particles, while the protonlike excitations are coherent superpositions of protons, Σ^0 and Λ—not simple nucleons. In quark language, a pion condensate corresponds to a finite expectation value in the matter of $\langle \bar{u}d \rangle$, while a kaon condensate corresponds to a finite expectation value of $\langle \bar{s}u \rangle$. In contrast to pion condensation, which would be expected to occur with a spatially varying condensate because of the attractive pion-nucleon p-wave interaction, kaon condensation would be more likely to occur in a spatially uniform state.

The rate of neutrino emission from a kaon condensate may be calculated in a fashion similar to that for a pion condensate. The neutrino emission processes are analogous to those for a pion condensate. For example, the Σ^- part of a neutronlike excitation can decay into the neutron part of a similar excitation, with the emission of an electron and an antineutrino. The chief differences between the two cases are that the kaon condensate is spatially uniform, and the weak-interaction matrix elements for a kaon condensate contain a factor $\sin\theta_C$, rather than $\cos\theta_C$ for the pion condensate, because it is the strangeness-changing part of the weak current that enters. The final result is (Brown, Kubodera, Page, and Pizzochero, 1988)

$$\dot{E}_K = \dot{E}_{\rm Urca} \frac{\theta_K^2}{8} \sin^2\theta_C \ , \tag{20}$$

where θ_K is the kaon condensation angle, analogous to θ_π for pion condensation. This result shows that for $\theta_K^2 \approx 0.1$, the neutrino luminosity of a kaon condensate is about one-thousandth of the typical nucleon direct Urca rate.

Yet another possibility for the state of matter at high densities is quark matter, in which quarks can move around essentially as free particles, rather than being bound together as color singlet entities, such as nucleons and pions. Neutrino emission from such a system was considered by Iwamoto (1980, 1982). The basic processes are the quark analogs of the nucleon direct Urca processes (1) and (2), i.e.,

$$d \rightarrow u + e^- + \bar{\nu}_e \tag{21}$$

and

$$u+e^{-}\rightarrow d+\nu_e \ . \tag{22}$$

The condition for beta equilibrium is

$$\mu_d=\mu_u+\mu_e \ , \tag{23}$$

the analog of Eq. (3) for nucleons. If quarks and electrons are treated as massless noninteracting particles, this condition is

$$p_{F_d}c=p_{F_u}c+p_{F_e}c \ , \tag{24}$$

which is identical to the condition for it to be just possible to conserve momentum for excitations near the respective Fermi surfaces. At threshold the momenta of the u quark, the d quark, and the electron must be collinear, but, as Iwamoto pointed out, the weak-interaction matrix element for this case vanishes. However, if quark-quark interactions are taken into account, the direct Urca process is kinematically allowed for quarks and electrons that are not collinear. To illustrate this effect, consider the case in which interactions may be treated perturbatively. To first order in the QCD coupling constant α, the quark chemical potentials are given by

$$\mu_i=\left[1+\frac{8}{3\pi}\alpha\right]p_{F_i}c, \quad i=u,d \ , \tag{25}$$

while the electron chemical potential is unchanged. Since α is positive, it is easy to see that the conditions for beta equilibrium [Eq. (23)] and momentum conservation may be satisfied simultaneously. Angles characterizing deviations from collinearity are typically of order $\alpha^{1/2}$. The calculation of the neutrino and antineutrino emission rates proceeds in essentially the same way as for the nucleon process, and the overall result for the luminosity is

$$\dot{E}_q=\frac{914}{315}\frac{G_F^2\cos^2\theta_C}{\hbar^{10}c^7}\alpha p_{F_d}p_{F_u}\mu_e(k_BT)^6 \ . \tag{26}$$

This has a form similar to the nucleon Urca rate (9), but there are some significant differences. First, there is a factor α, which reflects the fact mentioned above that the weak-interaction matrix element vanishes for collinear relativistic particles, whereas for nonrelativistic nucleons the corresponding matrix element is essentially independent of angle. The second difference is that the quantities p_{F_u}/c and p_{F_d}/c take the place of the nucleon masses. Third, the numerical coefficient is different because for quarks the angular dependence of the matrix element is important. However, since p_{F_u}/c and p_{F_d}/c are expected to be less than m_n, and α is less than or of the order of unity, the neutrino luminosity from quark matter is expected to be rather less than the characteristic rate for the nucleon process. However, it is important to note that for quark matter the electron fraction is uncertain. For instance, if u, d, and s quarks may be treated as massless and free, the electron fraction vanishes identically. Detailed estimates of the composition of quark matter for various models are given by Duncan, Shapiro, and Wasserman (1983) and Alcock, Farhi, and Olinto (1986). So far we have assumed the quark to be massless. While this is a good approximation for u and d quarks, it is poor for s quarks, which can participate in Urca processes even in the absence of strong interactions. However, detailed calculations show that the energy-loss rate from processes in which s quarks participate is less than that from the processes for u and d quarks considered above (Iwamoto, 1982).

To summarize, the neutrino emission rates of the exotic states that we have considered are closely related to the rate for the nucleon direct Urca process, since both phase space (which is governed by the fact that three degenerate fermions and one nondegenerate neutrino participate in the reactions) and matrix elements are similar, but they are generally smaller than the direct Urca process for nucleons.

V. RAPID COOLING BY HYPERONS AND Δ ISOBARS

At densities not far above that of nuclear matter, constituent other than neutrons, protons, electrons, and muons may appear. The lightest of these are the Λ and Σ^- hyperons, with masses of 1116 MeV and 1197 MeV, respectively. At zero temperature, it follows from the condition for chemical equilibrium that Λ's will appear when the energy of the lowest state for a Λ first lies below μ_n, while Σ^-'s will appear when the lowest energy state of a Σ^- first lies below $\mu_n+\mu_e$. The energy of the lowest hyperon state is the rest mass energy, plus the potential energy of interaction of the hyperon with the other constituents. As a rule, there is no kinetic-energy term, since it is expected on the basis of microscopic calculations that the lowest hyperon state will have zero momentum. In many calculations (e.g., Bethe and Johnson, 1974), Σ^-'s occur at lower densities than Λ's, because the electron chemical potential more than makes up for the greater mass of the Σ^-.

The simplest weak-interaction processes in which these hyperons can participate are

$$\Lambda\rightarrow p+e^{-}+\bar{\nu}_e \ , \tag{27}$$

$$\Sigma^{-}\rightarrow n+e^{-}+\bar{\nu}_e \ , \tag{28}$$

and their Urca partners that generate neutrinos. [Our treatment of hyperon Urca processes follows recent work by Prakash *et al.* (1991).] These processes are essentially the ones responsible for neutrino emission from kaon condensates. As in the case of the direct Urca process for nucleons, the processes are kinematically allowed provided the Fermi momenta satisfy the triangle inequalities. Minimum hyperon concentrations for which the Urca processes can proceed may be estimated by combining two of the triangle inequalities, and this leads to the conditions

$$p_{F\Lambda} \geq |p_{F_p} - p_{F_e}| \quad (29)$$

and

$$p_{F\Sigma^-} \geq |p_{F_n} - p_{F_e}| \ . \quad (30)$$

If electrons and protons were the only charged particles present, the electron and proton Fermi momenta would be equal, and Eq. (29) indicates that the direct Urca process could occur even for an infinitesimally small concentration of Λ's. Even if other negatively charged species were present, the threshold concentration of Λ's would be quite small, typically of the order of one part in a thousand. For the Σ^- decay (29) to take place, the Σ^- Fermi momentum must be large enough to make up the difference between the electron and neutron momenta, which means in practice that the threshold concentration is comparable to the threshold proton concentration for the nucleon direct Urca process.

Rates of neutrino emission may be estimated as was done for the nucleon direct Urca process. In hyperon Urca processes there is a change of strangeness, so characteristic neutrino emission rates are proportional to $\sin^2\theta_C$ and are therefore less than one-tenth of those for the nucleon Urca process. However, the luminosity produced in hyperon Urca processes will, if the processes are allowed, be comparable to that expected for exotic states and will exceed that from the modified Urca process at all temperatures less than tens of MeV.

With a greater variety of particles present, even more Urca processes could take place. For example, if both Σ^- and Λ are present, the process

$$\Sigma^- \rightarrow \Lambda + e^- + \bar{\nu}_e \quad (31)$$

is a candidate. There is no strangeness change, so the process is not Cabibbo suppressed: its matrix element squared is in fact about 20% of that for the nucleon Urca process. Threshold hyperon concentrations would not be large, since neutrons do not participate. Another particle with a mass only a little above that of the Σ^- is the Δ^-. This could participate in weak processes like $\Delta^- \rightarrow n + e^- + \bar{\nu}_e$. Whether any of these processes can occur in neutron stars is uncertain because of our ignorance of interactions among hyperons, isobars, and nucleons at densities well above nuclear density.

The important conclusion from the study of processes for hyperons and Δ isobars is that fast cooling is possible without exotic states and without proton concentrations high enough to allow the nucleon direct Urca process. In particular, minute traces of Λ hyperons would be a very effective refrigerant.

VI. SUPERFLUIDITY AND SUPERCONDUCTIVITY

Earlier I mentioned the theoretical possibility that neutrons and/or protons in neutron stars could undergo a phase transition to superfluid or superconducting states analogous to the Bardeen-Cooper-Schrieffer state of electrons in metallic superconductors. This was suggested by Migdal (1959) and by Ginzburg and Kirzhnits (1964) following the seminal paper by Bohr, Mottelson, and Pines (1958) that put in evidence BCS pairing effects in ordinary nuclei. Because neutrinos are produced only by thermal excitations and not by paired nucleons, superfluidity and superconductivity reduce neutrino production rates. Below the transition temperature to a paired state, the number of thermal excitations drops rapidly with decreasing temperature, the cooling rate is reduced, and the temperature of a neutron star remains higher than it would in the absence of pairing. Reliable theoretical estimates of transition temperatures are not yet available, so from theory alone it is at present impossible to say how important superconductivity and superfluidity of nucleons are.

I shall not discuss superfluidity and superconductivity at length in this Colloquium, since its main focus is to bring out the relationship between neutrino generating processes, especially those that give rise to rapid cooling. If neutron stars were observed to cool more slowly than could be explained by the slowest of the processes we considered earlier, the modified Urca process for normal nucleons, this could be a sign of the importance of superfluidity or superconductivity.

VII. A NEW STANDARD MODEL?

The lesson of the recent studies of neutrino processes is that there are many possible physical conditions that could result in neutron stars cooling fast. One of these is proton concentrations that were regarded as unacceptably high some time ago, but that are not outside the range currently regarded as being physically possible. Another is the presence of hyperons or delta isobars. In addition, there are the exotic states considered earlier.

Energy losses by the nucleon direct Urca process, if allowed, exceed those for any of the other processes previously considered. In addition, there are numerous other possible processes for which the losses have the same temperature dependence as that of the direct Urca process, and whose magnitudes are simply related to, but generally smaller than, that of the nucleon direct Urca process. It is therefore tempting to regard it, rather than the modified Urca process, as the "standard" one.

What can be done to shed light on which of the many possible states for dense matter actually occurs in neutron stars? First of all, intense efforts to detect surface emission from neutron stars should be continued. Observations need to be made in the far ultraviolet and soft x-ray bands. They are currently under way with the German ROSAT satellite, and the proposed Advanced X-Ray Astrophysics Facility (AXAF) would be an excellent instrument for such investigations. Providing unambiguous evidence for surface emission from neutron stars is difficult because other possible sources of emission, such as the star's magnetosphere, need to be removed, and because the spectrum of such radiation is not known *a* *priori* (see, e.g., Ögelman, 1991). The present observational situation as far as surface emission from neutron stars is concerned may be likened to the state one could imagine for optical emission from ordinary stars if one had only a few reported detections and no detailed spectral information. In such a young field, relatively modest amounts of data can lead to significant insights.

A second important way to try to pin down the state of matter in neutron stars is by theoretical studies. These are questions one should look at afresh: What is the proton fraction? Are hyperons present? Do pion or kaon condensates exist? Is there quark matter in neutron stars? Are nucleons superconducting or superfluid? In recent years there has been significant progress on the nuclear many-body problem, and these developments should be exploited to the full to help answer these questions. Of especial importance for answering these questions is the nature of the three-body interaction. Information about this that can be gleaned from studies of nuclei in the laboratory is sparse, but it is central to predicting the properties of matter at the densities of neutron star interiors. An important task is to characterize better the short-range part of this interaction.

A third source of information is laboratory studies of nuclei. In the next few years one can anticipate radioactive beam facilities that will make possible the conducting of experiments on rather large neutron-rich nuclei like ^{60}Ca, which has twice as many neutrons as protons. Data on such nuclei will be of great value in making extrapolations to the even more neutron-rich conditions expected in neutron stars.

In summary, the study of neutron star cooling has the potential for giving information about neutron star interiors. It is unlikely that observations alone will be sufficient to identify the states of dense matter, but coupled with theoretical studies of dense matter and information to be obtained from laboratory studies, they are likely to lead to important insights. In the years to come, one can look forward to a continuing interplay between astrophysical observations, the theoretical study of neutron stars, nuclear theory, and laboratory nuclear physics.

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