NEUTRAL CURRENTS IN ASTROPHYSICS

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INTRODUCTION :

Theoretical attempts at constructing a dynamical theory of weak interactions along the lines of the electromagnetic interactions have been with us for nearly a decade. One of the consequences of such theories is the prediction of a coupling between weakly interacting particles by a neutral current (N.C.) in addition to the coupling due to charged current (C.C.). Such neutral current interactions were looked for and have been found a couple of years ago. Hence the presence of neutral current is more or less established. The natural question then arises whether this new discovery has any astrophysical implication. Even though weak interactions play a fundamental role in astrophysics, most of them are of the charge changing type and hence will not be seriously affected by this new discovery. For example, the first reaction in the pp chain for the nuclear energy generation in stars is $p+p \rightarrow d+\nu+e^+$ which is a weak process of the charge changing type. But there are several scenarios scattered over the entire breadth of astrophysics, ranging from the early universe to the death of a star where the neutral currents may play a role and the purpose of this article is to point out those areas. The experimental results to this date will be summarized first and then the basic theoretical framework is introduced. The various reactions arising due to neutral currents will be enumerated next and the astrophysical applications will be indicated at the end.

EXPERIMENTAL INFORMATION :

The experimental information can be classified into two categories. Those experiments in which only leptons* are involved, which we term as pure leptonic, and those involving hadrons which are termed semi-leptonic.

(a) **Pure Leptonic Processes** :—

The reaction $\bar{\nu}_\mu + e^- \longrightarrow \bar{\nu}_\mu + e^-$ is allowed only if neutral currents are present as there is no charged current coupling between ν_μ and e. Hence if events of this type are observed, then they indicate the presence of neutral currents. Two such events have been reported from CERN (Hasert et al. 1973).

(b) **Semileptonic Processes** :—

Events of the type

$$\nu_\mu + N \longrightarrow \nu_\mu + X$$

and

$$\bar{\nu}_\mu + N \longrightarrow \bar{\nu}_\mu + X$$

where N is a nucleon and X denotes any hadron or hadrons, are allowed only if neutral currents are present. Under the charged current theory, one expects only muons in the final state and the absence of muons in the scattered beam will again point towards the presence of neutral currents. Several hundreds of such events have been observed (Hasert et al. 1973; Barish et al. 1974).

* Neutrino, electron and muon are called leptons and all strongly interacting particles are called hadrons.

THEORETICAL FRAMEWORK :

Theory of weak interaction dates back to the days of Fermi, who wrote down the interaction Hamiltonian for the beta decay from an analogy with the electromagnetic interactions. The charged current theory is well known and it includes the coupling between the particles due to vector and axial vector currents. Attempts to push the analogy with the electromagnetic interactions and thus to unify the theories of electromagnetic and weak interactions have been in progress since the early sixties. Most of these so called gauge theories imply the existence of neutral current weak interaction (Weinberg 1974; Rajasekharan 1974).

A general way of describing a weak process, for example $\nu\, e$ scattering, can be written down in terms of the Lagrangian for the interaction as

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \left\{ \bar{\nu}_e \gamma_\alpha (1-\gamma_5)\nu_e \right\} \left\{ \bar{e}\, \gamma_\alpha (a - b\gamma_5) e \right\} + \frac{G_F}{\sqrt{2}} \left\{ \bar{\nu}_\mu \gamma_\alpha (1-\gamma_5)\nu_\mu \right\} \left\{ \bar{e}\, \gamma_\alpha \left[(a-1) - (b-1)\gamma_5 \right] e \right\}, \tag{1}$$

where G_F is the Fermi coupling constant and a and b represent the vector and axial vector coupling constants. Muon-electron universality has been assumed in equation (1). In charged-current theory, a and b are unity. In the gauge theory of Weinberg -Salam, a and b can be written as

$$a = 2 \sin^2\theta_W + 0.5 \text{ and } b = 0.5, \tag{2}$$

where θ_W is a free parameter, called the Weinberg angle, which is related to the mass of the intermediate neutral vector boson. An analysis of the experimental results for the semileptonic processes has yielded the value of ~ 0.35 for $\sin^2\theta_W$. A general analysis by De Rujula et al. (1974) of the two purely leptonic events described above have yielded the following upper limits for the coupling constants a and b :

$$a = 1.5 \quad \text{and} \quad b = 1.5. \tag{3}$$

The above semiqualitative description of the theory is given only to introduce the astrophysicist to the situation prevailing in the particle physics so that it will be possible to understand the neutral current processes of astrophysical interest given below. For a detailed description of the theory or theories in the field, refer Weinberg (1974).

NEUTRAL CURRENT PROCESSES OF ASTROPHYSICAL INTEREST :

Though weak interactions play a dominant role in various branches of astrophysics, most of these are of charge changing type and hence will remain essentially unaffected by neutral currents. However, there are several processes of energy losses by neutrinos in the history of any star and these processes will be affected by neutral currents. These processes can again be classified into pure leptonic processes and semileptonic processes.

(a) **Pure Leptonic Processes** :—

(i) PAIR ANNIHILATION : In the electromagnetic theory, an electron-positron pair annihilates resulting in a photon. In the same manner, in the weak interaction theory, an electron-positron pair can annihilate to give a neutrino-antineutrino pair. This process will be affected by the neutral currents since it is not a charge exchange type of reaction. Further, muon neutrinos will also be emitted in addition to the electron neutrinos as the neutral current couples with both the types of neutrinos.

$$e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e \quad \text{(C.C. and N.C.)}$$

$$e^- + e^+ \rightarrow \nu_\mu + \bar{\nu}_\mu \quad \text{(N.C.)}$$

The energy loss due to these processes in the conventional charged current theory has been calculated by Beaudet, Petrosian and Salpeter (1967). Dicus (1972) has taken into consideration the modifications to these formulae due to the gauge theory of Weinberg. The formulae given by Dicus can however be adapted for any general neutral-current models. It is seen that the energy losses get modified due to neutral currents in the following fashion :

$$(2a^2 - 2a + 1)\, \epsilon_{cc} \quad \text{for } T \leqslant 10^8 \text{ and } 10^4 \leqslant \rho \leqslant 10^6,$$

$$\tfrac{1}{2}\left\{ a^2 + (a-1)^2 + (b-1)^2 + b^2 \right\} \epsilon_{cc} \quad (4)$$

$$\text{for } \rho > \;^7 \text{ g cm}^{-3},$$

where ϵ_{cc} is the energy loss in the conventional charged-current theory and a and b have been defined earlier.

(ii) PHOTONEUTRINO PROCESS : If the photon gets scattered off an electron due to the direct electron-neutrino coupling, a neutrino pair can be emitted.

$$\nu + e^- \rightarrow e^- + \nu_e + \bar{\nu}_e, \quad \text{(C.C. and N.C.)}$$

$$\nu + e^- \rightarrow e^- + \nu_\mu + \bar{\nu}_\mu, \quad \text{(N.C.).}$$

This process was considered in detail by Beaudet et al. (1967) in the framework of charged current theory and they have given formulae for the energy losses due to the process under a variety of conditions. Dicus (1972) has considered the modifications due to neutral-currents and these modifications are as given below :

$$\tfrac{1}{6}\left\{ a^2 + (a-1)^2 + 5b^2 + 5(b-1)^2 \right\} \epsilon_{cc}, \quad \text{for } \rho < 10^6 \text{ g cm}^{-3}, \quad (5)$$

$$\tfrac{1}{2}\left\{ a^2 + (a-1)^2 + b^2 + (b-1)^2 \right\} \epsilon_{cc}, \quad \text{for } \rho > 10^7 \text{ g cm}^{-3}.$$

(iii) PLASMA PROCESS : Under normal circumstances, a photon cannot directly decay into a neutrino-antineutrino pair, because photon being mass-less, this process is forbidden by the law of conservation of momentum and energy. However, in a medium whose dielectric constant is less than unity, for example a degenerate electron gas, the photon behaves as though it has a rest mass of $h\,\omega_p/2\pi c^2$ where ω_p is the plasma frequency. Such a photon is called a plasmon, and it can decay into a neutrino-antineutrino pair (Chiu 1968). This process is also an important source of energy loss in the star and the details of this process in the framework of the charged current theory have been worked out by Beaudet et al. (1967). The modifications due to neutral current as given by Dicus (1972) are

$$\left\{ a^2 + (a-1)^2 \right\} \epsilon_{cc}. \quad (6)$$

It should be mentioned here that the above formula was obtained by Dicus neglecting terms of the order of p^2 / m^2_W where p is the momentum of the electron and m_W the mass of the intermediate vector boson. Further, in considering this process, Dicus has completely ignored the contributions due to axial vector coupling, as these do not seem to contribute significantly under the conditions considered by him.

All the leptonic processes discussed above are all allowed by even the charged-current interaction (except of course the presence of muon neutrinos in addition to the electron type) and the gauge theory introduces only modifications. However, due to the possibility of a neutral coupling, several new semileptonic processes are opened up and these are discussed next.

(b) **Semileptonic Processes** :—

(i) COHERENT SCATTERING : It is well known that due to the electromagnetic coupling, the electron-nucleus scattering has a forward peak, i.e. electrons get scattered coherently off the nuclei. Since there can be a neutral coupling between the neutrinos and the nuclei, there will be an analogous coherent scattering of neutrinos off the nuclei. This process has been considered in detail by Freedman (1974) who gives the relation for the relevant cross section as (cf Schramm and Arnett 1975):

$$\sigma\,(\text{cm}^2) = 1.6 \times 10^{-44}\, a_0^2\, A^2\, E^2 \left(1 - \left(\frac{8bE^2}{3}\right) + \ldots\right), \quad (7)$$

where E is the neutrino energy in MeV, A is the mass number of the nucleus, $b \simeq 4.8 \times 10^{-6} A^{2/3}$ (MeV)$^{-2}$ from analogy to electron scattering, and a_0 is the coefficient of the isoscalar part of the neutral current; in the Weinberg model, $|a_0| = \sin^2 \theta_W$.

(ii) NEUTRINO DE-EXCITATION OF NUCLEI: This process is an analogue of the de-excitation of the excited states of nuclei by the emission of a photon. The only difference here is the emission of a neutrino-antineutrino pair instead of a photon.

$$(Z, A)^* \rightarrow (Z, A) + \nu + \bar{\nu}.$$

Bahcall, Treiman and Zee (1974) have considered this process in some detail. The kinematic analysis is similar to the ordinary beta decay with the decay rate given by Fermi and Gammow-Teller matrix elements. These matrix elements contain the neutral current contribution. Bahcall et al. (1974) has shown that the energy radiated in the form of neutrino-antineutrino pairs of both types per unit mass of stellar material is proportional to the mass fraction of the nuclei in which these transitions occur.

(iii) n - n SCATTERING: In the purely charged current theory inelastic n-n scattering will lead only to

$$n + n \rightarrow n + p + e^- + \bar{\nu}_e.$$

However in the case of neutral currents, the process

$$n + n \rightarrow n + n + \nu + \bar{\nu}$$

is also allowed. This new possibility, with the emission of both types of neutrino-antineutrino pairs, leads to an effective energy loss mechanism by the neutrino emission. Bond (1974) has considered this process in connection with the cooling of neutron stars and he finds that this process may be the most important cooling mechanism.

(iv) NEUTRINO BREMSSTRAHLUNG: Festa and Ruderman (1969) have considered the possibility of the emission of neutrino-antineutrino pairs when an electron gets scattered off the coulomb field of the nucleus. This process will be modified due to the presence of neutral currents. The calculations in the neutral current framework, analogous to the charged current ones by Festa and Ruderman, have not been done so far.

IMPLICATIONS OF NEUTRAL CURRENT PROCESSES IN ASTROPHYSICS:

All the leptonic and semileptonic processes considered in the last section have two types of roles to play in the history of a star. The neutrinos emitted escape from the star like the photons, except that the neutrino mean free paths are several orders of magnitude larger than those of photons. Thus, the neutrinos will behave like a very good cooling agent and this will affect the luminosity of the star. On the other hand, the neutrinos carrying energy, while escaping freely from the core, can deposit this energy in the outer regions of a star and hence can act as an effective agent delivering energy from the core to the envelope of a star and thus deposit sufficient energy in the envelope to blow it off. This will result in the disruption of the star, like in a supernova. We will see in some detail about these two applications before examining the possible effects in the early universe.

(a) **Neutrinos as the Cooling Agents :—**

(i) NEUTRON STARS: The neutrino cooling of neutron stars is shown by Tsuruta and Cameron (1966) to be most effective in the initial stages. Chitre, Narlikar and Ramadurai (1975) have applied the pure leptonic processes and have shown that, though the cooling rate by purely leptonic processes is altered by neutral currents, the overall cooling of a model neutron star remains practically unaffected. However preliminary calculations of Bond (1974) seem to suggest that the semileptonic process of n-n scattering may be the most effective cooling mechanism for the neutron stars. This is because of the fact that the associated charged current process is inhibited by the extremely degenerate sea of electrons. The calculations of Bond suggest that the neutrino luminosity may be three orders of magnitude greater by this process. This means the initial cooling time is reduced by this number. This may have some bearing on the transient X-ray sources discovered recently.

(ii) WHITE DWARFS: The pure leptonic processes mentioned above have been considered by Stothers (1970) in the general framework of gauge theories before the discovery of the neutral currents. Since the neutrinos affect the luminosites of the stars, he computed the number of white dwarfs which can be seen at the present time and from the statistics he came to the conclusion that the gauge theory predictions are well within the errors of observations. Bahcall et al (1974) have considered the semileptonic process of the de-excitation of some nuclei as a cooling mechanism. The only important nuclei are the ^{57}Fe, ^{40}K and ^{61}Ni as these are the ones with cosmic abundance greater than $\sim 10^{-7}$ that of hydrogen and with excited states of excitation energy < 0.3 MeV that can decay by allowed neutrino pair emission. However, due to our present lack of quantitative knowledge about abundances and appropriate nuclear levels and nuclear matrix elements, it is not possible to quantify the importance of this mechanism.

(iii) STELLAR EVOLUTION: The post main sequence evolution of stars, especially the evolution to the red giant phase is known to be affected by the neutrino emission processes. One of the important problems of astrophysics is the manner in which carbon burning is initiated in the core. In the last few years, this problem has received wide attention. It is known from the analysis by Gunn and Ostriker (1970) that the progenitors of pulsars are stars of masses $\sim 5M_\odot$. However, the stellar evolutionary calculations of Arnett (1969) have shown that the ignition of carbon in the degenerate cores of such stars is explosive and the entire star is disrupted without leaving any remnant. This puzzle was sought to be answered by the existence of the convectively driven URCA process carrying away the energy from the degenerate core. URCA process is nothing other than a double beta decay, i.e., an electron capture followed by an electron emission; in both the processes, a neutrino is emitted as follows:

$$e^- + (Z,A) \longrightarrow (Z+1, A)^* + \nu$$

$$(Z+1, A)^* \longrightarrow (Z,A) + e^- + \bar{\nu}$$

This process is supposed to stabilise the core carbon burning and detailed analyses by Paczynskii (1972, 1973) and Ergma and Paczynskii (1974) have shown that this is marginally sufficient. The existence of neutral currents might open up the possibility of increasing the neutrino emission and hence the core can be stabilised easily. Further, the evolution to the carbon burning stage might be affected in such a fashion that the temperature-density conditions in the core may inhibit the formation of completely degenerate carbon ccre. Such detailed calculations are in progress at various laboratories.

(b) **Neutrinos as Energy Carrier to the Envelope of the Star :—**

The role of neutrinos as agents to receive the energy from the core to deposit it in the envelope is an important one in the supernova explosion. Colgate and White (1966) proposed that at the end of thermonuclear burning, the iron core might gravitationally collapse whilst the neutrinos might transport the gravitational energy outwards and deposit them in the envelope. However, Wilson (1971) found that the neutrino transport is not able to deposit sufficient energy in the envelope to initiate the blowing off of the envelope. The existence of semileptonic neutral current process of the coherent neutrino scattering mentioned earlier was used by Wilson (1974) to revive this possibility. His detailed calculations demonstrated that while this process seems to help the explosion, it seemed to be effective only if the value of a_0 in equation (7) exceds unity whereas experimentally $a_0 \approx 0.35$. This demand on the parameter, while being not ruled out, may be unnecessary if one takes into account the degenerate nature of the electrons in the core and also the leptonic processes are included in the evolutionary calculations (Schramm and Arnett 1975). In this connection note that Adler (1975) has shown that if the neutral currents were scaler instead of vector and axial vector, then for the same scattering cross section, the neutrino radiation pressure can increase more than ten-fold. The current picture of a supernova explosion as given below hinges crucially on the neutral current processes.

Throughout most of the collapse, the electrons are extremely degenerate. Hence electron capture neutrinos will be copiously emitted. The effect of degeneracy is shown to manifest in increasing neutrino mean free paths. Thus, while in the non-degenerate models, the neutrinos deposit the energy close to the core, in the degenerate models, the neutrinos diffuse out of the core and deposit this energy in the envelope. Further, the coherent scattering of the neutrinos off the nuclei in the envelope transfers the momentum to the nuclei and this aids the blow off of the envelope. A complete hydrodynamical calculation incorporating all these effects is not yet available and such a calculation might demonstrate usefulness of the new processes in a quantitative manner.

(c) **Early Universe :—**

Apart from the dramatic effects mentioned above, there may be other places of applications of neutral current to astrophysics. The scene that suggests itself immediately is the early universe where temperatures and densities may be high enough for all the effects of particle physics to play a role. The neutral current will affect the cross section for the neutrino-electron scattering as well as opens up the possibility of ν_μ e elastic scattering. These reactions might change the picture of the thermal equilibrium of the particles. However, the tempertuare density relation of the early universe, with its entropy in the form of relativistic particles, remains unaffected whether the neutrinos are in thermal equilibrium or not. Hence there is no noticeable change in the observable quantities, like the He abundance, due to neutral currents.

CONCLUSIONS :

The existence of neutral currents has been shown to have enormous significance in a few areas of astrophysics. In the stellar evolutionary sequence, the neutral currents might provide the right amount of energy loss by neutrino emission so that the complete disruption of some stars may be prevented. Thus the formation of neutron stars may be aided by neutral currents. Further, the neutrinos undergoing coherent scattering might be able to effectively transport energy and momenta from the collapsing core to the envelope of a star. This will result in the blowing off of the outer envelope, which is seen as a supernova explosion. Further, the removal of the outer envelope leaves the core to have the right mass to collapse to become a neutron star. Hence, a better understanding of the neutral current processes might clear the mist surrounding these astrophysical problems.

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