Cosmic Neutrino Radiation

Abstract. New and more powerful methods for eliminating background intensity are needed in order to make possible the development of neutrino astronomy into a new, far-reaching branch of science.

In a recent paper F. Reines and C. L. Cowan mentioned the future possibility of detecting the cosmic neutrino flux reaching the earth (*1*). We wish to present a more quantitative picture of this most penetrating radiation of the universe.

Today experimental technique makes possible the detection of a reactor antineutrino flux of intensity $\mathfrak{J} = 10^{13}\ \bar{\nu}$ $cm^{-2}\ sec^{-1}$ in the energy interval 2 to 6 Mev with satisfying accuracy; this corresponds to a reaction rate of $\mathfrak{J}\,\sigma \cong 10^{-30}\ \bar{\nu}\ sec^{-1}$ per nucleus. Reines and Cowan (*2*) made use of the reaction

$$\bar{\nu} + p \rightarrow n + e^{+} \qquad (1)$$

(energy threshold 1.8 Mev). A neutrino flux may also be detected, with roughly comparable accuracy, by making use of the Pontecorvo-Davis reaction (*3*):

$$\nu + Cl^{37} \rightarrow Ar^{37} + e^{-} \qquad (2)$$

(energy threshold 0.8 Mev). It is hoped that the detection threshold can be lowered in the near future by one or two orders of magnitude, without extensive modification of the experimental method (*4*).

Apart from nuclear reactors, the sun is the most intensive source of neutrinos for laboratory observations; several percent of its energy production is carried off by the neutrino current ($\mathfrak{J} > 10^{10}\ \nu\ cm^{-2}\ sec^{-1}$ at the earth). If the fundamental fusion process taking place in the central part of the sun is the C-N cycle, the β^{+} activity of the isotopes N^{13} and O^{15} has to be taken into account as a source of neutrinos. Since the energy spectrum of these nuclei is known, the average cross section of reaction 2 is theoretically computable: $\sigma = 10^{-43}\ cm^2$, and this results in a reaction rate $\mathfrak{J}\,\sigma \cong 0.6 \times 10^{-32}\ \nu\ sec^{-1}$. If, however, the fundamental energy-producing process of the sun is direct H-D fusion, ending in

$$He^{3}\,(He^{3}, 2p)\,\alpha$$

the energy of the neutrinos originating from the reaction

$$2p \rightarrow D + e^{+} + \nu$$

lies lower than the threshold for the entire capture reaction (reaction 2), and consequently $\mathfrak{J}\sigma = 0$ (Fig. 1) (*5*).

According to the recent suggestion of W. A. Fowler (*6*), another possibility for completion of the H-D chain is

$$He^{3}\,(\alpha, \gamma)\,Be^{7}\,(e^{-}, \nu)\,Li^{7}\,(p, \alpha)\,\alpha$$

and this supplies neutrinos with energy comparable to those of the C-N cycle. The second neutrino of this chain is of low energy, so one arrives at an unexpected reaction rate $\mathfrak{J}\sigma \cong 0.3 \times 10^{-32}$ $\nu\ sec^{-1}$. It is possible, however, that the same chain is completed via

$$Be^{7}\,(p, \gamma)\,B^{8}\,(\beta^{+}\ \nu)\,Be^{8}\,(\alpha)\,\alpha$$

and the B^8 nucleus emits neutrinos with very high energy (end point at 14.1 Mev).

The abundance of this reaction depends on the (unknown) p capture cross section of Be^7. If the Be-B branch is supposed to give the whole energy production of the sun, with the calculated average neutrino capture cross section $\sigma = 2 \times 10^{-42}\ cm^2$, one arrives at the high detection rate $\mathfrak{J}\sigma \cong 8 \times 10^{-32}\ \nu\ sec^{-1}$. It is to be expected that a detection threshold of $\mathfrak{J}\sigma = 10^{-32}\ \nu\ sec^{-1}$ will be reached in a reasonable time; in this case one would be able to decide experimentally about the character of the fusion processes taking place in the inner part of the sun, and this would be equivalent to empirical determination of the temperature at the center. (Photons give us information—as a result of their smaller penetrating power—only about the surface temperature of the sun.)

It is impossible to find any difference between a distant celestial body built up from common matter and another one built up from antimatter (*7*) by observing their light, but in principle it would be possible to find a difference by observing their neutrino radiation (that is, $\gamma \equiv \bar{\gamma}$, $\nu \not\equiv \bar{\nu}$). (A star similar to our sun is a neutrino-emitter, but a star built up from antiatoms would be an antineutrino-radiator.) Whether this possibility will become available seems very questionable today. The problem of the "neutrino telescope" is discussed below.

The result of the small capture cross section of the neutrino is that the mean free path of the neutrinos of the 1 to 10 Mev energy region in the universe amounts to about 10^{30} light-years (that of the antineutrino is a little less). From this it follows that neutrino radiation offers a very useful opportunity for observation of events very distant in space and time (in principle, up to 10^{30} light-years and 10^{30} years, respectively), provided, naturally, that the problem of detection can be solved. For example, the character and intensity of the neutrino radiation reaching the earth from outside the solar system are very sensitive indicators of the way in which the chemical elements are formed. If the universe can be considered to be in a steady state, and if the origin of heavier nuclei is connected with the fusion of hydrogen in stars, the average neutrino density has to be equal to the density of neutrons; thus, a flux of $\mathfrak{J} \approx 10^{5}\ \nu\ cm^{-2}\ sec^{-1}$ is to be expected.

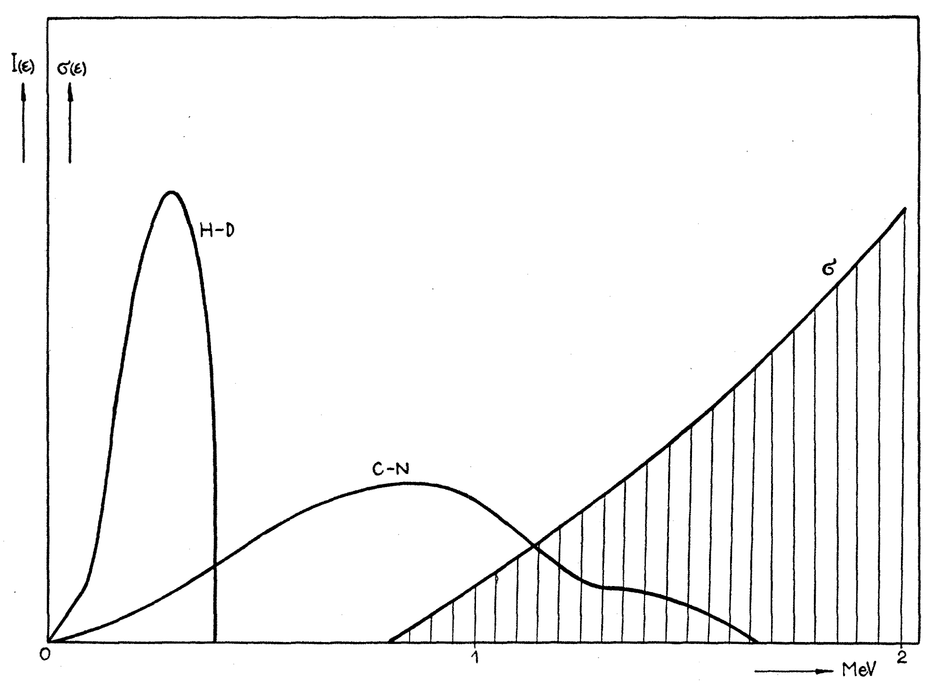

Fig. 1. Energy dependence of the cross section for neutrino detection and energy spectrum of neutrinos emitted in the H-D and C-N type fusion processes. (For the H-D-Be-B branch, the intensity becomes perceptible only above 2 Mev.)

The energy spectrum of this flux is similar to that of the sun, but in an expanding steady-state universe [suggested by the theory of Bondy and Gold (*8*)], the energy distribution is still lower as a result of the Doppler shift. One gets a reaction rate $\mathfrak{J}\,\sigma < 10^{-38}$ ν sec^{-1} for this flux, which is certainly a very small value. The antineutrino flux can be neglected.

If, on the other hand, the birth of heavy nuclei took place in an early, compressed state of the expanding universe, one would expect much more intensive neutrino radiation. In the highly compressed state of matter most of the nucleons had to be in a neutron-rich state, and during the formation of the proton-rich state of today, also an antineutrino flux of relatively high energy distribution and of relatively high intensity had to be emitted: $\mathfrak{J} \approx 10^7$ $\bar{\nu}$ cm^{-2} sec^{-1} [that is, the density of the neutrinos has to be comparable to the proton density (*9*)]. This corresponds to a detecting reaction rate $\mathfrak{J}\,\sigma \approx 10^{-35}$ $\bar{\nu}$ sec^{-1}. If the compressed state of matter were connected with a high temperature, a thermal neutrino and antineutrino radiation of considerable density also would have originated. Thermodynamic equilibrium between neutrinos and atoms can be attained in a state of nuclear density in microseconds; in a state of stellar density, in years; and in a state of the average density of today, in about 10^{30} years. This means that after a certain stage of expansion no interaction takes place any longer and the hot neutrino-antineutrino gas "freezes"; the intensity and spectrum of the gas are no longer regulated by the atomic interactions but by the adiabatic expansion. According to the laws of thermodynamics, experimental detection below a neutrino temperature of 10^{8}°K is not possible. An observed equal intensity of neutrino and antineutrino flux would be explicable on the basis of an origin connected with thermodynamical equilibrium. There seems to be only one other explanation: If celestial bodies built up from common matter and celestial bodies built up from antimatter are isolated from each other and occur in the universe in equal abundance—that is, if not only the physical laws but also the physical state of the universe are invariant with respect to PC transformation, being neutral with respect to electric charge and baryonic charge at the same time, the average neutrino and antineutrino density would be equal everywhere (*7*).

The answer to the question of whether the detection of neutrinos will make it possible to decide between the different cosmogonical views depends on whether the detection threshold attainable today, $\mathfrak{J}\,\bar{\sigma} = 10^{-30}$ $\bar{\nu}$ sec^{-1}, can be diminished by several orders of magnitude. The most difficult problems of decisive importance are that of eliminating the much more dominant neutrino radiation emitted by the sun and that of the antineutrino flux of terrestrial radioactivity; this background intensity is of a greater order of magnitude than the cosmic flux to be detected. Neutrinos of high energy distribution are emitted in the atmosphere also by the decaying mesons generated by cosmic rays, but the total intensity of this radiation is nevertheless negligible as compared to the neutrino fluxes mentioned above. The anisotropic angular distribution of the electron emission in certain neutrino capture reactions would serve as a useful basis for the construction of a "telescope" differentiating neutrinos of terrestrial or solar origin and neutrinos of stellar origin, respectively. The differential cross section of the capture reaction is as follows:

$$\sigma(\theta)\,d\Omega = \frac{f^2}{16\pi^2\hbar^4c^3}\left\{\left|\int 1\right|^2\left(1+\frac{v}{c}\cos\theta\right) + \left|\int \sigma\right|^2\left(1-\frac{1}{3}\frac{v}{c}\cos\theta\right)\right\} pE\,d\Omega$$

where θ denotes the angle between the direction of the captured neutrino and the emitted electron. In the case of reaction 1, the angular dependence of $\sigma(\theta)$ does not exist, but, for example, for the pure Gamow-Teller transition

$$\bar{\nu} + D \rightarrow n + n + e^{+} \qquad (3)$$

(energy threshold 4 Mev) one can draw conclusions about the direction spectrum of the incoming antineutrinos from the angular distribution of the positrons. Naturally this makes the telescope method applicable only for high-energy neutrinos and makes the possibility of detection much further away than is suggested by the accuracy $\mathfrak{J}\,\sigma = 10^{-30}$ $\bar{\nu}$ cm^{-2} sec^{-1} obtainable today. Another possibility would be that offered by measuring the neutrino energy spectrum—namely, by comparing the absorption rates in nuclei with different energy thresholds.

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Computer Analysis of Reflex Control and Organization: Respiratory Sinus Arrhythmia

Abstract. Respiratory sinus arrhythmia in waking man is described by differential equations which relate thorax circumference acceleration to instantaneous heart rate. Consequent experiments show that the arrhythmia is initiated by stretch receptors within the thorax rather than by hemodynamic or central factors, and that it is due mainly to superimposed biphasic inspiratory heart rate transients of about 15 seconds' duration. Analysis of respiration heart rate reflex provides a new quantitative physiological tool.

The changes in heart rate produced through changes in vagus inhibition, which accompany respiration, present both a varied and regular picture. The regularities appear as waves in the heart rate of the same frequency as the respiration. As a result of this regularity it has usually been assumed that a causal relation exists between inspiration and cardiac acceleration, and between expiration and deceleration (*1*). Certain investigators have observed, however, that the wavelike changes in the heart rate often show the opposite phasic relation to respiration (*2*). Recent work displays what appeared to look like a lag of one cycle between the respiration and the heart rate waves (*3*).

The irregularities in the heart rate trace have been difficult to relate to respiration. How much of the unwavelike and apparently irregular changes may be due to respiration as compared with other causes has remained undetermined. In order to investigate these conflicting results, we have applied the method of dynamic analysis as developed for automatic control system theory (*4*). Simulation by analog computer techniques, in experiments designed with the aid of control system theory, with unanesthetized human subjects, shows several results.

1) Two different biphasic reflexes are the main causes of changes in heart rate produced by respiration. One of these is produced only by inspiration and the other only by expiration. The two reflexes are both biphasic in the same direction. Each reflex first causes acceleration and then deceleration of the