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Observational Neutrino Astronomy

This branch of astronomy will provide information that cannot be obtained by conventional observations.

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A new branch of astronomy, observational neutrino astronomy, will yield its first positive results in 1965. This new branch of astronomy will provide (i) direct tests of the theory of nuclear energy generation in main sequence stars; (ii) some information about high-energy physics which is unobtainable with the available laboratory accelerators; (iii) a test of a hypothesis concerning the production of high-energy electrons in strong radio sources; and (iv) improved estimates of the average energy density in the universe. Moreover, the use of a radically different observational probe, neutrinos, may reveal unexpected phenomena, just as the more conventional fields of x-ray astronomy and radio astronomy have.

To understand the nature of neutrino astronomy, one must know the kinds of neutrinos which exist and the general characteristics of the forces which act on neutrinos. F. Reines has reviewed (*1*) our experimental knowledge of neutrinos and I therefore describe only those facts that are important for the currently envisioned astronomical observations.

Four kinds, or states, of neutrinos have been discovered (*1*). The first neutrino states found were the electron neutrino, ν_e, which appears, for example, when an argon-37 nucleus captures an atomic electron,

$$e^- + Ar^{37} \rightarrow \nu_e + Cl^{37}, \quad (1)$$

and the electron antineutrino, $\bar{\nu}_e$, which appears typically in ordinary neutron decay:

$$n \rightarrow p + e^- + \bar{\nu}_e. \quad (2)$$

More recently, two other neutrino states have been discovered (*1*), which appear in particle decays involving mu mesons. These new neutrino states are the muon neutrino, ν_μ, and the muon antineutrino, $\bar{\nu}_\mu$; they appear, for example, in the decays

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (3a)$$

and

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu. \quad (3b)$$

Here $\pi^\pm$ and $\mu^\pm$ are, respectively, charged pi and mu mesons, with masses 270 and 207 times the mass of the electron. Reactions 3*a* and 3*b* occur with a mean life of 2.6×10^{-8} second for pi mesons at rest. Strict selection rules exist forbidding certain reactions and decays; these selection rules enable one to distinguish among the four neutrino states.

Neutrinos of all kinds, however, are believed to interact with other particles primarily through "weak interaction" forces. These forces are so weak that a 10-Mev neutrino can pass through the entire earth with only about one chance in 10^{10} of being absorbed or scattered. This enormous penetrating power of neutrinos makes observational neutrino astronomy both difficult and exciting; the observations are difficult because large quantities (typically several tons) of material are required for detecting neutrinos, and they are exciting because the enormous penetrating power of neutrinos enables them to reach us from otherwise inaccessible regions of the universe.

In this article I discuss experiments to be performed in 1965 involving neutrinos from the sun, from the decay of cosmic-ray secondaries, and from strong radio sources. The foundations of the theoretical predictions and the significance of the experiments are emphasized. I also discuss briefly the role of neutrinos in cosmology.

Why Observe Solar Neutrinos?

The principal source of the energy radiated by main sequence stars like the sun is believed (*2*) to be the burning of hydrogen nuclei (protons) in the deep interiors of the stars, where the temperatures and densities are greatest. The nuclear reactions thought to be primarily responsible for the generation of energy in the sun are similar to the fusion reactions which occur in the explosion of a hydrogen bomb. The basic ideas of the theory of nuclear energy generation in main sequence stars are believed, by astronomers and physicists, to be correct, although no direct test of this theory has yet been possible. Since electromagnetic radiation has a mean free path of less than 1 centimeter under the conditions thought to exist in the sun's interior, no light can reach us from the interior regions of the sun. A direct test of the theory of stellar energy generation has been impossible hitherto because the collisions among nuclei that result in nuclear burning occur primarily in the deep interiors of the stars.

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All conventional astronomical observations are made on electromagnetic radiation emitted from the surfaces of stars. In our theoretical extrapolations from the observed conditions on the surfaces of stars to the vastly different conditions in the interiors of stars, have we overlooked anything crucial? It would be interesting to find out.

How can one test directly the theory of nuclear energy generation in stars? To make such a test, one needs to "see" into the deep interior of a star where the nuclear reactions are believed to occur; an information carrier with a mean free path of the order of 10^{11} centimeters (approximately the radius of the sun) is therefore required. Of the known particles, only neutrinos, with their enormous penetrating power, can enable us to "see" into the interior of a star. The observation of solar neutrinos would constitute the most direct test possible of the hypothesis that hydrogen-burning fusion reactions provide the principal source of the energy radiated by main sequence stars like the sun.

Even if one assumes that the theory of stellar energy generation is basically correct, there are other important reasons for trying to measure the intensity and energy spectrum of solar neutrinos. The long-range program should be a *neutrino-spectroscopic study of the solar interior*, as a means of determining quantitatively the conditions in the interior of the sun in much the same way that astronomers have already determined the conditions on the surface of the sun by photon spectroscopy. One can, for example, use neutrino absorbers with different energy thresholds to help determine the solar neutrino spectrum. Observations of this kind, which give information regarding conditions in the interior of the sun, are stringent tests of mathematical models describing the solar interior.

Recent theoretical (*3, 4*) and experimental (*5, 6*) results have changed qualitatively our ideas concerning the possibility of observing solar neutrinos. We consider first the theoretical developments.

Neutrino Production in the Sun

The hydrogen-burning fusion reactions in the sun are currently believed (*7*) to be initiated by the sequence

$$\mathrm{H}^1(p, e^+\nu)\mathrm{H}^2(p,\gamma)\mathrm{He}^3$$

and terminated by the sequences

$$\mathrm{He}^3(\mathrm{He}^3,2p)\mathrm{He}^4, \qquad \text{(i)}$$

$$\mathrm{He}^3(\alpha,\gamma)\mathrm{Be}^7(e^-,\nu)\mathrm{Li}^7(p,\alpha)\mathrm{He}^4, \qquad \text{(ii)}$$

and

$$\mathrm{He}^3(\alpha,\gamma)\mathrm{Be}^7(p,\gamma)\mathrm{B}^8(e^+\nu)\,\mathrm{Be}^{8*}(\alpha)\mathrm{He}^4. \qquad \text{(iii)}$$

Here, for example, He^3 represents an isotope of helium with a total of three neutrons and protons; the symbols p, α, e^-, e^+, γ, and ν represent, respectively, protons, alpha particles, electrons, positrons, gamma rays, and neutrinos. The net result of all of these sequences can be represented symbolically by the simple formula

$$4\,\mathrm{H}^1 \rightarrow \mathrm{He}^4 + 2e^+ + 2\nu_e \qquad (4)$$

(four protons are fused to form an alpha particle, two positrons, and two neutrinos), although the energies of the neutrinos emitted in each sequence differ. The carbon-nitrogen-oxygen cycle is believed to contribute only a few percent of the energy generation in the sun (*4*) and a negligible amount to the observable solar neutrino flux (*3*).

The rates for the hydrogen-burning fusion reactions listed above can be calculated as a function of stellar temperature and density with the aid of results from many laboratory experiments in low-energy nuclear physics and some elementary facts about nuclear reactions. The rate of the $\mathrm{Be}^7(p,\gamma)\mathrm{B}^8$ reaction which initiates sequence iii is, as we shall see later, crucial for the solar neutrino observations that are currently being planned. Unfortunately, the small cross section for this reaction at low proton energies has been measured only once (*8*), and its value is rather uncertain (*7*). This important laboratory experiment should certainly be repeated.

R. L. Sears and his collaborators (*4*) have calculated the neutrino fluxes (the numbers per square centimeter per second) at the earth's surface from all the nuclear reactions that are expected to be important in the sun. To predict the neutrino fluxes, Sears constructed mathematical models of the sun, with the aid of high-speed computing machines. More specifically, Sears numerically solved differential equations which state that at each point in the sun the pressure due to gravitational attraction is balanced by the gas pressure; the observed luminosity of the sun is attributed to the nuclear fusion reactions discussed above. These solar models require equations that describe the state of matter at high temperatures ($\sim 10^7$ degrees Kelvin) and high densities ($\sim$ 100 g/cm^3), as well as theoretical relations that describe the transport of energy under stellar conditions. Figure 1 is a schematic representation of the predicted solar neutrino spectrum.

Sears has also calculated the uncertainties in the theoretical values for solar neutrino fluxes which arise from uncertainties in our knowledge of the age, composition, and opacity of the sun, as well as our knowledge of nuclear parameters. On the basis of these calculations I estimate that our present knowledge of solar and nuclear parameters enables us to predict the most important neutrino fluxes with an accuracy of about $\pm$ 50 percent, provided the theories of stellar models and nuclear energy generation in stars are correct.

Neutrino Detection with Chlorine-37

R. Davis, Jr., of Brookhaven National Laboratory has proposed (*5*) a method of detecting solar neutrinos that makes use of the inverse electron-capture reaction,

$$\nu_e(\mathrm{solar}) + \mathrm{Cl}^{37} \rightarrow e^- + \mathrm{Ar}^{37}. \qquad (5)$$

B. Pontecorvo (*9*) first suggested, many years ago, that this reaction might provide a useful method of detecting neutrinos (Pontecorvo's epochal suggestions in nearly all new developments of neutrino astronomy and neutrino physics over the past 20 years include such diverse problems as neutrino energy loss from stars, high-energy neutrino experiments, and the role of neutrinos in cosmology). Notice that reaction 5 is the inverse of reaction 1, which describes the decay of radioactive argon.

On the basis of experience gained in a preliminary experiment involving two 500-gallon (1900-liter) tanks of perchlorethylene, C_2Cl_4 (an ordinary cleaning fluid), Davis and D. S. Harmer have undertaken an experiment in which a 100,000-gallon tank of perchlorethylene is used as a detector. Their detection system, based on reaction 5, requires an amount of cleaning fluid that would fill an Olympic-sized swimming pool. The most important features of their detection system are as follows: (i) tiny amounts ($\sim$200 atoms per month) of neutrino-produced Ar^{37} can be removed from the large volume of liquid detector (with 90 percent efficiency) by the simple procedure of sweeping the argon out of the liquid with helium gas; and (ii) the characteristic decay of Ar^{37} can be observed in a counter with essentially zero background.

In order to relate the observed number of Ar^{37} atoms produced per day in the proposed experiment to the solar neutrino fluxes, one must know the probability (cross section) that a neutrino of a given energy, incident on a Cl^{37} atom, will cause reaction 5. The reaction probabilities (average cross sections) have recently been calculated (*3*) for all neutrino sources believed to be important in solar energy generation. The calculations were performed by making a mathematical model of Cl^{37} and Ar^{37} nuclei; this model includes excited nuclear states of Ar^{37} which are crucial for the solar neutrino experiment but which have not yet been observed in the laboratory. The theoretical model has been used to make related predictions which can be tested experimentally and hence can be used to determine the accuracy of the model; a number of these experiments are currently being performed by nuclear physics groups in this country. Stimulated in particular by the experimental work (*10*) on potassium-37 of R. W. Kavanagh and D. Goosman of the Kellogg Radiation Laboratory, C. A. Barnes and I have recently pointed out (*11*) that the nuclear parameters necessary for predicting the rate of reaction 5 can be determined experimentally by studying the decay of the radioactive isotope calcium-37. The isotope Ca^{37} has not yet been observed in the laboratory [the prediction has been made (*3*) that Ca^{37} decays by positron emission in about 150 milliseconds], but it is currently being sought by at least one experimental group (*12*). The decay of Ca^{37} should be particularly informative because this decay is, in a technical sense, the mirror image of reaction 5.

Combining the results from the nuclear-model calculations with Sears's predictions for neutrino fluxes, I found that the neutrinos from B^8 decay (sequence iii), which have a maximum energy of about 14 Mev, should produce 90 percent of the observable reactions in the proposed experiment of Davis. The neutrinos from boron-8 decay, although they constitute less than 0.1 percent of the total solar neutrino flux (see Fig. 1), produce most of the reactions, because they are the most energetic of the neutrinos that are expected to come from fusion reactions in the sun. Calculations based on the best current estimates of all known uncertainties yield the following prediction for the number of neutrino captures per day:

$$(3.6 \pm 2) \times 10^{-35} \text{ per atom of terrestrial } Cl^{37} \text{ per sec.} \qquad (6)$$

This prediction corresponds to between 4 and 11 predicted solar neutrino captures per day in the 100,000-gallon experiment, with an estimated background (*5*) of less than 0.5 capture per day.

William A. Fowler, in his original discussion (*13*) of the solar neutrino flux from B^8 decays, showed that the B^8 neutrino flux is a sensitive function of the central temperature of the sun. This temperature sensitivity exists because the Coulomb barrier is large relative to solar thermal energies for the reaction $Be^7(p,\gamma)B^8$ of sequence iii. An experimental upper limit for the central temperature of the sun can therefore be obtained by combining the result of the preliminary experiment (*5*), which provides an upper limit for the number of neutrino captures per second per Cl^{37} atom, with the predicted rate (see relationship 6) and the known temperature dependence of the $Be^7(p,\gamma)B^8$ reaction. In calculating this upper limit

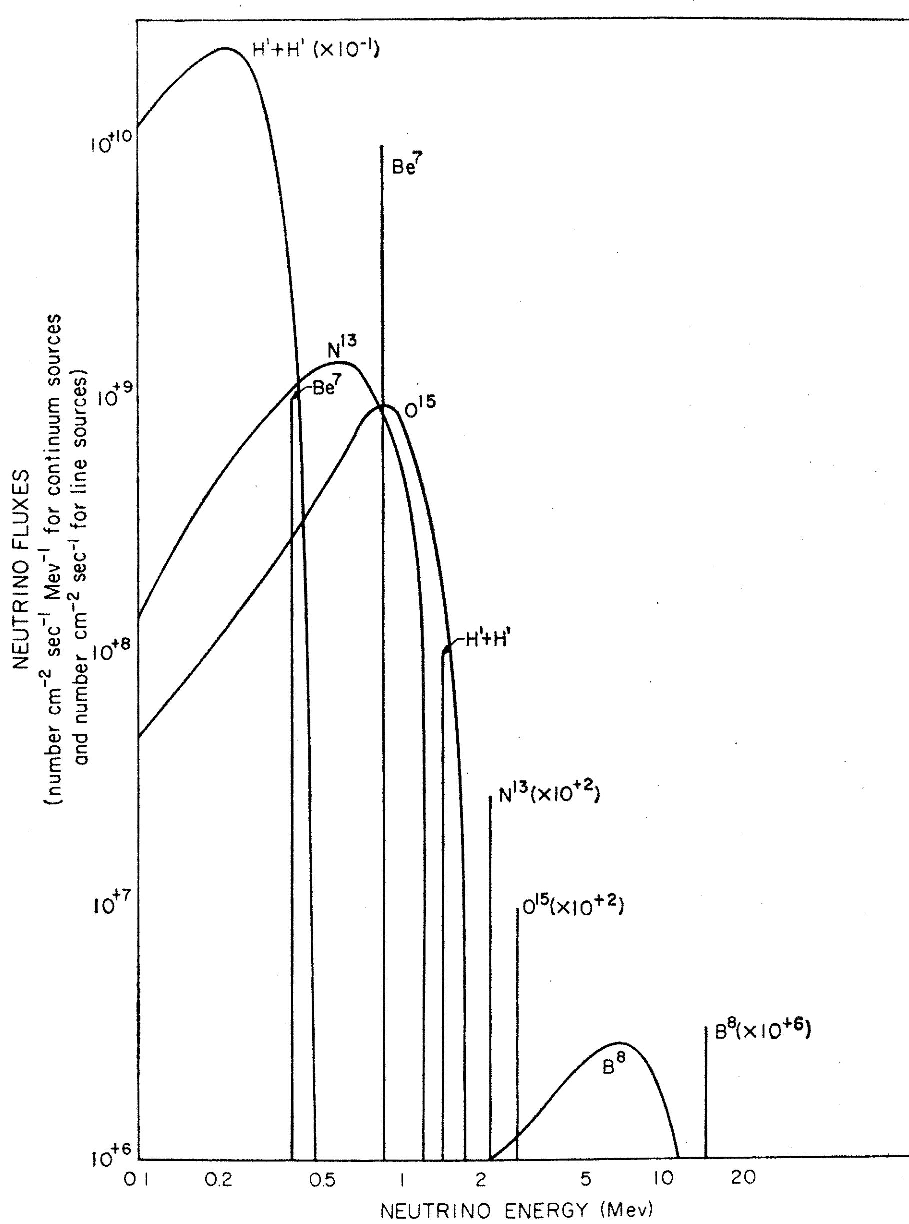

Fig. 1. Predicted neutrino spectrum from the sun. Fluxes given here are evaluated at the earth's surface. The neutrino lines are produced by the capture of free electrons; the small thermal widths ($\sim$ 1 kev) of these lines have been neglected in the figure. (See *3* and *4* for detailed information regarding the neutrino spectrum and the neutrino-producing reactions.)

for the central temperature, one can treat the solar luminosity and all other solar variables except the temperature as approximately constant, because the temperature dependence of the $Be^7(p,\gamma)B^8$ reaction rate is roughly exp$-[150\ T_6^{-1/3}]$, where T_6 is the temperature in millions of degrees Kelvin. One can show that the preliminary experiment implies that the central temperature of the sun must be less than 20 million degrees, and that a measurement of the B^8 neutrino flux accurate to $\pm$ 50 percent would determine the central temperature of the sun to $\pm$ 10 percent.

The expected cost of the Davis-Harmer experiment is about $600,000; it is nevertheless easy to show that this experiment can be considered a moderately priced thermometer for determining the sun's central temperature. An ordinary room thermometer costs approximately $4 and can measure temperatures up to about 400°K—that is, at a cost of about 1 cent per degree Kelvin. The proposed solar thermometer, which is designed to measure temperatures of the order of 16 million degrees, will cost only about 4 cents per degree Kelvin, and thus is not particularly expensive.

In a more serious vein, note that a positive result from the experiment of Davis and Harmer is subject to some ambiguity in interpretation because some of the observed neutrinos might come from the galaxy instead of the sun; present estimates of the probable galactic background indicate, however, that it is negligibly small. Davis (*5*) has pointed out that one method of distinguishing between solar and galactic neutrinos is to take advantage of the eccentricity of the earth's orbit about the sun to measure the expected 7 percent difference in the neutrino flux measured when the earth is at aphelion and perihelion. If the signal is as low as 7 captures per day, the success of such a method will be marginal; if a somewhat higher signal is observed, it will be possible to test for the seasonal variation of the neutrino flux.

Neutrino-Electron Scattering

F. Reines and W. R. Kropp have recently proposed (*6*) an experiment in which the solar neutrino flux is to be studied by observation of electron scattering by neutrinos; that is,

$$\nu_e(\text{solar}) + e \rightarrow \nu_e' + e'. \qquad (7)$$

Neutrino-electron scattering is, in principle, a source of information about the neutrino energy spectrum through the observation of the recoil energies of the scattered electrons. Moreover, under the experimental conditions suggested by Reines and Kropp, one can easily show (*14*) that the observed recoil electrons will be confined to a cone with opening angle of approximately 10 degrees with respect to the direction of the incident neutrinos. Thus, the observation of neutrino scattering by electrons can, in principle, enable one to determine the direction (presumably toward the sun) of a low-energy (~10 Mev) extraterrestrial neutrino source.

The conserved-vector-current theory of weak interactions (*15*) can be used to predict the probability of occurrence of reaction 7; the cross section (or reaction probability) is, in this theory, determined primarily by the rates of the familiar oxygen-14 and neutron beta decays. Reines and Kropp have already performed a preliminary experiment which consisted of looking for counts due to electrons with energy greater than 8 Mev in a 200-liter liquid scintillation detector. Their scintillation detector was surrounded by a large Cerenkov anticoincidence shield and was located 600 meters underground (to decrease background from cosmic-ray secondaries) in a salt mine. Their upper limit for the magnitude of the flux of neutrinos from solar B^8 decay times the value for the average cross section for reaction 7 is greater by only a factor of 20 than the value predicted by the symbolic product

$$(\text{Solar model theory}) \times (\text{conserved-vector-current theory}).$$

Neutrinos from Cosmic-Ray Secondaries

Primary cosmic rays produce neutrinos as a result of collisions with nucleons in the earth's atmosphere. A typical reaction of this kind, in which neutrinos are produced by the decay of cosmic-ray secondaries, is (here p represents a proton):

$$p_{\substack{\text{cosmic}\\\text{ray}}} + p_{\substack{\text{earth's}\\\text{atmosphere}}} \rightarrow \text{nucleons} + \text{mesons} \qquad (8a)$$

$$\rightarrow \text{nucleons} + \text{electrons, gamma rays, and neutrinos.} \qquad (8b)$$

The transition from the system represented by the right hand side of reaction 8*a*, in which mesons are present, to the system represented by 8*b*, in which only stable particles are present, occurs by way of mesonic decay processes such as the pion decay shown in reactions 3*a* and 3*b*.

Cosmic-ray primaries are now known to contain particles with energies as high as 10^{19} electron volts, some 10^8 times the highest energies currently attainable with man-made accelerators. Moreover, the spectrum and intensity of neutrinos from the decay in the earth's atmosphere of cosmic-ray secondaries can be calculated (*16*) from the well-known spectrum of cosmic-ray muons at sea level. The original reason for trying to observe neutrinos from the decay of cosmic-ray secondaries was, therefore, to use this known source of energetic neutrinos to study the properties (such as form factors and resonances) of neutrino interactions (weak interactions) at energies which cannot at present be reached with man-made accelerators. However, as we shall see later, experiments designed to study cosmic-ray neutrinos can also be used to provide information about some astronomical systems—in particular, strong radio sources.

Several experiments for detecting neutrinos produced by mesonic decays in the earth's atmosphere are under way. At least two of these experiments are currently being installed deep underground (to decrease background effects) and should be operating within a few months. The University of Utah group, under the direction of J. W. Keuffel and H. E. Bergeson, is installing an experimental facility in a mine 600 meters deep near Park City, Utah. This facility is expected to have excellent directional resolution in detecting the reaction products of high-energy neutrinos (*17*). Another group (*18*), headed by F. Reines of the Case Institute of Technology and J. P. F. Sellschop of the University of Witwatersrand, is testing a neutrino-detection system in a mine 3150 meters deep near Johannesburg, South Africa. The detection systems being employed in the Utah and South African experiments are different and will provide complementary information.

Deep-mine studies of the kind mentioned above can provide unexpected information about high-energy physics. For example, S. C. Frautschi and I have recently shown (*19*), using the results (*20*) of an experiment performed by the Tata Institute Group in a deep mine in the Kolar Gold Fields, that there are no "resonances" in the ν_μ-nucleon systems for neutrinos with laboratory energies of less than 2×10^3 Gev and no "resonances" in the ν_e-nucleon systems for laboratory neutrino energies of less than 30 Gev. When we speak of a neutrino-nucleon resonance at a particular energy, we mean that the probability for the reaction becomes as large as is theoretically possible, a phenomenon associated with the production of a specific intermediate state in a reaction.

Neutrinos from Strong Radio Sources

Recent observations (*21*) of radio waves emitted from some radio sources outside our galaxy have led to the conclusion that these radio sources emit energy at a mysteriously high rate. Frautschi and I, stimulated by unpublished observations by C. L. Cowan, investigated (*22*) the possibility of detecting neutrinos from strong radio sources. Our aim in this investigation was to find a way in which neutrino observations could add to the knowledge of radio sources obtained through electromagnetic observations. Unfortunately, one can show on the basis of simple arguments concerning the amount of energy emitted by these objects in the form of electromagnetic radiation that the neutrino fluxes which might be expected from radio sources are too small to be detected in practical experiments (to detect one neutrino-induced event per day would require 10^5 tons of material) *unless* some resonance (that is, exceptionally large probability of occurrence of a reaction at a particular energy) exists in neutrino interactions. The only practical laboratory targets for neutrinos are electrons and nucleons. Having analyzed several deep-mine cosmic-ray studies and neutrino experiments performed with high-energy laboratory accelerators, Frautschi and I are convinced that the only resonance which can be expected with the available laboratory targets is one proposed several years ago by S .L. Glashow (*23*)—namely, a resonance in the $\bar{\nu}_e$-e^- system.

This predicted resonance in $\bar{\nu}_e e^-$ scattering would be due to the production of the famous W^- boson (*1*), which, according to hypothesis, mediates the weak interactions in much the same way that photons mediate the electromagnetic interactions. The large cross section for a neutrino interaction associated with this resonance is expected to obtain at a neutrino energy greater than 10^3 Gev, corresponding to a mass for the intermediate boson of greater than 1 Gev. Guesses for the neutrino energy at resonance and for the mass of the intermediate W^- boson are currently in the ranges 4×10^3 Gev and 2 Gev, respectively. These numbers are only guesses at present, and for reliable values one must await the results of experiments being performed at high-energy physics laboratories.

To predict counting rates produced by neutrinos from strong radio sources, Frautschi and I advanced three hypotheses. The first is that the *highest*-energy electrons (several thousand Gev) inferred to exist in strong radio sources are produced by the Burbidge mechanism (*24*):

$$p + p \rightarrow \text{nucleons} + \text{mesons} \qquad (9a)$$

$$\rightarrow \text{nucleons} + \text{electrons, gamma rays, and neutrinos.} \qquad (9b)$$

Reactions 9*a* and 9*b*, which were assumed in our predictions to be occurring now in the radio sources of interest, are the same as reactions 8*a* and 8*b* except that in reactions 9*a* and 9*b* all interactions occur inside the radio source. The second hypothesis is that magnetic fields in the strong radio sources are in the range 10^{-5} to 10^{-3} gauss; the precise values of the fields were obtained from the theory of synchrotron radiation by an argument involving minimization of the total energy computed to exist in particles and fields. Finally, we assumed that the mass of the W^- meson is of the order of 1 Gev.

Using these three hypotheses, we predicted neutrino fluxes as a function of neutrino energy for various radio sources that have been observed to emit optical synchrotron radiation. The reason for confining the predictions to these radio sources is that the high neutrino energies necessary to excite the W^- resonance correspond to high-energy electrons which radiate predominantly in the optical range. Since reactions 9*a* and 9*b* produce gamma rays as well as neutrinos, we were also able to predict, with the same hypotheses, gamma-ray fluxes from strong radio sources.

The most promising method we proposed for testing the predictions, and hence the hypotheses upon which the predictions are based, was that of using the earth's crust as a neutrino target. In this scheme, high-energy neutrinos from radio sources are converted by interactions with terrestrial electrons into high-energy muons which are ultimately detected. The basic resonant reaction is then:

$$\bar{\nu}_e - e^- \rightarrow (W^-) \rightarrow \nu_\mu + \mu^-.$$

The angle which the muons from reaction 10 make with respect to the direction of the incident antineutrinos can be shown (*22*), from the principles of conservation of energy and momentum, to be $\lesssim (M_{W^-}c^2/q_{\text{lab}})$, where M_{W^-} is the mass of the W^- meson and q_{lab} is the laboratory neutrino energy at resonance. Since this angle is small ($\lesssim 10^{-3}$ radians), one can operate a neutrino telescope with the high-energy muons from reaction 10; this telescope has excellent angular resolution ($\sim 10^{-6}$ steradian).

The counting rates (~ 10 high-energy muons per square meter per year at a depth of 1 km) predicted from a number of radio sources on the basis of these considerations are detectable with equipment originally designed for observing neutrinos produced by cosmic-ray secondaries. At least two groups of experimentalists (*17, 18*) will be in a position to test our predictions in the coming year.

Neutrinos and Cosmology

Neutrinos play a major role in a number of cosmological speculations (*25, 26*). The essential fact with which all these speculations begin is that neutrinos interact so weakly with matter that a large, but as yet undiscovered, background of cosmic neutrinos could exist without contradicting any known facts. The mean free path of neutrinos with energies of the order of a few million electron volts to scattering or absorption by matter at cosmological densities is about 10^{48} centimeters—that is, the mean free path is about 10^{20} times the "radius of the universe." Because neutrinos interact so rarely with matter, the present upper limits on the possible cosmological energy density in the form of neutrinos and antineutrinos exceed by large amounts the estimates, based upon astronomical observations, of the average energy density of matter in the form of electrons and nucleons.

One interesting cosmological speculation (*25*) involves the supposition that a large cosmic-neutrino background actually exists and that this background consists of neutrinos and antineutrinos in equal numbers. Such a background of neutrinos and antineutrinos would make our universe symmetric with respect to matter and antimatter except for "small fluctuations" like the matter observed in our galaxy. Note, in this connection, that reaction 5, $Cl^{37}(\nu, e^-)Ar^{37}$, can occur only with neutrinos, but that reaction 7, neutrino-electron scattering, can occur both with neutrinos and with antineutrinos. Thus, if a detectably large background of neutrinos (or antineutrinos) exists, one can determine the ratio of matter (neutrinos) to antimatter (antineutrinos) in the cosmic signal. This kind of observation—which distinguishes matter from antimatter at astronomical distances—cannot be made with electromagnetic waves because the light from antiatoms is identical with the light from ordinary atoms (*28*).

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27. This work was supported in part by the Office of Naval Research [Nonr-220(47)] and the National Aeronautics and Space Administration [NGR-05-002-028]. Advances that have occurred since 1 September 1964 are not included in this review.

28. Developments in the field of neutrino astronomy that have occurred since 1 September 1964 are described in the article "Observational Neutrino Astronomy: a ν-Review," by J. N. Bahcall, which will appear in the Proceedings of the Second Texas Conference on Relativistic Astrophysics (to be published by University of Chicago Press).

Dynamics of Epidemics of Plant Disease

Population bursts of fungi, bacteria, or viruses in field and forest make an interesting dynamical study.

J. E. Van der Plank

The potato blight fungus survives the winter in diseased tubers. At the end of winter the potato stores are opened and diseased tubers are dumped outside in cull piles. Here the tubers sprout. The fungus invades the sprouts and in due course spreads from the diseased sprouts to young potato fields in the neighborhood. Alternatively, diseased tubers taken from the winter stores are planted as "seed." Shoots emerging from the seed become diseased, and from these primary diseased shoots the fungus spreads throughout the field, and from field to field. It has been found that in a very susceptible variety of potato there is about one primary diseased shoot per square kilometer of potato fields (*1*). To spread from the primary diseased shoots and destroy all the fields, the fungus must increase about a billionfold. In favorable conditions it can do this in less than 90 days.

That is a description of an epidemic process. Details of the process vary with the different blights, rusts, mildews, blasts, and other diseases that afflict our gardens, fields, orchards, forests, and plantations. But all epidemics have in common a dynamic process of increase of the pathogen—of the fungus, bacterium, or virus that causes the disease.

This dynamic process of increase is my topic, especially the rate of increase and the factors that govern the rate.

Originally the rate was studied largely with the practical aim of determining the best strategy for controlling the various diseases (*2*). But here I barely touch on practical problems of disease control and, instead, study the general pattern of disease increase, in the belief that understanding of the epidemiology of plant diseases can do much to illumine the wide problems of population dynamics.

In this study it is unnecessary to distinguish between an increase of disease in a population of plants and an increase of the population of the pathogen in these plants.

A Relative Infection Rate

To follow the increase of disease with time, we define an infection rate r as

$$\frac{dx}{dt} = rx(1-x) \qquad (1)$$

where x is the proportion of susceptible tissue infected at time t. The rate dx/dt is related both to the proportion x of

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