V. CONCLUSION

We have seen that the assumption of four neutrinos, ν_e, ν_e', ν_μ, and ν_μ', enables one to make the lepton-lepton and lepton-baryon weak interactions SU(3) symmetric. This simple scheme provides a rationale for writing down the weak interactions involving leptons, which is different from the (current)×(current) one. The SU(3) symmetric coupling automatically guarantees $\Delta Q=\Delta Y$ rule, no $\Delta Y=2$ and $\Delta T=\frac{1}{2}$ rule for leptonic decays. However, it introduces neutral lepton currents (though only $(\bar{\nu}\nu')$ and this seems to disagree with experiment. For this reason a broken SU(3) symmetry is considered. Further, we have shown that the weak interactions may satisfy, together with the electromagnetic interaction, a SU(2) symmetry which conserves K spin. This SU(2) symmetric model, however, gets into trouble with experiment if the CVC hypothesis is assumed.

We have not considered nonleptonic decays here. We believe that these should be treated separately and maybe examples of broken SU(3) Yukawa interactions of mesons and baryons which transform like $(F_6\pm iF_7)$ as has been suggested by various authors.[19]

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[19] N. Cabbibo, see Ref. 16 above. N. P. Chang, Nuovo Cimento (to be published). M. Gell-Mann, Phys. Rev. Letters **12**, 155 (1964). B. W. Lee, *ibid.* **12**, 62 (1964).

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Neutrino Astronomy and Intermediate Bosons*

JOHN N. BAHCALL AND STEVEN C. FRAUTSCHI
California Institute of Technology, Pasadena, California

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Neutrino fluxes from strong radio sources are estimated, assuming the neutrino-production mechanism: $p+p\rightarrow$ nucleons+mesons $\rightarrow$ nucleons+electrons, gamma rays, and neutrinos. The neutrino fluxes calculated on the basis of this mechanism are too small to be easily detected unless there are resonances in neutrino processes associated with the production of intermediate bosons. It is shown that a resonance in the antineutrino-electron system, associated with the usually hypothesized W^- resonance, could be used to test, with standard experimental techniques, whether strong radio sources emit high-energy neutrinos in the quantities estimated in this paper. Two kinds of observational tests are described and counting rates are estimated. Observational tests of the kind we propose would provide important information about: (1) the mechanism for production of high-energy electrons in strong radio sources, and (2) the magnetic fields in such sources. Some comments concerning other logically possible neutrino resonances are also included.

I. INTRODUCTION

A DIRECT test of the theory of solar energy generation, based upon the observation of low-energy neutrinos from nuclear reactions occurring deep in the interior of the sun, has recently been shown to be feasible.[1,2] Because the sun is much closer to us than any other star, the solar neutrino flux completely dominates the low-energy (i.e., several MeV) neutrino flux reaching the earth. Hence the sun is the only main-sequence star from which one expects to observe neutrinos.

In this article, we explore the possibilities of observing high-energy neutrinos from strong radio sources,[3] which are believed to possess high-energy $(0.3-10^{+3}$ BeV) electrons. We begin by estimating neutrino fluxes from radio sources and show that these fluxes are too small to be easily detected unless there are resonances in neutrino processes associated with the production of intermediate bosons. Two types of resonances are logically possible with the kinds of targets available in the laboratory: (1) a resonance[4,5] in the neutrino-nucleon system that possesses both lepton and baryon number; and (2) a resonance,[6] the usually hypothesized W^--meson, in the antineutrino electron system that possesses neither lepton nor baryon number. Cowan[7] has tentatively interpreted results of an experiment on

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[1] J. N. Bahcall, Phys. Rev. Letters **12**, 300 (1964).

[2] R. Davis, Jr., Phys. Rev. Letters **12**, 303 (1964).

[3] An excellent summary of the observational and theoretical literature has recently been given by G. R. Burbidge, E. M. Burbidge, and A. R. Sandage, Rev. Mod. Phys. **35**, 947 (1963).

[4] Y. Tanikawa and S. Watanabe, Phys. Rev. **113**, 1344 (1959); S. Oneda and Y. Tanikawa, *ibid.* **113**, 1354 (1959).

[5] T. Kinoshita, Phys. Rev. Letters **4**, 378 (1960).

[6] S. L. Glashow, Phys. Rev. **118**, 316 (1960). Some numerical errors that appeared in this manuscript have been corrected.

[7] C. L. Cowan, Bull. Am. Phys. Soc. **8**, 383 (1963), and private communication. A preprint of this work is now available.

cosmic neutrinos in terms of a type (1) resonance, i.e.,

$$\bar{\nu}_\mu + p \rightarrow (B_\mu{}^+) \rightarrow \mu^+ + n\,, \tag{1}$$

which would enable one to detect moderate energy (several hundred MeV) neutrinos. On the other hand, the W^- resonance, which is associated with a light target, could enable one to detect only very-high-energy ($\sim 10^{+3}$ BeV) neutrinos. Thus it is important to investigate whether previous experiments are consistent with the existence of the $B_\mu{}^+$ meson. We are able to show that the experimental results of Danby *et al.*[8] prove that the mass of the $B_\mu{}^+$ must exceed 2 BeV.[9]

This is, however, no evidence against a resonance in the antineutrino-electron system (W^- resonance). In fact, we are able to show that one can use the W^- resonance, if it exists, to obtain information about two important questions regarding strong radio sources that cannot be answered by observations of the radio emission alone. These two questions are: (1) What is the mechanism for the production of high-energy electrons in radio sources and (2) how large are the magnetic fields in such sources? We suggest some observations, involving standard experimental techniques, that can help answer these questions.

II. NEUTRINO FLUXES

A frequently discussed answer to the question of how high-energy electrons are produced in radio sources involves the following mechanism[3,10,11]:

$$p+p \rightarrow \text{nucleons} + \text{mesons} \rightarrow \text{nucleons} + \text{electrons, gamma rays, and neutrinos.} \tag{2}$$

We adopt mechanism (2) for the purpose of estimating neutrino fluxes[12] and assume, except where explicitly stated otherwise, that it is currently operative in radio sources.

The radio sources with which we are primarily concerned can be separated into two classes: (a) current optical synchrotron radiators (e.g. the Crab Nebula); and (b) current radio synchrotron radiators (e.g. Centaurus A).

The closest optical synchrotron radiator is the Crab Nebula. Using the observed[13] radio spectrum from the Crab, and equating photon and neutrino luminosities, we estimate a neutrino flux at the earth from the Crab Nebula given by:

$$n(q)dq \sim 10^{+2} q^{-1.6} dq \text{ cm}^{-2} \text{ yr}^{-1}, \tag{3}$$

where neutrino energies q are measured in BeV. We guess a high-energy cutoff in the neutrino spectrum, based upon uncertain estimates[13] of magnetic fields in the Crab, of about $2\times 10^{+3}$ BeV. We have also estimated a gamma-ray flux (due to π^0 decays) from the Crab; the gamma-ray flux is obtained from (3) by using the relation: $E_{\text{gamma}} \cong 2q$.[14]

Sandage[15] has kindly informed us that the optical radiation from the outer filaments of the radio galaxy M82 is almost completely polarized, indicating strong optical synchrotron radiation. We estimate neutrino and gamma-ray fluxes from M82 that are approximately 10^{-2} the fluxes given above for the Crab Nebula.

Current radio synchrotron radiators, class (b), probably possess electrons in the energy range $0.3-10$ BeV. For several of the most spectacular radio sources, the radio luminosity and the energy stored in the form of electrons, estimated from the synchrotron theory,[16] are given in columns two and three of Table I. If the process of electron and neutrino production is indeed continuous, then neutrino energy fluxes of the order

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[8] G. Danby, J.-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz, and J. Steinberger, Phys. Rev. Letters **9**, 36 (1962).

[9] The theory of Tanikawa and Watanabe (Ref. 4) does not lead to the verified consequences of the conserved vector current theory in any simple way. Hence we think it is probably incorrect. We have therefore ignored in our proposals of practical experiments the possibility of resonances in neutrino-nucleon processes that are not yet ruled out by previous experiments. It is nevertheless important for neutrino astronomy, as well as the theory of weak interactions, to carry the tests for possible resonances in neutrino-nucleon processes to higher energies.

[10] G. R. Burbidge, Astrophys. J. **127**, 48 (1958).

[11] Mechanism (2) produces more high-energy positrons than electrons. This fact must be carefully considered if one tries to explain cosmic rays as leakage from energetic ratio sources; observation at much lower energies ($\lesssim 1$ BeV) yield an e^+/e^- ratio $\lesssim \frac{1}{2}$ [J. De Shong, R. Hildebrand, and P. Meyer, Phys. Rev. Letters **12**, 3 (1964)]. At such low energies, direct acceleration of electrons already present in the radio source could well produce an excess of e^- over e^+. But at the highest energies considered in this paper ($\sim 10^{+3}$ BeV), we have assumed that the leptons are produced by proton-proton collisions. Thus we would predict, if radio sources produce most of the cosmic rays, that the e^+/e^- ratio should increase at high energies, approaching unity asymptotically.

[12] See in this connection the pioneering investigations of K. Greisen, in *Proceedings of the International Conference on High Energy Physics* (Interscience Publishers, Inc., New York, 1960), p. 209; and Ann. Rev. Nucl. Sci. **10**, 63 (1960). The neutrino cross sections used by Greisen do not include the effect, predicted by the conserved vector current theory, of nucleon form factors. Hence the neutrino cross sections used by Greisen are much larger than the nonresonant neutrino cross sections that we use.

[13] C. R. O'Dell, Astrophys. J. **136**, 809 (1963); J. H. Oort and T. Walraven, Bull. Netherlands Astron. Inst. **12**, 285 (1956).

[14] A stringent upper limit has been obtained for the flux of gamma rays from the Crab Nebula with energies in excess of 10^{+4} BeV [for references to this work, see J. V. Jelley and N. A. Porter, Quart. J. Roy. Astron. Soc. **4**, 275 (1963)]. This upper limit is, however, not inconsistent with our flux estimate since there is evidence (Ref. 13) for a rapid decrease in the optical synchrotron radiation from the Crab above 10^{+15} cps, i.e., electron energies of the order of $2\times 10^{+3}$ BeV.

[15] A. R. Sandage (private communication). For a discussion of the energetics of M82, see C. R. Lynds and A. R. Sandage, Astrophys. J. **137**, 1005 (1963). *Note added in proof.* New observations of the outer regions of M82 have been made by A. R. Sandage and W. C. Miller [Science **144**, 405 (1964)]. Their observations indicate an extensive system of filaments that appear to be radiating optical energy by the synchrotron process; Sandage and Miller conclude that the electron energies must be in the range 10^{+3}–10^{+4} BeV for reasonable magnetic field strengths (10^{-5}–10^{-6} G). These conclusions can be tested by the methods suggested above if the W^- resonance exists and mechanism (2) is operative.

[16] For values of the relevant distances and radio luminosities, see P. Maltby, T. A. Matthews, and A. T. Moffet, Astrophys. J. **137**, 153 (1963); M. Schmidt, Nature **197**, 1040 (1963); J. L. Greenstein and T. A. Matthews, *ibid.* **197**, 1043 (1963); and T. A. Matthews and A. R. Sandage, Astrophys. J. **138**, 30 (1963).

TABLE I. Radio sources.

Source	L_{radio} (ergs/sec)	$E_{\text{stored in electrons}}$ (ergs)	$L_{\mathrm{radio}}/4\pi R^2$ (BeV-cm^{-2} yr^{-1})
Centaurus A	$2\times 10^{+41}$	$1\times 10^{+58}$	2
Virgo A	$2\times 10^{+41}$	$1\times 10^{+57}$	0.3
Fornax A	$3\times 10^{+41}$	$1\times 10^{+58}$	0.2
Cygnus A	$4\times 10^{+44}$	$2\times 10^{+59}$	3
M82	$7\times 10^{+38}$	$1\times 10^{+54}$	0.01
3C48	$4\times 10^{+44}$	$1\times 10^{+58}$	0.1

of L_{radio}, with typical energies in the range 0.3–10 BeV, might be expected from the sources listed in Table I.

On the other hand, the production of energetic electrons and the accompanying neutrino emission may not be continuous but could take place in a brief initial burst. The duration of this burst might be expected to be less than the decay lifetime (10^{+2}–10^{+3} years) of electrons radiating in the optical synchrotron range.[17] In this case, we estimate that young radio and neutrino emitters would produce enormous neutrino luminosities, three or more orders of magnitude larger than the values of L_{radio} given in the first three rows of Table I. The large optical luminosities of quasistellar radio sources suggest[18] that these distant objects, e.g., 3C48, could be examples of such young radio and neutrino emitters.

One readily estimates, using the fluxes given above and neutrino cross sections predicted[19] with the conserved vector current theory, that about 10^{+5} tons of material would be necessary to obtain one neutrino-induced event a day from a strong radio source if no neutrino resonances exist.

III. ARGUMENT RULING OUT A LIGHT $B_\mu{}^+$

A resonance in reaction (1) would occur at a laboratory neutrino energy given by

$$q_{\mathrm{lab}}=\frac{M_B{}^2}{2M_N}\left[1-\left(\frac{M_N}{M_B}\right)^2\right], \tag{4}$$

where M_B is the boson mass and M_N is the nucleon mass. The intrinsic laboratory full widths for $B_\mu{}^+$ going to μ^++n or $\bar{\nu}_\mu+p$ satisfy[5]

$$\Gamma_{\mathrm{intr}}(\bar{\nu}+p)\approx\Gamma_{\mathrm{intr}}(\mu^++n)$$
$$\approx\frac{G}{2\pi}\frac{M_B{}^4}{M_N}\left[1-\left(\frac{M_N}{M_B}\right)^2\right]^3, \tag{5}$$

where $G=10^{-5}M_N{}^{-2}$. The effective laboratory full width is

$$\Gamma_{\mathrm{eff}}=2q_{\mathrm{lab}}\langle v/c\rangle_{\text{target nucleus}}\ \text{(classical Doppler shift)}. \tag{6}$$

For nucleons bound in a nucleus, $\langle v/c\rangle\approx\frac{1}{4}$. The effective laboratory cross section near resonance is

$$\sigma_{\mathrm{eff}}(\mu^++n)\cong 3\pi\lambda\!\!\!^{-2}\Gamma_{\mathrm{intr}}(\mu^++n)/\Gamma_{\mathrm{eff}}, \tag{7}$$

where $\lambda\!\!\!^{-}$ is the reduced wavelength in the center of mass. For $M_B=1.2\times 10^{+9}$ eV, one finds: $q_{\mathrm{lab}}=3\times 10^{+8}$ eV, $\Gamma_{\mathrm{intr}}(\mu^++n)=1\times 10^{+2}$ eV, $\Gamma_{\mathrm{eff}}=1.5\times 10^{+8}$ eV, and $\sigma_{\mathrm{eff}}(\mu^++n)=2\times 10^{-31}$ cm^2. The effective cross section defined by Eq. (7) is independent of boson mass.

We have analyzed the experiment of Danby *et al.*[8] using the observed number of muons produced in a given momentum interval and the estimated[20] neutrino fluxes. We find that the large effective cross section implied by a resonance in reaction (1) would require several orders of magnitude more muon production events than were observed by Danby *et al.* Hence, we conclude that $M_B>2$ BeV.[9,21]

IV. RESONANCE IN ANTINEUTRINO-ELECTRON SCATTERING

Glashow[6] has pointed out that the usual hypothesis[22] of a charged intermediate boson, without lepton or baryon number, leads to a resonance in anitneutrino-electron scattering, i.e.,

$$\begin{aligned}\bar{\nu}_\beta+e^-\to(W^-)&\to\bar{\nu}_\beta+e^-\\&\to\bar{\nu}_\mu+\mu^-\\&\to\pi^-+\pi^0\text{'s}.\end{aligned} \tag{8}$$

The formulas presented in (2) can be applied to the W^- resonance with only slight modifications: $M_B\to M_W$, $M_N\to m_e$, and $\langle v/c\rangle\to\alpha Z_{\mathrm{scr}}/n$, where Z_{scr} is the screened nuclear charge seen by an electron of principal quantum number n.

For the fashionable value $M_{W^-}\sim 1$ BeV, we find: $q_{\mathrm{lab}}=10^{+12}$ eV, $\Gamma_{\mathrm{intr}}(\bar{\nu}+e)=3\times 10^{+6}$ eV, and $\Gamma_{\mathrm{eff}}=(14Z_{\mathrm{scr}}/n)\times 10^{+9}$ eV. Assuming

$$\Gamma_{\mathrm{intr}}(\bar{\nu}+\mu^-)\approx\tfrac{1}{3}\Gamma_{\mathrm{intr}}(\text{total}),$$

we find $\sigma_{\mathrm{eff}}(\bar{\nu}+\mu^-)\cong(4n\times 10^{-}{}_{\mathrm{e}}{}^{0})/Z_{\mathrm{scr}}$ cm^2. If the earth's crust is used as a target, the average $\sigma_{\mathrm{eff}}(\bar{\nu}+\mu^-)$ per terrestrial electron is approximately 1×10^{-30} cm^2. The effective cross sections near resonance for reactions (8) are again independent of the mass of the intermediate boson.

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[17] From the ratio of optical and radio lifetimes alone, one might expect that objects in which such bursts were occurring would be some 10^{+4} times as rare as extragalactic radio sources. However, the great luminosity of objects in which energetic bursts are occurring could introduce a strong observational bias in their favor. Moreover, some systems in which high-energy electrons and neutrinos are produced may not have abailable the special physical conditions necessary for strong synchrotron radiation.

[18] G. R. Burbidge (private communication).

[19] T. D. Lee and C. N. Yang, Phys. Rev. Letters **4**, 307 (1960); T. D. Lee, P. Markstein, and C. N. Yang, *ibid.* **7**, 429 (1960); N. Cabibbo and R. Gatto, Nuovo Cimento **15**, 304 (1960).

[20] We are grateful to Professor L. M. Lederman for informing us that the neutrino flux in their experiment does not decrease rapidly below 0.3 BeV.

[21] A. Astbury and K. M. Crowe, Phys. Rev. Letters **11**, 234 (1960) searched for the $B_\mu{}^+$ but were only able to place an upper limit of 1090 MeV on the boson mass. J. V. Allaby, B. J. Gittelman, R. Prepost, D. M. Ritson, D. H. Coward, and B. Richter, Phys. Rev. **133**, B1514 (1964), showed that the mass of $B_\beta{}^0$ must exceed 1570 MeV by observing electron-proton scattering.

[22] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958); T. D. Lee and C. N. Yang, *ibid.* **119**, 1410 (1960).

The angle that the decay products of reactions (8) make with respect to the incident antineutrino direction is $\lesssim M_{W^-}/q_{\text{lab}}$, i.e., 10^{-3} rad. Hence, the muons, for example, from reaction (8) can be used to operate a neutrino telescope that has excellent angular resolution.

V. OBSERVATIONAL POSSIBILITIES

We suggest two observational methods[9] by which our flux estimates can be tested if the W^- resonance exists: (1) neutrino conversion in a detector; and (2) neutrino conversion in the earth producing muons that are ultimately detected.[23] A detector (e.g. a spark chamber or bubble chamber) that can be used to determine the line of flight of secondary particles and a clock to indicate the sidereal time of an event are necessary for both experiments in order to locate the astronomical source. Energy or charge discrimination could help eliminate background from cosmic ray secondaries, but such discrimination is not essential.

We estimate for method (1) a neutrino-induced reaction rate in a 10-m cube of material, with composition similar to that of the earth, of 10^{+2} reactions per year from the Crab Nebula and 1 reaction per year from M82.

If the earth is used as a target, as envisioned in method (2), we estimate a neutrino-induced counting rate at a depth of 1 km of 10^{-2} high-energy muons per cm^2 per year in the direction of the Crab and 10^{-4} per cm^2 per year in the direction of M82. The angular resolution, which is of the order of 10^{-6} sr, of a neutrino telescope operated by muons from the decay of the W^- resonance will not be appreciably affected by electromagnetic interactions of the muons in the earth. The muon background at a depth of 1 km from cosmic rays is $\lesssim 1$ muon per cm^2 per year.[24] The neutrino background from the decay of cosmic ray secondaries[11,25] is expected to be small because: (1) Most of these neutrinos are muon neutrinos and hence cannot excite the W^- resonance, and (2) the neutrino spectrum from cosmic ray secondaries is steeper than, for example, the neutrino spectrum we have calculated for the Crab. Hence the muon and neutrino backgrounds can easily be discriminated against by making use of the directional properties of the decay products of the W^- resonance.

If, for example, 3C48 is a young radio source in the process of formation, we estimate a neutrino-induced counting rate from 3C48 of about one-tenth the counting rate predicted for the Crab. If one were lucky enough to observe a young radio source at the distance of, say, Cygnus A, then one might have counting rates as large as 10^{+3} times those estimated above for the Crab.

The predictions in this section are based upon, in addition to the hypothesized W^- resonance, the assumed operation of mechanism (2) and a guess about magnetic field strengths.[26] Thus, observations of the kind outlined here can be interpreted in a way that gives significant information about radio sources.[27]

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[23] Professor Eugene Cowan has suggested an interesting variant of this experiment using a mountain as a target and taking advantage of the high rejection rate that is possible for muons coming in the opposite direction from the source.

[24] F. Ashton, Proc. Phys. Soc. (London) **77**, 587 (1961); J. Pine, R. J. Davisson, and K. Greisen, Nuovo Cimento **14**, 1181 (1959).

[25] For a complete treatment that includes kaon decays, see T. D. Lee, H. Robinson, M. Schwartz, and R. Cool, Phys. Rev. **132**, 1297 (1963).

[26] The cutoff particle energies corresponding to the observed cutoff frequencies in the optical synchrotron radiation depend strongly upon the assumed values for the magnetic fields. Thus, attempts to observe either high-energy gamma rays or neutrinos can give otherwise inaccessible information about magnetic fields in radio sources.

[27] After this work was completed, Professor F. Reines called our attention to the underground experiment described by M. G. K. Menon, P. V. Ramana Murthy, B. V. Sreekantan, and S. Miyake, Phys. Letters **5**, 272 (1963). This observation of muon intensities, performed at a greater depth than any previous observation, suggests that the neutrino flux from the Crab is an order of magnitude less than the estimate given in our paper. The result of Menon *et al.*, which is already of considerable significance, encourages us in the hope that additional tests of the predictions made in our paper will soon be forthcoming.