Are Neutrinos Stable Particles?*

John N. Bahcall, Nicola Cabibbo,† and Amos Yahil‡
Institute for Advanced Study, Princeton, New Jersey 08540
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It is pointed out that neutrinos with a finite mass could be unstable. We discuss the consequences of this possibility for solar-neutrino experiments.

It is generally assumed in textbooks on nuclear physics or elementary particles that neutrinos are stable particles. This assumption is necessary for the validity of the astrophysical conclusions that have been drawn[1] from the unexpectedly low counting rate in the currently operating Brookhaven solar-neutrino experiment.[2] In the context of solar-neutrino problems, it is convenient to adopt a limited definition of "stability"; we shall call a neutrino stable if the lifetime of a 1-MeV particle (typical energy expected for solar neutrinos) exceeds $\sim 5\times 10^2$ sec (the Sun-to-Earth light travel time). We show by examples that our present knowledge of neutrinos is insufficient to establish whether or not neutrinos are stable even in the very limited sense defined above. Our results provide a new possibility[3] for the interpretation of the ^{37}Cl experiment of Davis and his associates[2]; future experiments with solar neutrinos (see Table I) can determine whether the low counting rate in the ^{37}Cl experiment is due to neutrino decay or astrophysical uncertainties. We note in passing that our examples showing that ν_e need not be stable apply equally well to ν_μ, but we concentrate on ν_e since it is of most direct interest for solar-neutrino experiments.

Possible decay modes.—In order for a neutrino to be unstable, it must have a finite mass which may, however, be tiny. We assume for simplicity that the masses for all the decay products of ν_e are identically zero. The simplest example of a possible decay mode for ν_e is

$$\nu_e \to \nu' + \varphi, \tag{1}$$

where φ is a massless scalar or pseudoscalar boson[4] and ν' is some other neutrino that could be related to ν_μ or $\bar{\nu}_\mu$. If the coupling is of the form

$$h = g(\bar{\psi}_{\nu'}\psi_{\nu_e})\varphi \text{ or } g(\bar{\psi}_{\nu'}\gamma_5\psi_{\nu_e})\varphi, \tag{2a}$$

the mean decay lifetime for a neutrino of energy E and rest mass m is

$$\tau(E) = (16\pi\hbar/g^2mc^2)E/mc^2. \tag{2b}$$

The dimensionless coupling constant g can be written conveniently in terms of the relevant physical variables[5] as

$$g^2 = 1.7\times 10^{-14}\frac{E}{1\text{ MeV}}\left(\frac{60\text{ eV}}{mc^2}\right)^2\frac{500\text{ sec}}{\tau(1\text{ MeV})}.$$

Although the above value of g^2 suggest a rather weak interaction, an interaction of the same strength that allowed $\mu\to e+\varphi$ would lead to a partial lifetime shorter than the total observed muon lifetime and must be excluded. If ν' is identical to $\bar{\nu}_\mu$ or is unrelated to muon neutrinos, this exclusion can be achieved by known selection rules. If ν' is identified with ν_μ, then the exclusion of the $\mu\to e+\varphi$ coupling requires an *ad hoc* assumption. We note also that values of g^2 orders of magnitude larger than 10^{-14} are possible without

TABLE I. Implications for future experiments (see Ref 8). All counting rates are expressed in units of 10^{-36} captures per target atom per second.

Assumed ^{37}Cl capture rate	Assumed explanations	^{7}Li capture rate	^{87}Rb capture rate	ν-e scattering
1.5	Standard solar models incorrect	15±1 (Ref. 1)	5×10^2	Mostly low-energy neutrinos are scattered
	Most neutrinos decay [τ(1 MeV) = 33 sec]	5	1	Mostly high-energy ^{8}B neutrinos are scattered
≤ 0.4	Standard solar models very wrong	9	4×10^2	Only low-energy neutrinos are scattered
	Almost all neutrinos decay [τ(1 MeV) = 18 sec]	1	3×10^{-1}	Only high-energy ^{8}B neutrinos are scattered: intensity very low

violating any known experimental results, permitting much smaller values of τ or m than 500 sec or 60 eV.

More complicated decay schemes than Reaction (1) are in principle possible,[6] e.g., (i) $\nu_e \to \nu' + \varphi_1 + \varphi_2$; (ii) $\nu_e \to \nu' + V$; and (iii) $\nu_e \to \nu_1 + \nu_2 + \nu_3$, where V is a massless vector particle and φ_i and ν_i are other massless scalars and neutrinos, respectively. Process (iii) can be ruled out since it would require (for a ν_e unstable in our sense) a muon partial lifetime (via $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_1 + \nu_2 + \nu_3$) that is much shorter than the observed total lifetime. From a cursory examination of muon decay data,[7] we estimate that if ν_e is unstable through processes (i) or (ii) then $\tau(1\ \text{MeV}) \gtrsim 10^{-1}$ sec, so that we cannot exclude the possible role of (i) or (ii) in solar-neutrino experiments.

Astrophysical consequences.— The major astrophysical consequences of our considerations are illustrated in Table I. We consider two general classes of explanation for the unexpectedly low counting rate in the ^{37}Cl experiment: (1) Something is wrong with the theory of solar models (see Ref. 1 for specific possibilities); and (2) most of the neutrinos produced in the sun decay before they reach the Earth. In order to make our discussions more definite, we have calculated the expected counting rates for three kinds of targets (^{7}Li, ^{87}Rb, and ν-e scattering) that have been proposed[8] as possible solar-neutrino detectors; our calculations are given for two assumed levels of counting rates in the ^{37}Cl experiment, namely, the 1.5-SNU (1 solar-neutrino unit = 10^{36} captures per target particle per second) level tentatively reported by Davis, Rogers, and Rodeka[2] and ≤ 0.4 SNU (which represents approximately the ultimate sensitivity of the experiment). We calculated rows 2 and 4 of Table I assuming that the standard solar models are correct and that the failure to observe the predicted 9 SNU is due entirely to neutrino decay. For rows 1 and 3, we have made the opposite assumption, namely, that neutrinos are stable. We adopted for row 1 the suggestions for modifying the standard solar models given in Ref. 1. To obtain row 3, we assumed that only p-p and p-e-p neutrinos are produced in the Sun. The predicted rate for such low-energy neutrinos is practically model independent[1,9] and should contribute 0.3 SNU to the ^{37}Cl experiment.

Note that the expected capture rates in the different experiments considered depend strongly on whether the discrepancy between theory and observation for the ^{37}Cl experiment is ascribed to the solar models or neutrino decay. This difference is easily understood. The low-energy neutrinos from the basic p-p and p-e-p reactions[9] are most strongly affected by decay; on the other hand, the flux of high-energy ^{8}B neutrinos is most sensitive to changes in astrophysical parameters[1] but is least affected by decay. The ratio of neutrino flux at Earth to neutrino flux near the production region in the Sun is a very sensitive function of energy if decay is important since

$$\varphi_{\text{Earth}}(E) = \varphi_{\text{solar}}(E) \exp[-(500\ \text{sec})/\tau(E)]. \quad (3)$$

The exponential dependence upon neutrino lifetime in Eq. (3) suggests that a ratio of $\varphi_{\text{solar}}/\varphi_{\text{Earth}} \sim$ a few is unlikely and that the most likely outcome of the ^{37}Cl experiment, if neutrino decay is important, is an unmeasurably low capture rate.

Finally, we note that there is even a possibility that one of the decay products of ν_e, i.e., ν', could be detected in ν'-e scattering[10] experiments. This possibility adds to the physical as well as astrophysical interest of electron-neutrino scattering experiments.

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†Permanent address: Istituto di Fisica, Università di Roma, Rome, Italy.

‡On leave of absence from Tel-Aviv University, Ramat-Aviv, Tel Aviv, Israel.

[1]See, for example, J. N. Bahcall, Phys. Rev. Lett. 17, 398 (1966); J. N. Bahcall and R. K. Ulrich, Astrophys. J. 170, 479 (1971). Additional references are given in these papers and in Z. Abraham and I. Iben, Jr., Astrophys. J. 170, 157 (1971).

[2]R. Davis, Jr., Phys. Rev. Lett. 12, 303 (1964); R. Davis, Jr., D. S. Harmer, and K. C. Hoffman, Phys. Rev. Lett. 20, 1205 (1968); R. Davis, Jr., L. C. Rogers, and V. Rodeka, Bull. Amer. Phys. Soc. 16, 631 (1971).

[3]The decay processes discussed in the present paper should not be confused with the oscillatory processes ($\nu_e \leftrightarrow \nu_\mu$) discussed earlier by B. Pontecorvo, Zh. Eksp. Teor. Fiz. 53, 1717 (1967) [Sov. Phys. JETP 26, 984 (1968)]; V. Gribov and B. Pontecorvo, Phys. Lett. 28B, 493 (1969). The oscillatory processes typically lead to only a factor-of-2 reduction in the terrestrially detected flux of electron neutrinos when properly averaged over the spectrum of energies of solar neutrinos

[see J. N. Bahcall and S. C. Frautschi, Phys. Lett. 29B, 623 (1969)].

[4]A possible role for a massless pseudoscalar field in CP-violating interactions has been proposed by F. Gürsey and A. Pais, unpublished.

[5]The most severe limit that we know for m is $\lesssim 60$ eV, given by K. Bergkvist, in *Topical Conference on Weak Interactions, CERN, Geneva, Switzerland, 14–17 January 1969* (CERN Scientific Information Service, Geneva, Switzerland, 1969), p. 91.

[6]The lifetime for processes (i) and (ii) would be proportional to $m_\nu^{-4}E$. Specifically, for process (i), with $h=k(\bar{\psi}_\nu\psi_\nu)\varphi_1\varphi_2$, $\tau=3(2^8\pi^3)m_\nu^{-4}k^{-2}E$. In order to have instability in our sense one would need a fairly strong interaction (~ electromagnetic interactions) which, however, cannot be excluded by present data on muon decay. The lifetime for process (iii) is proportional to $m_\nu^{-6}E$, which would require, for instability in our sense, a very strong interaction that can be excluded by present data.

[7]We refer to the accurate e^+ spectra used for a determination of the ρ value. For a list of references, see M. Roos *et al.*, Phys. Lett. 33B, 32 (1970).

[8]The ^{87}Rb experiment was first proposed by A. W. Sunyar and M. Goldhaber, Phys. Rev. 120, 871 (1970); the ^{7}Li experiment by J. N. Bahcall, Phys. Lett. 13, 332 (1964); and the ν-e scattering experiment by F. Reines and W. R. Kropp, Phys. Rev. Lett. 12, 457 (1964). The counting rates given in Table I have been calculated in the usual way by averaging the relevant neutrino absorption cross section over the neutrino spectrum of each β-decay source [see J. N. Bahcall, Phys. Rev. 135, B137 (1964)]; the cross sections used were taken from J. N. Bahcall, Phys. Lett. 13, 332 (1964), and Phys. Rev. Lett. 23, 251 (1969); and G. V. Domogatsky, Lebedev Institute Report No. 153, 1971 (unpublished).

[9]Most of the expected low-energy neutrinos are from the basic reactions $p+p\to{}^2\mathrm{H}+e^++\nu_e$ and $p+e^-+p\to{}^2\mathrm{H}+\nu_e$. The *astrophysical* basis for expecting the calculated number of these low-energy neutrinos is very secure; the calculation depends mainly on the measured solar luminosity and the fact that four protons are ~ 25 MeV heavier than an α particle (see Ref. 1 and other references cited therein).

[10]This could happen, for example, if $\nu'=\nu_\mu$ (or $\nu'=\bar{\nu}_\mu$) and muon neutrinos are scattered by electrons, as predicted by some versions of weak-interaction theory; see S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970); G. 't Hooft, Phys. Lett. 37B, 195 (1971).

Observation of an S-Wave Resonance in the f^0 Mass Region*

J. T. Carroll,† R. N. Diamond, M. W. Firebaugh, and W. D. Walker‡
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

and

J. A. J. Matthews,† J. D. Prentice, and T. S. Yoon
Physics Department, University of Toronto, Toronto, Ontario, Canada

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We study $\pi\pi$ scattering in the reactions $\pi^-p\to n\pi^+\pi^-$ and $\pi^+n\to p\pi^+\pi^-$ at 7 GeV/c using the absorption-modified one-pion-exchange formalism. Fitting the $\pi\pi$ angular distributions we obtain S-, P-, and D-wave $\pi\pi$ phase shifts and inelasticities for $0.6<M(\pi\pi)<1.5$ GeV/c^2. We find an $I=0$ S-wave resonance with $M=1.25\pm0.04$ and $\Gamma=0.3\pm0.1$ GeV/c^2. Support for our phase shifts in the f^0 mass region is obtained from data on $\pi^+n\to pK^+K^-$ and $\pi^+n\to p\pi^0\pi^0$ at 7 GeV/c.

While $\pi\pi$ scattering in the ρ^0 resonance region has been studied by many authors,[1] there have been relatively few such studies in the f^0 mass region. Previously, Oh *et al.*[2] determined $\pi\pi$ phase shifts for $0.6\le M(\pi\pi)\le 1.4$ GeV/c^2 by fitting the $\pi\pi$ angular distribution in $\pi N\to N\pi\pi$ at 7 GeV/c. Beusch *et al.*[3] have studied the $I=0$ S wave (δ_S^0) in the $S^*(1060)$ mass region by examing inelastic $\pi\pi$ scattering in the reaction $\pi^-p\to K_1K_1n$ at 4 and 6.2 GeV/c. The Aachen-Berlin-CERN collaboration of Beaupre *et al.*[4] determined δ_S^0 near the f^0 peak in $\pi^+p\to\Delta^{++}\pi^+\pi^-$ at 8 GeV/c. In this work we direct our attention to the di-pion mass range 1.0–1.5 GeV/c^2 where we observe an S-wave resonance at 1.26 GeV/c^2 near the f^0 peak.

Our data were obtained from two exposures of the Midwestern Universities Research Association–Argonne National Laboratory 30-in. bubble chamber to 7-GeV/c pions. These experiments yielded 10 845 $\pi^+\pi^-$ events in the channels

$$\pi^-p\to n\pi^+\pi^-,\quad 4191 \text{ events;}\qquad(1)$$

$$\pi^+d\to p_sp\pi^+\pi^-,\quad 6654 \text{ events.}\qquad(2)$$