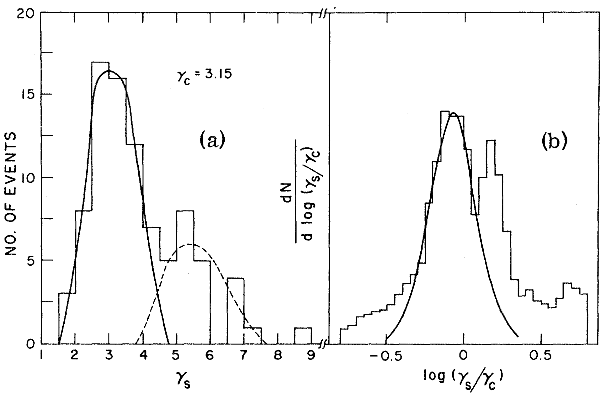

FIG. 3. (a) Distribution of values of $\gamma_{s,p}$ for 17-GeV $\pi^- $-$N$ collisions. Curves are free-hand fits of the experimental histogram of the author's work in Ref. 2. (b) Distribution of values of $\ln(\gamma_s/\gamma_c)$ for nuclear interactions of ~ 200-GeV cosmic rays in graphite observed by Erofeeva *et al.*, Ref. 11.

pointed out earlier.

In conclusion, we emphasize that the simple regularity of $\langle\gamma_s/\gamma_c\rangle_a$ is still not fully understood. However, the plot may provide us with an effective diagnosis for multiparticle processes.

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$$E_{\rm ch}=\frac{0.35\text{ GeV}}{\langle N_h\rangle^{1/4}\langle K_a\rangle}\sum_{i=1}^{n_s}\frac{1}{\sin\theta_i}, \qquad (4')$$

where $\langle K_a\rangle$ is the mean inelasticity of all charged secondaries which include the mean pionization products and those relating to leading particles, and is equal to ~ 0.75. $\langle N_h\rangle^{1/4}$ is introduced to correct for the effect of intranuclear cascade. Since $\langle n_s\rangle_{N_h\geq 1}=N_h^{1/4}\langle n_s\rangle_{N_h=0}$ and $\langle N_h\rangle=2.4$, Eqs. (4) and (4′) are equivalent [M. L. Shen, Nucl. Phys. B 3, 77 (1968)]. On the other hand $\langle N_h\rangle\propto n_s$, Eq. (4′) implies that $E_{\rm ch}$ of lower n_s events may underestimate E_p, while $E_{\rm ch}$ of larger n_s events may overestimate E_p.

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[11]The 17-GeV π^--N data were taken from Ref. 2 and the ~ 200-GeV nuclear collision data were quoted from I. N. Erofeeva *et al.*, Can. J. Phys. 46, S681 (1968).

Neutrinos of Nonzero Rest Mass*

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Some implications of neutrinos having nonzero rest masses and having finite lifetimes are considered.

All explanations of the anomalously low counting rate in the experiment of Davis and co-workers[1] to detect solar neutrinos which ascribe unusual properties to the neutrinos depend on the neutrinos having nonzero masses. Recently, we proposed a theory in which neutrinos are predicted to have nonzero masses; in particular, the muon and the electron neutrino are predicted to have masses 2.5 keV and 12 eV, respectively.[2] In this Letter we show that if the neutrinos have the masses as given above then there are severe, sometimes fatal, constraints on some of the possible explanations of the results of Davis and co-workers. In particular, we show that if neutrinos have the above masses, then (1) neutrino oscillations $\nu_e \rightleftharpoons \nu_\mu$ suggested by Gribov and Pontecorvo[3] as a possible explanation for the results from Ref. 1 can be ruled out; (2) limits for the decay rates $\nu_e\to\nu_1+\nu_2+\bar\nu_3$ and $\nu_e\to\nu_1+\gamma$ are $\Gamma_1 \leq 10^{-6}$ yr^{-1} and $\Gamma_2\leq 3\times10^{-13}$ yr^{-1}, respectively (where ν_1, ν_2, and ν_3 are three other neutrino states which can be identified with neutrinos lower in the spectrum in our theory), and hence these decay modes are too slow to account for the results given by Davis and co-workers; (3) if the anomalously low counting rate for solar neutrinos is due to the decay $\nu_e \to \nu_1 + \varphi$, via the interaction $h = g(\bar{\nu}_1, \nu_e)\varphi$ or $g(\bar{\nu}_1 \gamma_5 \nu_e)\varphi$, where φ is a massless boson, as suggested by Bahcall, Cabibbo, and Yahil,[4] the limit for the coupling constant g becomes $g^2 \geq 10^{-13}$.

We also consider some other implications of having neutrinos of nonzero rest mass.

According to our theory there exists an infinite series of neutrinos whose masses are given by $m_n = m_e/\rho^n$, where $\rho = m_\mu/m_e \simeq 207$ and n takes positive integral values.[2] The neutrinos coupled to the muon and the electron are the heaviest and have masses given above. The present experimental upper limits for the neutrino masses are 600 keV for ν_μ[5] and 55 eV for ν_e.[6] The upper limit for the ν_μ mass can be further improved by studying low-energy neutrino ends of $K_{\mu 3}$ or radiative pion decay.[7] With the present techniques it will be probably difficult to lower the limit for the mass of ν_μ beyond 100 keV.[8] Similarly, the present upper limit for the ν_e mass cannot be reduced much further by the usual method of estimating the end-point energy of the β spectrum of tritium.[6] It seems that improving the measurement of neutrino masses by several orders of magnitude must involve entirely different new techniques.

An interesting possiblilty is the measurement of the velocity of neutrinos of known energy. Because of the smallness of the neutrino mass, the velocity of detectable neutrinos will be so high that it is probably impossible to design a laboratory experiment to measure the neutrino velocity with sufficient accuracy. However, the use of astronomical methods for measuring neutrino velocity seems to be promising. If the neutrino undergoes decay, a possibility discussed later in this paper, these methods for measuring neutrino masses will fail. A lower limit for the neutrino mass can be obtained by observing neutrino pulses from a collapsing star. According to some theoretical calculations, during the collapse of a star of mass M in the range $3M_\odot \geq M \geq 1.2M_\odot$, there will be a pulse of neutrinos lasting for about 10^{-2} sec. Energy carried away by neutrinos is about 1% of the star mass, and the average energy of neutrinos is about 30 MeV. Thus if the neutrino is massive, there will be a time delay between the arrival of photons and neutrinos from the explosion. Measurement of this time delay will give a lower limit for the neutrino mass. If the neutrino has a mass predicted by us, then neutrinos from a supernova explosion at a distance of 10^4 light years will arrive about 1 sec later than photons. The main difficulty in performing such an experiment is the small probability (about one event per century) of observing a collapsing star in our galaxy. Recently, Bogatyrev[9] has suggested that construction of detectors to sense neutrinos from remote galaxies at a distance of 7–10 million light years is not beyond present-day technology. The time lag between the arrival of photons and neutrinos of energy 30 MeV from an object at 10 million light years is about 5 min. Observation of the time of arrival of neutrinos at detectors placed at different points on the earth will determine the direction of the exploding star as well as the velocity of neutrinos. Also, if there is any correlation between Weber pulses and neutrino fluxes on the earth,[10] the time delay in the arrival of these two signals could also be used to estimate the neutrino mass. For Weber pulses originating at the center of the galaxy any neutrinos (of energy of the order 10 MeV) associated with the event generating the gravitational waves should have a time lag of the order of 1 sec. Since, in collapse of more massive stars, copious ν_μ emission is expected,[11] the above methods may also be used to measure the mass of ν_μ.

Pontecorvo[12] showed that if the neutrino rest mass is nonzero and if the electronic and muonic lepton numbers are not exactly conserved, then oscillations $\nu_e \rightleftarrows \nu_\mu$ are possible with an oscillation length given by

$$l \leq 2E/(m_{\nu_\mu}^{\ 2} - m_{\nu_e}^{\ 2}), \tag{1}$$

where E is the energy of the neutrino. For masses of neutrinos given by our theory, the oscillation length turns out to be 10^{-8} cm, for neutrinos of energy 10 MeV. Because of the smallness of the oscillation length, electron events would be expected in muon-neutrino interactions. However, such events are not experimentally observed. Hence, if our predictions of masses are correct, the conservation of the muon and the electron lepton numbers should probably be strictly valid. Again the smallness of the oscillation length rules out the possibility that such oscillations[3] can account for the results of Ref. 1.

We pointed out earlier[2] that neutrinos can have decay modes of the form,

$$\nu_e \to \nu_1 + \nu_2 + \overline{\nu}_3, \tag{2}$$

where ν_1, ν_2, and ν_3 are three other neutrino states. If we assume a $V-A$ interaction of the form

$$H = (F/\sqrt{2})[\overline{\nu}_e \gamma_\mu (1+\gamma_5)\nu_2][\overline{\nu}_1 \gamma_\mu (1+\gamma_5)\nu_3], \tag{3}$$

then the decay rate for the above mode can be written as

$$\Gamma_1 = F^2 m_e^5 / 192\pi^3 \rho^{10}. \tag{4}$$

The experimental data on K and π decays into neutrinos gives $F \leqslant 10^6 G$, where G is the weak-interaction coupling constant.[13] Thus a lower limit for the lifetime of the electron neutrino against the above decay mode is about 10^6 yr and the lifetime of ν_μ against the same mode is about 4 days. Neutrinos do not have minimal electromagnetic interactions. However, a nonminimal off-diagonal electromagnetic interaction between different neutrinos of the form

$$(\lambda e/m_{\nu_e})\overline{\nu}_e \sigma_{\mu\nu} \nu_1 F_{\mu\nu}, \tag{5}$$

where m_{ν_e} is the mass of the electron neutrino and λ is a dimensionless constant, cannot be ruled out. The above interaction will permit the decay

$$\nu_e \to \nu_1 + \gamma \tag{6}$$

at a rate

$$\Gamma_2 = 2\alpha\lambda^2 m_{\nu_e}. \tag{7}$$

Thus for ν_e we get $\Gamma_2 \simeq 10^{15}\lambda^2$ sec^{-1}. A limit for the constant λ can be obtained from experimental data on electron-neutrino scattering, because the interaction (5) can lead to the process $\nu_e e \to \nu_1 e$ with a cross section of the order $10^{-8}\lambda^2$ [a dimensional consideration shows that the cross section must be of the order $(\lambda\alpha/m_{\nu_e})^2 \simeq 10^{-8}\lambda^2$; a more careful estimate gives a cross section of the same order of magnitude]. Since this has to be smaller than the experimentally observed cross section[14] (about 10^{-43} cm^2 for 1-MeV neutrinos) for electron-neutrino scattering $\nu_e e \to \nu_e e$, we get the limit $\lambda^2 < 10^{-35}$, giving $\Gamma_2 < 10^{-20}$ sec^{-1}.

In addition to the above, ν_e may decay into a massless scalar or pseudoscalar boson, as pointed out by Bahcall, Cabibbo, and Yahil.[4] The decay $\nu_e \to \nu_1 + \varphi$ can occur via an interaction of the form given by Bahcall, Cabibbo, and Yahil,[4] and insertion of our mass for ν_e in this formula gives $g^2 > 10^{-13}$ as the limit for the coupling constant.

Hence, if ν_e has a mass of 12 eV as predicted by us and its instability is responsible for the results, given by Davis and co-workers, then there should exist new massless bosons coupled only to neutrinos with a coupling strength $g^2 > 10^{-13}$.

With neutrinos of nonzero rest mass it is possible to invent a solution for the anomalously low rate of $K_L \to \mu^+\mu^-$.[15] We postulate the following new interaction:

$$\mathcal{L} = C(\overline{\nu}_\mu \gamma_5 \nu_\mu)(\overline{\mu}\gamma_5\mu + h_5^{\Delta S=1}),$$

where $h_5^{\Delta S=1}$ is a pseudoscalar neutral hadron current transforming like K_2^0. Then it is possible to get a cancelation between the contributions to $\mathrm{Im}(K_L^0 \to \mu^+\mu^-)$ from 2γ intermediate states and $\nu_\mu\overline{\nu}_\mu$ intermediate states with a choice of $cM_K^2/4\pi$ between α and $\frac{1}{10}\alpha$. This coupling would predict an anomalously large value for the $\nu_\mu + \mu^- \to \nu_\mu + \mu^-$ elastic cross section. This model is a specific realization of a class of models discussed by Sehgal,[16] where other consequences of such a coupling are considered. It is shown there that no conflict with the present experimental data arises from this new interaction.

The possibility that neutrino rest mass is nonzero can have many astrophysical implications. We have shown elsewhere that if the neutrino rest mass is close to the value predicted by us, then the submillimeter background radiation can arise from a new class of highly collapsed extragalactic objects.[17] Markov[18] raised the possibility that if the neutrino rest mass is nonzero, then "neutrino stars" consisting of vast assemblies of gravitationally bound neutrinos might exist. For our value of the ν_e mass, the radius of such an object is $\simeq 10^{21}$ cm and the mass is $\simeq 10^{15} M_\odot$. It has been suggested that if matter-antimatter collisions occur in the universe, then ν_μ fluxes at the earth must be high. However, since ν_μ may also undergo decay, the experimental limits on ν_μ fluxes at Earth cannot be used[19] to rule out the existence of systems where matter and antimatter are in collision. If the neutrinos decay fast enough, producing new particles, then this will have an important effect on the temperature dependence of an expanding radiation-filled universe, which in turn would affect predictions about cosmic helium abundance.[20]

Note added in proof.—If the instability of ν_e is responsible for the results given by Davis and co-workers and if ν_μ has identical coupling (i.e., μ-e universality persists), then in our model there is a limit on the lifetime of ν_μ given by

$$\tau_{\nu_\mu} \leqslant (m_{\nu_e}/m_{\nu_\mu})\tau_{\nu_e} \approx 2.5 \text{ sec}.$$

Both the possibility of $\nu_e \leftrightarrow \nu_\mu$ flip and the possible photonic decay of neutrinos were considered by Nakagawa *et al.*[21] in 1963. A detailed discussion of neutrino oscillations which takes the energy spectrum into account was given by Bahcall and Frautschi.[22] This would make our argument against neutrino oscillations even stronger.

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Antiproton Annihilation on Deuteron and Bound States in the Nucleon-Antinucleon System

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The momentum distributions of the recoil nucleon (spectator) in the reaction $\bar{p}+d \to n+(N\bar{N})$ have been calculated taking into account the possible levels in the $N\bar{N}$ system. The comparison of the theory with the experimental data on $\bar{p}$ annihilation at rest shows the existence of a $\bar{p}n$ bound D state with quantum numbers $J^{PG}=1^{-+}$.

In recent studies on $\bar{p}$ annihilations at rest in deuterium, bubble-chamber evidence for the existence of the $n\bar{p}$ bound state was obtained.[1] Data have also been published indirectly indicating the existence of levels in the $N\bar{N}$ system near threshold (i.e., with masses close to the double-nucleon one).[2-5] The near-threshold bound states were predicted earlier.[6-9] The near-threshold resonances in the $N\bar{N}$ system (i.e., states with masses close but above the double nucleon mass) were treated by Bogdanova et al.[10] In this Letter we present the theoretically expected momentum spectrum of recoil nucleons in the reaction

$$\bar{p}+d \to N+X, \qquad (1)$$

where X is the $N\bar{N}$ bound state, and compare it with experimental results.

The main point we would like to stress is that the shape of the spectrum, i.e., the positions and the widths of its maxima, depends not only on the complex masses of the bound states, but (because of comparatively large annihilation widths) on their orbital angular momenta as well. We consider Reaction (1) proceeding from the pick-up mechanism (Fig. 1) which is well known in nuclear physics. It should be noted that the choice of a specific peripheral mechanism is not essential for the main conclusions, though some shift of the maximum under consideration can occur when going, for example, from a pickup to a $\bar{p}$-p