and f_0 and their oppositely charged counterparts. As the elementary particles are known to be magnetically neutral, we envisage the following neutral composites : mesons comprise $(f_0, -f_0)$ and the baryon hard core comprises $(2f_0, -f_0, -f_0)$, with the reverse configuration for the antiparticles. Let us then consider the renormalisation effects owing to the presence of these magnetic charges. The coupling constant g_m involving magnetic charges in analogy with the case of electric charges, can be written as (using Eq. 11):

$$g_m = \sqrt{\frac{f_0^2}{\hbar c}} = \sqrt{\frac{e^2}{a^2 \hbar c}} = \frac{1}{a^{1/2}} . \qquad (12)$$

Since the interaction is super-strong it is adequate to consider only lowest order terms[10]. For mesons with two magnetic charges we will have two vertices and for the baryon core three vertices, *i.e.*, from the three magnetic charges. Accordingly, the renormalization factor for mesons is

$$\frac{1}{2} \left(\frac{1}{a^{1/2}} \right)^2 = \frac{1}{2a} ;$$

the number 2 being a weight factor. Similarly for baryon core the three vertices give a factor

$$\left(\frac{1}{a^{1/2}} \right)^3 = \frac{1}{a^{3/2}} :$$

Thus for mesons and the parton (baryon hard core) the renormalised frequencies will be given by

$$\omega_M = \frac{1}{2a} \omega_e \qquad (13)$$

$$\omega_P = \frac{1}{a^{3/2}} \omega_e. \qquad (14)$$

As explained before[1], a relativistic oscillator model is needed for mesons and baryons. Thus for mesons the eigen masses are given by :

$$m(n_M) = \frac{\hbar \omega_e}{2a} [n_M + 1]^2. \qquad (15)$$

The baryons are composed of the parton hard core and the meson clouds, each having independent oscillations. Thus the eigen masses are given by

$$m(n_M, n_P) = \hbar \omega_e \left[\frac{(n_M + 1)^2}{2a} + \frac{(n_P + 1)^2}{a^{3/2}} \right]. \qquad (16)$$

The parton core being in the unexcited state we can put $n_P = 0$ and rewrite Eq. (16) as :

$$m(n_M, n_B) = \hbar \omega_e \left[\frac{(n_M + 1)^2}{2a} + \frac{n_B}{a^{3/2}} \right] \qquad (17)$$

with $n_n = 1$, for baryons and $n_B = 0$ for mesons.

The present model of hadrons is in conformity with the Vigier model of elementary particles[11]. In this model the particles are assumed to be relativistic droplets having six degrees of freedom.

In the present case we can think of quantized rotation for the parton hard core and the meson cloud each having a different centre of mass. This will give rise to six degrees of freedom. Work in this direction is in progress. It may be remarked that the meson cloud is held to the parton by strong interaction forces which are much weaker than the super-strong forces holding the parton.

In the foregoing we have discussed the physical basis of the formula developed earlier. The previous paper gave the results of the computations.

1. Sivaram, C. and Sinha, K. P., *Curr. Sci.*, 1973, 42, 4.
2. Ross, D. K., *Nuovo Cimento*, 1972, 8 A, 603.
3. Motz, L., *Ibid.*, 1972, 12 B, 329.
4. Rosen, G., *Phys. Rev.*, 1971, 4 D, 275.
5. Reissner, H., *Ann. der. Phys.*, 1916, 50, 106.
6. Nordström, G., *Verhandl. Konikl, Nod. Akad. Wetenschap. Afdel, Natuurk*, 1918, 20, 1238.
7. Dirac, P. A. M., *Proc. Roy. Soc.* (London), Sec A, 1931, 133, 60.
8. Schwinger, J., *Science*, 1969, 165, 757.
9. Amaldi, A., In *Old and New Problems in Elementary Particles,* Ed. G. Puppi, Academic Press, New York, 1968.
10. Wellner, M., *Ann. Phys.* (New York), 1972, 73, 180.
11. de Broglie, L., *The Vigier Theory of Elementary Particles,* Elsvier, 1963.

SOME ASSORTED LEPTONIC PUZZLES*

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I WOULD like to talk about what seem to me to be some outstanding puzzles which I call

leptonic because they all involve leptons in one way or another. According to current conventional wisdom, not all of them have to do with leptons, as we shall see. I will first indicate these puzzles, and then discuss briefly some recent speculations which bear on them[1-4].

The oldest, most venerable of these is the muon puzzle, sometimes phrased as why a muon?

(reminiscent of the why a duck ? routine[5] of Chico and Groucho Marx). The experimental facts leading up to this puzzle are (a) the existence of muon and muon-neutrino, (b) its mass, i.e., the fact that $m_\mu/m_e \simeq 207$, (c) e-μ universality in electromagnetic interactions as inferred from $(g-2)_\mu$ and μ-p scattering compared to $(g-2)_e$ and e-p scattering with good accuracy, and (d) e-μ universality in weak interactions or rather the interchangeability of (e, ν_e) with (μ, ν_μ) as inferred from semileptonic decay rates with not-so-good accuracy (especially for $\triangle S = 1$ decays).

There are many attempts to "explain" the muon. The following gives an idea of some of the approaches taken :

(i) One approach takes its hint from the fact that $m_e/m_\mu \sim 0(\alpha)$ and so invokes electromagnetism. Starting with a massless fermion spontaneous breakdown of the scale symmetry can lead to two solutions for the masses.

(ii) By having leptons satisfy wave equations more complicated than Dirac and which allow more than one mass and spin, muon and other heavy leptons can be generated.

(iii) Muon can be made to have anomalous interactions (which the electron does not have). These have some difficulty satisfying e-μ universality as observed.

(iv) There are complicated models based on discontinuities in the gravitational field.

(v) Dirac's model of the electron as a charged "soap bubble", muon being identified as the first excited state obtained on quantization.

(vi) Gauge theories of unified weak and electromagnetic interactions in some versions "need" a muon to cancel anomalies.

Another problem is the existence of heavy leptons. Namely, are there heavy leptons or not ? If yes, (a) what are their masses, (b) do they have their own neutrinos (and hence new quantum numbers) or couple only through ν_μ and ν_e ?

A similar problem is the properties and existence of neutrinos. For example, are the masses of ν_μ and ν_e zero or not ? Are there other neutrinos ? What are their masses ? How do they couple ? Are neutrinos in π-decay and K-decay identical? Are neutrinos emitted in μ⁻-decay really ν_μ and $\bar{\nu}_e$ as conventionally assumed ?

The above questions about heavy leptons and neutrinos are obviously experimental as well as theoretical.

The next puzzle is the $K_L \to \mu^+\mu^-$ puzzle ; namely, the fact that K_L into $\mu^+\mu^-$ does not go ! The puzzle comes about as follows. Unitarity

allows one to write $\mathcal{J}m(K_L \to \mu^+\mu^-)$ in terms of on mass shell intermediate states, viz., $\gamma\gamma$, $2\pi\gamma$, and 3π. Of these 3π is expected not to contribute much, the $\gamma\gamma$ contribution can be calculated and $2\pi\gamma$ can be well estimated. Then one has a limit on the branching ratio of $K_L \to \mu^+\mu^-$ (to all):

$$B \cdot R \cdot (K_L \to \mu^+\mu^-) \geqslant 6 \times 10^{-9}.$$

A similar limit derived for η is satisfied. An experiment at Berkeley failed to find any decays of $K_L \to \mu^+\mu^-$ and placed a limit

$$B \cdot R \cdot (K_L \to \mu^+\mu^-) < 1\ 8 \times 10^{-9}.$$

This experimental result, if correct, conflicts with the unitarity bound given above and hence creates a serious problem. In the meantime, another experiment by Columbia-NYU-CERN collaboration has observed the decay mode and further found the rate to satisfy the unitarity bound. At this writing, it seems like an experimental problem and so one waits for an experimental resolution.

Another leptonic puzzle is the lack of neutrinos from the sun. If the energy source of the sun is the burning of hydrogen to make helium as believed, then neutrinos are emitted in the process. The most energetic come from the decay of Boron

$$B^8 \to Be^8 + e^+ + \nu_e + 14\ MeV$$
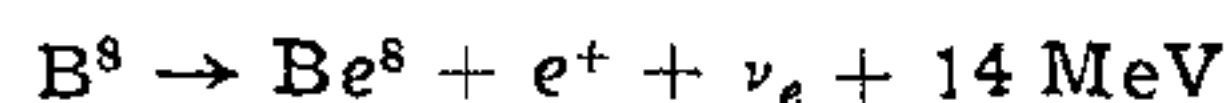
with a small flux since this decay occurs in a chain which is not the favoured path. Davis has set up a huge detector in the Homestake mines in South Dakota in which the reaction

$$\nu_e + Cl^{37} \to Ar^{37} + e^-$$

can take place and the presence of Ar^{37} is to be detected by searching for the tell-tale radioactivity of Ar^{37}. This reaction is particularly sensitive to the high energy neutrinos from B^8 decay. Using all the "machinery" now available, one can calculate a counting rate that Davis should observe——this comes out to be $\Sigma\phi_\nu\sigma \simeq 6 \pm 3$ SNU. (SNU stands for solar neutrino unit, 1 SNU being equal to 10^{-36} capture/target atom/sec.) Calculation of this number involves standard parameters of the sun, rates for nuclear reactions (some to be extrapolated to very low energies), standard stellar evolution model, knowledge or guess about relative abundance of heavy elements inside the sun, etc. The bulk of the 6 SNU comes from B^8 neutrinos but 0·3 SNU comes from neutrinos from the basic reaction

$$p + e^- + p \to D + \nu_e,$$
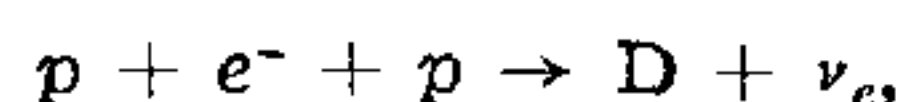
and there are no uncertainties in this prediction. So 0·3 SNU represents a lower limit which must be seen. Davis finds that the counting rate is less than 1 SNU. This discrepancy may have something to do with the properties of neutrinos or it may not.

The final "puzzle" that I want to mention is the fact that strangeness changing decays of hadrons in which leptons are emitted are, in general, an order of magnitude slower than the corresponding strangeness conserving decays. This suppression is usually referred to as the "Cabibbo angle." The latter is defined, roughly speaking, as

$$\frac{\Gamma(K \to \mu\nu_\mu)}{\Gamma(\pi \to \mu\nu_\mu)} = \tan^2\theta\gamma.$$

where γ is the ratio of the phase space factors. Experimentally, tan θ is about $\frac{1}{4}$ and roughly the same suppression occurs in all $\Delta S = 1$ semileptonic decays. There are many attempts to understand θ in terms of properties of hadrons and their interactions. Here we will take the heretic point of view and associate the suppression factor tan θ with leptons rather than hadrons.

All of these puzzles are tied together in a somewhat far out model of lepton mass spectrum suggested by Tennakone and myself. We suggest that the lepton mass spectrum is of the form

$$m_n = m_e \rho^n,$$

where n is an integer and $\rho = m_\mu/m_e \approx 207$. To avoid charged leptons lighter than the electron (i.e., when n is negative), we define the charge as

$$Q = \frac{e}{2}(1 + |n|/n).$$

We then identify particles with negative n with neutrinos. There are two possibilities for couplings of neutrinos to charged leptons: (a) assigning a specific neutrino to each charged lepton or (b) many neutrinos (possibly even an infinite number) couple to a charged lepton with different coupling strengths (chosen to give finite total probabilities). While this suggestion does not solve the fundamental problem of the existence of muon, it changes the problem to that of explaining the discrete scale invariance of the mass spectrum and the property of charge and of weak currents. It does offer an answer to the questions of existence of heavy leptons and of neutrino properties as follows.

We predict a heavy lepton l with rest mass $m_l = 22$ GeV with an estimated lifetime of $\tau_l \approx 10^{-18}$ sec. Its important decay modes are electron + neutrinos, muon + neutrinos, and hadrons + neutrino with a branching ratio of roughly 1/3 each. The next lepton ($n = 3$) is at 4554 GeV! We also predict that ν_μ and ν_e each have rest masses of 2.5 KeV and 12 eV, respectively, to be compared with the current experimental upper limits of 600 KeV and 55 eV, respectively.

With ν_e having non-zero rest mass and other lighter neutrinos in the model, it is natural to ask whether decays of ν_e such as into three lighter neutrinos ($\nu_e \to \nu_1 + \bar{\nu}_2 + \nu_3$) or into one lighter neutrino and a photon ($\nu_e \to \nu_1 + \gamma$) can be fast enough to explain the Davis result. It can be shown that these decays cannot occur fast enough for that. So one is reduced to the unpleasant expedient of inventing one more particle—a massless boson ϕ—and a new interaction which makes ν_e decay into a lighter neutrino and ϕ ($\nu_e \to \nu_1 + \phi$) at just the right rate to explain the Davis result. Explanations of Davis result based on mixing between ν_e and ν_μ or ν_e and a number of other neutrinos can also be ruled out in our model.

It is also possible to invent a solution for $K_L \to \mu^+\mu^-$ puzzle, in case one is needed. This is made possible by the non-zero rest mass of ν_μ. One postulates a new interaction, following Sehgal,

$$L_{int.} = C(\bar{\nu}_\mu\gamma_5\nu_\mu)(\bar{\mu}\gamma_5\mu + h_0\Delta S=1).$$

With $Cm_k^2/4\pi \sim \alpha/\sqrt{10}$, one can make $K_L \to \nu_\mu\bar{\nu}_\mu \to \mu^+\mu^-$ interfere with the $\gamma\gamma$ contribution almost maximally. This particular "solution predicts fairly hefty cross section for $\nu_\mu\mu \to \nu_\mu\mu$.

Non-zero rest masses of neutrinos also have interesting astrophysical effects. One is the time lag between neutrinos of different energies arriving on the earth coming from, e.g., supernovas; in principle, neutrino masses can be measured this way. Another is the fact that a collection of neutrinos can form a neutrino star with typical parameters like $R \sim 10^{21}$ cm, $M \sim 10^{15} m_-$. Such objects could have large red shifts.

If we consider the alternative that a given charged lepton couples with many neutrinos, then the following intriguing possibility arises. The suppression of $\Delta S = 1$ to $\Delta S = 0$ decay rates can be blamed on a different combination of neutrinos appearing in the leptonic current coupling to $\Delta S = 1$ hadronic current compared to the one coupling to $\Delta S = 0$ hadronic current. In other words, ν's from π and K decay would not be identical. Such a radical proposal is, in principle, testable in many ways: e.g., masses of ν^π and ν^k would be different, counting rates for reactions such as $\bar{\nu}^k + p \to n + \mu^+$ would be suppressed compared to $\bar{\nu}^\pi + p \to n + \mu^+$, etc.

1. Tennakone, K. and Pakvasa, S., *Phys. Rev., Letters*, 1971, 27, 757.
2. — and —. *Phys. Rev.*, 1972, 6 D, 2494.
3. Pakvasa, S. and Tennakone, K., *Phys. Rev. Letters*, 1972, 28, 1415.
4. Tennakone, K. and Pakvasa, S., *Neutrino Spectrum and the Origin of the Cabibbo Angle*, University of Hawaii Preprint, UH-511-126-72, unpublished.
5. The alternative to seeing the movie "Coconuts" is to look up *Why a Duck?* Edited by R. J. Anobile, Darien House, Inc., New York, 1971, p. 40.