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STRONGLY INTERACTING HEAVY LEPTONS

Boris Arbuzov ^{*)}, Gino Segrè ^{**)} and Jacques Weyers

CERN -- Geneva

ABSTRACT

A simple model of heavy leptons with strong interactions is proposed for ψ particles and di-muon production in ν interactions

^{*)} On leave from Institute of High-Energy Physics, Serpukhov, USSR.

^{**)} J.S. Guggenheim Foundation Fellow, on leave from University of Pennsylvania, PA., USA.

The rich spectroscopy of new resonances ¹⁾ discovered in the last year, as well as the remarkable threshold effect observed ²⁾ in e^+e^- annihilation around 4 GeV, definitely require new fundamental fermions in addition to the traditional leptons (μ , e and their neutrinos) and quarks (p , n , λ in three colour varieties). The most attractive models ³⁾ proposed so far postulate the existence of one or more new quarks (c , ...) carrying new additive quantum numbers [which will generically be called charm ⁴⁾]. A prediction, common to all these models, is the existence of explicitly charmed mesons ($\bar{p}c$, $\bar{n}c$, ...) below 2 GeV: this is indeed the only natural way, within these models, to accommodate the factor of $O(10^3)$ between the widths of $\psi''(4.0)$, $\psi'''(4.4)$ and those of $\psi(3.1)$ and $\psi'(3.7)$. So far the experimental search for these charmed mesons has given negative results. On the other hand, totally unexpected μ - e events have been observed ⁵⁾ at SPEAR and are presently interpreted as evidence for the existence of at least one heavy lepton (L). If heavy leptons take part only in the usual weak and electromagnetic interactions, they clearly have no bearing on the ψ spectroscopy. They could, however, provide a satisfactory explanation for the behaviour of $\sigma(e^+e^-)$ if more than one charged heavy lepton with $m_L \lesssim 2$ GeV is discovered.

In this letter we explore some simple consequences of the idea ⁶⁾ that heavy leptons do participate in strong or semi-strong interactions. The lowest lying ψ particles can then be identified with genuine $\bar{L}L$ bound states, and the large widths of ψ'' and ψ''' simply arise because these resonances decay into their constituents. The main difference between our point of view and a charm scheme is that our new fundamental fermions have something in common with leptons (quantum numbers) and with quarks (interactions) ⁷⁾ but, at least in the simplest model considered here ⁸⁾, they are not confined. They can exist as free particles and indeed have been observed as such! An interesting consequence of this difference concerns di-muon ⁹⁾ events observed in ν interactions: our model gives the correct order of magnitude for the effect and predicts an energy behaviour and x distribution which agree with experiment.

For simplicity our discussion here will be restricted to a model with one charged heavy lepton. More elaborate models will be considered elsewhere ¹⁰⁾.

1. ψ SPECTROSCOPY

Whatever the details of the dynamical mechanism responsible for the binding of heavy leptons, we do expect for ψ -like particles a standard fermion-antifermion spectrum with orbital and radial excitations. Our

assignments for $\psi(3.1)$ and $\psi'(3.7)$ are thus conventional: $\psi(3.1)$ is the lowest 3S_1 state and $\psi'(3.7)$ its first radial excitation. To estimate the strength and range of the forces responsible for the binding of ψ 's, we have taken a Hulthen potential

$$V(r) = -V_0 \frac{e^{-r/a}}{1 - e^{-r/a}}, \quad V_0 = \frac{g^2}{4\pi a}. \quad (1)$$

Ignoring spin complications, we obtain from $m_L = 1.9$, $m_\psi = 3.1$ and $m_{\psi'} = 3.7$

$$a = 0.8 \text{ GeV}^{-1}, \quad \frac{g^2}{4\pi} = 1.2. \quad (2)$$

With these parameters the same potential predicts a second radial excitation around $m = 4.3 \text{ GeV}$ whose width is of the order of several hundred MeV. These numbers should, of course, not be taken too seriously: they simply illustrate the facts that if ψ is a $\bar{L}L$ bound state, the forces between L 's are at least of semi-strong origin, and furthermore that a $\bar{L}L$ resonance above threshold can have a considerable width because it decays into its constituents.

It is worth pointing out that independently of the branching ratios one assumes for the various decay modes of the heavy lepton, our model predicts that all events coming from the ψ'' or ψ''' resonance will either contain charged leptons or appear energetically unbalanced (one or more neutrinos emitted).

Concerning the decay modes of ψ -like particles, we proceed as follows: let us assume that the forces binding heavy leptons are due to the exchange of some vector meson (ξ_μ). Consider then the interaction Lagrangian

$$\mathcal{L} = g_1 \bar{L} \gamma^\mu L \xi_\mu + g_2 \bar{Q} \gamma^\mu Q \xi_\mu + g_3 \bar{L} L \xi^\mu \xi_\mu + g_4 \bar{Q} Q \xi^\mu \xi_\mu, \quad (3)$$

where Q stands for a quark field.

To avoid unessential complications, we can view the g_3 and g_4 type terms of Eq. (3) as corresponding to the coupling of both heavy leptons and quarks to a scalar ($J^{PC} = 0^{++}$) particle σ . Structurally, the Lagrangian (3) is then equivalent to

$$\mathcal{L} = g_1 \bar{L} \gamma^\mu L \xi_\mu + g_2 \bar{Q} \gamma^\mu Q \xi_\mu + g_3 \bar{L} L \sigma + g_4 \bar{Q} Q \sigma. \quad (4)$$

From the ψ spectrum we have seen that g_1 is of order 1. From the decay modes $\psi \rightarrow \text{hadrons}$ and $\psi' \rightarrow \psi \pi \pi$ we obtain the following qualitative estimates ¹¹⁾

$$\frac{g_2^2}{4\pi} \cong 2 \cdot 10^{-4}, \quad \left(\frac{g_3 g_4}{4\pi} \right)^2 = \lambda \cong 0.4.$$

With these values of the parameters, we are led to the following predictions:

- i) diffraction of heavy leptons and ψ 's off ordinary hadrons is roughly of the order of 10% ($\sim \lambda^2$) of ordinary hadronic diffraction;
- ii) $\Gamma(\psi' \rightarrow \psi \eta)$ is of order λ^4 and hence of the right order of magnitude;
- iii) $\Gamma(^1S_0 \rightarrow \text{hadrons}) / \Gamma(^3S_0 \rightarrow \text{hadrons}) = O(\lambda^4 / g_1^2 g_2^2)$ and hence

$$\Gamma(\chi(2.8) \rightarrow \text{hadrons}) = (1 \text{ to } 10) \Gamma(\psi);$$

- iv) $\Gamma(^3P_0 \rightarrow \text{hadrons}) : \Gamma(^3P_2 \rightarrow \text{hadrons}) : \Gamma(^3P_1 \rightarrow \text{hadrons}) = \lambda : \lambda^2 : \lambda^3$. The widths of the P states thus differ considerably from the ψ width! In the 3200-3700 MeV region, one also expects the first radial recurrence of $\chi(2.8)$ as well as the 1P_1 state. The width of this last state is of the order $(g_1 g_2)^2 \lambda$, i.e., the 1P_1 is expected to be as narrow if not narrower than the ψ !

- v) radiative decays such as $\psi \rightarrow \pi \gamma$ or $\psi \rightarrow \eta \gamma$ are $O(e^2 \lambda^4)$ and hence are compatible with experimental limits ^{1), 2)}.

2. WEAK INTERACTIONS AND DI-MUONS

The heavy lepton $L^\pm$ will be assumed to generate a new term in the leptonic weak current ¹²⁾

$$j_\alpha(\text{leptonic}) \rightarrow j_\alpha(\text{leptonic}) + \bar{L} \gamma_\alpha (1 - \gamma_5) \nu_L.$$

With the standard current-current interaction, we then expect the lifetime of L to be about 10^{-13} secs. To order G_F we have the following decay modes

$$\begin{aligned} L^+ &\rightarrow \bar{\nu}_L + \text{hadrons}, \\ L^+ &\rightarrow \mu^+ + \nu_\mu + \bar{\nu}_L, \\ &\rightarrow e^+ + \nu_e + \bar{\nu}_L. \end{aligned}$$

To order $G_F \lambda$ we also have

$$L^+ \rightarrow \mu^+ + \nu_\mu + \bar{\nu}_L + \pi^+ \pi^- \dots$$

Let us define

$$\eta = \frac{\Gamma(L^+ \rightarrow \bar{\nu}_L + \mu^+ + \nu_\mu)}{\Gamma(L^+ \rightarrow \bar{\nu}_L + \text{hadrons})}$$

As a reasonable guess we will assume $\eta \sim 10\%$.

With $\nu_L \neq \nu_\mu, \bar{\nu}_\mu$ we exclude direct production of L in neutrino interactions. We do have, however, the more complicated process, illustrated in Fig. 1

$$\nu_\mu + N \rightarrow \mu^- + \nu_L + L^+ + X ; \quad (5)$$

where X is a purely hadronic final state. The subsequent leptonic decay of the heavy lepton in Eq. (5) leads to di-muons¹³⁾. We have calculated the cross-section corresponding to Fig. 1 and obtain

$$\frac{d\sigma(\nu, \text{dimuons})}{dx} = \frac{G_F^2 \eta S^2 \bar{\sigma}}{18(2\pi)^4} \left\{ x(3x-2) \ln x + \frac{1-x^2}{2} \right\},$$

$$\frac{d\sigma(\nu, \text{dimuons})}{dy} = \frac{G_F^2 \eta S^2 \bar{\sigma}}{9(2\pi)^4} y(1-y + \frac{1}{3}y^2), \quad (6)$$

$$\sigma(\nu, \text{dimuons}) = \frac{G_F^2 \eta \bar{\sigma} S^2}{36(2\pi)^4}.$$

In the above s , x and y are the usual variables, and $\bar{\sigma}$ is the LN total cross-section which we have taken as a constant. Formulae (6) have been obtained in a pole approximation for the intermediate L and neglecting all masses compared to $\sqrt{s}$. The most striking feature of Eq. (6) is that $\sigma_\nu \sim s^2$, i.e., a gross violation of scaling.

From the ψN cross-section estimates we may take

$$\bar{\sigma} \approx \frac{1}{2} \text{ millibarn}.$$

We find then, for incoming neutrino energy of 150 GeV

$$\frac{\sigma(\nu, \text{dimuons})}{\sigma(\nu)} = 8\eta 10^{-2}.$$

For $\eta \sim 10\%$ this agrees with the NAL results ⁹⁾ on di-muon production both in magnitude and x distribution. Because of the s^2 dependence, our formula agrees as well with the appreciably lower di-muon production cross-section at Serpukhov ⁹⁾. We emphasize that particularly with regard to energy dependence our results seem more satisfactory than charm model calculations.

From Eq. (2) ($g \sim 1$), the diagram of Fig. 2 will lead, at very high energies, to an appreciable cross-section for the process

$$\nu + N \rightarrow \mu^- + \mu^- + \dots$$

when both L^+ 's of Fig. 2 decay into ν_L + hadrons. We expect

$$\begin{aligned} \sigma(\nu; \mu^- \mu^-) : \sigma(\nu; \mu^- \mu^- \mu^+) : \sigma(\nu; \mu^- \mu^+ \mu^+) : \sigma(\nu; \mu^- \mu^+ \mu^+) = \\ = 1 : 2\eta : \eta : \eta^2. \end{aligned}$$

Our model for heavy leptons clearly leads to $\mu^- e^+$, $\mu^+ e^-$... final states as well, since $L^\pm$ may decay into electrons as well as muons.

The simple model described in this letter has, of course, several shortcomings some of which (like the value of R) can be cured by adding a second charged heavy lepton. It does, however, lead to a unified explanation of the new phenomena observed both in e^+e^- experiments and in ν experiments. The idea that in addition to the usual lepton and quarks there are new fermions which share some properties with both, certainly strengthens the case for a unified description of all fundamental fermions. Whether this can be done in a simple and elegant model remains to be seen. It should be stressed, however, that if this idea is correct, we may expect a plethora of spectacular effects in very high-energy reactions such as "hadrolepton" resonances, for example.

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- 8) One may, of course, imagine models where some of the new fermions are
confined but still carry leptonic quantum numbers.
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- 10) B. Arbuzov, G. Segré and J. Weyers to be published. In particular, we
will consider models with more than one charged heavy lepton as
well as implications for prompt leptons observed in hadronic inter-
actions.
- 11) These values of the coupling constants are, in some sense, a dynamical
implementation of the Zweig-Iizuka rule.
- 12) ν_L could refer to a new neutrino (with or without semi-strong inter-
action). It could also be identified with, e.g., ν_e . For
simplicity we assume that ν_L does not take part in semi-strong
interactions and that $m_{\nu_L} < m_{L^\pm}$. More than one additional term in
 j_α (leptonic) is, of course, also possible; see Ref. 10).
- 13) It should be pointed out that the cross-section for di-muon events is
the same in neutrino and antineutrino interactions, provided
 $\sigma(L^+N) = \sigma(L^-N)$.

FIGURE CAPTIONS

Fig. 1 : Diagram responsible for di-muon events.

Fig. 2 : Production of single, di-, tri- and tetra-muon events.

FIG.1

FIG.2