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REMARKS ON HEAVY LEPTONS*†

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This paper is for presentation at the International Colloquium on Science, Culture and Peace in honor of Victor F. Weisskopf.

We know so much and yet so little about the leptons. So much about their properties and masses, so little about what sets those masses or why there are generations. In 1934 Victor Weisskopf[1] initiated ideas which led to the mathematical methods we use to eliminate the divergent integrals associated with the mass and self energy of the electron. In 1972, referring to the divergent integrals which appear in calculating the natural width of spectral lives, Weisskopf wrote the following.[2]

> "They [divergent integrals] have not yet been resolved; they are still there after 40 years. One ought to be ashamed of it."

Fundamental questions of understanding and calculating the masses of the leptons are still with us. The leptons are such beautiful and simple particles, we ought to be ashamed that these questions are still unanswered.

The solution to these questions may lie in one of the current theories of elementary particles, or more likely it will require a new idea, a new theoretical direction. One role of experiment is to test current theories. But when we are without a solution as we are now, experiment must provide new data which will lead to a solution. In this talk I remark on what experiment has taught us about heavy leptons, and on what experiment can teach us at the SLC and LEP electron-positron colliders.

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Charged Heavy Leptons

The work of Zichichi and his colleagues[3] began the search for unstable charged heavy leptons which decay to their own neutrino through processes such as

$$L^- \to \nu_L + e^- + \bar{\nu}_e \tag{1a}$$

$$L^- \to \nu_L + \mu^- + \bar{\nu}_\mu \tag{1b}$$

$$L^- \to \nu_L + \text{hadrons} \tag{1c}$$

This requires

$$m_{\nu_L} < m_L \quad , \tag{2}$$

a relation I will return to in a few paragraphs. At the SPEAR electron-positron storage ring we had sufficient energy for the reaction.

$$e^+ + e^- \to \gamma_{virtual} \to \tau^+ + \tau^- \tag{3}$$

and were able to discover the τ heavy lepton, Perl *et al.*[4] The τ is the third of what I call charged sequential leptons. The τ mass is

$$m_\tau = 1784. \pm 3. \text{ MeV/c}^2 \tag{4a}$$

Two recent upper limits on the τ neutrino mass are

$$\begin{aligned} m_{\nu_\tau} &< 70 \text{ MeV/c}^2 \text{ , 95\% CL (Ref.5)} \\ m_{\nu_\tau} &< 50 \text{ MeV/c}^2 \text{ , 90\% CL (Ref.6)} \end{aligned} \tag{4a}$$

The finding of the τ required an overlap of the energy range of an electron-positron collider with twice the mass of the charged lepton. At PETRA and PEP we have not been as fortunate. The lower limit on the mass of the next charged sequential lepton, if it exists at all, is[7]

$$m_{L^-} > 22.7 \text{ GeV/c}^2 \text{ , 95\% CL} \tag{5}$$

from experiments at PETRA.

Stable charged heavy leptons with double charge, unit charge and fractional charge (1/3, 2/3, 4/3, and 5/3) have been sought at PEP and PETRA. The lower limits[7] on their mass are in the range of 15 to 20 GeV/c^2.

Close-Mass Lepton Pairs

Thus we have been very disappointed in searches for new charged leptons at PEP and PETRA. But perhaps we have been looking for the wrong particle. In the last months I have begun to look for what I call close-mass lepton pairs in our Mark II detector data from PEP. I consider the possibility of a pair (L^-, ν_L) with:

$$m_{\nu_L} \text{ less than but close to } m_L \tag{6}$$

Then for the reaction in Eq. 1 the maximum electron momentum in the laboratory frame is

$$p_{max} = E_{beam}\left[1 - \left(\frac{m_{\nu_L}}{m_L}\right)^2\right]\left[1 + \left(1 - \left(\frac{m_L}{E^2_{beam}}\right)^2\right)^{1/2}\right] \Big/ 2 \tag{7}$$

where E_{beam} is the beam energy. When m_{ν_L}/m_L is close to 1, p_{max} is small. But a minimum total energy criterion is used in all searches for unstable charged leptons, and events from a pair with m_{ν_L}/m_L sufficiently close to 1 would be excluded by that criterion.

There are known reactions which can obscure the signal from a close-mass lepton pair. The most annoying backgrounds are from

$$e^+ + e^- \rightarrow (e^+ + e^-) + e^+ + e^-,\ (e^+ + e^-) + \mu^+ + \mu^- \tag{8}$$

where the e^+ and e^- in parenthesis are not detected because they are produced along the beamline. My first step has been to study this background, comparing the calculations[7] with experiment[8]. the next step will be to see what we can say experimentally about close-mass lepton pairs.

I know of no theoretical need for close-mass pairs, but I am intrigued by the possibility that such a pair could be missed by conventional search methods.

Neutral Heavy Leptons and Generation Mixing

In recent years definitive searches for new charged leptons have used the copious production reaction $e^+ + e^- \rightarrow \gamma_{virtual} \rightarrow L^+ + L^-$. The corresponding production reaction for neutral leptons

$$e^+ + e^- \rightarrow Z^0_{virtual} \rightarrow L^0 + \bar{L}^0 \tag{9}$$

has too small a cross section at the energies of operating electron-positron colliders to permit definitive searches, assuming the L^0 obeys conventional weak interaction theory.

Therefore almost all searches have depended upon the new neutral lepton mixing in some way with the e, μ, or τ generations. For example, if a new L^0 is supposed to mix with the (μ^-, ν_μ) pair, then it might be seen in π^- decay

$$\pi^- \rightarrow \mu^- + L^0 \tag{10}$$

Or if it mixed with the (e^-, ν_e), the reaction

$$e^+ + e^- \rightarrow L^0 + \bar{\nu}_e \tag{11}$$

could have a large cross section through the t-exchange of an e^-. As you know, in spite of the range and ingenuity of the L^0 searches depending upon mixing, nothing new has been found[10].

Since this Colloquium is dedicated to a broader view of science, I will take the liberty of expressing my philosophical prejudice about the concept of the mixing of lepton generations. I am uneasy with that concept. The leptons as we know them behave so simply that it seems natural for there to be perfect isolation between the generations. And experiment keeps reducing the upper limits on the mixing parameters. Lepton generation mixing may be one of those ideas in physics that we keep around not because we feel it must be true, but because it gives us something to work on, experimentally and theoretically.

Conversely, consider how little we know, and how little we have been able to do experimentally, on neutral leptons which do not mix with the known leptons; be these singlets, members of a pair, or members of a more complicated system. Such neutral leptons might have zero mass or masses of many GeV/c^2 or any other mass. They might be stable or unstable. And except for the few cases I mention at the end of this paper, we have no experimental limits on their existence.

Fortunately, we will soon be able to make general and comprehensive searches for neutral leptons using Z^0 intermediate bosons from the SLC and LEP electron-positron colliders.

Neutral Heavy Leptons and the Z^0

The decay process

$$Z^0_{real} \rightarrow L^0 + \bar{L}^0 \tag{12}$$

offers three ways of searching for new neutral leptons:

(*a*) direct or indirect measurement of the Z^0 width Γ_Z;

(*b*) measurement of the cross section for the sequence $e^+ + e^- \rightarrow Z^0 + \gamma,\ Z^0 \rightarrow L^0 \bar{L}^0$; and

(*c*) direct detection of the decays of an unstable L^0.

Taking these methods in order, Γ_Z can be measured directly in the reaction

$$e^+ + e^- \rightarrow Z^0_{real} \rightarrow \text{detectable decay modes} \tag{13}$$

by moving the total e^+e^- energy, E_{tot}, across the Z^0 peak. The main term in the cross section is

$$\sigma = \text{constant} \Big/ \left[\left(E^2_{tot} - M^2_Z \right)^2 + \Gamma^2_Z M^2_z \right] \quad , \tag{14}$$

but this simple form is altered by the electroweak interference, by electromagnetic and weak radiative corrections, and by the spread in E_{tot} of the electron-positron collider.

As you know, Γ_Z is predicted to be about 2.8 GeV based on electroweak theory, the six established leptons, and five establshed quarks. Γ_Z is of course increased by the existence of an additional L^0 or any additional elementary particle -- a new quark, a supersymmetric particle -- as long as the new particle interacts through the weak force and has sufficiently small mass. A new L^0, a convenient example, adds

$$\Delta \Gamma_Z = 0.06 \beta \Gamma_Z \tag{15}$$

where $\beta = \left(1 - 4m^2_L / m^2_Z\right)^{1/2}$. We have been studying[11] how well we can explore Z^0 physics using our rebuilt Mark II detector at the SLC -- the first major experiment at the SLC. We find that with sufficient attention to experimental and theoretical details we can measure Γ_Z with an error of ± 2-or-3%. Comparing this to Eq. 15, we ought to be able to detect the presence of a new L^0, but it will take time, patience, and care.

The indirect determination of Γ_Z requires a measurement of $\sigma(e^+e^- \rightarrow Z^0 \rightarrow \mu^+\mu^-)$ at the Z^0 peak and uses

$$\sigma(e^+e^- \rightarrow Z^0 \rightarrow \mu^+\mu^-) = \frac{12\pi}{M^2_Z} \frac{\Gamma_{z,e}\Gamma_{z,\mu}}{\Gamma^2_Z} \tag{16}$$

with $\Gamma_{z,e} = \Gamma_{z,\mu}$. The expected error in this determination of Γ_Z is also[11] ± 2-or-3%.

The method[12,13] using

$$e^+ + e^- \rightarrow Z^0 + \gamma,\ Z^0 \rightarrow L^0 + \bar{L}^0 \tag{17}$$

offers an alternative way to search for a view L^0, or any other neutral weakly-interactly particle, provided the new particle is <u>stable</u> relative to the detector size. Then the signal in the detector is a single photon. The three known L^0's, the ν_e, ν_μ, and ν_τ, contribute the cross section[13] in Fig. 1. The advantage of this method is that an additional L^0 makes a proportionately large change in the cross section for this reaction. The disadvantages are that the measurement of this process requires taking data off the Z^0 peak, and the process $e^+ + e^- \rightarrow e^+ + e^- + \gamma$ is a serious background.

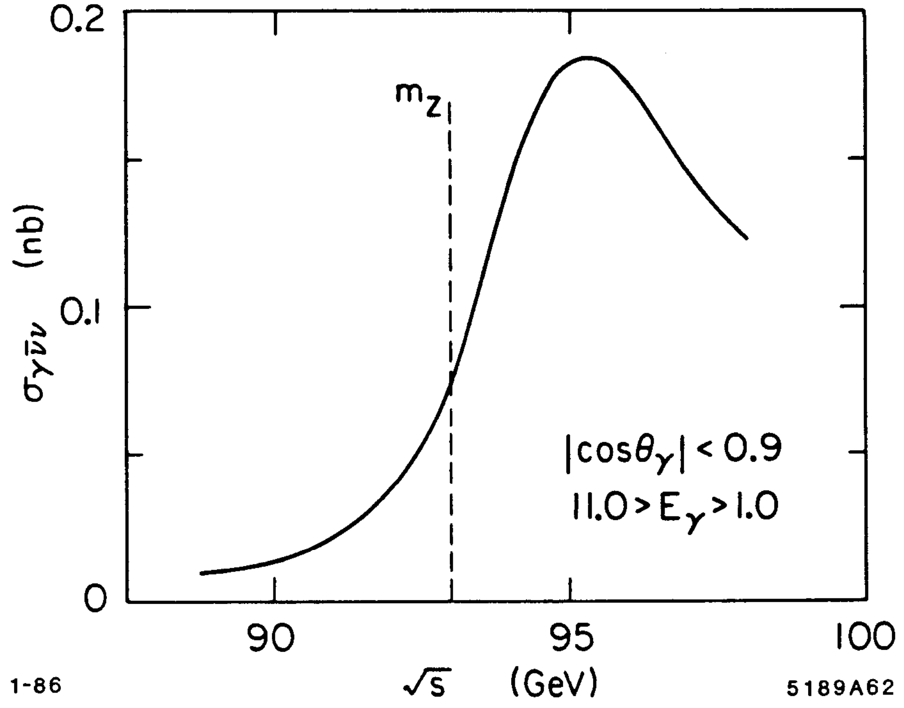

Figure 1

Unstable Neutrals Leptons at the Z^0

The third method for finding a new L^0 from Z^0 decay requires the L^0 to be unstable so that its decay modes can be detected. Excluding mixing with the known leptons, there are two simple possibilities. In one possibility there is a pair (L^-, L^0) with unique, conserved lepton number and

$$m_{L^0} > m_{L^-} \tag{18}$$

The L^0 is then unstable. Indeed the decays of the Z^0 would contain two sets of signatures for this pair: (a) the decays of the L^0 from $Z^0 \to L^0 + L^0$, and (b) the direct production of a new stable lepton, the L^-, via $Z^0 \to L^+ + L^-$.

We can say something experimentally about the neutral lepton represented by Eq. 18. Since we already know[7] that the lower limit on a new, stable L^- is 20 GeV/c^2, then $m_{L^0} > 20$ GeV/c^2 for this model.

The other simple possibility for an unstable neutral lepton without mixing lies outside of conventional weak interaction theory. Consider a pair of neutral leptons $(L^0, L^{0\prime})$ with unique conserved lepton number and

$$m_{L^0} > m_{L^{0\prime}} \tag{19}$$

In this, one of my favorite speculative models, I assume decay modes such as

$$\begin{aligned} L^0 &\to L^{0\prime} + \nu_\ell + \bar{\nu}_\ell \\ L^0 &\to L^{0\prime} + \ell^+ + \ell^- \\ L^0 &\to L^{0\prime} + \text{hadrons} \end{aligned} \tag{20}$$

where $\ell = e,\ \mu$ or τ; and $L^{0\prime}$ is assumed stable.

We looked[15] for such L^0's using the Mark II detector at PEP, assuming the reaction sequence

$$e^+ + e^- \to L^0 + \bar{L}^0 \tag{21a}$$
$$L^0 \to L^{0\prime} + \ell^+ + \ell^- \tag{21b}$$
$$\bar{L}^0 \to \bar{L}^{0\prime} + \ell^+ + \ell^- \tag{21c}$$

and taking $m_{L^{0\prime}}$ as zero. Nothing was found, with the 90% confidence level upper limits given in Fig. 2. Here σ_{stan} is the standard weak interaction cross section for the reaction in Eq. 21a. We will look for this again with our rebuilt Mark II detector at the SLC; then σ_{stan} will be much larger and the search will be much more sensitive.

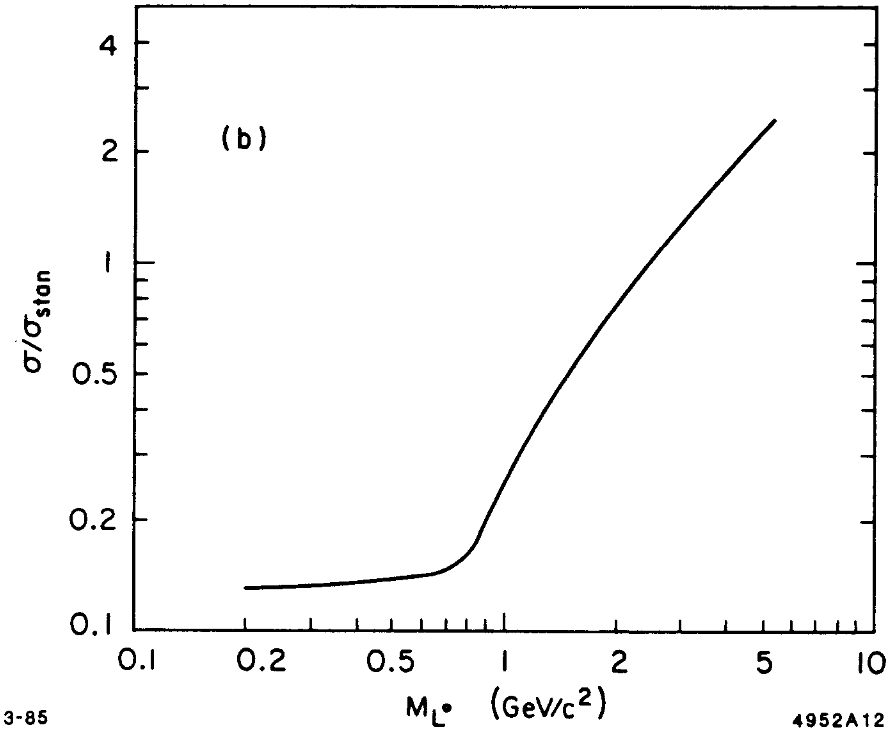

Figure 2

Conclusion

I began this paper on a pessimistic note in connection with the problem of lepton mass, and I used a quotation from Victor Weisskopf. I end on a more optimistic note again quoting him.[2]

> "Obviously, our theoretical insight into these phenomena has lagged, but we expected too much. We are apt to forget how much experimental material had to be accumulated before quantum mechanics was discovered. When we learn about these things today, we never hear about the tedious and torturous ways in which those insights were reached; we only learn the most logical and direct approach."

Drawing on Victor Weisskopf's patient optimism about the power of experiment interacting with theory, and looking forward to the coming of the SLC and LEP, I am optimistic that we will soon make progress in the fundamental questions associated with the leptons.

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