Comments and Addenda

The section *Comments and Addenda* is for short communications which are not appropriate for regular articles. It includes only the following types of communications: (1) *Comments on papers previously published in The Physical Review or Physical Review Letters.* (2) *Addenda to papers previously published in The Physical Review or Physical Review Letters, in which the additional information can be presented without the need for writing a complete article. Manuscripts intended for this section must be accompanied by a brief abstract for information-retrieval purposes. Accepted manuscripts follow the same publication schedule as articles in this journal, and page proofs are sent to authors.*

Use of $\Delta\phi$ -angle test to rule out neutral heavy leptons

Carl H. Albright

Fermi National Accelerator Laboratory,* Batavia, Illinois 60510
and Department of Physics, Northern Illinois University, DeKalb, Illinois 60115†

J. Smith‡

CERN, Geneva, Switzerland

(Received 11 December 1978)

The strong energy dependence of the $\Delta\phi$ distribution signal for neutrino production of neutral heavy leptons is pointed out in an effort to clarify the use of these distributions to suggest or rule out the existence of such leptons.

The present limits on the mass of a hypothetical neutral heavy lepton are at best rather tenuous. On the one hand, a lower limit of $10 \text{ GeV}/c^2$ was placed on such a heavy M^0 muon as the sole source of neutrino-induced dimuon events by the Harvard-Pennsylvania-Wisconsin-Fermilab group¹ in 1975. Subsequent experiments² have revealed that the major (if not total) portion of the signal is due to single-charm production by the charged weak current, so the former limit is negated by the copious background signals. More recent evidence bearing on this issue comes from a SPEAR experiment³ which looked for L^0 's resulting from the pair production of charged heavy leptons $L^\pm$, the L^0 's being identified by their decay into the exclusive $e\pi$ and $\mu\pi$ channels. The null result obtained suggested a lower bound of $1.2 \text{ GeV}/c^2$ on the mass of such an L^0 . A beam-dump experiment⁴ at Fermilab also failed to detect L^0 's decaying into $\mu\pi$ or $e\pi$ modes (unaccompanied by μ^- 's with $p_\mu > 10 \text{ GeV}/c$) with a mass less than $1 \text{ GeV}/c^2$ and a lifetime in the range 10^{-10} – 10^{-8} seconds.

A relatively light (1.5 – $3 \text{ GeV}/c^2$) neutral muon is not inconsistent with the present Aachen-Padova and CERN-Dortmund-Heidelberg-Saclay (CDHS) data.^{5,6} Indeed, it has been suggested by the Aachen-Padova group that of the order of 10^4 "quiet" μ^-e^+ events (little hadron energy) best fit the characteristics of the reaction

$$\nu_\mu + N \rightarrow M^0 + X \rightarrow \mu^- + \nu_e e^+ (\nu_\mu \mu^+). \quad (1)$$

The CDHS trimuon data can partially be understood with an L^0 of mass $1.5 \text{ GeV}/c^2$ being produced in association with a heavy quark. Preliminary evidence from the BEBC group even suggested that an M^0 with mass $1.8 \text{ GeV}/c^2$ had been identified by its decay into the $\mu\pi$ mode.⁷ Subsequent experimental searches have not borne this out.

Clearly there is need for sensitive tests which can pinpoint the presence of an M^0 heavy lepton at the level of 10% or less of the substantial charm background reaction

$$\nu_\mu + d(s) \rightarrow \mu^- + c \rightarrow s(d) + \nu_\mu \mu^+ (\nu_e e^+). \quad (2)$$

The Pais-Treiman test⁸ requiring the muon-average-energy ratio to be in the range $0.5 \leq \langle E_{\mu^+} \rangle / \langle E_{\mu^-} \rangle \leq 2.0$ is not very useful in the presence of a large charm background. The α -parameter test,⁹ where $\alpha = (E_{\mu^-} - E_{\mu^+}) / (E_{\mu^-} + E_{\mu^+})$, is better but suffers from any antineutrino contamination in the neutrino beam. In a previous Letter¹⁰ we suggested the combined use of the transverse-momentum and opening-azimuthal-angle tests to signal M^0 production followed by the charged-dilepton decay mode. While reaction (2) exhibits a strong backward peaking of the azimuthal-opening-angle ($\Delta\phi$) distribution of the two leptons measured in a plane perpendicular to the beam direction, in reaction (1) both charged leptons originate from the decay of the M^0 and the $\Delta\phi$ distribution tends to be peaked

forward at the higher energies.

The purpose of this note is to point out that the shape of the $\Delta\phi$ distribution for reaction (1) is very energy dependent, so the ϕ -angle test must be used with caution. The critical variable is E/E_{th} , where $E_{th} = [(M+m)^2 - m^2]/(2m)$ is the threshold energy for production of an M^0 of mass M and m is the nucleon mass. For typical neutrino-beam energies $\leq 2E_{th}$, the $\Delta\phi$ distribution can, in fact, be slightly peaked in the backward hemisphere,¹¹ since the M^0 tends to be produced almost directly forward in the laboratory. Only at energies $\geq 5E_{th}$ does the pronounced forward peaking occur when the M^0 can be produced at sizable angles relative to the neutrino beam direction.

These features are clearly illustrated in Fig. 1(a) where the distributions are drawn for a 2-

FIG. 1. $\Delta\phi$ distributions expected for (a) $M = 2 \text{ GeV}/c^2$ neutral heavy leptons produced by the CERN PS and Fermilab 400-GeV double-horn beams. In (b) the $\Delta\phi$ distributions pertain to $M = 5$ and $8 \text{ GeV}/c^2$ neutral heavy leptons produced by the Fermilab horn beam. The solid (dashed) curves refer to LL (LR) helicity couplings in the M^0 decay matrix element.

GeV M^0 heavy lepton ($E_{th} \approx 4 \text{ GeV}$) produced in a double-horn experiment at the CERN PS and in a double-horn experiment at Fermilab (or the SPS) with 400-GeV primary protons. The results are somewhat helicity dependent and curves are drawn for both $(V-A) \cdot (V-A)$ and $(V-A) \cdot (V+A)$ decay matrix elements. In the latter case more so than in the former case, the two charged leptons tend to be emitted back-to-back in the heavy-lepton rest frame so that the $\Delta\phi$ distributions reflect this fact.

As cited earlier, the Aachen-Padova neutrino group has reported⁵ finding of the order of 10 "quiet" $\mu^- e^+$ events which fit the characteristics of reaction (1). In particular the $\Delta\phi$ distribution for this small sample of events exhibits a plateau in the backward hemisphere. But we see from Fig. 1 that with a considerably harder neutrino energy spectrum, a pronounced peaking should occur in the forward hemisphere; moreover, the cross section for a $2\text{-GeV}/c^2$ M^0 produced in reaction (2) should no longer be suppressed by threshold effects. Hence, the heavy-lepton signal should

FIG. 2. $\Delta\phi'$ distributions corresponding to Fig. 1.

compete more favorably with the charm background and peaks at both $\Delta\phi = 0$ and 180° should be observed. This has not been confirmed,¹² and the possibility that such M^0 's are produced by neutrinos is small.

The situation is not at all clear for heavier neutral leptons, however. In Fig. 1(b) we show $\Delta\phi$ distributions for both $5 \text{ GeV}/c^2$ and $8 \text{ GeV}/c^2 M^0$'s with the Fermilab double-horn beam. Note that with $E \approx 20\text{--}40 \text{ GeV}$ and $\langle E/E_{\text{th}} \rangle \approx 2$, the $\Delta\phi$ curves are again higher in the backward hemisphere. With the $8\text{-GeV}/c^2 M^0$ contribution suppressed by threshold factors and superposed on the charm background curve, it is clear that the $\Delta\phi$ curve will only exhibit a backward peak.

One can also plot $\Delta\phi'$ distributions, where $\Delta\phi'$ represents the azimuthal opening angle between the two charged leptons projected onto a plane perpendicular to the hadron-jet direction. We show such plots in Fig. 2(a) for a $2\text{-GeV}/c^2 M^0$ lepton and both CERN PS and Fermilab horn beams; in Fig. 2(b) we give the $\Delta\phi'$ distributions for 5- and $8\text{-GeV}/c^2 M^0$'s with the Fermilab horn beam only. In nearly every case, these curves are peaked forward. Dileptons from charm production would tend to exhibit rather flat $\Delta\phi'$ distri-

butions, so these plots can help to unravel a heavy-lepton signal on a substantial charm background. We remark that $\Delta\phi'$ distributions in general are subject to larger experimental errors than $\Delta\phi$ distributions, since the error in determining the apparent hadron jet direction is non-negligible. This is especially true in bubble-chamber experiments where hadrons can escape the chamber without being detected.

In summary, we have attempted to clarify the sensitivity of $\Delta\phi$ distributions to M^0 heavy-lepton production and decay through leptonic modes yielding dilepton events. It appears that current experiments will not be able to place a higher mass limit than $4\text{--}5 \text{ GeV}/c^2$ on M^0 's produced with full strength couplings. This contrasts rather sharply with corresponding limits¹³ of $7.5 \text{ GeV}/c^2$ and $12 \text{ GeV}/c^2$ recently placed on M^- and M^+ heavy leptons.

We wish to thank Professor Charles Baltay for stimulating our interest in this problem. This work was supported in part by the National Science Foundation under Grants Nos. PHY 77-07864 and PHY 76-15328 and by the Department of Energy.

*Operated by Universities Research Association, Inc. under contract with the Energy Research and Development Administration.

†Permanent address.

‡On leave of absence from the Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, N. Y. 11794.

¹A. Benvenuti *et al.*, Phys. Rev. Lett. **35**, 1203 (1975).

²Recent results are reported in J. Blietschau *et al.*, Phys. Lett. **60B**, 207 (1976); P. Bosetti *et al.*, Phys. Rev. Lett. **38**, 1248 (1977); C. Baltay *et al.*, *ibid.* **39**, 62 (1977); B. C. Barish *et al.*, *ibid.* **39**, 981 (1977); M. Holder *et al.*, Phys. Lett. **69B**, 377 (1977); H. C. Ballagh *et al.*, Phys. Rev. Lett. **39**, 1650 (1977); A. E. Asratyan *et al.*, Phys. Lett. **71B**, 439 (1977); P. C. Bosetti *et al.*, *ibid.* **73B**, 380 (1978); A. Benvenuti *et al.*, Phys. Rev. Lett. **41**, 1204 (1978).

³D. I. Meyer *et al.*, Phys. Lett. **70B**, 469 (1977).

⁴D. J. Bechis *et al.*, Phys. Rev. Lett. **40**, 602 (1978).

⁵H. Faissner *et al.*, in *Neutrinos '77*, proceedings of the International Conference on Neutrino Physics and

Neutrino Astrophysics, Baksan Valley, U.S.S.R., 1977, edited by M. A. Markov *et al.* (Nauka, Moscow, 1978).

⁶M. Holder *et al.*, Phys. Lett. **77**, 114 (1978) and Nucl. Phys. B (to be published).

⁷See, e.g., F. Sciulli, in *Proceedings of the Topical Conference on Neutrino Physics at Accelerators*, Oxford, 1978, edited by D. Perkins (Rutherford Laboratory, Chilton, Didcot, Oxfordshire, England, 1978), p. 405.

⁸A. Pais and S. B. Treiman, Phys. Rev. Lett. **35**, 1206 (1975).

⁹See, e.g., Benvenuti *et al.*, Ref. 2.

¹⁰C. H. Albright and J. Smith, Phys. Lett. **77B**, 94 (1978).

¹¹This feature was illustrated in D. Rein, L. M. Sehgal, and P. M. Zerwas, Nucl. Phys. **B138**, 85 (1978), as a possible interpretation of the Aachen-Podova experiment cited in Ref. 5.

¹²See especially M. Holder *et al.*, in Ref. 1.

¹³A. M. Cnops *et al.*, Phys. Rev. Lett. **40**, 144 (1978); M. Holder *et al.*, Phys. Lett. **74B**, 277 (1978).