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[1]*Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic, New York, 1966); *Proceedings of the Second Conference on Nuclear Isospin, Asilomar, California, March 1969*, edited by J. D. Anderson, S. D. Bloom, W. W. True, and J. Cerny (Academic, New York, 1969); W. R. Coker and C. F. Moore, Phys. Today 22, No. 4, 53 (1969).

[2]For a general review of this area as well as for references consult G. T. Garvey, Ann. Rev. Nucl. Sci. 19, 433 (1969).

[3]E. P. Wigner and E. Feenberg, Rep. Progr. Phys. 8, 274 (1941); E. P. Wigner, in *Proceedings of the Robert A. Welch Foundation Conferences on Chemical Research, Houston, Texas, 1957*, edited by A. Milligan (Robert A. Welch Foundation, Houston, Tex., 1957), Vol. 1, Chap. 4, p. 86; S. Weinberg and S. B. Treiman, Phys. Rev. 116, 465 (1959).

[4]D. H. Wilkinson, Phys. Lett. 12, 348 (1964).

[5]We use natural units with $\hbar = c = 1$ throughout.

[6]See, for example, L. I. Schiff, *Quantum Mechanics* (McGraw-Hill, New York, 1968), 3rd ed., Chap. 8, p. 285.

[7]Weinberg and Treiman, Ref. 3, Eqs. (3) and (4).

[8]Equations (13) and (14) are an immediate consequence of the fact that $H_\gamma^{(1)}$ and $H_\gamma^{(2)}$ are linear and bilinear, respectively, in the electromagnetic field operator.

[9]A. I. Sanda and Graham Shaw, Phys. Rev. Lett. 24, 1310 (1970).

[10]M. Goldhaber and J. Weneser, Ann. Rev. Nucl. Sci. 5, 1 (1955); N. Dombey and P. K. Kabir, Phys. Rev. Lett. 17, 730 (1966).

[11]G. Morpurgo, Phys. Rev. 114, 1075 (1959); E. K. Warburton and J. Weneser, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), pp. 175-228.

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# DECAY INTO MUON PAIRS OF PHOTOPRODUCED $\varphi$ MESONS*

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We have measured the yield of $\varphi$ mesons photoproduced from carbon and decaying into muon pairs. We find that the product of the lepton-pair branching ratio for the $\varphi$ and the $t=0$ photoproduction cross section is $(0.66 \pm 0.10) \times 10^{-4}$ mb/GeV$^2$. This number is compared with existing measurements of the branching ratio and the cross section.

We report on an experiment in which the photoproduction of $\varphi$ mesons from a carbon target was studied by observing the $\mu^+\mu^-$ decay mode of the $\varphi$. The $\varphi$ yield, which appears as a peak in the muon-pair mass spectrum above the Bethe-Heitler background, is proportional to the product of the $\varphi$ production cross section and the muon-pair branching ratio of the $\varphi$. Hence this experiment can serve as a consistency check on other experiments which measure the latter quantities. Assuming electron-muon universality, we find that our results are not consistent with preliminary reports of recent measurements of the cross section and the electron-pair branching ratio. If this inconsistency should prove to be true, it would mean that electron-muon universality was violated at the $\varphi$ mass. On the other hand, if some of the experiments are eventually shown to be in error, then the magnitude of the phi-photon coupling constant derived from them will have to be adjusted.

The experiment was performed at the Cornell University Wilson Synchrotron Laboratory. The apparatus employed differed only slightly from that used in previous experiments.[1,2] The direction of each muon was determined by a counter hodoscope and the energy of each muon was determined by its range in iron. The apparatus accepted muons with production angles between 7.5° and 12.5°, and energies between 2.58 and 3.85 GeV. At larger angles the ratio of $\varphi$ signal to Bethe-Heitler background increases. However, larger angles require detection of muons with lower energies which, in the case of an experiment using iron absorber to identify muons, results in increased background due to photoproduced pions. The present experiment was designed for the maximum $\varphi$ signal consistent with negligible pion background. Data were taken with bremsstrahlung peak energies at 9.8 and 8.3 GeV, and the muon-pair yield was the same in each case. Previous experience had indicated that such agreement is a good test for the absence of pion background.[3] After correction for random coincidences (4% maximum) and counter inefficiencies, more than 25 000 events remained. Target-out yield contributed $0.5 \pm 0.5\%$.

Pairs of muons in our range of mass ($775 < M_{\mu\mu} < 1550$ MeV, where $M_{\mu\mu}$ is the muon-pair invariant mass) and $t$ ($0 < -t < 0.2$ GeV$^2$, where $t$ is the square of the four-momentum transfer to the nucleus) are due to the muonic decay of photoproduced vector mesons $\varphi$, $\rho$, and $\omega$, and also to Bethe-Heitler production. The Bethe-Heitler contribution may be divided into three classes; elastic, inelastic, and "pion" inelastic, as discussed in Ref. 2. Following the technique detailed in that reference, two forms of the inelastic yield were evaluated; one of these (INLOW) is expected to be valid for small $|t|$ and was used successfully in a previous low-$|t|$ experiment[1] while the other (INHI) is expected to be valid for larger $|t|$ and gave a somewhat better fit in a larger-$|t|$ experiment.[2] The "pion" inelastic yield in the present experiment was small, contributing 4% to the total yield.

We have assumed a phi cross section of the form[4]

$$B_{\varphi\mu\mu} d\sigma/dt = (C_\varphi/1.1)(e^{50t}+0.1e^{5t}). \tag{1}$$

The parameter $C_\varphi$ is the product of the extrapolated $t=0$ photoproduction cross section and the muonic branching ratio, $B_{\varphi\mu\mu}$, of the $\varphi$ meson.

Since the exact mass distribution in the $\rho$-$\omega$ region is uncertain, the $\rho$ yield was calculated using two forms for the mass distribution. One form ignored $\rho$-$\omega$ interference:

$$R_1(m^2) = \frac{1}{m^2}\left|\frac{1}{m^2-m_\rho^2+im_\rho\Gamma_\rho}\right|^2; \tag{2}$$

while the other included this effect[5]:

$$R_2(m^2) = \frac{1}{m^2}\left|\frac{1}{m^2-m_\rho^2+im_\rho\Gamma_\rho} + \frac{\eta}{9}\left(\frac{m_\omega}{m_\rho}\right)^4 \frac{e^{i\varphi}}{m^2-m_\omega^2+im_\omega\Gamma_\omega}\right|^2. \tag{3}$$

The notation and parameters used are those of Ref. 5. For each form we assumed a differential cross section with a $t$ dependence of

$$e^{47t}+0.043e^{10t}. \tag{4}$$

The $t=0$ production cross section[6] and the muonic decay branching ratio[7] of the $\rho$ were taken to be 8.5 mb/GeV$^2$ and $6.2\times10^{-5}$, respectively. The pionic decay of the $\rho$ with subsequent decay of the pions into muons was approximately one-fifth of the total $\rho$ yield. Figure 1 presents the 8.3-GeV data as a ratio ($R_{\rm BH}$) of observed counts to the total Bethe-Heitler yield versus $M_{\mu\mu}$ [Fig. 1(a)] and $-t$ [Fig. 1(b)]. In Fig. 1(a), the data are displayed in 50-MeV mass bins. The enhancements due to the vector mesons are clearly visible. The apparent width of the $\varphi$ meson is due to the mass resolution of the apparatus (±50 MeV).

We determined the parameter $C_\varphi$ by performing least-squares fits to the observed mass distributions. The total theoretical yield $Y$ was parametrized as

$$Y = N(Y_{\rm BH}+C_\varphi Y_\varphi+RY_\rho), \tag{5}$$

where $Y_{\rm BH}$ is the expected Bethe-Heitler yield,[8] $C_\varphi Y_\varphi$ is the expected phi yield for a given $C_\varphi$, and $Y_\rho$ is the total expected $\rho$ yield. $N$, $C_\varphi$, and $R$ are the free parameters, and the expected values of $N$ and $R$ are unity.

The results of these fits are presented in Table I. It can be seen that the value of $C_\varphi$ obtained is relatively insensitive to (1) the $\rho$ mass shape employed (fits 1, 4), (2) the bremsstrahlung peak energy (fits 1, 5), (3) the form of Bethe-Heitler inelastic theory (fits 1, 3), and (4) cuts on $t$ (fits 1, 2). The data prefer the $\rho$ form $R_2$, which incorporates $\rho$-$\omega$ interference, to form $R_1$, which does not. When plotted as a function of $t$ [Fig. 1(b)], the data prefer the inelastic form INLOW to the form INHI. For this reason fit No. 1 was used to generate the solid lines of Fig. 1. The insensitivity of $C_\varphi$ to cuts on $t$ supports the as-

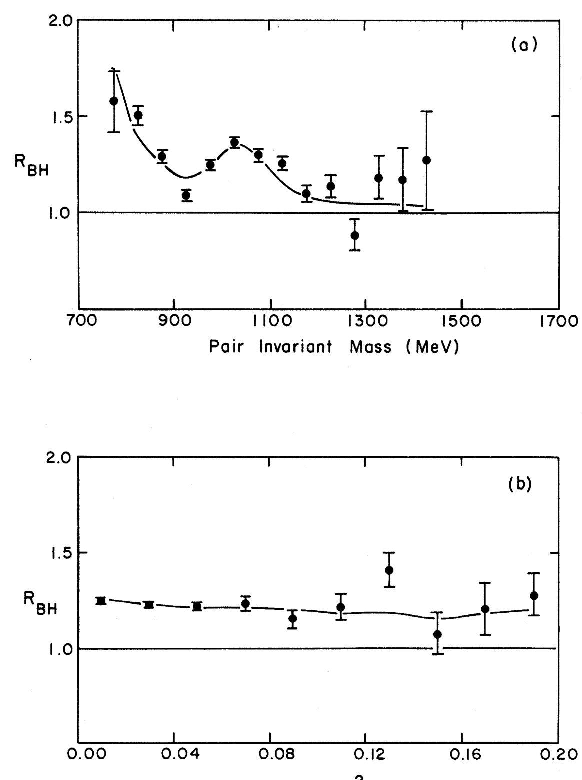


FIG. 1. Ratio of observed counts to expected Bethe-Heitler yield versus (a) pair invariant mass and (b) $t$. In (a) only events with $|t| < 0.04$ GeV$^2$ are plotted. In (b) all events are plotted. The solid lines indicate the total yield derived from fit No. 1 of Table I.

Table I. Results of fits of theoretical yield [Eq. (5)] to observed mass distributions. Indicated errors are statistical only. In column 4, "YES" means data with $|t| > 0.04$ GeV$^2$ were excluded.

| Fit No. | Rho form | Inelastic | Cut on $t$ | Peak energy (GeV) | $N$ | $C_\varphi$ | $R$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|
| 1 | $R_2$ | INLOW | YES | 8.3 | $0.92 \pm 0.03$ | $0.66 \pm 0.07$ | $1.22 \pm 0.17$ | 28.5 |
| 2 | $R_2$ | INLOW | NO | 8.3 | $0.92 \pm 0.02$ | $0.63 \pm 0.06$ | $1.30 \pm 0.14$ | 28.5 |
| 3 | $R_2$ | INHI | YES | 8.3 | $0.94 \pm 0.03$ | $0.63 \pm 0.07$ | $1.13 \pm 0.17$ | 30.8 |
| 4 | $R_1$ | INLOW | YES | 8.3 | $0.91 \pm 0.03$ | $0.66 \pm 0.07$ | $1.21 \pm 0.18$ | 38.3 |
| 5 | $R_2$ | INLOW | YES | 9.8 | $0.89 \pm 0.04$ | $0.65 \pm 0.10$ | $1.36 \pm 0.21$ | 25.9 |

sumed $t$ dependence of the $\varphi$ cross section. However, the results for $-t < 0.04$ GeV$^2$ should probably be preferred since for this $t$ range the $\varphi$ yield is predominantly coherent. For this reason we have plotted only events with $-t < 0.04$ GeV$^2$ in the mass spectrum in Fig. 1(a). On the basis of these fits we conclude that

$$C_\varphi = (0.66 \pm 0.10) \times 10^{-4} \text{ mb/GeV}^2, \qquad (6)$$

where the uncertainty reflects the statistical error, the variations among the different fits, the uncertainty in the $\varphi$ angular distribution, and an estimated 7% normalization uncertainty.

There are two theoretical corrections to our value for $C_\varphi$ which have not been applied because they are not well known. The first is radiative corrections. Estimates based on a soft-photon correction formula gave corrections which varied from $-1\%$ to $-4.5\%$. (The negative sign here means the true value of $C_\varphi$ is larger than the observed value.) A potentially larger correction comes from $\rho$-$\varphi$ interference. The magnitude of this effect depends on the relative production phase, $\theta$, for $\rho$ and $\varphi$ from carbon. An evaluation based upon a relativistic Breit-Wigner form for the mass distribution of both the $\rho$ and $\varphi$ gave a fractional contribution to the $\varphi$ yield of

$$0.01 \cos\theta + 0.18 \sin\theta. \qquad (7)$$

Thus, if $\theta = 0°$, as expected for diffraction production, the correction is small. At worst the correction could be 18%.

Our result for $C_\varphi$ can be compared with results of other experiments through the relation

$$C_\varphi = B_{\varphi\mu\mu}(d\sigma_\varphi/dt)_{t=0}. \qquad (8)$$

If we assume electron-muon universality, then $B_{\varphi\mu\mu} = B_{\varphi ee} \times 0.9993$. It would appear that at present the best known of the above quantities is $B_{\varphi ee}$, which has been measured in an Orsay colliding-beams experiment[9] with the result $(3.73 \pm 0.25) \times 10^{-4}$. The production cross section from carbon has been measured in two experiments, but to date only preliminary results have been given. A DESY group reported[10] $0.34 \pm 0.06$ mb/GeV$^2$ while a Cornell group originally found[11] $0.38 \pm 0.06$ mb/GeV$^2$ for this quantity. Subsequent analysis of their data by the Cornell group has suggested that the cross section may be lower than the preliminary value by a substantial factor, which may be as large as 2.[12] If one takes the Orsay value for $B_{\varphi ee}$ and assumes universality, then our data yield

$$d\sigma_\varphi/dt = C_\varphi/B_{\varphi ee} = 0.177 \pm 0.029 \text{ mb/GeV}^2. \quad (9)$$

This is clearly not consistent with the above mentioned values.[13-15]

The photon-$\varphi$-meson coupling constant has been derived from the branching ratio of $\varphi$ mesons decaying into electron pairs,[9] as well as from a detailed analysis of photoproduction cross sections of $\varphi$ mesons from complex nuclei.[11] The prediction of simple vector meson dominance is that the coupling constants derived independently from these two measurements should agree. The experimental discrepancy between our results and the above-mentioned measurements of $B_{\varphi ee}$ and photoproduction cross sections casts doubt on the significance of such a comparison of coupling constants based on present data.

We wish to thank Professor D. Yennie and Professor S. Brodsky for helpful suggestions on estimating radiative corrections. We also thank J. Knowles for help in running an early stage of the experiment.

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[1]S. Hayes *et al.*, Phys. Rev. Lett. 22, 1134 (1969).
[2]S. Hayes *et al.*, Phys. Rev. Lett. 24, 1369 (1970).
[3]S. Hayes *et al.*, in *High-Energy Physics and Nuclear Structure*, edited by S. Devons, (Plenum, New York, 1970), p. 656; S. Hayes *et al.*, in *International Symposium on Electron and Photon Interactions at High Ener-*

*gies, Liverpool, England, September 1969,* edited by D. W. Braben (Daresbury Nuclear Physics Laboratory, Daresbury, Lancashire, England, 1970), Abstract No. 165 and p. 7. At these conferences, we reported on a preliminary run of this experiment done at lower muon energies. Subsequent analysis indicated a background in the lowest energy bin of about 10% to 20% of the Bethe-Heitler rate, and negligible background in the higher energy bins. This background also varied strongly with peak bremsstrahlung energy. The size of the phi signal then observed agrees quite well with our present result for $C_\varphi$, indicating that the background, while troublesome, did not effect our sensitivity to such a narrow resonance. It should be noted that the branching ratio quoted at those conferences *assumed* the correctness of the production cross sections as quoted in S. C. C. Ting, in *Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September 1968,* edited by J. Prentki and J. Steinberger (CERN) Scientific Information Service, Geneva, Switzerland, 1968), p. 64; G. McClellan *et al.*, Cornell University Laboratory of Nuclear Studies Reports No. CLNS-69 and No. CLNS-70, September 1969 (unpublished), presented by A. Silverman in *International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, September 1969,* edited by D. W. Braben (Daresbury Nuclear Physics Laboratory, Daresbury, Lancashire, England, 1970), p. 83.

[4]This form is the result of an empirical fit by us to preliminary data on the angular distribution of phi mesons photoproduced from carbon. These data come from an unpublished experiment done by N. Mistry and others at the Cornell synchrotron. The form of the coherent term is consistent with well established results of coherent $\rho$ photoproduction. The incoherent term makes only a small contribution to our results when larger $t$ events are excluded. We thank Dr. Mistry for the use of these data.

[5]P. J. Biggs *et al.*, Phys. Rev. Lett. 24, 1197 (1970).

[6]G. McClellan *et al.*, Phys. Rev. Lett. 22, 377 (1969).

[7]J. E. Augustin *et al.*, Phys. Rev. Lett. 20, 126 (1968).

[8]We have assumed the validity of quantum electrodynamics (QED) for this mass range. This is justified by the results of Ref. 2.

[9]J. Perez-y-Jorba, in *International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, September 1969,* edited by D. W. Braben (Daresbury Nuclear Physics Laboratory, Daresbury, Lancashire, England, 1970), p. 213.

[10]Ting, Ref. 3.

[11]McClellan *et al.*, Ref. 3.

[12]R. Talman and N. Mistry, private communication.

[13]We have spent some time in searching for normalization errors in our experiment. In particular, three independent calculations of our expected $\varphi$ rate using Eq. (1) agreed. We point out that the excellent agreement with the absolute Bethe-Heitler rates indicated in Table I is itself a check on all our normalization factors.

[14]It should be noted that the preliminary measurement of the $\varphi$ photoproduction cross section from hydrogen in Ref. 11 is higher by about a factor of 2 than the value reported by a group at Stanford Linear Accelerator Center [R. Anderson *et al.*, Phys. Rev. D 1, 27 (1970)].

[15]U. Becker *et al.*, Phys. Rev. Lett. 21, 1504 (1968). This gives $B_{\varphi ee} = (3.1 \pm 0.9) \times 10^{-4}$. The large quoted uncertainty in this result makes it compatible both with our results and those of Ref. 7, 10, and 11.

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# DECAY OF SOME HIGH-MASS BOSONS TO $\pi^+\pi^0$ †

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We present evidence for three boson structures with masses 1.65, 1.97, and 2.16 GeV/$c^2$ and widths less than 80 MeV/$c^2$ from a study of the reaction $\pi^+p \to p\pi^+\pi^0$ at 13.1 GeV/$c$. These structures are shown to have $I^G = 1^+$, therefore excluding even $J$ assignments. This result favors the interpretation of the 1.97 state as a member of the $A_2$ daughter trajectory.

In this Letter we present evidence for the production of three narrow-width charged boson structures with $I^G = 1^+$ in the reaction

$$\pi^+p \to p\pi^+\pi^0 \qquad (1)$$

at 13.1 GeV/$c$. These states occur in the mass regions of the $R_1$ ($g$), $S$, and $T$ seen with the CERN missing mass spectrometer (CMMS),[1] although significant differences from the $S$ and $T$ are noted below. Henceforth, they will be denoted in this Letter by $R_1$ ($g$), $S'$, and $T'$.

The data presented were obtained from an 8.0-event/$\mu$b exposure of 13.1-GeV/$c$ $\pi^+$ mesons incident in the 82-in. hydrogen bubble chamber, using the rf separated beam from the Stanford linear accelerator. The film was scanned twice for interactions with two charged final-state particles and no associated strange-particle decays. The events found were measured on scanning and measuring projectors and conventional film-plane measuring machines[2] and processed using the TVGP-SQUAW system. Every event included