SEARCH FOR THE DECAY OF PHOTOPRODUCED φ MESONS INTO $\mu^+ + \mu^-$†

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A brief experiment has been performed to study the feasibility of extending previous work[1] on photoproduction of muon pairs to higher values of the invariant $\mu\mu$ mass. The experiment was done at Cambridge Electron Accelerator using a 6-BeV bremsstrahlung beam and a carbon target. An iron filter was used to identify muons. The detection techniques, electronics, etc., have been described in previous notes.[1,2] We wish to comment here on a result of this experiment which is of some current interest in the question of photoproduction of φ mesons.[3-6]

Table I shows, for four mass bins, the expected yield due to the Bethe-Heitler process assuming quantum electrodynamics (QED) is correct in this mass region.[7] This yield was calculated by methods outlined in earlier notes and includes, as do the ρ^0 and φ yields discussed below, the effects of Coulomb scattering in the iron.[1,2] This scattering dominates the mass resolution.

A second column shows the expected yield in this mass region due to $\rho^0 \to 2\mu$. Although the ρ yield in this mass region is small, we will review the calculation of this yield, because the φ yield is calculated in the same way. The ρ^0 yield is calculated as outlined previously[1,8] by assuming that the ρ-production cross section has the form

$$d^3\sigma/dk\,dm\,d\Omega = g(k)f(m)(e^{-At} + be^{-Dt})$$

which results in a yield of

$$Y_\rho = B_\rho C_\rho \int \left[nQ\left(\frac{k}{4.4}\right)^2 (e^{-At} + be^{-Dt})\,d\varphi\,d\cos\theta\right] \times \left[\frac{1}{k}\right][f(m)dm]\,[f(\bar{\theta})d\bar{\varphi}\,d\cos\bar{\theta}]. \qquad (1)$$

In these equations n is the number of nuclei per cm^2 in the target, Q is the number of equivalent quanta striking the target, k is the photon energy in BeV, and t is the square of the four-momentum transferred to the nucleus. The terms e^{-At} and be^{-Dt} represent the coherent and incoherent ρ production from the carbon nucleus. As discussed previously,[1] $b = 0.098$, $A = 45$, and $D = 10$. C_ρ is evaluated from the cross section for photoproduction of ρ^0 at $t = 0$ at 4.4 BeV, and $C_\rho = 86 \times 10^{-27}$ cm^2/sr. θ is the ρ production angle with respect to the γ-ray beam. $\bar{\theta}$ is the angle of one of the μ's in the center of mass of the ρ, taken with respect to the ρ direction of motion in the laboratory. The invariant mass of the μ pair is m, and $f(m)$ is a normalized Breit-Wigner resonance shape with $M_0 = 740$ MeV, and a full width at half-maximum of 150 MeV. $B_\rho \equiv [\mathrm{No.}(\rho \to 2\mu)]/[\mathrm{No.}(\rho \to \mathrm{all})]$ converts the yield to that for muon decay of the ρ^0. The yield in terms of the above variables is transformed to laboratory variables by the appropriate transformation equations and a 6×6 Jacobian. The integration is then performed over the laboratory acceptance intervals.

The second column of Table I shows the yield from $\rho^0 \to 2\mu$ in the given mass intervals, using $B_\rho = 4.4 \times 10^{-5}$.

In order to calculate the φ yield Eq. (1) was again used, with the φ mass and width used for $f(m)$. In doing this we have assumed, following the theoretical literature, that the mechanism for φ photoproduction (e.g., the t dependence) is the same as for ρ^0 photoproduction.[3,4,6] B_φ and C_φ are not yet known, and it is our purpose to set a limit on these quantities. In order to do this it is convenient to calculate theoretical yields, $Y_{\varphi,\mathrm{theor}}$, which would result if $B_\varphi\sigma_\varphi = B_\rho\sigma_\rho$. We will then compare the experimental yields to this prediction in order to scale down $B_\varphi\sigma_\varphi$ to its experimental value. Column 3 of Table I lists $Y_{\varphi,\mathrm{theor}}$ calculated for $B_\varphi\sigma_\varphi = B_\rho\sigma_\rho$.

Finally, in column 4 of Table 1 we list the

Table I. Experimental and theoretical yields in various mass regions. Yields are defined in the text material. Note particularly that $Y_{\varphi,\mathrm{theor}}$ is the theoretical yield for μ pairs from φ on the assumption that $\sigma_\varphi B_\varphi = \sigma_\rho B_\rho$.

Mass (MeV/c^2)	Y_{BH}	Y_ρ	$Y_{\varphi,\mathrm{theor}}$	Y_{expt}
930-970	52.0	14.2	52.2	69.0
970-1010	24.0	6.0	72.4	33.0
1010-1050	5.0	1.0	35.5	2.9
1050-1090	2.6	0.5	25.4	2.1
Totals	83.6	21.7	185.5	107.0 ±11

corrected experimental yields in the given mass regions. Corrections made to the raw data have been previously described.[1,2]

Now, since the yields $Y_{\varphi,\,\text{theor}}$ were calculated assuming $B_\varphi\sigma_\varphi = B_\rho\sigma_\rho$ it follows that

$$R \equiv \frac{B_\varphi\sigma_\varphi}{B_\rho\sigma_\rho} = \frac{Y_{\varphi,\,\text{expt}}}{Y_{\varphi,\,\text{theor}}} = \frac{Y_{\text{expt}} - Y_{\text{BH}} - Y_\rho}{Y_{\varphi,\,\text{theor}}}. \tag{2}$$

From Table I we find

$$R = 0.009 \pm 0.060. \tag{3}$$

The errors quoted are statistical errors only in Y_{expt}.[7] We would now like to estimate an upper limit on R. Errors in Y_{expt} due to normalization problems are expected to be less than 15%, or ±15 counts. Other errors in Y_{expt} are negligible. The error (of negative sign) in Y_ρ due to uncertainties in the measured value of B_ρ is negligible in this mass region. The maximum expected error (of negative sign) in $Y_{\varphi,\,\text{theor}}$ is about 20%, and due to the error (of negative sign) in B_ρ. The value of B_ρ we use is that measured in earlier work[1,9] on photoproduction of muon pairs and confirmed in work on pion production of muon pairs.[10] Including the two-standard-deviation statistical errors, the normalization errors in Y_{expt}, and the maximum expected error in Y_φ, the "two-standard-deviation" upper limit on R is

$$R < 0.26. \tag{4}$$

In the literature we find no previous results for R or for $B_\varphi\sigma_\varphi$ (photoproduction) with which to compare our results.

We may, however, compare with theoretical predictions.[3-6] We find that our experimental upper limit is 3 to 10 times lower than the unbroken SU(3) theoretical values[3,4] given in the literature, depending upon the assumed mass dependence of $\Gamma(V \to 2\mu)$. Following Freund[3,11] we find for a theoretical prediction of this quantity $R_{\text{theor}} = 2.68$. Using instead Harari's assumptions for the mass dependence of $\Gamma(V^0 \to 2\mu)$, we find $R_{\text{theor}} = 0.83$. Both of these values are well above our own two-standard-deviation upper limit for R_{expt}. Harari's result is of special interest since it contains the least favorable mass dependence of $\Gamma(V^0 \to 2\mu)$ in the literature. But even this low theoretical value of R is more than three times our upper limit.

We conclude that $\sigma_\varphi B_\varphi/\sigma_\rho B_\rho$ is markedly lower than predicted by attractively simple and general SU(3) arguments.[3,4] Previous disagreement with these same arguments has been found in bubble-chamber results[12] for $\sigma_\varphi/\sigma_\rho$. These results show $\sigma_\varphi/\sigma_\rho$ to be about 8 times lower than predicted.[3,4] The present experiment cannot separate the value of $\sigma_\varphi/\sigma_\rho$ from B_φ/B_ρ, but finds an independent failure of the predictions.[3,4] Our results may be interpreted as confirming the bubble-chamber results. This seems worth mention even in view of the more recent theoretical work[5,6] that supports the bubble-chamber results. The earlier theoretical results[3,4] have been considered sufficiently constrained that the bubble-chamber results have been questioned.[4] In particular, recent theoretical work[5,6] has not yet been extended to test the consequences of the assumptions on other processes, such as $\gamma + p \to \rho^0 + N^*$. But independent of such questions our results are in disagreement with the earlier theoretical work[3,4] and not in disagreement with more recent work.[5,6]

Next, we may use the experimental value[12] of $\sigma_\rho/\sigma_\varphi$, and solve Eq. (1) for B_φ/B_ρ. We use the value $\sigma_\rho/\sigma_\varphi = 38$ from recent bubble-chamber work.[11] Our results are

$$B_\varphi = (0.34 \pm 2.28)B_\rho, \tag{5}$$

where, as in Eq. (3), the errors are only statistical. Allowing for errors in normalization of Y_{expt}, and for errors of $Y_{\varphi,\,\text{theor}}$ as previously outlined, this yields for a two-standard-deviation upper limit

$$B_\varphi < 9.9 B_\rho, \tag{6a}$$

$$B_\varphi < 4.4 \times 10^{-4}. \tag{6b}$$

These results are based upon a ratio of production cross sections $\sigma_\rho/\sigma_\varphi = 38$, and must be scaled for any future changes in this ratio. In particular, the current value of the ratio has an error of 40%. We may include this error by multiplying Eq. (6) by $(1 \pm 0.4)^{-1}$. Including the quoted[12] error in the bubble-chamber measurements,

$$B_\varphi < 17 B_\rho, \tag{7a}$$

$$B_\varphi < 7.4 \times 10^{-4}. \tag{7b}$$

This limit agrees with a previous upper limit[13] on B_φ, and is approximately an order of magnitude smaller. Note here that we have again used the assumption, previously emphasized, that the mechanism for the φ production is the same as for the ρ production.[3,4,6]

These results may again be compared to theoretical predictions[3,4] based upon SU(3), direct photon-vector meson coupling, and $\omega\varphi$ mixing with $\cos\theta = \sqrt{\frac{2}{3}}$. Using the results of Freund[3,11] we obtain $B_{\varphi,\,\text{theor}} = 12.1 B_\rho$, and using the results of Harari[4] we obtain $B_{\varphi,\,\text{theor}} = 3.75 B_\rho$. Both of these are within our two-standard-deviation upper limit, Eq. (7), and hence we cannot yet comment upon the mass ambiguity.

In summary, our experimental upper limit on $\sigma_\varphi B_\varphi / \sigma_\rho B_\rho$ is in disagreement with apparently constrained SU(3) arguments,[3,4] and underscores disagreement with these arguments already found in bubble-chamber work.[5,6,12] In addition, using the bubble-chamber value[12] for $\sigma_\rho/\sigma_\varphi$, assuming the validity of QED for muons in this mass region,[7] and assuming that the mechanism for φ production is the same as that for ρ production,[3,4,6] we set an upper limit $B_\varphi < 17 B_\rho \approx 7.4\times10^{-4}$, which is in agreement with, and approximately an order of magnitude improvement on, earlier work.[13]

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[7]In our earlier work (Ref. 2) we noted that there was an indication ($2\frac{1}{2}$ standard deviations) of disagreement with Bethe-Heitler theory such that the experimental yield decreased as the invariant mass increased. If this effect is real, and not due to cumulative systematic errors, then "Y_{BH}" of Table I should be decreased. This results in an increase in the upper limit on B_φ and on $B_\varphi\sigma_\varphi/B_\rho\sigma_\rho$. We here calibrate this uncertainty by noting that each 12% decrease in the QED yield is equivalent to adding to the central values of Eqs. (3) and (5) an amount equal to the one-standard-deviation error in the central values. Extending the discussions of error following Eqs. (3) and (5), we find that a 50% breakdown in QED approximately doubles our two-standard-deviation upper limits given in Eqs. (4) and (6) or (7).

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[9]Note that in Ref. 1, under the explicit assumption of an isotropic decay in the ρ^0 center-of-mass system, a value of $B_\rho = 3.3\times10^{-5}$ was reported. As noted in Ref. 2, footnote 10, and by R. Weinstein, in Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, California, 1966 (to be published), the probable decay angular distribution is $1+\cos^2\theta$. This results in a factor of almost exactly $\frac{4}{3}$ and a resulting value $B_\rho = (4.4^{+2.1}_{-0.9})\times10^{-5}$.

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[11]After this Letter was submitted we received a preprint from P. G. O. Freund [Enrico Fermi Institute for Nuclear Studies Report No. EFINS 67-2 (to be published)]. In it Freund extends his earlier work of Ref. 3 to include SU(3)-breaking effects and lower lying Regge trajectories. He finds $R^3 = 0.175$ and $B_\varphi B_\rho = 6.7$. Our results are not in disagreement with these values.

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