in which all low-lying hadron states have zero isospin. Below the threshold for production of states with nonzero isospin, only the isoscalar component of the electromagnetic current would be observed. This isoscalar probe would not distinguish between proton and neutron. Low-energy experiments would indicate a deuteron made of two identical spin-$\frac{1}{2}$ nucleons, each with charge $\frac{1}{2}$, and peculiar statistics allowing two identical particles in a symmetric state. Only after the excitation of the isovector states of the two-nucleon system would it be clear that there was a hidden degree of freedom and two kinds of nucleons with integral charges.

[8]This result is expected, since the three-triplet model was constructed to give all the Gell-Mann–Zweig properties of observed particles. Given a set of hadron states in the conventional quark model, corresponding hadron states in the three-triplet model can be constructed for which the matrix elements of the electromagnetic current operator are identical to those of the quark model.

Photoproduction and Forbidden Decays of φ Mesons*

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Photoproduction of φ mesons from hydrogen and carbon was studied at 5.2 GeV by observing $\varphi\to K^+K^-$ decays. The results show that φ's are produced diffractively with a φ-nucleon cross section $\sigma_{\varphi N}=9.8^{+2.9}_{-3.3}$ mb. In addition, 80 000 pion pairs were measured to search for the G-parity–nonconserving decay $\varphi\to\pi^+\pi^-$. Assuming complete interference between $\rho\to\pi^+\pi^-$ and $\varphi\to\pi^+\pi^-$, we found an upper limit of $\Gamma_{\varphi\to 2\pi}/\Gamma_{\varphi\to\text{all}}=2.7\times10^{-4}$ at the 95% level.

In an experiment performed at the DESY 7.5-GeV electron synchrotron we studied the production of $\varphi\to K^-K^+$ and searched for the decay of $\varphi\to\pi^+\pi^-$, both at forward angles, from

$$\gamma+p\to p+\varphi+\cdots,\quad \varphi\to K^+K^-$$
$$\gamma+\text{C}\to\text{C}+\varphi,\quad \varphi\to K^+K^- \tag{1}$$
$$\gamma+\text{C}\to\text{C}+\varphi,\quad \varphi\to\pi^+\pi^-$$

For K^-K^+ pairs, measurements were made at the fixed K^-K^+ laboratory momentum of $p=5.2$ GeV with $K_{\max}=6.2$ GeV. The $\pi^+\pi^-$ pairs were detected at a fixed laboratory momentum of 6.7 GeV with $K_{\max}=7.4$ GeV. The object of the experiment was twofold: (1) to provide an accurate determination of the forward production cross section of φ from hydrogen and carbon for comparison with the diffraction model and to extract the φ-nucleon cross section $\sigma_{\varphi N}$ from vector-dominance models for comparison with quark-model predictions[1]; (2) to search for the decay $\varphi\to\pi^+\pi^-$ and compare it with our measured decay $\omega\to\pi^+\pi^-$ and various theoretical models.[2]

φ and ω mesons both decay strongly into three pions. Their 2π decay mode does not conserve G parity. The order of magnitude expected for $\varphi\to2\pi$ and $\omega\to2\pi$ decay amplitudes, as compared with $\rho\to2\pi$ decay amplitude, is the fine-structure constant α. Such a result can be visualized as a one-photon–exchange mechanism where φ (or ω) $\to\gamma\to\rho\to2\pi$ with corresponding partial widths $\Gamma_{\omega\to2\pi}\approx10$ keV, $\Gamma_{\varphi\to2\pi}\approx0.6$ keV. Our previously measured width $\Gamma_{\omega\to2\pi}$ is a factor of 10 larger than the simple predicted value. It is of interest to see if the $\varphi\to2\pi$ width is also correspondingly larger.

The K^+K^- pairs were detected by a double-arm magnetic spectrometer which has been described in a previous publication.[3] The separation of K^+K^- from the background of $\pi^+\pi^-$ and e^+e^- was accomplished by four large-aperture threshold Cherenkov counters and two lead-Lucite shower counters. Protons were rejected by time-of-flight techniques. The contaminations of π, p, and e in the final $\varphi\to K^+K^-$ events were <1.5%. The accidentals were typically 1–2%. The acceptance of the apparatus was calculated by the Monte Carlo method, in which multiple scattering and both two-body and three-body decays of the kaons along the spectrometer were considered. Corrections were also made for dead time of the electronics, beam attenuation in the target, target out rate, and K absorption in the spectrometer material. A total of 11 104 events were measured. The typical K^+K^- mass spectra are shown in Figs. 1(a) and 1(b). The mass resolution of the hodoscope system (± 5 MeV) has not been unfolded. The errors in Fig. 1 are statistical only. An additional normalization uncertainty of ± 10% is not included.

As seen from Fig. 1, in the K^+K^- invariant mass (m) region 1000 to 1050 MeV, the spectra are dominated by φ production. Within the statistical accuracy, no other enhancements were observed.

The analysis of φ production data follows closely that of ρ production.[4] It is greatly simplified, however, because of the narrow width of the φ as compared to that of the ρ. To obtain two-body φ cross sections from the reactions

$$\gamma + p\ (\mathrm{C}) \to p\ (\mathrm{C}) + \varphi \qquad (2)$$

the following steps were taken:

(I) Assuming all the φ's are from (2), we fit the data with the equation

$$d\sigma/d\Omega\, dm = Cp^2 e^{at} 2mR(m) + G,$$

where $R(m)$ is the p-wave relativistic Jackson Breit-Wigner formula and G is the nonresonant K^+K^- background,[4] taken to be flat over the narrow φ peak. For the hydrogen target, $a = 5\ \mathrm{GeV}^{-2}$ from hydrogen bubble-chamber data,[5] whereas for carbon the slope a is measured directly by this experiment.

(II) After background subtraction, the measured spectra were then integrated from $m = 1005$ to 1047 MeV. An additional 5% was added for contributions outside this mass region to obtain $d\sigma/d\Omega$.

(III) To obtain the two-body cross section of Eq. (2), the nondiffractive production $\gamma + p \to p + \varphi + \pi^+ + \pi^-$ was subtracted by using the data of the DESY bubble-chamber group.[6] For the carbon target, the incoherent contributions were subtracted using the closure model of Trefil.[7] The solid curves in Figs. 1(a) and 1(b) are the mass distributions from Monte Carlo generated φ's ($m = 1019.5$, $\Gamma_\varphi = 4.0$ MeV) weighted with the cross section $P^2 e^{at} \times 2mR(m)$ and passed through the spectrometer, allowing for multiple scattering and K decay. The dashed line is an estimate of nonresonant background.

This analysis yields the following information.

(A) From the hydrogen data: The two-body cross section $(d\sigma/d\Omega)_{\theta=0°} = 23.0 \pm 4.5\ \mu\mathrm{b/sr}$, or $(d\sigma/dt)_{t=0} = 2.76 \pm 0.54\ \mu\mathrm{b/GeV}^2$. The errors include the uncertainty in $\gamma + p \to p + \varphi + 2\pi$ and other

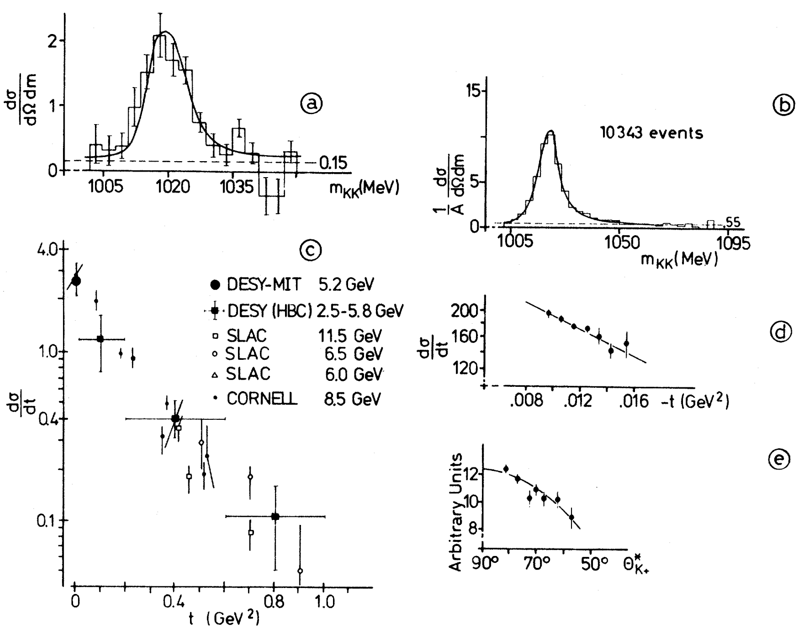

FIG. 1. (a) Kaon-pair mass spectrum at $p = 5.2$ GeV from H_2 (in μb/sr MeV). (b) Kaon-pair mass spectrum from carbon target (in μb/sr nucleon MeV). (c) A comparison of $d\sigma/dt$ as a function of t for H_2 (in $\mu\mathrm{b/GeV}^2$). See Refs. 5 and 8. (d) Behavior of $d\sigma/dt$ for carbon as a function of t (in $\mu\mathrm{b/GeV}^2$ atom). The solid curve is the best fit, $e^{(58\pm12)t}$. (e) The angular distribution of K^+ in the φ rest system. As seen, the data agree well with the $\sin^2\theta^*$ distribution function (solid curve).

background subtractions. Fig. 1(c) compares our result with other experiments.[5,8] The quantity $(d\sigma/dt)_{t=0}$ enables us to determine the φ-nucleon total cross section $\sigma_{\varphi N}$ from the vector-dominance relation[1]

$$\left.\frac{d\sigma}{dt}\right|_{t=0}=\frac{\alpha}{64\pi}\left(\frac{\gamma_\varphi^{\,2}}{4\pi}\right)^{-1}(1+\beta^2)\sigma_{\varphi N}^{\,2}, \qquad (3)$$

where $\gamma_\varphi^{\,2}/4\pi=4.0\pm0.7$ is our measured φ-photon coupling strength and $\beta=-0.48^{+0.33}_{-0.45}$ is our measured value for the ratio of real-to-imaginary amplitude for φ-nucleon scattering.[9]

From (3) we obtain $\sigma_{\varphi N}=9.8^{+2.9}_{-3.3}$ mb. The value of $\sigma_{\varphi N}$ is compatible with the prediction of the quark model,[1] $\sigma_{\varphi N}=2(\sigma_{K^+p}-\sigma_{\pi^+p})+\sigma_{\pi^-p}\approx 12$ mb at 5.2 GeV.

(B) From the carbon data: Integrating the spectrum of Fig. 1(b), after subtraction of background, we obtain $(d\sigma/d\Omega)_{\langle\theta\rangle\approx 0°}=1.61\pm0.16$ mb/sr atom at an average momentum $\langle p\rangle=5.2$ GeV and $\langle t\rangle=0.0111$ GeV^2. Subtracting the incoherent contributions,[7] we obtain a coherent cross section of 1.54 ± 0.15 mb/sr atom.

As seen in Fig. 1(d), in the t region $0.009<|t|<0.016$ GeV^2 the data are fitted well by $d\sigma/dt\propto e^{at}$ with $a=58\pm12$ GeV^{-2} in agreement with the photoproduction data[4] of ρ mesons.

Figure 1(e) shows the comparison of the angular distribution with the function

$$W_{K^+K^-}(\theta^*)=\tfrac{3}{8}\pi^{-1}\sin^2\theta^*,$$

where θ^* is the angle between decay products and the recoil target particle measured in the K^+K^- c.m. system. The data indicate that φ's are produced transversely polarized, consistent with the other evidence that they are produced via diffraction off the whole nucleus.

Search for $\varphi\to\pi^+\pi^-$.—With the φ production mechanism and cross section known for carbon, we can now proceed a step further to search for the as yet unobserved $\varphi\to2\pi$ decay from the reaction

$$\gamma+\mathrm{C}\to\mathrm{C}+\varphi\to\mathrm{C}+2\pi.$$

A total of 80 000 pion pairs at $\langle p\rangle=6.7$ GeV were detected with invariant mass in the range 900–1150 MeV in search of this forbidden decay mode. The pion pairs were produced in a 0.5-cm carbon target and detected in a modified double-arm spectrometer[10] with a mass resolution of 8 MeV (full width at half-maximum). The data are part of those obtained in a detailed study of the dipion mass spectrum in the mass range 600–1150 MeV. In the 600–900-MeV region [Fig. 2(a)] the spectrum cannot be fitted by $\rho^0\to2\pi$ alone (dashed curve). The data show clear $\omega\to2\pi$ interference with $\rho\to2\pi$ (solid curve).[11]

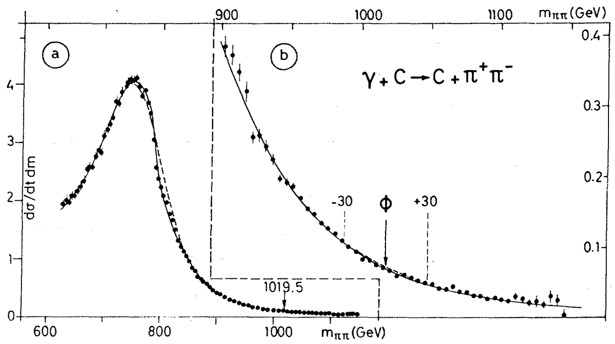

FIG. 2. (a) Cross sections $d\sigma/dt\,dm$ [in μb/(GeV^2 MeV nucleon)] as functions of pion-pair mass. The solid curve is the best fit including the $\omega\to2\pi$ contribution. The dashed line is $\rho\to2\pi$ alone (see Ref. 11). (b) Cross sections (same units in expanded scale) for $900<m<1150$ MeV. The solid line is the best fit with $\varphi\to2\pi$ contribution for η and α given in the text, and the dashed line has no $\varphi\to2\pi$ contribution.

To search for the small $\varphi\to2\pi$ contribution, we obtained from the data a cross-section grid $d\sigma(m,p,t_\perp)/dt\,dm$ with dimensions (50, 5, 5) and step sizes of 5 MeV, 400 MeV, and 0.002 GeV^2, respectively. This grid was compared with the phenomenological function

$$d\sigma(m,p,t_\perp)/dt\,dm=F(m)e^{at}. \qquad (4)$$

Here $t=t_\perp+t_\parallel$, and $t_\parallel$ is the minimum four-momentum transfer for production of a particle of mass m and momentum P from carbon. The function

$$F(m)=\left|P(m)+\eta\frac{(2mm_\varphi\Gamma_\varphi/\pi)^{1/2}e^{i\alpha}}{m_\varphi^{\,2}-m^2-im_\varphi\Gamma_\varphi}\right|^2$$

was used for the mass distribution, where Γ_φ is the total width of the φ. $P(m)=b+cm+dm^2+em^3$ describes the mass dependence consistent with the tail of the mass distribution from $\rho\to2\pi$ decay. The quantity η is related to the branching ratio B by

$$B=\frac{\Gamma_{\varphi\to2\pi}}{\Gamma_\varphi}=\frac{\eta^2}{[d\sigma(\gamma\mathrm{C}\to\mathrm{C}\varphi)/dt]_{t=0}} \qquad (5)$$

The analysis was done in two steps. (1) To obtain the mass distribution unbiased by the φ, we matched Eq. (4) with $\eta=0$ to the data, excluding the mass region $m_\varphi\pm30$ MeV. An acceptable fit with (χ^2 per degree of freedom) $=388.9/385=1.01$ was obtained, yielding an exponential slope $a=43.3\pm4.1$ GeV^{-2}. (2) Keeping all parameters from step (1) fixed, we applied the fit to all data, allowing for a $\varphi \to 2\pi$ contribution. Fig. 2(b) shows the cross section on an enlarged scale for pair masses bigger than 900 MeV together with the described fits. Since no structure as a function of P and $t_\perp$ was observed, the cross-section matrix $d\sigma(m,p,t_\perp)/dt\,dm$ was contracted to $p=6.4$ GeV and $t_\perp = 0.001$ GeV^2. From this we found $\eta = 0.045 \pm 0.020$ (μb/GeV^2 nucleon)$^{1/2}$ and $\alpha = 82° \pm 20°$ (with $\chi^2 = 582.3$ for 557 degrees of freedom). With the use of the coherent cross section $[d\sigma(\gamma C \to C\varphi)/dt]_{t=0} = 27$ μb/GeV^2 nucleon, Eq. (5) yielded $B = (0.75^{+0.82}_{-0.52}) \times 10^{-4}$ or $\Gamma_{\varphi\to 2\pi} = 0.30^{+0.33}_{-0.21}$ keV.[12]

The fit from Eq. (4) assumes full interference[13] of the φ with the $\pi^+\pi^-$ pairs of the continuum. The result obtained is consistent with no $\varphi \to 2\pi$ contribution. The corresponding upper limit on the branching ratio is 0.027%, at the 95% confidence level. In a recent experiment at Orsay,[14] $B < 0.5\%$ was obtained. Our limit is considerably smaller than our measured[11] $\omega \to 2\pi$ branching ratio of $(1.22 \pm 0.30)\%$. It is interesting to note that, whereas the measured width $\Gamma_{\omega\to 2\pi}$ is an order of magnitude larger than expected from the simple $\omega(\varphi) \to \gamma \to \rho \to 2\pi$ picture, the value of $\Gamma_{\varphi\to 2\pi} = 0.30^{+0.33}_{-0.21}$ keV is consistent with this picture (≈ 0.6 keV).

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[1]J. J. Sakurai, in *Lectures in Theoretical Physics: Elementary Particle Physics*, edited by K. T. Mahanthappa, W. E. Brittin, and A. O. Barut (Gordon and Breach, New York, 1969), Vol. XIA; H. Joos, Acta Phys. Austr. Suppl. No. IV, 320 (1967).

[2]For a survey of previous experimental work on ρ,ω interference, see G. Goldhaber, in *Experimental Meson Spectroscopy*, edited by C. Baltay and A. H. Rosenfeld (Columbia U. Press, New York, 1970), p. 59. For theoretical work see A. S. Goldhaber, G. C. Fox, and C. Quigg, Phys. Lett. 30B, 249 (1969); D. Horn, Phys. Rev. D 1, 1421 (1970); G. R. Allcock, Nucl. Phys. B21, 269 (1970); M. Gourdin, L. Stodolsky, and F. M. Renard, Phys. Lett. 30B, 347 (1969); R. G. Sachs and J. F. Willemsen, Phys. Rev. D 2, 133 (1970); S. L. Glashow, in *Experimental Meson Spectroscopy*, edited by C. Baltay and A. H. Rosenfeld (Columbia U. Press, New York, 1970), p. 135; A. Dar and V. F. Weisskopf, Phys. Lett. 26B, 670 (1968); also S. L. Glashow and T. Walsh predicted a $\varphi \to 2\pi$ branching ratio of $\approx 1.5 \times 10^{-4}$, private communication.

[3]J. G. Asbury *et al.*, Phys. Rev. 161, 1344 (1967).

[4]H. Alvensleben *et al.*, Nucl. Phys. B18, 333 (1970), and Phys. Rev. Lett. 25, 1373 (1970). The $R(m)$ used here corresponds to $R_5(m)$ in the ρ papers. See also J. D. Jackson, Nuovo Cimento 34, 1644 (1964). For theoretical discussions of nonresonant background see M. Ross and L. Stodolsky, Phys. Rev. 149, 1172 (1966); G. Kramer and J. L. Uretsky, Phys. Rev. 181, 1918 (1969); P. Soeding, Phys. Lett. 19, 702 (1966). Because of uncertainties in these models and the narrow φ width, we have taken the background under φ to be flat.

[5]Aachen-Bonn-Hamburg-Heidelberg-München Collaboration, Phys. Rev. 175, 1669 (1968), and Phys. Rev. 188, 2060 (1969). Note that since $\langle t\rangle \approx 0.01$ GeV^2, the value of a does not play an important role in determining the forward cross sections. The branching ratio 0.464 for $(\varphi \to K^+K^-)/(\varphi \to \text{all})$ was used; see A. Rittenberg *et al.*, Rev. Mod. Phys. Suppl. 43, 1 (1971).

[6]We thank Dr. H. Spitzer for making the data on $\gamma + p \to p + \varphi + 2\pi$ available to us.

[7]J. S. Trefil, Nucl. Phys. B11, 330 (1969).

[8]G. McClellan *et al.*, Phys. Rev. Lett. 26, 1593 (1971), and Laboratory for Nuclear Studies, Cornell University Report No. CLNS-168, 1971 (unpublished); R. Anderson *et al.*, Phys. Rev. D 1, 27 (1970).

[9]U. Becker *et al.*, Phys. Rev. Lett. 21, 1504 (1968); H. Alvensleben *et al.*, Phys. Rev. Lett. 27, 444 (1971); J. Perez-Y-Jorba, Daresbury Report No. DNPL/R7, 1970 (unpublished).

[10]H. Alvensleben *et al.*, Nucl. Phys. B25, 333 (1971).

[11]H. Alvensleben *et al.*, Phys. Rev. Lett. 27, 888 (1971).

[12]With the same χ^2 a second minimum was found at $\eta = 1.52 \pm 0.02$ and $\alpha = 89.2° \pm 0.6°$, corresponding to a branching ratio of $(8.5 \pm 0.3)\%$. It should be noted that this minimum is extremely close to the point where the φ term cancels the φ-ρ interference at $\eta = (2\pi\Gamma_\varphi)^{1/2} \times P(m)$ and $\alpha = 90°$. A branching ratio of 8.5% should be visible in reactions with a different φ-production mechanism, i.e., different α. The upper limit found in K^-p reactions is 5%. For these reasons we consider the minimum given in the text only. See also S. Lindsey and G. A. Smith, Phys. Rev. 147, 913 (1966).

[13]In the other extreme case of no interference, where the φ would appear superimposed on the smooth curve, we obtain $B \leq 0.08\%$.

[14]J. C. Bizot *et al.*, Lett. Nuovo Cimento 4, 1273 (1970).