EXPERIMENTAL LIMIT ON HIGH-ENERGY DIFFRACTION PHOTOPRODUCTION OF THE φ MESON*

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The purpose of this Letter is to show that a relatively small upper limit of 0.56 ± 0.2 μb can be placed on the high-energy (9 to 15 GeV/c) diffraction photoproduction of the φ meson on protons. This deduction comes from a recent measurement[1] of the 5.5-GeV/c K^--meson flux produced at zero degrees in a beryllium target by a 16-GeV/c electron beam, and is obtained by attributing the entire flux of 5.5-GeV/c K^- mesons near zero degrees ($\theta < 0.36°$) to φ production. This limit is close to the (0.42 ± 0.16)-μb cross section given for photoproduction of the φ at lower energies (3.5 to 5.8 GeV/c).[2]

The theory of diffraction photoproduction of the neutral vector mesons, ρ^0, ω, and φ, predicts that these mesons, having the same quantum numbers as the photon, can be photoproduced on a nucleon or nuclear target through a diffraction process. The four-momentum-transfer dependence and energy dependence of the process should be the same as the diffraction-peak behavior of the elastic scattering of hadrons on nucleons or nuclei. These dependences are given by $(d\sigma/dt) = C\exp(-B|t|)$.[3,4] Here t is the square of the four-momentum transfer and C and B are dependent on the type of target but not on the energy. If one assumes a model in which a photon is first coupled to ρ, ω, and φ with coupling constants proportional to[5]

$$\tfrac{1}{2}\sqrt{3}(\rho^0 + \tfrac{1}{3}\omega^0 - \tfrac{1}{3}\sqrt{2}\,\varphi^0),$$

as suggested by SU(3) with mixing, and then these vector particles are scattered by the target nucleon, one would expect the ratio of the production cross sections to be roughly 9:1:2. This assumes that the elastic cross sections between nucleon and ρ^0, ω, and φ are equal. It has been a great puzzle that the cross section $\gamma + p \to \varphi + p$ is so small compared with $\gamma + p \to \rho + p$ (0.42 ± 0.16 and 16 ± 1 μb, respectively, at 3.5 to 5.8 GeV/c).[2]

One explanation uses, to explain the puzzle, the concept of Regge trajectories which interfere.[6] This interference, however, should only exist at lower energies.[6] Other authors[7,8] have allowed the scattering amplitude of these vector particles on the nucleon to be different for the ρ^0, ω, and φ. Using the quark model,[7] or Regge trajectories,[8] they relate these scattering amplitudes to different combinations of the $\pi^\pm + p$ and $K^\pm + p$ total cross sections, also obtaining thereby some energy dependence. For example, Freund[8] obtains additional reduction of the φ cross section by about a factor of 10. All of these theories[6-8] require strong SU(3) breaking, and it is interesting to see if this breaking occurs at high energies. Therefore a high-energy test of the 9:1:2 prediction is of interest.

The sequence of interactions in this experiment is that the 16-GeV/c electron beam, incident on the 1.8-radiation-length beryllium target, produces photons through the bremsstrahlung process. Because of the diffraction production of the φ, a photon of energy k produces a φ of energy k and these φ's are produced in the very forward direction in the laboratory system. The φ can then produce K^- mesons by the decay mode $\varphi \to K^+ + K^-$ which has 50% probability. The small Q value of the φ, 32 MeV, leads again to very forward-going K^- mesons. Therefore, the zero-degree and near zero-degree K^- flux is strongly dependent on the φ production. Furthermore a K^- of specific momentum can only come from φ's and hence photons in a limited energy range. For example, the 5.5-GeV/c forward-produced K^- mesons, if produced through φ decay, must come from 9- to 15-GeV/c photons, thus providing a relatively high-energy test of the theory. There are three steps in the calculation: first, the evaluation of the diffraction process to give the φ production; second, the introduction of the φ density matrix to give the subsequent K^- distribution; and third, the summation of this process over the bremsstrahlung spectrum. Detailed formulas and a method of calculation for this entire process have been made by Tsai.[9]

The diffraction photoproduction on a nucleus is the sum of the diffraction photoproduction on the entire nucleus (called coherent production), and of the diffraction photoproduction on the individual nucleons in the nucleus (called incoherent production). For the incoherent production we use $B = 10$ (GeV/c)$^{-2}$. For the coherent production we take B from the measurements of Bellettini et al.,[10] on elastic proton beryllium scattering, which leads to a range of B values from 77 to 43 $(\text{GeV}/c)^{-2}$. We present calculations for both of these limits, but we believe that $B=43$ $(\text{GeV}/c)^{-2}$ is a more realistic number. The reason behind that is that $B=77$ $(\text{GeV}/c)^{-2}$ is true only for small values of $|t|$ and since one needs a rather sizable value of $|t|$ to produce K^- at $\theta=0°$, the slope of the diffraction peak at larger values of t must be used. The experiment of Bellettini et al.,[10] shows that B at larger values of $|t|$ [0.03-0.06 $(\text{GeV}/c)^{+2}$] is much smaller than 77 $(\text{GeV}/c)^{-2}$. By $\sigma_{\gamma+p\to\varphi+p}$, $\sigma_{\gamma+n\to\varphi+n}$, and $\sigma_{\gamma+\text{Be}\to\varphi+\text{Be}}$ we denote the total cross section for diffraction photoproduction of the φ on a single proton, on a single neutron, and coherently only on a Be nucleus. We use $\sigma_{\gamma+n\to\varphi+n}=\sigma_{\gamma+p\to\varphi+p}$ and $\sigma_{\gamma+\text{Be}\to\varphi+\text{Be}}=5.5\ (\sigma_{\gamma+p\to\varphi+p})$. Here the factor 5.5 is the ratio of the high-energy proton-beryllium total coherent elastic cross section[10] to the proton-proton total elastic cross section.[12] Now for the incoherent production one may not simply add the contributions from protons and neutrons because any φ produced deep inside the nucleus can get absorbed before it emerges on the surface of the nucleus and furthermore the Pauli exclusion principle suppresses the small-momentum-transfer events. These effects can be taken into account directly by using the same number of effective nucleons as was found experimentally by Belletini et al.[10] in incoherent proton-plus-beryllium elastic scattering. This number is 3.5 effective nucleons.

The theory of diffraction photoproduction requires the same density matrix to be used for the φ as that found experimentally for the ρ. This requires complete spin alignment of the φ along its direction of flight as given in the center-of-mass system of the φ and the recoiling target nucleon or nucleus. Then the K^- angular distribution is given by $\sin^2\beta$, where β is the angle in the φ rest system between the K^- and the previously defined φ direction.

The K^- flux is obtained by integrating the K^- production over the target length using the thick-target bremsstrahlung spectrum of Ref. 9 and Tsai and Whitis,[13] allowing for K^- attenuation by nuclear absorption in the target. We have used an attenuation length equal to 1.65 radiation lengths based on a K^-+p total cross section[14] of 24 mb and using the experimentally known total absorption cross-section[10,14,15] ratio of $p+p$ to $p+\text{Be}$. The results of the complete calculation are shown in Table I, based on a 1.0-μb cross section for $\sigma_{\gamma+p\to\varphi+p}$.

The experimental value of the K^- flux at 5.5 GeV/c under the conditions of Table I is $(14\pm5)\times10^{-5}$ K^- per GeV per steradian. If one attributes this entire flux to φ production, the results of Table I lead to a cross section of 0.56 ± 0.2 μb for $\sigma_{\gamma+p\to\varphi+p}$, for photons of 9- to 15-GeV energy and $B=43$ $(\text{GeV}/c)^{-2}$. For $B=77$ $(\text{GeV}/c)^{-2}$ this value is increased to 0.89 ± 0.3 μb. If the simple diffraction photoproduction theory is correct, the cross section for ρ production $(\sigma_{\gamma+p\to\rho+p})$ should still be 16 ± 1 μb at those high energies. SU(3) then leads to a predicted $\sigma_{\gamma+p\to\varphi+p}$ of 3.6 ± 0.2 μb; there is still a gross violation of the simple theory, and the puzzle which exists at lower energies continues at higher energies.

Needless to say, there are some uncertainties involved in the way we handled the beryllium nucleus, and the thick target. For example, we ignored the smearing of angle due to multiple and single scatterings of the K^- in the target, which will tend to fill up the dip in the cross section at 0° and make our upper limit still lower. Most of the uncertainties can be overcome of course by using a hydrogen target. Any uncertainty involved in the decay angular distribution of φ can also be overcome if the data have a wider range of distributions in angle and energy. Table I contains some examples of the K^- flux from φ decay at other momenta and angles. Finally, the importance of using the maximum available photon energy should be emphasized.

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Table I. Calculated yields of K^- mesons from φ decay for a 16-GeV electron incident on a 1.8-radiation-length beryllium target. The yield is based on a 1.0-μb cross section for $\sigma_{\gamma+p\to\varphi+p}$, and is in units of 10^{-5} K^- particles per GeV per steradian per incident electron. p (in GeV/c) is in the momentum of the K^- meson and θ (in degrees) is the angle of emission of the K^- with respect to the incident electron direction. The incoherent yield is the total yield from diffraction photoproduction on only the individual nucleons, using 3.5 effective nucleons per beryllium nucleus. The coherent yield is the yield from only the coherent diffraction photoproduction on the entire beryllium nucleus. B gives the dependence of the diffraction process on t (square of the four-momentum transfer) through the equation $d\sigma/dt = C\exp(-B|t|)$.

p (GeV/c)	θ Degrees	Incoherent Yield ($B=10$ (GeV/c)$^{-2}$)	Coherent Yield ($B=43$ (GeV/c)$^{-2}$)	Coherent Yield ($B=77$ (GeV/c)$^{-2}$)
9.0	0.0	0.88	3.6	2.5
9.0	0.2	0.86	3.5	2.8
9.0	0.4	0.80	3.2	2.8
9.0	1.0	0.48	1.1	0.73
9.0	2.0	0.070	0.27	0.23
5.5	0.0	8.5	15.2	6.1
5.5	0.2	8.5	16.0	6.9
5.5	0.4	8.3	17.9	9.1
5.5	1.0	7.1	23.0	20.7
5.5	2.0	3.6	6.3	3.1
2.0	0.0	4.0	4.7	1.0
2.0	0.2	4.0	4.8	1.1
2.0	0.4	4.0	4.8	1.2
2.0	1.0	3.9	5.7	1.6
2.0	2.0	3.7	7.0	3.2

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