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Test of the Okubo-Zweig-Iizuka Rule in ϕ Production

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We have measured the reaction $\pi^- p \to K^+K^-K^+K^- n$ at 22.6 GeV/c and detect strong φ signals in the K^+K^- effective-mass plots. We do not observe the expected Okubo-Zweig-Iizuka–rule suppression of the $\varphi\varphi n$ final state and conclude that the rule is working poorly in the observed production processes.

The Okubo-Zweig-Iizuka (OZI) rule[1] is an essential ingredient in the successful quark-model explanation of the decay of the φ, f', J/ψ, and ψ' resonances. In recent attempts[2] to extend the model to detailed predictions of the production of resonances, the OZI rule again plays an important part. Experimental studies of "forbidden" and "allowed" processes are required in order to shed some light on the precise nature of the rule. Perhaps the best available reactions for this purpose involve φ-meson production since its dominant $(s\bar{s})$ quark structure leads to inhibition of many exclusive channels[3]—for example, single or multiple φ production unaccompanied by strange particles is predicted to be suppressed in πp interactions.

We have studied the interaction

$$\pi^- p \to K^+K^-K^+K^- n \tag{1}$$

at 22.6 GeV/c. A major purpose of the experiment was to search for resonances in the $\varphi\varphi$ system. The results of that search were published earlier[4]; details were given of the apparatus and experimental procedure. Briefly, the Brookhaven National Laboratory multiparticle spectrometer was used to select and reconstruct events[5] for Reaction (1). A sensitivity of approximately 15 events/nb was achieved. The neutron-recoil cut defined for this paper is the same as used in Fig. 1(c) in Ref. 4; that is, a missing-mass–squared cut of < 2.0 GeV^2 was applied and the counters around the target were used as a veto.

We wish to consider the reactions

$$\pi^- p \to \varphi[K^+K^-]n, \quad \varphi \to K^+K^- \tag{2}$$

$$\pi^- p \to \varphi\,\varphi n, \quad \varphi \to K^+K^-,\ \varphi \to K^+K^- \tag{3}$$

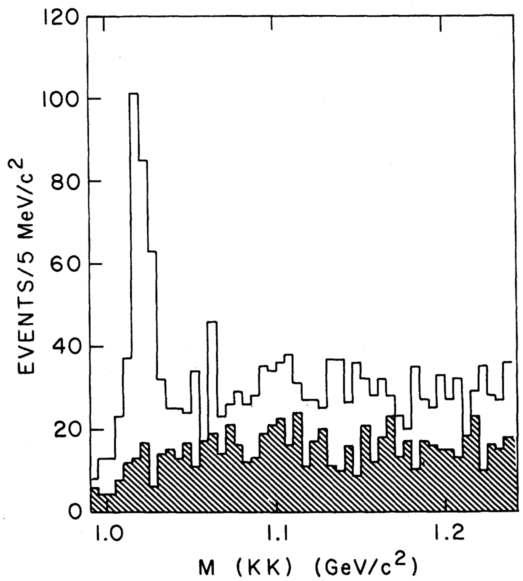

FIG. 1. KK effective masses of all events of Reaction (1) after removal of events satisfying Reaction (3). The open histogram includes all four K^+K^- combinations for each event. The shaded histrogram is the sum of the K^+K^+ and K^-K^- effective-mass spectra. As discussed in the text, some of the combinations are $\bar{p}p$ pairs misinterpreted as K^+K^-.

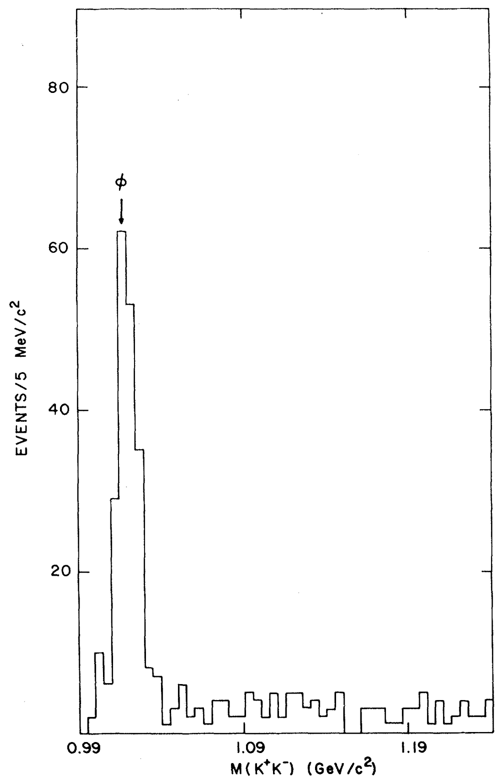

FIG. 2. Distribution of the effective mass of each K^+K^- pair for which the other pair lies in the φ-mass band.

where $[K^+K^-]$ indicates that this K^+K^- pair does not lie in the φ-mass band. As mentioned above, Reaction (2) is allowed, but Reaction (3) is suppressed by the OZI rule.

In order to study Reaction (2) we remove from the data sample those events which satisfy Reaction (3), i.e., have two K^+K^- pairs with $1.00 \leq M(K^+K^-) < 1.04$ GeV$/c^2$. The K^+K^- effective-mass combination are shown in Fig. 1 for the remaining events. Four K^+K^- combinations are plotted for each event. In addition, the shaded curve is the mass spectrum of like-sign K pairs, which gives some indication of the extra background due to multiple combinations. A clear φ signal is obtained, corresponding to Reaction (2). The peak-height-to-background ratio[6] is about 4:1; correction by a factor of 2 to allow for multiple combinations gives 8:1.

In order to study Reaction (3) we select events with a K^+K^- pair in the φ-mass band, plot the effective mass of the other K^+K^- pair, and obtain the mass spectrum shown in Fig. 2.[7] A clear φ signal is seen, corresponding to Reaction (3). The peak-to-background ratio is about 20:1. If the OZI suppression were 100%, no φ signal would be seen in Fig. 2.

We therefore have the unusual situation that the "forbidden" Reaction (3), produces a higher φ enhancement over K^+K^- background than the allowed Reaction (2), although equal enhancements cannot be ruled out because of the possible contamination of the data with $p\bar{p}$ pairs. It is interesting to note that a simple model based on the final-state interactions of two uncorrelated K^+K^- pairs would predict comparable enhancements in the two processes; such a model is not allowed in the OZI framework.

In an attempt to deduce a value for the ratio of total cross sections for Reactions (2) and (3), another measure of the degree of OZI suppression, we have used a Monte Carlo program to estimate our acceptance for the two processes. For Reaction (2), events were generated for various φKK effective masses. The φKK system was allowed to decay isotropically with a three-body phase-space distribution, followed by the φ decaying isotropically in its center of mass. The four kaons were tracked through the multiparticle spectrometer and checked to see if the event would have been detected. The acceptance was

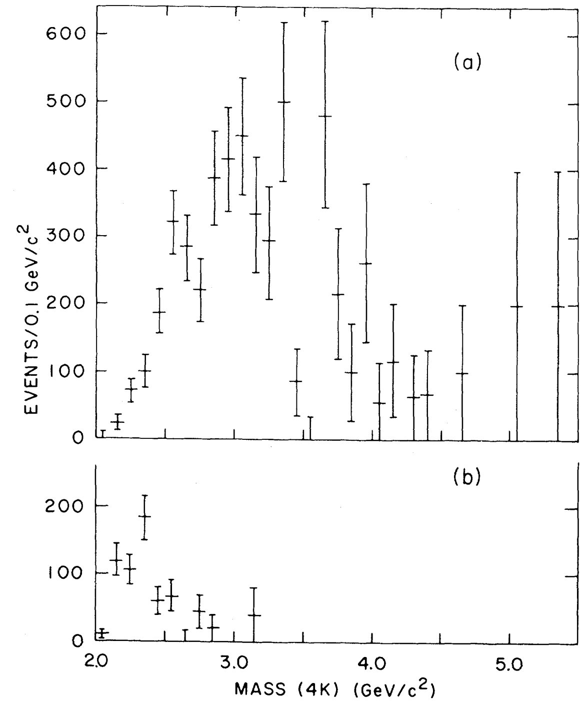

FIG. 3. (a) $[\varphi K^+K^-]$ effective-mass distribution for those events with one K^+K^- pair in the φ-mass band, the other outside. (b) $\varphi\varphi$ effective-mass distribution. Each spectrum has been corrected for the detection efficiency of the apparatus as described in the text. As discussed in the text, some of the combinations are $\bar{p}p$ pairs misinterpreted as K^+K^-

then calculated as a function of the φKK and $[K^+K^-]$ effective masses and applied as a correction to the data. The resulting φKK mass spectrum is shown in Fig. 3(a). A similar procedure was applied to the $\varphi\varphi$ data (except that the initial decay is two-body) to give the $\varphi\varphi$ spectrum shown in Fig. 3(b).

The φKK spectrum shows a broad distribution occupying most of the available phase space, while the $\varphi\varphi$ spectrum peaks at low effective mass with a sharp cutoff at ~2.5 GeV/c^2. If we integrate the two spectra we get a ratio of the total cross sections of Reaction (2) to Reaction (3) of about 10. Detailed examination indicates that the simple phase-space model does not fit the data perfectly for φKK events, but our method of correcting the data as a function of both φKK and KK effective masses is designed to reduce the effects of too simple a model.

The t distribution used to calculate the acceptance for the two reactions $\varphi\varphi$ and φK^+K^- was the one observed for the data. Furthermore, it should be noted that the acceptance of our apparatus is fairly flat in t and thus the exact t distribution assumed in the acceptance calculation should not have any appreciable effect on the results for the ratios of the cross sections.

We also note that Reaction (2) could be contaminated by $p\bar{p}$ pairs, while the clear $\varphi\varphi$ peak observed in Reaction (3) rules out substantial contamination. We feel, therefore, that the ratio obtained for Reactions (2) and (3) is probably less than 10.

Our results indicate that the OZI-suppressed reaction, (3), is only an order of magnitude lower in cross section than the allowed Reaction (2).[8] The degree of suppression is not easily exactly calculable and would, of course, be model dependent. However in the context of a simple disconnected (i.e., hairpin) quark-line diagram suppression, one would expect the suppression to be of the same order of magnitude as φ production in $\pi^-p \to \varphi n$ or in φ decay. This suppression factor is estimated to be ~100, while we observe a suppression factor of less than 10.

The arguments applied earlier[9] to explain a similar problem in the reactions

$$\pi^-p \to \varphi K^+K^-\pi^-p \quad \text{(OZI allowed)}$$

and

$$\pi^-p \to \varphi\pi^+\pi^-\pi^-p \quad \text{(OZI suppressed)},$$

which have comparable cross sections,[10] invoked a large (~100) penalty factor associated with the production of an extra pair of kaons. In our case, the two reactions involve the same number of final-state kaons (or s and $\bar{s}$ quarks); so this penalty factor does not apply. It is possible that $\varphi\varphi$ production proceeds through intermediate resonant states containing both $(s\bar{s})$ and u or d quarks; this mixing would circumvent the OZI rule. Barring this possibility, we conclude that the OZI rule is working poorly in the observed production process.

The authors wish to thank the members of the Alternating-Gradient Synchrotron, Particle Detector, and Experimental Planning and Support Divisions of the Accelerator Department of Brookhaven National Laboratory for their help in the execution of this experiment. We thank the technical support staff of the Multiparticle Spectrometer and of the On-Line Data Facility for their valuable aid. We also wish to acknowledge the assistance of S. Eiseman during the data taking. This research was supported by the U. S. Department of Energy under Contract No. EY-76-C-02-0016, and the City College of New York work was supported by the National Science Foundation and the City University of New York PSC-BHE Research Award Program.

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[3]It would be interesting to pursue similar studies for hadron production of J/ψ since its decay shows even larger inhibitions than does the φ. Unfortunately, the production cross section is sufficiently small that no exclusive channel has been observed.

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[5]Since a threshold Cherenkov counter was used (to veto pions) our data sample consists of K^+K^- and $p\bar{p}$ pairs. We can estimate the $\bar{p}p$ contamination using information from observation of single $\bar{p}p$ pair production in the reaction $\pi^- p \rightarrow p\bar{p}n$ at 15 GeV/c. The ratio of single $\bar{p}p$ to single K^+K^- pairs is about 1:1 [see H. H. Williams, SLAC Report No. 142, 1972 (unpublished)], while at 11 GeV/c the $p\bar{p}$ pair production is less than 20% of the K^+K^- production [B. D. Hyams *et al.*, Nucl. Phys. B22, 189 (1970)]. Our experiment was at higher energy, but an additional pair of particles is produced. We estimate, therefore, that the $\bar{p}p$ contamination is less than 50%, integrated over the whole K^+K^- spectrum.

[6]Our K^+K^- effective-mass resolution is about 14 MeV/c^2 (full width at half-maximum). Since the width of the φ (Γ) is 4.1 MeV/c^2, the true enhancement is about a factor of 3 larger.

[7]Note that every K^+K^- pair accompanied by a φ meson is plotted in the spectrum, hence each $\varphi\varphi$ event is plotted twice. This procedure preserves the correct signal-to-background ratio.

[8]This ratio is typical of resonance-to-background ratios in allowed reactions—for example, C. Baltay *et al.*, Phys. Rev. Lett. 40, 87 (1978), find that the ω production accounts for about 5% of the $\pi^+\pi^-\pi^0$ spectrum in the reaction $\pi^- p \rightarrow \Delta^{++}\pi^+\pi^-\pi^0$ at 15 GeV/c.

[9]P. L. Woodworth *et al.*, Phys. Lett. 65B, 89 (1976).

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Gluon Jets from Quantum Chromodynamics

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Following the idea of Sterman and Weinberg, we calculate the jet angular radius of a gluon jet and its energy dependence in the framework of perturbative quantum chromodynamics. The result is free of infrared and mass singularities and does not depend on the gluon fragmentation function. We find that the gluon jet spreads much more (i.e., less jetlike) than a quark jet; this renders the detection of gluon jets very difficult.

The hope that quantum chromodynamics (QCD) provides a complete description of hadron physics is widely spread. One of the key characteristics of QCD is the existence of gluons. A crucial verification of QCD would thus be the observation of its gluonic structure. Partly motivated by the observation of hadronic jets (which we shall refer to as quark jets, since they are believed to be jets arising from energetic quarks) in e^+e^- annihilation,[1] we expect the gluons to reveal themselves in the form of gluon jets (i.e., hadronic jets arising from energetic gluons). In fact, gluon jets are expected to be produced in many experimental processes such as large-p_T scattering, e^+e^- annihilation, lepton-proton deep inelastic scattering, and Drell-Yan dimuon experiments.

Recently it has been emphasized that, in QCD, the three-gluon decay mode[2] of the upsilon[3] Υ (or some other heavy-quark-antiquark bound states) would provide a very clean place to find and study the gluon jet.[4] From e^+e^- annihilation we learn that a quark jet is observable when the initial quark has an energy $E_q \geq 3$ GeV. Since the mass of Υ is around 9 GeV, the average energy per gluon is 3 GeV. Hence, whether a gluon jet from