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Study of the Okubo-Zweig-Iizuka–rule–violating reactions $\pi^+ n \to \phi p$ and $\pi^+ p \to \phi \Delta^{++}$ at 10 GeV/c

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We have measured the cross sections for the Okubo-Zweig-Iizuka–rule–violating reactions $\pi^+ n \to \phi p$ and $\pi^+ p \to \phi \Delta^{++}$ at 10 GeV/c using the large-aperture-solenoid spectrometer at the Stanford Linear Accelerator Center. We measure the total cross sections for these two reactions to be 179 ± 72 nb for the ϕp reaction and 172 ± 75 nb for the $\phi \Delta^{++}$ reaction. Both of these cross sections are consistent with the hypothesis of the ϕ being produced solely by its nonstrange-quark component as determined from the octet-singlet mixing angle resulting from application of the Gell-Mann–Okubo mass formula to the vector-meson nonet. These data are thus inconsistent with an ideally mixed ϕ meson.

We investigate the Okubo-Zweig-Iizuka[1] (OZI) quark-combination rule through a study of the apparently OZI-rule-violating reactions

$$\pi^+ n \to \phi p \text{ and } \pi^+ p \to \phi \Delta^{++} \ . \qquad (1)$$

Under the hypothesis of ideally mixed vector mesons the quark content of the ϕ meson is entirely the $s\bar{s}$ state, and so these reactions cannot be represented by planar connected quark diagrams, and are thus forbidden by the OZI rule. We measure the cross sections for these two reactions, and compare these results with the predictions of a model in which the ϕ meson is not ideally mixed but contains a small admixture of nonstrange quarks. In this model the nonstrange-quark content of the ϕ meson can be estimated using the Gell-Mann-Okubo mass formula on the vector-meson nonet. The cross sections for these reactions can then be estimated using the measured cross sections for the OZI-rule-allowed reactions

$$\begin{aligned} &\pi^+ n \to \rho^0 p \, , \\ &\pi^+ n \to \omega p \, , \\ &\pi^+ p \to \rho^0 \Delta^{++} \ , \\ &\pi^+ p \to \omega \Delta^{++} \ . \end{aligned} \qquad (2)$$

Our data are in agreement with these predictions, and thus indicate that the nonstrange-quark content of the ϕ is sufficient to account for both reactions.

The data are from an exposure of the large-aperture-solenoid spectrometer (LASS) at the Stanford Linear Accelerator Center (SLAC) to a 10-GeV/c π^+ beam incident on a one-meter-long liquid-deuterium target. The LASS facility has been described in the literature.[2] It is built around two large magnets: The upstream magnet is a superconducting solenoid with a 23-kG magnetic field parallel to the beam axis. The downstream magnet is a 30-kG-m dipole with a vertical field. The solenoid is effective in measuring the final-state charged particles which have large production angles and relatively low momenta. High-momentum particles close to the beam axis are minimally affected in the solenoid, but are well measured by the dipole. The computed mass resolution in the region of the ϕ is ± 5 MeV. Nearly complete 4π steradian acceptance for charged particles is achieved by this spectrometer.

The trigger for this experiment required at least one fast-forward charged particle to traverse the entire downstream spectrometer and to produce no light in either of two Čerenkov counters. The upstream Čerenkov counter is a 38-segment atmospheric-pressure counter located between the solenoid and dipole and filled with Freon 12. The downstream Cerenkov counter is an 8-segment 2-atmosphere counter filled with Freon 12 and located downstream of the last spark chamber after the dipole. The absence of light in the Čerenkov counters indicates the presence of a charged particle with the mass of a K meson or heavier for momenta greater than about 2.8 GeV/c. Particles of momentum less than about 3 GeV/c will not get through the dipole, and thus will miss the downstream Čerenkov counter. We therefore trigger on events which feature at least one fast-forward charged particle which is heavier than a pion accompanied by at least one other charged particle.

We recorded 5.2×10^6 primary physics triggers on magnetic tape, and processed all of the events through computer programs first for track finding and reconstruction, and then through vertex finding and vertex fitting. For the purposes of this study we consider only three-prong events with charge +1 and four-prong events with charge +2, and with no missing neutrals (e.g., π^0's) and no associated neutral decays (e.g., K^0's or Λ^0's). In addition we required each event to have two particles of opposite charge with momenta greater than 3 GeV/c. The requirement of no light in the Čerenkov counters eliminates events with fast-forward pions from large-cross-section diffractive processes, and leaves $p\bar{p}$ production as the only significant background to the K^+K^- events. Monte Carlo simulations of the reaction (1) which assume a forward production mechanism show that there are virtually no K mesons of momentum less than 3.5 GeV/c from the ϕp reaction, and virtually no K mesons of momentum less than 3.2 GeV/c from the $\phi\Delta$ reaction. The Monte Carlo studies also indicate that the proton in each of the reactions (1) has a momentum less than 2.0 GeV/c. A time-of-flight counter, located directly behind the upstream Čerenkov counter, distinguished protons from pions and kaons up to 2.0 GeV/c, and thus provided a positive identification for protons. A cut at 2.0 GeV/c in proton momentum was imposed on all candidate events for these reactions. No acceptance corrections are therefore needed to compensate for either this momentum cut on protons or for the momentum cut on forward K mesons. The data have been corrected for the geometric acceptance of the spectrometer [45% for $\pi^+n \to \phi p$ and 53% for $\pi^+p \to \phi\Delta^{++}$ (Ref. 3)], for chamber efficiencies, and for track-finding and reconstruction efficiencies [71% event efficiency for $\pi^+n \to \phi p$ and 48% for $\pi^+p \to \phi\Delta^{++}$ (Ref. 4)]. We have also corrected for vertex finding (90% efficient) and for geometric fitting of the events (99.9% efficient). These efficiencies have been determined through a Monte Carlo simulation of the apparatus.

Figure 1 shows the K^+K^- invariant mass distributions for the three-prong and four-prong events. In the four-prong case the cut $M(p\pi^+) < 1.35$ GeV has been imposed on the data in order to select Δ^{++} events. A fit to the $p\pi^+$ mass distribution of the p-wave Breit-Wigner form for the Δ^{++} resonance plus a polynomial background shows that this cut results in a sample which contains 83% of all true Δ^{++} events. The sample also contains a 29% background of non-Δ^{++} events. The strength of the Δ^{++} signal as determined in this fit is used for the cross-section determinations. Thus, these events correspond to the reactions $\pi^+n \to K^+K^-p$ and $\pi^+p \to K^+K^-\Delta^{++}$, respectively. We have determined the strength of the ϕ signal in each case by fitting the background to a polynomial. The large backgrounds under the ϕ signal are due to two sources: nonresonant K^+K^- pairs and $\bar{p}p$ pairs. Large K^+K^- backgrounds are expected

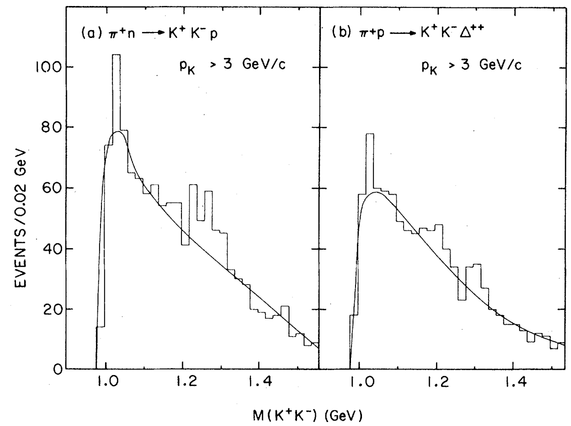

FIG. 1. Distributions in $M(K^+K^-)$ for the reactions (a) $\pi^+n \to K^+K^-p$ and (b) $\pi^+p \to K^+K^-\Delta^{++}$. The events shown also have the selection $p(K^+) > 3.0$ GeV/c. The smooth curves show the results of fits to the backgrounds under the ϕ-meson peaks.

since the reactions $\pi^+n \to K^+K^-p$ and $\pi^+p \to K^+K^-\Delta^{++}$ are both OZI-rule-allowed. The $\bar{p}p$ background is expected to be comparable to the K^+K^- background at this energy.[5] We find the cross sections for reactions (1) to be

$$\pi^+n \to \phi p\text{:}\quad 179 \pm 72 \text{ nb}$$

and

$$\pi^+p \to \phi\Delta^{++}\text{:}\quad 172 \pm 75 \text{ nb}.$$

These cross sections have been corrected for beam contamination (negligible), beam attenuation (10%), Glauber screening (4%), interactions in the target walls (negligible), the track-finding and reconstruction efficiencies mentioned above, and for the ϕ-decay branching ratio into K^+K^- (0.486 $\pm$ 0.012). The quoted errors include the effects of both the statistical and the systematic errors in background determinations. We note that the cross section for the reaction $\pi^-p \to \phi n$ has been measured to be 263 ± 56 nb [$|t| < 0.5$ (GeV/c)^2] at 11 GeV/c.[6] This reaction is related to the reaction $\pi^+n \to \phi p$ by charge conjugation, and the two cross sections are in agreement within errors.

The cross sections for reactions (1) are consistent with the ϕ being produced solely by its nonstrange-quark component as determined from the octet-singlet mixing angle resulting from application of the Gell-Mann-Okubo mass formula to the vector-meson nonet. We show this by comparing the cross sections for the two ϕ-producing reactions with the cross sections for the corresponding OZI-rule-allowed reactions in which the vector meson is an ω meson, i.e., $\pi^+n \to \omega^0 p$ and $\pi^+p \to \omega^0\Delta^{++}$. Data for these reactions are shown in Fig. 2, along with the measurements of this experiment. Also shown

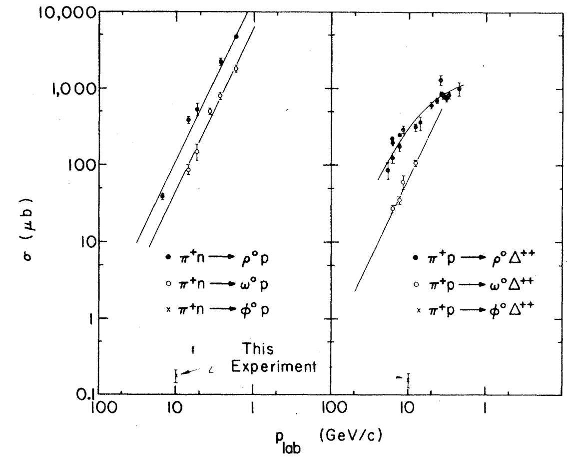

FIG. 2. Cross sections for the reactions (a) $\pi^+n \to V^0p$ and (b) $\pi^+p \to V^0\Delta^{++}$, in which V^0 stands for a neutral vector meson: ρ^0, ω, or ϕ. The smooth curve through the $\pi^+p \to \rho^0\Delta^{++}$ data shows the result of a single-pion-exchange model with absorption. The straight lines are in each case fits to the data of functions of the form $\sigma = Ap_{\rm lab}^{-n}$. Values of n thus determined are as follows: For $\pi^+n \to \rho^0p$, 2.10 ± 0.06; for $\pi^+n \to \omega p$, 2.10 ± 0.08; for $\pi^+p \to \omega\Delta^{++}$, 2.10 ± 0.15.

are the cross sections for the similar reactions $\pi^+n \to \rho^0p$ and $\pi^+p \to \rho^0\Delta^{++}$.[7] The difference between the ρ^0 and corresponding ω cross sections has long been thought to be due to the fact that the ω reactions are largely spin-flip, while the ρ^0 reactions feature a large forward non-spin-flip amplitude.[8] The strong suppression of the ϕ reactions observed here is due to the largely strange-quark content of the ϕ, as these reactions with a ϕ meson made of strange quarks are forbidden by the OZI rule. From the Gell-Mann-Okubo quadratic mass formula and the physical masses of the members of the vector-meson nonet, as reported in the 1980 edition of the Particle Data Tables,[9] one may predict the ratio of ϕ to the corresponding ω cross sections.[10] The result is

$$R = \frac{\sigma(\pi^+n \to \phi p)}{\sigma(\pi^+n \to \omega p)} = \frac{\sigma(\pi^+p \to \phi\Delta^{++})}{\sigma(\pi^+p \to \omega\Delta^{++})}$$

$$= 0.0037 \pm 0.0003 .$$

The data show that

$$R = \frac{\sigma(\phi p)}{\sigma(\omega p)} = 0.0037 \pm 0.0015$$

and

$$R = \frac{\sigma(\phi\Delta)}{\sigma(\omega\Delta)} = 0.0026 \pm 0.0011 .$$

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[1]S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig, 1964 (unpublished); and J. Iizuka, Prog. Theor. Phys. Suppl. 21, 37 (1966).

[2]D. Aston *et al.*, Phys. Lett. 99B, 502 (1981). See also L. S. Durkin, SLAC Report No. 238, 1980 (unpublished); A. K. Honma, Ph. D. thesis, Stanford University, 1980 (unpublished).

[3]The principal losses come from K-meson decays in the solenoid upstream of the first Čerenkov counter and slow protons which do not emerge from the target.

[4]The lower efficiency for the reaction $\pi^+p \to \phi\Delta^{++}$ is due to the presence of two low-momentum tracks in the cylinder chambers surrounding the target in the solenoid which have lower efficiency (70%) than faster solenoid tracks (95%) or dipole tracks (95%).

[5]H. H. Williams, SLAC Report No. 142, 1972 (unpublished).

[6]B. D. Hyams *et al.*, Nucl. Phys. B22, 189 (1970).

[7]T. C. Bacon *et al.*, in *Proceedings of the Second Topical Conference on Resonant Particles, Athens, Ohio, 1965*, edited by B. A. Munir (Ohio Univ. Press, Athens, Ohio, 1965) ($\rho p, \omega p$ at 1.7 GeV/c); R. J. Miller *et al.*, Phys. Rev. 178, 2061 (1969) ($\omega p, \rho p$ at 2.7 GeV/c); M. S. Farber *et al.*, Nucl. Phys. B29, 237 (1971) ($\omega p, \rho p$ at 5.4 GeV/c); D. Cohen *et al.*, Phys. Rev. Lett. 38, 269 (1977) (ϕp at 6 GeV/c); J. A. J. Mathews *et al.*, *ibid.* 26, 400 (1971) ($\rho p, \omega p$ at 6.95 GeV/c); M. Aderholz *et al.*, Nucl. Phys. B11, 259 (1969) ($\omega\Delta$ at 8 GeV/c); M. Aderholz *et al.*, *ibid.* B14, 255 (1969) ($\phi\Delta$ at 8 GeV/c); C. Caso *et al.*, Nuovo Cimento 13A, 343 (1973) ($\rho\Delta$ at 11.7 GeV/c); D. Evans *et al.*, Nucl. Phys. B51, 205 (1973) ($\omega\Delta$ at 11.7 GeV/c); J. Gaidos *et al.*, Phys. Rev. D 1, 3190 (1970) ($\rho\Delta$ at 13 GeV/c); J. Gaidos *et al.*, Nucl. Phys. B72, 253 (1974) ($\omega\Delta$ at 13 GeV/c); J. Gaidos *et al.*, Phys. Rev. D 12, 2565 (1975) ($\rho\Delta$ at 13 GeV/c); J. E. Richey *et al.*, *ibid.* 15, 3155 (1977) (ρp at 15 GeV/c); J. Ballam *et al.*, *ibid.* 4, 1946 (1971) ($\rho\Delta$ at 16 GeV/c); M. Deutschmann *et al.*, Nucl. Phys. B99, 397 (1975) ($\rho\Delta$ at 16 GeV/c); R. Honecker *et al.*, *ibid.* B106, 365 (1976) ($\rho\Delta$ at 16 GeV/c); H. Grassler *et al.*, *ibid.* B115, 365 (1976) ($\omega\Delta$ at 16 GeV/c); N. N. Biswas *et al.*, Phys. Rev. D 2, 2529 (1970) ($\rho\Delta$ at 18 GeV/c).

[8]See, for example, G. C. Fox, in *Phenomenology in Particle Physics, 1971*, edited by C. Chiu, G. C. Fox, and A. J. G. Hey (California Institute of Technology, Pasadena, California, 1971), and references contained therein.

[9]Particle Data Group, Rev. Mod. Phys. 52, S1 (1980).

[10]H. J. Lipkin, Phys. Lett. B60, 371 (1976).