Observation of ωp Enhancement from the Reaction $\pi^- p \to \pi^- \omega p$ at 4.5, 6, and 14 GeV/c*

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An enhancement near the ωp threshold has been observed with a mass of 1820 MeV and a width of about 120 MeV from the reaction $\pi^- p \to \pi^- \omega p$ at 4.5, 6, and 14 GeV/c. There is no strong evidence for πN or ρN decay modes. We examine spin and parity and production characteristics.

Experimental studies of nucleon resonances mainly come from πN formation experiments and from production experiments by measuring the missing mass or detecting their decays into stable particles. In this Letter, we present evidence for a well-defined enhancement in the ωp system at a mass value of 1820 MeV with a width of 120 MeV from the reaction $\pi^- p \to \pi^- \omega p$ at 4.5, 6, and 14 GeV/c.[1]

The data for this study come from three separate bubble-chamber experiments. The 4.5-GeV/c experiment was an exposure in the Stanford Linear Accelerator Center (SLAC) 82-in. chamber. The 6-GeV/c experiment was an exposure in the Brookhaven National Laboratory (BNL) 80-in. chamber. The 14-GeV/c experiment was a hybrid experiment with the SLAC 40-in. chamber. The triggered bubble-chamber experiment was performed by detecting and momentum analyzing the scattered pion from the reaction $\pi^- p \to \pi^- X$ in a wire-spark-chamber magnetic spectrometer located downstream from the bubble chamber. Details of the experimental arrangement have been reported elsewhere.[2] Since the characteristics of the 4.5- and 6-GeV/c data are similar, we have combined them for the purpose of presentation.

To isolate the $\pi^- \omega p$ final states, Fig. 1(a) shows the $(\pi^+\pi^-\pi^0)$ mass spectrum from 0.6 to 1.0 GeV from the final state $\pi^-(\pi^-\pi^+\pi^0)p$ for 4.5- and 6-GeV/c data. Strong ω production is evident. The shaded area in Fig. 1(a) shows the events with a peripheral cut ($|t_{\pi\to\pi}| < 0.4$ GeV^2). We note that in the ω region (0.77–0.80 GeV for the 4.5- and 6-GeV/c data), the signal-to-background ratio, $R = \omega/B$, is about 3.4. The 14-GeV/c data have a larger background in the ω

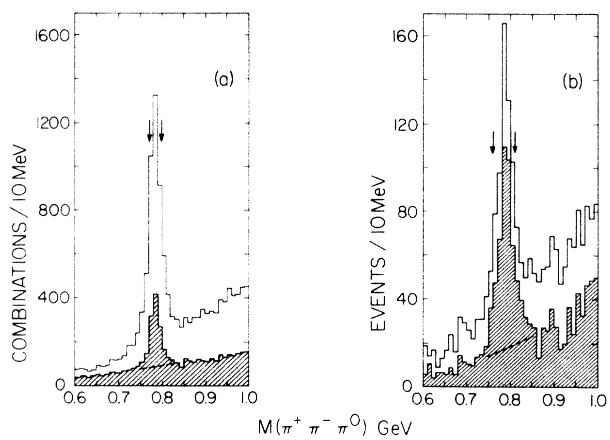

FIG. 1. (a) Mass spectrum for $\pi^+\pi^-\pi^0$ for 4.5- and 6-GeV/c data. Shaded areas, combinations with a peripheral cut ($|t_{\pi\to\pi}| < 0.4$ GeV^2). (b) Mass spectrum for $\pi^+\pi^-\pi^0$ for 14 GeV/c data with a peripheral cut ($|t_{\pi\to\pi}| < 0.4$ GeV^2). Shaded area, events subjected to a "Dalitz-plot cut."

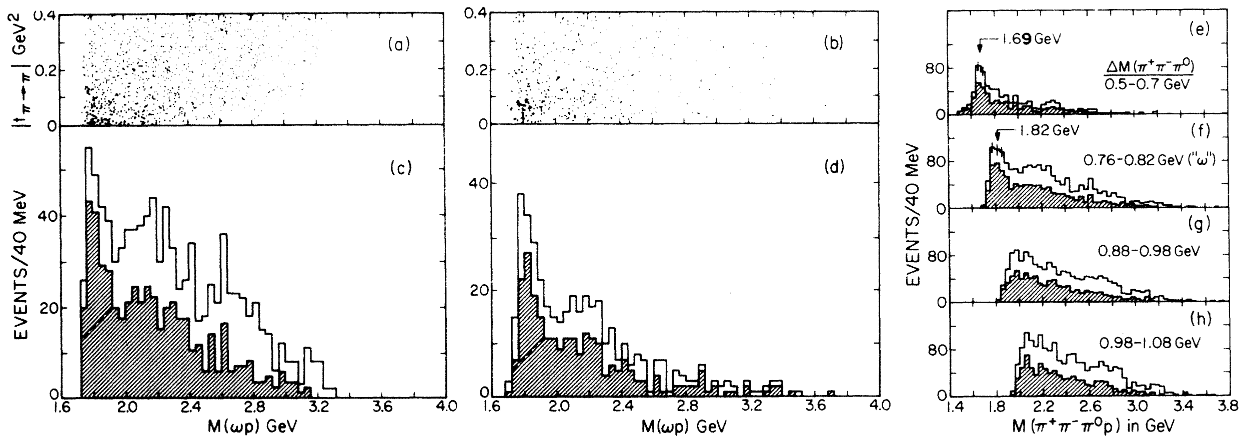

FIG. 2. (a) Chew-Low plot for the reaction $\pi^-p\to\pi^-\omega p$ at 4.5 and 6 GeV/c. (b) Same as (a) but for 14 GeV/c. (c), (d) Mass projections of ωp for $|t_{\pi\to\pi}|<0.4$ (solid line) and 0.15 (shaded area) GeV^2 for 4.5- and 6-GeV/c and 14-GeV/c data, respectively. Dashed lines, estimated signal for the purpose of cross-section calculations. (e)–(h) Combined $\pi^+\pi^-\pi^0p$ mass spectrum for all momenta as a function of $\pi^+\pi^-\pi^0$ mass regions as shown. Histograms, events with $|t_{\pi\to\pi}|<0.4$ GeV^2; shaded areas, events with $|t_{\pi\to\pi}|<0.15$ GeV^2.

region (0.76–0.81 GeV) as shown in Fig. 1(b), with $R=2$. This larger background is mainly due to ambiguities in kinematic fits since no ionization information is currently available. To improve the ratio R for the 14-GeV/c data, we take advantage of the fact that the spin and parity (J^P) for the ω is 1^-, so that a selection of events in the central region of the $\pi^+\pi^-\pi^0$ Dalitz plot will enhance the 1^- signal relative to the background. The shaded area in Fig. 1(b) shows the events in the ω region subjected to such a "Dalitz-plot cut." We note that R for the 14-GeV/c data increases to about 3.5. Thus we have reduced the background in this operation by about a factor of 2 with only a 20% reduction of ω signal. In the subsequent analysis, we use the "cut" samples only for the 14-GeV/c data.

To search for peripheral production of ωp states, we have examined the Chew-Low plots shown in Figs. 2(a) amd 2(b). There are concentrations of peripheral events ($|t_{\pi\to\pi}|<0.15$ GeV^2) in the 1.82-GeV region for all data. Figures 2(c) and 2(d) show ωp mass projections with $|t_{\pi\to\pi}|<0.4$ GeV^2. The peak at 1820 MeV with a width of about 120 MeV is present at all three momenta. To show the peripheral nature of this peak, the mass projections with a cut of $|t_{\pi\to\pi}|<0.15$ GeV^2 are shown in the shaded area of Figs. 2(c) and 2(d).

To ensure that this ωp enhancement observed in all three momenta is indeed a real ωp effect, we have examined whether the general feature of a low-mass $\pi^+\pi^-\pi^0p$ enhancement just above threshold exists in the regions of $M(\pi^+\pi^-\pi^0)$ outside the ω region. Figures 2(e)–2(h) show $M(\pi^+\pi^-\pi^0p)$ distributions for four $\pi^+\pi^-\pi^0$ mass regions from 0.5 to 1.08 GeV as indicated. We see no evidence for a narrow enhancement (about 120 MeV) near the threshold in the $M(\pi^+\pi^-\pi^0p)$ distributions for the two $\pi^+\pi^-\pi^0$ mass regions above the "ω" region [Figs. 2(g) and 2(h)]. However, there is a narrow enhancement at 1.69 GeV in the $M(\pi^+\pi^-\pi^0p)$ spectrum for the $\pi^+\pi^-\pi^0$ mass region below the "ω" region. We note that this 1.69-GeV enhancement appears well above threshold and that its mass and width are consistent with the known $N_{1/2}^*(1.69)$. Thus it is not clear how one can use the $M(\pi^+\pi^-\pi^0p)$ spectrum for $\pi^+\pi^-\pi^0$ below the "ω" region as a true control region for the purpose of this investigation since this enhancement may be due to the $\pi^+\pi^-\pi^0p$ decay mode of the $N_{1/2}^*(1.69)$. We have also examined Dalitz plots of the $\pi^-\omega p$ final state (not shown) and have found that no known resonances in $\pi^-\omega$ and π^-p systems reflect into this ωp peak at 1.82 GeV.[3]

We conclude that we have observed a real ωp enhancement for all three momenta, and Fig. 3(a) shows the combined ωp mass spectrum for $|t_{\pi\to\pi}|<0.15$ GeV^2. We now proceed to examine the characteristics of this ωp enhancement.

(a) *Isospin.*—Observation of the ωp decay mode implied an isospin of $\frac{1}{2}$ for this object.

(b) *Spin and parity.*—We have examined the decay angular distributions of the ωp system using the polar and azimuthal angles, θ and φ,

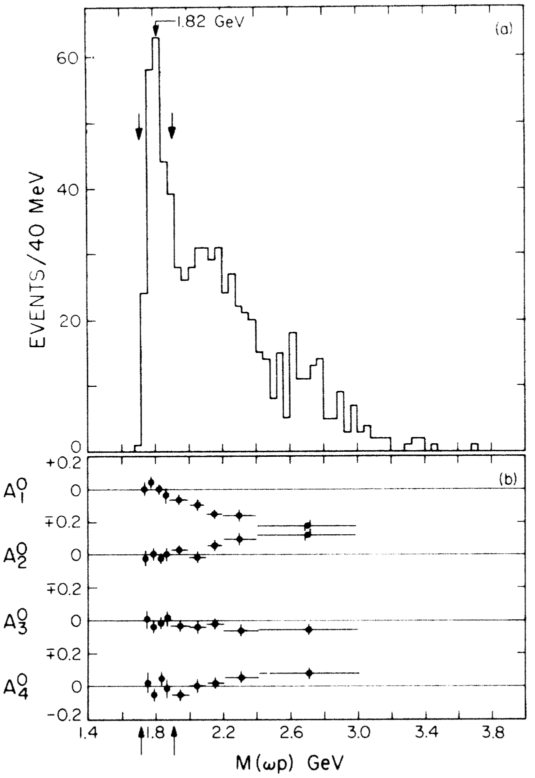

FIG. 3. (a) Combined ωp mass spectrum for all momenta with $|t_{\pi\to\pi}|<0.15$ GeV^2. (b) Distributions of the coefficients of the normalized even moments (see text for details) as functions of the ωp mass for events with $|t_{\pi\to\pi}|<0.15$ GeV^2.

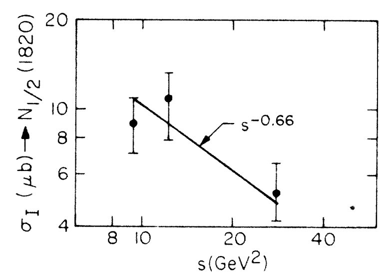

FIG. 4. Cross sections for the ωp enhancement for $|t_{\pi\to\pi}|<0.15$ GeV^2 as a function of s. Solid line, fit to the data as shown.

which define the direction of the ω in the ωp rest frame in both the Gottfried-Jackson and helicity frames. In the ωp mass region of 1.7 to 1.9 GeV, the decay distributions are consistent with isotropy in either frame at all three momenta, whereas this is not the case outside the region of the enhancement. We have studied the moments $W(\theta,\varphi)=\sum A_l^m Y_l^m(\theta,\varphi)$ of the angular distribution in both frames as functions of the ωp mass at each momentum. Since the results are similar for each momentum, we show only those for the combined data for the Gottfried-Jackson frame in Fig. 3(b) for $|t_{\pi\to\pi}|<0.15$ GeV^2 and for $l\leq 4$, and $m=0$. It is evident that moments for ωp mass below 2 GeV are consistent with zero,[4] whereas the moments above this mass region show deviations from zero. With the present data the moment analysis suggests a low-spin assignment (such as $J=\frac{1}{2}$ or $\frac{3}{2}$) for the ωp enhancement. However, since nonresonant background interference can confuse the interpretation of angular distributions, we cannot rule out other assignments with the present data.

(c) *Decay modes.*—We have searched for other decay modes (πN, ρN, and $\pi^+\pi^-\pi^0 p$) from the similar final states and have found no evidence for them, thus placing upper limits for them: $(\pi N)^+/(\omega p)<36\%$[5] and $(\rho^0 p)/(\omega p)<12\%$[6] with 90% confidence level. The search for the $\pi^+\pi^-\pi^0 p$ decay mode is particularly difficult since the possible $\pi^+\pi^-\pi^0 p$ decay mode of $N_{1/2}^*(1.69)$ tends to obscure the 1.82-GeV region at our level of statistics. In any case, we see no obvious structure at the 1.82-GeV region [see Fig. 2(e)].

(d) *Production characteristics.*—We have estimated the cross section for production of the ωp enhancement at 4.5, 6, and 14 GeV/c for $|t_{\pi\to\pi}|<0.15$ GeV^2 where the signal is strong and background is easier to estimate as indicated by the dashed lines in Figs. 2(c) and 2(d). Figure 4 shows this peripheral cross section, σ_I, versus the square of the total center-of-mass energy, s. We have fitted the cross sections to a functional form s^n and obtained $n=-0.66\pm0.06$. This is to be contrasted with the known $N_{1/2}^*$ production such as $\pi^- p\to\pi^- N_{1/2}^*(1.69)$ with very little or no energy dependence for the small-t region.[7] Furthermore, the differential cross section for the events in the ωp mass region, 1.7 to 1.9 GeV, can be fitted to a functional form $\exp(bt_{\pi\to\pi})$ with a value of $b=6.5\pm1$ GeV^{-2} for $|t_{\pi\to\pi}|<0.4$ GeV^2.

To conclude our studies of this near-threshold ωp enhancement, we wish to make the following remarks in regard to possible interpretations of this enhancement. (a) Unlike the shapes of other threshold enhancements [e.g., $N_{1/2}^*(1.47)$ of A_1], which feature a sharp rise from threshold and then a slow fall (producing a broad width of ~300 MeV), this enhancement is well defined and stable from 4.5 to 14 GeV/c with a width of about 120 MeV. (b) From a formation experiment[8] of $\pi^+ n\to\omega p$, a suggestive peak at this mass was also observed. Large errors in cross sections due to deuterium and normalization difficulties precluded any definite conclusions.[9] *If* we assume this peak is the same object that we observe in this experiment, then it couples not only to ωp but also to πN although our upper limit of $(\pi N)^+/(\omega p) < 36\%$ indicates that the πN coupling is small.

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[1]A 2.5-standard-deviation ωp enhancement in this mass region from the reaction $\pi^- p \to \pi^- \omega p$ at 7 GeV/c was reported by M. S. Milgram *et al.*, Nucl. Phys. B18, 1 (1970). Further observation of ωp enhancement from the reaction $K^+ p \to K^+ \omega p$ at 12 GeV/c was reported by P. J. Davis *et al.*, [Nucl. Phys. B44, 344 (1972)], but they reported no evidence for narrow structure near the threshold region.

[2]A. R. Dzierba *et al.*, Phys. Rev. D 7, 725 (1973); A. R. Dzierba *et al.*, in *Proceedings of the International Conference on Instrumentation for High Energy Physics, Frascati, Italy, 8–12 May 1973,* edited by S. Stipcich (Laboratori Nazionali del Comitato Nazionale per l'Energia Nucleare, Frascati, Italy, 1973), p. 56.

[3]In the Dalitz plots for all the data, we note that there is no kinematic overlapping region between this peak in ωp and the $B(1250)$ meson. Furthermore, the peripheral cut of $|t_{\pi \to \pi}| < 0.4$ GeV^2 removes most of the events with $M(\pi^- p) < 1.7$ GeV.

[4]We have also examined the moments where $m \neq 0$ and found them to be consistent with zero. Furthermore, distributions of the normal to the ω-decay plane are found to be uncorrelated with decay angles in the ωp rest frame.

[5]Data from 6 and 14 GeV/c were used to deduce this upper limit; 4.5-GeV/c data are not available for this comparison.

[6]Data from all three momenta were used to deduce this upper limit.

[7]See, for example, E. W. Anderson *et al.*, Phys. Rev. Lett. 25, 699 (1970).

[8]J. S. Danburg *et al.*, Phys. Rev. D 2, 2564 (1970), and earlier references therein.

[9]Further evidence for a large s-wave contribution to the $\pi^- p \to \omega n$ cross section near threshold has been reported by D. M. Binnie *et al.*, Phys. Rev. D 8, 2789 (1973).

Search for Fractionally Charged Quarks Produced by 200- and 300-GeV Proton-Nuclear Interactions

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We describe an experimental search for particles with fractional charge (quarks) with mass below 11 GeV/c^2 produced by proton-nucleus collisions at 200 and 300 GeV. No evidence for such particles was found. Limits on the quark production cross section are given.

We have searched for fractionally charged particles (quarks) among secondaries produced by 200- and 300-GeV protons incident on a 12-in. beryllium target. The experiment was performed at the National Accelerator Laboratory. The $M2$ beam of the meson area was used to select the momentum of the secondaries. The principal detector was a set of eight scintillation counters which provided ionization loss information on particles transmitted by the beam channel.