COMPARISON OF $\bar{p}p$ ANNIHILATIONS AND πp AND Kp BACKWARD ELASTIC SCATTERING USING CROSSING RELATIONS*

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In a recent series of experiments, $\pi^{\pm}p$ and $K^{\pm}p$ backward scattering and $\bar{p}p$ annihilations into $\pi^{+}\pi^{-}$ and $K^{+}K^{-}$ in the forward-backward direction have been measured. These data are compared assuming the dominance of a baryon-exchange amplitude and the validity of the crossing-symmetry relations.

The concept of crossing symmetry, which, in the case of two-body scattering, relates the amplitudes between processes for which a pair of particles is interchanged between the initial and the final state, is a fundamental assumption of the S-matrix theory of strong interactions.[1] It would be obviously desirable to have an experimental check on this important property. However, it is not possible to apply these relations except at asymptotic energies unless assumptions are made about the analytic form of the scattering amplitudes so that the analytic continuation necessary for the crossing can be performed.

A recent series of experiments at the Brookhaven alternating-gradient synchrotron has enabled us to make quantitative comparisons of $\bar{p}p$ $\rightarrow \pi^{\pm}\pi^{\mp}$ with $\pi^{\mp}p$ backward elastic scattering and $\bar{p}p \rightarrow K^{\pm}K^{\mp}$ with $K^{\mp}p$ backward elastic scattering in the momentum interval of 1.0–3.0 GeV/c.[2,3]

As an example, consider πp scattering as indicated in Fig. 1: (a) $\pi^{+}p \rightarrow \pi^{+}p$, s channel; (b) $\bar{p}p \rightarrow \pi^{-}\pi^{+}$, t channel; (c) $\pi^{-}p \rightarrow \pi^{-}p$, u channel. We make comparisons of channel (a) and channel (b) at a fixed, small (negative) value of u, the four-momentum transfer between the outgoing π^{+} and the incoming proton. Clearly u maintains its meaning between channels (a) and (b) when we make this crossing between s and t. Small u implies near backward scattering for channel (a) and a forward-going π^{-} for channel (b). So this pair is closely related by a common u channel. Similar comparisons can be made for the other three pairs of reactions in Fig. 1.

The statement of crossing symmetry is that,

given the scattering amplitude $T(s,u)$ describing channel (a), one can perform an analytic continuation to obtain $T(t,u)$ describing channel (b). However, since in general the analytic form of the scattering amplitude is not known, one cannot perform this continuation. In the asymptotic case ($s \rightarrow \infty$, $u \approx 0$), if the amplitudes become constant the annihilation cross section $d\bar{\sigma}(t,u)/du$ is related to the backward elastic scattering amplitude $d\sigma(s,u)/du$ by[4]

$$\frac{d\bar{\sigma}}{du}(t,u) = \frac{1}{2}\frac{d\sigma}{du}(s,u), \qquad (1)$$

where the factor of $\frac{1}{2}$ is just the ratio of the number of initial spin states in the backward-scat-
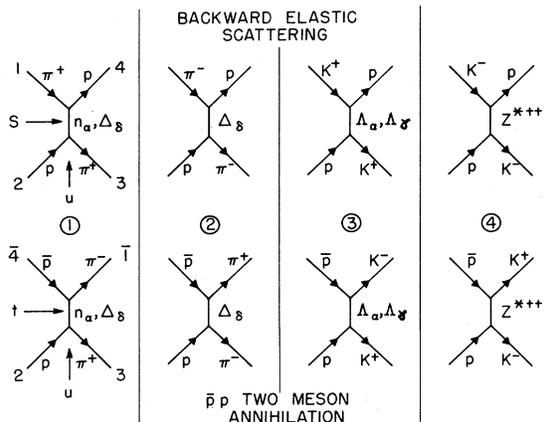
FIG. 1. Exchange diagrams for the four pairs of backward-scattering and annihilation reactions. Reaction (1) indicates how the top two arms of the diagram are interchanged to give the s and t channels. Some of the possible exchanged baryon trajectories are included.

tering and the annihilation reactions.

More recently, Barger and Cline[5] have assumed the dominance of Reggeized baryon-exchange contributions common to both the annihilation and backward-scattering reactions as indicated in Fig. 1. Under this assumption they are able to derive a crossing relation over the entire range of momenta where these exchanges are dominant. The concepts of "duality" have indicated that, at least in an energy-averaged sense, these exchanges are dominant at much lower momenta than previously expected.[6]

Experimentally one can look at the cross sections as a function of s, and if they do not have large oscillations one can assume that this lack of oscillation is a possible indication of u-channel exchange. The $K^{\pm}p$ backward cross sections are especially promising in this respect.[3]

The formula of Barger and Cline for our case is

$$\frac{d\bar{\sigma}}{du} = \frac{1}{2}\frac{d\sigma}{du}\frac{[s-(m-\mu)^2][s-(m+\mu)^2]}{s[s+u+2(m^2-\mu^2)]}, \quad (2)$$

where m is the nucleon mass and μ is either the pion or kaon mass depending on the reaction involved.[5] The conditions are as follows: (i) If there are different signature exchanges, the exchange of one signature must be dominant or the exchanges must be exchange degenerate; (ii) with respect to the transformation $\sqrt{u} \to -\sqrt{u}$, the even part of the exchange amplitude must be dominant over the odd part. Very little specific knowledge

of the exchange amplitude is required, and although this formula was derived for the Regge-pole model, the conditions could be met more generally by other exchange models.

Regge-pole fits to backward cross sections indicate that condition (i) is met in most cases. How well condition (ii) is satisfied is difficult to determine experimentally, but since it is not unreasonable and without it the formulation of Eq. (2) becomes much more dependent on the details of the exchange, we shall use Eq. (2) throughout this discussion. At large values of s and small u, the odd terms mentioned in (ii) are of order $1/s$ with respect to the even terms.

Ideally one would make these comparisons at a fixed value of u, but kinematics and the restricted angular regions measured make this difficult; therefore we have decided to make the comparisons at a fixed angle, $\cos\theta_{c.m.} = \pm 0.98$, for the annihilation reaction and have chosen the angle for the backward scattering at the same value of u. This allows us to make the comparison over a much larger range of s than otherwise possible. The range of u for the two-pion annihilation is -0.44 to -0.20 $(\text{GeV}/c)^2$, and -0.03 to -0.14 $(\text{GeV}/c)^2$ for the two-kaon annihilation. From this point on we refer to the pairs of crossed reactions by the numbers indicated in Fig. 1.

In Fig. 2 we show the results of the comparison of the four pairs of cross sections as a function of s. The backward cross sections have been
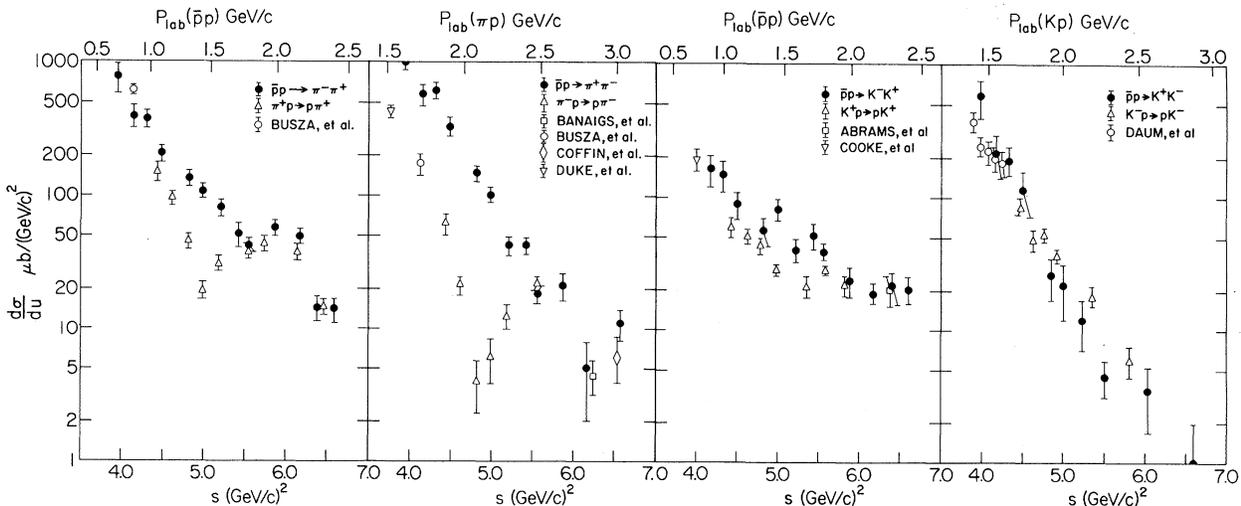
FIG. 2. Comparison of backward-scattering and annihilation reactions as a function of s at fixed $\cos\theta_{c.m.}$ for the annihilation. The backward-scattering cross sections have been multiplied by the factor given by Eq. (2) in all cases. The annihilation cross sections are from Ref. 2 and the open triangles are from Ref. 3. References for the backward-scattering cross sections from other groups are given in Ref. 7. For convenience the laboratory momentum scales for the various incident particles are shown as well as the invariant s.

multiplied by the crossing factor of Eq. (2) which increases from ~0.19 to ~0.29 over the range of s covered for both πp and Kp scattering. The errors shown are only statistical and do not include the normalization errors of up to 10% in the different experiments. However, since both the backward-scattering and annihilation data were taken under very similar conditions, it is expected that systematic effects should change them both in the same direction. We have included data from some other experiments in order to extend the range in s.[7]

Reaction (1) shows reasonable agreement everywhere except near $s = 5.0$ $(\mathrm{GeV}/c)^2$ where there is a strong dip in the backward $\pi^+ p$ cross section. Considering the presence of many resonances and the large number of possible exchanges, the comparison for Reaction (1) is somewhat better than one would expect a priori. Also it is interesting to note that both cross sections show a similar shoulder at $s \approx 6.0$ $(\mathrm{GeV}/c)^2$. For Reaction (2) the direct-channel effects, specifically the $N^*(2190)$, eliminate any quantitative agreement between them. Clearly these pairs of reactions should be studied at higher momenta where the influence of the direct-channel resonances for πp scattering is not important.

For Reactions (3) and (4) the agreement is striking considering the low momenta at which the comparison is being made. The agreement for Reaction (3) is not surprising as the backward $K^+ p$ scattering can be fitted with an exchange-degenerate $\Lambda_\alpha, \Lambda_\gamma$ exchange which meets conditions (i) and (ii).[8] This is further evidence that the $K^+ p$ system is dominated by exchange amplitudes down to ~1 GeV/c. On the other hand, the good agreement for Reaction (4) is not at all expected in this model since it is usually believed that $K^- p$ backward scattering is dominated by direct-channel amplitudes.[3]

At the highest momenta we can make a comparison of the pairs of cross sections at fixed s as a function of u. This is shown in Fig. 3 where the annihilation data have been averaged over four different momenta [ranging from $s = 5.4$ to $s = 6.2$ $(\mathrm{GeV}/c)^2$] in order to improve the statistics. As before, the backward-scattering data at approximately the same s have been multiplied by the crossing factor of Eq. (2). For Reactions (2) and (4) there is no significant disagreement over the range of u. While the agreement is generally good near $u = -0.23$ for Reaction (1) and $u = -0.15$ for Reaction (3) ($\cos\theta_{c.m.} = 0.98$ for the annihilation), where the compari-

sons in Fig. 2 have been made, away from this direction there is a marked deviation possibly due to the presence of odd terms of the type mentioned in condition (ii). This is a good indication of how these crossing relations could be used to help determine the detailed functional form of the baryon-exchange amplitudes.

From these initial results one can conclude that, where the appropriate conditions are met, the crossing relations are reasonably well satisfied. While the $K^+ p$ system seems to be dominated by an exchange contribution down to ~1 GeV/c, the $\pi^\pm p$ system shows strong direct-channel effects up to at least 2.5 GeV/c; thus further experiments are required at higher momenta. Finally, the surprisingly good agreements of Reaction (4) over two orders of magnitude need some further comments. Presently available experimental information does not exclude the possibility that $K^- p$ backward scattering can be expressed by a Reggeized Z^{*++} ($S = 1$, $B = 1$) exchange with $\alpha(0) \sim -4.0$.[9] If such a trajectory had a slope of 1 $(\mathrm{GeV}/c)^{-2}$ it would pass in the vicinity of the higher $I = 1$ peaks of the $K^+ p$ total cross section.[10] On the other hand, this agreement may be indicative of a crossing relation which is more general than that derived from the Reggeized baryon-exchange model.

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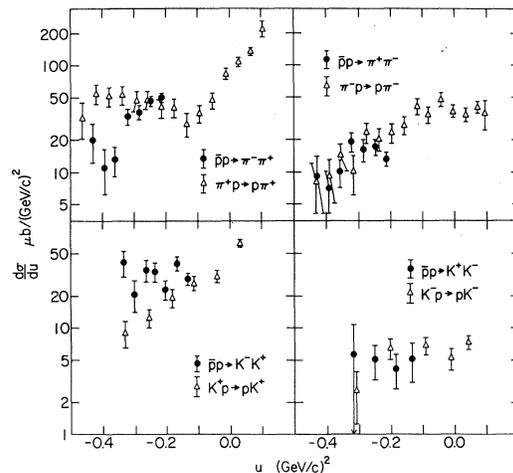
FIG. 3. Comparison of backward-scattering and annihilation reactions as a function of u at approximately the same value of s. The annihilation data have been averaged over four-momenta as discussed in the text to provide better statistical accuracy. The annihilation data are all at a mean s of 5.80 $(\mathrm{GeV}/c)^2$ and the $\pi^+ p$, $\pi^- p$, and $K^\pm p$ backward-scattering data are at 5.70, 5.65, and 5.82 $(\mathrm{GeV}/c)^2$, respectively. All cross sections are from Refs. 2 and 3.

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EVIDENCE FOR A $\pi\eta$ RESONANCE AT 970 MeV PRODUCED IN $K^- p \to \Lambda\pi^+\pi^-$MM AT 3.9, 4.6, and 5.0 GeV/c *

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Evidence is presented for the existence of a boson resonance (δ) with $M = 970 \pm 15$ MeV and $\Gamma \lesssim 50$ MeV produced in the reaction $K^- p \to \Sigma^+(1385)\delta^-$, $\delta^- \to \pi^-\eta$. By studying the δ^- produced in association with $\Sigma^+(1385)$, we are able to rule out possible kinematic effects as a source of the enhancement in our data. We give upper limits to other decay modes such as 2π, 3π, and $K\bar{K}$.

Since the first evidence[1] was presented for the existence of an $I = 1$ meson resonance (δ) with mass approximately 960 MeV and narrow width, several contradictory experiments concerning this resonance have been reported. These have involved searches in a variety of final states and with different detection techniques.[2] Following our earlier suggestion[3] of the production of such an object in the reaction $K^- p \to \Lambda\pi^+\delta^- \to \Lambda\pi^+\pi^-$ [+ neutrals (MM)], indications favoring the existence of this state have been reported by Ammar et al.[4] in the reaction $K^- p \to \Lambda\pi^+ "\delta^-" \to \Lambda\pi^+\pi^-\eta \to \Lambda\pi^+\pi^-$MM at 5.5 GeV/c and by Miller et al.[5] in the reaction $K^- n \to \Lambda"\delta^-" \to \Lambda\pi^-$MM at 4.5 GeV/c.[6] However, some doubt was cast recently on the

validity of these results when Crennell et al.,[7] studying the same reaction as Miller et al. at 3.9 GeV/c, pointed out previously unsuspected kinematic effects in this type of final state. In this Letter we present evidence for the existence of the $\pi^-\eta$ resonance, hereafter called δ, and rule out the above-mentioned kinematic effects as a source of the observed enhancement.

The present results are based on a continuing study of $K^- p$ interactions in the Brookhaven National Laboratory 80-in. bubble chamber exposed to K^- beams with momenta of 3.9, 4.6, and 5.0 GeV/c. When all the exposures are combined, the sensitivity of this experiment amounts to 12.8 events/μb.[8] Within statistics the different expo-