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A Study of $\pi^+ p \to K^+ \Sigma^+$ and $\pi^+ p \to K^+ Y^{*+}$

Using the Focusing Spectrometer Facility

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We propose to use the focusing spectrometer facility to detect K^+ mesons produced in association with Σ^+, $Y^*(1385)$ and $Y^*(1670)$ by $\pi^+ p$ interactions. These processes will be studied over a momentum range 20 to 120 GeV/c and from t_{min} to about 0.8 GeV^2.

PHYSICS INTEREST

Much of our knowledge of strong interactions comes from scattering experiments. While many of the early NAL experiments will study diffractive scattering, both elastic and inelastic, only a few of the reactions studied will be dominated by the exchange of objects other than the Pomeron. Nondiffractive experiments which have been approved are the following:

$$\pi^- p \to \pi^0 n \qquad (1)$$

$$\pi^- p \to \eta\ n \qquad (2)$$

$$K_L^0 p \to K_S^0 p \qquad (3)$$

These reactions are presumably dominated by ρ, A_2, and ω exchange, respectively.

The reactions which we propose to study,

$$\pi^+ p \to K^+ \Sigma^+, \qquad (4)$$

$$\pi^+ p \to K^+ Y^{*+}, \qquad (5)$$

are generally assumed to be dominated by $K^*(890)$ and $K^*(1420)$ exchange. In the symmetry scheme SU(3) these two K^*'s are related to the ρ and A_2, respectively; information on reactions 4 and 5 thus compliments that obtained for reactions 1 and 2. Data from the four reactions taken together can provide a considerably more stringent test of theory than is possible taking each reaction separately.

The energy dependence of the cross sections is crucial to our understanding of high energy processes. Do the cross sections become dominated by single leading trajectories at high energies? Do the forward peaks shrink? How important are cuts? Will the unexpectedly slow fall off of the elastic scattering cross section have consequences for the nondiffractive processes?

Reactions 4 and 5 have been studied up to 14 GeV.[1, 2] The small angle Σ^+ cross section shows an exponential dependence on t going roughly as e^{10t} from 4 to 14 GeV/c. At momenta 3 to 5 GeV/c a minimum occurs in the differential cross section at about 0.5 GeV^2, followed by a broad maximum in the region of 1 GeV^2. As the energy increases the second maximum dies away and beyond a break at 0.5 GeV^2 the cross section still falls, but not as rapidly as at small t. As the incident momentum increases, the point at which this break occurs moves out in momentum transfer such that the cross section at the break falls rapidly:

$$\frac{d\sigma}{dt}\ (0^o) / \frac{d\sigma}{dt}\ (\text{break}) \approx 7p$$

where p is the incident momentum in GeV/c. The forward part of the cross section with the e^{10t} dependence goes roughly as (250 μb)/p from 4 to 14 GeV/c.

The differential cross section for $Y^*(1385)$ production shows a markedly different t dependence.[2] There is a dip in the forward direction followed by a maximum near 0.15 GeV^2, and then an exponential falloff going as e^{5t}. In the region 6 to 14 GeV/c the cross section for $Y^*(1385)$ production goes roughly as 70 μb/p for p in GeV/c. A strong bump in the missing mass distribution has also been observed for $Y^*(1670)$ at these momenta.

The polarization of the Σ^+ in reaction 4 has been measured from 3 to 14 GeV/c. The Σ^+ has a very convenient analyzer since the decay $\Sigma^+ \rightarrow p\,\pi^o$ occurs with a 52% branching ratio and $\alpha = -0.99 \pm 0.02$; further, the kinematics are favorable, the proton being emitted at rather small angles with respect to the Σ^+ direction. Although rather large positive polarizations have been measured for $-t > 0.4\ GeV^2$ the polarization appears to be close to 0 for $-t < 0.3\ GeV^2$. For example, at 14 GeV/c the average polarization from t_{min} to 0.3 GeV^2 is 0.06 ± 0.14. Both the experiments at Argonne and Brookhaven had troubles with high counting rates in their Σ detectors because of beam halo problems.

While it would be clearly desirable to measure the Σ polarization at high energies, such a measurement seems marginal; at small t where we hope to have reasonable statistics the polarization is likely very close to zero, while at large momentum transfers where the polarization may be considerable the rates will be very low. The spectrometer itself is relatively immune to high beam rates and halo problems, and the detection of the decay proton might well force us to turn the beam down by a factor of 10. Although we have written this proposal without a Σ detector, we plan to install one if experience with the beam and spectrometer so indicates.

We believe reactions 4 and 5 to be the most easily studied of the hypercharge exchange reactions. The reaction

$$K^- p \rightarrow \pi^- \Sigma^+, \qquad (6)$$

for example, would be of great interest since it is related to reaction 4 by line reversal; exchange degeneracy of the two K^* trajectories would give equal cross sections. Unfortunately, the low flux of K^- expected in the beam will likely preclude a study of reaction 6, the ratio of beam fluxes being 100:1. Other hypercharge exchange reactions such as

$$\pi^- p \rightarrow K^o (\Lambda, \Sigma) \qquad (7)$$

can be studied with a large-aperture multiparticle spectrometer. Although these reactions are among the easiest which can be studied with such a spectrometer, the effort involved is still considerably more than that involved in the study of the $\pi^+ \rightarrow K^+$ reactions with the focusing spectrometer.

EXPERIMENTAL ARRANGEMENT

Positive pions in the 2.5-milliradian beam will interact in a liquid hydrogen target and produce K^+ mesons which will be detected with the single-arm focusing spectrometer. We do not plan to observe the recoil but if experience with the beam and spectrometer indicates feasibility we could add chambers or counters near the target to measure the Σ^+ polarization.

Cerenkov counters in the beam will be used to tag the incoming light particles (π, μ and e). Measurements of the muon and electron contamination will be made with appropriate counters in the spectrometer with the spectrometer set to zero degrees. Horizontal and vertical counter hodoscopes of about 10 counters each will be used to define the incident angle to about $\pm$ 0.2 milliradian. Assuming a beam spill of one second we would expect to run at 2×10^6 beam particles/burst for 0 degree runs and about 10^7 at the larger angles. As shown by Table I, this latter flux will require that the beam momentum slits be set to a full width acceptance of about 100 MeV/c.

If the beam can be tuned to allow the spectrometer to run in an energy-loss mode, considerably higher rates could be obtained at the large s and t points. The only beam counters used in this case would be differential Cerenkov counters set to veto K^+ in the beam; since the dominant pions and protons would not count in these counters, the counting rates would remain tolerable. The solid angle of the beam would be reduced so that beam hodoscopes would not be required to tag the incident angle.

We will require liquid hydrogen targets of two different lengths, 6" and 20". The shorter target will be used for the large angle running at low energy where the projected target length of the 20-inch target would become prohibitively large. These targets will need to be changed at most a few times during the experiment. Provision will be required for empty target running.

The single-arm focusing spectrometer facility itself has been described in detail in NAL Proposal 96. We would expect to run with configurations corresponding to a maximum momentum of 50 and 120 GeV/c. These two separate tunes will require movement of the first quadrupole dipole; if this movement proves to be reasonably easy, we would re-tune and optimize the spectrometer at each of the five momenta. Some of the spectrometer parameters are shown in Table II.

An estimate of Cerenkov-counter rejection needed can be obtained by comparing the cross section for elastic scattering with that for $K^+ \Sigma^+$ production:

$$\frac{\frac{d\sigma}{dt}\,(\pi^+ p \rightarrow \pi^+ p)}{\frac{d\sigma}{dt}\,(\pi^+ p \rightarrow K^+ \Sigma^+)} = \frac{30\, e^{9t}\ \mathrm{mb/GeV}^2}{\frac{2.5}{p}\, e^{9t}\ \mathrm{mb/GeV}^2} = 12p \qquad (8)$$

for p in GeV/c. At 120 GeV/c the ratio of cross sections is thus about 1500. Fortunately, the elastic scattering kinematics are somewhat different from those for $K^+\Sigma^+$, but still a pion rejection factor of about 10^4 is required for the spectrometer Cerenkov counters at 120 GeV/c. Such a factor should not be difficult to achieve with the counters already envisioned for the facility. The beam Cerenkov counters must reject K^+ mesons with a factor of about 10^3 if K^+ elastic scattering is to be adequately suppressed; again, such a rejection should not be difficult.

The Cerenkov counters which will already exist in the beam and spectrometer at the time of this experiment may not be suitable for work below 50 GeV/c. If this is the case, we will supply appropriate Cerenkov counters for the lower momenta. These counters will need to be shorter and work at a larger Cerenkov angle than those designed for higher momenta.

The trigger is straight forward and clean. One will require a good incident π^+ together with a K^+ signal from the spectrometer. Knowing the four momentum of both the π^+ and K^+, one can calculate the missing mass with the formula

$$M_x^2 = M_p^2 + 2M_p\,(E_\pi - E_K) + t \qquad (9)$$

where t is the usual four-momentum transfer squared. Reaction 4 then appears as a bump in the M_x^2 distribution at a value of 1.42 GeV^2. Reaction 5 contributes bumps at values of 1.9 and 2.8 GeV^2 for $Y^*(1385)$ and $Y^*(1670)$ production. Elastic-scattering leak-throughs due to Cerenkov counter inefficiency appear as a peak at 0.9 GeV^2. This latter peak is a useful calibration point and, in fact, short runs will be taken with the Cerenkov counter logic changed so as to measure the elastic scattering cross section for normalization purposes and to check the position and width of the peak in the missing mass distribution.

The identification of the reactions of interest depends critically on both good Cerenkov identification and momentum resolution. The single-arm focusing spectrometer facility is particularly well suited for both requirements. The uncertainity in missing mass squared is given approximately by

$$\sigma_{M_x^2} = 2M_p \left[\sigma_\pi^2 + \sigma_K^2 \right]^{1/2} \qquad (10)$$

where σ_π and σ_K are the uncertainties in π and K momentum, respectively. As shown in Table III the combined uncertainity of these momenta is expected to be ± 50 or 60 MeV/c (compared with the ± 60 MeV/c typical of the previous experiments). We thus expect an uncertainity of about ± 50 MeV for the Σ mass.

Although one would like to vary s and t over the widest range, practical considerations limit us to incident momenta between about 20 and 120 GeV/c and momentum transfers from t_{min} up to about 0.8 GeV^2. The upper limit of 120 GeV/c for the beam momentum is given by the falling pion yields, combined with the rapidly increasing yields of protons at high momenta; at 120 GeV/c the ratio of protons to π^+ is already estimated[3] to be 20:1.

The lower momentum limit is somewhat fuzzy and will be determined by how well the beam and spectrometer work at low momentum. At 20 GeV/c the spectrometer length of 130 meters is nearly one mean decay length for K^+ mesons. Also, it will be difficult to obtain large t values at low momentum because of the large laboratory angles involved.

The upper limit on momentum transfer will be given primarily by counting rates. In the counting rate calculations shown in Table III we have assumed a straight exponential fall off of e^{10t}; if the cross section continues to level off at large t, we may be able to go out somewhat further than the 0.8 GeV^2 estimated at this time.

At very small angles the unscattered beam particles leaking through the Cerenkov-counter criteria may give an uncomfortable trigger rate. These false triggers can be easily suppressed with a counter at the momentum focus to veto particles having the beam momentum (the particles of interest will have lower momenta, a difference of 300 MeV/c for Σ^+ production and 550 MeV/c for Y^*_{1385}).

We anticipate running 5 different beam momenta from about 20 to 120 GeV/c. At each momentum we would take a run with the spectrometer sitting at zero degrees and the beam turned down to about 2×10^6 particles per burst. The counting rates of these runs are shown in Table III. From 1 to 3 additional settings of the spectrometer will cover t values up to 0.8 GeV^2, depending on the beam momentum.

The range in M_x^2 which is covered by a $\pm$ 1% momentum bite of the spectrometer is approximately

$$\Delta M_x^2 = .04p \qquad (11)$$

for the momentum in GeV/c. At 20 GeV/c each reaction will require a separate momentum setting while at 50 GeV/c one momentum setting will cover the range 0.5 to 2.5 GeV^2, allowing data to be taken simultaneously in the elastic scattering, Σ^+ and $Y^*(1385)$ regions.

Based on the rates shown in Table III, about 400 hours for production running seems reasonable. This could be split up to give about 10^4 Σ^+ events at each momentum up to and including 80 GeV/c and about 3000 Σ^+ events at 120 GeV/c. Roughly comparable numbers of

Y^* events would also be obtained. If the e^{10t} dependence holds, the average cross section for the t bin from 0.6 to 0.7 GeV^2 will be down by a factor of about 600 from the 0^o cross section; ten to twenty events should be obtained in this region at each momentum up to 80 GeV/c.

An additional 100 hours will be required to check out the low-momentum Cerenkov counters and to perform various systematic checks such as elastic scattering and empty target runs. We thus ask for a total of 500 hours of running time.

APPARATUS

We assume that most of the experimental equipment will exist and will have been checked out prior to our using it. This includes the beam, hydrogen target, focusing spectrometer facility with wire proportional detectors, and on-line computer.

The principle additional equipment which we will likely need to supply for this experiment are Cerenkov counters for both the beam and spectrometer for the range 20 to 50 GeV/c. These counters would presumably become a part of the facility.

We would like to run as soon as possible after the initial spectrometer experiment (Proposal 96).

REFERENCES

1) Pruss, *et al.*, Phys. Rev. Letters **23**, 189 (1969); **24**, 1353 (1970); and Physics Letters 30B, 289 (1969).

2) J. Kirz, Third International Conference on High Energy Collisions (Stony Brook, 1969); and Stony Brook - Wisconsin preprints.

3) D. Carey, *et al.*, NAL Report TM-223 (March, 1970).

Table I. Fluxes Assumed for the 2.5 mrad Beam (based on Fig. III-5 of Carey, et al., Ref. 3). The second column shows the momentum bite required to obtain a total of 10^7 positively charged particles from 3 x 10^{12} interacting protons and the fourth column shows the corresponding number of pions.

Momentum (GeV/c)	$\frac{\Delta p}{p}$	proton/π^+/K^+	N_{π^+} x 10^6
20	0.50%	..2/1/.01	8.4
32	0.33%	.2/1/.03	7.9
50	0.20%	.4/1/.05	7.0
80	0.13%	1.6/1/.07	3.8
120	0.05%	20/1/.13	0.5

Table II. Spectrometer Parameters.

P_{max}	50	120 GeV/c
Acceptance		
$\Delta\Omega$	40	20 μster
$\Delta x'_o$	±1.6	± 1.2 mrad
$\Delta\Delta y'_o = \Delta\theta_{production}$	±6	± 4 mrad
Resolution		
σ_θ	±0.15	± 0.10 mrad
$\sigma_{p/p}$	±0.06%	± 0.04%

Table III. Resolution and Counting Rates for $\pi^+ p \rightarrow K^+ \Sigma^+$

Momentum	$\sigma_{p_\perp}$	$\sigma_{(p_\pi - p_K)}$	0° Setting: -t Range (GeV^2)	0° Setting: Σ^+ Rate	-t Range at large angles (GeV^2)	Σ^+ Rate for 0.6 to 0.7 GeV^2 bin
20 GeV/c	±5 MeV/c	±50 MeV/c	.004 to .018	600/hr.	.4 to .8	0.5/hr.
32	8	50	.002 to .04	1200	.3 to .8	0.6
50	12	60	.0014 to .09	1900	.09 to .8	0.6
80	18	60	.0009 to .10	900	.07 to .8	1.0
120	27	60	.0006 to .23	150	.04 to 1.3	0.14

Counting Rate Assumptions

2×10^6 particles/burst at 0°; 10^7 at large angles

800 bursts/hour

20-inch liquid hydrogen target (6 inches at large t, $p \leqslant 50$ GeV/c)

$\frac{d\sigma}{dt} = 2.5\, e^{10t}/p\ \text{mb}/\text{GeV}^2$ (for p in GeV/c)

$\Delta\Omega = 20\ \mu$ster (40 μster for $p \leqslant 50$ GeV/c)

Rates are corrected for decays in flight.

Supplement to Fermilab Proposal 99

A Study of $\pi^+ p \to K^+ \Sigma^+$ and $\pi^+ p \to K^+ Y^{*+}$ Using the Single Arm Spectrometer Facility

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Although several of the details have changed, the basic thrust of the original proposal, written nearly four years ago, is still valid today. There are very few experiments studying nondiffractive exclusive processes at NAL, and none of the other experiments can look at our reactions, $\pi^+ p \to K^+ \Sigma^+$, $\pi^+ p \to K^+ Y^{*+}$. The exchanges expected to dominate these reactions, $K^*(890)$ and $K^*(1420)$, should be related to the ρ and A_2 exchanges of the reactions $\pi^- p \to \pi^o n$ and $\pi^- p \to \eta n$ studied by E-111. Data from the different reactions taken together should provide a greater insight to the mechanisms of such processes than is possible from each reaction taken separately.

As listed below, some of the technical aspects of the experiment have improved while others are not as good as originally anticipated. By and large these have cancelled one another, except that the spectrometer solid angle is four times smaller than in the proposal. Typically a few thousand (instead of 10^4) Σ^+ events are expected at each of five incident momenta in the total of 500 hours requested. The counting rates at low t should be typically 100/hour, allowing us to follow the cross section over two and a half decades (out to $-t \approx 0.6$ GeV^2 for e^{10t}). At low t we are limited by how close we can get to the beam, $-t \geq .02$ to $.04$ GeV^2.

With its good resolution and massive Cerenkov power, the Single Arm Spectrometer Facility appears ideally (and uniquely) suited to the study proposed. Although no new equipment is required, prior commitments (not the least of which is the analysis of E-96) prevent us from running the experiment before Fall, 1975.

We now list some of the differences between the proposal and the real world of today:

1. No new Cerenkov counters are required; the existing ones should be able to go down to 20 GeV/c. We already have a complement of 7 counters, 3 in the beam and 4 in the spectrometer (a DISC counter, 2 differential counters, and 4 threshold counters).
2. We will not attempt to measure the Σ^+ polarization. At ZGS and AGS energies the polarization is very small for $-t \leqslant 0.3$ GeV^2; at larger t our counting rates will be too low.
3. We will use the existing 10-inch and 20-inch hydrogen targets.
4. The useful spectrometer solid angle will be 10 μster up to 75 GeV/c and 5 μster at higher momenta. The change in solid angle will be achieved by simply repowering the front quadrupoles - not a physical movement.
5. The useable beam for the big-t runs will probably be 4×10^6 (instead of the 10^7 in the original proposal). At small t, 2×10^6 is still valid.
6. The resolution on the difference between beam and spectrometer momenta is worse than anticipated: $\sigma_{\Delta p} \approx \pm 70$ MeV/c at low momenta where multiple scattering dominates, $\sigma_{\Delta p}/p \approx 0.1\%$ at higher momenta. The error on the Σ^+ mass thus ranges from ± 55 MeV at low momenta to ± 120 MeV at 150 GeV/c incident; this can be compared with the 194 MeV separation of Σ^+ and Y^{*+} (1385). We hope that the high-momentum resolution will improve; we believe that some of it is due to short-term drifts or hunting of magnet power supplies.

7. With 300-GeV/c protons incident on the Meson Laboratory (instead of 200 GeV/c) we are no longer limited by the π^+/proton ratio in the secondary beam to ≤ 120 GeV/c. The present useful limit is due to resolution, 140 to 175 GeV/c; the rates at these high energies would be substantially improved if 400 GeV/c protons should become available.

8. The K^-/π^- ratio is typically 4% (instead of 1%) and we will try looking for the reaction $K^- p \to \pi^- \Sigma^+$ at one momentum in the low t region. Although this reaction is 40% larger at 10 GeV/c than its line reversed partner, our $\pi^+ p \to K^+ \Sigma^+$ reaction, one might expect equality at higher energy.

9. The useful momentum bite of the spectrometer is ±2% (instead of ± 1%). This means that, except for the 20-GeV/c runs, we will be able to cover the entire mass region of interest with one momentum setting of the spectrometer.

10. We will simultaneously take some elastic scattering events and normalize the $K^+\Sigma^+$, etc., cross sections to the known (by that time) elastic scattering cross sections. This will simplify the analysis and allow us to use large fiducial cuts to maximize the useful number of events.