Coherent K_S Regeneration on Protons from 30 to 130 GeV/c

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Precise measurements at $t=0$ of the $K_L p \to K_S p$ amplitude (modulus and phase) were made. Over 50 000 $K_{\pi 2}$ decays along with normalizing $K_{\mu 3}$ events were detected behind a 7.2-m-long liquid-hydrogen regenerator. The momentum dependence of the modulus and phase are presented, and the results are combined with those of other experiments to extract the relevant parameters of ω exchange.

It is by now well known that particle-antiparticle amplitude differences, to which only $C=-1$ exchanges contribute, are particularly useful for determining the Regge structure of high-energy processes. The study of K_S regeneration is especially rewarding as it permits the direct determination of *both* the magnitude and the phase of a K^0, $\bar{K}^0$ amplitude difference. In an earlier paper,[1] we presented the application of these concepts to regeneration by carbon. We report here precise measurements of the reaction

$$K_L + p \to K_S + p \tag{1}$$

at $t=0$, i.e., of coherent K_S regeneration by hydrogen,[2] at the highest available K_L energies. Reaction (1) involves essentially only ρ and ω exchange; Gilman[3] first pointed out its importance for the study of the ω trajectory, by which it is expected to be dominated.

We first summarize a few basic notions on regeneration. The rate of (charged) $K_{\pi 2}$ decays at a proper time τ after leaving the exit face of a regenerator is given by

$$dI_{+-}/d\tau = N_L(1/\tau_S)B_{+-}^{\ s}|\rho\exp[-\tau/2\tau_S]+\eta_{+-}\exp[(i\Delta m-1/2\tau_L)\tau]|^2. \tag{2}$$

Here N_L is the transmitted K_L flux, $B_{+-}^{\ s}$ is the $K_S \to \pi^+\pi^-$ branching ratio, $\tau_{L(S)}$ are the K_L (K_S) mean lives, and $\Delta m=(M_L-M_S)c/\hbar$ the corresponding mass difference. The η_{+-} term is the (CP-nonconserving) K_L amplitude, while ρ is the regenerated K_S amplitude, viz.

$$\rho = \{i\pi NL[f(0)-\bar{f}(0)]/k\}\varphi(l)/l, \tag{3}$$

where N is the number density of regenerator nuclei, $f(0)$ and $\bar{f}(0)$ are K^0 and $\bar{K}^0$ forward scattering amplitudes, $\hbar k = p$, the kaon momentum, and $\varphi(l)$ is a known function[4] of $l=L/\Lambda_s(p)$, where L is the regenerator length and $\Lambda_s(p)$ is the K_S decay length.

The experimental method is to detect $K_{\pi 2}$'s behind the regenerator and to fit their τ distribution (for each p bin) to Eq. (2). While the *shape* of $dI_{+-}/d\tau$ alone determines ρ/η_{+-}, the statistical power is greatly increased by knowing N_L. This is achieved by simultaneously detecting $K_{\mu 3}$ decays, with a rate given by

$$dI_{\mu 3}/d\tau = (1/\tau_L)N_L B_{\mu 3}\exp[-\tau/\tau_L], \tag{4}$$

where $B_{\mu 3}$ is the $K_{\mu 3}$ branching ratio.[5]

The apparatus has been described previously.[1,6] It is a neutral-V spectrometer with provision for tagging $K_{\mu 3}$ and K_{e3} decays, operated in the $M4$ neutral beam line at Fermilab.[6] The present experiment required a long liquid-hydrogen target of 5.5×5.5 cm^2 cross section and 727 cm in length. Because of the large percentage of neutrons in the beam ($n:K_L = 5:1$) and the relative rarity of regeneration events [$\sigma(K_L p \to K_S p)/\sigma_T(K_L p) \simeq 4\times10^{-5}$ at 100 GeV/c] it was necessary to veto unwanted events efficiently. To accomplish this without additional material in the beam, the flask was provided with highly reflecting inner walls and a transparent end window. The Cherenkov light produced in the liquid by charged secondaries was viewed with a single phototube and used as a veto.

The target was mounted in two alternate locations to accommodate evacuated decay regions of different lengths (27 and 43 m), ensuring good $K_{\pi2}$ acceptances over the entire usable spectrum, i.e., from 30 to 130 GeV/c.[1,6] Approximately equal time was spent running with each configuration. A total of 7.5×10^6 triggers were recorded, and the events were reconstructed on line[7] between beam bursts. Coherent $K_{\pi2}$'s and $K_{\mu3}$'s were selected by off-line analysis. The selection criteria for $K_{\pi2}$'s were (a) absence of a lepton tag; (b) effective di-pion mass $m_{\pi\pi} = (m_{K^0} \pm 12)$ MeV/c^2; (c) the square of the transverse momentum, p_T^2, of the di-pion system with respect to the K_L direction less than 200 (MeV/c)^2. The sizes of these cuts were dictated by the experimental resolution as illustrated in Fig. 1. The selection criteria for $K_{\mu3}$'s were one muon in the final state and an unambiguous solution[1] for the kaon momentum.

The $K_{\pi2}$'s so selected still contained background, primarily unsuppressed K_{l3}'s, and unvetoed K_S's inelastically produced near $p_T^2 = 0$. The background magnitude depends on p_T^2 and τ, and averages 4.5%. It was removed by subtractions based on ($m_{\pi\pi}, p_T^2$) distributions of identified $K_{\mu3}$ and K_{e3} events, and on an exponential extrapolation of p_T^2 of the inelastic events. As a check on the subtraction procedure, a second analysis was performed with very tight $m_{\pi\pi}$ and p_T^2 cuts to yield a pure but reduced sample of $K_{\pi2}$ decays. This sample required no background subtraction and gave results in excellent agreement with the sample discussed above.

The final sample of 50 000 $K_{\pi2}$'s was corrected for acceptance (as determined by a Monte Carlo calculation) and fitted with $dI_{+-}/d\tau$ for the magnitude and the phase of ρ, i.e., of $[f(0) - \bar{f}(0)]/k$; in these fits, the values of Trippe *et al.*[5] for $\tau_{S(L)}$, Δm, argη_{+-}, $B_{+-}{}^s$, and $B_{\mu3}$ were adopted. We found, however, that the "recommended"[5] value of $|\eta_{+-}|$, $2.27(2)\times10^{-3}$, yields poorer fits than $|\eta_{+-}| = 2.15(3)\times10^{-3}$.[8] This fact is illustrated in Fig. 2, which shows, for several p bins, the

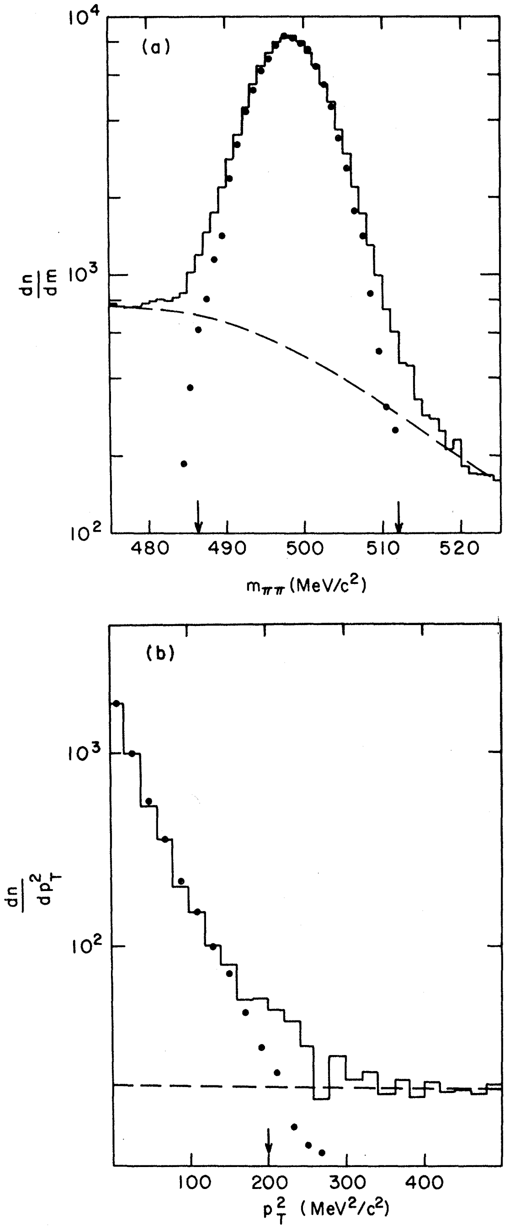

FIG. 1. (a) Mass histogram for $K_{\pi2}$ candidates. (b) Transverse-momentum distribution for $K_{\pi2}$ candidates with $p = 65 \pm 5$ GeV/c. Dots represent Monte Carlo predictions. Subtracted backgrounds drawn as dashed curves. Final cuts as indicated by arrows.

data points and their fitted curves for both values of $|\eta_{+-}|$. Lower values of $|\eta_{+-}|$ appear also to be preferred by other recent data,[9] and were furthermore obtained by us from data independent of those reported here.

The results of the fits are listed in Table I. They are also displayed in Fig. 3, together with previous results.[9-11] The data are consistent

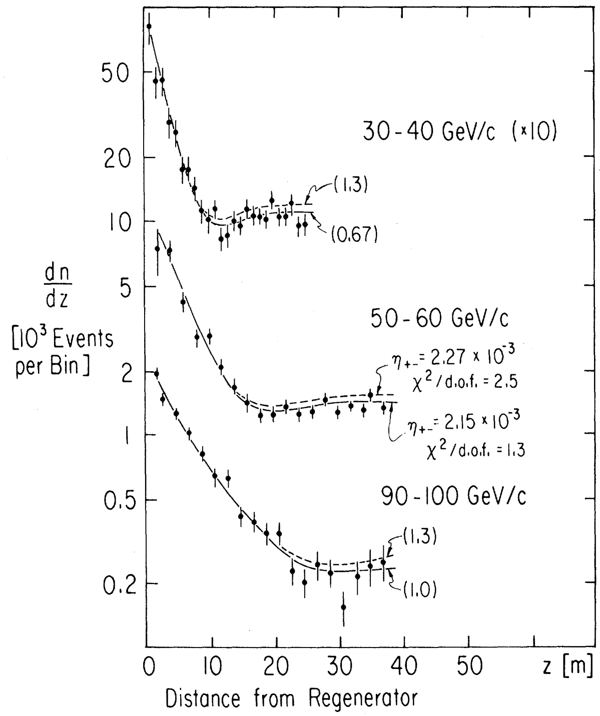

FIG. 2. Vertex distributions of acceptance-corrected $K_{\pi 2}$'s for three p bins. Curves indicate best fits for the indicated two values of $|\eta_{+-}|$. Numbers in parentheses are χ^2 per degree of freedom.

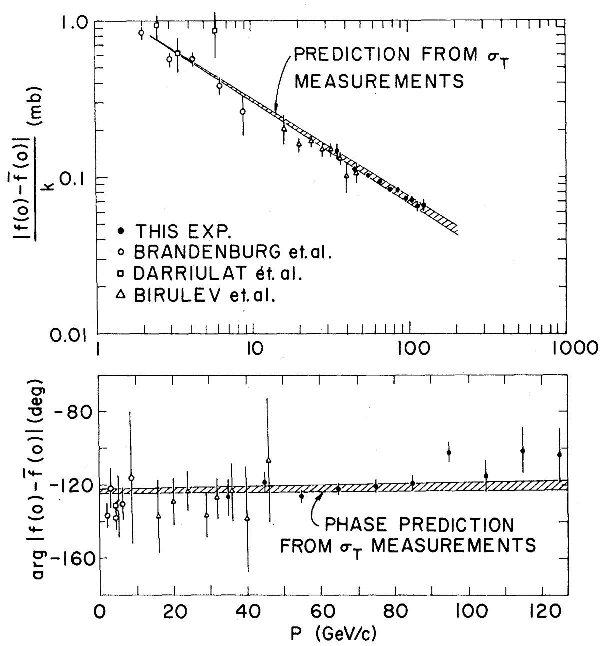

FIG. 3. Momentum dependence of the modulus and argument of $(f-\bar{f})/k$. Shaded bands represent predictions based on ρ- and ω-trajectory parameters derived from σ_T data and given in the text.

with a simple p^{-n} dependence of the modulus, and a constant phase.

We now discuss our results in terms of Regge trajectories.[3,12] In the notation of Ref. 12,

$$[f(0)-\bar{f}(0)]/k \equiv (f-\bar{f})_0/k = 2\hbar\{\beta_{Kp}{}^{\rho}[\tan\tfrac{1}{2}\pi\alpha_{\rho}(0)+i]p^{\alpha_{\rho}(0)-1} - \beta_{Kp}{}^{\omega}[\tan\tfrac{1}{2}\pi\alpha_{\omega}(0)+i]p^{\alpha_{\omega}(0)-1}\}, \quad (5)$$

TABLE I. Determinations of the modulus and phase of $[f(0)-\bar{f}(0)]/k$ in 10-GeV/c p bins. Errors in the least significant digit are shown in parentheses. The results are given for the two values of $|\eta_{+-}|$ discussed in the text.

Momentum (GeV/c)	$\eta_{+-}=2.15\times10^{-3}$ $\|f-\bar{f}\|/k$ (mb)	arg$(f-\bar{f})$ (deg)	$\eta_{+-}=2.27\times10^{-3}$ $\|f-\bar{f}\|/k$ (mb)	arg$(f-\bar{f})$ (deg)
35 ±5	0.145(15)	−127(10)	0.155(16)	−119(9)
45 ±5	0.111(5)	−119(6)	0.115(6)	−111(5)
55 ±5	0.103(3)	−126(4)	0.104(3)	−120(4)
65 ±5	0.094(2)	−123(3)	0.093(2)	−116(3)
75 ±5	0.082(2)	−121(4)	0.080(2)	−112(4)
85 ±5	0.081(3)	−120(5)	0.079(2)	−112(5)
95 ±5	0.072(3)	−102(6)	0.071(3)	−95(6)
105 ±5	0.071(4)	−116(9)	0.068(4)	−106(9)
115 ±5	0.065(5)	−102(13)	0.063(5)	−91(12)
125 ±5	0.066(6)	−104(15)	0.064(6)	−96(14)

where the β's are residues and the $\alpha(0)$'s trajectory intercepts at $t=0$. Before fitting the data, we compare with the predictions based on the values $\beta_{Kp}{}^{\rho}=1.31(2)$ mb, $\alpha_{\rho}(0)=0.575(7)$, $\beta_{Kp}{}^{\omega}=7.91(7)$ mb, and $\alpha_{\omega}(0)=0.433(7)$ derived from fits to to total cross sections[7,12] assuming ρ universality [or SU(3)].[13] Figure 3 shows these predictions, with their uncertainties. The agreement is excellent.

Since the ω contribution dominates (5) we fit the hydrogen regeneration data for its parameters, fixing $\beta_{Kp}{}^{\rho}$ and $\alpha_{\rho}(0)$. Two such fits are presented in Table II. Fit A, using ρ parameters from the total cross-section fit above yields ω parameters in very good agreement with the total-cross-section fit. The ω intercept disagrees with the result[1] $\alpha_{\omega}(0)=0.39(1)$, derived from regeneration by carbon, as was recently emphasized by Diu and Ferraz de Camargo.[14] Fit B uses ρ pa-

TABLE II. Result of fitting the hydrogen data of Refs. 9, 10, and 11, and the present experiment to Eq. (5) for the ω parameters. The input ρ parameters are discussed in the text. (d.o.f. = degrees of freedom.)

Input ρ parameters	Resulting ω parameters	χ^2 (49 d.o.f.)
$(A)^a$ $\beta_{Kp}{}^{\rho}=1.31(2)$ mb, $\alpha_\rho(0)=0.575(7)$	$\beta_{Kp}{}^{\omega}=7.34(30)$ mb $\alpha_\omega(0)=0.44(1)$	50.3
$(B)^b$ $\beta_{Kp}{}^{\rho}=1.74(3)$ mb, $\alpha_\rho(0)=0.481(4)$	$\beta_{Kp}{}^{\omega}=8.17(34)$ mb $\alpha_\omega(0)=0.41(1)$	52.0

[a]Refs. 12 and 13. [b]Refs. 15 and 16.

rameters derived from (π^-, π^0) charge-exchange data[15] and yields an ω intercept somewhat closer to the carbon result.[16] It is interesting to point out that regeneration by nuclei from Al to Pb *cannot* be fitted with $\alpha_\omega(0)=0.44$, while taking $\alpha_\omega=0.39$ as an "effective" value gives good agreement.[17]

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