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COHERENT REGENERATION OF K_S's BY CARBON AS A TEST OF REGGE POLE EXCHANGE THEORY*

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A measurement of the coherent regeneration amplitude in carbon in the energy range 30-130 GeV is presented. The results are consistent with the dominance of this process by ω-exchange, and a precise value of the intercept of the ω-trajectory is obtained: $\alpha_\omega(0) = 0.390 \pm 0.014$.

Cabibbo[1] suggested many years ago that coherent (t=0) regeneration of K_S's by I=0 nuclei could be interpreted in terms of the exchange of a single Regge trajectory, the ω; he predicted the phase of the regeneration amplitude from the then approximately known intercept $\alpha_\omega(0)$ of that trajectory. The present work is a precise determination of the coherent regeneration amplitude in carbon at kaon energies (30 - 130 GeV) where the Regge formalism should work well. We find that the description of this process in terms of single trajectory exchange works remarkably well, and, assuming that description to be correct, obtain a precise value for $\alpha_\omega(0)$. Both phase and magnitude of the amplitude are measured, providing a check of the Regge formalism not possible in other types of experiments.

When a K_L beam interacts with a target (length L, N scatterers per unit volume) the K_S amplitude regenerated in the forward direction is given by $|K_S\rangle = \rho|K_L\rangle$, where

$$\rho = i\pi \, NL(f(0) - \bar{f}(0))/k. \qquad (1)$$

Here f(0), $\bar{f}(0)$ are the K°, $\bar{K}^\circ$ forward scattering amplitudes, and k is the kaon wave number.[2] On general grounds, one expects $(f - \bar{f})/k$ to vanish at infinite energy,[3] while Regge theory makes specific predictions for its approach to zero. First, the ω trajectory (C=-1, I=0) should be the dominant contribution to $f - \bar{f}$.[4] The analytic form[5] of the ω Regge amplitude implies for $f(0) - \bar{f}(0)$ two facts:

i) Power law momentum dependence of the modulus--

$$|f(0) - \bar{f}(0)|/k = C(0)P_K^{\alpha_\omega(0)-1} \sim P_K^{-n} \qquad (2a)$$

ii) Constant phase, determined by the exponent n--

$$\arg (f(0) - \bar{f}(0)) = \frac{-\pi}{2}(\alpha_\omega(0) + 1) = \frac{-\pi}{2}(2-n) \qquad (2b)$$

Thus the simultaneous determination of $|f - \bar{f}|/k$ and $\arg (f - \bar{f})$ constitutes a unique check of the predicted momentum dependence-phase relationship of Regge amplitudes.

In the present work, regeneration is detected via $K^\circ \rightarrow \pi^+\pi^-$ ($K_{\pi 2}$) decays following a carbon target in a K_L beam. Because K_S and K_L both decay into $\pi^+\pi^-$, these decay amplitudes interfere, giving an intensity vs. proper time τ downstream of the target

$$I_{+-}(\tau) \propto N_L(|\rho|^2 e^{-\Gamma_s\tau} + 2|\rho||\eta_{+-}| e^{-\Gamma_s\tau/2} \cos(\Delta m\tau + \phi) + |\eta_{+-}|^2) \qquad (3)$$

where N_L is the incident K_L flux, Γ_s is the K_s decay rate, η_{+-} is the CP-violation parameter, $\Delta m = (m_L - m_S)\, c^2/\hbar$, $\phi = \arg (\rho/\eta_{+-})$ and the dependence of Eq. 3 on $\Gamma_L (<< \Gamma_S)$ has been neglected.

By measuring I_{+-} over a sufficiently long decay region,[6],[7] one can determine $|\rho|$ and $\arg \rho$ given $|\eta_{+-}|$ and $\arg \eta_{+-}$. We have also monitored the flux N_L via $K_L \rightarrow \pi\mu\nu$ ($K_{\mu 3}$) decays recorded simultaneously. This information further constrains the fits for the regeneration parameters.

The experiment was performed at FERMILAB in the M4 neutral beam, using the wire spark chamber spectrometer shown in Fig. 1.

This spectrometer is essentially a longitudinally stretched version of the one used by some of us earlier at Argonne National Laboratory,[8],[9],[10] and will be described in detail in a separate publication.

The 7.25 mrad neutral beam consists of K_L's and neutrons, roughly in the ratio 1:5, with a typical intensity of $\simeq 10^5 K_L$'s per 10^{12} protons on target. The detected K_L spectrum peaked at $\simeq$ 70 GeV/c.

To make efficient use of the broad range of available K_L-momenta, we collected data with two different length decay regions, 26 and 48 meters. The reconstructed neutral V events ($\simeq$ 80% of all triggers) were cut to isolate $K_{\pi 2}$ and $K_{\mu 3}$ decays occurring in the evacuated decay pipe. Figure 2(a) shows the effective π-π mass of the $K_{\pi 2}$ sample. Additional cuts and subtractions, used to obtain the proper time distribution of the $K_{\pi 2}$ sample and the total number of $K_{\mu 3}$ events as functions of kaon momentum, are described below.

<u>$K_{\pi 2}$</u>: The small background - seen in Fig. 2(a) - is assumed to consist mainly of unsuppressed $K_{\ell 3}$ decays. This background was estimated by fitting it to a linear combination of <u>observed</u> and <u>identified</u> $K_{\mu 3}$ and K_{e3} events (<u>not</u> Monte Carlo). The goodness of these fits supports our assumption that the background is mainly $K_{\ell 3}$ decays.[11]

$\underline{K_{\mu 3}}$: In general, two momentum solutions, P_+ and P_-, are obtained for $K_{\mu 3}$ events: $P_{\pm} = P_o(1 \pm \sqrt{\delta P^2})$, where P_o and δP^2 are functions of kinematical quantities. To obtain a sample of $K_{\mu 3}$ events of "unambiguous" momentum, we selected events (20% of the total sample) for which P_+ and P_- differ by less than 20%, and used their average as the momentum P_K. Fig. 2b shows the δP^2-distribution of all $K_{\mu 3}$'s.

The final data sample contained 57,000 $K_{\pi 2}$ events and 41,000 unambiguous $K_{\mu 3}$ events.

The acceptances, $\varepsilon(P_K, \tau)$, for $K_{\pi 2}$ and $K_{\mu 3}$ decays were calculated by Monte Carlo, taking into account multiple scattering and measurement error, π-μ decays in flight, K_L diffraction scattering in the regenerator, and pattern recognition inefficiency in the analysis program. This last effect was handled by filtering all Monte Carlo events with the analysis program used on the real data. As can be seen in Fig. 2, the simulated resolution agrees quite well with the data.

Fits of the distribution $I_{+-}(\tau)\varepsilon(P_K, \tau)$ to the data in momentum bin P_K were done both with and without the constraint imposed by the $K_{\mu 3}$ events. The two sets of results were consistent, providing a check on our understanding of $K_{\mu 3}$ and $K_{\pi 2}$ acceptances. The final results were obtained with $K_{\mu 3}$-constrained fits and are presented in Table I.

Fig. 3 shows $|f - \bar{f}|/k$ vs. P_K, extracted from measurements of $|\rho|$ in carbon.[12]-[15] Both our data alone and all data taken together are well fit by a power law P_K^{-n}, yielding the results in Table 2. Fig. 3 also shows arg $(f - \bar{f})$ vs. P_K.

The results are clearly consistent with the predicted constant phase, <u>strongly</u> supporting the hypothesis of ω-exchange dominance. The values of $\alpha_\omega(0)$ derived from the average phase are also shown in Table 2. Using our data alone to fit for the parameter $\alpha_\omega(0)$ [16] gives

$$\alpha_\omega(0) = 0.390 \pm 0.014. \quad (4)$$

This result may be compared with other measurements of the intercept of the ω-trajectory:

i) An extrapolation to $M^2 = 0$ of the line connecting the ω-meson and its 3^- recurrence[17] gives $\alpha_\omega(0) = 0.43 \pm 0.02$.

ii) The momentum dependence of $K^\pm D$ total cross-section difference (also dominated by ω-exchange) gives[18] $\alpha_\omega(0) = 0.41 \pm 0.03$.

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Data taking for this experiment was concluded in July, 1975 after several minor improvements to the spectrometer described in our preceeding proposals had been incorporated. Preliminary analysis yielded the following very interesting results.

(i) the regeneration amplitude ρ, proportional to $(f - \bar{f})/k$ falls from 4 GeV to 110 GeV with a power law k^{-n}, with $n = 0.594 \pm 0.009$;

(ii) the phase of $(f - \bar{f})/k$ is constant in the same range, with a value $\phi_{21} = -128.1^{\circ} \pm 3.1^{\circ}$;

(iii) the absolute magnitude of $(f - \bar{f})/k$ is in good agreement with optical model calculations.

The prime interest of these results lies in the fact that while K_S regeneration is generally mediated by the exchange of ρ and ω trajectories, only the ω contributes for an $I = 0$ target such as carbon. Thus we have a clean measurement of the ω trajectory, yielding $\alpha(o) = 0.406 \pm 0.009$. Note that the phase predicted from the power behavior is $- 126.5^{\circ}$. Since our work has begun, a 3^{-} recurrence of the ω has been reported at 1675 MeV ; a straight line extrapolation on the Chew-Frautschi plot yields $\alpha(o) = 0.43$, in good agreement with our current (preliminary) result. Thus a "nuclear physics" experiment has yielded valuable information on elementary particle properties.

We have collected a total of $\simeq$ 60K events coherently regenerated by carbon, and plan to reprocess these with an off-line version of our on-line program in the very near future. The final accuracy in $(f - \bar{f})/k$ will be $\lesssim$ 3% in each of 7 momentum bins between 40 and 100 GeV, while the phase will be determined in the same range with an uncertainty of $\lesssim$ 2 degrees.

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Table 1. $|f - \bar{f}|/k$ and $\arg(f - \bar{f})$ in 10 GeV/c momentum bins. For the values of Δm, Γ_s, η_{+-} and $K_{\mu 3}$ branching ratio used, see Ref. 17.

Momentum (GeV/c)	$\|f-\bar{f}\|/k$, (mb)	$\arg(f-\bar{f})$, (deg)
35 ± 5	1.589 ± .092	-130.2 ± 10.2
45 ± 5	1.411 ± .020	-123.6 ± 4.2
55 ± 5	1.195 ± .013	-125.4 ± 3.4
65 ± 5	1.131 ± .012	-130.3 ± 3.6
75 ± 5	1.025 ± .013	-125.1 ± 3.7
85 ± 5	0.998 ± .041	-124.0 ± 5.6
95 ± 5	0.880 ± .018	-123.5 ± 5.7
105 ± 5	0.853 ± .023	-112.1 ± 6.8
115 ± 5	0.726 ± .029	-117.3 ± 11.7
125 ± 5	0.731 ± .041	-126.4 ± 21.2

Table II. Determinations of $\alpha_\omega(0)$ from carbon regeneration data.

Quantity	This experiment (30-130 GeV/c)	All data (4-130 GeV/c)
$\alpha_\omega(0)$ from n and Eq. (2a)	0.393 ± 0.020	0.379 ± 0.003
$\alpha_\omega(0)$ from measured phase and Eq. (2b)	0.389 ± 0.018	0.410 ± 0.015

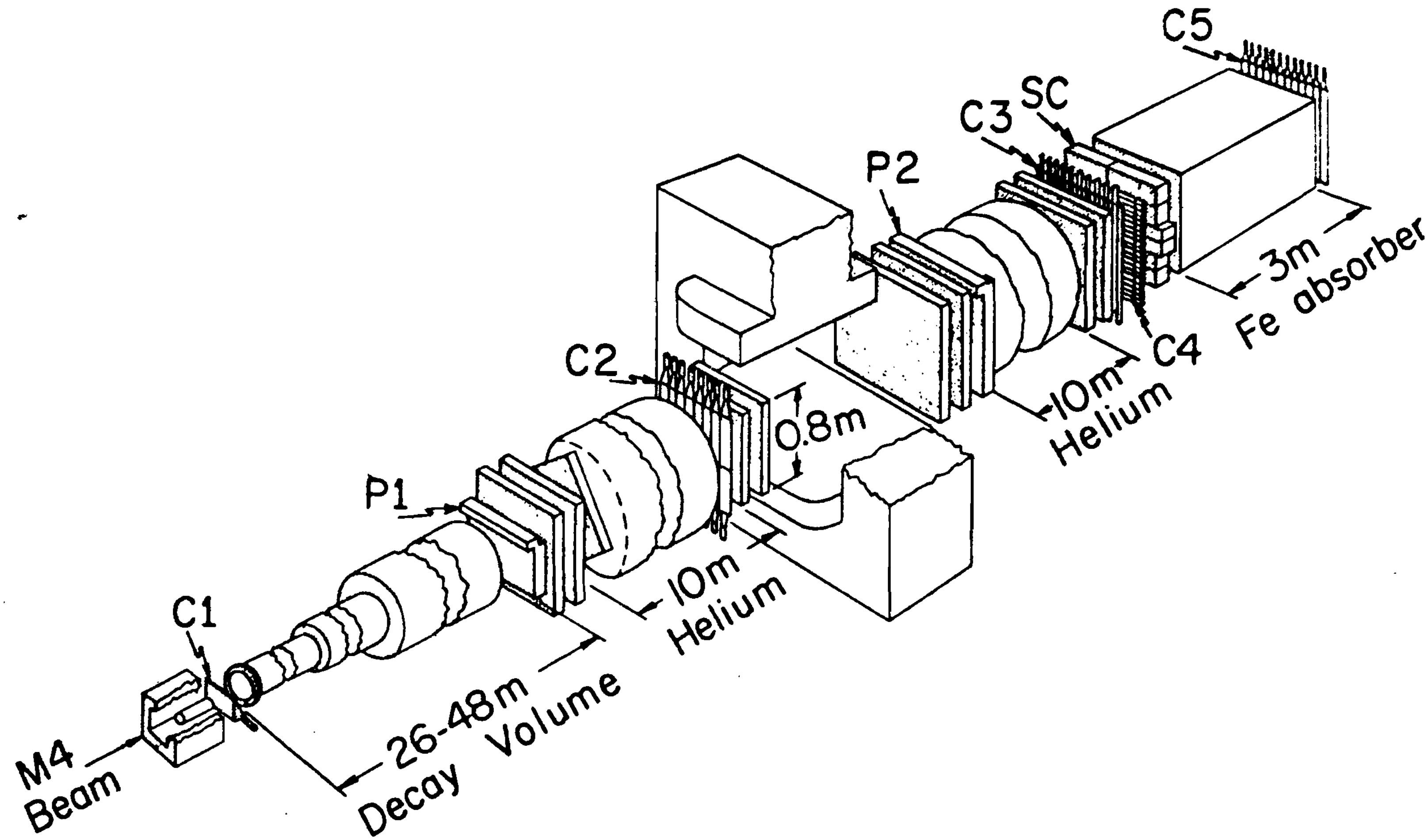
Figure Captions

Fig. 1 The spectrometer. The regenerator, sweeping magnet, and veto counter C1 are at the lower left. P1, P2 are multiwire proportional chambers; C2-C5 are counter hodoscopes; SC is a shower counter. The wire spark chambers are downstream of P1 and C2 and upstream of P2 and C3. The decay volume is evacuated.

Fig. 2(a) The π-π invariant mass distribution for $K_{\pi 2}$ triggers. The histogram represents the 48m data and the dots are the Monte Carlo results. The background is discussed in the text.

(b) The δP^2 distribution of the 26m $K_{\mu 3}$ data. The vertical lines indicate the region of unambiguous momentum events used in the analysis.

Fig. 3 $|f - \bar{f}|/k$ and $\arg(f - \bar{f})$ vs. P_K for all carbon data. The $\arg(f - \bar{f})$ data of Ref. [14] is plotted for clarity as a single point, given in Ref. [14]. The solid line is the best fit to P_K^{-n}. The dashed line is the phase predicted by the measured exponent n.


C5
SC
C3
P2
C4
3m
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Helium
C2
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P1
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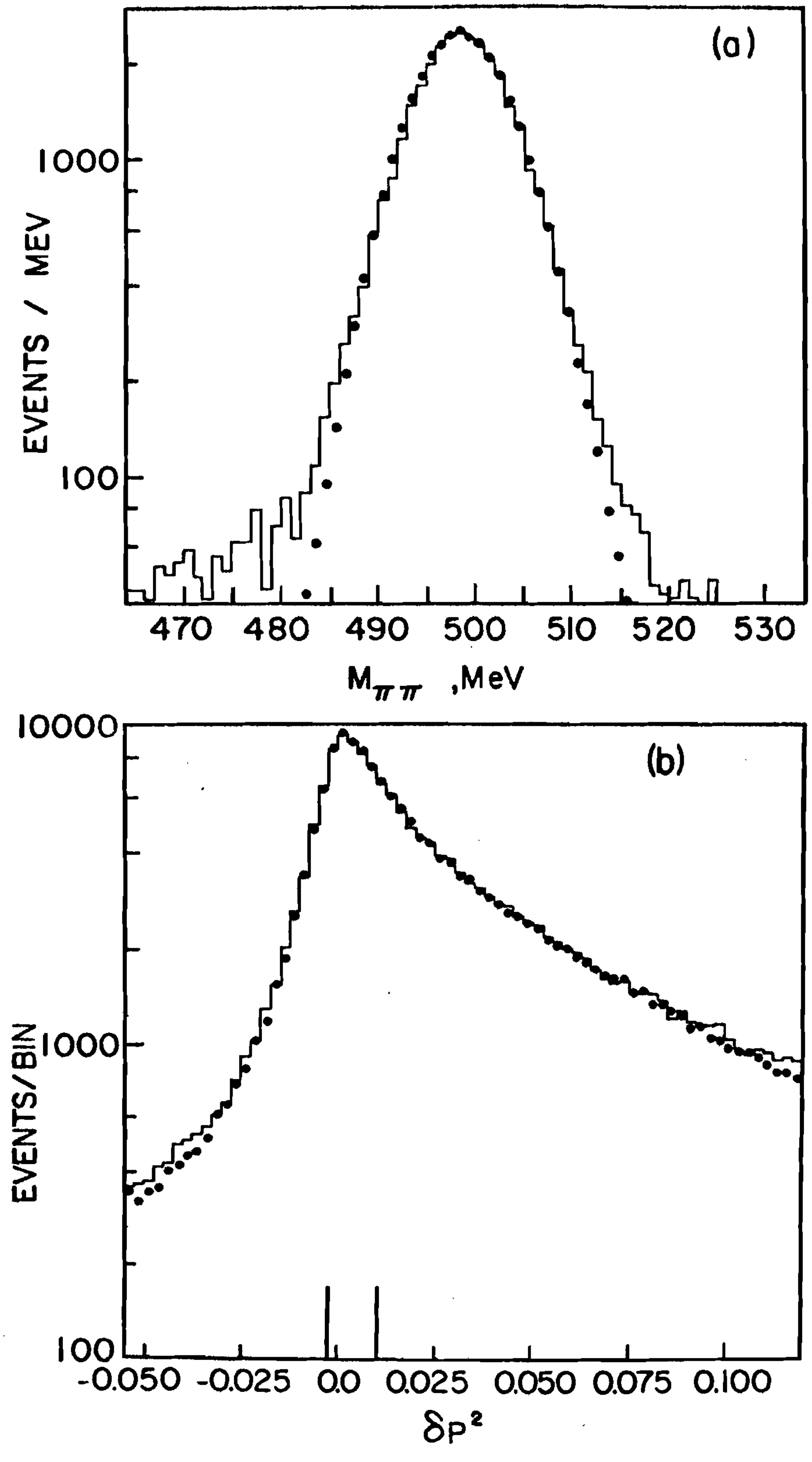
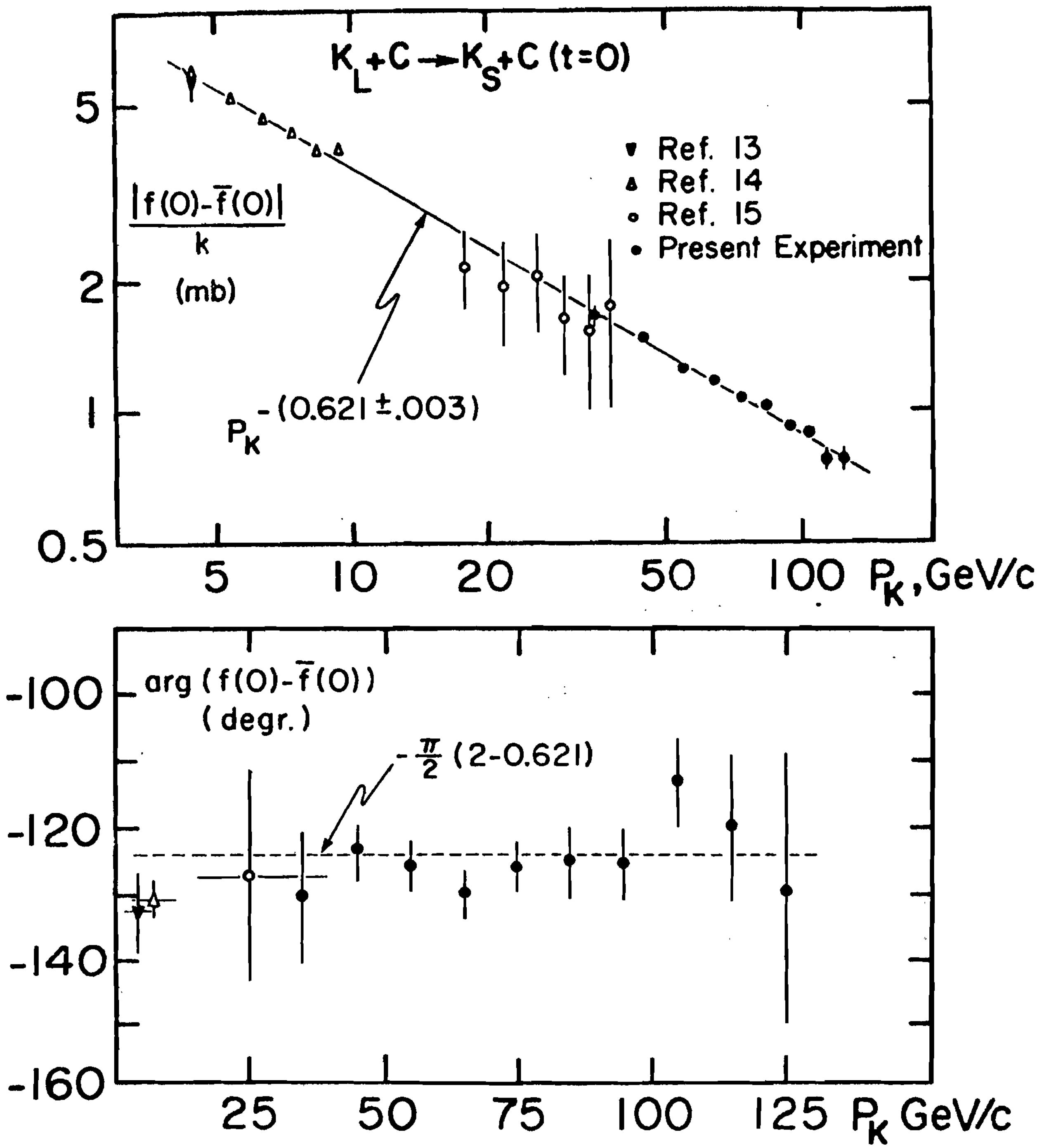
Helium
C1
26-48m
Decay Volume
M4
Beam


(a)
EVENTS / MEV
1000
100
470 480 490 500 510 520 530
$M_{\pi\pi}$,MeV
(b)
EVENTS/BIN
10000
1000
100
-0.050 -0.025 0.0 0.025 0.050 0.075 0.100
δP^2


K_L+C → K_S+C (t=0)
Ref. 13
Ref. 14
Ref. 15
Present Experiment
|f(0)-f̄(0)| / k (mb)
P_K^-(0.621±.003)
5
2
1
0.5
5 10 20 50 100 P_K, GeV/c
arg (f(0)-f̄(0)) (degr.)
-π/2 (2-0.621)
-100
-120
-140
-160
25 50 75 100 125 P_K GeV/c