38B, 519 (1972).
[4]G. Feinberg, Phys. Rev. 110, 1482 (1958).
[5]B. Pontecorvo, Zh. Eksp. Teor. Fiz. 6, 429 (1958) [Sov. Phys. JETP 33, 549 (1957)], and 7, 172 (1958) [34, 247 (1958)]; V. Gribov and B. Pontecorvo, Phys. Lett. 28B, 493 (1969).
[6]T. G. Trippe *et al.*, Rev. Mod. Phys. 48, No. 2, Pt. 2, S51 (1976).
[7]This is consistent with known upper limits {S. M. Korenchenko *et al.*, Zh. Eksp. Teor. Fiz. 70, 3 (1976) [Sov. Phys. JETP 43, 1 (1976)]} and the preliminary findings of the Zurich group. [Private communications from H. Fritzsch and Y. Ne'eman.]
[8]S. M. Bilenky, S. T. Petcov, and B. Pontecorvo, to be published; T. P. Cheng and L.-F. Li, Phys. Rev. Lett. 38, 381 (1977); F. Wilczek and A. Zee, Phys. Rev. Lett. 38, 531 (1977); W. Marciano and A. Sanda, Rockefeller University Report No. C00-2232B-116 (to be published).
[9]Cf. J. D. Bjorken and S. Weinberg, Phys. Rev. Lett. 38, 622 (1977).
[10]If we naively estimate the K_L-K_S mass difference by simply multiplying the coupling constants in Eq. (15) by the cube of the pion mass, we find $\epsilon\theta_2^2 \sim 10^{-6}$ to be contrasted with upper bound of 3×10^{-4} furnished by the present limit on $K \to \pi\nu\bar{\nu}$.

Coherent Regeneration of K_S's by Carbon as a Test of Regge-Pole-Exchange Theory*

J. Roehrig, A. Gsponer,† W. R. Molzon, E. I. Rosenberg, V. L. Telegdi,‡ and B. D. Winstein
Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

and

H. G. E. Kobrak, R. E. Pitt, and R. A. Swanson
Physics Department, University of California–San Diego, La Jolla, California 92093

and

S. H. Aronson and G. J. Bock
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
(Received 3 February 1977)

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

$$\rho = i\pi NL[f(0) - \bar{f}(0)]/k. \tag{1}$$

Here $f(0)$ and $\bar{f}(0)$ are the K^0, $\bar{K}^0$ 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,

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

(ii) *constant* phase, determined by the exponent n,

$$\arg[f(0) - \bar{f}(0)] = -\tfrac{1}{2}\pi[\alpha_\omega(0) + 1] = -\tfrac{1}{2}\pi(2-n). \tag{2b}$$

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

In the present work, regeneration is detected via $K^0 \to \pi^+\pi^-$ ($K_{\pi 2}$) 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 versus proper time τ downstream of the target,

$$I_{+-}(\tau)\propto N_L[\,|\rho|^2\exp(-\Gamma_S\tau)+2|\rho||\eta_{+-}|\exp(-\Gamma_S\tau/2)\cos(\Delta m\tau+\varphi)+|\eta_{+-}|^2], \tag{3}$$

where N_L is the incident K_L flux, Γ_S is the K_S decay rate, η_{+-} is the CP-nonconservation parameter, $\Delta m=(m_L-m_S)c^2/\hbar$, $\varphi=\arg(\rho/\eta_{+-})$, and the dependence of Eq. (3) on $\Gamma_L(\ll\Gamma_s)$ 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 $K_L\to\pi\mu\nu$ ($K_{\mu 3}$) 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,[9-11] 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 decay-length regions, 26 and 48 m. 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.

$K_{\pi 2}$.—The small background, seen in Fig. 2(a), is assumed to consist mainly of unsuppressed K_{l3} decays. This background was estimated by fitting it to a linear combination of *observed* and *identified* $K_{\mu 3}$ and K_{e3} events (*not* Monte Carlo). The goodness of these fits supports our assumption that the background is mainly K_{l3} decays.[12]

$K_{\mu 3}$.—In general, two momentum solutions, P_+ and P_-, are obtained for $K_{\mu 3}$ events: $P_\pm=P_0(1\pm\sqrt{\delta P^2})$, where P_0 and δP^2 are functions of kinematical quantities. To obtain a sample of $K_{\mu 3}$

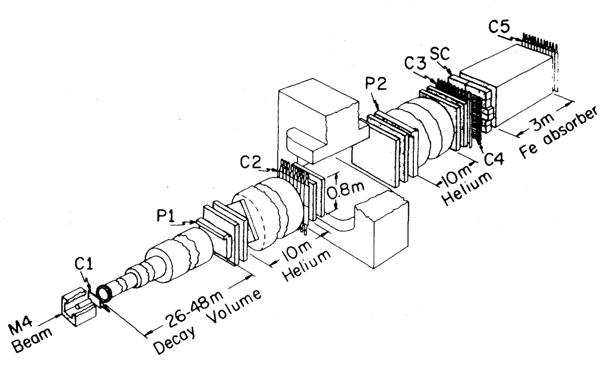

FIG. 1. The spectrometer. The regenerator, sweeping magnet, and veto counter $C1$ are at the lower left. $P1$ and $P2$ are multiwire proportional chambers; $C2$–$C5$ are counter hodoscopes; SC is a shower counter. The wire spark chambers are downstream of $P1$ and $C2$ and upstream of $P2$ and $C3$.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

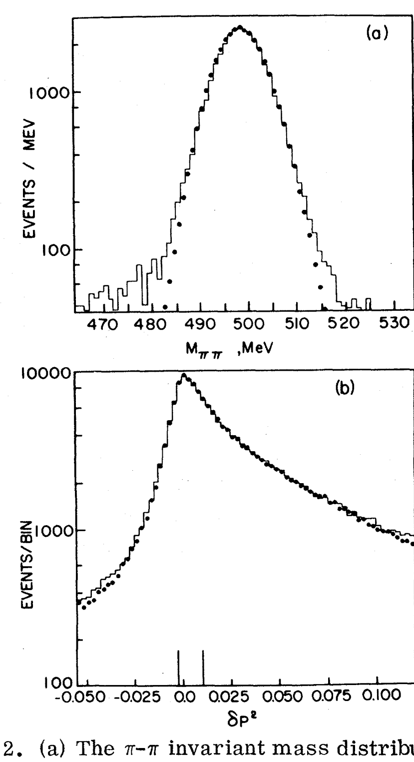

FIG. 2. (a) The π-π invariant mass distribution for $K_{\pi 2}$ triggers. The histogram represents the 48-m data and the dots are the Monte Carlo results. The background is discussed in the text. (b) The δP^2 distribution of the 26-m $K_{\mu 3}$ data. The vertical lines indicate the region of unambiguous momentum events used in the analysis.

TABLE I. $|f-\bar{f}|/k$ 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. 8.

Momentum (GeV/c)	$\|f-\bar{f}\|/k$ (mb)	$\arg(f-\bar{f})$ (deg)
35 ± 5	1.589 ± 0.092	− 130.2 ± 10.2
45 ± 5	1.411 ± 0.020	− 123.6 ± 4.2
55 ± 5	1.195 ± 0.013	− 125.4 ± 3.4
65 ± 5	1.131 ± 0.012	− 130.3 ± 3.6
75 ± 5	1.025 ± 0.013	− 125.1 ± 3.7
85 ± 5	0.998 ± 0.041	− 124.0 ± 5.6
95 ± 5	0.880 ± 0.018	− 123.5 ± 5.7
105 ± 5	0.853 ± 0.023	− 112.1 ± 6.8
115 ± 5	0.726 ± 0.029	− 117.3 ± 11.7
125 ± 5	0.731 ± 0.041	− 126.4 ± 21.2

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°. Figure 2(b) 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, $\epsilon(P_K, \tau)$, for $K_{\pi 2}$ and $K_{\mu 3}$ decays were calculated by Monte Carlo methods, 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 $I_{+-}(\tau)\epsilon(P_K, \tau)$ 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.

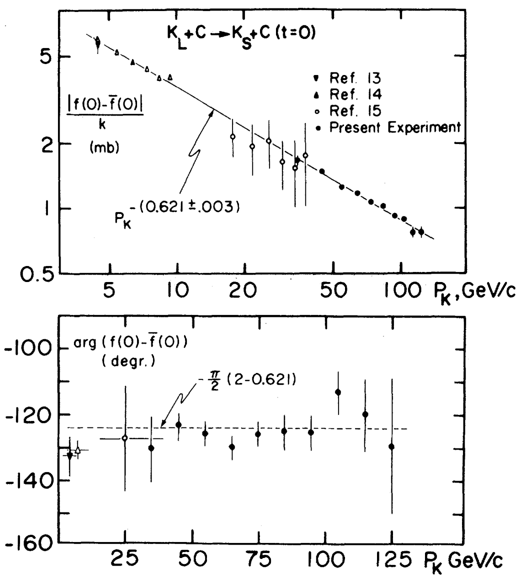

FIG. 3. $|f-\bar{f}|/k$ and $\arg(f-\bar{f})$ vs P_K for all carbon data. The $\arg(f-\bar{f})$ data of Ref. 15 is plotted for clarity as a single point, given in Ref. 15. The solid line is the best fit to P_k^{-n}. The dashed line is the phase predicted by the measured exponent n.

Figure 3 shows $|f-\bar{f}|/k$ vs P_K, extracted from measurements of $|\rho|$ in carbon.[13-16] Both our data alone and all data taken together are well fitted by a power law P_K^{-n}, yielding the results in Table II. Figure 3 also shows $\arg(f-\bar{f})$ vs P_K. The results are clearly consistent with the predicted constant phase, *strongly* supporting the hypothesis of ω-exchange dominance. The values of $\alpha_\omega(0)$ derived from the average phase are also shown in Table II. Using our data alone to fit for the parameter $\alpha_\omega(0)$[17] gives

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

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[8] gives $\alpha_\omega(0)=0.43\pm0.02$. (ii) The momentum dependence

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

of $K^{\pm}D$ total cross-section difference (also dominated by ω exchange) gives[18] $\alpha_{\omega}(0)=0.41\pm0.03$.

We are indebted to the Fermilab staff, in particular P. Koehler and U. Patel, for the efficient operation of the $M4$ beam line. We thank A. Alexander, A. Beretvas, T. Morgan, T. A. Nunamaker, R. Norton, and T. K. Shea (Univ. of Chicago), K. Mattison and R. Pepping (Univ. of Wisconsin), and A. L. Read (Fermilab) for contributions to the early phases of this work and for continued technical support. Finally, we are grateful to P. G. O. Freund, V. Barger, F. Halzen, and W. R. Frazer for illuminating discussions.

*Work supported by National Science Foundation Grants No. PHY7680260 and No. PHY72-04430 and by U. S. Energy Research and Development Administration Contract No. E(11-1)-881.

†Visitor from Eidgenössische Technische Hochschule, Zürich, Switzerland.

‡Present address: Swiss Federal Institute of Technology, Zürich, CH-8049 Switzerland.

[1]N. Cabibbo, Phys. Lett. 22, 212 (1966).

[2]Equation (1) holds for $L \ll \Lambda_S$, the K_S decay length. For the exact expression see R. H. Good *et al.*, Phys. Rev. 124, 1223 (1961).

[3]See, for example, R. J. Eden, *High Energy Collisions of Elementary Particles* (Cambridge Univ. Press, Cambridge, 1967).

[4]F. J. Gilman, Phys. Rev. 171, 1453 (1968).

[5]See, for example, V. Barger and D. Cline, *Phenomenological Theories of High Energy Scattering* (Benjamin, New York, 1968).

[6]N. Cabibbo, in *Symmetries in Elementary Particle Physics*, edited by A. Zichichi (Academice, New York, 1965), p. 256.

[7]M. Bott-Bodenhausen *et al.*, Phys. Lett. 20, 212 (1966); C. Alff-Steinberger *et al.*, Phys. Lett. 20, 207 (1966).

[8]T. G. Trippe *et al.*, Rev. Mod. Phys. 48, No. 2, Pt. 2, S51 (1976).

[9]D. A. Jensen *et al.*, Phys. Rev. Lett. 23, 615 (1969).

[10]S. H. Aronson *et al.*, Phys. Rev. Lett. 25, 1057 (1970).

[11]S. H. Aronson *et al.*, Nuovo Cimento 32A, 236 (1976).

[12]A more complete description of the analysis will be published elswhere.

[13]Our preliminary results appear in A. N. Diddens, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, 1974,* edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975), p. I-58.

[14]M. Bott-Bodenhausen *et al.*, Phys. Lett. 23, 277 (1966).

[15]W. C. Carithers *et al.*, Phys. Rev. Lett. 34, 1240 (1975); W. C. Carithers *et al.*, to be published.

[16]K.-F. Albrecht *et al.*, Nucl. Phys. B93, 237 (1975).

[17]The results of other experiments cannot be included in this determination, as the correlation between the values of the modulus and phase, included in Eq. (4), is unknown to us for Refs. 14–16.

[18]A. S. Carroll *et al.*, Phys. Lett. 61B, 303 (1976).

Search for High-Energy Deuterons in the ^{3}He + ^{3}He Reaction and the Solar Neutrino Problem

W. G. Davies, G. C. Ball, A. J. Ferguson, J. S. Forster, and D. Horn
Atomic Energy of Canada Ltd., Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0

and

R. E. Warner*
Oberlin College, Oberlin, Ohio 44604
(Received 4 March 1977)

As the result of a recently reported experiment, a search has been made for deuterons from the reaction $^3\mathrm{He}+{}^3\mathrm{He}\rightarrow\alpha+d+e^++\nu$. Two independent experiments were done at $E_{\mathrm{He}}=15$ and 25 MeV. In both cases, upper limits were obtained which are about a factor of 20 below the previously measured cross section (3.4 nb/MeV sr).

In a recent Letter,[1] Slobodrian, Pigeon, and Irshad (SPI) reported a cross section of 3.4 nb/MeV sr for the reaction $^3\mathrm{He}+{}^3\mathrm{He}\rightarrow{}^4\mathrm{He}+d+e^++\nu$. Such a cross section is too large by about a factor of 10^8 [1,2] to be a conventional weak-interaction process but might explain the low flux of high-energy solar neutrinos observed in experiments by Davis *et al.*[3] That a small increase in the $p+p$ cross section would indeed explain the absence of high-energy solar neutrinos was shown by Newman and Fowler,[2] who also argued that a cross section of 3.4 nb/MeV sr was completely incompatible with current models of solar structure and with the experimental literature on β-decay