TABLE II. Tabulation of systematic corrections.

Description	Corrections (ppm)
Events passing final cuts	$+3010 \pm 360$
Pion absorption	-290 ± 221
Pion decay	$+431 \pm 41$
Pion penetration	-394 ± 271
Beam interactions	$+8 \pm 19$
Pulse-height variation	-2 ± 2
Asymmetric contributions to "ambiguous" event group	-25 ± 25
Asymmetric elimination of multiple C-counter events	$+65 \pm 65$
Regeneration	-16 ± 6
Accidentals	-8 ± 10
Final corrected charge asymmetry	$+2779 \pm 509$

ing results in the $K_{\pi 2}{}^0$ modes,[2] which yield Reϵ $= (1.51 \pm 0.07) \times 10^{-3}$. If we assume the $K_{\pi 2}{}^0$ result for Reϵ, we may compute limits on the $\Delta S = -\Delta Q$ amplitudes. Assuming Im$x = 0$, we find Re$x = -0.04 \pm 0.10$. Thus, the results of this experiment are completely consistent with the class of theories assigning the CP-invariance violation entirely to the K^0-$\bar{K}^0$ mass matrix,[6] and with the absence of $\Delta S = -\Delta Q$ amplitudes.

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[1]T. T. Wu and C. N. Yang, Phys. Rev. Lett. 13, 380 (1964).

[2]K. Winter, in *Proceedings of the Amsterdam International Conference on Elementary Particles*, edited by A. G. Tenner (North-Holland, Amsterdam, 1971).

[3]R. Coombes *et al.*, Nucl. Instrum. Methods 98, 317 (1972).

[4]J. D. Jackson and R. L. McCarthy, Lawrence Berkeley Laboratory Report No. LBL-742 (to be published).

[5]D. Dorfan *et al.*, Phys. Rev. Lett. 19, 987 (1967); S. Bennett *et al.*, Phys. Rev. Lett. 19, 993 (1967); J. Marx *et al.*, Phys. Lett. 32B, 219 (1970); R. L. McCarthy, thesis, Lawrence Berkeley Laboratory Report No. LBL-550, 1971 (to be published); V. Ashford *et al.*, Phys. Lett. 38B, 47 (1972).

[6]The best known of these is the superweak theory, L. Wolfenstein, Phys. Rev. Lett. 13, 562 (1964).

Comparison of Particle-Antiparticle Elastic Scattering from 3 to 6 GeV/c*

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Differential cross sections for $\pi^{\pm}p$, $K^{\pm}p$, pp, and $\bar{p}p$ elastic scattering were measured at 3, 3.65, 5, and 6 GeV/c for momentum transfers from 0.03 to 1.5 GeV^2 using the Argonne effective mass spectrometer. Particular attention was paid to the relative particle-antiparticle normalization. The crossover points are consistent with no energy dependence, average values being 0.14 ± 0.03, 0.190 ± 0.005, and 0.160 ± 0.007 GeV^2 for π's, K's, and protons, respectively.

The difference between elastic scattering of particles and antiparticles from protons is due to interference terms between amplitudes of opposite charge conjugation (C) in the t channel. For example, the $K^{\pm}p$ cross sections are believed to be dominated by P, f (or P'), and ω nonflip exchange,

$$d\sigma(K^{\pm}p)/dt = |P+f\mp\omega|^2 \approx |P+f|^2 \mp 2\,\mathrm{Im}(P+f)\,\mathrm{Im}\,\omega,$$

where the $P+f$ amplitude is assumed to be mainly imaginary. The experimentally defined quantity

$$\Delta_K = \frac{d\sigma(K^-p)/dt - d\sigma(K^+p)/dt}{\{8[d\sigma(K^-p)/dt + d\sigma(K^+p)/dt]\}^{1/2}}$$

should then be a good approximation to the nonflip amplitude $\mathrm{Im}\,\omega$. Similar formulas hold for pp and $\bar{p}p$ scattering. For $\pi^{\pm}p$, however, ω exchange is forbidden by G parity and the dominant $C=-1$ exchange is expected to be ρ, so that $\Delta_\pi \approx \mathrm{Im}\,\rho$.

The quantities Δ_π, Δ_K, and Δ_p all go through zero near $-t=0.15$ GeV^2, a fact that is hard to explain in a Regge *pole* model. Davier and Harari[1] have used a dual absorption model to explain this crossover effect as the first zero of the Bessel function $J_0(r(-t)^{1/2})$, where $r\approx 1$ F is the interaction radius. Such behavior is expected if absorption suppresses the amplitude at small impact parameters; this results in dominant contributions from the peripheral partial waves with $l \approx qr$, as is also suggested by the important s-channel resonances and two-component duality.

There have been many studies of elastic scattering [2,3,4] but no systematic survey of particle-antiparticle elastic scattering has been done in this energy region. In particular, one of the largest sources of uncertainty in π-N amplitude analysis[5] comes from the uncertainty in $d\sigma(\pi^-p)/dt - d\sigma(\pi^+p)/dt$. In this experiment special care was taken to reduce the systematic errors between particle and antiparticle cross sections so that reliable difference cross sections would result.

As shown in Fig. 1, the spectrometer consisted of a large-aperture bending magnet with magnetostrictive spark chambers to measure the incident beam direction and the momentum and direction of particles scattered in the 20-in. liquid hydrogen target. The beam particles were identified by four threshold Cherenkov counters and were momentum analyzed to $\pm 0.2\%$. The basic trigger consisted of a good beam particle in coincidence with a downstream hodoscope element and with one of two proton recoil detectors, each subtending a 60° azimuth. Two veto counters along the magnet pole faces suppressed inelastic events. To monitor the efficiency of the recoil counters and to extend the measurements to $-t \leq 0.04$ GeV^2, a single counter downstream of the magnet triggered on small-angle scatters from 30 to 110 mrad. This counter was fallowed by a Cherenkov counter to veto decays of beam kaons. The magnet polarity was periodically reversed to make the spectrometer look the same to particles and antiparticles.

Cuts were made in the data for incident beam direction, proton recoil azimuth, track reconstruction criteria, and missing mass. The cross sections for $-t>0.04$ GeV^2 were derived from recoil counter triggers, while for $-t<0.04$ GeV^2

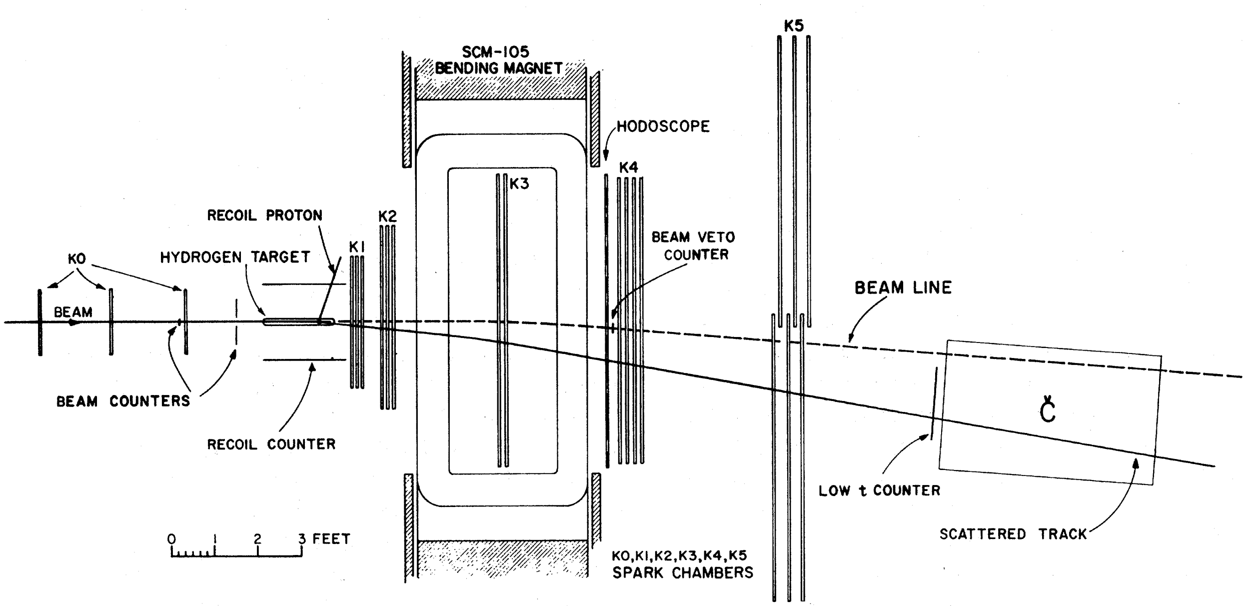

FIG. 1. Sketch of the experimental apparatus.

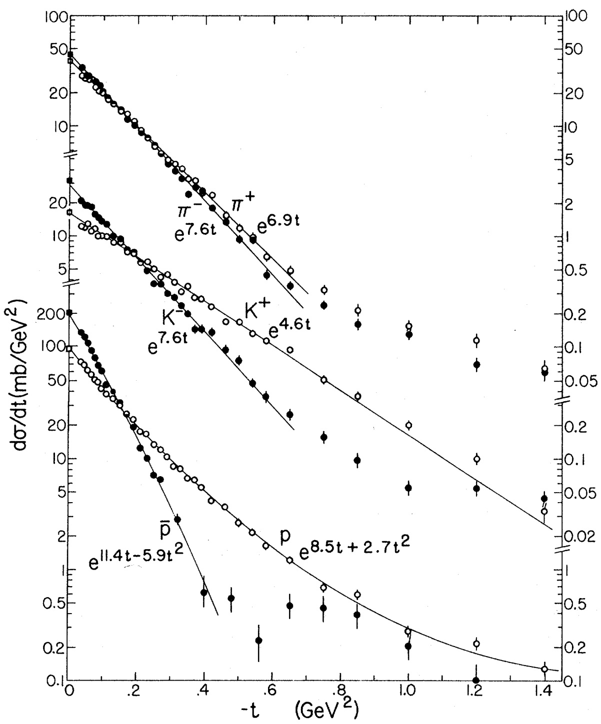

FIG. 2. Differential cross sections for the elastic scattering of six different particles from protons at a laboratory momentum of 5 GeV/c. The points denoted by squares at $t=0$ were derived via the optical theorem from previous measurements.

only the downstream counter was required. The cross-section measurement satisfied the following consistency conditions: equality for the two triggering schemes and for the two magnet polarities, and independence of fiducial volume cuts.

Corrections have been made for the following effects: geometric acceptance, accidental triggers and vetos (~3%), spark-chamber inefficiency (~2%), decays in flight, attenuation, and double scattering. The inelastic background was determined to be $<(1.5\pm 1)\%$ and a 1.5% correction was made in the π^+ and K^+ data at 3 GeV/c for backward inelastic events. The muon and electron contamination of the pion beam was measured with a special gas-filled Cherenkov counter downstream of the magnet. The overall normalization uncertainties are estimated to be $\pm 4\%$ for all particles and momenta except $\pm 5\%$ for K's at 3 and 3.65 GeV/c. The relative particle-antiparticle normalization uncertainty is estimated to be $\pm 1.5\%$ for π's and K's and $\pm 2.3\%$ for $p/\bar{p}$.

The data were also corrected for single Coulomb scattering at small t using values of the real-to-imaginary ratio of the forward scattering amplitude determined from previous experiments and dispersion relations. The largest corrections were for K^+, where 11% was required at $-t=0.025$ GeV^2, but less than 5% for $-t>0.05$ GeV^2.

The final data sample contains about 80 000 events at each of the four incident momenta: 3, 3.65, 5, and 6 GeV/c. The 5-GeV/c data are shown in Fig. 2. The $\pi^{\pm}$ and $K^{\pm}$ cross sections appear linear on the semilog plot out to about 0.5 GeV^2. The proton data, on the other hand, required a quadratic term in the exponential for a satisfactory fit. The problem of accurately determining the slope for pp scattering has been known for some time,[6] but assumes new importance with the advent of results from the CERN intersecting storage rings.[7] Table I contains the results of the fits.

A check of our normalization is afforded by the optical theorem, which together with the real-to-imaginary ratio for the forward amplitude can be used to predict the $t=0$ cross section. $A^{\pm}$ in Table I are the ratios of fitted $t=0$ values to the predicted values; agreement is found to within a few percent and the results are compatible with the predicted values. The large errors shown for $A(K^+)$ result mainly from the uncertainty of ± 0.15 assumed for the forward real-to-imaginary ratio; our data prefer values closer to zero than is usually assumed. The values of this ratio for K^+p determined by fitting our data are -0.38 ± 0.06, -0.33 ± 0.08, -0.19 ± 0.10, and -0.17 ± 0.11 for 3, 3.65, 5, and 6 GeV/c, respectively.

The locations of the crossover points, t_c, were determined from linear fits to the semilog plots over small intervals in t near the crossover and are given in Table I. The pion crossover point is particularly sensitive to the relative normalization between π^+ and π^- cross sections; the $\pm 1.5\%$ uncertainty leads to a systematic uncertainty in t_c of ± 0.025 GeV^2, comparable with the statistical uncertainty at each energy. Systematic errors on the kaon and proton crossovers are about ± 0.004 and ± 0.006 GeV^2, respectively. The crossover values are consistent with energy independence, averages being 0.14 ± 0.03, 0.190 ± 0.005, and 0.160 ± 0.007 GeV^2 for π's, K's, and protons, respectively. Equating the crossover points to the zeros of $J_0(r(-t)^{1/2})$ in the absorption picture of Davier and Harari[1] yields effective radii of 1.27 ± 0.13, 1.09 ± 0.02, and 1.19 ± 0.03 F. Crossover values approximately independent of incident momenta are expected by absorption models, but the empirical behavior $-t_c$

TABLE I. Fit results. The crossover points t_c were obtained from fits of the type $a\exp(bt)$ over the range 0.05 to 0.28 GeV^2 for $\pi^\pm$ and $K^\pm$ and over the more restricted range 0.08 to 0.22 GeV^2 for p and $\bar{p}$. Fits with $A\exp(Bt)$ were made for $\pi^\pm$ and $K^\pm$ over the range 0.05 to 0.44 GeV^2; the form $A\exp(Bt+Ct^2)$ was used for p and for $\bar{p}$ over the intervals 0.05 to 1.0 GeV^2 and 0.05 to 0.44 GeV^2, respectively. The quantity A is expressed in terms of the cross section expected at $t=0$ from the optical theorem (corrected for the real part of the forward amplitude). The superscripts ± refer to the charge of the incident particle. Errors shown include statistical errors, uncertainty in the corrections for single Coulomb scattering, and the uncertainty in the real-to-imaginary ratio at $t=0$.

Beam	p GeV/c	$-t_c$ GeV^2	A^+	B^+ GeV^{-2}	C^+ GeV^{-4}	A^-	B^- GeV^{-2}	C^- GeV^{-4}
π	3	.094±.040	1.12±.05	7.03±.12		1.02±.03	7.61± .11	
	3.65	.166±.023	1.02±.05	6.75±.12		1.02±.03	7.60± .12	
	5	.158±.022	1.01±.04	6.94±.09		.99±.03	7.66± .09	
	6	.125±.016	1.01±.04	7.08±.10		.97±.03	7.70± .08	
K	3	.186±.006	.95±.11	3.64±.11		1.00±.03	7.96± .13	
	3.65	.189±.006	.98±.11	4.12±.12		.95±.04	7.57± .13	
	5	.189±.007	.98±.09	4.62±.10		.90±.03	7.65± .10	
	6	.202±.010	.96±.08	4.87±.11		.89±.04	7.57± .13	
p	3	.167±.005	1.07±.04	7.80±.15	2.66±.20	.98±.06	12.2 ± .8	-5.7±2.4
	3.65	.155±.004	1.06±.04	8.29±.16	3.06±.22	1.03±.08	12.1 ±1.0	-7.6±3.0
	5	.157±.006	1.01±.04	8.46±.16	2.66±.22	.95±.08	11.4 ±1.0	-5.9±2.9
	6	.170±.010	.97±.04	8.63±.16	2.50±.23	1.06±.13	12.4 ±1.5	-2.5±4.0

$=0.35/\sqrt{p_{\rm lab}}$ found by Cline and Matos[8] for $K^\pm p$ elastic scattering is inconsistent with the data.

Experimental values for Δ at 5 GeV/c are shown in Fig. 3, together with fits to the form $a\exp(bt)J_0(r(-t)^{1/2})$ over the interval $0\le -t\le 0.8$ GeV^2. Although the data are reasonably consistent with the fits out to 0.8 GeV^2, there is a discrepancy at larger t. This is not unexpected since J_0 was introduced as an approximate form and real parts and spin-flip terms are probably important at large t.

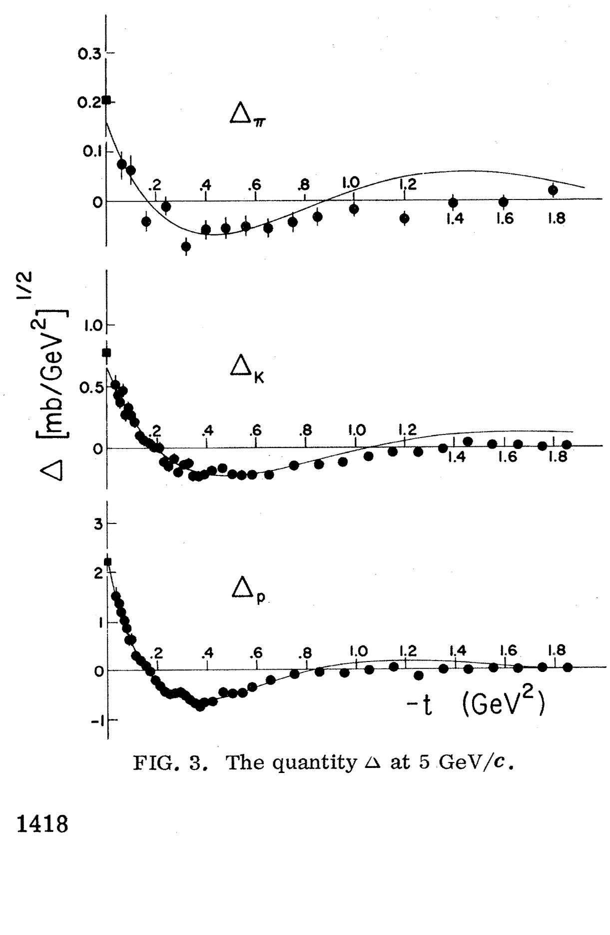

FIG. 3. The quantity Δ at 5 GeV/c.

Assuming ω exchange to dominate Δ_p and Δ_K, ω universality predicts[9]

$$\Delta_p = 3\Delta_K.$$

Our results are in qualitative agreement with this prediction out to about 0.6 GeV^2.

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[1]M. Davier and H. Harari, Phys. Lett. 35B, 239 (1971).

[2]C. T. Coffin *et al.*, Phys. Rev. 159, 1169 (1967).
[3]K. J. Foley *et al.*, Phys. Rev. Lett. 11, 425, 503 (1963).
[4]V. Chabaud *et al.*, Phys. Lett. 38B, 441, 445, 449 (1972).
[5]F. Halzen and C. Michael, Phys. Lett. 36B, 367 (1971).
[6]R. A. Carrigan, Jr., Phys. Rev. Lett. 24, 168 (1970).
[7]G. Barbiellini *et al.*, Phys. Lett. 39B, 663 (1972).
[8]D. Cline and J. Matos, Nucl. Phys. B33, 421 (1971).
[9]V. Barger, K. Geer, and F. Halzen, Nucl. Phys. B44, 475 (1972).

$SU(3) \otimes SU(3)$ Algebra and the Cabibbo Angle*

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We investigate the possibility that the physically relevant currents may be different from those that satisfy the usual $SU(3) \otimes SU(3)$ algebra. This approach offers new insight into the nature of the Cabibbo angle. A modified soft-pion theorem for the K_{l3} decay is also obtained, which provides better agreement with the present data.

Following the idea of Gell-Mann,[1] it is generally assumed that the vector and axial-vector currents that satisfy the $SU(3) \otimes SU(3)$ algebra (hereafter referred to as the canonical currents and the canonical algebra) are also the physical currents that probe electromagnetic and weak interactions. Indeed, this idea has met with a great deal of success through the hypotheses of conserved vector currents (CVC) and of partially conserved axial-vector currents (PCAC), and through the current-algebra sum rules. In this paper we investigate the possibility that the physically relevant currents may be different from the canonical currents and examine how several of the results of the standard formalism (including the Adler-Weisberger sum rule) can still be maintained. To be sure, some differences emerge, and as an example we obtain a new soft-pion theorem for K_{l3} decays which provides better agreement with the present data. Most importantly, however, with an appropriate definition of the Cabibbo current, we get new insight into the nature of the Cabibbo angle.

Since a closed algebraic structure for the currents plays a central role in the usual theory, we shall assume that the physical currents also form a closed algebra, though not in the canonical form. Thus, we shall take the physical currents to be proportional to the canonical currents, with scaling or normalization factors generally different from unity. Now it is widely recognized[2] that the current-algebra sum rules are exact consequences in a world which is invariant under chiral symmetry realized through the appearance of suitable pseudoscalar Nambu-Goldstone bosons. Prompted by the success of the sum rules that follow from the symmetry algebras (like the Adler-Weisberger sum rule), we shall make the following *Ansatz*: The relevant physical currents, and therefore the algebra, should reduce to the canonical form in the limit of the appropriate symmetry or subsymmetry. The normalization factors for the physical currents can thus be regarded as functions of one or more symmetry-breaking parameters, reducing to unity in appropriate symmetry limits.

Let $\overline{V}_\mu{}^\alpha(x)$ and $\overline{A}_\mu{}^\alpha(x)$ ($\alpha = 1, 2, \ldots, 8$) denote the canonical vector and axial-vector current densities, satisfying the canonical current algebra, and let the physical current densities be denoted by $V_\mu{}^\alpha(x)$ and $A_\mu{}^\alpha(x)$ ($\alpha = 1, 2, \ldots, 8$). Since isospin invariance and hypercharge conservation would be assumed throughout, our *Ansatz* implies $V_\mu{}^\alpha(x) = \overline{V}_\mu{}^\alpha(x)$ for $\alpha = 1, 2, 3$, and 8. For the rest of the currents, we shall introduce the normalization factors α, β, γ, and δ:

$$A_\mu{}^\pi(x) = \alpha \overline{A}_\mu{}^\pi(x), \quad V_\mu{}^K(x) = \beta \overline{V}_\mu{}^K(x), \quad A_\mu{}^K(x) = \gamma \overline{A}_\mu{}^K(x), \quad A_\mu{}^8(x) = \delta \overline{A}_\mu{}^8(x), \tag{1}$$

where $\pi = 1, 2$, and 3 and $K = 4, 5, 6$, and 7. Using the canonical algebra for $\overline{V}_\mu{}^\alpha$ and $\overline{A}_\mu{}^\alpha$, we construct the algebra for the physical currents (aside from possible Schwinger terms which we shall omit