The average deviations for Pb and Ba differ by only 2 ± 14 eV. The recent evaluations of a graph of order $\alpha^2(\alpha Z)^2$ gave controversial results, two papers[13] claiming this contribution to be of the order of 1 eV or less, and one paper[14] quoting contributions to the transition energies in question of -35 eV for Pb and -22 eV for Ba. The present experiment does not confirm such large corrections. It should be mentioned that the calculated energies in Table I also suffer from uncertainties of 7–10 eV.[5]

From our measurement we conclude that the validity of QED in the domain of muonic atoms, even for high-Z atoms, is confirmed to an accuracy of about 0.5%, regarding the average deviation from calculation. The measurement is in contradiction to the measurements of Ref. 2, and also, although less significantly, to the conclusions of Ref. 3. It is, however, in agreement with our early measurement on muonic Pb.[1]

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Coherent K_S^0 Regeneration in Hydrogen and Deuterium from 3.5 to 10.5 GeV/c*

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The amplitude and phase for coherent regeneration in hydrogen and deuterium have been measured for six momentum bins in the range 3.5–10.5 GeV/c. Over this region the phase, φ_f, is consistent with being constant and has the value $-60° \pm 8°$ for hydrogen and $-46° \pm 8°$ for deuterium. Power-law fits of the form $p_{\mathrm{lab}}{}^n$ for the amplitudes when combined with other data give $n = -0.60 \pm 0.02$ for hydrogen and $n = -0.52 \pm 0.02$ for deuterium.

In its interactions with matter the $K_L{}^0$ state must be considered as a superposition of the strangeness eigenstates K^0 and $\bar{K}^0$. Since their respective forward elastic scattering amplitudes $f(0)$ and $\bar{f}(0)$ are not equal, a nonzero amplitude for the $K_S{}^0$ state is coherently regenerated. This regenerated amplitude can be observed via the $\pi^+\pi^-$ decay mode as it interferes with the known

CP nonconserving amplitude for $K_L{}^0 \to \pi^+\pi^-$. Thus a proper-time distribution of $\pi^+\pi^-$ decays both in and downstream of a target can be used to determine the amplitude and phase of the quantity $[f(0)-\bar{f}(0)]/k$. Previous coherent-regeneration experiments on hydrogen have been reported by Darriulat *et al.*[1] and Buchanan *et al.*[2] Also in this range Brandenburg *et al.*[3] have measured incoherent or diffractive regeneration. Their data when extrapolated to $t=0$ and combined with total-cross-section differences can be directly compared to coherent experiments. At higher momenta Birulev *et al.*[4] and Albrecht *et al.*[5] have measured coherent regeneration in hydrogen and deuterium respectively.

If the wave function for the decaying state is written as $|K_L{}^0\rangle + \rho(z,p)|K_S{}^0\rangle$ in which z is the coordinate along the beam direction ($z=0$ at the beginning of a target of length l) and p is the kaon momentum, the expression for $\rho(z,p)$ in the target is

$$\rho(z,p) = i\pi N\Lambda_S \frac{f(0)-\bar{f}(0)}{k} \times \left| \frac{1-\exp[(i\delta m - \frac{1}{2})z/\Lambda_S]}{-(i\delta m - \frac{1}{2})} \right|$$

and downstream of the target it is

$$\rho(z,p) = \rho(l,p)\exp[(i\delta m - \tfrac{1}{2})(z-l)/\Lambda_S],$$

where N is the number density of target nuclei, Λ_S is the mean decay length of a $K_S{}^0$, $\Lambda_S = \tau_S\beta\gamma c$, $\delta m = m_L - m_S$, and $k = 2\pi p/h$.

The intensity of $\pi^+\pi^-$ decays observed with the target full is given by

$$I_f(z,p) = \alpha_f \epsilon_f(z,p) S_L(p) |\eta_{+-} + \rho(z,p)|^2,$$

where η_{+-} is the CP-nonconservation parameter, α_f is a normalization constant proportional to the number of incident kaons, $\epsilon_f(z,p)$ is the detection efficiency, and $S_L(p)$ is a function describing the incident kaon momentum spectrum. With the target empty (under vacuum), $\rho=0$ and the ratio of intensities is given by

$$R(z,p) = \frac{I_f(z,p)}{I_v(z,p)} = \frac{\alpha_f\epsilon_f(z,p)}{\alpha_v\epsilon_v(z,p)} \left| 1 + \frac{\rho(z,p)}{\eta_{+-}} \right|^2. \qquad (1)$$

The experiment was performed in the 4.7° neutral beam at the Brookhaven National Laboratory alternating gradient synchrotron (AGS). This beam was produced by 28.5-GeV/c protons striking the G10 internal-production target. A 5-cm-thick lead converter followed by a sweeping magnet, located 22 m from the AGS target, removed γ rays from the beam. The apparatus used was the portion of that which Banner *et al.*[6] needed to measure the $\pi^+\pi^-$ decay rate, modified to contain a cryogenic target 122 cm long and 15 cm in diam. The upstream end of the target was located 52 m from the production target and 5.9 m from the center line of the magnet. The decay region downstream of the hydrogen target was filled with helium to reduce multiple scattering. The magnetic spectrometer consisted of optical spark chambers on both sides of a 72D18 magnet set to a transverse momentum of 206 MeV/c. The spark chambers were triggered when two charged particles emerged from the magnet roughly parallel to the beam line. The parallel requirement was defined by two vertical scintillation-counter hodoscopes, separated by 3 m, with elements 5 cm wide. Two Cherenkov counters, located between the hodoscopes and filled with air at atmospheric pressure, were used to identify electrons. Muons were identified by a counter bank positioned behind a wall consisting of 1.2-m concrete and 30-cm steel. A fraction (12%) of the identified leptonic events were included in the trigger for systematic studies and monitoring purposes. For each event we recorded on magnetic tape all counters which had fired including the leptonic identification. Data was taken in alternating runs of several days duration for each of the target conditions (vacuum, hydrogen, deuterium). The resulting film was digitized automatically using the Princeton precision encoding and pattern recognition system. The residuals obtained for reconstructed tracks indicated an error on the spark positions of ± 300 μm.

Event reconstruction consisted of identifying "vees" associated with decays of the type $K^0 \to \pi^+\pi^-$. Each of the two tracks associated with an event was required to have a minimum of twelve out of a possible 24 sparks and to satisfy a suitable χ^2 criterion. A vertex cut was implemented by forcing the two tracks to intersect at a common point and cutting on the resulting change in χ^2. We also calculated a collinearity parameter θ^2, the square of the angle between the reconstructed total momentum vector and the line of flight of the $K_L{}^0$ meson, and Δm, the difference between the effective mass of the reconstructed particles assumed to be pions and the kaon mass. Leptonic events were identified by using the counter information and were used as an internal monitor. The selection criteria for the final sample were $|\Delta m|/p_k < 0.0036$ corresponding to $\pm 3.5\sigma$ and $\theta^2 < 10$ mrad^2 which produced a signal loss of $<2.5\%$ for all momenta.

The selected samples still contained background due mainly to $K_{\mu 3}$ decays and neutron-induced reactions. These were treated by performing a linear fit to the θ^2 distributions for events falling outside our selection criteria. We found that the intercepts of these distributions were different for events with vertices inside and outside the target, but were otherwise independent of vertex position, momentum, and target filling. This difference is expected since neutron-induced background dominates in the target region. The background was subtracted for each bin in momentum and position using a linear extrapolation from $\theta^2 = 15-40$ mrad^2 to $\theta^2 = 0$, requiring that the intercept be 97 ± 7 mrad^2 for events in the target and 58 ± 2 mrad^2 for downstream events. This procedure is illustrated in the θ^2 distributions shown in Fig. 1. The numbers of good $K^0 \to \pi^+\pi^-$ events remaining were 5593, 3738, and 4679 for hydrogen, deuterium, and vacuum, respectively.

For all momenta the observed vertex distributions for target empty were in good agreement with those obtained from a Monte Carlo calculation. The experimental distribution for the 5.5-6.5-GeV/c momentum bin for hydrogen is shown in Fig. 2. The full-line histogram is the signal after subtraction of the background (dotted-line histogram). The regeneration of K_S^0 is clearly seen and the discontinuous structure of the target, which shows up in the background, has disappeared for events with the background subtracted.

As a relative monitor of the effective incident K_L^0 flux for target-full and target-empty data we used the combined number of reconstructed downstream $K_{2\pi}$, K_{e3}, and $K_{\mu 3}$ events in each case. This method avoided problems associated with possible target-dependent reconstruction efficiencies due to a change in the average number of neutron-induced background tracks present when the target was full. Defining $M_{fv} = \epsilon_f/\epsilon_v$ we obtained for hydrogen $M_{\mathrm{H}v} = 0.89 \pm 0.03$ and for deuterium $M_{\mathrm{D}v} = 0.95 \pm 0.05$.

The experimental ratios of the vertex distributions for deuterium and hydrogen were fitted by the function $R(z,p)$ as given in Eq. (1). Corrections were applied for the absorption of incoming K_L^0 and decay pions in the target material. For the quantities $|\eta_{+-}|$, φ_{+-}, δm, and τ_S appearing in the expression for $R(z,p)$, we used the values given by Soergel.[7] We varied the quantities $|f(0) - \bar{f}(0)|/k$ and $\varphi_f = \arg i[f(0) - \bar{f}(0)]$ in a two-dimensional matrix and calculated the χ^2 between the expected function $R(z,p)$ and the experimentally observed ratios for each Δz and Δp bin. The vertex z-position resolution function was convoluted with $R(z,p)$ over the Δp interval appropriate for each bin.

The results obtained for the phase are shown

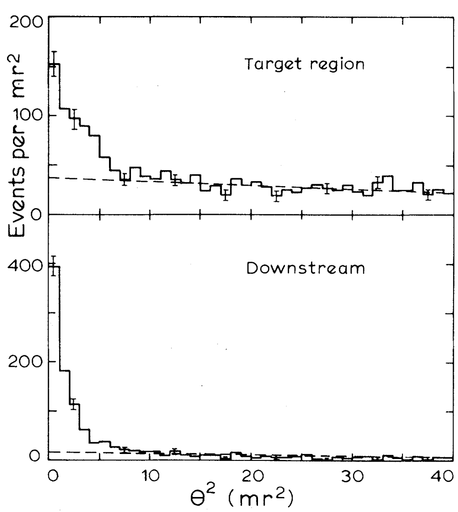

FIG. 1. Distributions of the square of the collinearity angle for hydrogen data in the momentum interval 5.5-6.5 GeV/c after application of all other selection criteria. The dashed lines are linear fits to the background in the region 15-40 mrad^2. They extrapolate to intercepts of $\theta^2 = 97 \pm 7$ mrad^2 for events in the target and $\theta^2 = 58 \pm 2$ mrad^2 for downstream events. The reduced χ^2's for the fits are 1.2 and 1.0 for the downstream and target regions, respectively.

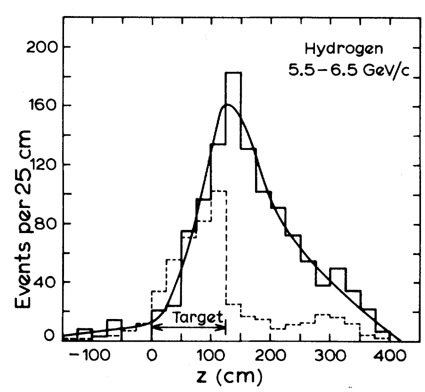

FIG. 2. Decay vertex z distributions for $K^0 \to \pi^+\pi^-$. The dotted histogram indicates the amount of background subtraction. The solid histogram is the data after background subtraction. The region of the target is indicated. The solid curve is the calculated vertex distribution using the fitted values for amplitude and phase.

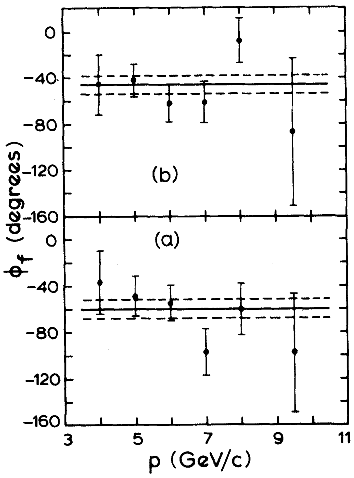

FIG. 3. Regeneration phases as a function of momentum for (a) hydrogen and (b) deuterium. The solid lines show the average values for all momenta with the errors shown as dashed lines.

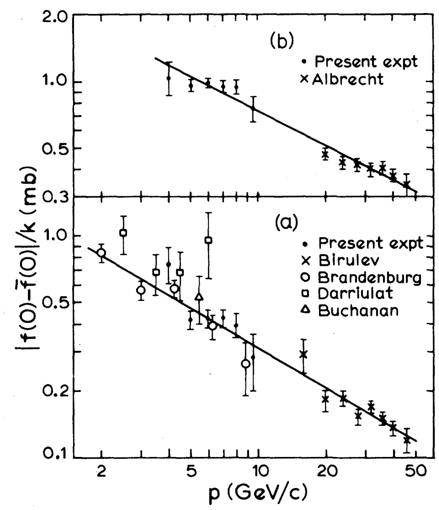

FIG. 4. Regeneration amplitudes for (a) hydrogen and (b) deuterium using average phases of $-45° \pm 3°$ and $-39° \pm 4°$, respectively. The straight lines represent fits of the form $p_{lab}{}^n$.

in Fig. 3. Errors are obtained by projecting the $\chi^2 + 1$ contour onto the φ_f axis. For hydrogen and deuterium the phases are consistent with being constant over the entire momentum interval. As a result the data were reanalyzed with the requirement that the phase be the same for all momenta. This gives an average phase $\varphi_f = -60° \pm 8°$ for hydrogen and $\varphi_f = -46° \pm 8°$ for deuterium. The values of $|f(0) - \bar{f}(0)|/k$ corresponding to these phases are given in Table I for hydrogen and deuterium. In addition we have tested our sensitivity to the monitor ratios by allowing them to vary. Minimum χ^2's were obtained for monitor values equal to those used within experimental errors.

Combining our phases with those of other experiments[1-5] we obtain weighted averages of $\bar{\varphi}_f = -45° \pm 3°$ for hydrogen and $\bar{\varphi}_f = -39° \pm 4°$ for deuterium over the momentum range from 2–50 GeV/c. In Fig. 4 we plot our values of $|f(0) - \bar{f}(0)|/k$ corresponding to these average phases. They are slightly different from those in Table I due to a weak correlation with φ_f.[8] Also shown are points from Refs. 1–5 corrected whenever possible to correspond to the same CP parameters used here. All the data were fitted with power laws of the form $p_{lab}{}^n$ giving $n = -0.60 \pm 0.02$ for hydrogen and $n = -0.52 \pm 0.02$ for deuterium. These values are consistent with ρ and ω Regge exchanges for the hydrogen data and with pure ω exchange for the deuterium data.[9]

TABLE I. Regeneration amplitudes and phases in hydrogen and deuterium.

p (GeV/c)	$\lvert f(0) - \bar{f}(0)\rvert/k$ (mb) Hydrogen	Deuterium
3.5– 4.5	0.78 ± 0.14	1.05 ± 0.18
4.5– 5.5	0.47 ± 0.04	0.99 ± 0.06
5.5– 6.5	0.48 ± 0.04	1.01 ± 0.05
6.5– 7.5	0.48 ± 0.04	0.98 ± 0.06
7.5– 8.5	0.44 ± 0.05	0.97 ± 0.08
8.5–10.5	0.33 ± 0.09	0.78 ± 0.10
3.5–10.5	$\varphi_f = -60° \pm 8°$	$\varphi_f = -46° \pm 8°$

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Search for More J Particles

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We report here on an experiment done at the 30-GeV proton synchrotron at Brookhaven National Laboratory using a large-acceptance ($\Delta m = 1$ GeV) pair spectrometer with a mass resolution of ± 5 MeV, to search for additional long-lived particles which decay into $K^-\pi^+$, $K^+\pi^-$, $\bar{p}p$, K^+K^-, $\pi^+\pi^-$, K^-p, π^-p, $K^+\bar{p}$, or $\pi^+\bar{p}$. The result, based on 2×10^7 events, shows that, to a sensitivity comparable to or lower than the production of J particles [(production) $\times$ (decay branching ratio) $\approx 10^{-34}$ cm^2], no additional states were found.

We report here the results of an experiment done at the 30-GeV alternating-gradient proton synchrotron at Brookhaven National Laboratory. The purpose of this experiment is to search for additional narrow resonances. Their existence may give a clue to the understanding of the recently discovered J particles.[1-3] In this Letter we will present the results of a systematic search for new particles from reactions

$$p + \mathrm{Be} \to \begin{pmatrix} K^-\pi^+ \\ K^+\pi^- \\ \bar{p}p \\ K^+K^- \\ \pi^+\pi^- \\ K^-p \\ K^+\bar{p} \\ \pi^-p \\ \pi^+\bar{p} \end{pmatrix} + X$$

by measuring the pairs directly.

Data also exist on $p + N \to p + p + J'$, by measuring the two protons and studying the missing-mass structure, and

$$p + \mathrm{Be} \to \begin{pmatrix} K^-K^- \\ K^-\pi^- \\ \bar{p}\bar{p} \\ \pi^-\pi^- \end{pmatrix} + \ldots$$

to search for multibody decays. These data will be presented later.[4]

This experiment used a pair spectrometer described previously for the discovery of the J particle.[1] The spectrometer measures a pair of 90° decay particles from a resonance produced at rest in the p-p center-of-mass system.

The 8000-wire proportional-chamber system provides a mass resolution of ± 5 MeV. There are eleven planes of chambers in each arm rotated 20° with respect to each other so as to be able to sort out up to eight tracks per arm. Timing is provided by thin two-dimensional hodoscopes behind the chambers.

For the hadron-pair runs three modifications were made on the original setup:

(a) In order to reduce the random accidentals to a minimum we put in a new target system