Precise Measurement of the Λ^0 and $\bar{\Lambda}^0$ Masses and a Test of *CPT* Invariance

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A precision measurement of the masses of the Λ^0 and $\bar{\Lambda}^0$ hyperons is obtained from Gaussian fits to the invariant mass distributions for 20 138 Λ^0's and 18 309 $\bar{\Lambda}^0$'s. The Gaussians have standard deviations of 0.49 and 0.51 MeV/c^2 for the Λ^0 and $\bar{\Lambda}^0$, respectively. Systematic errors were reduced by calibrating the spectrometer with 60000 exclusive events containing a K_S^0. We find $M_\Lambda = 1115.678 \pm 0.006 \pm 0.006$ MeV/c^2 and $M_{\bar{\Lambda}} = 1115.690 \pm 0.008 \pm 0.006$ MeV/c^2. The Λ^0-$\bar{\Lambda}^0$ mass difference testing *CPT* invariance is -0.012 ± 0.010 MeV/c^2.

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We report precision measurements of the masses of the Λ^0 and $\bar{\Lambda}^0$ hyperons more than an order of magnitude more accurate than the last previously reported values [1], which were done more than 20 years ago with limited statistics. The Λ^0 mass was reported to be 1115.59 ± 0.08 MeV/c^2 by Hyman *et al.* [2] (935 events in a helium bubble chamber), 1115.39 ± 0.12 MeV/c^2 by Mayeur *et al.* [3] (195 events in emulsions), and 1115.65 ± 0.07 MeV/c^2 by Schmidt [4] (488 events in a hydrogen bubble chamber). Measurements of the $\bar{\Lambda}^0$ mass are not reported in Ref. [1]. It is important to improve the knowledge of these fundamental constants with modern techniques. The mass values also constrain quark models [5] and test the predictions [6] of mass relations and QCD calculations of hyperfine interactions such as the $\Sigma^0 \rightarrow \Lambda^0$ transition [7]. Invariance under *CPT* [8] predicts equality of particle antiparticle masses. Although tested to extraordinary accuracy for nonstrange baryons [9] and K^0 mesons [1], *CPT* tests with nonzero strangeness baryons are no more stringent than the mass measurements. The current world average [1] Λ^0-$\bar{\Lambda}^0$ mass difference is 0.00 ± 0.12 MeV/c^2. Since *CPT* invariance is thought to be a fundamental principle, improved tests of its validity are essential.

The data were amassed at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratories in experiment E766 [10]. A proton beam with an average momentum of 27.5 GeV/c entered a 12-in.-long liquid hydrogen target. Charged particles from a pp interaction were detected and measured in a spectrometer located in the aperture of an analyzing magnet, 4 ft high, 6 ft wide, and 6 ft deep. The average $\int B\,dl$ of the analyzing magnet was 1.17 Tm (350 MeV/c). The trajectories of particles passing through the magnetic field were measured by six drift chambers. The spectrometer was designed with a minimum amount of material to reduce multiple Coulomb scattering. The incoming proton beam momentum and direction were measured in a separate spectrometer system [11]. (Details of the spectrometers, the data acquisition system, the triggers, and the specialized electronics systems involved are presented elsewhere [12,13].) With beam intensities of 10^6 to 10^7 protons per second delivered in 1.2-s-long pulses every 3 s, ~ 1500 events were recorded each beam pulse. In a two week exposure, $\sim 3 \times 10^8$ events were recorded on magnetic tape.

The 2.0 to 3.5 mm wire spacing of the drift chambers, the accuracy of the spatial measurements (~ 150 μm), and the redundancy afforded with four views per chamber proved sufficient to allow accurate track reconstruction even with twenty particles in the final state. The momentum of each particle was obtained from the shape of the trajectory and a detailed knowledge of the magnetic field. The momentum resolution $\Delta p(\text{FWHM})/p$ was 0.01. In a typical event, most tracks come from a common point —the primary vertex or interaction point of the incoming proton. The position of a vertex was used as a constraint to improve the momentum measurement. Vertices separated from the primary vertex are candidate particle decays. The tracks forming a separated vertex were assigned all possible $(e^\pm, \mu^\pm, \pi^\pm, K^\pm, p, \bar{p}, d)$ particle identities. For each assignment, the invariant mass of the

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decaying particle was calculated. If that mass was within broad limits of the accepted value for a known particle, the separated vertex was labeled as the decay point of that particle. The track information, the tentative assignments from the verticizing process, the particle identification from the Cherenkov counter and time-of-flight scintillator hodoscopes, and the conservation of momentum, energy, charge, and baryon number were then used to select that subset of the data which are completely measured or exclusive reactions. Our sample yielded $\sim 2\times 10^6$ exclusive events.

Exclusive events have advantages for a precise mass measurement. The selection demands the magnitude of the vector sum of the transverse momenta in the final state be ≤ 100 MeV/c and the initial and final state sums of the difference of the particle energy and longitudinal momentum be equal to ± 30 MeV/c. These stringent demands require accurate determination of each particle's momentum vector. Background for exclusive events from mismeasured, nonexclusive events was $\leq 5\%$. The kinematic ambiguity between $\Lambda \to p\pi^-$ and $K_S^0 \to \pi^+\pi^-$ is small because of the mass resolution of the spectrometer and because exclusive events must satisfy the additive conservation laws (baryon number, strangeness, charge, etc.).

To improve the mass resolution, charged particles from a decay were required to be bent by the magnetic field toward the original direction of the parent particle. This selection reduces the resolution-broadening correlation between the measurements of the decay opening angle and the track momenta.

The exclusive event samples thus selected for this measurement included 59814 events with a K_S^0 from the final states $ppK_S^0K^{\pm}\pi^{\mp}n(\pi^+\pi^-)$, $n=0,1,2,3$; 45697 with a Λ^0 from the final states $p\Lambda^0K^+n(\pi^+\pi^-)$, $n=1,2,3,4$; and 6281 with a $\bar{\Lambda}^0$ from the final states $ppp\bar{\Lambda}K^-n(\pi^+\pi^-)$, $n=0,1,2,3$; $pp\Lambda^0\bar{\Lambda}^0n(\pi^+\pi^-)$, $n=0,1,2,3$ and $ppp\bar{\Lambda}^0K_S^0\pi^-n(\pi^+\pi^-)$, $n=0,1,2$. The $K_S^0 \to \pi^+\pi^-$, $\Lambda^0 \to p\pi^-$, and $\bar{\Lambda}^0 \to \bar{p}\pi^+$ decays were used.

The three components of the magnetic field of the spectrometer were measured to ± 1 G with the Fermilab ZIPTRACK system [14], providing ~ 300000 measurements on a 2 in. by 2 in. grid perpendicular to the beam direction and a 1 in. spacing along the beam direction. The measurements covered the 48 in.$\times$72 in.$\times$127 in. aperture of the spectrometer. The field map was initially positioned relative to the analyzing magnet and the coordinate system of the spectrometer using direct surveying techniques and the symmetry of the field. Further checks were made by measuring the momentum of a track using different portions of the spectrometer and therefore different sections of the field.

The final alignment of the field grid was obtained with the sample of exclusive events containing a K_S^0 decay. The K_S^0 mass was calculated for subsets of this sample based on the location of the decay point, the trajectories of the decay products, the K_S^0 trajectory, the orientation of the plane of the decay, and the K_S^0 momentum. These calculations were repeated for ~ 40 different locations and orientations of the measurements with respect to the spectrometer coordinate system allowing the field position to be determined with an uncertainty of ± 0.05 in. in each direction.

We investigated quantitatively features of the tracking that might influence the mass determination using both data and Monte Carlo generated tracks. Two problems were corrected. First, the momentum measurement was improved by 0.15% by reducing the step size used to fit the track trajectory to the position measurements (6 in. to 2 in.). Second, the determination of the momentum components along the beam direction and along the vertical differed slightly (0.1%) and were corrected.

Considerable attention was devoted to the time dependent stability of the magnetic field of the spectrometer magnet. At Brookhaven, a typical power supply is regulated [15] to $\pm 0.1\%$. The magnet was operated at field values below saturation. Therefore, the magnetic field of the spectrometer was proportional to the output of the supply. Without more detailed knowledge of the field, mass measurements would also be limited to $\pm 0.1\%$. However, it was possible to use an inclusive K_S^0 mass measurement as a function of time to determine and correct for the time variation of the magnetic field. Since $\sim 1.6\times 10^5$ events were written to a magnetic tape every 6 min, each tape contains between 10^3 and 10^4 separated vertices with a $\pi^+\pi^-$ invariant mass within ± 20 MeV of the K_S^0 mass. The central values of the mass distributions of these vertices from each of the 2000 tapes during the experiment provided a direct measure of the variations in the magnetic field (typically $\pm 0.05\%$). We used this information to correct on a tape-by-tape basis for the changes in the magnetic field.

To improve the resolution further, (i) only decays which occurred downstream of the liquid hydrogen target were accepted to eliminate a major source of multiple

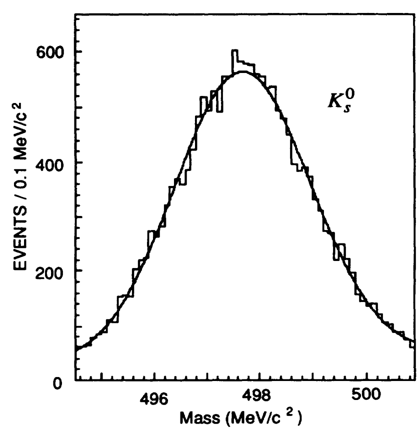

FIG. 1. Invariant mass for the exclusive K_S^0 events fit to a Gaussian and a linear background shown explicitly. The standard deviation is 1.28 MeV/c^2.

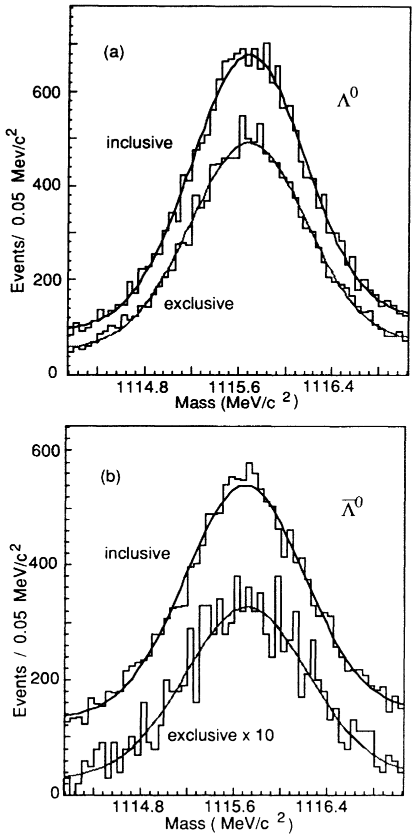

FIG. 2. Invariant mass for (a) Λ^0 and (b) $\bar{\Lambda}^0$. The $\bar{\Lambda}^0$ exclusive sample has been multiplied by 10. Fits are Gaussians with linear backgrounds shown explicitly. Standard deviations are ~ 0.5 MeV/c^2.

Coulomb scattering and systematic uncertainties due to energy loss corrections. (ii) Tracks of the decay products were not permitted to share wire hits in the drift chambers. (iii) The plane of the decay had to be within $\pm 60°$ of the horizontal. The width of the mass distributions increased $\sim 35\%$ for decay planes parallel to the vertical magnetic field. (iv) Tracks of the decay products had to be measured by at least four chambers. These requirements reduced the data sample by a factor of 3.

The K_S^0 invariant mass was then plotted for the exclusive events with a K_S^0. The distribution was fit to a Gaussian signal and a linear background function. The magnetic field of the spectrometer was normalized to set the center of the Gaussian at the current world average [1] of 497.671 ± 0.031 MeV/c^2. This required a change in the normalization of 0.06% from the value obtained from an NMR probe calibration of the ZIPTRACK system.

The K_S^0 mass distribution is shown in Fig. 1. There are 19 187 events plotted in 0.1 MeV/c^2 bins between 494.411 and 500.931 MeV/c^2. The Gaussian has a central value of 497.6711 ± 0.0118 MeV/c^2 with a standard deviation of 1.28 MeV/c^2. The χ^2 is 54 for 59 degrees of freedom indicating that the data are well described. The largest correlation coefficient involving the central value is -0.015 (with the intercept of the linear background).

TABLE I. Fits to the mass distributions for exclusive (a) and inclusive (b) Λ^0 and $\bar{\Lambda}^0$, showing Gaussian standard deviations and quality of fit.

Events		Mass	σ	$\chi^2 N_{DF}$
Λ^0 (a)	14 287	1115.681 ± 0.006	0.495	65/53
$\bar{\Lambda}^0$ (a)	992	1115.710 ± 0.023	0.53	36/40
Λ^0 (b)	20 138	1115.678 ± 0.006	0.486	66/53
$\bar{\Lambda}^0$ (b)	18 309	1115.690 ± 0.008	0.508	59/53

The invariant mass distributions for the Λ^0 and $\bar{\Lambda}^0$ exclusive events were then plotted in 0.05 MeV/c^2 bins between 1114.13 and 1117.07 MeV/c^2 and fit. The results are shown as the lower curves in Figs. 2(a) and 2(b) and presented in Table I.

To reduce the uncertainty in the $\bar{\Lambda}^0$ measurement, the analysis was extended to the inclusive samples. The $\bar{\Lambda}^0$ inclusive sample was ~ 60000 events before the criteria to improve the resolution were imposed. The Λ^0 inclusive sample was limited to roughly the same size because of the systematic uncertainties discussed below. After applying the criteria, the results are shown as the upper curves in Figs. 2(a) and 2(b) and presented in Table I. A linear background was used in all fits. The exclusive and inclusive results agree nicely. We choose to quote the higher statistics inclusive measurements as our final result.

The systematic errors on these values are dominated by the uncertainties in the world average values of the K_S^0, p, $\bar{p}$, and $\pi^\pm$. To calculate these systematic errors and to permit an accurate correction of our results and a reduction in the size of our systematic uncertainty should new world averages of these particles be obtained, we present in Table II the derivatives of the hyperon mass to each and the size of the contribution to the systematic error. The total systematic error combines these contributions in quadrature.

We investigated the effects of the cuts applied to the sample. We calculated the K_S^0 mass for the following samples: (i) sharing of hits in the drift chambers al-

TABLE II. Systematic errors (MeV/c^2) in the Λ mass due to uncertainties in the particle masses used. The derivatives can correct our results if world averages [1] improve. The effect of the π mass depends on whether (a) the K_S^0 mass remains unchanged or (b) changes as the π mass moves ($\partial m_{K_S}/\partial m_\pi = 1.4$).

Mass	Value used	Derivative	Contribution
K_S^0	497.671 ± 0.031	$\partial m_\Lambda/\partial m_{K_S} = 0.19$	0.0059
p	938.2731 ± 0.00028	$\partial m_\Lambda/\partial m_p = 1.0$	0.00028
π	139.5679 ± 0.0007	$\partial m_\Lambda/\partial m_\pi = 1.0$	0.0007 (a) -0.0002 (b)

TABLE III. Effect of cuts on mass of K_S^0.

Change in cut	Shift in $M_{K_S^0}$
Allow sharing of hits	0.001
Decay plane within $\pm 53°$	0.006
Decay plane within $\pm 66°$	0.011
E and p Cons. $\pm 11\%$	0.001
Allow 3 chamber tracks	0.002

lowed; (ii) the plane of the decay restricted to within 53° of the horizontal and loosened to within 66°; (iii) reasonable variations to width of the energy and momentum conservation requirements for the exclusive event selection; and (iv) three-chamber tracks allowed. The shift in the K_S^0 mass for each of these samples is shown in Table III. Since all shifts are less than the statistical error and do not indicate any particular bias, we have not increased the systematic error. Finally, the tape-to-tape corrections for the variations of the magnetic field were removed and the complete analysis repeated. The Λ^0 mass in that analysis increased by 0.001 MeV/c^2, $\sim \frac{1}{6}$ of the statistical error.

Thus, our measurement of the masses yields $M_\Lambda = 1115.678 \pm 0.006 \pm 0.006$ MeV/c^2 and $M_{\bar{\Lambda}} = 1115.690 \pm 0.008 \pm 0.006$ MeV/c^2 where the errors shown are statistical and systematic in that order. Our result has over 20 times the statistics of the Hyman *et al.* [2] result and has an uncertainty 12 times smaller. A constrained fit to determine new world averages following the procedures of Ref. [1] using the data and errors they report yields the results in Table IV.

TABLE IV. New world averages (MeV/c^2).

Λ^0	1115.667 ± 0.009
Σ^+	1189.37 ± 0.06
Σ^0	1192.58 ± 0.09
Σ^-	1197.46 ± 0.05
Λ^0-$\bar{\Lambda}^0$	-0.012 ± 0.015
Σ^--Λ^0	81.71 ± 0.07
Σ^0-Λ^0	76.85 ± 0.19
Σ^--Σ^0	4.88 ± 0.08
Σ^--Σ^+	8.19 ± 0.14

A simultaneous measurement of particle and antiparticle masses in the same apparatus greatly reduces the systematic uncertainty in testing the *CPT* invariance prediction of particle-antiparticle mass equality. Since systematic effects change the Λ^0 and $\bar{\Lambda}^0$ mass in the same fashion in this measurement, we compare the masses using only the statistical uncertainties. The Λ^0-$\bar{\Lambda}^0$ mass difference for the inclusive samples is -0.012 ± 0.010 MeV/c^2. The fractional mass difference (difference/average) is $-1.08 \pm 0.90 \times 10^{-5}$. We interpret this agreement with 0 to 1.2 standard deviations as confirmation that invariance under *CPT* is verified in the Λ^0-$\bar{\Lambda}^0$ system to 1 part in 10^5. Our result is more than a factor of 10 improvement over the most recent world average.

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