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Precise measurement of the Σ^0 mass

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We have obtained precise measurements of the Σ^0 mass and the Σ^0-Λ^0 mass difference from a fit to the $\Lambda^0\gamma$ invariant mass distribution of 3327 $\Sigma^0\rightarrow\Lambda^0+\gamma$ decays. Our measurements yield $M_{\Sigma^0}=1192.65\pm0.020\pm0.014$ MeV/c^2 and $M_{\Sigma^0}-M_{\Lambda^0}=76.966\pm0.020\pm0.013$ MeV/c^2, where the uncertainties are statistical and systematic in that order. This represents a significant improvement over all previous determinations and is the first direct measurement of the Σ^0 mass itself. [S0556-2821(97)00717-0]

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The precise measurement of fundamental physical constants such as the hyperon masses and mass differences between hyperons represents an important task of experimental physics. In addition to making a significant improvement in our knowledge of these fundamental constants, we note that the precise measurement of the baryon masses, the Σ^0-Λ^0 system in particular, provides essential input to modern theoretical work in understanding the constituent interactions [1]. This includes recent work in determining the baryon octet and decuplet mass relationships [2]. Thus, a program to determine the baryon masses to high precision is an important contribution to a quantitative understanding of the strong interaction.

Given the importance of these quantities, it is surprising that our knowledge of some of these masses is based on analyses of limited statistics data collected by emulsion and bubble chamber experiments, some of which were performed over two decades ago [3–7]. The best experimental values of the Σ^0 hyperon mass and the Σ^0-Λ^0 mass difference, for instance, are those of Schmidt [4]—$M_{\Sigma^0}=1192.41\pm0.14$ MeV/c^2 and $M_{\Sigma^0}-M_{\Lambda^0}=76.63\pm0.28$ MeV/c^2, which were determined in 1965 with 208 events in a hydrogen bubble chamber. It is also surprising that in all previous experiments, the measured parameter is the mass difference rather than the mass of the Σ^0 itself. In this paper, we report a measurement of the Σ^0 mass that is not only the first direct measurement of that quantity but is also significantly more precise than any previous determination.

Our measurements were made on data collected by experiment E766 at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS). Using a spectrometer consisting of six narrow-wire-spacing, high-rate drift chambers, the E766 detector [8] measured charged particle trajectories produced by 27.5 GeV/c proton interactions in a 30 cm long liquid hydrogen target. In a data taking period of two weeks, 300 million high multiplicity final state pp interactions were written to tape. This sample was reconstructed with a specially designed dedicated hardware processor [9]. Various components of the detector, data acquisition system, electronics, and triggers are described in greater detail elsewhere [8–13]. The mass resolution achieved in this spectrometer is rather high. The standard deviation of the Λ^0 mass distribution is 0.5 MeV/c^2 [12].

As shown in Ref. [12], a limiting factor in the accuracy of a mass measurement is the knowledge of the magnetic field in the momentum analyzing spectrometer. For that reason, we went to some length to calibrate the field as follows. The magnetic field map of the spectrometer was determined with the Fermilab ZIPTRACK system [14] and initially aligned using surveying techniques and the symmetry of the field. Using a sample of 60 000 exclusive events containing a K_S^0, a detailed study of the dependence of the K_S^0 mass on various parameters such as the location of the decay point, the ori-

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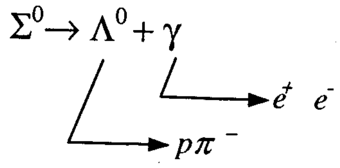
entation of the plane of decay, the trajectories of the K_S^0 decay products, and the K_S^0 momentum enabled us to improve the initial alignment of the field grid to within an uncertainty of ± 0.127 cm in each direction. As a final step, the entire field was then normalized to fix the measured mass of the K_S^0 at the world average of 497.672 ± 0.031 MeV/c^2 [7]. More details concerning these procedures involving the magnetic field can be found in Ref. [12].

The Σ^0 mass measurement utilized events of the decay



(1)

where the γ converts into an electron pair in the material in the spectrometer. Candidates for reaction (1) consisted of events containing a single Λ^0 vertex and a single γ candidate whose $\Lambda^0\gamma$ invariant mass was within ± 20 MeV/c^2 of the current world average Σ^0 mass of 1192.55 MeV/c^2 [7]. The procedures to select Λ^0 vertices are described in Ref. [12]. γ candidates were identified by looking for small-opening-angle, oppositely charged, particle pairs. For such pairs, we measured q_T, the transverse component of the relative pair momentum in the c.m. frame defined by $q_T = 2|\vec{P}^+ \times \vec{P}^-|/|\vec{P}^+ + \vec{P}^-|$ where $\vec{P}^+$ and $\vec{P}^-$ are the laboratory momentum vectors of the positive and negative particles, respectively [11].

Special attention was given to the determination of the conversion point of the decay γ from the Σ^0. Since the electron and positron from γ conversion are produced with a small-opening angle (on the order of m_e/E_e), their momenta at the conversion point is nearly parallel to the momentum of the γ. Thus, the location of the conversion point along the γ momentum direction would naively seem difficult to ascertain. However, since the magnetic field of the spectrometer causes the two oppositely charged particles from the γ conversion to bend in opposite directions, q_T^2 increases as the two tracks move away from the conversion point. Thus, the position of the conversion point can be located by searching for that point where q_T^2 is a minimum. In that search, the particle tracks are refit using the conversion point position as a constraint. The position where q_T^2 is minimized is taken as the correct γ conversion point. Figure 1 shows the q_T^2 distribution of the small-opening-angle pairs after the correct conversion point was obtained. A pair was considered to be a γ candidate if $q_T^2 < 10$ (MeV/c)^2.

The electron pair produced by the conversion of the decay γ from the Σ^0 loses energy due to ionization and bremsstrahlung in the detector material. The resulting $\Lambda^0\gamma$ invariant mass distribution is asymmetric exhibiting a low-energy "tail." In order to minimize these effects, we restricted our analysis to those γ's which converted in material outside the liquid hydrogen. In addition, because no analytic description of this distribution can be reliably obtained, we have resorted to a detailed Monte Carlo simulation of the detector in order to produce the expected invariant mass distribution.

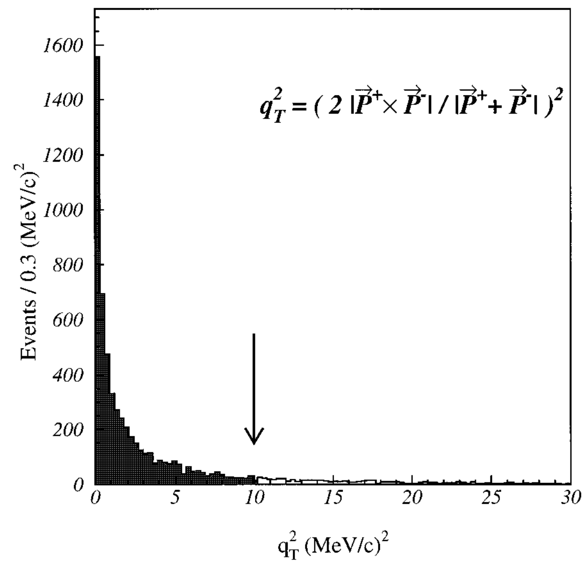


FIG. 1. q_T^2 distribution of candidate e^+e^- pairs from the γ conversion of $\Sigma^0 \to \Lambda^0 + \gamma$ events. The arrow shows the location of the cut used.

The code used for the Monte Carlo simulation of the detector was written specifically for BNL E766 and has been validated in a number of analyses [8,11,13]. For the Σ^0 mass analysis, we have improved the simulation of photon pair production [15] and electron energy loss through ionization [16] and bremsstrahlung [17].

The events generated for the simulation were derived from the real data with the hybrid Monte Carlo technique [18]. In order to insure that our simulated events were as realistic as possible, all of the detector data from the real Σ^0 data sample were retained except for those related to the decay children of the Σ^0. For each generated event, a Σ^0 of fixed mass ($M_{\Sigma^0} = 1.19255$ GeV/c^2) was decayed isotropically in its center-of-mass system into a Λ^0 and a γ which were boosted into the laboratory frame using the original Σ^0 momentum from the real data. The Λ^0 was allowed to decay isotropically in its center-of-mass system into a p and a π^- and with an exponential decay length distribution having a mean lifetime of 2.63×10^{-10} sec [7]. The p and π^- were then boosted into the laboratory frame with the Λ^0 momentum. The γ was propagated through the simulation of the detector and converted into an e^+e^- pair at a frequency determined by its conversion cross section in the detector material. Finally, all four particles: p, π^-, e^+, and e^- were propagated through the detector simulation producing the appropriate detector responses. The resulting data tape was then subjected to the same reconstruction and analysis algorithms as the real data.

Comparing the distributions of the simulated data with those of the actual data revealed biases due to the acceptance of the detector and the reconstruction algorithms. These biases selected against low momentum Σ^0's and events with interaction vertices in the downstream portion of the liquid hydrogen target. Corrections were made in the simulation by generating more events with low momentum Σ^0's and downstream interaction vertices such that the final distributions agreed.

The resulting $\Lambda^0\gamma$ invariant mass distribution was then

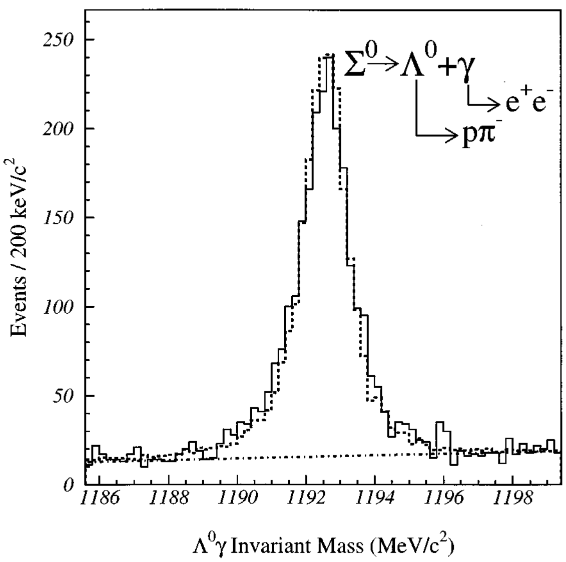


FIG. 2. Invariant mass for $\Sigma^0 \to \Lambda^0 + \gamma$ events (solid line) fit to the Monte Carlo distribution (dashed line) added to a linear background (dot-dashed line).

taken to represent the expected distribution for the Σ^0 decay in the detector subject to all of the relevant energy loss mechanisms. This simulated distribution was used to fit the actual data using a fitting procedure that involved varying four parameters. The simulated distribution was allowed to shift in invariant mass and its integrated area was allowed to vary (two parameters). A linear background term was also added to this distribution (two parameters). The χ^2 formed by the square of the difference between the simulated distribution and the actual distribution was minimized by allowing these four parameters to vary. The final Σ^0 mass value was obtained by shifting the value input to the event generator in the same amount that the initial simulated distribution was shifted to obtain a minimum χ^2.

For the real Σ^0 sample, selecting only events with γ candidates converting in material outside the liquid hydrogen resulted in 3327 events with a $\Lambda^0\gamma$ invariant mass between 1185.6 and 1199.4 MeV/c^2. The $\Lambda^0\gamma$ invariant mass

$$M^2_{\Lambda^0\gamma} = M^2_{\Lambda^0} + 2(E_{\Lambda^0} P_\gamma - \vec{P}_{\Lambda^0} \cdot \vec{P}_\gamma)$$

was calculated using the world average Λ^0 mass of 1115.684 MeV/c^2 [7] and the reconstructed laboratory momenta of the Λ^0 and the γ. The solid line in Fig. 2 shows this distribution in 0.2 MeV/c^2 bins. Using the procedure described above,

TABLE I. Systematic uncertainties in the Σ^0 mass, and Σ^0-Λ^0 mass difference due to uncertainties in the values of the K^0_S and Λ^0 masses used (values used are $M_{K^0_S} = 497.672 \pm 0.031$ MeV/c^2 and $M_{\Lambda^0} = 1115.684 \pm 0.006$ MeV/c^2).

	Derivatives	Uncertainty (MeV/c^2)	Contribution (MeV/c^2)
Σ^0	$\partial M_{\Sigma^0} / \partial M_{K^0_S} = 0.25$	± 0.031	± 0.0077
	$\partial M_{\Sigma^0} / \partial M_{\Lambda^0} = 1.0$	± 0.006	± 0.006
Σ^0-Λ^0	$\partial (M_{\Sigma^0} - M_{\Lambda^0}) / \partial M_{K^0_S} = 0.25$	± 0.031	± 0.0077
	$\partial (M_{\Sigma^0} - M_{\Lambda^0}) / \partial M_{\Lambda^0} = 0.0$	± 0.006	± 0.0

TABLE II. The procedure to determine these values follows the outline in Ref. [7] using Lagrange multipliers to implement the constraints and adding the Σ^0 mass as another measurement. The italicized values differ from those in Ref. [7] by more than 1σ.

New world averages (MeV/c^2)			
Σ^-	1197.451 ± 0.031	Σ^--Λ^0	*81.694±0.066*
Σ^0	*1192.65±0.025*	Σ^0-Λ^0	*76.96±0.03*
Σ^+	1189.37 ± 0.06	Σ^--Σ^0	4.86 ± 0.07
Λ^0	1115.683 ± 0.006	Σ^--Σ^+	8.10 ± 0.11

this result was fit to the Monte Carlo distribution which is shown by the dotted line superimposed on the real distribution in Fig. 2. The observed width of the $\Sigma^0 \to \Lambda^0 + \gamma$ decay is reproduced nicely by the simulated events. The value of the Σ^0 mass from this fit is 1192.65 ± 0.020 MeV/c^2. The χ^2 is 79 for 65 degrees of freedom. By subtraction, this result yields $M_{\Sigma^0} - M_{\Lambda^0} = 76.966 \pm 0.020$ MeV/c^2. We note that our determination of the Σ^0 mass is the first direct measurement of that parameter [19].

Two sources of systematic uncertainties in our measurements are the uncertainty in the value of the Λ^0 mass used in obtaining these results and the uncertainty in the value of the K^0_s mass used in calibrating the magnetic field [12]. In order to determine the systematic uncertainties and to permit accurate corrections of our results if the world averages of the Λ^0 and K^0_s masses change, we present in Table I the derivatives of M_{Σ^0} and $M_{\Sigma^0} - M_{\Lambda^0}$ with respect to M_{Λ^0} and $M_{K^0_s}$ and the contributions of each of these to the systematic uncertainties.

We investigated possible systematic effects on the Σ^0 mass from the acceptance corrections in the simulation described above. The complete analysis was performed with samples in which the acceptance correction was varied significantly. Extrapolating to the cases where the χ^2 agreement between the real data and the simulated data increased by one from the optimum, we estimate that the systematic error due to this correction could be no larger than ± 0.0005 MeV/c^2.

To study possible systematic effects due to the uncertainties ($\pm 5\%$) in the amount of material used in the simulation, the complete analysis was repeated with that material increased by 10%. The contribution to the systematic error from this source is less than ± 0.01 MeV/c^2.

Combining the contributions from all four sources mentioned above in quadrature gives systematic uncertainties of ± 0.014 MeV/c^2 for M_{Σ^0} and ± 0.013 MeV/c^2 for $M_{\Sigma^0} - M_{\Lambda^0}$.

In conclusion, we report the following values measured in this experiment:

$$M_{\Sigma^0} = 1192.65 \pm 0.020 \pm 0.014 \ \ \text{MeV}/c^2$$

and

$$M_{\Sigma^0} - M_{\Lambda^0} = 76.966 \pm 0.020 \pm 0.013 \ \ \text{MeV}/c^2.$$

Our result for the Σ^0 mass has an uncertainty that is 7 times smaller than the result of Schmidt [4] with about 16 times the statistics. The uncertainty on the $\Sigma^0 - \Lambda^0$ mass difference is

14 times better than the result in this same reference. The existence of these improved values and the first direct Σ^0 mass measurement suggest a need to recalculate the world averages. With our value of the Σ^0 mass included as a directly measured quantity, we do a constrained fit following the procedures described in Ref. [7] and using their reported values and uncertainties for all other masses. This yields the new world averages presented in Table II.

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