PHYSICAL REVIEW D, VOLUME 61, 031101(R)

Measurement of the $\overline{\Sigma}^-$ lifetime and direct comparison with the Σ^+ lifetime

R. F. Barbosa,[1] I. F. Albuquerque,[1,*] N. F. Bondar,[3] R. Carrigan,[2] D. Chen,[9] P. S. Cooper,[2] Dai Lisheng,[4] A. S. Denisov,[3] A. V. Dobrovolsky,[3] T. Dubbs,[7] A. M. F. Endler,[11] C. O. Escobar,[1,†] M. Foucher,[13,‡] V. L. Golovtsov,[3] H. Gottschalk,[2,§] P. Gouffon,[1] V. T. Grachev,[3] A. V. Khanzadeev,[3] M. A. Kubantsev,[8] N. P. Kuropatkin,[3] J. Lach,[2] J. Langland,[7] Lang Pengfei,[4] Li Chengze,[4] Li Yunshan,[4] M. Luksys,[10] J. R. P. Mahon,[1,‖] E. McCliment,[7] A. Morelos,[2,¶] C. Newsom,[7] M. C. Pommot Maia,[12] V. M. Samsonov,[3] V. A. Schegelsky,[3] Shi Huanzhang,[4] V. J. Smith,[5] Tang Fukun,[4] N. K. Terentyev,[3,**] S. Timm,[6,††] I. I. Tkatch,[3] L. N. Uvarov,[3] A. A. Vorobyov,[3] Yan Jie,[4] Zhao Wenheng,[4] Zheng Shuchen,[4] and Zhong Yuanyuan[4]

(E761 Collaboration)

[1]*Instituto de Física, Universidade de São Paulo, Brazil*
[2]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[3]*Petersburg Nuclear Physics Institute, Gatchina, Russia*
[4]*Institute of High Energy Physics, Beijing, People's Republic of China*
[5]*H. H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
[6]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[7]*University of Iowa, Iowa City, Iowa 52242*
[8]*Institute of Theoretical and Experimental Physics, Moscow, Russia*
[9]*State University of New York at Albany, Albany, New York 12222*
[10]*Universidade Federal da Paraiba, João Pessoa, Brazil*
[11]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[12]*Conselho Nacional de Pesquisas CNPq, Rio de Janeiro, Brazil*
[13]*J. W. Gibbs Laboratory, Yale University, New Haven, Connecticut 06511*

(Received 4 October 1999; published 21 December 1999)

We have measured the lifetime of the $\overline{\Sigma}^-$ using the Fermilab Proton Center 375 GeV/*c* charged hyperon beam. We obtained $(80.43\pm0.80\pm0.14)$ ps. We also measured the lifetime of the Σ^+, obtaining $(80.38\pm0.40\pm0.14)$ ps, in agreement with the Particle Data Group value. A direct comparison between the two lifetimes from the ratio of the decay curves gives a fractional lifetime difference of $\Delta\tau/\overline{\tau}=(-0.06\pm1.12)\%$, consistent with equal lifetimes for baryon and antibaryon as required by *CPT* invariance.

PACS number(s): 14.20.Jn, 11.30.Er

I. INTRODUCTION

The E761 experiment was performed at the Fermilab Proton Center beam line during the 1990 fixed target run. The main goals of the experiment were to measure the asymmetry parameter and the branching ratio of the weak hyperon radiative decays $\Sigma^+\to p\gamma$ [1,2] and $\Xi^-\to\Sigma^-\gamma$ [3]. Data taken with the negative beam had a sufficient number of $\overline{\Sigma}^-$ to allow the measurement of its lifetime, using the decay $\overline{\Sigma}^-\to\overline{p}\pi^0$. The positive beam used for the Σ^+ radiative decay allowed the measurement of the Σ^+ lifetime through the more copious decay $\Sigma^+\to p\pi^0$. This can be compared with the currently accepted value [4] and allows a direct comparison with its antiparticle lifetime. This comparison is a test of *CPT* conservation, which requires equal lifetimes for a particle and its antiparticle.

II. EXPERIMENTAL SETUP

The 800 GeV/*c* proton beam was focused on a 1 interaction length (15 cm) Cu target (0.5 mm wide, 2.0 mm high) to produce a 375 GeV/*c* charged hyperon beam. This target was placed at the beginning of a channel inside the 7.3 m long hyperon magnet (Fig. 1). One could choose between a positive or negative hyperon beam by reversing the polarity of the hyperon magnet and all the spectrometer magnets without modifying the geometry of the apparatus.

The spectrometer was divided into three main components in order to measure the momenta of the hyperon and the baryon, and the photon energy in the decays $\Sigma^+\to p\gamma$ and $\Sigma^+\to p\pi^0$ followed by $\pi^0\to2\gamma$. The hyperon spectrometer was formed by three 50 μm pitch, silicon strip detector (SSD) stations, each with 3 views (0°, 90°, and 45°), and

*Present address: Fermi National Accelerator Laboratory, Batavia, IL 60510.

†Present address: Instituto de Física da Universidade Estadual de Campinas, Depto. de Raios Cósmicos, Campinas SP, Brazil.

‡Present address: Raytheon Systems Company, P. O. Box 1201, Tewksbury, MA 01876.

§Present address: IBM do Brazil, São Paulo, Brazil.

‖Present address: Universidade Estadual do Rio de Janeiro, Brazil.

¶Present address: Instituto de Física, Universidad Autónoma de San Luis Potosí, San Luis Potosí, S.L.P. 78240 Mexico.

**Present address: Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213.

††Present address: Department of Physics, SUNY Albany, Albany, NY 12222.

0556-2821/99/61(3)/031101(4)/$15.00

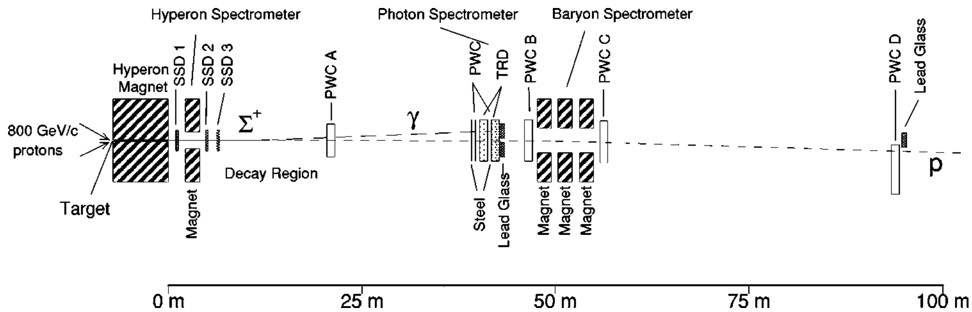

FIG. 1. Plan view of the E761 apparatus in the Fermilab Proton Center charged beam line (not to scale).

one dipole magnet with a field integral of 4.75 T m. The resolutions (σ) achieved by this spectrometer were $\sigma_p/p = 0.7\%$, 12 μrad, and 5 μrad for momentum, horizontal (bend plane), and vertical (nonbend plane) angles, respectively, at 375 GeV/c. The baryon spectrometer was composed of three 1 mm wire spacing and one 2 mm wire spacing, multiwire proportional chamber (MWPC) stations, a total of 30 planes in 4 views ($8\times0°$, $8\times90°$, $7\times45°$, and $7\times135°$) with three dipole magnets connected in a series, with a field integral of 7.9 T m. The resolutions (σ) achieved were $\sigma_p/p=0.2\%$, 9 μrad, and 6 μrad for momentum, horizontal, and vertical angles, respectively. Between the hyperon and the baryon spectrometers a 12 m long decay region was filled with helium bags in order to minimize the multiple scattering. The photon spectrometer, consisting of a set of transition radiation detectors (TRD) and an array of lead glass blocks, is described in detail in [1,2]. The photon spectrometer was part of the trigger but its data were not used in this analysis. One relevant characteristic is the existence of a 7.6×7.6 cm^2 hole in the lead-glass calorimeter which allowed the passage of the beam and the antiproton (proton).

The trigger required one charged particle in the hyperon spectrometer, one in the baryon spectrometer and electromagnetic energy in the photon calorimeter.

III. DATA ANALYSIS

The analysis was done using the data taken by E761 with negative beam in the configuration described above, for the $\overline{\Sigma}^-$. A small fraction of the total Σ^+ sample with positive beam was also used in order to compare the lifetimes with similar statistical precision.

A. Event reconstruction and selection

Tracks were fit in the hyperon and baryon spectrometers and accepted if the reduced χ^2 was less than 4.0 and 2.0, respectively. The ratio of the baryon momentum P_B to the hyperon momentum P_Y, $R=P_B/P_Y$ was required to be greater than 0.6 and the angle Θ_{YB} between the hyperon and the baryon momenta to be less than 0.8 mrad in order to select the $\overline{\Sigma}^-\to\overline{p}X$ decay. Events with $R>0.95$ and $\Theta_{YB}<50$ μrad were discarded as beam interactions. Furthermore, the reconstructed squared mass of the neutral particle, m_X^2, in the hypothesis of a $\overline{\Sigma}^-$ decaying into an antiproton and a neutral particle was required to be within 0.028 (GeV/c^2)^2 of the π^0 squared mass, selecting $\overline{\Sigma}^-\to\overline{p}\pi^0$ events. The $\pi°$ squared mass peak has a standard deviation of 0.0028 (GeV/c^2)^2. The width of the cut is thus 10σ, so a good sample of the background is available on both sides of the peak for later subtraction.

From these events, we selected those that had a reconstructed vertex in the decay volume with an uncertainty $\sigma<1$ m and the $\overline{\Sigma}^-$ momentum between 340 and 420 GeV/c. The extrapolated baryon track was required to be at least 1.5 mm from the walls of the hole in the lead-glass photon calorimeter.

The main background is the $K^{-(+)}\to\pi^{-(+)}\pi^0$ decay. The events which satisfied this decay hypothesis [$|m_X^2-m_{\pi^0}^2|<0.004$(GeV/$c^2$)^2] were discarded. The π^0 squared mass peak for this decay has a standard deviation of 0.0019 (GeV/c^2)^2.

The decay vertex position was then translated to the $\overline{\Sigma}^-$ proper time assuming $m_{\overline{\Sigma}^-}=m_{\Sigma^+}$. This hypothesis was verified by comparing the reconstructed Σ^+ and $\overline{\Sigma}^-$ masses using the Particle Data Group [4] values for the π^0 (m_{π^0}) and proton (m_p) masses and considering that the mass of the proton and the antiproton are the same. The reconstructed masses differ by less than 0.03%, much less than the precision of the lifetime measured here. The masses also agree with the current value for the Σ^+ mass [4].

The data were divided into 8 momentum bins (from 340 to 420 GeV/c) and 20 proper time bins (from 17.5 ps to 117.5 ps). For each bin, the reconstructed squared mass of the neutral particle (m_X^2) was histogrammed. The number of decays for each proper time and momentum bin was determined using side band subtraction in the m_X^2 histogram and stored in a two-dimensional histogram, proper time vs momentum, in order to do the acceptance correction.

Of the 1.78×10^6 negative beam analyzed events, about 0.132×10^6 survived the cuts.

B. Acceptance correction

The decay curve was corrected assuming that the acceptance of the apparatus depends on the vertex position (now proper time) and momentum only. The apparatus was simulated using a GEANT V3.21 based Monte Carlo program [5]. In order to evaluate the acceptance correction, 16×10^6 decays were generated. Half of this sample was reconstructed using the same cuts as the data and histogrammed with the same binning and side band subtraction technique as de-

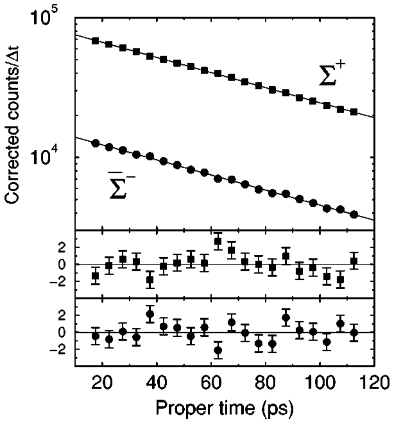

FIG. 2. Decay curves of the $\overline{\Sigma}^-$ and Σ^+ after acceptance correction. The pull variables $[(Counts-Fit)/\sigma_{Counts}]$ are shown at the bottom.

scribed above for the data. The momentum and decay position of the other half was histogrammed directly from the simulated values. The ratio of the two histograms was calculated for each bin, giving the efficiency $\epsilon(T_i,p_j)$ at a proper time T_i and momentum p_j as

$$\epsilon(T_i,p_j)=\frac{R(T_i,p_j)}{G(T_i,p_j)},$$

where $R(T_i,p_j)$ is the number of reconstructed Monte Carlo events from the first half and $G(T_i,p_j)$ the number of generated Monte Carlo events of the second half.

The number of events in each bin of the data histogram was then divided by the corresponding efficiency, giving the number of decays. The momentum was then integrated, giving the decay curve shown in Fig. 2. The statistical uncertainty was propagated through all the steps.

An exponential was fit to this histogram, giving a lifetime of (80.43 ± 0.80) ps with a total χ^2 of 22.0 with 18 degrees of freedom. Figure 2 includes the plot of the pull variables (data minus fit)/σ of the fit, showing the quality of the fit.

The same analysis was done using a sample of 1.67×10^6 positive beam events, of which 0.64×10^6 survived the cuts.[1] The fitted lifetime is (80.38 ± 0.40) ps with a total χ^2 of 23.4 with 18 degrees of freedom.

C. Systematic errors

Quantities that could affect the lifetime are momentum calibration and selection cuts. A detailed magnet calibration was done for the determination of the Σ^+ and $\overline{\Sigma}^-$ hyperon magnetic moments [7], with an accuracy (0.15%) much higher than the statistical precision obtained here. Its effects on the momentum, and thus on the proper time, is negligible. The fact that the reconstructed masses agree with the PDG values is also an evidence of the correct momentum calibration.

The cuts that had some effect on the lifetime are the track χ^2, the Z-vertex resolution, the neutral mass for the kaon decay, the sideband subtraction limits, and the decay volume size. For each of these, the value of the cut was varied and the derivative of the lifetime with respect to the cut was estimated fitting a straight line. These derivatives were multiplied by what would be a reasonable variation for the cut (an estimate of a standard deviation) and all the products added in quadrature.

Finally, the possible effect of resolution smearing in the decay curves was studied. The vertex uncertainty, required to be below 1 m, has a peak at 0.32 m with less than 20% of the events above 0.5 m. The variation of the lifetime while going from 40, 0.3 m wide to 10, 1.2 m wide bins, is less than 1/10 of the statistical uncertainty. Including this small effect with the others discussed above, the final value for the estimate of the systematic uncertainty is 0.14 ps.

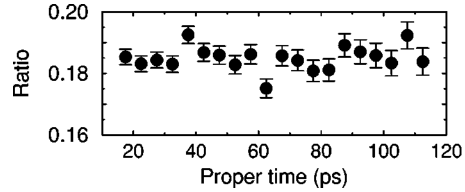

FIG. 3. Ratio of the $\overline{\Sigma}^-$ to the Σ^+ uncorrected decay curves, $\overline{\Sigma}^-/\Sigma^+$.

D. Direct comparison

As noted above, the magnets of the apparatus could have the polarity reversed, passing from the $\Sigma^+\to p\pi^0$ to the $\overline{\Sigma}^-\to\overline{p}\pi^0$ decay without moving detectors and scintillators. One can assume then that the geometrical acceptance and the reconstruction efficiencies are the same for both decays. If this is true, then the histograms of the number of particles decaying at a given proper time with a given momentum would have to be corrected by the same amount. Taking the ratio of these numbers will cancel out the efficiency correction.

This was done by dividing the uncorrected $\overline{\Sigma}^-$ decay histogram by the Σ^+ one, as a function of proper time and momentum, bin by bin. The momentum was then integrated and the ratio as a function of proper time, shown in Fig. 3, was fit with different functions: a constant, a line, a parabola, and an exponential. The fit of a constant is acceptable ($\chi^2=48.4$ with 39 degrees of freedom), higher order polynomials do not improve the fit. If there was a difference in the lifetimes, the ratio would be an exponential. The fit of an exponential yields a decay constant difference of $(37\pm1152)\times10^6$ s^{-1} with a $\chi^2=47.8$ with 38 degrees of freedom, slightly better than that of a straight line ($\chi^2=48.3$ with 38 degrees of freedom).

[1]The fact that proportionally many more Σ^+ in the positive beam sample survived the cuts, than the $\overline{\Sigma}^-$ in the negative beam sample is due to the relative beam fraction: 4.0% of the positive beam is composed of Σ^+ at the target while only 0.1% to 0.2% of the negative beam are $\overline{\Sigma}^-$ [6].

IV. SUMMARY AND CONCLUSION

The lifetime of the $\overline{\Sigma}^-$ is $(80.43 \pm 0.80 \pm 0.14)$ ps, where the first uncertainty is statistical and the second systematic, in agreement with the value for the Σ^+ published by the Particle Data Group [4], (79.9 ± 0.4) ps. The value obtained for the lifetime of the Σ^+ is $(80.38 \pm 0.40 \pm 0.14)$ ps which is also compatible. The direct comparison of the decay curves shows no difference between the lifetimes. This confirms the result that one can deduce from the values obtained here, after correcting the decay curves.

In our measurements we have assumed equality of the Σ^+ and $\overline{\Sigma}^-$ masses, as required by the *CPT* theorem. This is consistent with our data and was verified by comparing the reconstructed Σ^+ and $\overline{\Sigma}^-$ masses, assuming the same mass for p and $\overline{p}$.

The relative lifetime difference can be written as

$$\frac{\tau_{\Sigma^+} - \tau_{\overline{\Sigma}^-}}{(\tau_{\Sigma^+} + \tau_{\overline{\Sigma}^-})/2} = (-0.06 \pm 1.12)\%.$$

The CPT theorem requires equality of the lifetime of the baryon and its corresponding antibaryon. Comparing this with the Λ and the Ξ^- systems [4] we note that the corresponding relative lifetime differences are $(4 \pm 9)\%$ and $(2 \pm 18)\%$, respectively. Thus this measurement represents the most precise measurement of baryon, antibaryon lifetime differences.

ACKNOWLEDGMENTS

R.F.B. and I.F.A. were supported by FAPESP, Brazil. P.G. and J.R.P.M. were partially supported by Fapesp and CNPq, Brazil. M.A.K. was partially supported by the International Science Foundation. A.M. was partially supported by CONACyT, Mexico.

[1] M. Foucher *et al.*, Phys. Rev. Lett. **68**, 3004 (1992).
[2] S. Timm *et al.*, Phys. Rev. D **51**, 4638 (1995).
[3] T. Dubbs *et al.*, Phys. Rev. Lett. **72**, 808 (1994).
[4] Particle Data Group, C. Caso *et al.*, Eur. Phys. J. C **3**, 690 (1998).
[5] GEANT 3.21 CERN Program Library W5103, CERN 1993; N. Kuropatkin (private communication).
[6] J. L. Langland, ''Hyperon and antihyperon production in *p*-Cu interactions,'' Ph.D. thesis, University of Iowa, 1995.
[7] A. Morelos, Phys. Rev. Lett. **71**, 3417 (1993).