Fermi National Accelerator Laboratory

FERMILAB-Pub-95/163-E
E687

First Measurement of the Lifetime of the Ω_c^0

P.L. Frabetti et al.
For the E687 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

June 1995

Submitted to *Physics Letters B*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

FIRST MEASUREMENT OF THE LIFETIME OF THE Ω_c^0

E687 Collaboration

July 14, 1995

P. L. Frabetti
Dip. di Fisica dell'Università and INFN - Bologna, I-40126 Bologna, Italy

H. W. K. Cheung[a], J. P. Cumalat, C. Dallapiccola[b], J. F. Ginkel, S. V. Greene, W. E. Johns, M. S. Nehring
University of Colorado, Boulder, CO 80309, USA

J. N. Butler, S. Cihangir, I. Gaines, P. H. Garbincius, L. Garren, S. A. Gourlay, D. J. Harding, P. Kasper, A. Kreymer, P. Lebrun, S. Shukla, M. Vittone
Fermilab, Batavia, IL 60510, USA

S. Bianco, F. L. Fabbri, S. Sarwar, A. Zallo
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

R. Culbertson[c], R. W. Gardner, R. Greene[d], J. Wiss
University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

G. Alimonti, G. Bellini, M. Boschini, D. Brambilla, B. Caccianiga, L. Cinquini[e], M. Di Corato, M. Giammarchi, P. Inzani, F. Leveraro, S. Malvezzi, D. Menasce, E. Meroni, L. Moroni, D. Pedrini, L. Perasso, F. Prelz, A. Sala, S. Sala, D. Torretta[a]
Dip. di Fisica dell'Università and INFN - Milano, I-20133 Milan, Italy

D. Buchholz, D. Claes[f], B. Gobbi, B. O'Reilly
Northwestern University, Evanston, IL 60208, USA

J. M. Bishop, N. M. Cason, C. J. Kennedy[g], G. N. Kim[h], T. F. Lin, D. L. Puseljic[i], R. C. Ruchti, W. D. Shephard, J. A. Swiatek, Z. Y. Wu
University of Notre Dame, Notre Dame, IN 46556, USA

V. Arena, G. Boca, C. Castoldi, G. Gianini, S. P. Ratti, C. Riccardi, L. Viola, P. Vitulo
Dip. di Fisica Nucleare e Teorica dell'Università and INFN - Pavia, I-27100 Pavia, Italy

A. Lopez, University of Puerto Rico at Mayaguez, PR 00709, Puerto Rico

G. P. Grim, V. S. Paolone, P. M. Yager,
University of California-Davis, Davis, CA 95616, USA

J. R. Wilson, University of South Carolina, Columbia, SC 29208, USA

P. D. Sheldon, Vanderbilt University, Nashville, TN 37235, USA

F. Davenport, University of North Carolina-Asheville, Asheville, NC 28804, USA

G.R. Blackett, K. Danyo, M. Pisharody, T. Handler
University of Tennessee, Knoxville, TN 37996, USA

B. G. Cheon, J. S. Kang, K. Y. Kim
Korea University, Seoul 136-701, Korea

We present the first measurement of the lifetime of the Ω_c^0 baryon. The data were collected in the Fermilab high energy photoproduction experiment E687. The measured lifetime is $\tau = 86^{+27}_{-20}(stat.) \pm 28(syst.)$ fs. Thus the Ω_c^0 has one of the shorter lifetimes among the weakly decaying singly charmed baryons.

Our collaboration has previously measured the lifetimes[1, 2] of all the weakly decaying singly charmed mesons and baryons except the Ω_c^0, finding $\tau_{\Xi_c^0} = 101^{+25}_{-17} \pm 5\ fs$, $\tau_{\Lambda_c^+} = 215 \pm 16 \pm 8\ fs$ and $\tau_{\Xi_c^+} = 410^{+110}_{-80} \pm 20\ fs$. Recently [3] we have published evidence for the Ω_c^0 decay into $\Sigma^+ K^- K^- \pi^+$ (where the Σ^+ hyperon can decay into both channels $n\pi^+$ and $p\pi^0$) at a mass $m_{\Omega_c^0} = (2699.9 \pm 1.5 \pm 2.5)\ MeV/c^2$. Now we present a first measurement of the Ω_c^0 lifetime.

Charm baryon decays are neither helicity nor color suppressed. Therefore W-exchange and light quark interference effects are expected to play a large role and can produce significant differences in the lifetimes of the various singly charmed baryons. Theoretical estimates of the four singly charmed baryon lifetimes have been made [4, 5, 6, 7]. Also Blok and Shifman [8] have reviewed the hierarchical problem of the charm baryon lifetimes and concluded that the Ω_c^0 lifetime is either the shortest or the longest of the set and they conjectured that it may depend upon the importance of the spin-spin interaction between quarks.

The Ω_c^0 lifetime has never been measured before and it completes the picture of the weakly decaying singly charmed baryons helping to discriminate between different theoretical models.

The work presented here is based on the analysis of the decay channel $\Omega_c^0 \rightarrow \Sigma^+ K^- K^- \pi^+$ (in this paper references to specific charge states should be taken to include the charge conjugate state). Data were collected by the fixed target photoproduction experiment E687 at Fermilab during the 1990-91 run period. Approximately 5×10^8 hadronic triggers were recorded on tape. The E687 detector, photon beam and reconstruction methods are described elsewhere [9]. Details on the analysis and selection cuts of the $\Omega_c^0 \rightarrow \Sigma^+ K^- K^- \pi^+$ channel can be found in Reference [3].

Even a cursory inspection of the raw proper time distribution indicates that the lifetime is quite short, comparable to the spectrometer proper time resolution which is predicted by Monte Carlo to be $70 \sim 80$ fs. To successfully measure such short lifetimes, we have had to modify our normal approach to the lifetime analysis by taking accurate account of the smearing of the proper time distribution due to finite vertex resolution and to efficiency and acceptance corrections. Since smearing will cause some true signal events to appear to have negative proper time, events with negative proper time have been included in the fits. Finally, because of low statistics and short lifetime we are unable to check the stability of our results against the significance of detachment (L/σ) as we have done in previous analyses. We have instead studied the stability of the fitted lifetimes against the smallest proper time allowed in the fits, as discussed below.

In the analysis presented here the Σ^+ is observed through its decay modes to $n\pi^+$ and $p\pi^0$.

We treat the twofold ambiguity in the Σ^+ momentum [3] by assigning a weight equal to 0.5 to each solution in cases where both solutions passed all selections. This attempts to avoid possible biases in the proper time distribution. Figures 1a, b and c show the mass plots for the combined

$\Sigma^+ \rightarrow n\pi^+$ and $\Sigma^+ \rightarrow p\pi^0$ samples for all proper times, for proper times greater than -50 fs, and for positive proper times (sample with the best signal-to-noise ratio) respectively. Since the $\Sigma^+ \rightarrow n\pi^+$ and $\Sigma^+ \rightarrow p\pi^0$ samples are kinematically different, the mass, width, amount of background, acceptance and detection efficiency are slightly different. Within the signal region ($m_0 \pm 2\sigma$) there are 43.5 events in the $\Sigma^+ \rightarrow n\pi^+$ sample including background, and 24.0 events in the $\Sigma^+ \rightarrow p\pi^0$ sample including background. The fitted mass and sigma for these two samples are $m_0 = 2700.0\ MeV/c^2$ and $\sigma = 5.6\ MeV/c^2$ for $\Sigma^+ \rightarrow n\pi^+$ and $m_0 = 2698.8\ MeV/c^2$ and $\sigma = 6.4\ MeV/c^2$ for $\Sigma^+ \rightarrow p\pi^0$. These widths are consistent with our mass resolution. Figures 2a and 2b show the proper time distributions for the combined sample in the signal region and sidebands respectively. From our resolutions and backgrounds (Figures 2a and 2b), it is apparent that the information contained in the negative part of the proper time distribution cannot be neglected in the lifetime fit and that special care has to be used to model the acceptance and resolution of the spectrometer.

The number of events in the signal region (defined previously) is $n_{ev} = n_{sig} + n_{bk}$ where n_{sig} is the number of actual signal events and n_{bk} is the number of background events. The actual signal proper time has an expected probability distribution which is a convolution of an exponential with a correction function due to the smearing and acceptance which affect the proper time measurement. The distribution is

$$F^0(t^*) = \int_0^\infty g(t^*, t) \frac{1}{\tau} e^{-t/\tau} dt$$

where t^* is the observed proper time, τ is the Ω_c^0 lifetime, t is the *true* proper time and $g(t^*, t)$ is the acceptance and resolution function. The function $g(t^*, t) dt dt^*$ gives the fraction of events originally generated in an interval dt around the *true* proper time t and *reconstructed* (after acceptance by the apparatus and distortion by resolution) in an interval dt^* around the observed time t^*. The integral over t can be approximated by the following sum

$$F^0(t^*) = \sum_j \frac{1}{\tau} e^{-t_j/\tau} \int_{t_j-\Delta}^{t_j+\Delta} g(t^*, t) dt$$

provided Δ, the half-width of the bin of true or generated t is small enough that $e^{-t_j/\tau}$ can be considered constant over the interval $(t_j - \Delta, t_j + \Delta)$. We

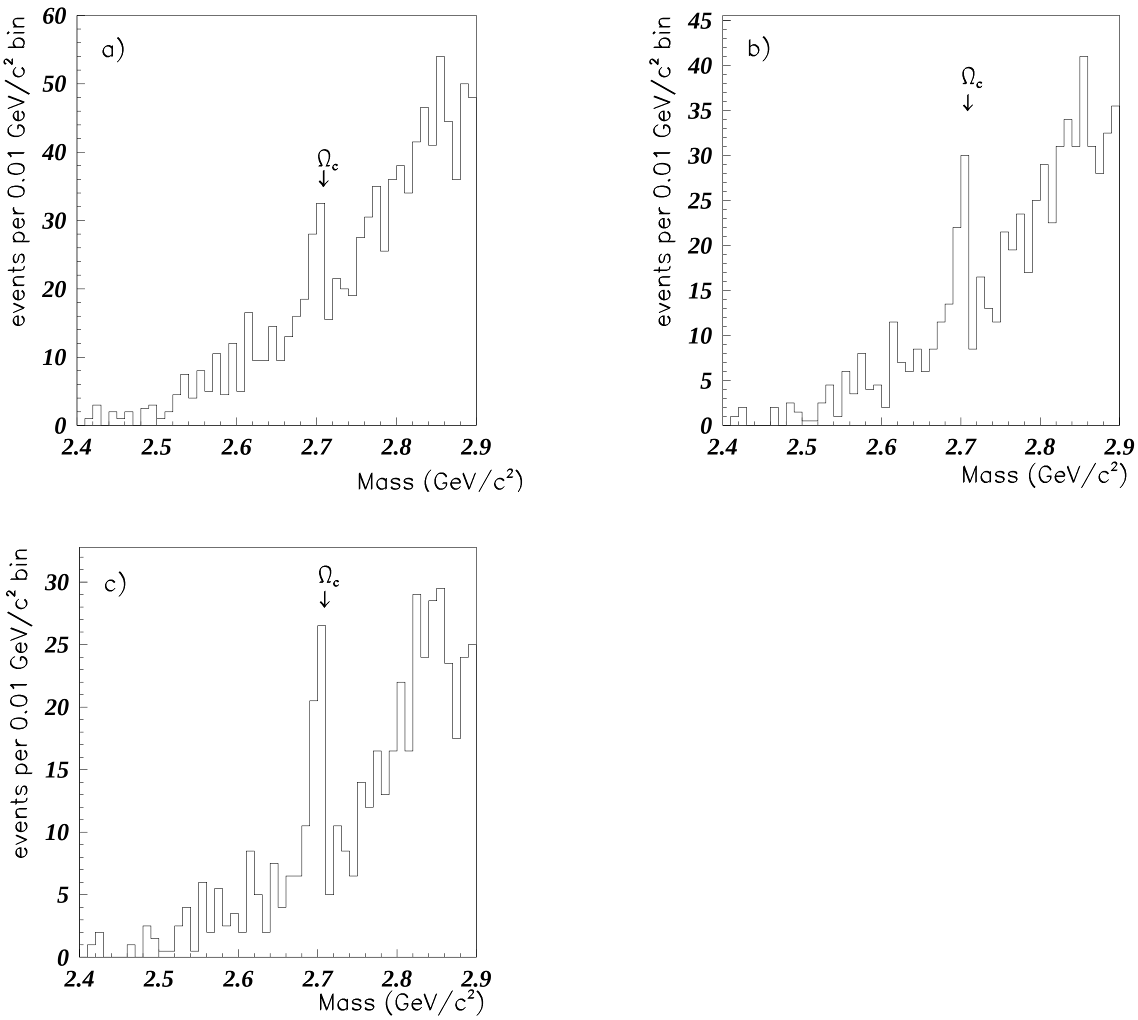

Figure 1: a) The mass distribution for the combined sample; b) the mass distribution for the combined sample for proper times greater than -50 fs; c) the mass distribution for the combined sample for positive proper times.

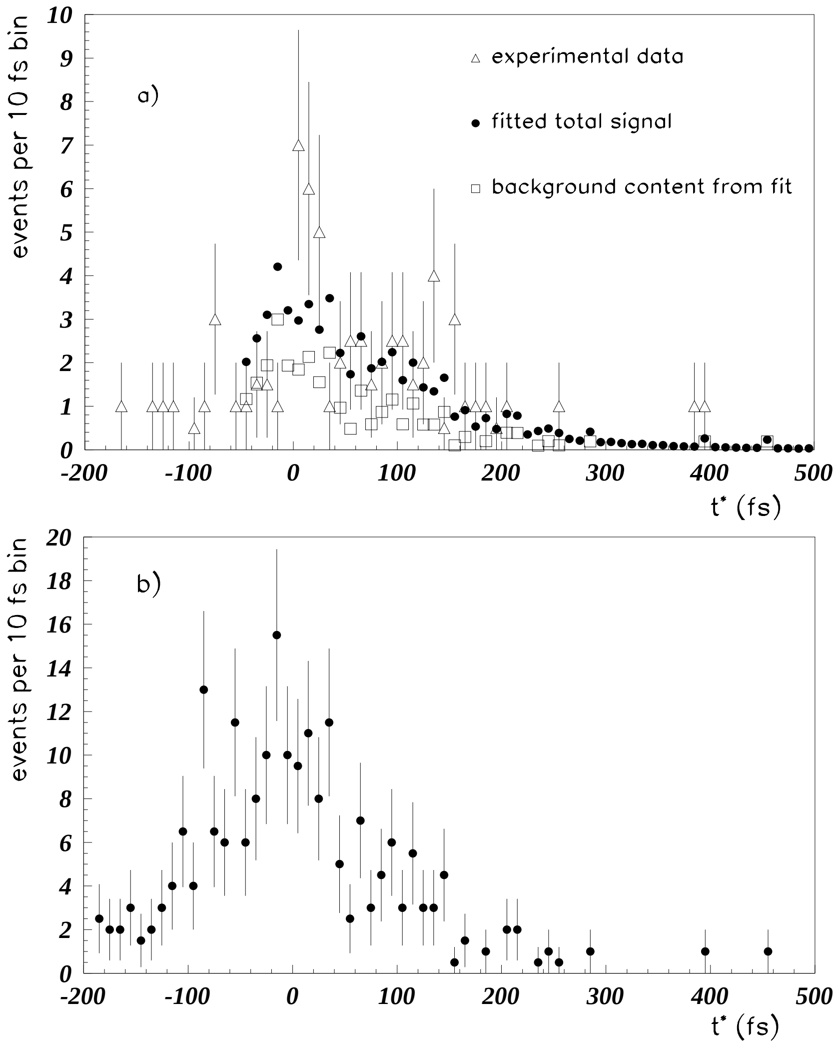

Figure 2: The observed proper time (t^*) distributions for the combined sample : a) in the signal region. The solid circles are the total signal obtained from the fit while the squares are the background contribution. Note that the fit results start from $t^* > -50$ fs, corresponding to the final choice of t^*_{cut} (see text); b) in the sidebands. (The sizes of the sidebands are given in the text).

measure the lifetime using a binned maximum likelihood fitting procedure (described in detail in Ref.[2]) to the data proper time distribution extended to negative values and binned at 10 fs. In the binned maximum likelihood method the likelihood is constructed using a multinomial probability [10] that the predicted number of events n_i in a bin centered around the proper time t_i^*, matches the observed number of events s_i. This is the proper distribution to describe the bin populations when the total number of predicted entries in the histogram is fixed.[1] The likelihood function is

$$\mathcal{L} = \frac{n_{ev}!}{s_1!s_2!\cdots s_r!}\prod_{i=1}^{r}(\frac{n_i}{n_{ev}})^{s_i} = \frac{n_{ev}!n_{ev}^{-n_{ev}}}{s_1!s_2!\cdots s_r!}\prod_{i=1}^{r}(n_i)^{s_i}$$

where s_i is the number of experimentally observed events in the i^{th} bin of proper time; r is the number of bins in the proper time distribution and $\sum_{i=1}^{r} s_i = \sum_{i=1}^{r} n_i = n_{ev}$.

The proper time distribution of background in the Ω_c^0 mass signal region is constrained by using the level of the high and low sidebands, i.e. $(m_0 - 15\sigma)$ to $(m_0 - 5\sigma)$ and from $(m_0 + 5\sigma)$ to $(m_0 + 15\sigma)$. The number of background events in the i^{th} time bin is $n_{bk}\frac{b_i}{s_{bk}}$, where b_i is the number of sideband events in the bin centered at t_i^*, $s_{bk} \equiv \sum b_i$ and n_{bk} is the number of background events in the signal region (a free parameter of the fit).

Finally we can express the predicted events n_i as

$$n_i = (n_{ev} - n_{bk})\frac{\sum_j f(t_i^*, t_j)e^{-t_j/\tau}}{\sum_k \sum_j f(t_k^*, t_j)e^{-t_j/\tau}} + n_{bk}\frac{b_i}{s_{bk}}$$

where we define

$$f(t_i^*, t_j) \equiv \int_{t_i^*-\delta}^{t_i^*+\delta} dt^* \int_{t_j-\Delta}^{t_j+\Delta} g(t^*, t)dt$$

and δ is the half-width of the reconstructed proper time bins ($\delta = 5$ fs). The functions $f(t_i^*, t_j)$, which are independent of τ by construction, were calculated by generating ten million events for each decay channel of the Σ^+ hyperon using the PYTHIA[13] event generator with JETSET[13] fragmentation. The functions include the acceptance and resolution of the apparatus,

[1]Since we always normalize the sum of predicted bin populations to the total number of observed events this leads to exactly the same likelihood distribution as given by the Poisson likelihood used in our earlier papers.[1, 2, 11, 12]

and possible biases in the measured lifetime such as the pull of the primary vertex caused by (undetected) recoil charm particles produced with the Ω_c^0. Figure 3 shows some of the Monte Carlo generated functions $f(t_i^*, t_j)$ for the two samples $\Sigma^+ \to n\pi^+$ (Figures 3a,b) and $\Sigma^+ \to p\pi^0$ (Figures 3c,d). Figure 3 indicates the presence of a bias towards 0 measured lifetime in Figures b) and d) and at most a slight variation in the experimental resolution as a function of t.

An additional factor, the Poisson probability for finding the observed number of events in the background mass sidebands when the expected number is αn_{bk}, is included in the likelihood to tie the value of n_{bk} to the background level expected from the sidebands :

$$\mathcal{L}_{bk} = \frac{e^{-\alpha n_{bk}} \times (\alpha n_{bk})^{s_{bk}}}{s_{bk}!}$$

where α is the ratio of the number of background events in the sidebands to the number of background events under the peak calculated by fitting the experimental $\Sigma^+ K^- K^- \pi^+$ mass plot with a second degree polynomial background function plus a Gaussian. A separate value of α is calculated for each of the two Σ^+ decay mode samples. The total likelihood function is

$$\mathcal{L}_{tot} = \mathcal{L}^{n\pi^+} \times \mathcal{L}_{bk}^{n\pi^+} \times \mathcal{L}^{p\pi^0} \times \mathcal{L}_{bk}^{p\pi^0}$$

where the superscripts refers to the $\Sigma^+ \to n\pi^+$ and $\Sigma^+ \to p\pi^0$ samples respectively. The free parameters of the fit are the Ω_c^0 lifetime τ and the numbers of background events in the signal region for the two samples $n_{bk}^{n\pi^+}$ and $n_{bk}^{p\pi^0}$. The results of the fits to all events and to events with proper times greater than a cut value, defined as t_{cut}^*, are shown in Table 1. This lower proper time cut replaces our usual detachment cut for checking the stability of the fit results. The results are shown graphically in fig. 4. The upper limit on the fitted t_{cut}^* was simply taken as 500 fs, since that range includes all candidate events within the Ω_c^0 signal mass region. The last column in Table 1 shows the results of the Kolmogorov-Smirnov test [14] which gives an estimation of the consistency between the data and the functional form of the fitted function. Limited statistics prevents the study with a t_{cut}^* above 30 fs. We believe that a statistical fluctuation makes the fitted $\Sigma^+ \to p\pi^0$ sample lifetimes shorter than those of the $\Sigma^+ \to n\pi^+$ sample. However within the statistical errors returned by the fit, all fitted lifetime

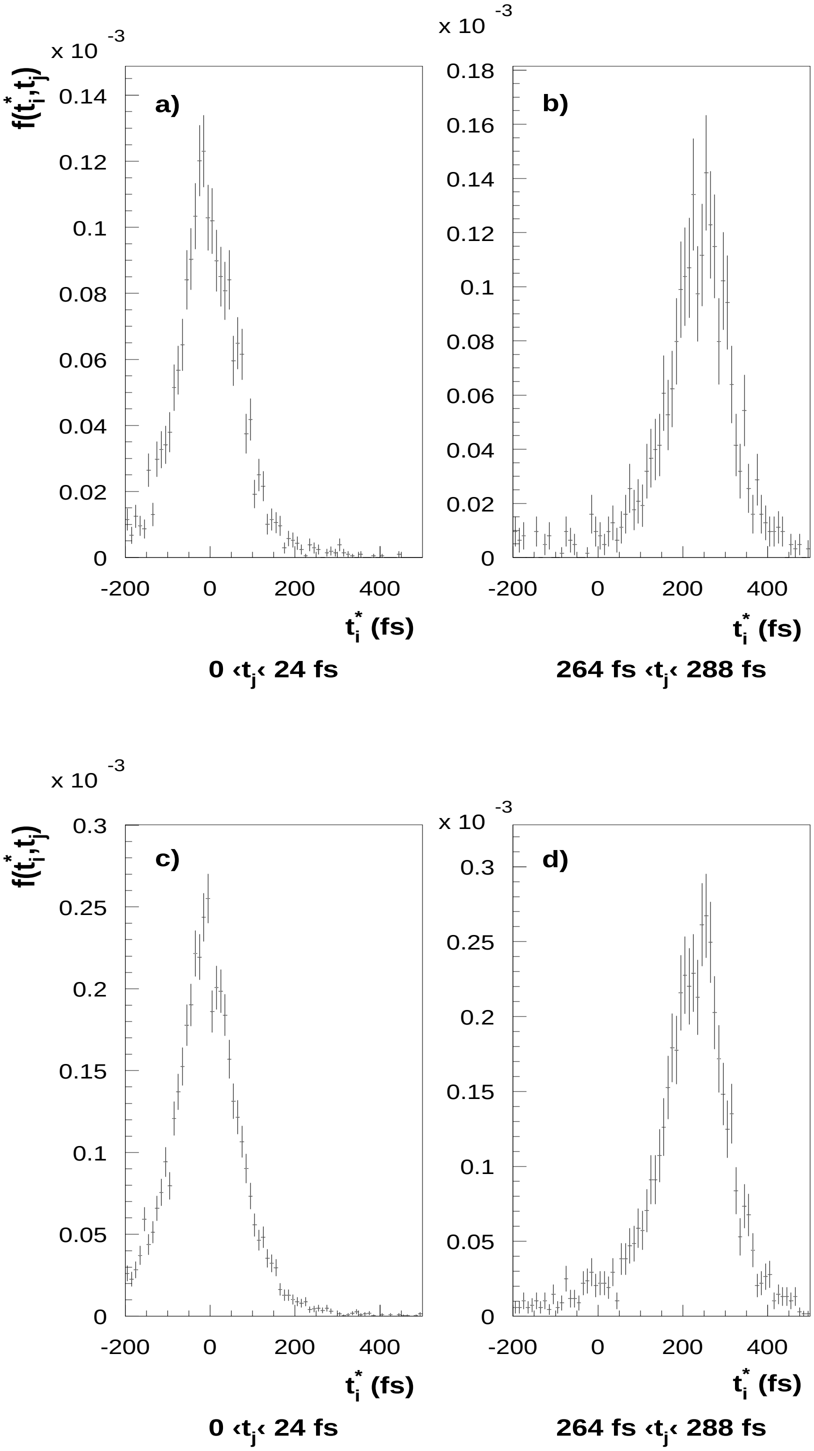

Figure 3: a),b) Monte Carlo generated resolution function $f(t_i^*, t_j)$ for $\Sigma^+ \rightarrow n\pi^+$; t_j is the generated or true lifetime, t_i^* is the reconstructed or observed lifetime; c),d) Monte Carlo generated resolution function $f(t_i^*, t_j)$ for $\Sigma^+ \rightarrow p\pi^0$.

	$\tau(n\pi^+)$	$\tau(p\pi^0)$	τ (combined)	$n_{bk}(n\pi^+)$	$n_{bk}(p\pi^0)$	Signal/Noise	K.S.
t^*_{cut}	All values in fs						probability(%)
all t^*	108^{+47}_{-29}	71^{+51}_{-31}	97^{+32}_{-22}	24.6 ± 2.0	16.1 ± 1.7	0.48 ± 0.08	50.11
$t^* \geq -100$ fs	103^{+43}_{-27}	69^{+49}_{-30}	93^{+30}_{-21}	21.9 ± 1.9	14.2 ± 1.6	0.55 ± 0.1	54.77
$t^* \geq -50$ fs	94^{+38}_{-25}	64^{+44}_{-28}	86^{+27}_{-20}	17.3 ± 1.8	11.5 ± 1.4	0.87 ± 0.21	62.51
$t^* > 0$ fs	76^{+28}_{-21}	38^{+29}_{-30}	64^{+19}_{-16}	11.0 ± 1.4	8.5 ± 1.3	1.40 ± 0.46	53.64
$t^* \geq 10$ fs	84^{+33}_{-23}	39^{+29}_{-30}	71^{+22}_{-17}	9.9 ± 1.3	7.6 ± 1.2	1.17 ± 0.38	48.51
$t^* \geq 20$ fs	86^{+35}_{-24}	43^{+31}_{-26}	74^{+25}_{-18}	8.8 ± 1.3	6.4 ± 1.1	1.08 ± 0.36	48.41
$t^* \geq 30$ fs	100^{+46}_{-28}	37 ± 26	80^{+28}_{-20}	7.8 ± 1.2	5.7 ± 1.0	0.79 ± 0.21	50.72

Table 1: Summary of the fitted Ω_c^0 lifetimes for different t^*_{cut}. The values in the $n_{bk}(n\pi^+)$ and $n_{bk}(p\pi^0)$ columns are the background for the $\Sigma^+ \to n\pi^+$ and $\Sigma^+ \to p\pi^0$ decay channels respectively, returned by the combined sample fit.

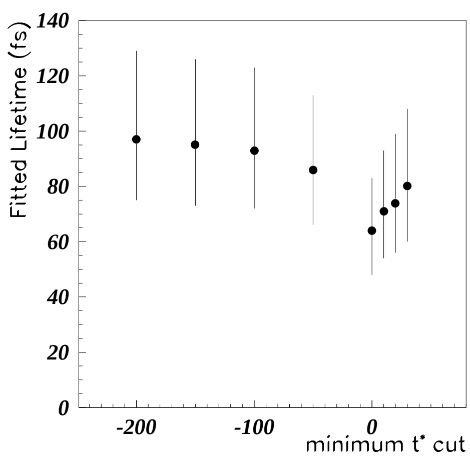

Figure 4: Lifetime of the Ω_c^0 for different minimum t^* cuts.

values are compatible.[2] The signal-to-noise ratio worsens as more bins of negative proper times are included and the signal vanishes as more bins of positive proper time are excluded (see Table 1). We adopt the sample with $t^*_{cut} > -50$ fs as a compromise between a good signal-to-noise ratio and the largest possible statistics. The chosen sample also gives a good probability of the fit based on the Kolmogorov-Smirnov test and the lifetime value is $\tau = 86^{+27}_{-20}$ fs. The solid circles in fig. 2a are the prediction of the fit for the proper time distribution.

The level of systematic uncertainty was investigated by varying the size and location of the sidebands, changing the lifetime of the background, changing the methods of weighting the double solutions, using different bin widths (10, 20, 30 fs) in the proper time plot, using a Gaussian fit to the $f(t^*_i, t_j)$ functions instead of the numerical values directly obtained from Monte Carlo, increasing or decreasing the proper time resolution of the apparatus given by the PYTHIA-JETSET Monte Carlo by 20%, and using a different event generator than PYTHIA-JETSET to calculate the $f(t^*_i, t_j)$ correction functions. The latter was used to generate specific particles recoiling against the Ω^0_c : either a $\overline{\Xi}^0_c$ or a D^- or a mixture of anti-charm particles; the purpose of this check was to investigate the effect on the lifetime of a possible primary vertex "pull" depending on the recoil anti-charm particle lifetime. The contribution of all the above effects is estimated to be ± 7.7 fs.

The relatively large variations of the fitted lifetimes obtained by using different t^*_{cut} values indicates a possible systematic uncertainty. We estimate an upper limit of ± 12.9 fs for this uncertainty. We directly used the calculated lifetimes for two different Ω^0_c momentum ranges to estimate an upper limit of the uncertainty introduced by the possible imperfect simulation of the Ω^0_c momentum spectrum. Due to the relatively large difference between these two lifetimes we obtained a conservative upper limit of ± 21.7 fs. Also we calculated a systematic uncertainty of ± 8.0 fs due to the calculation of the correction function with limited Monte Carlo statistics. Summing in quadrature the above mentioned contributions results in a total systematic uncertainty of ± 27.6 fs. Finally for this short-lived state, the absorption

[2] In fact, the two signal region events near $t^*_{cut} = 400$ fs in Figure 2a are both from the $\Sigma^+ \to n\pi^+$mode. Excluding these two high lifetime points would decrease the lifetime for the $\Sigma^+ \to n\pi^+$mode by approximately 20 fs.

correction was found to be negligible. The final value for the Ω_c^0 lifetime is

$$\tau = 86^{+27}_{-20}(stat) \pm 28(syst)\ fs.$$

We conclude that the Ω_c^0 has one of the shorter lifetimes among the weakly decaying singly charmed baryons, not one of the longest lifetimes.

We wish to acknowledge the assistance of the staff of the Fermi National Accelator Laboratory, the Italian National Institute of Nuclear Physics (INFN) and the Physics Departments of the collaborating institutions. This research was supported by the U.S. National Science Foundation, the U.S. Department of Energy, the Italian Istituto Nazionale di Fisica Nucleare and Ministero delle Università della Ricerca Scientifica e Tecnologica and the Korean Science and Engineering Foundation. One of us (V. A.) acknowledges the support of Fondazione Angelo della Riccia for a fellowship.

References

[a] Present address: Fermilab, Batavia, IL 60510, USA.

[b] Present address: University of Maryland, College Park, MD 20742, USA.

[c] Present address: Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA.

[d] Present address: Syracuse University, Syracuse NY 13244-1130 , USA

[e] Present address: University of Colorado, Boulder, CO 80309, USA.

[f] Present address: University of New York, Stony Brook, NY 11794, USA.

[g] Present address: Yale University, New Haven, CN 06511, USA.

[h] Present address: Pohang Accelerator Laboratory, Pohang, Korea.

[i] Present address: Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA.

[1] a) P. L. Frabetti *et al.*, Phys. Rev. Lett. **70** (1993) 1755;
b) P. L. Frabetti *et al.*, Phys. Rev. Lett. **70** (1993) 1381;
c) P. L. Frabetti *et al.*, Phys. Rev. Lett. **70** (1993) 2058;
d) P. L. Frabetti *et al.*, Phys. Rev. Lett. **71** (1993) 827.

[2] P. L. Frabetti *et al.*, Phys. Lett. **B323** (1994) 459.

[3] P. L. Frabetti *et al.*, Phys. Lett. **B338** (1994) 106.

[4] B. Guberina, R. Rückl, J. Trampetić., Z. Phys. **C33** (1986) 297.

[5] M. B. Voloshin and M. A. Shifman, Zh. Eksp. Teor. Fiz. **91** (1986) 1180 [Sov. Phys. JETP **64** (1986) 698].

[6] V. Gupta and K.V.L. Sharma, Int. J. Mod. Phys. **A5** (1990) 879.

[7] H. Cheng, Phys. Lett. **B289** (1992) 455.

[8] B. Blok and M. Shifman, in Proc. of Third Workshop on the Tau-Charm Factory, Ed. J. Kirkby and R. Kirkby, (Edition Frontieres, 1994)p. 247.

[9] P. L. Frabetti *et al.*, Nucl. Instrum. Meth. **A320** (1992) 519;
P. L. Frabetti *et al.*, Nucl. Instrum. Meth. **A329** (1993) 62.

[10] W.Eadie, D.Drijard, F.James, M.Ross, B.Sadoulet; Statistical Methods in Experimental Physics; North Holland Publishing Company, (1971) p. 46.

[11] P. L. Frabetti *et al.*, Phys. Lett. **B251** (1990) 639.

[12] P. L. Frabetti *et al.*, Phys. Lett. **B263** (1991) 584.

[13] T. Sjöstrand, Comput. Phys. Commun. **39** (1986) 347;
T. Sjöstrand and M. Bengtsson, Comput. Phys. Commun. **43** (1987) 367;
H.-U. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. **46** (1987) 43.

[14] W.Eadie, D.Drijard, F.James, M.Ross, B.Sadoulet; Statistical Methods in Experimental Physics; North Holland Publishing Company, (1971) p. 269.