Z. Phys. C – Particles and Fields 32, 343–348 (1986)

Zeitschrift für Physik C Particles and Fields

A Measurement of the D^0 Lifetime

The TASSO Collaboration

M. Althoff[1], W. Braunschweig, R. Gerhards, F.J. Kirschfink, H.-U. Martyn, P. Rosskamp, W. Wallraff

I. Physikalisches Institut der RWTH Aachen, D-5100 Aachen, Federal Republic of Germany[14]

B. Bock, J. Eisenmann, H.M. Fischer, H. Hartmann, A. Jocksch, H. Kolanoski, V. Mertens, R. Wedemeyer

Physikalisches Institut der Universität Bonn, D-5300 Bonn, Federal Republic of Germany[14]

B. Foster

H.H. Wills Physics Laboratory, University of Bristol, Bristol, UK[15]

E. Bernardi, Y. Eisenberg[2], A. Eskreys[3], K. Gather, H. Hultschig, P. Joos, B. Klima, H. Kowalski, A. Ladage, B. Löhr, D. Lüke, P. Mättig[4], D. Notz, D. Revel[2], E. Ronat[2], W. Schütte, D. Trines, T. Tymieniecka[5], R. Walczak[6], G. Wolf, W. Zeuner

Deutsches Elektronen-Synchrotron, DESY, Notkestrasse 85, D-2000 Hamburg 52, Federal Republic of Germany

E. Hilger, T. Kracht, H.L. Krasemann[7], J. Krüger, E. Lohrmann, G. Poelz, K.-U. Pösnecker

II. Institut für Experimentalphysik der Universität Hamburg, D-2000 Hamburg, Federal Republic of Germany[14]

D.M. Binnie, P.J. Dornan, D.A. Garbutt, C. Jenkins, W.G. Jones, J.K. Sedgbeer, D. Su, J. Thomas[8], W.A.T. Wan Abdullah[9]

Department of Physics, Imperial College London, UK[15]

F. Barreiro, E. Ros

Universidad Autonoma de Madrid, Madrid, Spain[16]

M.G. Bowler, P. Bull, R.J. Cashmore, P. Dauncey, R. Devenish, G. Heath, D.J. Mellor, P. Ratoff, J.M. Yelton

Department of Nuclear Physics, Oxford University, UK[15]

S.L. Lloyd

Department of Physics, Queen Mary College, London, UK[15]

G.E. Forden, J.C. Hart, D.K. Hasell, D.H. Saxon

Rutherford Appleton Laboratory, Chilton, UK[15]

S. Brandt, M. Holder, L. Labarga[10], B. Neumann

Fachbereich Physik der Universität-Gesamthochschule Siegen, D-5900 Siegen, Federal Republic of Germany[14]

U. Karshon, G. Mikenberg, R. Mir, A. Montag, G. Yekutieli, A. Shapira

Weizmann Institute, Rehovot, Israel[17]

G. Baranko, A. Caldwell, M. Cherney[11], D. DeMille, J.M. Izen[12], J. Messersmith, S. Ritz, D. Strom, M. Takashima, E. Wicklund[13], Sau Lan Wu, G. Zobernig

Department of Physics, University of Wisconsin, Madison, Wisconsin, USA[18]

Received 23 May 1986

[1] Now at Siemens, D-8000 München, Federal Republic of Germany
[2] On leave from Weizmann Institute, Rehovot, Israel
[3] On leave from Institute of Nuclear Physics, Cracow, Poland
[4] Now at IPP Canada, Carleton University, Ottawa, Canada
[5] Now at Warsaw University, Warsaw, Poland
[6] On leave from Warsaw University, Warsaw, Poland
[7] Now at GKSS, D-2057 Geesthacht, Federal Republic of Germany
[8] Now at CERN CH-1211 Geneva 23, Switzerland
[9] Now at Universiti Maylaya, Kuala Lumpur
[10] On leave from Universidad Autonoma de Madrid, Madrid, Spain
[11] Now at Lawrence Berkeley Laboratory, Berkeley, California, USA
[12] Now at University of Illinois at Urbana-Champaign, Urbana, Illinois, USA
[13] Now at California Institute of Technology, Pasadena, California, USA
[14] Supported by the Deutsches Bundesministerium für Forschung und Technologie
[15] Supported by the UK Science and Engineering Research Council
[16] Supported by CAICYT
[17] Supported by the Minerva Gesellschaft für Forschung mbH
[18] Supported by the US Department of Energy contract DE-AC02-76ER00881 and the US National Science foundation grant number INT-8313994 for travel

Abstract. We have determined the D^0 lifetime from reconstructed vertices of D^0 mesons produced in e^+e^- annihilations at an average center of mass energy of 42.2 GeV. From fifteen events the D^0 lifetime was determined to be $(4.3^{+2.0}_{-1.4}\pm 0.8)\times 10^{-13}$ s.

I. Introduction

Measurements of the lifetimes of charmed mesons help to clarify the dynamics of their decay. The difference between the lifetimes of the neutral D meson and the charged D meson [1] shows that the charm quarks in these mesons do not decay independently of the light quark to which they are bound, and that different mechanisms are important for the decays of the charged and neutral D mesons. This difference, and a similar one found in the comparison of semi-leptonic branching ratios of the charged and neutral D mesons [2], has led to much theoretical activity [3]. Two separate mechanisms have been proposed: one which suppresses the hadronic decay of the charged D meson [4], and the other which enhances the hadronic decay of the neutral D meson [5]. Direct experimental evidence for the latter mechanism has recently been reported [6], but the relative importance of these two mechanisms remains an open question [3]. Measurements of the neutral D lifetime also allow the calculation of partial widths for various decay modes of neutral D mesons to be made from the measured branching ratios. These partial widths can then be used to test the theoretical picture of charm meson decay.

Previous measurements have detected neutral D mesons produced in fixed targets by incident neutrino [7], hadron [8], and photon beams [9], and in storage rings by collisions of electrons with positrons [10]. Here we present a measurement of the neutral D meson lifetime carried out using the TASSO detector at the PETRA e^+e^- storage ring.

This measurement employed the TASSO vertex detector to reconstruct D^0 decay vertices which were selected from a hadronic event sample with a mean center of mass energy 42.2 GeV and a total integrated luminosity of 49 pb^{-1}. The TASSO vertex detector is a high precision drift chamber which contains 720 sense wires in 8 cylindrical layers at radii ranging from 8.1 to 14.9 cm. For isolated tracks, the resolution of measured space points in the plane perpendicular to the beam is approximately 100 μm. The high resolution of this detector and its proximity to the interaction point allow the reconstruction of the decay vertices from the D^0 mesons. From the measured decay lengths and momenta of the mesons, the proper decay times can be inferred. Other details of the TASSO detector [11] and the vertex detector [12] have been given elsewhere.

II. Event Selection

The neutral D mesons were identified in the decay $D^{*+}(2010)\to D^0\pi^+$. (Here, and in what follows, reference to the charge conjugate states is implied.) In high energy e^+e^- annihilations the selection of D^0 mesons based on the decay products of the D^0 mesons alone must contend with a large background from random combinations of tracks. However, by taking advantage of the small Q value of the reaction $D^{*+}\to D^0\pi^+$, clean samples of D^0 mesons can be obtained by computing the difference between the reconstructed D^{*+} and D^0 masses [13]. This unique decay signature, together with the hard momentum spectrum of D^{*+} mesons produced in high energy e^+e^- annihilation, has facilitated the detection of these mesons [14]. For this measurement, D^0 mesons were identified from the following decay modes: $D^0\to K^-\pi^+$, $D^0\to K^-\pi^+\pi^-\pi^+$, and $D^0\to K^-\pi^+\pi^0$. Identification of the decays in the last decay is possible without actually reconstructing the π^0 meson. This mode is reconstructed by using $K^-\pi^+$ combinations from a satellite peak whose invariant mass falls in the region below the D^0 mass. In this so-called S^0 mode, the decay $D^0\to K^-\pi^+\pi^0$ proceeds primarily through the intermediate state $D^0\to K^-\rho^+$, so that in some circumstances the π^0 carries away relatively little momentum [15]. The $D^{*+}-D^0$ mass difference can therefore still be used to identify these decays.

The decay mode $D^0\to K^-\pi^+$ has been reconstructed using a new method based on tracks which contain vertex detector information. The other decay modes have been reconstructed as described in previous TASSO publications [14].

Events containing the decay $D^0\to K^-\pi^+$ were selected using tracks [16] which include information from the three chambers which comprise the inner detector: the vertex detector, the inner proportional chamber and the central drift chamber. To ensure that the tracks had been reliably reconstructed in the vertex chamber, only those tracks were utilized which had more than 4 vertex detector hits and $\chi^2_{r\phi}$ less than 2.5, where $\chi^2_{r\phi}$ is the χ^2 per degree of freedom calculated for the entire track when reconstructed in the plane perpendicular to the beam. In other respects, the analysis selection criteria closely followed that of our previous analysis [14]. All charged tracks in a given hemisphere, as defined by the sphericity axis, were considered as both pions and as kaons. Combinations of tracks interpreted as

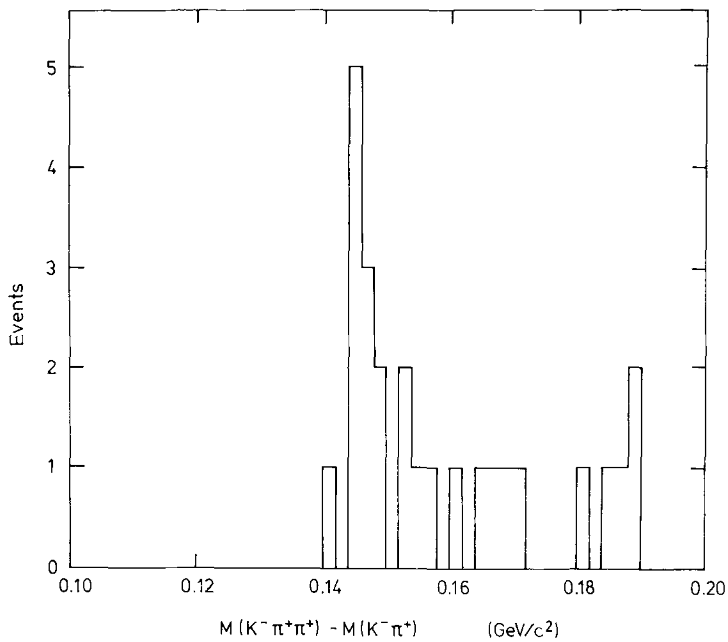

Fig. 1. The distribution of the difference in mass between D^{*+} candidates and constrained D^0 candidates for decays of the type $D^{*+} \to D^0 \pi^+ \to K^- \pi^+ \pi^+$. The signal region is taken to be $M(K^- \pi^+ \pi^+) - M(K^- \pi^+) < 0.15$ GeV/c^2

$K^- \pi^+$ were formed among those tracks of momentum greater than 0.8 GeV/c and then geometrically fitted to a common vertex and kinematically constrained to the D^0 mass [17, 18]. After cuts to remove badly reconstructed decays, those combinations having a χ^2 for the kinematic constraint less than 5.0, were paired with the other positively charged tracks in the same hemisphere with momentum greater than 0.3 GeV/c to form D^{*+} candidates. The mass difference between the D^{*+} and D^0 mass combinations for those candidates with $x = E_{D^{*+}}/E_{\text{beam}} > 0.5$ is shown in Fig. 1. The eleven decays having a $D^{*+} - D^0$ mass difference less than 0.15 GeV were taken as the event sample. The background in this region was estimated by a Monte Carlo calculation to be about 13%. Those combinations which consisted entirely of tracks from other decay modes of the D^0, for example $D^0 \to K^- \pi^+ \pi^0$, were not included in the background estimate, as they are not a background to the lifetime determination.

In the decay modes $D^0 \to K^- \pi^+ \pi^0$ and $D^0 \to K^- \pi^+ \pi^- \pi^+$ the events selection was based on tracks reconstructed with information from the central drift chamber and inner proportional chamber alone, as in our previous publications [14]. This method of event selection is advantageous as it could be tested using the large sample of events obtained before the installation of the vertex chamber. Events were selected using the same $D^{*+} - D^0$ mass difference criterion as in the $D^0 \to K^- \pi^+$ analysis. To perform vertex fits, these tracks were then matched with tracks containing information from the entire inner detector. In the case of decays of the type $D^{*+} \to D^0 \pi^+$; $D^0 \to K^- \pi^+ \pi^0$, all of the tracks, including the transition pion from the D^{*+} decay, were required to have at least 4 vertex detector hits and $\chi^2_{r\phi} < 2.5$. Decays of the type $D^{*+} \to D^0 \pi^+$; $D^0 \to K^- \pi^+ \pi^- \pi^+$ were required to have at least 4 vertex detector hits on each track comprising the D^0, but the $\chi^2_{r\phi}$ requirement was relaxed somewhat: if after the deletion of one or two hits the track had $\chi^2_{r\phi} < 2.5$, it was accepted. If a single event contained more than one combination which could form a D^0 mass, the one closest to the D^0 mass was used. In all of the modes the association of measured vertex detector hits to tracks was then checked event by event with an independent track finder [19].

Application of these selection criteria to the data yielded eleven events in the mode $D^0 \to K^- \pi^+$ and three events in the mode $D^0 \to K^- \pi^+ \pi^- \pi^+$. Four events with valid vertex detector tracks were found in the satellite peak of the $K^- \pi^+$ mass combination. No additional events with valid vertex detector tracks were found in the mode $D^0 \to K^- \pi^+ \pi^0$ (seen).

III. Lifetime Analysis

The decay vertex of each event was determined by fitting the tracks from the decay products of each D^0 meson to a common vertex in 3 dimensions [17]. These tracks were then kinematically constrained to the D^0 mass, except in the case of the S^0 mode where not all of the decay products of the D^0 were reconstructed. The constraint to the D^0 mass has been shown to give a 16% improvement in the determination of the vertex position [18]. If the χ^2 for the addition of the mass constraint was greater than 5, the event was rejected. In the S^0 mode, the tracks fitted to the vertex were required to have a $K^-\pi^+$ mass between 1.5 and 1.744 GeV/c^2, and to give a $(K^-\pi^+\pi^+)-(K^-\pi^+)$ mass difference less than 0.15 GeV/c^2.

If the confidence level of the χ^2 for the vertex fit alone was less than 0.01, the vertex was determined in two dimensions without a mass constraint. In the $D^0\to K^-\pi^+\pi^-\pi^+$ mode, the two dimensional χ^2 confidence level was also required to be more than 0.01.

For those D^0 decays containing only two tracks, a check on the vertex position was made by using the transition pion. The D^{*+} decay has a very low Q value (5.8 MeV) so that the direction of flight of the emitted transition pion is very nearly that of the D^0 meson. A second fit for each D^0 meson candidate was then performed by combining the transition pion with the products of the D^0 decay. This vertex was determined as above, and required to be consistent with the vertex found by using only the decay products of the D^0.

To determine the decay distance of the D^0 mesons, it is necessary to know the position of the event vertex. The best estimate was derived from the beam spot position and size. The beam spot was determined for individual fillings of the storage ring. At least 50 beam associated tracks were used in each determination. The center of the beam spot was determined to an accuracy better than 150 µm. The beam spot has been measured to be approximately 500 µm wide in the x direction, in agreement with predictions from the machine parameters [20]. In the y direction, the beam is expected to be of negligible extent so that the error on the y coordinate of the beam spot is dominated by the statistical error. In the z direction, the position of the event vertex is poorly known and so only the direction of flight of the D^0 meson is used. The most likely decay distance in three dimensions was then computed from

$$l=\frac{x_v\sigma_{yy}t_x+y_v\sigma_{xx}t_y-\sigma_{xy}(x_v t_y+y_v t_x)}{\sigma_{yy}t_x^2-2\sigma_{xy}t_x t_y+\sigma_{xx}t_y^2}$$

where σ is formed by adding the error matrix determined in the fit to that from the beam spot, t_x and t_y are the three dimensional direction cosines of the D^0 momentum, and x_v and y_v are the coordinates, relative to the beam center, found by the vertex fit. The above equation is obtained by minimizing χ_l^2 with respect to l, where

$$\chi_l^2=\Delta\,\sigma^{-1}\,\Delta^t$$

and

$$\Delta=(l\,t_x-x_v,\,l\,t_y-y_v).$$

The minimum value of χ_l^2 gives an indication of the quality of the fit. If the confidence level of χ_l^2 was less than 0.01, the decay was rejected. This cut did not eliminate any of the combinations in the signal region, but did eliminate some of decays in the background region (see below).

Following these procedures we obtained eleven events in the mode $D^0\to K^-\pi^+$, two events in the mode $D^0\to K^-\pi^+(\pi^0)$, and two in the mode $D^0\to K^-\pi^+\pi^-\pi^+$. The decay distances were then converted to proper times by dividing by $\gamma\beta=p_{D^0}/M_{D^0}$. In the S^0 mode, the true D^0 momentum is unknown, so $\gamma\beta$ was taken to be $p(K^-\pi^+)/M(K^-\pi^+)$. Monte Carlo calculations show that this approximation is good to about 6%. The distribution of proper decay times, weighted by their errors, is shown in Fig. 2a.

The D^0 lifetime was extracted using a maximum likelihood fit to the measured proper time of each decay. In order to perform the maximum likelihood fit, it was necessary to describe the contributions to the data sample. The true D^0 portion had two contributions: primarily produced D^0 mesons and D^0 mesons produced in B meson decays. The contribution from the former was described by a Gaussian convoluted with an exponential where the width of the Gaussian was taken from the calculated error on the most likely decay distance [21, 22]. To take account of the secondary D^0 mesons produced in B meson decays, two exponentials were convoluted with each other, and then with a Gaussian. The amount of D^{*+} signal originating from B meson decay was estimated using a Monte Carlo calculation to be 4.5%. This calculation incorporated the measured production of D^{*+} mesons from B mesons [23]. A lifetime of 11×10^{-13} s was assumed for the B mesons [1]. The B meson boost was estimated from the boost of the D meson. A Monte Carlo calculation showed that the approximation $\langle\gamma\beta_B\rangle=0.5\langle\gamma\beta_D\rangle$ was good to 10%.

A term also added to take into account a 13% background in the mode $D^0\to K^-\pi^+$, and a 30% background in the decay modes $D^0\to K^-\pi^+\pi^-\pi^+$ and $D^0\to K^-\pi^+\pi^0$ [14]. Those background combinations consisting of two or more tracks from B hadron decay can give the background a small effective lifetime. Monte Carlo calculations showed this contribution to the background could be described in the same way as the seondary D^{*+} production: 95.5% of the background was described as a single Gaussian centered at zero, and the remainder as a

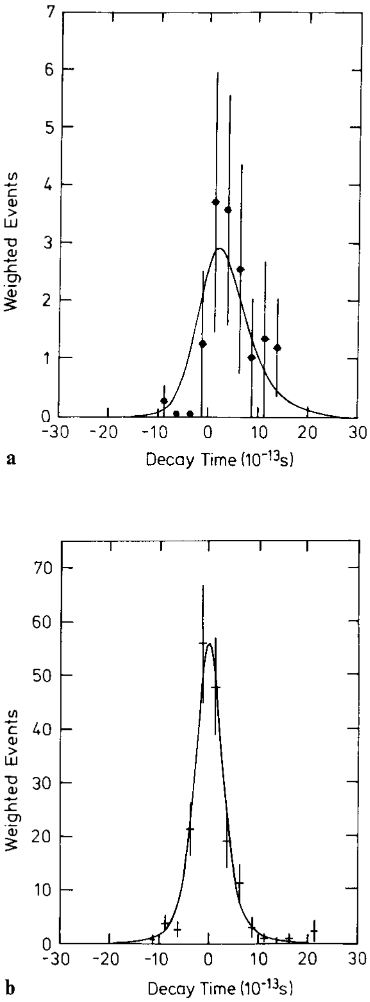

Fig. 2. a The weighted distribution of the proper decay times of the fifteen reconstructed D^0 mesons. The curve was produced from the fitting function described in the text with the D^0 lifetime set to the value found in the maximum likelihood fit. **b** The weighted distribution of the 172 background events. In computing the curve, the D^0 lifetime was set to zero, and the contribution from B decay retained

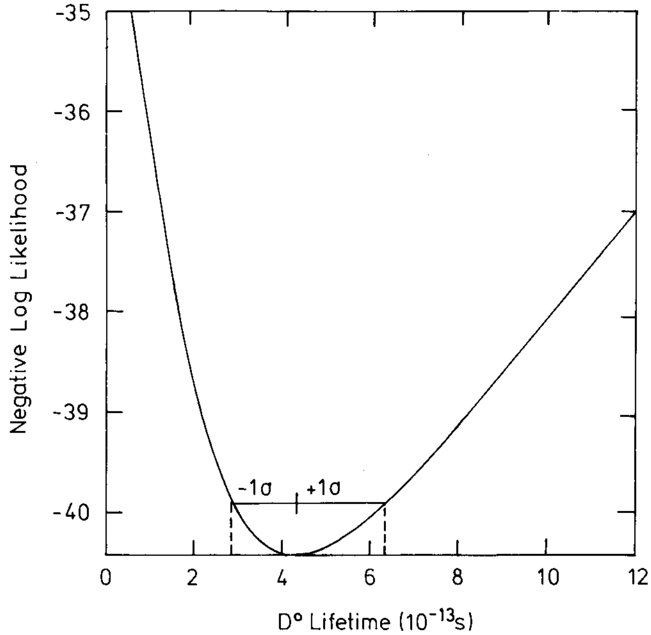

Fig. 3. The negative logarithm of the likelihood function for the fifteen reconstructed proper decay times. The one standard deviation errors are indicated

Gaussian folded with an exponential with the effective B lifetime.

Applying this maximum likelihood fit to the data sample gave:

$$\tau_{D^0}=(4.3^{+2.0}_{-1.4})\times 10^{-13}\,\mathrm{s}.$$

This value of D^0 lifetime was used in the fitting function described above to produce the curve superimposed on Fig. 2a. The negative logarithm of the likelihood function is shown in Fig. 3.

Several checks were made to ensure that the result was not biased and to estimate the systematic errors. To show that the detector had no bias towards positive or negative lifetimes we examined a sample of background decays topologically similar to true D^0 decays. Events were selected from the upper D^0 side bands ($3.0 \pm 0.5\,\mathrm{GeV/c^2}$) of the $D^0 \to K^- \pi^+$ and the $D^0 \to K^- \pi^+ \pi^- \pi^+$ modes, and then passed through the same analysis procedure as the data, except that no kinematic fit could be performed. The decay times from these 172 events were fitted to the same function as the data, including the term from the B meson decay. The distribution is shown in Fig. 2b. The maximum likelihood fit gave a lifetime of $(0.1 \pm 0.3) \times 10^{-13}$ s.

To check the dependence of the result on the assumed detector resolution, we let the width of the Gaussian be scaled by a factor α. Fitting to both the lifetime and to α, the value of τ_{D^0} increased by 0.4 $\times 10^{-13}$ s, and we obtained $\alpha = 0.9^{+0.4}_{-0.3}$. Equivalently, changing the assumed vertex detector resolution $\pm 20\%$ changed the resulting value for τ_{D^0} by ± 0.5 $\times 10^{-13}$ s. Varying the size of the beam spot by $\pm 20\%$, changed τ_{D^0} by $\pm 0.2 \times 10^{-13}$ s. Changing the detector vertex alignment with respect to the central drift chamber by approximately 100 μm, gave rise to changes in τ_{D^0} of about $\pm 0.3 \times 10^{-13}$ s. Varying the assumed B lifetime by $\pm 50\%$ changed the value for τ_{D^0} by less than $\pm 0.1 \times 10^{-13}$ s. Varying the fraction of accepted D^0 mesons from B meson decay between 1.5% and 7.0%, changed the value of τ_{D^0} by $\pm 0.15 \times 10^{-13}$ s. Changing the assumed background fraction by $\pm 50\%$ of their value gave changes in τ_{D^0} of $\pm 0.3 \times 10^{-13}$ s. Adding all of these effects in quadrature we obtained a systematic error $\pm 0.8 \times 10^{-13}$ s.

In conclusion, we have measured the D^0 lifetime using fifteen events and found it to be:

$$\tau_{D^0} = (4.3^{+2.0}_{-1.4} \pm 0.8) \times 10^{-13}\ \mathrm{s}.$$

This result is in good agreement with other measurements of the D^0 lifetime – a recent average [1] gave $(4.0 \pm 0.3) \times 10^{-13}$ s. Our result is also shorter than the average [1] for the D^+ lifetime, $(8.6 \pm 0.7) \times 10^{-13}$ s.

Acknowledgments. We gratefully acknowledge the PETRA machine group for their efforts to provide high luminosity running, and the DESY directorate for their support. Those of us from abroad wish to thank the DESY directorate for the hospitality extended to us.

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