Search for the Rare Leptonic Decay $B^- \to \tau^- \bar{\nu}_\tau$

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0031-9007/05/95(4)/041804(7)$23.00

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(Received 20 July 2004; published 20 July 2005)

We present a search for the decay $B^- \to \tau^- \bar{\nu}_\tau$ in a sample of 88.9×10^6 $B\bar{B}$ pairs recorded with the *BABAR* detector at the Stanford Linear Accelerator Center B factory. One of the two B mesons from the $\Upsilon(4S)$ is reconstructed in a hadronic or a semileptonic final state, and the decay products of the other B in the event are analyzed for consistency with a $B^- \to \tau^- \bar{\nu}_\tau$ decay. We find no evidence of a signal and set an upper limit on the branching fraction of $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) < 4.2 \times 10^{-4}$ at the 90% confidence level.

DOI: 10.1103/PhysRevLett.95.041804 PACS numbers: 13.20.He, 14.40.Nd, 14.60.Fg

In the standard model (SM) the leptonic decay $B^- \to \tau^- \bar{\nu}_\tau$ [1] proceeds via the annihilation of the b and $\bar{u}$ quarks into a virtual W boson. Its amplitude is thus proportional to the product of the Cabibbo-Kobayashi-Maskawa matrix [2] element $|V_{ub}|$ and the B-meson decay constant f_B. The SM branching fraction is given by

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B = (9.3 \pm 3.9) \times 10^{-5}, \qquad (1)$$

where G_F is the Fermi coupling constant, m_τ and m_B are the τ lepton and B^--meson masses, and τ_B is the B^- mean lifetime. We have used $\tau_B = (1.671 \pm 0.018)$ ps, $|V_{ub}| = (3.67 \pm 0.47) \times 10^{-4}$, and $f_B = (0.196 \pm 0.032)$ GeV (obtained from lattice QCD calculations) [3]. The branching fractions for $e^- \bar{\tau}_e$ and $\mu^- \bar{\nu}_\mu B^- \to \tau^- \bar{\nu}_\tau$ are helicity suppressed by factors of $\sim 10^{-8}$ and $\sim 10^{-3}$, respectively. Physics beyond the SM, such as supersymmetry or two-Higgs doublet models, could enhance $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$ by up to a factor of 5 through the introduction of a charged Higgs boson [4].

A search for this decay is challenging due to the presence of at least two undetectable neutrinos in the final state. No observation has been reported yet and the most stringent published limit on the decay is $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) < 5.7 \times 10^{-4}$ at the 90% confidence level [5].

The data used in this analysis were recorded with the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring. The sample consists of $(88.9 \pm 1.0) \times 10^6$ $B\bar{B}$ pairs (81.9 fb^{-1}) collected at the $\Upsilon(4S)$ resonance (“on resonance”) and 9.6 fb^{-1} collected about 40 MeV below the $B\bar{B}$ threshold (“off resonance”).

The *BABAR* detector is described in detail elsewhere [6]. Detection of charged particles and measurement of their momenta are performed by a five-layer double-sided silicon vertex tracker and a 40-layer drift chamber, which operate in a 1.5-T solenoidal magnetic field. A detector of internally reflected Cherenkov light is used to identify charged kaons and pions. Photons and electrons are detected in an electromagnetic calorimeter consisting of an array of CsI(Tl) crystals. Muons and neutral hadrons are identified in the flux return, which is instrumented with multiple layers of resistive plate chambers. A GEANT4-based [7] simulation of the *BABAR* detector, including machine backgrounds, is used to study signal event selection and background rejection.

We first select a sample of events with one B meson (the *tag B*) reconstructed in a hadronic or a semileptonic final state. The reconstruction constrains the kinematics and reduces the combinatorics in each event. This is critical since at least two neutrinos result from the $B^- \to \tau^- \bar{\nu}_\tau$ decay. All the neutral and charged particles not used for the tag B are assumed to come from the B meson recoiling against it. We use two methods to search this recoil system for evidence of a $B^- \to \tau^- \bar{\nu}_\tau$ signal.

In our first method, we reconstruct the tag B semileptonically. The semileptonic B meson, B_{s1}, is reconstructed as $B^+ \to \bar{D}^0 \ell^+ \nu_\ell X$, where $\ell = e, \mu$, and X can be a γ, π^0, or nothing. We select semileptonic B-decay events with several missing particles (such as neutrinos) by requiring at least one lepton with center-of-mass (c.m.) momentum ($|\vec{p}_\ell^{\,*}|$) above 1.0 GeV$/c$, zero event charge, a ratio of the Fox-Wolfram moments [8] $H_2/H_0 < 0.9$, and missing mass greater than 1.0 GeV$/c^2$. Here, the missing mass is determined by subtracting the total energy and momentum of all reconstructed tracks and neutrals from the four-momentum of the $\Upsilon(4S)$ system. We reconstruct $\bar{D}^0$ mesons in the modes $\bar{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^-\pi^+$, $K^+\pi^-\pi^0$, and $K_S^0\pi^+\pi^-$ and require their reconstructed masses to be within 3 standard deviations of the observed mean. The $\bar{D}^0$ mesons are then paired with leptons with $|\vec{p}_\ell^{\,*}| > 1.0$ GeV$/c$ to form $D\ell$ candidates. If the $\bar{D}^0$ decay contains a charged kaon, the lepton must have the same charge as the kaon. The $\bar{D}^0$ and lepton are required to originate from a common vertex, but we do not mass constrain the vertex fit. We assume that the only missing particle is a neutrino and calculate the cosine of the angle between the momentum vectors of the $D\ell$ candidate and the B meson,

$$\cos\theta_{B,D\ell} \equiv \frac{2E^*_{\rm beam}E^*_{D\ell} - m_B^2 - m_{D\ell}^2}{2\sqrt{E^{*2}_{\rm beam} - m_B^2}\,|\vec{p}^{\,*}_{D\ell}|}. \qquad (2)$$

The c.m. energy and momentum of the $D\ell$ candidate are $E^*_{D\ell}$ and $\vec{p}^{\,*}_{D\ell}$, respectively. The B-meson energy is taken to be the beam energy, $E^*_{\rm beam}$. Calculated values of $\cos\theta_{B,D\ell}$ may lie outside the physical range for events where the $D\ell$ candidate did not arise as presumed, or due to detector energy and momentum resolution. We place an asymmetric restriction on this variable, $-2.5 < \cos\theta_{B,D\ell} < 1.1$, to admit $\bar{D}^{*0}$ states where additional decay products are present. If there is more than one acceptable $D\ell$ candidate, we choose the one whose $\bar{D}^0$ mass is closest to the mean of the fitted distribution.

After identifying the B_{s1}, the remaining particles are required to be consistent with $B^- \to \tau^- \bar{\nu}_\tau$, where $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ or $\mu^- \bar{\nu}_\mu \nu_\tau$. Exactly one track with a small impact parameter relative to the primary vertex must remain. The track must have $p^* < 1.2$ GeV$/c$, and must be identified as either an electron or a muon. We reject $e^+e^- \to \tau^+\tau^-$ events by restricting the angle of the track with respect to the event thrust axis ($|\cos\theta_{\vec{p},\vec{T}}| < 0.9$) and the minimum invariant mass constructible from any triplet of tracks in the event ($M_3^{\min} > 1.5\ \text{GeV}/c^2$). In general, continuum events tend to peak sharply at $|\cos\theta_{\vec{p},\vec{T}}| = 1$, and $\tau^+\tau^-$ events, in particular, tend to peak at values of $M_3^{\min}$ below the τ mass.

The signal yield in the data is determined using the distribution of the total energy deposited in calorimeter clusters (with a minimum energy of 0.020 GeV) by neutral particles not associated with the $\bar{D}^0$ decay in the semileptonic B_{s1} candidate, E_{extra} (Fig. 1). This variable peaks near zero for signal, while for background it rises with increasing E_{extra}. For $E_{\text{extra}} < 1.0$ GeV, we find from Monte Carlo simulations a signal efficiency of $(4.77 \pm 0.35) \times 10^{-4}$ and a background estimate of 124 ± 7 events.

The signal efficiency quoted above is determined using a detailed signal simulation. We study the differences between simulation and data in the semileptonic B reconstruction, neutral-energy reconstruction, and lepton identification to derive an efficiency correction. The most significant effect comes from the B_{s1} reconstruction efficiency, and is determined using a sample of events in data and Monte Carlo simulations where both B mesons are reconstructed as $B \to D\ell\nu X$. The total efficiency correction from all sources is determined to be 0.878 ± 0.076, and the corrected signal efficiency is $(4.19 \pm 0.31_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-4}$.

Probability density functions (PDFs) are constructed from the E_{extra} distributions in signal $[F(E_{\text{extra}})_s]$ and background $[F(E_{\text{extra}})_b]$ simulations. The E_{extra} distribution for signal events is modeled as the sum of an exponential and two Gaussian distributions. The double-Gaussian models signal events where the X in $B^+ \to \bar{D}^0\ell^+\nu_\ell X$ is a π^0 or photon with a characteristic energy around 0.15 GeV. The exponential models signal events where such neutral particles are absent. To model background, as determined from Monte Carlo simulations, we use a third-order polynomial. The PDFs are combined into an extended maximum likelihood function,

$$\mathcal{L}(s + b) \equiv \frac{e^{-\mu_s-\mu_b}}{n!}\prod_{i=1}^{n}[\mu_s F(E_i)_s + \mu_b F(E_i)_b], \quad (3)$$

where E_i is the E_{extra} in the ith event, n is the total number of events in the data, and μ_s and μ_b are the signal and background yields to be fitted in the data. Studies of the choice of PDF parametrization and of variations in shape suggest that the chosen PDFs yield a consistently conservative limit for the upper bound of the branching fraction. We fix the PDF shape parameters and fit the data (Fig. 1). The fit yields 14.8 ± 6.3 signal events and 115.2 ± 11.8 background events. This signal yield has a statistical significance of 2.3σ.

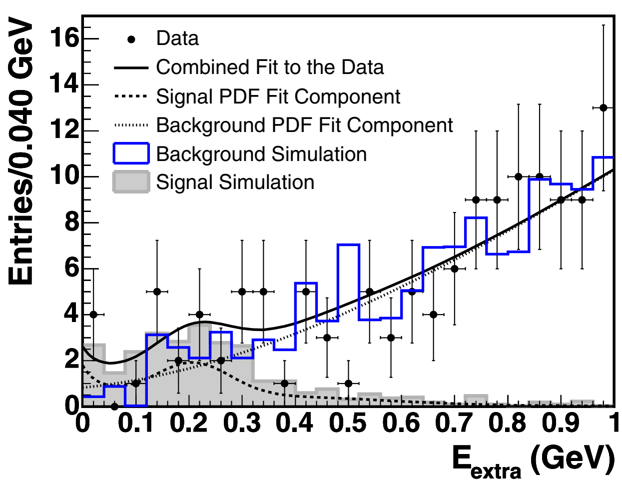

FIG. 1 (color online). The distribution of E_{extra} after applying all selection criteria. The fit to the data and its components are also shown. The background is normalized to the data luminosity, and the signal simulation is normalized arbitrarily.

We set a limit on the branching fraction at the 90% confidence level (C.L.) using the "CLs method" described in Refs. [9,10]. We define our statistical estimator Q to be the fitted signal yield and compare the value of Q in data to its value in a large number of experiments generated by sampling the likelihood function over a range of signal hypotheses. The uncertainty in the signal efficiency estimate is included by assuming a Gaussian uncertainty in the signal hypothesis. Using our fitted signal yield, efficiency, and the total number of B mesons in the data sample we determine that $\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) < 6.7 \times 10^{-4}$ (90% C.L.). In the absence of signal, we expect to set an upper limit of 2.7×10^{-4}.

In our second method, we reconstruct the tag B candidate, B_{had}, decaying into a set of purely hadronic final states, $B^+ \to \bar{D}^{(*)0}X^+$. The $\bar{D}^{*0}$ is reconstructed in the mode $\bar{D}^0\pi^0$, and X^+ is a system of hadrons composed of $n_1\pi^\pm + n_2K^\pm + n_3\pi^0 + n_4K_S^0$, where $n_1 = 1, \ldots, 5$, $n_2 = 0, 1, 2$, $n_3 = 0, 1, 2$, and $n_4 = 0, 1$. Rejection of background processes is based on two kinematic quantities: ΔE, the difference between the B_{had} and beam energies, and the beam-energy-substituted mass m_{ES},

$$m_{\text{ES}} \equiv \sqrt{[(s/2 + \vec{p}\cdot\vec{p}_B)^2/E^2] - |\vec{p}_B|^2}, \quad (4)$$

where $\sqrt{s}$ is the total energy of the e^+e^- system in the c.m. frame, and $(E, \vec{p})$ and $(EB, \vec{p}_B)$ are the four momenta of the e^+e^- system and the B_{had}, respectively, both in the laboratory frame.

For each mode the m_{ES} distribution of the reconstructed candidates with $-0.1 < \Delta\text{E} < 0.08$ GeV and $m_{\text{ES}} > 5.21\ \text{GeV}/c^2$ is fitted using the sum of a "Crystal Ball function" [11] to model the signal component peaking at m_B and an "ARGUS function" [12] to model the continuum and combinatorial B background. Figure 2 shows the fit to the m_{ES} distribution for the B_{had} candidates in data.

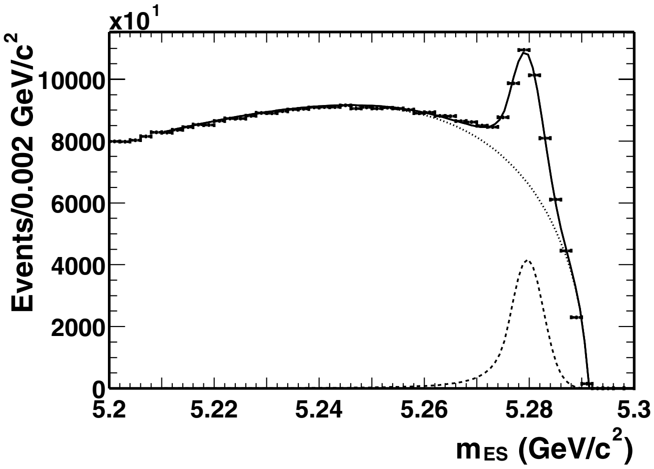

FIG. 2. Distribution of m_{ES} for the B_{had} candidates in data. The events lie in the region $-0.1 < \Delta E < 0.08$ GeV. The solid curve shows the result of the fit with the sum of a Crystal Ball function (dashed curve) and an ARGUS function (dotted curve).

We define the signal region as $-0.09 < \Delta E < 0.06$ GeV and $m_{\mathrm{ES}} > 5.27\ \mathrm{GeV}/c^2$. We define a *sideband* region, $5.21 < m_{\mathrm{ES}} < 5.26\ \mathrm{GeV}/c^2$, to provide a control sample for studying continuum and combinatorial B background. The yield in the signal region, determined from the fit, is $N_{B_{\mathrm{had}}} = (167.8 \pm 1.2_{\mathrm{stat}} \pm 3.0_{\mathrm{syst}}) \times 10^3$. The error is dominated by systematic uncertainty in the functional form of the peak at m_B.

We identify the τ lepton using the following decay channels: $\tau^- \to e^- \bar{\nu}_e \nu_\tau$, $\mu^- \nu_\tau \bar{\nu}_\mu$, $\pi^- \nu_\tau$, $\pi^- \pi^0 \nu_\tau$, and $\pi^- \pi^+ \pi^- \nu_\tau$. We require the charged particles to be identified as leptons or pions, as appropriate. Mode-specific constraints are placed on the particles recoiling against the B_{had}. For the lepton and single-pion modes, we reject events with π^0 or K_S^0 mesons in the recoil. The event is required to have zero charge and, in the recoil, at most one photon candidate not associated with a π^0. Events with such a photon candidate are accepted only if $50 < E_\gamma < 100$ MeV ($50 < E_\gamma < 110$ MeV for the $\tau^- \to e^- \bar{\nu}_e \nu_\tau$, $\mu^- \nu_\tau \bar{\nu}_\mu$, and $\pi \nu_\tau$ modes) in the laboratory frame. Further requirements are made on the total missing momentum of the event, $p_{\mathrm{miss}} > 1.2\ \mathrm{GeV}/c$ ($> 1.4\ \mathrm{GeV}/c$ for $\tau^- \to \pi^- \pi^0 \nu_\tau$), the total momentum of the track(s) in the parent-B rest frame ($p_{\pi^-} > 1.2\ \mathrm{GeV}/c$ for $\tau^- \to \pi^- \nu_\tau$, $p_{\pi^- \pi^+ \pi^-} > 1.6\ \mathrm{GeV}/c$ for $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$), and the invariant mass of two or three pions ($0.60 < m_{\pi\pi} < 0.95\ \mathrm{GeV}/c^2$ and $1.10 < m_{\pi\pi\pi} < 1.60\ \mathrm{GeV}/c^2$ for $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$, $0.50 < m_{\pi^- \pi^0} < 1.00\ \mathrm{GeV}/c^2$ for $\tau^- \to \pi^- \pi^0 \nu_\tau$).

We use detailed Monte Carlo simulations to determine for each τ-decay channel the selection efficiencies ε_i weighted by the corresponding branching fractions [3]. The systematic uncertainties in selection efficiency arise from tracking efficiency, neutral reconstruction, particle identification, and π^0 reconstruction. The total $B^- \to \tau^- \bar{\nu}_\tau$ selection efficiency (see Table I) is $(10.5 \pm 0.2)\%$. Misreconstruction and contamination amongst the τ-decay channels are taken into account.

Continuum and combinatorial B background is determined by extrapolating the ARGUS function from the m_{ES} sideband into the m_{ES} signal region. The background that peaks in the m_{ES} signal region is determined from Monte Carlo simulations of B^+B^- events. Events where a B^0 is incorrectly reconstructed as a B^+ provide a negligible contribution.

We correct the expected background, b_i, to take into account possible dependencies of the fitted ARGUS shape on a given discriminating variable (p_{miss}, invariant masses, etc.). The correction factor for a given variable is the ratio of the selected continuum and combinatorial background events determined using two separate methods. In the first method, we study the variable distribution for events in the m_{ES} sideband reweighted by a unique ARGUS signal-to-sideband ratio. In the second method, we use as reweighting factors bin-dependent ratios. The systematic error on b_i is estimated as the deviation from unity of the total correction factor for each τ-decay mode. The expected background and the total systematic uncertainty in each τ-decay channel is reported in Table I, along with the number n_i of selected candidates in data.

The systematic uncertainty in $N_{B_{\mathrm{had}}}$ (1.8%) is estimated as the change in the yield in the signal region in Fig. 2 when we use a double Gaussian as an alternative to the Crystal Ball function. Other models for the signal or the background distribution result in negligible changes.

We observe a total of 15 $B^- \to \tau^- \bar{\nu}_\tau$ candidates, which is consistent with the expected background of $17.2 \pm 2.1_{\mathrm{stat}} \pm 1.3_{\mathrm{syst}}$ events. The distribution of these events is also consistent with background.

We determine the $B^- \to \tau^- \bar{\nu}_\tau$ branching fraction from the number of signal candidates s_i expected for each τ-decay mode, where $s_i \equiv N_{B_{\mathrm{had}}} \mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) \varepsilon_i$. The results for each decay channel are combined using the estimator, Q. Here we define Q to be $\mathcal{L}(s+b)/\mathcal{L}(b)$, where

TABLE I. Branching fraction ($\mathcal{B}$) [3], efficiency (ε_i), expected background (b_i) with statistical and systematic errors, and observed data candidates (n_i) for each reconstructed τ-decay mode.

Selection	$\mathcal{B}(\%)$	$\varepsilon_i(\%)$	b_i	n_i
$e\nu\nu$	17.84 ± 0.06	3.4 ± 0.1	$0.7 \pm 0.4 \pm 0.1$	2
$\mu\nu\nu$	17.37 ± 0.06	1.9 ± 0.1	$0.9 \pm 0.5 \pm 0.1$	0
$\pi\nu$	11.06 ± 0.11	2.6 ± 0.1	$1.3 \pm 0.6 \pm 0.2$	2
$\pi^-\pi^+\pi^-\nu$	9.52 ± 0.10	0.6 ± 0.1	$4.3 \pm 1.0 \pm 0.3$	4
$\pi^-\pi^0\nu$	25.41 ± 0.14	2.0 ± 0.1	$10.0 \pm 1.6 \pm 1.3$	7
All	81.20 ± 0.22	10.5 ± 0.2	$17.2 \pm 2.1 \pm 1.3$	15

$$\mathcal{L}(s+b) \equiv \prod_{i=1}^{n_{\rm ch}} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{n_i}}{n_i!}, \qquad \mathcal{L}(b) \equiv \prod_{i=1}^{n_{\rm ch}} \frac{e^{-b_i} b_i^{n_i}}{n_i!} \quad (5)$$

are the likelihood functions for signal-plus-background and background-only hypotheses and $n_{\rm ch}$ is the total number of reconstructed τ-decay channels.

Since we have no evidence of signal, we set an upper limit on the branching fraction. The statistical and systematic uncertainties in the expected background are included in the estimator Q by convolving the likelihood functions with a Gaussian function having as the standard deviation the combined statistical and systematic errors in the background estimate [13]. We determine that $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) < 4.2 \times 10^{-4}$ (90% C.L.). In the absence of signal, we expect to set an upper limit of 3.8×10^{-4}.

To combine the results from the statistically independent hadronic and semileptonic samples, we first calculate the likelihood ratio estimator, $Q \equiv \mathcal{L}(s+b)/\mathcal{L}(b)$, using the likelihood functions from each method. We create a combined estimator from the product of the semileptonic ($Q_{\rm sl}$) and hadronic ($Q_{\rm had}$) likelihood ratio estimators, $Q = Q_{\rm sl} \times Q_{\rm had}$. The measured branching fraction, which is the value that maximizes the likelihood ratio estimator, is $(2.3^{+1.5}_{-1.3}) \times 10^{-4}$. The lower 1 standard deviation bound does not include zero because of the small excess of signal events observed in the semileptonic analysis. Since this value is compatible with a zero branching fraction, we set a combined upper limit,

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) < 4.2 \times 10^{-4} \text{ (90\%C.L.)}. \quad (6)$$

The semileptonic analysis does not contribute significantly to the combined limit because of the observed small excess of signal events. In the absence of signal, we expect a combined upper limit of 2.8×10^{-4}.

We use Eqs. (1) and (6) and the measured value of $|V_{ub}|$ to set a limit on f_B. We find $f_B < 0.510$ GeV (90% C.L.).

In conclusion, we have searched for $B^- \to \tau^- \bar{\nu}_\tau$ in the recoil of hadronic and semileptonic B decays. We have set the most stringent upper limit to date on this process.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), the A. P. Sloan Foundation, Research Corporation, and the Alexander von Humboldt Foundation.

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§Deceased.

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