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BAG-MODEL MATRIX ELEMENTS OF THE PARITY-VIOLATING WEAK HAMILTONIAN FOR CHARMED BARYONS

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1. Introduction

The understanding of nonleptonic weak decays of baryons in the context of the unified electroweak theory has attracted considerable attention recently. A particularly convenient framework for calculating the relevant baryon-baryon matrix elements of weak baryon decays is the MIT-bag model[1] which manifestly allows the confinement of relativistic quarks inside hadrons. This model has been successfully applied to the calculation of the low-lying hadron mass spectrum and of static hadronic parameters, and later on, to a study of nonleptonic decays of hyperons[2-3] and charmed baryons[4-6]. In previous approaches to nonleptonic baryon decay phenomena one considered only baryon-baryon matrix elements of the parity-conserving weak Hamiltonian. As the analogous matrix elements of the parity-violating weak Hamiltonian must vanish in the limit of SU(3) or SU(4) symmetry due to the Lee-Swift theorem[7], their contribution was generally ignored in the literature. In a recent paper[8] Golowich and Holstein adressed to this question once more in the framework of the bag model and argued that the corresponding contributions can indeed reasonably be neglected for nonleptonic hyperon decays. On the other hand, they anticipated that for charm-changing transitions, where symmetry-breaking effects are expected to be much larger, parity-violating matrix elements will be quite significant, perhaps even comparable to their parity-conserving counterparts.

Motivated by these considerations, we shall reinvestigate in this paper the Cabibbo favoured charmed-baryon decays considered in our earlier work[4] by carefully exploring the parity-violating matrix elements, too. The paper is organized as follows. In Sect. 2 we shall estimate and compare the baryon-baryon matrix elements of the parity-violating and parity-conserving weak Hamiltonian. Their ratio will be listed in Table II. Table III gives a compilation of various contributions to the S- and P-wave decay amplitudes. Finally, Sect. 3 contains discussions and conclusions.

2. Nonleptonic Charmed-Baryon Decays

Our analysis is based on the following expression for the charm-changing part of the QCD corrected effective weak Hamiltonian of the Weinberg-Salam model[9]

$$
\begin{aligned}
H_w &= \frac{G}{\sqrt{2}}\cos^2\theta_c\left(f_- O^- + f_+ O^+\right), \\
O^{\mp} &= \frac{1}{2}\left\{(\bar{s}c)_L(\bar{u}d)_L \mp (\bar{s}d)_L(\bar{u}c)_L\right\},
\end{aligned}
\tag{1}
$$

where $f_- = 1.96$, $f_+ = 0.64$, and $(\bar{s}c)_L$ is a shorthand notation for $(\bar{s}c)_L = \bar{s}^i\gamma_\mu(1+\gamma_5)c^i$ (the operators $O^\pm$ are understood to be normal ordered; colour indices are henceforth suppressed). The matrix element for nonleptonic baryon decays $B_\alpha \to B'_\beta + \mathcal{M}_k$ takes the form

$$
\langle \mathcal{M}_k(q)\,\beta_{p'}|H_w|\alpha_p\rangle = i\,\bar{u}_\beta(p')\left[A + B\gamma_5\right]u_\alpha(p)\,\varphi_{\mathcal{M}_k}(q), \tag{2}
$$

where A and B are the (parity-violating) S wave and (parity-conserving) P wave amplitudes, respectively. Furthermore we denote baryon-baryon matrix elements of the parity-conserving (PC) and parity-violating (PV) parts of H_w by

$$
\begin{aligned}
\langle\beta|H_w^{PC}|\alpha\rangle &= a_{\beta\alpha}\,\bar{u}_\beta u_\alpha, \\
\langle\beta|H_w^{PV}|\alpha\rangle &= b_{\beta\alpha}\,\bar{u}_\beta\gamma_5 u_\alpha .
\end{aligned}
\tag{3}
$$

By applying standard current-algebra techniques[10] the A and B amplitudes may be expressed as a sum of commutator terms, baryon pole terms and factorizable contributions (for a graphical representation of these expressions in terms of quark diagrams see Fig. 1a-c)

$$
\begin{aligned}
A &= -\frac{1}{\sqrt{2}F_k}\left(I^k_{\beta\gamma}a_{\gamma\alpha} - I^k_{\varrho\alpha}a_{\beta\varrho}\right) \\
&\quad -\frac{1}{\sqrt{2}F_k}(M_\alpha - M_\beta)\left[\frac{g^A_{k\beta\delta}\,b_{\delta\alpha}}{M_\alpha + M_\delta} - \frac{g^A_{k\gamma\alpha}\,b_{\beta\gamma}}{M_\beta + M_\gamma}\right] + A^{fac}, \\
B &= -\frac{1}{\sqrt{2}F_k}\left(I^k_{\beta\gamma}b_{\gamma\alpha} - I^k_{\varrho\alpha}b_{\beta\varrho}\right) \\
&\quad -\frac{1}{\sqrt{2}F_k}(M_\alpha + M_\beta)\left[\frac{g^A_{k\beta\delta}\,a_{\delta\alpha}}{M_\alpha - M_\delta} + \frac{g^A_{k\gamma\alpha}\,a_{\beta\gamma}}{M_\beta - M_\gamma}\right] + B^{fac},
\end{aligned}
\tag{4}
$$

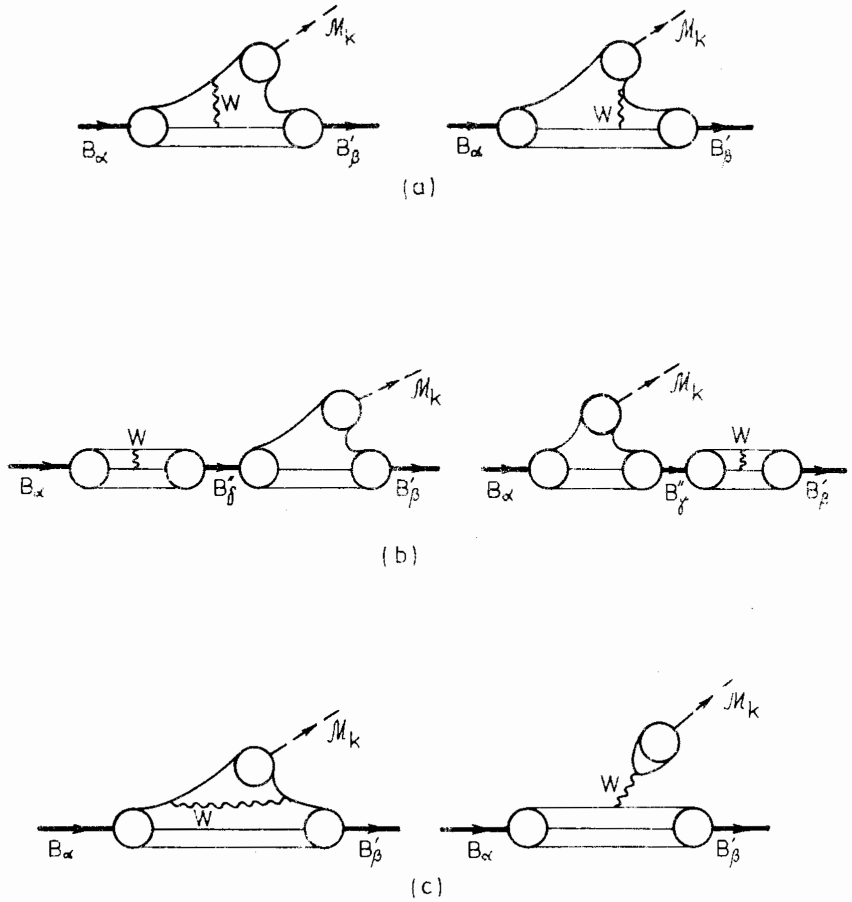

Fig. 1

Typical quark diagrams for nonleptonic baryon decays $B_\alpha \to B'_\beta + \mathcal{M}_k$ contributing to the commutator term (a), the pole term (b) and the factorizable term (c) in eq. (4) of the text. Notice that the first diagram in (c) can be Fierz-rearranged into a form equivalent to the second diagram.

where $I^k_{\beta\gamma}$ are unitary-spin matrix elements, M_α, etc., are baryon masses and $F_\pi = 93$ MeV, $F_K = 1.27\, F_\pi$ are meson decay constants (the index k refers to meson states π^+, K^+, $\bar{K}^0$, etc.). As usual, we included additional factorizable contributions A^{fac}, B^{fac} which are associated with quark decay diagrams (cf. Fig. 1c) and take the form of a product of matrix elements of currents,

$$A^{fac} = -\frac{1}{3} G F_k \cos^2\theta_c \left[2f_+ \pm f_-\right](M_\alpha - M_\beta)\, g^V_{k\beta\alpha}\,, \tag{5}$$

$$B^{fac} = \frac{1}{3} G F_k \cos^2\theta_c \left[2f_+ \pm f_-\right](M_\alpha + M_\beta)\, g^A_{k\beta\alpha}\,.$$

Here $g^A_{k\beta\alpha}$, $g^V_{k\beta\alpha}$ are axial and vector coupling constants and the +(-) sign in the brackets refers to $\pi^+(\bar{K}^0)$ emission. The PC baryon-baryon matrix elements $a_{\beta\alpha}$ may be expressed in the bag model as linear combinations of the two four-quark overlap integrals

$$J_1 = \int_{bag} d^3x\,(u_u^2 + v_u^2)(u_s u_c + v_s v_c) = 0.29\; R^{-3}, \tag{6}$$

$$J_2 = \int_{bag} d^3x\,(v_u u_s - u_u v_s)(u_u v_c - v_u u_c) = -0.5\cdot 10^{-2}\, R^{-3},$$

where u_i, v_i are the usual large and small Dirac components of the quark spinor in the bag, and R is the bag radius. The axial and vector coupling constants appearing in eqs. (4) and (5) take the form of two-quark integrals

$$g^{A(V)} = C^{A(V)} \int_{bag} d^3x\,(u_i u_j + r^{A(V)} v_i v_j) \tag{7}$$

with $r^A = -\frac{1}{3}$, $r^V = 1$. The indices i, j label the flavour of the quarks in the corresponding transition currents and $C^{A(V)}$ are pure SU(4) coefficients. We direct the reader to Ref. 4 for a compendium of the various $a_{\beta\alpha}$ amplitudes and coupling constants $g^{A(V)}_{k\beta\alpha}$ *). As in this work, we shall use the following set of parameters for quark masses m_i, frequencies $\omega_{1,-1}(i)$ and bag radius R: $m_u = 44$ MeV, $m_s = 300$ MeV, $m_c = 1529$ MeV, $\omega_{1,-1}(u) = 2.148$, $\omega_{1,-1}(s) = 2.864$, $\omega_{1,-1}(c) = 7.77$ and $R^{-1} = 211.9$ MeV.

Let us now calculate the PV baryon-baryon matrix elements contributing in eq. (4). For definiteness we again consider the processes $\Lambda_c^+ \to (\Lambda\pi^+, p\bar{K}^0, \Xi^0 K^+, \Sigma^0\pi^+)$, $A^+ \to \Xi^0\pi^+$, $A^0 \to \Xi^-\pi^+$

*) Formula (7) in our preprint[4] contains a misprint. Replace everywhere $0^- \to \frac{1}{2}0^{-PC}$ in this formula. The baryon intermediate state contributing to the A^+ decay is S^0, not A^0.

Table I

Compilation of the PV-matrix elements $b_{\beta\alpha}$ $(C = G/\sqrt{2}\,\cos^2\theta_c f_-)$

$b_{\Sigma^+\Lambda_c^+}/C$	$\frac{4}{3}\sqrt{\frac{2}{3}}\left(\frac{M_{\Sigma^+}M_{\Lambda_c^+}}{M_{\Sigma^+}+M_{\Lambda_c^+}}\right)(X+4Y-3Z)$	$-0.49\,R^{-3}$
$b_{\Lambda\Sigma_c^0}/C$	$\frac{4}{3}\sqrt{\frac{2}{3}}\left(\frac{M_\Lambda M_{\Sigma_c^0}}{M_\Lambda+M_{\Sigma_c^0}}\right)(3X+4Y-Z)$	$-0.27\,R^{-3}$
$b_{\Xi^0A^0}/C$	$-\frac{4}{3}\sqrt{\frac{2}{3}}\left(\frac{M_{\Xi^0}M_{A^0}}{M_{\Xi^0}+M_{A^0}}\right)(X-2Y+3Z)$	$-0.45\,R^{-3}$
$b_{\Xi^0S^0}/C$	$-\frac{4}{3}\sqrt{2}\left(\frac{M_{S^0}M_{\Xi^0}}{M_{S^0}+M_{\Xi^0}}\right)(X+2Y-Z)$	$0.37\,R^{-3}$
$b_{\Sigma^0\Sigma_c^0}/C$	$\frac{8\sqrt{2}}{9}\left(\frac{M_{\Sigma^0}M_{\Sigma_c^0}}{M_{\Sigma^0}+M_{\Sigma_c^0}}\right)(X+Z)$	$0.13\,R^{-3}$

Table II

Relative size of $b_{\beta\alpha}$ and $a_{\beta\alpha}$ matrix elements

	$b_{\gamma\delta}/a_{\gamma\delta}$
$\Lambda_c^+ \to \Sigma^+$	-0.71
$\Sigma_c^0 \to \Lambda$	0.39
$A^0 \to \Xi^0$	-0.64
$S^0 \to \Xi^0$	0.31
$\Sigma_c^0 \to \Sigma^0$	0.11

and $T^0 \to \Xi^0 \bar{K}^0$. The various sets of baryon intermediate states contributing to the pole diagrams of these processes are*)

$$\{(\Sigma^+, \Sigma_c^0); \Sigma^+; (S^0, \Sigma^+); (\Sigma^+, \Sigma_c^0); S^0; \Xi^0; (S^0, A^0)\}.$$

As was explained in Ref. 8, a naive calculation of the matrix element in eq. (3) would yield the uncorrect result $b_{\beta\alpha} = 0$, as follows simply from the vanishing of the bag integral by a parity argument. Following this work one should instead consider the Fourier transform

$$F_{\beta\alpha}^{PV}(q) = \int_{bag} d^3x\, e^{-i\vec{q}\cdot\vec{x}}\, {}_B\langle\beta|\, H_w^{PV}(\vec{x})\,|\alpha\rangle_B\,, \tag{8}$$

where the index B indicates the use of MIT-bag wave-packet states. The $b_{\beta\alpha}$ amplitudes are then determined by expanding eq. (8) in powers of q and working to the lowest nontrivial order. One characteristically encounters the following three overlap integrals in analytical expressions for the $b_{\beta\alpha}$ amplitude

$$X = \int_{bag} r\, d^3x\, (u_s v_u^2 v_c - v_s u_u^2 u_c) = 0.034\ R^{-2},$$

$$Y = \int_{bag} r\, d^3x\, (u_s u_c u_u v_u - v_s v_c v_u u_u) = -0.045\ R^{-2}, \tag{9}$$

$$Z = \int_{bag} r\, d^3x\, (u_u^2 u_s v_c - v_u^2 v_s u_c) = 0.007\ R^{-2}.$$

Table I exhibits the various $b_{\beta\alpha}$ matrix elements. Observe that in the limit of SU(4) invariance the $b_{\beta\alpha}$ amplitudes become proportional to $(X+Y)$ which is seen from eq. (9) to vanish in the symmetry limit. This way our bag model results are consistent with the requirements of Ref. /7/. The relative size of the $b_{\beta\alpha}$ and $a_{\beta\alpha}$ matrix elements is quoted in Table II. Notice, that these ratios are generally larger than the typical value 0.1 obtained for hyperon decays but nevertheless smaller than the value 1 supposed in Ref. /8/. Table III contains a compilation of the estimates for the commutator terms, pole contributions and factorizable terms contributing to the A and B amplitudes, and the bag model predictions for the partial widths Γ. In our calculations we have used the following values of the baryon masses, $M_{\Lambda_c^+} = 2282$ MeV /11/, $M_{\Sigma_c} = 2450$ MeV /11/ and $M_{A^+} = 2460$ MeV /12/.

*) Our notation is $\Lambda_c^+(c[u,d])$, $A^{+(0)}(c[s,u(d)])$, $\Sigma_c^0(cdd)$, $S^0(c\{s,d\})$ and $T^0(css)$.

Table III

Numerical estimates of the commutator terms, pole terms and factorizable terms contributing to the S- and P-wave amplitudes for different nonleptonic charmed-baryon decays. The $a_{\beta\alpha}$-contributions to the A and B amplitudes are taken from Ref. /4/. In the last column the numerical predictions for the partial rates calculated from the A and B amplitudes are given in units of $10^{11}\,\mathrm{sec}^{-1}$.

Amplitude x 10^6	Commutator term	Pole terms	Fact. terms	Total	Γ
$A(\Lambda_c^+ \to \Lambda\pi^+)$	0	0.16	1.23	1.39	3.8
$A(\Lambda_c^+ \to p\bar{K}^0)$	-0.61	-0.04	-0.44	-1.09	1.7
$A(\Lambda_c^+ \to \Xi^0 K^+)$	$-7.49\cdot 10^{-3}$	-0.18	0	-0.19	0.1
$A(\Lambda_c^+ \to \Sigma^0\pi^+)$	1.09	-0.13	0	0.96	1.2
$A(A^+ \to \Xi^0\pi^+)$	-0.78	0.05	1.49	0.76	1.4
$A(A^0 \to \Xi^-\pi^+)$	0.78	0.03	1.49	2.3	10.1
$A(T^0 \to \Xi^0\bar{K}^0)$	-1.50	0.17	-0.38	-1.71	3.7
$B(\Lambda_c^+ \to \Lambda\pi^+)$	0	-0.23	-3.24	-3.47	
$B(\Lambda_c^+ \to p\bar{K}^0)$	0.43	0.43	0.91	1.77	
$B(\Lambda_c^+ \to \Xi^0 K^+)$	-0.04	1.12	0	1.08	
$B(\Lambda_c^+ \to \Sigma^0\pi^+)$	-0.77	-0.49	0	-1.26	
$B(A^+ \to \Xi^0\pi^+)$	0.50	1.59	-4.42	-2.33	
$B(A^0 \to \Xi^-\pi^+)$	-0.50	-0.58	-4.42	-5.50	
$B(T^0 \to \Xi^0\bar{K}^0)$	-0.46	1.07	-0.31	0.3	

The masses of the T^0 and S^0 baryons are taken from the quark mass formulas of Ref.[6b].

3. Discussion and Conclusions

In this paper we have calculated the baryon-baryon matrix elements of the parity-violating Hamiltonian for charmed baryons. We indeed find that for charm-changing transitions the ratio of the PV and PC matrix elements $b_{\beta\alpha}$ and $a_{\beta\alpha}$ is generally larger than the typical value 0.1 obtained for nonleptonic hyperon decays but nevertheless smaller than the value 1 anticipated in Ref.[8] (cf. Table II). Their relative contribution to the S- and P- wave decay amplitudes A, B can easily be estimated from eq. (4). Let $A_a, A_b (B_a, B_b)$ denote the contributions to the $A(B)$ amplitude from the a and b matrix elements. Using $g^A_{k\beta\alpha} \sim 1$ we then have

$$\frac{A_b}{A_a} \sim \frac{B_b}{B_a} \sim \frac{M_c - M}{M_c + M} \; \frac{b}{a} \sim 10^{-1}, \qquad (10)$$

where $(M_c - M)/M_c + M \sim 1/3$ is a typical mass splitting between charmed and ordinary baryons. Note that unlike the case of hyperon decays, the PV matrix elements contribute now already at the 10-20% level. The increase of the ratios A_b/A_a, B_b/B_a for charmed baryons by an order of magnitude with respect to hyperon decays in eq. (10) is a combined effect of both the larger factor of mass splittings and the increase of the b/a ratio. The same order of magnitude estimate (10) roughly holds also for the ratios $A_b/\tilde{A}$, $B_b/\tilde{B}$ where $\tilde{A}$, $\tilde{B}$ include now the factorizable contribution, too. However, as a more careful analysis shows, the ratio (10) may be significantly enhanced in some processes, when the respective commutator and factorizable terms in the A amplitude or the pole and factorizable terms in the B amplitude interfere destructively. Thus, by inspecting Table III, we have, for example, $A_b/\tilde{A}\ (\Lambda_c^+ \to \Xi^0 K^+) = 2.4$, $B_b/\tilde{B}\ (\Lambda_c^+ \to \Sigma^0 \pi^+) = 1.6$ and $B_b/\tilde{B}\ (T^0 \to \Xi^0 \bar{K}^0) = -0.6$. By comparing the partial widths listed in Table III with our earlier results (cf. Ref.[4]) we generally find corrections at the 20% level due to the PV baryon-baryon matrix elements*). The changes are, however, more dramatic if one considers such subtle quantities like the asymmetry parameter α,

$$\alpha = \frac{2k \,\mathrm{Re}(AB^*)}{|A|^2 + k^2 |B|^2} \; ; \quad k = \sqrt{\frac{E-M}{E+M}} \; . \qquad (11)$$

In this case we find, e.g., $\alpha(\Lambda_c^+ \to \Xi^0 K^+) = -0.9$ instead of -0.1 or $\alpha(\Lambda_c^+ \to \Sigma^0 \pi^+) = -0.7$ instead of -0.2. Finally, let us compare our results with the existing experimental data. Note that our estimate $\Gamma(\Lambda_c^+ \to p\bar{K}^0) = 1.7$ is compatible with the experimental value $\Gamma(\Lambda_c^+ \to p\bar{K}^0) = (1.00^{+0.86}_{-0.78}) \times 10^{11}$ $\sec^{-1}$ [11]. Moreover, our ratio $\Gamma(\Lambda_c^+ \to \Sigma^0 \pi^+)/\Gamma(\Lambda_c^+ \to p\bar{K}^0) = 0.71$ is consistent with recent data on Λ_c^+ decays obtained with the Fermilab bubble chamber[13]. However, as before the decay width $\Gamma(\Lambda_c^+ \to \Lambda\pi^+)$ unfortunately comes out too large by a factor of about three when compared with experiment. In this process the commutator term vanishes and the factorizable term seems to be overestimated. The inclusion of the PV term actually does not solve this discrepancy. The question whether excited $(70,1^-)$ or $(168,1^-)$ baryon intermediate states, as proposed in Ref.[14], may yield the needed suppression deserves further study.

In conclusion, we have proved the conjecture of Ref.[8] that PV baryon-baryon matrix elements may give non-negligible contributions to nonleptonic charmed-baryon decays and should therefore be included in careful theoretical calculations. In fact, such effects are expected to become even more important for weak decays of beauty baryons because of a larger breaking of SU(5) symmetry. This point and the implications of the PV-terms for $\Delta C \neq 0$, $\Delta B \neq 0$ weak radiative transitions deserve further attention.

*) This concerns also the processes with enhanced ratios mentioned before. Since the contribution of the B amplitude is suppressed in the partial width relative to the contribution of the A amplitude by a kinematical factor, relative large changes in B for the decays $\Lambda_c^+ \to \Sigma^0 \pi^+$, $T^0 \to \Xi^0 \bar{K}^0$ lead only to relatively small changes in Γ. Note also that the partial width of the decay $\Lambda_c^+ \to \Xi^0 K^+$ is predominantly determined by the B amplitude since the $\tilde{A}$ amplitude is rather small.

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Каллис В., Эберт Д. E2-83-863

Матричные элементы слабого гамильтониана с нарушением четности для очарованных барионов в модели мешка

Вклад матричных элементов от нарушающей четности части слабого гамильтониана с $\Delta C \neq 0$ может оказаться значительным, даже сравнимым с вкладом матричных элементов от сохраняющей четность части гамильтониана вследствие более сильного нарушения симметрии. В работе найдены выражения для этих новых матричных элементов в рамках MIT-мешка и изучено их значение для ранее рассмотренных нелептонных распадов очарованных барионов.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Ebert D., Kallies W. E2-83-863

Bag-Model Matrix Elements of the Parity-Violating Weak Hamiltonian for Charmed Baryons

Baryon matrix elements of the parity-violating part of the charm-changing weak Hamiltonian might be significant and comparable with those of the parity-conserving one due to large symmetry breaking. In this work we derive expression for these new matrix elements by using the MIT-bag model and estimate their implications on earlier calculations of nonleptonic charmed-baryon decays.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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