

## Asymmetries in the Nonmesonic Weak Decay of Polarized $\Lambda$ Hypernuclei

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(Received 26 October 2004; published 1 March 2005)

The nonmesonic weak decay of *polarized*  $\Lambda$  hypernuclei is studied for the first time by taking into account, with a Monte Carlo intranuclear cascade code, the nucleon final state interactions. A one-meson-exchange model is employed to describe the  $\Lambda N \rightarrow nN$  processes in a finite nucleus framework. The relationship between the intrinsic  $\Lambda$  asymmetry parameter  $a_\Lambda$  and the asymmetry  $a_\Lambda^M$  accessible in experiments is discussed. A strong dependence of  $a_\Lambda^M$  on nucleon final state interactions and detection threshold is obtained. Our results for  $a_\Lambda^M$  are consistent with  ${}^1_1\bar{B}$  and  ${}^{12}_\Lambda\bar{C}$  data but disagree with observations in  ${}^5_\Lambda\bar{He}$ .

DOI: 10.1103/PhysRevLett.94.082501

PACS numbers: 21.80.+a, 13.75.Ev, 25.80.Pw, 27.20.+n

The physics of the weak decay of hypernuclei has experienced a recent important development. Because of theoretical [1–6] and experimental [7–9] progress, we are now on the path towards a solution to the long-standing puzzle [10] of the ratio  $\Gamma_n/\Gamma_p$  between the nonmesonic weak decay (NMWD) rates for the processes  $\Lambda n \rightarrow nn$  and  $\Lambda p \rightarrow np$ . This has been possible mainly thanks to the study of nucleon coincidence observables [5,7]. According to the analysis of High Energy Accelerator Research Organization (KEK) data [7] made in Refs. [5,11], the  $\Gamma_n/\Gamma_p$  ratio for both  ${}^5_\Lambda\text{He}$  and  ${}^{12}_\Lambda\text{C}$  is around 0.3–0.4, in agreement with recent pure theoretical estimates [1–4]. Confirmation of these results are awaited from forthcoming experiments at DAΦNE [12] and J-PARC [13].

Despite this recent progress, the reaction mechanism for the hypernuclear NMWD is not fully understood. Indeed, an intriguing problem, of more recent origin, is open: it concerns the asymmetry of the angular emission of NMWD protons from polarized hypernuclei. This asymmetry is due to the interference between parity-violating and parity-conserving  $\vec{\Lambda}p \rightarrow np$  transition amplitudes [14]. The study of the asymmetric emission of protons from polarized hypernuclei is supposed to provide information on the spin-parity structure of the  $\Lambda N \rightarrow nN$  process and hence new constraints on the dynamics of the nonmesonic decay.

The intensity of protons emitted in  $\vec{\Lambda}p \rightarrow np$  decays along a direction forming an angle  $\theta$  with the polarization axis is given by (for details, see Ref. [15])

$$I(\theta) = I_0[1 + \mathcal{A}(\theta)], \quad \mathcal{A}(\theta) = P_y A_y \cos\theta, \quad (1)$$

where  $P_y$  is the hypernuclear polarization and  $A_y$  is the hypernuclear asymmetry parameter. Moreover,  $I_0$  is the (isotropic) intensity for an unpolarized hypernucleus, which we normalize as the total number of primary protons produced per NMWD,  $I_0 = 1/(1 + \Gamma_n/\Gamma_p)$ . In the shell model weak-coupling scheme, angular momentum algebra expresses the polarization of the  $\Lambda$  spin,  $p_\Lambda$ , in terms of  $P_y$ :

$p_\Lambda = P_y$  if  $J = J_C + 1/2$  and  $p_\Lambda = -P_y J/(J + 1)$  if  $J = J_C - 1/2$ ,  $J$  ( $J_C$ ) being the hypernucleus (nuclear core) total spin. By introducing the intrinsic  $\Lambda$  asymmetry parameter,  $a_\Lambda = A_y$  if  $J = J_C + 1/2$  and  $a_\Lambda = -A_y(J + 1)/J$  if  $J = J_C - 1/2$ , one obtains  $\mathcal{A}(\theta) = p_\Lambda a_\Lambda \cos\theta$ . In the hypothesis that the weak-coupling scheme provides a realistic description of the hypernuclear structure,  $a_\Lambda$  can be interpreted as the intrinsic  $\Lambda$  asymmetry parameter for the elementary process  $\vec{\Lambda}p \rightarrow np$  taking place inside the hypernucleus. This scheme is known to be a good approximation for describing the ground state of  $\Lambda$  hypernuclei, and previous calculations [3,15] have proved that, thanks to the large momentum transfer, the nonmesonic decay is not very sensitive to nuclear structure details.

Nucleon final state interactions (FSI), subsequent to the NMWD, are expected to modify the weak decay intensity of Eq. (1). Experimentally, one has access to a proton intensity  $I^M(\theta)$  which is generally assumed to have the same  $\theta$  dependence as  $I(\theta)$ :

$$I^M(\theta) = I_0^M[1 + p_\Lambda a_\Lambda^M \cos\theta]. \quad (2)$$

Then, the observable asymmetry  $a_\Lambda^M$  is determined as

$$a_\Lambda^M = \frac{1}{p_\Lambda} \frac{I^M(0^\circ) - I^M(180^\circ)}{I^M(0^\circ) + I^M(180^\circ)}. \quad (3)$$

Concerning the determination, from data, of the intrinsic  $\Lambda$  asymmetry parameter  $a_\Lambda$ , it is important to stress the following two problems originated by nucleon FSI: (i) one should demonstrate (experimentally and/or theoretically) that the angular dependence of  $I^M(\theta)$  employed in experimental analyses is realistic; (ii) if this is verified, one should investigate the relationship between  $a_\Lambda$  and  $a_\Lambda^M$ , since  $a_\Lambda^M$  is expected to depend on experimental conditions such as the proton detection threshold and the considered hypernucleus.

The  $n(\pi^+, K^+)\Lambda$  reaction is able to produce  $\Lambda$  hypernuclear states with a sizable amount of spin polarization [16] preferentially aligned along the axis normal to the

reaction plane. Until now, four KEK experiments measured the proton asymmetric emission from polarized  $\Lambda$  hypernuclei. The 1992 KEK-E160 experiment [17], which studied  $p$ -shell hypernuclei, suffered from large uncertainties: only poor statistics and energy resolution could be used; moreover, the values of the  $\Lambda$  polarization  $p_\Lambda$  needed to determine the asymmetry  $a_\Lambda^M$  had to be evaluated theoretically. More recently,  $a_\Lambda^M$  was measured by KEK-E278 [18] for the decay of  ${}^5_\Lambda\vec{\text{He}}$ . The values of  $p_\Lambda$  used to obtain  $a_\Lambda^M$  were determined by observing the asymmetry,  $\mathcal{A}^{\pi^-} = p_\Lambda a_\Lambda^{\pi^-}$ , in the emission of negative pions in the  ${}^5_\Lambda\vec{\text{He}}$  mesonic decay, after assuming [19]  $a_\Lambda^{\pi^-}$  to be equal to the value for the free  $\Lambda \rightarrow \pi^- p$  decay,  $a_\Lambda^{\pi^-} = -0.642 \pm 0.013$ . A similar measurement of  $p_\Lambda$  is very difficult, instead, for  $p$ -shell hypernuclei due to their small branching ratio and expected asymmetry  $\mathcal{A}^{\pi^-}$  for the mesonic decay; even the recent and more accurate experiment KEK-E508 [20] had to resort to theoretical estimates [21] for the  $\Lambda$  polarization in  ${}^{12}_\Lambda\vec{\text{C}}$  and  ${}^{11}_\Lambda\vec{\text{B}}$ . Recently,  $a_\Lambda^M$  was measured again for  ${}^5_\Lambda\vec{\text{He}}$ , by KEK-E462 [20], but with improved statistics.

In Table I we report the results for  $a_\Lambda^M$  obtained by the above mentioned experiments, together with recent theoretical estimates for  $a_\Lambda$ . While theoretical models predict negative  $a_\Lambda$  values [24], with a moderate dependence on the hypernucleus, the experiments seem to favor negative values for  $a_\Lambda^M({}^{12}_\Lambda\vec{\text{C}})$  but positive values for  $a_\Lambda^M({}^5_\Lambda\vec{\text{He}})$ .

Concerning the above comparison between theory and experiment, it is important to stress that, while one predicts  $a_\Lambda({}^5_\Lambda\vec{\text{He}}) \simeq a_\Lambda({}^{12}_\Lambda\vec{\text{C}})$ , there is no known reason to expect this approximate equality to be valid for  $a_\Lambda^M$ . Indeed, the relationship between  $I(\theta)$  of Eq. (1) and  $I^M(\theta)$  of Eq. (2)

TABLE I. Theoretical and experimental determinations of the asymmetry parameters ( $a_\Lambda$  and  $a_\Lambda^M$ , respectively). The predictions for  $a_\Lambda$  have been obtained with different weak transition potentials.

Reference and model	${}^5_\Lambda\vec{\text{He}}$	${}^{12}_\Lambda\vec{\text{C}}$
Sasaki <i>et al.</i> [1] $\pi + K + \text{direct quark}$	-0.68	
Parreño <i>et al.</i> [3] $\pi + \rho + K + K^* + \omega + \eta$	-0.68	-0.73
Itonaga <i>et al.</i> [22] $\pi + K + \omega + 2\pi/\rho + 2\pi/\sigma$	-0.33	
Barbero <i>et al.</i> [23] $\pi + \rho + K + K^* + \omega + \eta$	-0.54	
Parreño <i>et al.</i> [6] $\pi + K + \text{contact terms}$	0.24	0.21
KEK-E160 [17]		$-0.9 \pm 0.3^a$
KEK-E278 [18]	$0.24 \pm 0.22$	
KEK-E508 (prel.) [20]		$-0.44 \pm 0.32$
KEK-E462 (prel.) [20]	$0.07 \pm 0.08$	

<sup>a</sup>This result corresponds to the weighted average (discussed on p. 95 of Ref. [10]) among different  $p$ -shell hypernuclear data.

can be strongly affected by FSI of the emitted protons: this fact prevents establishing a direct relation between  $a_\Lambda$  and  $a_\Lambda^M$  and making a direct comparison among results for these quantities. In order to overcome this problem, in the present work we evaluate the effects of the nucleon FSI on the NMWD of  ${}^5_\Lambda\vec{\text{He}}$ ,  ${}^{11}_\Lambda\vec{\text{B}}$ , and  ${}^{12}_\Lambda\vec{\text{C}}$ , and we perform the first theoretical estimate of  $a_\Lambda^M$ .

The  $\Lambda N \rightarrow nN$  weak transition is described with the one-meson-exchange potential of Ref. [3], which accounts for the exchange of  $\pi$ ,  $\rho$ ,  $K$ ,  $K^*$ ,  $\omega$ , and  $\eta$  mesons and well reproduces the new  $\Gamma_n/\Gamma_p$  ratios extracted from KEK data [7] via the weak-interaction-model independent analysis of Refs. [5,11]. The strong final state interactions acting between the weak decay nucleons are taken into account through a scattering  $nN$  wave function from the Lippmann-Schwinger equation obtained with the Nijmegen soft-core NSC97 (versions ‘‘a’’ and ‘‘f’’) potentials [25]. The two-nucleon stimulated process  $\Lambda NN \rightarrow nNN$  [10,26] is safely neglected in our analysis. The fraction of protons from two-nucleon induced decays which escapes from the nucleus with an energy above the typical detection threshold is predicted [5] to be small with respect to the fraction originating from  $\Lambda N \rightarrow nN$ . The propagation of primary (i.e., weak decay) and secondary nucleons (due to FSI) inside the residual nucleus is simulated with the Monte Carlo code of Ref. [27].

In Fig. 1 (2) we show the proton intensity obtained for the nonmesonic decay of  ${}^5_\Lambda\vec{\text{He}}$  ( ${}^{12}_\Lambda\vec{\text{C}}$ ) using the full one-meson-exchange model with the NSC97f potential (the NSC97a potential predicts very similar results). We note that the hypernuclear polarization has been taken to be  $P_y = 1$  in these figures, so that the hypernuclear asymmetry parameter  $A_y$  can be directly extracted from the values of the weak decay intensity at  $\theta = 0^\circ$  and  $\theta = 180^\circ$ . The continuous histograms correspond to the intensity  $I(\theta)$  of primary protons [Eq. (1)]. The inclusion of the nucleon FSI strongly modifies the spectra. With vanishing kinetic en-

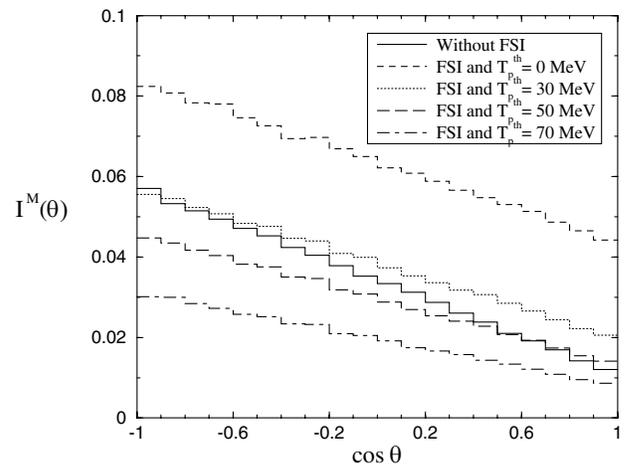
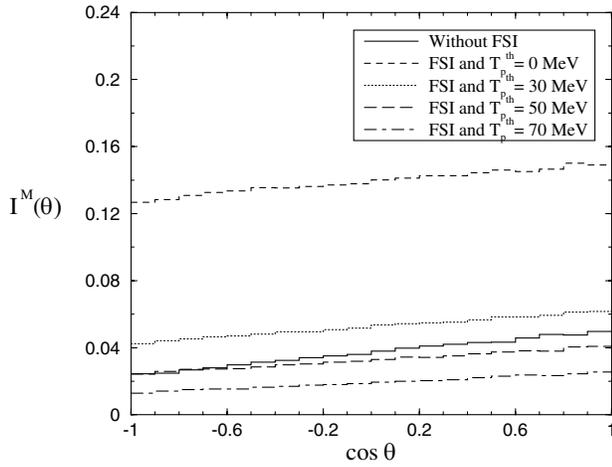


FIG. 1. Angular intensity of protons emitted per NMWD of  ${}^5_\Lambda\vec{\text{He}}$ . See the text for details.

FIG. 2. The same as Fig. 1 for  $^{12}_{\Lambda}\bar{C}$ . See the text for details.

ergy detection threshold,  $T_p^{\text{th}}$ , the intensities are strongly enhanced, especially for  $^{12}_{\Lambda}\bar{C}$ . For  $T_p^{\text{th}} = 30$  or  $50$  MeV, the spectra are closer to  $I(\theta)$ , although with a different slope, reflecting the fact that FSI are responsible for a substantial fraction of outgoing protons with energy below these thresholds. A further reduction of  $I^M(\theta)$  is observed for  $T_p^{\text{th}} = 70$  MeV.

It is evident from Figs. 1 and 2 that the simulated intensities turn out to be well fitted by the linear law in  $\cos\theta$  of Eq. (2). We can thus estimate  $a_{\Lambda}^M$  by using Eq. (3) with  $p_{\Lambda} = 1$  for  $^5_{\Lambda}\bar{\text{He}}$ ,  $p_{\Lambda} = -1/2$  for  $^{12}_{\Lambda}\bar{C}$ , and  $p_{\Lambda} = -5/7$  for  $^{11}_{\Lambda}\bar{\text{B}}$ . To do this,  $I^M(0^\circ)$  [ $I^M(180^\circ)$ ] is evaluated numerically as the proton intensity in the bin with  $\cos\theta \in [0.9, 1]$  ( $\in [-1, -0.9]$ ). In Table II (III) we show our predictions for  $I_0$ ,  $I_0^M$ ,  $a_{\Lambda}$ , and  $a_{\Lambda}^M$  for  $^5_{\Lambda}\bar{\text{He}}$  ( $^{11}_{\Lambda}\bar{\text{B}}$  and  $^{12}_{\Lambda}\bar{C}$ ). They refer to the one-pion-exchange (OPE) and the full one-meson-exchange (OME) models, both using the NSC97f potential. As a result of the nucleon FSI,  $|a_{\Lambda}| \geq |a_{\Lambda}^M|$  for any value of the proton threshold: when  $T_p^{\text{th}} = 0$ ,

TABLE II. Proton intensities and asymmetry parameters for the nonmesonic weak decay of  $^5_{\Lambda}\bar{\text{He}}$ .

Model	$I_0^M$	$a_{\Lambda}^M$
OPE		
Without FSI ( $I_0, a_{\Lambda}$ )	0.92	-0.25
FSI and $T_p^{\text{th}} = 0$ MeV	1.56	-0.12
FSI and $T_p^{\text{th}} = 30$ MeV	0.99	-0.18
FSI and $T_p^{\text{th}} = 50$ MeV	0.78	-0.20
FSI and $T_p^{\text{th}} = 70$ MeV	0.52	-0.20
OME		
Without FSI ( $I_0, a_{\Lambda}$ )	0.69	-0.68
FSI and $T_p^{\text{th}} = 0$ MeV	1.27	-0.30
FSI and $T_p^{\text{th}} = 30$ MeV	0.77	-0.46
FSI and $T_p^{\text{th}} = 50$ MeV	0.59	-0.52
FSI and $T_p^{\text{th}} = 70$ MeV	0.39	-0.55
KEK-E462 (prel.) [20]		$0.07 \pm 0.08$

$a_{\Lambda}/a_{\Lambda}^M \approx 2$  for  $^5_{\Lambda}\bar{\text{He}}$  and  $a_{\Lambda}/a_{\Lambda}^M \approx 4$  for  $^{11}_{\Lambda}\bar{\text{B}}$  and  $^{12}_{\Lambda}\bar{C}$ ;  $|a_{\Lambda}^M|$  increases with  $T_p^{\text{th}}$  and  $a_{\Lambda}/a_{\Lambda}^M \approx 1$  for  $T_p^{\text{th}} = 70$  MeV in all cases.

In Tables II and III our results are compared with the preliminary KEK data of Ref. [20], which correspond to a proton detection threshold varying (from event to event) between 30 and 50 MeV. For these conditions, we obtain OME asymmetries  $a_{\Lambda}^M$  rather independent of the hypernucleus and in the range  $-0.55$  to  $-0.37$ . The  $a_{\Lambda}^M$  values are smaller in size than the corresponding asymmetries before FSI effects,  $a_{\Lambda}$ , by 25% to 50%. It is evident that our OME results are in agreement with the  $^{12}_{\Lambda}\bar{C}$  datum, barely compatible with the  $^{11}_{\Lambda}\bar{\text{B}}$  datum, and inconsistent with the  $^5_{\Lambda}\bar{\text{He}}$  datum. One also sees that the OPE asymmetries are systematically smaller, though less realistic from the theoretical point of view, than the OME ones.

In view of the above large discrepancy, we have proved, numerically, that positive  $a_{\Lambda}^M$  values—such as the ones measured at KEK for  $^5_{\Lambda}\bar{\text{He}}$ —can be obtained only if positive values for the intrinsic asymmetry  $a_{\Lambda}$  are enforced in the weak decay intensity  $I(\theta)$  of Eq. (1): indeed,  $a_{\Lambda}$  and  $a_{\Lambda}^M$  always have the same sign. However, unless there are large SU(3) violations in the coupling constants, it seems unlikely that the meson-exchange models give rise to a positive or vanishing value of the intrinsic  $\Lambda$  asymmetry. Indeed, we have analyzed the origin of the large and negative asymmetry parameter in the one-meson-exchange model of Ref. [3], by calculating the two-body  $\Lambda N(2S+1L_J) \rightarrow nN(2S'+1L'_J)$  amplitudes  $a, b, c, d, e, f$  for  $^5_{\Lambda}\bar{\text{He}}$ , and determining the intrinsic asymmetry through the following relation [28]:

$$a_{\Lambda} = \frac{2\sqrt{3} \text{Re}[ae^* - b(c - \sqrt{2}d)^*/\sqrt{3} + f(\sqrt{2}c + d)^*]}{|a|^2 + |b|^2 + 3[|c|^2 + |d|^2 + |e|^2 + |f|^2]}.$$

In a framework with real  $\Lambda N$  and  $nN$  wave functions, the OPE mechanism produces a large and negative  $a_{\Lambda}$  value due, mainly, to an interference between a large and nega-

TABLE III. Same as in Table II for  $^{11}_{\Lambda}\bar{\text{B}}$  and  $^{12}_{\Lambda}\bar{C}$ .

Model	$I_0^M$	$^{11}_{\Lambda}\bar{\text{B}}$	$I_0^M$	$^{12}_{\Lambda}\bar{C}$
		$a_{\Lambda}^M$		$a_{\Lambda}^M$
OPE				
Without FSI ( $I_0, a_{\Lambda}$ )	0.91	-0.30	0.93	-0.34
FSI and $T_p^{\text{th}} = 0$ MeV	2.84	-0.08	3.15	-0.09
FSI and $T_p^{\text{th}} = 30$ MeV	1.16	-0.17	1.22	-0.20
FSI and $T_p^{\text{th}} = 50$ MeV	0.76	-0.24	0.78	-0.28
FSI and $T_p^{\text{th}} = 70$ MeV	0.47	-0.32	0.46	-0.38
OME				
Without FSI ( $I_0, a_{\Lambda}$ )	0.70	-0.81	0.75	-0.73
FSI and $T_p^{\text{th}} = 0$ MeV	2.44	-0.18	2.78	-0.16
FSI and $T_p^{\text{th}} = 30$ MeV	0.96	-0.39	1.05	-0.37
FSI and $T_p^{\text{th}} = 50$ MeV	0.62	-0.55	0.65	-0.51
FSI and $T_p^{\text{th}} = 70$ MeV	0.38	-0.70	0.38	-0.65
KEK-E508 (prel.) [20]		$0.11 \pm 0.44$		$-0.44 \pm 0.32$

tive tensor amplitude  $d$  ( ${}^3S_1 \rightarrow {}^3D_1$ ) and the parity-violating amplitudes  $b$  ( ${}^1S_0 \rightarrow {}^3P_0$ ) and  $f$  ( ${}^3S_1 \rightarrow {}^3P_1$ ), which are both positive and of moderate size. The inclusion of kaon exchange modifies this picture drastically. Destructive interference with the pion in the tensor channel reduces the  $d$  amplitude by a factor of 4, which would lead to a sensitive decrease in the size of  $a_\Lambda$ . However, the negative  $a$  ( ${}^1S_0 \rightarrow {}^1S_0$ ) and  $c$  ( ${}^3S_1 \rightarrow {}^3S_1$ ) amplitudes become 1 order of magnitude larger in size. Their interference with the positive  $e$  ( ${}^3S_1 \rightarrow {}^1P_1$ ) and  $f$  ( ${}^3S_1 \rightarrow {}^3P_1$ ) amplitudes end up producing a final value for  $a_\Lambda$  which is even 50% larger in size than for OPE alone. The inclusion of the heavier mesons does not change this qualitative behavior.

Summarizing, we have seen how FSI are an important ingredient when studying the NMWD of polarized hypernuclei. The first relationship between the intrinsic asymmetry  $a_\Lambda$  and the observable asymmetry  $a_\Lambda^M$  has been established. Unfortunately, not even an analysis including FSI can explain the present experimental data. From the theoretical point of view, we believe it is unlikely that new reaction mechanisms are responsible for the present discrepancies. Only small and positive values of  $a_\Lambda$ , not predicted by any existing model, could reduce  $a_\Lambda^M$  to small and positive values.

In order to avoid possible statistical fluctuations of the data, new and/or improved experiments, better establishing the sign and magnitude of  $a_\Lambda^M$  for  $s$ - and  $p$ -shell hypernuclei (possibly also exploring the full angular region of the proton intensities) will be important to provide guidance for a deeper understanding of the  $\Lambda N \rightarrow nN$  process in nuclei. The study of the inverse reaction  $\bar{p}n \rightarrow p\Lambda$  [29] should also be encouraged since it could further supply richer and cleaner information on the lambda-nucleon weak interaction and especially on the  $\Lambda$  spin-dependent observables [28]. In our opinion, a closer collaboration among theoreticians and experimentalists (as the one experienced in the recent analyses of the  $\Gamma_n/\Gamma_p$  ratio) is also desirable to disclose the origin of the asymmetry puzzle.

This work was partly supported by EURIDICE HPRN-CT-2002-00311, MIUR 2001024324\_007, INFN, DGICYT BFM2002-01868, and Generalitat de Catalunya SGR2001-64. Discussions with H. Bhang, T. Maruta, T. Nagae, and H. Ota are acknowledged.

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