CONF-8405193--22

BINDING ENERGIES OF HYPERNUCLEI AND Λ-NUCLEAR INTERACTIONS*

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ABSTRACT

Variational calculations indicate that a reasonable description of Λp scattering and of Λ separation energies can be obtained in terms of ΛN plus dispersive and TPE ΛNN forces. Results for the ΛΛ interaction and for $^{6}_{\Lambda\Lambda}$He obtained from an analysis of $^{10}_{\Lambda\Lambda}$Be are discussed. Coulomb and ΛN charge symmetry breaking effects in the A=4 hypernuclei are discussed.

CONF-8405193--22

DE84 014760

1. Λp SCATTERING AND S-SHELL HYPERNUCLEI (A<5)

Low energy Λp scattering determines the total cross section due to s-wave scattering $\bar{\sigma}^{\Lambda p} = (\sigma_s + 3\sigma_t)/4$ (s=singlet, t=triplet, a bar denotes the spin average) which effectively determines the scattering length $\bar{a}^{\Lambda p} \approx -1.9$ and the effective range $\bar{r}_0^{\Lambda p} \approx 3.4$ (all lengths in fm). We use a ΛN potential with a theoretically reasonable attractive part due to 2π exchange (dominated by its OPE transition tensor part) $V_A = -VT_\pi^2(r)$ where T_π is the OPE tensor shape with cutoff (refs. [1,2]). With such a theoretically reasonable attractive range, a repulsive core V_c about the same as for V_{NN} is needed to fit $\bar{\sigma}^{\Lambda p}$, giving an intrinsic range b≈2 fm (about the same as that of ref. [3]). Thus we use the central ΛN potential $V_{\Lambda N} = V_{2\pi} = V_c - (\bar{V} - \frac{1}{4}V_\sigma \vec{\sigma}_\Lambda \cdot \vec{\sigma}_N)T_\pi^2$. V_c is a Woods-Saxon repulsive core (ref. [2]), close to that obtained for V_{NN} (ref. [1]), and $\bar{V} = (V_s + 3V_t)/4$, $V_\sigma = V_s - V_t$ are conveniently used to parameterize $V_{\Lambda N}$ (all potential strengths are in MeV and refer to Λp+Λn averages unless otherwise specified). Then $\bar{\sigma}^{\Lambda p}$ determines $\bar{V}^{\Lambda p} = 6.2 \pm .05$, $0 \lesssim V_\sigma \lesssim .5$. $\bar{V}^{\Lambda p}$ is well determined by $\bar{\sigma}^{\Lambda p}$, whereas the spin dependence V_σ is effectively undetermined by Λp scattering. With charge symmetry breaking (CSB) determined from A=4 (sect. 4), $\bar{V}_{scatt} = 6.15 \pm .05$.

Coupling to Σs (and/or Δs or other excited baryons) gives ΛNN, ΛNNN, ... forces when the Σ, Δ, ... degrees of freedom are projected out to leave only the Λ and N degrees of freedom. This procedure gives two types of ΛNN forces (e.g. ref. [4]).

1) Dispersive ΛNN forces $V^D_{\Lambda NN}$ (associated with "suppression" of the ΣN channel) due to modification of 2-meson exchange (e.g. TPE) contributions to $V_{\Lambda N}$ (between Λ and N_1) resulting from modification of

*This work supported by the U. S. Department of Energy under contract W-31-109-ENG-38.

the propagation ("dispersion") of the intermediate Σ, N, ... by the medium (a 2nd nucleon N_2). We consider two phenomenological forms.

I. Spin independent (refs.[2,5]): $V^{DW}_{\Lambda NN}=WT^2_\pi(r_{1\Lambda})T^2_\pi(r_{2\Lambda})$

II. Spin dependent (ref.[2]): $V^{DS}_{\Lambda NN}[1+\vec{\sigma}_\Lambda\cdot(\vec{\sigma}_1+\vec{\sigma}_2)/6]$.

$V^{DW}_{\Lambda NN}$ and $V^{DS}_{\Lambda NN}$ are equivalent for spin zero core nuclei, in particular for ${}^5_\Lambda He$. $V^{DS}_{\Lambda NN}$ is obtained by assuming the dispersive (suppressive) modifications act only for triplet ΛN_1 states and then symmetrizing between N_1 and N_2. This represents phenomenological suppression of ΛN-ΣN coupling occurring predominantly in the ${}^3S_1$ state via the tensor OPE coupling (refs.[6,7]).

2) Two-pion exchange ΛNN forces $V^{2\pi}_{\Lambda NN}$ (refs.[3,4,8]), assuming only relative ΛN s states.

$$V^{2\pi}_{\Lambda NN}=C[1+(3\cos^2\theta-1)T_\pi(r_{1\Lambda})T_\pi(r_{2\Lambda})]Y_\pi(r_{1\Lambda})Y_\pi(r_{2\Lambda}),$$

where Y(r) is the OPE Yukawa function and $\cos\theta=\hat{r}_{1\Lambda}\cdot\hat{\sigma}_{2\Lambda}$. Theoretical estimates give $C\approx1$-2.

Λ separation energies B_Λ for $A<5$. $A=4^*$ denotes the excited J=1 state of (${}^4_\Lambda H$, ${}^4_\Lambda He$) ; the average excitation energy for A=4, 4^* is $\Delta E_4=1.1\pm.06$. (All energies in MeV.)

Variational calculations using product wave functions, and the procedures described in refs.[2,5], have been made for $V_{\Lambda N}+V^D_{\Lambda NN}+V^{2\pi}_{\Lambda NN}$.

These calculations then give the following relations between V_A (spin average ΛN strength for A), W(dispersive ΛNN strength) and C(TPE ΛNN strength) appropriate to the experimental B_Λ of the s-shell hypernuclei. V_A is given in terms of $\bar{V}$ and V_σ.

A=3:	$V_3=\bar{V}+(V_\sigma/2)=$	$6.27 + 5W(1/3)+ \gamma_3 C$
A=4:	$V_4=\bar{V}+(V_\sigma/4)=$	$6.19 + 7.5W(2/3) \quad .035\ C$
$A=4^*$:	$V_4^*=\bar{V}-(V_\sigma/12)=$	$6.075 + 7.2W(10/9)- \ .028\ C$
$A=44^*$:	$V_\sigma=3(V_4-V_4^*)=$	$0.345 + 0.9W(-10) - .021\ C$
A=5:	$V_5=\bar{V}=$	$6.015 + 10.5W \ + \ .0175\ C$

The numbers in parentheses are the modifying factors due to the use of $V^{DS}_{\Lambda NN}$ instead of $V^{DW}_{\Lambda NN}$. Note especially the large modifications for V_σ and also for V_3. These are in the direction expected for suppression of $V_{\Lambda N}$ in the ${}^3S_1$ state. (The relation for V_σ is essentially determined by ΔE_4). The value of γ_3 has not yet been determined but is expected to be small and negative. Note also the change in sign for $V^{2\pi}_{\Lambda NN}$ between A=5 (repulsive) and A=4,4^* (attractive). However the quantitative change (even that in sign) in the relative contribution of $V^{2\pi}_{\Lambda NN}$ is cutoff dependent and our pertinent conclusions are only semi-quantitative.

A. $V_{\Lambda N}$ (ΛN forces only): With W=C=0, the above relations give:

A=3,4 $\rightarrow$ $\bar{V}=6.11$, $V_\sigma=0.32$ and A=4,4^* $\rightarrow$ $\bar{V}=6.105$, $V_\sigma=.345$. These values are consistent with each other and with $\bar{V}_{scatt}$. Thus B_Λ of A=3,4 and 4* are (just) consistent with only ΛN forces. This conclusion agrees with other analyses in particular that of ref. [3].

${}^5_\Lambda He(B_\Lambda=3.12) \rightarrow \bar{V}=6.015$, whereas $\bar{V}_{scatt} \rightarrow B_\Lambda=5.7\pm1$. This is the well known "overbinding" of ${}^5_\Lambda He$ (ref. [4]). Note that this result depends on the scattering only through $\bar{V}_{scatt}$ which is rather well determined by $\bar{\sigma}^{\Lambda p}$ apart from CSB corrections.

B. $V_{\Lambda N}+V^D_{\Lambda NN}$ (ΛN + dispersive ΛNN forces): With C=0, A=5 determines a relation between $\bar{V}$ and W which using $\bar{V}_{scatt}$ gives W=0.013±.005 (for both $V^{DW}_{\Lambda NN}$ and $V^{DS}_{\Lambda NN}$) corresponding to strongly repulsive ΛNN forces.

I. $V^{DS}_{\Lambda NN}$ (spin independent dispersive ΛNN forces): A=4,4*,5 → $\bar{V}=6.30$, W=.028, $V_\sigma=.37$, and A=3,4,5 → $\bar{V}=8.01$, W=.19, $V_\sigma=-1.58$.

II. $V^{DS}_{\Lambda NN}$ (spin dependent dispersive ΛNN forces): A=4,4*,5 → $\bar{V}=6.30$, W=.027, $V_\sigma=.10$, and A=3,4,5 → $\bar{V}=6.48$, W=.044, $V_\sigma=-.26$.

For both $V^{DW}_{\Lambda NN}$ and $V^{DS}_{\Lambda NN}$ the two sets of values are mutally inconsistent and also inconsistent with $\bar{V}_{scatt}$. This is because $V^D_{\Lambda NN}$ gives a sizable repulsive contribution for A=3,4 whereas these are consistent with only $V_{\Lambda N}$. Thus, $V_{\Lambda N}+V^D_{\Lambda NN}$ is unacceptable for both spin independent and spin dependent dispersive ΛNN forces.

C. $V_{\Lambda N}+V^D_{\Lambda NN}+V^{2\pi}_{\Lambda NN}$ (ΛN + dispersive ΛNN + TPE ΛNN forces)

I. $V^D_{\Lambda NN}=V^{DW}_{\Lambda NN}$: A=4,4*,5+$\bar{V}_{scatt}$ → W=.011±.005, C=1.13±.37, and $V_\sigma=.33\pm.01$. V_σ is only weakly dependent on W and C and is well determined since $V^{DW}_{\Lambda NN}+V^{2\pi}_{\Lambda NN}$ is spin independent and V_σ is mainly determined by ΔE_4. The net ΛNN contributions for A=3,4,4* are small: $V^{2\pi}_{\Lambda NN}$ makes a repulsive contribution for A=5 but an attractive one for A=4,4* (and most probably for A=3), whereas $V^{DW}_{\Lambda NN}$ is repulsive for all A.

With $\bar{V}=6.15\pm.05$, $V_\sigma=.33\pm.01$ one has $a_s^{\Lambda p}\approx-3.3$, $a_t^{\Lambda p}\approx-1.6$ ($\bar{a}^{\Lambda p}\approx-2.03$) and a good fit to $\bar{\sigma}^{\Lambda p}$. Note the large spin dependence.

II. $V^D_{\Lambda NN}=V^{DS}_{\Lambda NN}$: A-4,4*,5 + $\bar{V}_{scatt}$ → W=.011±.005, C=1.13±.37, and $V_\sigma=.22\pm.04$. The reduced ΛN spin dependence results from the spin dependence of $V^{DS}_{\Lambda NN}$ which accounts for ≈ 40% of ΔE_4. The net ΛNN contributions are now appreciable for A=4* but again small for A=3,4. Now: $a_s^{\Lambda p}\approx-2.7$, $a_t^{\Lambda p}\approx-1.7$ ($\bar{a}^{\Lambda p}\approx-1.94$) and again there is a good fit to $\bar{\sigma}$, now with only a moderate spin dependence. The spin dependence obtained from the s-shell may be reconciled with the quite small spin dependence obtained from the p-shell hypernuclei (ref. [9]) because of the different combination of Talmi integrals which enter (ref. [10]).

Note that W and especially C have theoretically reasonable values (perhaps somewhat fortuitously for C because of the cutoff dependence). Thus $V_{\Lambda N}+V^D_{\Lambda NN}+V^{2\pi}_{\Lambda NN}$ give satisfactory and theoretically reasonable fits to σ and to the s-shell B_Λ, thus providing a reasonable phenomenology; furthermore with a spin dependent dipersive ΛNN force the ΛN spin dependence is moderate.

2. HEAVIER HYPERNUCLEI A>5 WITH SPIN ZERO (J_c=0) CORE NUCLEI

To date we have made calculations only for $V_{\Lambda N} + V^D_{\Lambda NN}$ for ${}^9_\Lambda$Be, ${}^{13}_\Lambda$C, and the well depth D(A=∞). These are described in ref. [2] and will be only briefly discussed. With J_c=0, $V_{\Lambda N}$ enters only through $\bar{V}$; also $V^{DW}_{\Lambda NN}$ and $V^{DS}_{\Lambda NN}$ are equivalent. For A>5 a new feature is that $V_{\Lambda N}$ for ℓ>1 now contributes significantly. With $V_{\Lambda N}=V_0(r)\,[1-\varepsilon+\varepsilon P_x]$, Λp scattering at moderate energies gives ε≈0.25. The p-state ΛN potential is given in terms of the s-state potential V_0 by $V_1=V_0(1-2\varepsilon)$.

Well depth D(≈30±3). Results have been obtained with the Fermi hypernetted chain (FHNC) approximation (ref. [2,11]). The conclusions are:

1. With only $V_{\Lambda N}$ and with $\bar{V}_{scatt}$ → D=71±7, i.e., strongly overbound!
2. $V_{\Lambda N} + V^D_{\Lambda NN}$ such as to give $B_\Lambda({}^5_\Lambda He)$ → D=46±3.
3. $V_{\Lambda N}(\varepsilon\approx.25)+V^D_{\Lambda NN}$ → D≈36±3, i.e., with $V_1 = V_0/2$ one obtains agreement for D.

COMMENTS: 1. Coupled channel ΛN−ΣN G-matrix calculations give suppression of the ΛN−ΣN OPE coupling which can reduce D by ≈ 20 MeV (ref. [6]). This is consistent with our FHNC result $\langle V^D_{\Lambda NN}\rangle$ ≈ 20 MeV for W ≈ .013. However there is some doubt about the lowest-order G matrix calculations which may substantially overestimate the suppression.

2. The lowest-order cluster approximation $D^{(0)}$ is an excellent approximation to the full FHNC result. $D^{(0)}$ corresponds to the use of effective interactions $\tilde{V}_{\Lambda N}$, $\tilde{V}^D_{\Lambda NN}$ which involve the ΛN correlation function determined by nuclear-matter calculations. $\tilde{V}_{\Lambda N}$, $\tilde{V}^D_{\Lambda NN}$ may then be used for finite nuclei in a first-order (folding) calculation.

3. For our ΛN potential (which gives a moderate wound integral κ≈.07) the lowest-order G-matrix results are very close to the FHNC values (within ≈ 1 MeV).

${}^9_\Lambda$Be (B_Λ=6.71±.04). We use a 2α+Λ model implemented by 3-body variational calculations (ref. [2]). The αα potential $V_{\alpha\alpha}$ is fitted to αα scattering. The αΛ potential $V_{\alpha\Lambda}=V^{(2)}_{\alpha\Lambda}+V^{(3)}_{\alpha\Lambda}$(=ΛN+ΛNN contributions) is obtained by folding $\tilde{V}_{\Lambda N}$ and $\tilde{V}^D_{\Lambda NN}$ with ρ_α and reproduces $B_\Lambda({}^5_\Lambda He)$. $V_{\alpha\alpha\Lambda}$ is the effective ααΛ potential due to the Λ interacting via $V_{\Lambda NN}$ with pairs of nucleons each in a different α and is also obtained by folding; $V_{\alpha\alpha\Lambda}$ is proportional to W and is completely determined for a given $V_{\alpha\Lambda}$. The conclusions are:

1. With only $V^{(2)}_{\alpha\Lambda}$ and with $\bar{V}_{scatt}$ → B_Λ ≈ 11.5, again strongly overbound.
2. Only $V_{\alpha\Lambda}$(fit to $B_\Lambda({}^5_\Lambda He)$) → B_Λ ≈ 7.8 ($\langle V_{\alpha\Lambda}\rangle$≈ −15.8)
3. $V_{\alpha\Lambda} + V_{\alpha\alpha\Lambda}$ → B_Λ ≈ 6.9 ($\langle V_{\alpha\alpha\Lambda}\rangle$=0.85)
4. $V_{\alpha\Lambda} + V_{\alpha\alpha\Lambda}$ with reduced p-state $V_{\Lambda N}$ (ε≈.25)→B_Λ≈6.5 ($V_1 = V_0/2$ is estimated to reduce B_Λ by ≈ 0.4 MeV). A repulsive contribution from $V_{\alpha\alpha\Lambda}$ is needed to avoid ${}^9_\Lambda$Be being overbound by ≈ 1 MeV. Thus ${}^9_\Lambda$Be strongly indicates the presence of ααΛ and hence of ΛNN forces.

${}^{13}_\Lambda$C. B_Λ was calculated by obtaining the Λ−^{12}C potential by folding $\tilde{V}_{\Lambda N}$,

$\tilde{V}^D_{\Lambda NN}$ with the density of ^{12}C. The conclusions are effectively the same as for D and $^9_\Lambda Be$.

Thus, dispersive ΛNN forces consistent with $^5_\Lambda He$ together with ΛN forces consistent with scattering and with a weakened p-state interaction give satisfactory B_Λ for hypernuclei with A>5 and with spin zero core nuclei.

We believe that a combination of dispersive + TPE ΛNN forces which fit $B_\Lambda(^5_\Lambda He)$ will not significantly change this conclusion, but this remains to be shown.

3. ΛΛ HYPERNUCLEI: $^{10}_{\Lambda\Lambda}Be$ AND $^6_{\Lambda\Lambda}He$

Our calculations for these are described in ref. [12], and will be only briefly discussed.

$^{10}_{\Lambda\Lambda}$($B_{\Lambda\Lambda}$=17.71±.08) is the best established and most critically examined ΛΛ hypernucleus event. We use an α+2Λ model for $^6_{\Lambda\Lambda}He$ and a 2α+2Λ model for $^{10}_{\Lambda\Lambda}Be$ with $V_{\alpha\Lambda}$, $V_{\alpha\alpha}$ and $V_{\alpha\alpha\Lambda}$ obtained as for $^9_\Lambda Be$. For $V_{\Lambda\Lambda}$ we use a variety of shapes and ranges both for the repulsive core V_c and for the attractive part V_A. Variational 4-body calculations for $^{10}_{\Lambda\Lambda}Be$ determine one parameter (e.g. the strength of V_A) of $V_{\Lambda\Lambda}$. "Reasonable" $V_{\Lambda\Lambda}$ (V_c comparable to that for V_{NN}, reasonable range for V_A) give $a^{\Lambda\Lambda} \approx -(2.5-3.5)$, $r_0^{\Lambda\Lambda} \approx 2.6-3.1$. The ΛΛ interaction is strongly attractive, comparable to or even more attractive than the ΛN force, and is not far from giving a bound ΛΛ state. Meson-exchange models obtained by the Nijmegen group (ref. [13]) predict $a^{\Lambda\Lambda} \approx -0.26$, i.e. a very weakly attractive $V_{\Lambda\Lambda}$. This discrepancy could be tentative evidence for a 6q state with the quantum numbers of a $^1S_0$ ΛΛ state and not too far above the ΛΛ threshold.

$^{10}_{\Lambda\Lambda}Be$ and $^6_{\Lambda\Lambda}He$. Calculations for various $V_{\Lambda\Lambda}$ with differing shapes and strengths give an approximately linear relation between $B_{\Lambda\Lambda}(^{10}_{\Lambda\Lambda}Be)$ and $B_{\Lambda\Lambda}(^6_{\Lambda\Lambda}He)$. For the experimental value of $B_{\Lambda\Lambda}(^{10}_{\Lambda\Lambda}Be)$ this relation predicts much too small values of $B_{\Lambda\Lambda}(^6_{\Lambda\Lambda}He)$ well outside the errors quoted for this event.

4. COULOMB EFFECTS AND CHARGE SYMMETRY BREAKING (CSB) FOR A=4.

Coulomb corrections. The Coulomb repulsion between the protons in $^4_\Lambda He$ contributes $\Delta B_c < 0$ to $\Delta B_\Lambda = B_\Lambda(^4_\Lambda He) - B_\Lambda(^4_\Lambda H)$. To 1st order in V_c: $\Delta B_c = -\Delta E_c = -[E_c(^4_\Lambda He) - E_c(^3He)]$, where ΔE_c is the increase in the Coulomb energy of the ^3He core due to the Λ. ΔB_c has been calculated (ref. [14]) for our charge symmetric (CS) potential $V_{2\pi}$. The energies of $^4_\Lambda He$, ^3He, and hence ΔB_c, were calculated variationally for several values of q^2 in the range $0 \le q^2 \le 9$ where $V_c = q^2e^2/r$; i.e. the Coulomb repulsion is artificially boosted. For $q^2 \lesssim 3$ the dependence on q^2 is linear and interpolation to $q^2 = 1$ gives the He values with improved accuracy. We obtain the rather small values: $|\Delta B_c| = .05 \pm .02$, $|\Delta B_c^*| = .025 \pm .015$, which are also consistent with the calculated values of ΔE_c. Our values are consistent with those of ref. [15], but significantly less than those of ref. [3]. Adding our values to the appropriate experimental ΔB_Λ then gives the following values to be attributed to CSB effects: $\Delta B_\Lambda = .40 \pm .06$, $\Delta B_\Lambda^* = .27 \pm .06$.

Phenomenological charge symmetry breaking potential. For this we consider a $T_\pi^2(r)$ shape. This is to be used together with our CS potential $V_{2\pi}$. Fitting to the above values of ΔB_Λ, ΔB_Λ^* gives $V^{CSB} \approx -0.054\ \tau_3\ T_\pi^2(1 + 0.0054\ \vec{\sigma}_\Lambda \cdot \vec{\sigma}_N)$. For $a_s = a_t \approx -1.9$ this potential gives $\Delta a_s \approx .39$, $\Delta a_t \approx .36$, where $\Delta a = -(a^{\Lambda p} - a^{\Lambda n})$ and is positive if the Λp is more attractive than the Λn interaction. Thus the CSB potential is only slightly spin dependent. (Actually less so than would be suggested simply by the values of ΔB_Λ, ΔB_Λ^*.) We have checked that for our shape of V^{CSB} the connection between ΔB_Λ, ΔB_Λ^* and Δa_s, Δa_t is in good agreement with that obtained in ref. [16]. The two acceptable spin dependent CS solutions of sect. 1 give $\Delta a_s \approx .55$, $\Delta a_t \approx .25$, the larger difference reflecting the CS spin dependence.

Comparison with meson-exchange models. An instructive illustrative model is $V_{\sigma K}^{CS} + V_\pi^{CSB}$; the CS potential ($b \approx 2$ fm) has a hard core, kaon exchange (with $g_{\Lambda NK}^2 = 16$) which gives a ΛN tensor force, and σ-meson exchange chosen to give a total $a \approx -2$; the CSB potential is the OPE potential due to Λ-Σ° mixing (refs. [4,17]). This model gives $\Delta a_s \approx -.1$, $\Delta a_t \approx .15$, qualitatively similar to the results of the more complete models of Nagels et al. (ref. [13]) which also include ρ and δ exchange and the effect of the Σ^+, Σ^- mass difference, and which give $\Delta a_s \approx -.3$, $\Delta a_t \approx .1$ to $.2$ (for their models B, D, F). It is important to note that the major contribution to Δa_t in our model comes from the CSB tensor part acting together with the CS tensor part. This gives a contribution proportional to $V_T^{CSB}\ V_T^{CS}$, i.e. to $V_{K,T}^{CS}\ V_{\pi,T}^{CSB}$ for our model with a contribution of .12 to Δa_t. Thus uncertainties in the CS tensor part (e.g. in $g_{\Lambda NK}^2$) will give corresponding uncertainties in Δa_t. Furthermore (probably moderate) differences between the calculated ΛN values and the phenomenological values obtained from ΔB_Λ, ΔB_Λ^* can arise from many-body and nuclear structure effects. Since in any case there is no major discrepancy between the meson-exchange and phenomenological values of Δa_t, we conclude that the triplet CSB interaction obtained from the A=4 hypernuclei is consistent with meson-exchange models.

For the singlet difference Δa_s there is no uncertainty corresponding to that arising from V_T^{CS} for Δa_t. Furthermore, many-body and nuclear structure effects are expected to be less than for Δa_t. The large differences (even the opposite sign) between the meson-exchange and phenomenological results for Δa_s then strongly suggest that meson-exchange models of the singlet CSB interaction are inconsistent with the A=4 data indicating that there may be important quark structure contributions.

Of course complete calculations with ΛN and NN tensor forces are required for the A=4 hypernuclei in order to definitely establish that nuclear structure effects do not change the above conclusions.

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