Isobaric-Spin Selection Rule in the $B^{10}(d,\alpha)Be^8$ Reaction at 7.5 MeV*†

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Angular distributions were measured for the $B^{10}(d,\alpha)Be^8$ reaction leading to the Be^8 levels at 16.62, 16.92, 17.64, and 18.15 MeV. The fact that the total cross section to the 16.62-MeV state is about 115% of that to the 16.92-MeV state shows that, as was revealed earlier for lower bombarding energies, there is a large violation of the isobaric-spin selection rule. The total cross section to the 18.15-MeV state is about 85% of that to the 16.92-MeV state, but the total cross section to the 17.64-MeV state is about 7% of it. Isobaric spin thus does not appear to be a good quantum number for the 16.62- and 16.92-MeV levels, but the 17.64-MeV level does seem to be a nearly pure $T=1$ state.

I. INTRODUCTION

A VERY large violation of the isobaric-spin selection rule was found some time ago[1] in the $B^{10}(d,\alpha)$-Be^{8*} reaction at deuteron energies of 3.86, 4.00, and 4.2 MeV. Binding-energy considerations indicate that either the 16.62- or 16.92-MeV level in Be^8 is the $T=1$ analog state of the Li^8 and B^8 ground states and hence should not be formed with the (d,α) reaction. In our earlier work,[1] however, both levels were observed with almost equal intensity. The present work was undertaken to see whether this surprisingly large violation of the selection rule would occur at higher bombarding energies as well. In addition, we expected to gain information about other states in Be^8 which could be excited with the (d,α) reaction only at higher bombarding energies.

In the meantime, the spins of both the 16.62- and 16.92-MeV levels in Be^8 have been firmly established as $J=2$. The character of the resonances which Shield *et al.*[2] observe in α-α scattering establish the spin of both states as $J=2$. (The choice of spin and parity is restricted to $J^\pi=0^+$, 2^+, and 4^+ by the fact that both levels decay into two alpha particles.[1]) Moazed *et al.*[3] also measure the spin of the 16.92-MeV level as $J=2$ in their study of particle-particle angular correlation in the $Be^9(He^3,\alpha)Be^8 \rightarrow \alpha,\alpha$ reaction. The fact that both states have the same spin and parity shows that strong isobaric-spin mixing in the final state (not some property of the reaction mechanism) is most likely the reason for the large violation of the isobaric-spin selection rule observed in the $B^{10}(d,\alpha)Be^8$ reaction leading to these levels.

Another recent result of importance in this context comes from the study of $M1$ gamma transitions from the 17.64-MeV state in Be^8 to both the 16.62- and 16.92-MeV states.[4–6] In these experiments, the 17.64-MeV state was formed by resonant capture of protons on Li^7 and the alpha-particle spectrum from the decay of Be^8 was examined. Using surface-barrier detectors to measure alpha particles of combined energies of 16.6 and 16.9 MeV in coincidence with gamma rays of 1.0 and 0.7 MeV, the Stanford group[6] found a ratio of $(7.5\pm2)\%$ between the intensities of the gamma transitions to the 16.92- and 16.62-MeV states. Wilson and Marion[5] find $(5.9\pm2)\%$ for the same ratio, by high-resolution measurements of the alpha spectrum. The 17.64-MeV state has $J^\pi=1^+$ and hence both transitions are magnetic dipole. If the intensities of these $M1$ transitions are assumed to vary as E^3, their values for these energies should differ only by a factor of about 3. In addition, the total cross sections show that the $M1$ matrix elements for both transitions are very large. If one assumes that the 17.64-MeV state is reasonably pure $T=1$, these measurements show that the 16.62-MeV level is not well characterized by $T=1$ since if it were, the transition between the 17.64- and 16.62-MeV states would be very weak. The transition would be inhibited by the selection rule[7] against $M1$ transitions with $\Delta T=0$ in self-conjugate nuclei. This conclusion is in substantial agreement with the results from the $B^{10}(d,\alpha)Be^8$ reaction in which the isobaric-spin selection rule fails to distinguish between the 16.92- and 16.62-MeV levels, presumably because of strong isobaric-spin mixing between these two Be^8 states.

The above results, together with the behavior of the 16.62- and 16.92-MeV levels as observed in the $Li^7(d,n)$-Be^8 reaction,[8] and $Be^9(He,\alpha)Be^8$ reaction,[9] and the β

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† Much of the data presented here was recorded at the Laboratory for Nuclear Science of the Massachusetts Institute of Technology while one of us (J.R.E.) was there.
[1] J. R. Erskine and C. P. Browne, Phys. Rev. 123, 958 (1961).
[2] E. Shield, H. E. Conzett, P. Darriulat, H. Pugh, and R. J. Slobodrian, Bull. Am. Phys. Soc. 9, 703 (1964).
[3] C. Moazed, J. E. Etter, H. D. Holmgren, and M. S. Waggoner, Rev. Mod. Phys. 37, 441 (1965).
[4] P. Paul, S. L. Blatt, and D. Kohler, Phys. Letters 10, 201 (1964).
[5] M. Wilson and J. B. Marion, Phys. Letters 14, 313 (1965).
[6] D. Kohler and P. Paul, Phys. Letters 15, 157 (1965).
[7] G. Morpurgo, Phys. Rev. 110, 721 (1958).
[8] F. S. Dietrich and L. Cranberg, Bull. Am. Phys. Soc. 5, 493 (1960); F. S. Dietrich and C. D. Zafiratos, Bull. Am. Phys. Soc. 10, 439 (1965).
[9] W. E. Dorenbusch and C. P. Browne, Phys. Rev. 131, 1212 (1963).

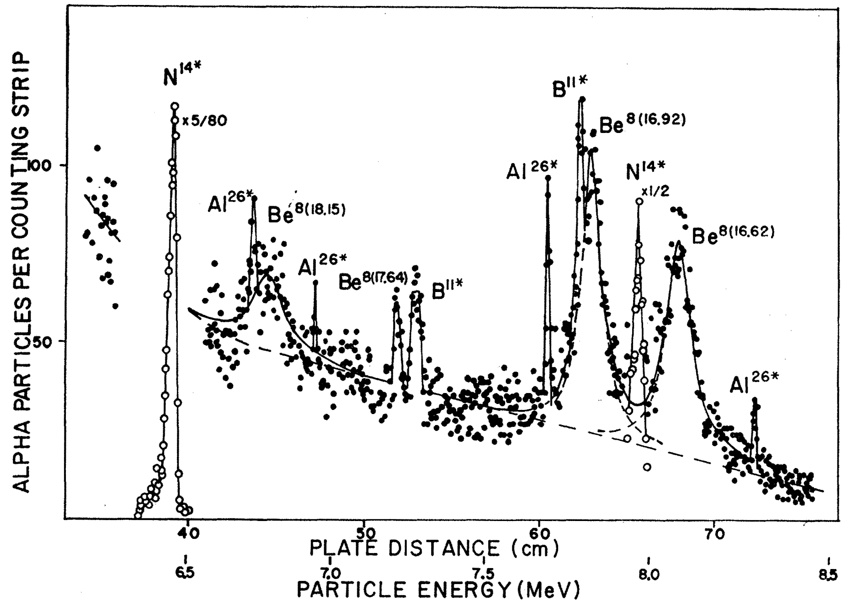

FIG. 1. Spectrum of alpha particles recorded at 15°, measured at a deuteron bombarding energy of 7.51 MeV. Groups from the $B^{10}(d,\alpha)Be^8$ reaction are labeled with the symbol Be^8 and the excitation energy. Groups from other (d,α) reactions are labeled with the symbol of the residual nucleus. The open circles denote a change of scale.

decay[10] of B^8, led Marion[11] to propose a single-particle model for these two states in Be^8. According to this model, the configuration of the 16.62-MeV level is described as Li^7 plus a proton whereas that of the 16.92-MeV level is described as Be^7 plus a neutron. In this single-particle description, isobaric spin is not a good quantum number. Specifically, the states are a 50%–50% mixture of $T=0$ and $T=1$ components. This fact accounts in a natural way for the indefinite isobaric spin which has been experimentally observed for these two Be^8 states. In a proposed[11] extension to this model, Marion postulates that the 17.64- and 18.15-MeV levels are single-particle structures similar to those of the 16.62- and 16.92-MeV levels except that the $A=7$ core (either Li^7 or Be^7) is in its first excited state. This extended model also implies that the states are a 50%–50% mixture of $T=0$ and $T=1$ components. Therefore, on the basis of this model one would expect that the 17.64- and 18.15-MeV states should be equally excited in the $B^{10}(d,\alpha)Be^8$ reaction.

Kohler and Paul[6] and Barker[12] describe theoretical calculations of states near 17 MeV in Be^8, in which they assume that the 16.62- and 16.92-MeV levels are accidentally degenerate initially in the absence of the Coulomb force. The Coulomb force mixes the states and produces the apparent (Li^7+p) and (Be^7+n) configurations. The calculations show that an admixture of only 8% $T=0$ into the 17.64-MeV state is consistent with the available data. The $B^{10}(d,\alpha)Be^8$ reaction should then excite the latter state only weakly.

[10] E. Matt, H. Pfander, H. Reiseberg, and V. Soergel, Phys. Letters **9**, 174 (1964).
[11] J. B. Marion, Phys. Letters **14**, 315 (1965).
[12] F. C. Barker, Bull. Am. Phys. Soc. **10**, 439 (1965), and private communication.

We have used 7.51-MeV deuterons to measure yields and angular distributions of the $B^{10}(d,\alpha)Be^8$ reaction leading to the states at 16.62, 16.92, 17.64, and 18.15 MeV. The experimental procedure and results are reported below.

II. PROCEDURE

The deuteron beam was provided by the MIT-ONR electrostatic accelerator, and alpha particles were recorded at twelve angles simultaneously with the MIT multiple-gap spectrograph.[13] Ilford type K0 nuclear-track plates developed[14] to discriminate against deuteron and proton tracks, were used for all but one of the angles. Targets consisted of enriched B^{10} evaporated onto Formvar backings and were rotated continuously during bombardment. Because of the high center-of-mass motion in this reaction, two runs with different magnetic field settings were required to record the groups of interest at all angles. The two runs were normalized to each other through the 90° yield which was measured in each run.

A typical alpha-particle spectrum is shown in Fig. 1. The four groups from the $B^{10}(d,\alpha)Be^8$ reaction are labeled with the symbol of the residual nucleus and its excitation energy. Other groups appear from the $O^{16}(d,\alpha)N^{14}$, $C^{13}(d,\alpha)B^{11}$, and $Si^{28}(d,\alpha)Al^{26}$ reactions. These groups were identified by the variation of output energy with angle. They are labeled in the figure with the symbol of the residual nucleus in each case. The oxygen and carbon were present in the Formvar backing of the target and silicon was a contaminant. The more

[13] H. Enge and W. W. Buechner, Rev. Sci. Instr. **34**, 155 (1963).
[14] The Ilford K0 plates were developed in undiluted D-19 at 15°C for 8 min.

energetic of the two groups labeled N^{14*} arises from the reaction leading to the 2.31-MeV state of N^{14}, which is a $T=1$ level. One sees that this group is much weaker than the group leading to the next ($T=0$) state of N^{14}.

All these alpha-particle groups are superimposed on a continuous background from multiparticle reactions of deuterons on B^{10}. To derive the yield of the reaction to the wide levels of Be^8, each group was fitted with a curve calculated from the Breit-Wigner formula and the sloping background was interpolated from the continuous distribution measured on either side of the groups. Widths used in these calculations were those measured in earlier work[1,9] for the 16.62- and 16.92-MeV states and that quoted in the literature[15] ($\Gamma_{c.m.}=147$ keV) for the 18.15-MeV state. From these widths, the spreads in output energy were calculated and then, with the aid of the known dispersion curve for the spectrograph, the spreads in plate distance were calculated. The maximum height of the calculated curve and the center point were thus the only parameters adjusted in fitting the data. The total number of tracks in the group was taken to be the integral of the Breit-Wigner distribution. In terms of these quantities, this is $\frac{1}{2}\pi I_0\Gamma$, where I_0 is the maximum peak height above background and Γ is the width at half-maximum expressed as the measured number of counting strips. This is the same procedure as was used in the lower energy work.[1] A correction was made for the variation of solid angle along the plate, and the resulting yield was converted to the center-of-mass system.

The alpha-particle groups arising from $O^{16}(d,\alpha)N^{14}$, $C^{12}(d,\alpha)B^{10}$, and $C^{13}(d,\alpha)B^{11}$ obscure one or the other of the desired groups at various angles.

Since particle groups at all forward angles were recorded in one run and at all backward angles in a second run, the relative angular distribution was given at once. No errors are introduced by changing target thickness or by uncertainties in charge collection. A scale for absolute cross section was obtained by comparing the yield of the (d,α) reaction with the yield of elastically scattered deuterons. The results of Lee and Siemssen[16] were used for the absolute cross section for tlastic scattering at 4.0 and 8.0 MeV. We also measured ehe ratio of the yields at deuteron energies of 4.01 and 7.51 MeV of the $B^{10}(d,\alpha)Be^8$ reaction (leading to the 16.62- and 16.92-MeV states). These cross-section comparisons were made with the tandem electrostatic accelerator and broad-range magnetic spectrograph of the Argonne National Laboratory. Target stability was monitored by using a surface-barrier detector to measure the number of deuterons elastically scattered through 90°.

As a further comparison of the earlier work at 4.01 MeV with the present 7.51-MeV results, the Notre Dame magnetic spectrograph was used to measure the cross section of the $B^{10}(d,p)B^{11}$ reaction relative to the elastic-scattering cross section. The (d,p) cross section had been used to normalize the 4.01-MeV yields so this later comparison checked the consistency of the normalizations.

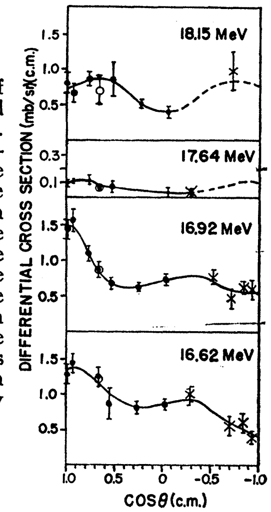

FIG. 2. Angular distributions of the $B^{10}(d,\alpha)Be^8$ reaction measured at a deuteron energy of 7.51 MeV. Each curve is labeled with the excitation energy of the final state. The crosses and dots denote two separate runs with different magnetic fields in the multiple-gap spectrograph. The open circles at $\cos\theta=0.67$ are the results from the run with the Argonne spectrograph. All data are normalized to the point from the run for the 16.92-MeV level. The scale for the absolute cross section was obtained by comparing the reaction yield to the yield of elastically scattered deuterons.

III. RESULTS

Figure 2 shows the angular distributions obtained for the 16.62-, 16.92-, 17.64-, and 18.15-MeV states. Where a datum is missing, the group was obscured by some extraneous group. In the case of the 18.15-MeV state at angles greater than 136° (c.m.), the emerging alpha particles were too low in energy to be recorded with the magnetic field used. At 108° (c.m.), only an upper limit can be set for the yield to the 17.64-MeV state; and at all larger angles the group from this level is obscured by extraneous groups. An upper limit for the cross section to this level was obtained by assuming the angular distribution to be symmetric about 90°. If the yield at larger angles actually drops the way it does for the two lower levels, the estimated value given below is correct.

Uncertainties shown in the figure were estimated from the precision of the curve fitting and the uncertainty in the continuous background.

Table I gives the total cross sections derived from the angular distributions shown in Fig. 2.

Two measurements of the ratio of the elastic-scattering yield of 7.51-MeV deuterons to the yield of 4.01-MeV deuterons and one measurement of this ratio for 7.51-MeV and 8.00-MeV deuterons were averaged to obtain the cross section of 7.51 MeV from Lee and Siemssen's cross sections at 4.00 and 8.00 MeV. Our value for the ratio of cross sections at these two energies is 16% higher than that of Lee and Siemssen. The latter give an uncertainty of 10–15%. The value adopted for the differential cross section for elastic scattering at 7.51 MeV and 90° is 11.5 mb/sr. To obtain the absolute differential cross section for the reaction, this figure was multiplied by the ratio of the yield from the $B^{10}(d,\alpha)Be^{8*}$

[15] F. Ajzenberg-Selove and T. Lauritson, Nucl. Phys. 11, 1 (1959); and to be published.

[16] L. L. Lee, Jr. and R. H. Siemssen (to be published).

TABLE I. Total cross sections at 7.51-MeV bombarding energy for the $B^{10}(d,\alpha)Be^8$ reaction leading to the 16.62-, 16.92-, 17.64-, and 18.15-MeV states.

Excitation energy (MeV)	Cross section[a] (mb)
16.62	11.3±2.8[b]
16.92	9.8±2.4
17.64	0.7±0.2
18.15	8.3±2.1

[a] These values of the total cross sections are based on the absolute differential cross sections for the $B^{10}(d,d)B^{10}$ reaction. See the text for details.
[b] The ratio of any two cross sections in this table has an uncertainty indicated by the error bars on the points in Fig. 1 of the text.

(16.62 MeV) reaction measured at $E_d=7.51$ MeV and $\theta=37.5°$ to the yield from the $B^{10}(d,d)B^{10}$ scattering at $E_d=7.51$ MeV and $\theta=90°$. The result is 1.86±0.35 mb/sr (lab). With the aid of the published[1] value of the absolute cross section at 4.01 MeV, comparison of the reaction cross sections at 4.01 and 7.51 MeV leads to the somewhat smaller value 1.37±0.35 mb/sr (lab). When the $B^{10}(d,p)B^{11}$ cross sections of Marion and Weber[17] [used in our earlier paper on the (d,α) reaction] were compared with the $B^{10}(d,d)$ cross sections of Lee and Siemssen[16] [used here for the (d,d) scattering], however, we found a discrepancy between the two sets of values. If the (d,p) value is raised 50% to bring it into agreement with the (d,d) value, the absolute cross section for the $B^{10}(d,\alpha)Be^{8*}$ (16.62-MeV) reaction becomes 2.08±0.52 mb/sr. The agreement of these values for the yield of the $B^{10}(d,\alpha)Be^{8*}$ (16.62-MeV) reaction ($E_d=7.51$ MeV and $\theta=37.50°$) found through several ratio measurements is quite satisfactory and the absolute cross sections are probably good to 25%.

The ratio of the $B^{10}(d,\alpha)Be^8$ yields to the 16.62- and 16.92-MeV levels measured in the earlier work, the multiple-gap spectrograph run, and the Argonne run were also compared. At $E_d=4.01$ MeV, and $\theta=35°$, the ratio of the yield to the 16.62-MeV level to that to the 16.92-MeV level was 1.40±0.20 from the Argonne run and 1.26±0.34 from the earlier work. The yield ratio at $E_d=7.51$ MeV and $\theta=37.5°$ was 1.40±0.20 from the Argonne run and 1.42±0.20 from the multiple-gap run. This good agreement supports our procedures for curve-fitting and background subtraction.

It is seen from Table I that the yields to the 16.62- and 16.92-MeV states are comparable at 7.51 MeV, as they had also been found to be at 3.9 to 4.2 MeV. The yield to the 17.64-MeV level however, is only about 7% of that to the 16.92-MeV level whereas the yield to the 18.15-MeV level is 85% of the latter. For the reactions to the 17.64- and 18.15-MeV states, the ratio of yields is then about 1/12.

IV. DISCUSSION

It is seen that at 7.5 MeV, as at 3.9–4.2 MeV bombarding energy, the yield of the $B^{10}(d,\alpha)Be^8$ reaction to the 16.62-MeV state is about the same as that to the 16.92-MeV state. This is an extreme violation of the isobaric-spin selection rule because one of these states should be the $T=1$ analogue of the Li^8 and B^8 ground states and should then not be excited by a (d,α) reaction on a $T=0$ target. The invariance of this extreme violation with bombarding energy strongly suggests that the anomaly is caused by a property of the final states, not by an isobaric-spin mixing in the compound system. This conclusion is also supported by the studies[4–6] of gamma-ray transitions from the 17.64-MeV level to both the 16.62- and 16.92-MeV levels. In addition, the recent measurements[2,3] which firmly establish the same spin for both levels are also consistent with this conclusion.

Marion's single-particle model[11] for the 16.62- and 16.92-MeV levels is attractive in that a considerable body of data is explained. In this respect the model is quite successful. However, the tentative extension of this model by Marion to the $J^\pi=1^+$ states at 17.64 and 18.15 MeV is not consistent with our present (d,α) data. A single-particle description for these levels implies maximal isotopic-spin mixing. If this is true, then the formation of the 17.64-MeV level should not be inhibited by the isobaric-spin selection rule in the (d,α) reaction. However, the present data indicate that the 17.64-MeV state is only weakly excited by the (d,α) reaction, the cross section being only about 7% of the total cross section of the 16.92-MeV level. A $J^\pi=1^+$ state at 18.15 MeV is strongly excited; its yield is about 85% of that of the 16.92 MeV state. Consequently, it appears that the Coulomb barrier for an α particle leaving the Be^8 nucleus is not causing the reduction in yield to the 17.64-MeV level. Furthermore, there is no difficulty in exciting the 17.64-MeV level by means of the $Li^6(He^3,p)$-Be^8 and $Be^9(He^3,\alpha)Be^8$ reactions.[9] Unpublished data from the (He^3,α) work[9] suggests that the 18.15-MeV state is also comparably excited. These considerations indicate that the $T=1$ character of the 17.64-MeV level is probably the reason for its low yield in the (d,α) reaction. The present data show that the state has in it a small $T=0$ impurity of roughly 10%, not the 50% required by the extended single-particle model of Marion.

To see whether or not Marion's[11] single-particle description of the 16.62- and 16.92-MeV levels of Be^8 could be consistent with the shell model, Barker[12] recently performed a normal shell-model calculation with a charge-independent effective interaction that leaves two states near 17 MeV with $J^\pi=2^+$, $T=0$ and 1 nearly degenerate. Then the addition of the Coulomb interaction mixes and splits these states. If the approximate equality between the widths of the 16.62- and 16.92-MeV levels is taken to mean that both states have the same admixture of $T=1$ and $T=0$, then the calculated yields in the $Li^7(d,n)Be^8$ and $Be^9(He^3,\alpha)Be^8$ reactions are in agreement with the experiment. There is an unresolved problem here, however, in that the assumption that the two states are totally admixed and yet are

[17] J. B. Marion and G. Weber, Phys. Rev. 103, 1408 (1956).

observed to lie 300 keV apart requires that the off-diagonal Coulomb matrix element H_C should be 150 keV. This is about twice as large as the theoretical value of H_C. This was first pointed out by Kurath[18] and more recently by Barker.[12]

Barker has also carried out calculations concerning the 17.64- and 18.15-MeV levels. He fits the $M1$ matrix elements for the observed transitions from the 17.64-MeV level to the 16.64- and 16.94-MeV levels, and also the known value of the channel-spin ratio for the 17.64-MeV level, by adjusting the amount of Coulomb admixture. He finds that the 17.64-MeV level contains about 92% $T=1$. However, the H_C which would be required to give this degree of admixture is again over twice the value found by calculation. Our present result, in which the intensity of the reaction to the 17.64-MeV $(1^+,1)$ state is shown to be 8% or less of that of the reaction to the 18.15-MeV $(1^+,0)$ state, is in substantial agreement with Barker's results. This small isobaric-spin impurity contradicts Marion's suggestion that these levels might have the form of a nucleon plus Li^7 or Be^7 core in the first excited state.

At present it appears that the observed ratio of the yields of the (d,α) reactions to the 16.62- and 16.92-MeV states of Be^8 can be explained in terms of a single-particle model. It appears possible to derive the latter from the normal nuclear shell model by the use of initially degenerate $T=0$ and $T=1$, $J^\pi=2^+$ states split by the Coulomb interaction. However, the Coulomb matrix element H_C needed to fit the data appears to be about twice the theoretical value. The observed ratio of the yields of the (d,α) reaction to the 17.64- and 18.15-MeV states argues against the single-particle picture with its maximal isobaric-spin mixing. The isobaric-spin selection rule appears to reduce the yield in the (d,α) reaction of the 17.64-MeV $J^\pi=1^+$ state to a few percent of that of the $J^\pi=1^+$ state at 18.15 MeV, and hence it appears that the 17.64-MeV and 18.15-MeV states are reasonably well characterized by $T=1$ and $T=0$, respectively.

It would be interesting to measure the ratio of the yield of the (d,α) reactions to the 3^+, $T=0$ and $T=1$ states lying near 19 MeV. The presence of strong groups from carbon and oxygen contamination and the large continuum from multiparticle breakup make this difficult, but we are pursuing this work.

[18] D. Kurath (private communication).

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