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Nuclear Physics A579 (1994) 197–206

NUCLEAR PHYSICS A

Mechanisms involved in the production of the $A-3$ residual nucleus by p2n, dn and t emission in ^{7}Li-induced nuclear reactions

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Received 17 March 1993

Abstract

The competition between p2n, dn and t emission for three ^{7}Li-induced reactions on ^{19}F, ^{30}Si and ^{51}V targets as well as the absolute p2n, dn and t emission cross sections in the reaction $^{19}F + ^7Li$ have been measured, each at several bombarding energies, and compared with relevant statistical-model calculations. This comparison, indicating that at least one of the dn and p2n exit channels is induced with significant strength by a non-statistical mechanism, suggests that, in addition to the traditionally expected direct α transfer and evaporation, a third non-statistical reaction mechanism is involved even at very low bombarding energies. The characteristics of this third mechanism are presented and discussed.

Keywords: NUCLEAR REACTIONS ^{19}F, ^{30}Si, ^{51}V, (^{7}Li,X), $E = 10$–18 meV; measured relative $\sigma(E)$ for (p2n), (dn), t-emission; ^{19}F(^{7}Li,X), $E = 10$–18 MeV; measured absolute $\sigma(E)$ for (p2n), (dn), t-emission; calculated relative, absolute $\sigma(E)$ for p2n, dn and t evaporation. Statistical model.

1. Introduction

With respect to the mechanism of (^{7}Li, t) reactions, traditional consensus holds that the postulation of only two mechanisms, evaporation from a compound nucleus and direct α transfer, may be sufficient to describe the evolution of the character of these reactions over a wide range of bombarding energies. By now, however, that assumption may be considered as less certain on the basis of accumulated evidence testifying against that tidy picture even at relatively low bombarding energies.

SSDI 0375-9474(94)00278-U

The observation, for instance, of non-statistical multiparticle emission in the $^{30}Si(^7Li$, p2n/dn/t) and $^{51}V(^7Li$, P2n/dn/t) reactions [1,2] constitutes such an evidence. That observation, suggesting that in addition to the t at least one of the p2n and/or dn emission proceeds via a non-statistical mechanism, is puzzling since in the case of direct α transfer it is traditionally expected that the t cluster emission is dominant and the dn and p2n emission is insignificant because the latter can be induced only by second-order effects. Any significant dn and p2n emission should be assigned, therefore, to a competing evaporation mechanism and thus be of a statistical nature. That seemingly self-evident argument explains probably why the study of the p2n and dn emission in ^7Li-induced reactions has been largely ignored in comparison to the t emission which almost always has been the main subject of investigation.

Furthermore, the loosely bound nature of the projectile has been since the very early days [3] a point of concern in ^7Li-induced reactions. The ^7Li breakup has been since then implicated to affect strongly not only the (^7Li, t) channel, see for instance Refs. [4,5], but also the total strength of the fusion reaction [6]. It is interesting to notice that in Ref. [4], in addition to triton, non-statistical deuteron emission was also observed, assigned to a two-body fragmentation of the projectile.

Finally, a novel reaction mechanism, namely molecular orbiting [7], has been suggested to be present even at low energies in ^7Li-induced reactions [8]. This mechanism can also induce non-statistical emission in multinucleon exit channels.

Apparently, the nature as well as the energy dependence of the physical mechanisms coexisting in (^7Li, t) reactions are not at all clear, demanding therefore a more detailed experimental as well as theoretical investigation. Such an investigation is attempted in the present study, whereby, however, in addition to the traditionally investigated (^7Li, t) channel the dn and p2n exit channels competing for the production of the same $A-3$ residual nucleus were also monitored hoping that the exploitation of their combined information may be more profitable.

2. Experiments and results

In the present study the p2n, dn and t emission in ^7Li-induced reactions has been investigated with a light (^{19}F), medium (^{30}Si) and a heavier (^{51}V) target.

The experimental method involves the measurement of the competition between p2n, dn and t emission via light-charged-particle–γ coincidence techniques as well as the measurement of the total $\sigma_{p2n+dn+t}$ absolute cross section via γ-ray counting.

For the absolute cross-section measurements the data at the various bombarding energies were normalized with the aid of the intensity of the 278.9-keV γ-ray transition in ^{197}Au, emitted in the Coulomb excitation of the Au used as backing in the target.

The method for the measurement of the triple competition has been described previously [1]. Briefly, light-charged-particle-gamma coincidence techniques were utilized in order to directly observe the competition between exit channels producing individual residual states. The discrete coincident γ-rays were used to identify the heavy residual nucleus. Thin, 100 $\mu g/cm^2$, targets of various isotopes deposited on Ta or Au backing, sufficiently thick to stop the beam, were bombarded with ^{7}Li beams supplied by the tandem accelerator of demokritos National Research Center. For particle detection a ΔE–E counter telescope of silicon detectors of various thickness was used in a semicircular scattering chamber. The γ-rays were observed with Ge(Li) detectors with the axis in the reaction plane at 90° with respect to the beam, at a distance of 2 cm from the target. Previous studies [1,9,10] have indicated that the competition ratio of charged-particle emission measured at 0° represents the ratio of integrated cross sections of the competing exit channels. Thus the present measurements were all carried out at $\Theta_p = 5°$.

The above experimental method has been previously tested in the investigation of the triple evaporation competition in several heavy-ion-induced reactions known to proceed via the formation of a compound nucleus [1]. That investigation has revealed that the competition between t, dn and p2n evaporation depends mainly on the excitation energy available to the $A-3$ residual nucleus irrespectively of the interacting system. Furthermore, this systematic behavior of the experimental competition was very nicely reproduced by statistical-model Hauser–Feshbach calculation [1]. This previous experimental and theoretical experience with the competition between t, dn and p2n evaporation provides a framework which can be used with increased confidence in the interpretation of the *exceptional* t, dn and p2n competition values which, as it will be demonstrated below, have been observed in the case of ^{7}Li-induced reactions.

The experimental behavior of the reaction ^{30}Si(^{7}Li, p2n/dn/t), which is demonstrated in Table 1 together with the statistical-model predictions, will be used to discuss the essential features of the competition between p2n, dn and t emission as influenced by the direct α-transfer mechanism expected to be present.

The theoretical calculations of the competition between t, dn and p2n evaporation were carried out in the framework of the Hauser-Feshbach theory, using the code STARPE [11] which was modified in this laboratory in order to account for t emission. Experimental discrete energy levels and branching ratios were taken

Table 1
Experimental and Hauser–Feshbach relative cross sections for the production by p2n, dn and t emission of the ^{34}S residual nucleus in the ^{7}Li + ^{30}Si reaction at the specified bombarding energies

E_{lab} (MeV)	Relative cross section (%)					
	Experimental			Theoretical		
	σ_{p2n}	σ_{dn}	σ_t	σ_{p2n}	σ_{dn}	σ_t
15	3 ± 1	7 ± 2	90 ± 9	84.1	12.8	3.1
16	10 ± 2	13 ± 2	77 ± 9	85.5	12.4	2.1
17	18 ± 3	16 ± 2	66 ± 5	86.1	12.2	1.7
18	26 ± 4	20 ± 4	54 ± 5	86.6	12.0	1.4

from the literature. For the rest of the levels the *back-shifted* Fermi gas model [12] assuming the Lang formula [13], was used. The values of the parameters entering this model, that is the single-particle level density α, the fictive ground-state position Δ and the effective moment of inertia J_{eff}, in most of the cases were taken from the literature. If no previous level-density parameters were available, the values ($\alpha = A/7.5$) proposed by Dauk [14] were adopted. Transmission coefficients for emitted light particles were obtained from optical-model calculations using parameters previously proposed [15-19]. The entrance-channel transmission coefficients $T_l(E)$ were calculated according to the formulae reported in Ref. [20]. More details about these calculations may be found in Ref. [1].

The experimental data in Table 1 demonstrate that the ^{34}S residual nucleus is mainly produced via t emission, although it should be noted that the competing p2n and dn contributions are not at all negligible. The comparison of the experimental relative cross sections with those expected from pure evaporation clearly suggests that the experimental competition cannot be accounted for by pure evaporation. The experimental triton contribution in particular exceeds by more than an order of magnitude that expected from evaporation, clearly indicating a dominant presence of direct components in the ^{30}Si(^{7}Li, t) reaction at all bombarding energies.

The presence of multiparticle p2n and dn exit channels in the experimental measurements suggests on first inspection a coexistence of direct and evaporation mechanisms in the ^{30}(^{7}Li, p2n/dn/t) reaction. If, however, the p2n and dn emission in this reaction resulted from pure evaporation, their relative cross section should have been correctly predicted by the relevant statistical calculations, as the agreement between experimental and statistically predicted competition between p2n, dn and t evaporation in all cases of previously studied heavy-ion-induced reactions has amply demonstrated [1]. The experimental multiparticle contributions, however, are in striking disagreement with those statistically expected. The $\sigma_{\mathrm{p2n}}/\sigma_{\mathrm{dn}}$ ratio for instance assumes experimental values 0.8 ± 0.3 and 1.3 ± 0.3 at 16.0 and 18.0 MeV, respectively, compared to 6.9 and 7.2 expected from pure evaporation. The non-statistical ratio of these two cross sections does not necessarily imply that both emissions take place with a non-statistical mechanism. Even if only the dn emission were of non-statistical nature the ratio of these cross sections would not be in accord with the statistical expectations. The issue, therefore, of which exit channels involve non-statistical multiparticle emission demands further clarification.

With respect to the energy dependence of the non-statistical multiparticle emission, it should be noted that the relative probabilities for multiparticle emission are significantly larger at the higher bombarding energies. That information by itself, however, does not necessarily ensure an increasing contribution from non-statistical multiparticle emission with increasing bombarding energy since it can equally well imply an enhancement with increasing energy of the evaporation component against the contribution of the coexisting direct ^{4}He-transfer mechanism. The former mechanism at the present energy range will preferentially feed the multiparticle exit channels and decrease the relative contribution of the

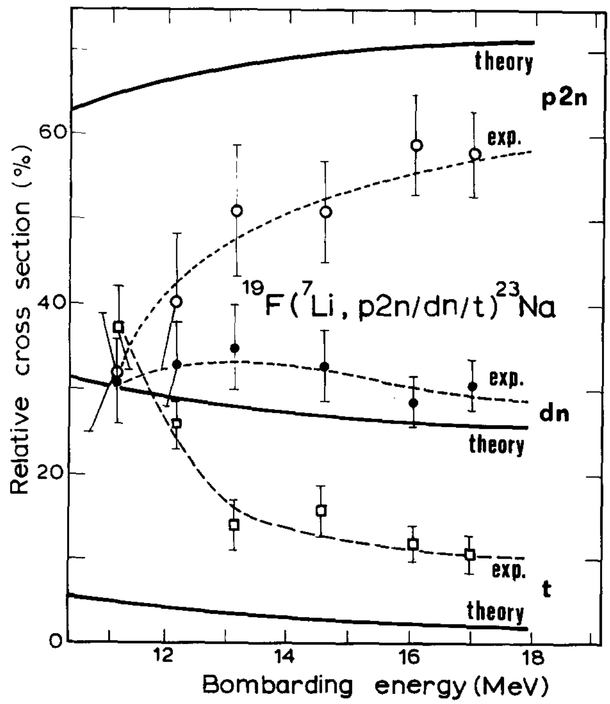

Fig. 1. Experimental (data points) and statistically expected (solid lines) relative cross sections for the production of ^{23}Na by p2n, dn or t emission in the reaction ^{19}F(^{7}Li, p2n/dn/t) at the indicated laboratory bombarding energies. The broken lines through the data points simply serve to guide the eye.

composite triton emission [1] thus providing a plausible explanation of the above observations.

In order to resolve the above dilemma, and also to test whether the non-statistical multiparticle emission is not particular to the ^{30}Si + ^{7}Li reaction, detailed excitation functions of the competition between p2n, dn and t emission over a wide energy range were measured in the ^{19}F(^{7}Li, p2n/dn/t). The experimental results are shown in Fig. 1 together with the relative probabilities expected from pure evaporation. It is seen that, while the dn contribution always remains closely parallel to the statistically expected, the deviations of the experimental p2n and t contributions from the statistical calculations are the strongest at the lower bombarding energies. In fact as the bombarding energy increases, experimental and statistically expected contributions tend to overlap. Fig. 2 demonstrates that a very similar behavior is also observed in the ^{51}V(^{7}Li, p2n/dn/t) reaction.

If, as usually, we assume that only compound-nucleus and direct ^{4}He-transfer mechanisms contribute, the conclusion suggested by the above data is that the increasing bombarding energy favors the compound-nucleus component against the direct-reaction contribution.

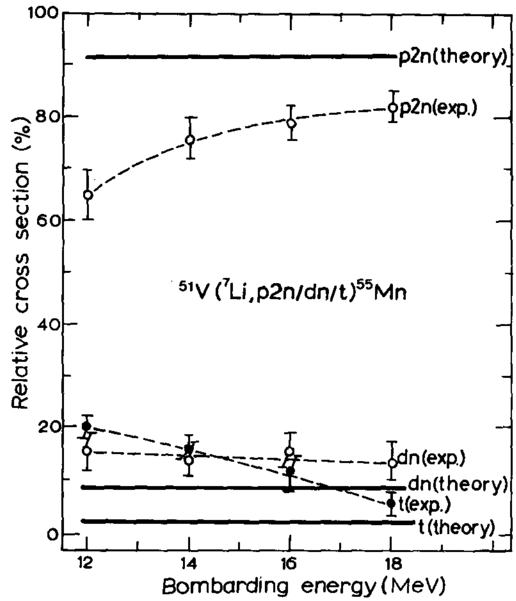

Fig. 2. Experimental (data points) and statistically expected (solid lines) relative cross sections for the production of ^{55}Mn by p2n, dn or t emission in the reaction ^{51}V(^{7}Li, p2n/dn/t) at the indicated laboratory bombarding energies. The broken lines through the data points simply serve to guide the eye.

In spite of a previous evidence [21] for anomalous energy dependence of the competition between direct and evaporation mechanisms in the ^{16}O(^{7}Li, t) reaction, where a stronger direct contribution was seen at 24 rather than at 32 MeV bombarding energy, it is rather premature to accept this as a more general trend. Consequently, an independent measurement of an additional nuclear property depending on the involved reaction mechanisms is needed.

Such a property is the absolute cross section for the production of the $A-3$ residual nucleus by p2n, dn and t emission. The absolute cross section for the production of the first-excited 440-keV state of ^{23}Na in the reaction ^{19}F(^{7}Li, p2n + dn + t) measured in the same energy range with the triple competition data is demonstrated in Fig. 3a together with the relevant statistical-model calculations. The measurement of this cross section was carried out via monitoring the 440-keV first-excited-to-ground-state γ-ray transition in ^{23}Na thus taking into account the side as well as the cascade feeding of that state.

Since the triple-competition measurements were carried out via the same 440-keV γ-ray transition, taking also into account side and cascade feeding, these two measurements (Figs. 1 and 3a) should be mutually consistent as far as the involved reaction mechanism is concerned.

This, however, does not seem to be presently the case. Specifically, while Fig. 1 demonstrates that with increasing energy the triple competition tends towards that

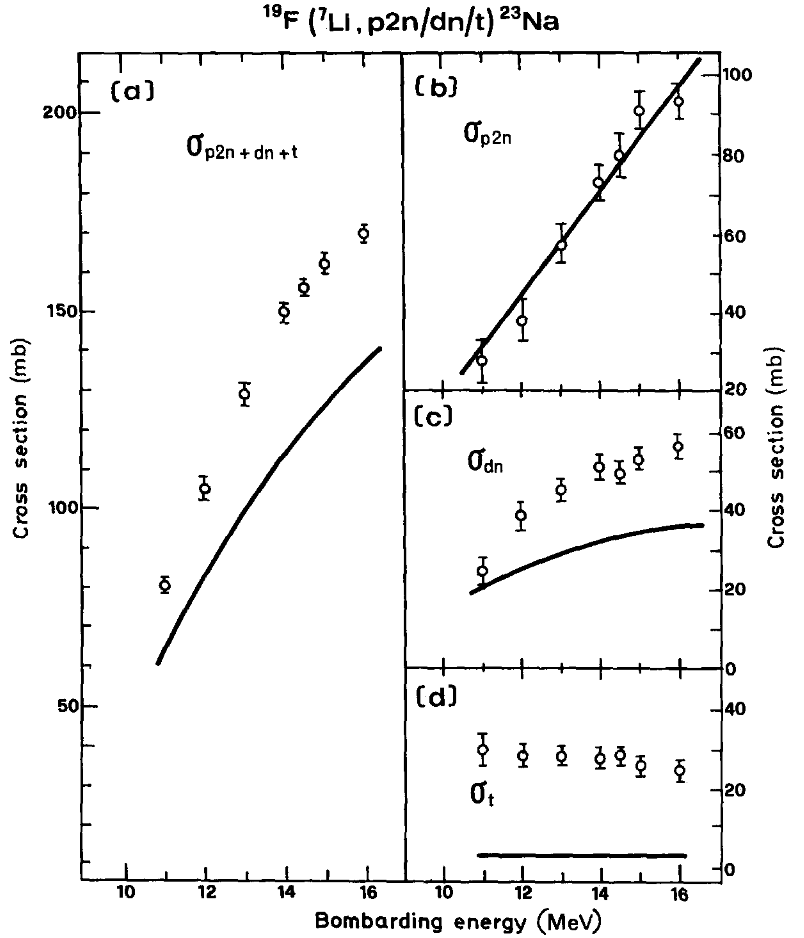

Fig. 3. Experimental (data points) and statistically expected (solid lines) total and partial absolute cross sections for the production of ^{23}Na by p2n, dn or t emission in the reaction ^{19}F(^{7}Li, p2n/dn/t) at the indicated laboratory bombarding energies.

expected from pure evaporation, Fig. 3a shows that over the same energy range the total experimental cross section increases faster than that expected from pure evaporation. It is most probable that this inconsistent behavior results because of our attempt to interpret these data in terms of only evaporation and direct-transfer mechanisms, thus giving a first hint that a third reaction mechanism may be present in these ^{7}Li-induced reactions.

A similar discrepancy is noted with respect to the ^{51}V(^{7}Li, 2n/dn/t) reaction. In that case while the triple-competition data measured here closely resemble predominant evaporation, a previous measurement at 18 MeV has identified significant forward peaking, via forward-backward-asymmetry measurements, not only of the tritons but also of the protons and deuterons associated with the p2n and dn exit channels [2]. On closer inspection, nevertheless, the present data for that reaction, demonstrated in Fig. 2, are not in contradiction with the previous findings. For instance, while the experimental σ_{p2n}/σ_{dn} ratio measured here assumes the value 4.4 ± 0.6 at 16 MeV bombarding energy, the statistically expected value of this ratio is 10.1, indicating that at least one of these exit channels proceeds non-statistically.

The issue of the identification of the involved mechanisms, however, demands further scrutiny. A useful relevant information may be furnished by the partial absolute cross-section values for each of the p2n, dn and t competing exit channels, which for the reaction $^{19}F + ^{7}Li$ can be now derived from the data on the total absolute cross section (Fig. 3a) and the p2n/dn/t competition (Fig. 1). The thus derived partial absolute cross sections are compared in Figs. 3b–d with those expected from pure evaporation. In the case of the p2n emission, the very good agreement between the experimental and statistically predicted cross sections indicates that this emission is predominantly induced by evaporation. On the other hand, almost all tritons and significant fraction of dn are emitted via a non-statistical mechanism. Clearly, the non-statistical dn component significantly increases with increasing bombarding energy.

With respect to the dn emission it is noted that approximately 15 mb, that is about 50% of the t emission cross section, is in fact proceeding via a non-statistical mechanism. It is, therefore, highly improbable that this considerable non-statistical dn emission is induced via second-order effects by the direct α-transfer mechanism. It is reasonable to expect that the wave function of ^{7}Li in addition to the dominant $^{4}He + t$ component will also contain secondary cluster configurations, such as ^{4}He + dn. Although various cluster configurations, $n + ^{6}Li(I = 0)$, $n + ^{6}Li(I = 2)$ and $d + ^{5}He$, have been identified [22] in ^{7}Li, we are not aware of any results concerning the contribution of three-cluster configurations such as those discussed here. However, it seems highly unlikely that these secondary three-cluster components will be strong enough to be commensurate with the strength of the non-statistical dn emission observed here. Therefore, since that cross section cannot be attributed either to the direct α transfer, which predominantly causes the non-statistical t emission, or to the statistical evaporation, which causes the p2n emission as well as the background under dn and t, it should be attributed to a third reaction mechanism.

3. Discussion

The presence of non-statistical multiparticle emission leading to the production of the $A - 3$ residual nucleus, identified in three ^{7}Li-induced reactions in which widely different targets and a relatively broad range of bombarding energies were employed, permits to conclude rather safely, that this emission, and consequently the presence of a third reaction mechanism that such emission implies, constitutes a general characteristic of ^{7}Li-induced reactions.

Accordingly, it seems highly improbable that the mechanism involved in this non-statistical emission is associated with the formation of a broad molecular resonance, as previously postulated [8], which just happened to be accidentally excited in all the investigated reactions; especially since these non-statistical multiparticle emissions persist over a wide range of bombarding energy. In fact, pending to a definite identification, it may de considered outstanding whether the non-statistical emission observed in certain reaction exit channels in Ref. [8] is indeed due to the excitation of a broad resonance since in all these reactions loosely bound projectiles are involved and this may not be irrelevant to the non-statistical emissions observed therein.

The present experimental data, although not permitting a straightforward identification, indicate nevertheless certain qualifications of the third mechanism involved in ^{7}Li-induced reactions. Specifically, by the nature of the present particle–γ coincidence measurements, no matter what the mechanism is, its net effect is that an α particle is removed from the projectile to the target, accompanied by non-statistical emission in at least one of the multiparticle exit-channels leading to the production of the $A-3$ residual nucleus. Furthermore, these non-statistical emissions apparently increase with increasing bombarding energy and at a given energy they depend on the target nucleus.

About the exact nature of this third mechanism we can only speculate. The above qualifications hint that this mechanism may have to do with a breakup of the projectile to an α particle and t, dn and probably p2n ejectiles accompanied by fusion of the α particle with the target nucleus. Although the breakup of ^{7}Li is usually considered in terms of $\alpha+\mathrm{t}$, it should be mentioned that the various breakup modes such as those discussed here, i.e. $\alpha+\mathrm{dn}$ and $\alpha+\mathrm{p2n}$, have been previously observed with heavy as well as light targets [23], albeit at the considerably higher energy of 77 MeV. However, since in a thorough study [24] of ^{6}Li breakup at 22 MeV no evidence for a three-particle dissociation of ^{6}Li into $\alpha+\mathrm{p}+\mathrm{n}$ was found, it seems even less probable that an $\alpha+\mathrm{d}+\mathrm{n}$ dissociation occurs in ^{7}Li, although it should be noted that the experimental method presently used is especially suited to single out reaction events, even of low probability over the total reaction cross section, as long as these lead to the production of the $A-3$ residual nucleus.

Finally, an other possible path is suggested by the evidence that ^{7}Li contains very significant $\mathrm{d}+{}^5$He components [22]. It may, therefore, be possible that a ^{5}He is transferred to the target followed by neutron evaporation, thus producing the $A-3$ residual nucleus with an apparent non-statistical dn emission.

A final but very important question concerns the involvement of the third reaction mechanism in the emission of composite tritons. In an attempt to address that question we have calculated the (^{7}Li, t) α-transfer cross section for the production of the 440 keV state in ^{23}Na using the code DWUCK-4 [25]. In this calculation the side as well as the γ-cascade-feeding from several excited states to the 440 keV state were taken into account. Specifically, all the excited states in ^{23}Na studied in the ^{19}F(^{6}Li, d)^{23}Na reaction [26] were included. The thus calculated triton-emission cross section demonstrates the same energy dependence with that experimentally observed. The calculated cross section, however, assumes a value of 12 mb which is about half of the experimental value even when the theoretical Hauser–Feshbach contribution is added to it. This missing strength, which under different circumstances could be assigned to the third mechanism, does not necessarily presently imply the involvement of such a mechanism in the emission of composite tritons since the excited states of ^{23}Na taken into account in the calculation, for which spectroscopic information exists, terminate to an excitation energy of about 6 MeV [26] compared to about 25 MeV of excitation involved in the present experiment. The question, therefore, of how many reaction mechanisms are involved in the (^{7}Li, t) channel should remain outstanding. Nevertheless, the parallel energy dependence of the experimental and the DWBA (^{7}Li, t) cross section may be taken as a hint that a third mechanism is not involved in the emission of composite tritons.

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