Eur. Phys. J. A **26**, 265–269 (2005)
DOI 10.1140/epja/i2005-10172-5

THE EUROPEAN PHYSICAL JOURNAL A

Characterization of quasiparticle states at and beyond stability in ytterbium isotopes: Spectroscopy of ^{175}Yb, ^{176}Yb and ^{177}Yb

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Received: 25 July 2005 / Revised version: 11 November 2005 /
Published online: 28 November 2005 –
Communicated by R. Krücken

Abstract. Excited states in ^{175}Yb, ^{176}Yb and ^{177}Yb were populated via the bombardment of a ^{176}Yb target with a 750 MeV ^{136}Xe beam. Gamma-ray decays from these states were measured with the AFRODITE multi-detector spectrometer. The rotational band previously assigned to the ground state of ^{177}Yb has been reassigned to the first-excited state of ^{175}Yb. A new rotational band based on the ground state of ^{177}Yb is presented, and the band based on the $K^\pi = 4^-$ two-quasiparticle state in ^{176}Yb has been identified. Also a candidate for the rotational band based on the $K^\pi = 8^-$, $T_{1/2} = 11.4(3)$ s two-quasiparticle state in ^{176}Yb has been found. Comparisons of g_K values derived from in-band branching ratios are consistent with the $\nu 9/2^+[624]$ assignment to the ground state of ^{177}Yb, the $\nu^2\{9/2^+[624] \otimes 1/2^-[510]\}$ assignment to the $K^\pi = 4^-$ state and with the $\nu^2\{9/2^+[624] \otimes 7/2^-[514]\}$ assignment to the $K^\pi = 8^-$ metastable excited state in ^{176}Yb.

PACS. 29.30.Kv X- and γ-ray spectroscopy – 23.20.Lv γ transitions and level energies – 21.10.-k Properties of nuclei; nuclear energy levels – 27.70.+q $150 \le A \le 189$

1 Introduction

Studies of multi-quasiparticle metastable states in deformed atomic nuclei offer unique opportunities to further our understanding of the interplay of collective behaviour and individual particle motion in an isolated hadronic system. In particular, the $A \sim 170$–180 mass region of prolate-deformed nuclei is replete with long-lived multi-quasiparticle states which arise from configurations that have large angular-momentum projections, K, onto the nuclear symmetry axis [1,2]. The characterization of these states can be eluciated by measuring the properties of their decay and, where possible, those of the associated rotational band.

Predictions that energetically favoured high-K multi-quasiparticle states reside in or beyond the heaviest stable nuclei in the $A = 180$ region [2,3] have thrown down a challenge to experimentalists, since these nuclei cannot be populated in what might be considered conventional fusion-evaporation reactions. This has forced the use of different population mechanisms. One approach is to use incomplete-fusion reactions [4–10] with relatively low-mass heavy-ions such as ^{7}Li, ^{9}Be and ^{11}B, which possess a cluster-type structure from which the reaction mechanism is a consequence. An alternative approach is to bombard a target with heavy, relatively neutron-rich beams at energies in the region of $\sim$ 10–20% above the mutual Coulomb barrier to initiate so-called deep inelastic processes whereby states of interest can be populated in the target (or beam) and target(or beam)-like nuclei. This latter approach has achieved notable successes in the identification and characterization of states of interest in a number of nuclei [11–13] and was employed in the present investigation. A third way is to fragment a relativistic heavy beam, such as 1 A GeV ^{208}Pb, and study isomeric γ-ray decays of mass/charge selected products [14].

The choice of ^{176}Yb as the target in the present study was partly motivated by the desire to investigate its $K^\pi = 8^-$ metastable state [15], since the analogous states in the heavier isotones exhibit a structural change from a mixed two-quasiparticle character in ^{178}Hf [16] to an essentially pure two-quasiproton configuration in ^{180}W [15, 17]. Transfer processes were also likely to populate a variety of hitherto inaccessible states in target-like nuclei.

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2 Experimental details

Beams of ^{136}Xe ions were delivered by the Separated Sector Cyclotron (SSC) facility [18] of iThemba LABS at an energy of 750 MeV and a maximum intensity of $\sim$ 1 pnA. The beams were directed onto an enriched ^{176}Yb target of $\sim$ 2 mg/cm^2 thickness (backed with a thick layer of Au), which was located at the centre of the AFRODITE γ-ray spectrometer [19]. Eight Compton-suppressed clover detectors and seven unsuppressed Low-Energy Photon Spectrometers (LEPSes) were employed. At the front of the target, the beam energy was $\sim$ 15% above the Coulomb barrier. Events were recorded when at least three of fifteen AFRODITE HPGe detectors fired within $\sim$ 200 ns of one another, of which at least two had to be clovers, time-referenced to the radio-frequency pulsing of the SSC accelerator. Energy and efficiency calibrations of the AFRODITE HPGe detectors were obtained from the placement of standard ^{152}Eu and ^{133}Ba sources at the target position.

3 Data analysis and results

The event-by-event data were sorted into E_γ-E_γ correlation matrices with the MTsort package [20] which were reformatted in order to enable them to be analyzed with RADWARE [21]. Background-subtracted coincidence spectra were generated from placing slices on the matrices and examples are shown in fig. 1. Ground-state rotational bands of ytterbium isotopes in the mass range $A = 172$ to 177 were observed, with the exception of ^{173}Yb. Also, the ground-state band of ^{178}Hf was observed to its 8^+ member, as were the first two transitions in the band based on the $T_{1/2} = 4.0$ s, $K^\pi = 8^-$ mixed two-quasiparticle state at 1147 keV [16]. A number of noteworthy results are listed below and shown in fig. 2:

- A new band based on the ground-state $9/2^+[624]$ neutron in ^{177}Yb was observed.
- The band previously assigned to the ground state of ^{177}Yb [22] is suggested to be based on the first-excited state in ^{175}Yb (note that the orbital involved in each case is the $9/2^+[624]$ Nilsson state).
- A band based on a $K^\pi = 15/2^+$ three-quasineutron state in ^{177}Yb has been located via its decay to the ground-state band.
- The band associated with a $K^\pi = 4^-$ two-quasineutron state in ^{176}Yb has been identified.
- A candidate for the band based on the $K^\pi = 8^-$, $T_{1/2} = 11.4(3)$ s two-quasineutron state in ^{176}Yb has been found.

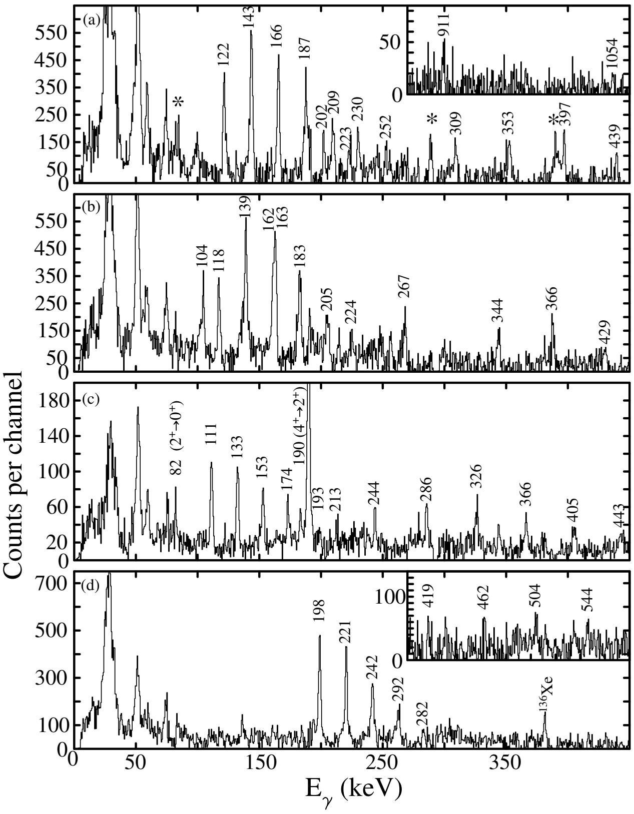

Fig. 1. (a) Sum-of-gates spectrum for the $9/2^+[624]$ ground-state band (g.s.b.) in ^{177}Yb (an $*$ denotes ground-state band transitions in ^{176}Yb which arise due to slight contamination of the 187.2 keV gate with the 189.5 keV $4^+ \to 2^+$ transition); inset: higher-energy portion that shows the 911 and 1054 transitions which decay from the head of the $K^\pi = 15/2^+$ band (the 202 and 223 keV members are labelled) to the g.s.b.; (b) sum-of-gates spectrum for the $9/2^+[624]$ first-excited band in ^{175}Yb; (c) coincidence spectrum selected by the 1069 keV transition which shows the band associated with the $K^\pi = 4^-$ state in ^{176}Yb; and (d) sum-of-gates set on the $\Delta J = 1$ cascade transitions for the band possibly associated with the $T_{1/2} = 11.4$ s, $K^\pi = 8^-$ state in ^{176}Yb. The 381 keV peak from the $4^+ \to 2^+$ transition in ^{136}Xe arises from its coincidence with the 197 keV $6^+ \to 4^+$ transition. Inset: higher-energy portion that shows the $E2$ crossover transitions.

4 Discussion

The assignment of transitions to the $\nu 9/2^+[624]$ ground-state band of ^{177}Yb was consistent with data obtained from the ^{176}Yb(^{9}Be, 2α)^{177}Yb reaction [23] which corresponded to a single-neutron transfer to the target selected by measuring γ-rays in coincidence with the two break-up α-particles. The first two $\Delta J = 1$ cascade transitions and the associated $E2$ crossover transitions of the $9/2^+[624]$ band were observed, though these differed from those previously published [22]. In fact, the $11/2^+$ and $13/2^+$ levels were clearly observed in (d, p) data [24] with energies consistent with those found here. Moreover, the differential cross-section for the population of the $13/2^+$ state was consistent only with an $l = 6$ transfer. This was also the case for the corresponding level in ^{175}Yb [25] when populated via the (d, t) reaction.

Branching ratios, λ, were used to determine the magnitude of mixing ratios, δ, from the standard rotational model formula, which assumes strong coupling, and hence

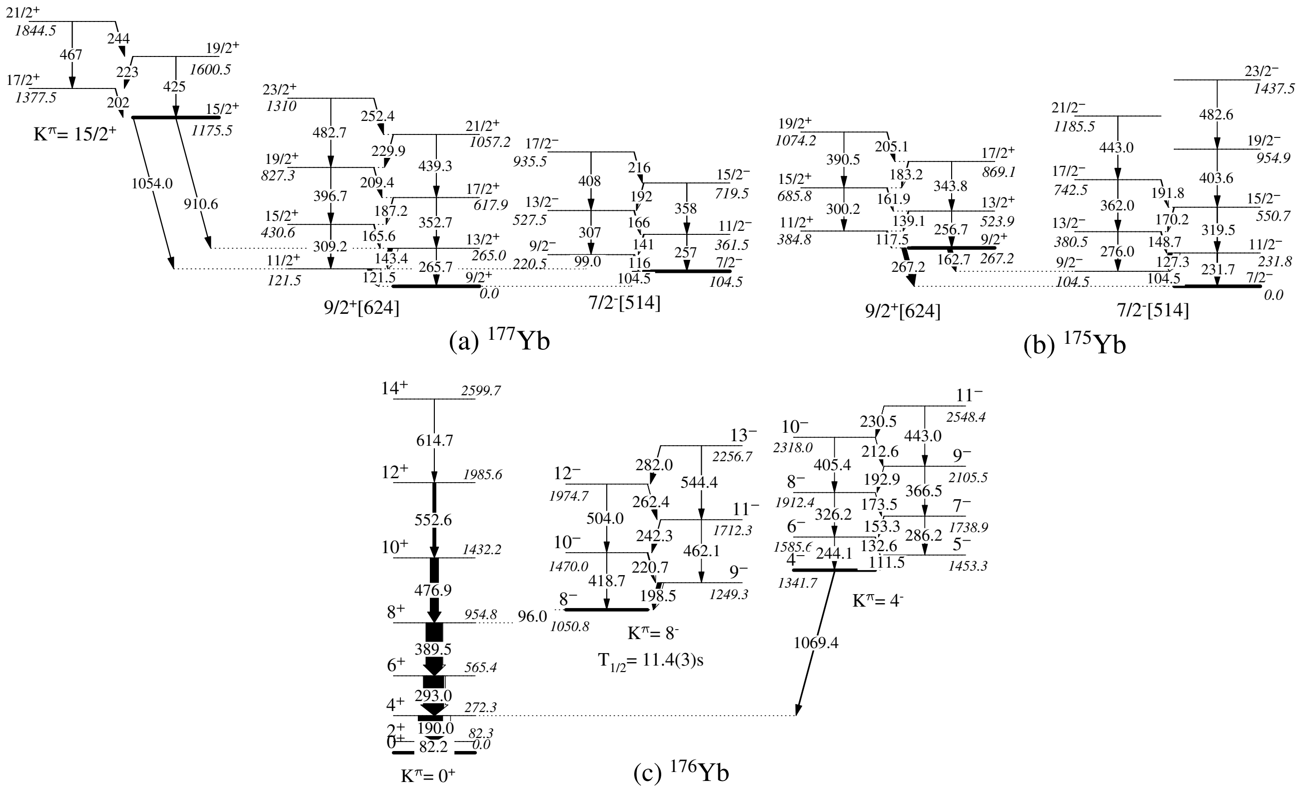

Fig. 2. Level schemes for bands associated with (a) the $\nu 9/2^+[624]$ ground-state, $\nu 7/2^-[514]$ first-excited state and $K^\pi = 15/2^+$ three-quasiparticle state in ^{177}Yb; (b) the $\nu 7/2^-[514]$ ground-state and $\nu 9/2^+[624]$ first-excited states in ^{175}Yb; and (c) the ground state and the $K^\pi = 4^-$ two-quasineutron state in ^{176}Yb, together with the candidate for the band based on the $K^\pi = 8^-$, $T_{1/2} = 11.4$ s isomer.

Table 1. Branching ratios and $(g_K - g_R)$ values for the $9/2^+[624]$ band in ^{177}Yb, together with those for the $K^\pi = 4^-$ and candidate $K^\pi = 8^-$ bands in ^{176}Yb.

J^π	$E_{\gamma,\Delta J=1}$ (keV)	$E_{\gamma,\Delta J=2}$ (keV)	λ	$\lvert g_K - g_R \rvert^{(a)}$ (exp.)
$9/2^+[624]$				
$13/2^+$	143	266	0.28(10)	0.54(13)
$15/2^+$	166	309	0.78(15)	0.47(12)
$17/2^+$	187	353	1.20(27)	0.50(10)
$19/2^+$	209	397	1.05(25)	0.66(13)
$21/2^+$	230	439	1.01(27)	0.78(17)
$23/2^+$	252	483	1.24(38)	0.81(18)
$K^\pi = 4^-$				
6^-	133	244	0.42(10)	0.46(8)
7^-	153	286	0.80(20)	0.51(9)
8^-	173	326	0.91(44)	0.62(19)
$K^\pi = 8^-$				
10^-	221	419	0.35(10)	0.34(16)
11^-	242	462	0.34(10)	0.53(18)
12^-	262	504	0.84(23)	0.42(9)

([a]) In all cases, the intrinsic quadrupole moment was taken as $Q_0 = 7.8(1.3)$ eb.

that K is well defined:

$$\frac{\delta^2}{1+\delta^2} = \frac{2K^2(2J-1)}{(J+1)(J-1+K)(J-1-K)} \frac{E^5_{\gamma,\Delta J=1}}{E^5_{\gamma,\Delta J=2}} \lambda .$$

The mixing ratios were used to extract the values of $g_K - g_R$ for the $9/2^+[624]$ band in ^{177}Yb (and the bands in ^{176}Yb, which will be discussed below) shown in table 1 from the formula

$$\frac{g_K - g_R}{Q_0} = \pm \frac{0.933 E_{\gamma,\Delta J=1}}{\delta\sqrt{J^2-1}} .$$

Lack of statistics prevented an angular-correlation analysis from which the sign of δ could, in principle, be determined explicitly. If the negative sign is taken, along with values for the intrinsic quadrupole moment (Q_0) of 7.8(1.3) eb (from the 2^+ first-excited state in ^{176}Yb [26]) and the rotational g-factor (g_R) of 0.3, a weighted average value of $-0.28(5)$ results, as shown in table 2, which is in accord with the Nilsson model estimate of -0.24. This also agrees with the isotone ^{179}Hf where a value of $-0.22(4)$ was extracted [9] for the $9/2^+[624]$ ground-state band. For completeness, if the positive sign is taken for $(g_K - g_R)$, a value of $g_K = 0.88(5)$ results.

The band assigned to the three-quasineutron $K^\pi = 15/2^+$ configuration in ^{177}Yb was identified from the decay of the bandhead to the $11/2^+$ and $13/2^+$ rotational

Table 2. Proposed configurations and g_K values for bands in ^{176}Yb and ^{177}Yb.

Nucleus	Configuration				$\|g_K - g_R\|^{(a)}$	g_K (expt)		g_K (Nilsson)	
	K^π	ν		π		$\|\ldots\|^{(a)}$ − ve	$\|\ldots\|^{(a)}$ + ve	ν	π
^{177}Yb	$9/2^+$	$9/2^+[624]$		–	0.58(5)	$-0.28(5)^{(b)}$	$+0.88(5)^{(b)}$	−0.24	–
^{176}Yb	4^-	$1/2^-[510]\otimes 9/2^+[624]$		–	0.49(6)	$-0.11(6)^{(c)}$	$+0.87(6)^{(c)}$	−0.05	–
^{176}Yb	8^-	$7/2^-[514]\otimes 9/2^+[624]$	or	$7/2^+[404]\otimes 9/2^-[514]$	0.42(7)	$-0.04(7)^{(c)}$	$+0.80(7)^{(c)}$	−0.02	1.00

(^{a}) Weighted averages of values in table 1.
(^{b}) Calculated with $g_R = 0.30$.
(^{c}) Calculated with $g_R = 0.381(18)$ (from [26]).

levels associated with the $9/2^+[624]$ ground state. It probably arises from the $\nu^3\{9/2^+[624]\otimes 7/2^-[514]\otimes 1/2^-[510]\}$ configuration, but due to the weakness with which the band was populated, it was not possible to extract branching ratios for comparison with the proposed assignment. The assignment is consistent with the observation of the $K^\pi = 4^-$ $\nu^2\{1/2^-[510]\otimes 9/2^+[624]\}$ configuration in the ^{176}Yb core (see discussion below), which suggests that the $K^\pi = 15/2^+$ configuration in ^{177}Yb can be interpreted as $\nu 7/2^-[514]\otimes\nu^2\{4^-\}$. This differs with the observation in the isotone ^{179}Hf of the related $K^\pi = 17/2^+$ state [9] which results from parallel coupling of all three quasiparticle angular momenta. This is consistent with the $K^\pi = 5^-$, rather than 4^-, coupling of the $\nu^2\{1/2^-\otimes 9/2^+\}$ configuration that is observed in the ^{178}Hf core. Why the favoured coupling differs between the two $N = 106$ isotones is not clear.

The band associated with the probable $K^\pi = 4^-$ two-quasiparticle state in ^{176}Yb was identified via coincidences with the 1069 keV transition which depopulates the bandhead to the 4^+ member of the ground-state rotational band. This transition had been identified previously in the β^--decay of ^{176}Tm [27], and it was also observed in the ^{176}Yb(^{9}Be, $2\alpha n$)^{176}Yb reaction [23]. In the latter data, a positive A_2 coefficient was extracted for the 1069 keV transition, consistent with those found for the 120.4 and 208.3 keV, $\Delta J = 0$ $E1$ transitions in ^{177}Hf [6]. The ground-state spin and parity of ^{176}Tm have been assigned tentatively as $J^\pi = (4^+)$, consistent with the $\pi 1/2^+[411]\otimes\nu 9/2^+[624]$ configuration and the Gallagher-Moszkowski rule. It is suggested here that the direct β^--decay to the bandhead at 1341.7 keV is of first-forbidden $\Delta l = 1$ character, namely $\pi 1/2^+[411]\rightarrow\nu 1/2^-[510]$. This is consistent with the absence of any low-lying positive-parity $\Omega = 1/2$ neutron orbitals. Hence it is proposed that the $K^\pi = 4^-$ state arises from the $\nu^2\{1/2^-[510]\otimes 9/2^+[624]\}$ two-quasineutron configuration. Branching ratios from the 6^-, 7^- and 8^- states are shown in table 1. They were used to extract a weighted average value of $g_K = -0.11(6)$ shown in table 2, if $g_R = g_R(2^+) = 0.381(18)$ [28] and $Q_0 = 7.8(1.3)$ eb, which is consistent with a Nilsson model estimate of $g_K = -0.05$. If the positive sign is adopted for δ, then a value of $g_K = 0.87(6)$ results, which is consistent to within 2σ with a pure, two-quasiproton singlet configuration, for which $g_K = 1.0$. This possibility is, however, clearly unphysical, since this state is populated *directly* in the ground-state β^--decay of ^{176}Tm, so it *must* have two-quasineutron character.

The assignment of the band shown in fig. 1(d) to the $K^\pi = 8^-$, $T_{1/2} = 11.4(3)$ s two-quasiparticle state in ^{176}Yb was based on the following:

- The lack of coincidences between the band members and known transitions in any of the ytterbium isotopes that were populated. This is consistent with a bandhead lifetime at least in the μ-second range. It should be noted that the isomer was clearly populated, since the 96 keV unstretched $E1$ decay through which it deexcites [15] was observed in coincidence with all transitions of the ground-state band of ^{176}Yb below the 8^+ member.
- The band was populated with an intensity similar to those of the ground-state bands of ^{177}Yb and ^{175}Yb.
- Under the assumption that the band is indeed associated with the $K^\pi = 8^-$ state, a weighted average g_K value of $-0.04(7)$ was extracted from the 10^-, 11^- and 12^- branches, as is shown in table 2. This is consistent with a pure two-quasineutron singlet configuration, which suggests that any mixing with the $K^\pi = 8^-$ two-quasiproton configuration is weak compared to that observed in ^{178}Hf, which, in turn, indicates that the orbitals involved ($7/2^+[404]$ and $9/2^-[514]$) are sufficiently far from the proton Fermi surface at $Z = 70$ when compared to $Z \geq 72$. For completeness, it should be noted that a value of $g_K = 0.80(7)$ results if the positive sign is taken for δ.
- The possibility that the band could be associated with the $K^\pi = 6^+$, $T_{1/2} = 0.83$ s isomer in ^{174}Yb was discounted, since this structure has recently been identified to its 14^+ member [29], guided by the knowledge that the first cascade transition energy should be 153 keV [30]. It is worth noting that the band assigned here to the $K^\pi = 4^-$ two-quasineutron state in ^{176}Yb is isospectral above the 6^- level with the $K^\pi = 6^+$ band in ^{174}Yb to within a keV. Inspection of the mutual coincidence intensities in the present data for the 153, 173 and 193 keV subset of transitions suggests that the $K^\pi = 6^+$ in ^{174}Yb was populated to its 9^+ member. Also, the 992 keV transition that constitutes the strongest decay branch from the $K^\pi = 6^+$ bandhead was observed in coincidence with the ground-state band below and including the $6^+ \rightarrow 4^+$ member.

5 Summary

In summary, γ-ray coincidence data have been measured with the AFRODITE array when a thick ^{176}Yb target was bombarded with a 750 MeV ^{136}Xe beam. A rotational band based on the $9/2^+[624]$ ground-state orbital in ^{177}Yb was identified which differs from that published the literature. The previously published band was reassigned to the $9/2^+[624]$ first-excited state in ^{175}Yb.

In addition, a new band was observed to decay to the $9/2^+[624]$ band in ^{177}Yb, and it was identified with the $K^\pi = 15/2^+$ $\nu^3\{9/2^+[624] \otimes 7/2^-[514] \otimes 1/2^-[510]\}$ configuration.

Furthermore, a new band was identified in ^{176}Yb via coincidences with the previously known 1069 keV transition which decays from the bandhead to the 4^+ member of the ground-state band. It is probably associated with the $K^\pi = 4^-$, $\nu^2\{9/2^+[624] \otimes 1/2^-[510]\}$ configuration.

Finally, a new band structure that could not be connected with known states was assigned to the $K^\pi = 8^-$, $T_{1/2} = 11.4(3)$ s isomer in ^{176}Yb. Branching ratios were extracted from which a value $g_K = -0.04(7)$ was derived, which is consistent with the $\nu^2\{9/2^+[624] \otimes 7/2^-[514]\}$ two-quasineutron configuration.

The staff of the Accelerator Group at iThemba LABS are thanked for the beam delivery and support in general.

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