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Coulomb energy differences between isobaric analogue states in ^{70}Br and ^{70}Se

Identification of excited states of the $T_z = 0$ nucleus ^{70}Br

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Abstract. Gamma ray transitions de-exciting states in the $N = Z$ nucleus ^{70}Br have been identified for the first time using the GASP and EUROBALL arrays coupled with ancillary detectors. The level scheme of ^{70}Br has been established by means of particle-gated γ-γ and γ-γ-γ coincidences. The Coulomb energy differences between isobaric analogue states in ^{70}Br and ^{70}Se show a deviation from the expected behaviour which could be related to dripline effects.

PACS. 23.20.Lv Gamma transitions and level energies – 21.10.Sf Coulomb energies – 27.50.+e $59 \leq A \leq 89$

1 Introduction

The charge independence of nuclear forces demands that the energy spectra of mirror nuclei are identical. Any small differences which arise between energy levels can be interpreted entirely in terms of Coulomb effects. Recently, the Coulomb energy difference (CED), which is the energy difference between isobaric analogue states, has been investigated in a series of mirror nuclei in the $f_{7/2}$ shell, allowing us to study the spatial behaviour of the active valence nucleons [1–4]. Since the Coulomb energy is due only to protons, it has been pointed out that when a $J = 0$ proton pair recouples to another J configuration, the Coulomb energy decreases [5]. In the $J = 0$ coupling the overlap of the proton wave functions (and therefore the Coulomb repulsion) is at a maximum. CEDs have been found to be extremely sensitive to both microscopic and macroscopic nuclear-structure effects allowing us to study rotational alignment and even the evolution of nuclear radii along the yrast line [6,7].

The dependence of the excitation energy differences of $T = 1$ states as a function of T_z can be investigated in isobaric triplets. This is of particular interest in nuclei close to the dripline where differences in proton radii should manifest themselves through differences in the behaviour of CEDs.

In this context the $N = Z = 35$ dripline nucleus ^{70}Br is of particular interest since the excitation energies of the $T = 1$ levels can be directly compared with their isobaric analogue states in ^{70}Se. Its neighbour ^{69}Br has been found to be proton unbound in a recent fragmentation reaction study [8]. The half-lives of two β-decaying states in ^{70}Br have been reported. A state with $T_{1/2} = 79.1(8)$ ms was

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assigned 0^+ on the basis of its $0^+ \to 0^+$ Fermi decay [9]. A second state with $T_{1/2} = 2.19(9)$ s was assigned to a 9^+ state [10,11]. Nothing is known about the relative energies of these states and no excited structure built on either of them has been identified. A reported identification of the excited states in ^{70}Br [12] was later revised [13].

We report here an experimental investigation of the low-spin states of the $N = Z = 35$ ^{70}Br nucleus. CEDs obtained for isobaric analogue states in ^{70}Br and ^{70}Se show negative values which are tentatively interpreted in terms of an extended proton radius. Partial results of this work have previously been published in ref. [14].

2 Experimental details

High-spin states in the neutron-deficient nucleus ^{70}Br were populated using the $^{32}\mathrm{S} + {}^{40}\mathrm{Ca}$ reaction in two different experiments with the GASP and EUROBALL arrays. In the first experiment, where a few γ-rays were assigned for the first time to ^{70}Br [15], the 90 MeV ^{32}S beam was delivered by the Tandem XTU of the Laboratori Nazionali di Legnaro, Italy. The target consisted of a foil of isotopically enriched (99.9%) ^{40}Ca with a thickness of 1 mg/cm^2 on a 14 mg/cm^2 gold backing. Double and higher fold γ-γ coincidences were acquired with the 4π spectrometer GASP [16] consisting of 40 Compton-suppressed, large volume germanium detectors and of an inner BGO ball acting as a multiplicity filter and total-energy spectrometer. In order to improve the selectivity of the apparatus for reaction channels involving the evaporation of charged particles, the ISIS Si-ball [17] was mounted inside the inner ball of the GASP spectrometer. This charged-particle hodoscope is composed of 40 $\Delta E - E$ silicon telescopes covering about 70% of the total solid angle. Evaporated neutrons were detected in six BC501A liquid-scintillator detectors [18]. Neutron-γ discrimination was obtained by combining pulse shape and time-of-flight information. This ring of neutron detectors replaced a ring of the BGO ball at the most forward angles. The efficiencies for protons and for neutrons were estimated to be about 53% and 3%, respectively. The second experiment was performed using the EUROBALL array. ^{70}Br was populated using the $^{32}\mathrm{S} + {}^{40}\mathrm{Ca}$ reaction at 90 and 95 MeV bombarding energies. The beam was delivered by the VIVITRON accelerator of IRES (Strasbourg). The target consisted of 1 mg/cm^2 enriched (99.9%) ^{40}Ca on a gold backing of 15 mg/cm^2. Gamma-rays were detected with the EUROBALL array [19] consisting of 15 cluster and 26 clover composite Compton-suppressed Ge detectors coupled to the 4π charged-particle detection device EUCLIDES [20], consisting of 40 silicon $\Delta E - E$ telescopes partially segmented, and to the Neutron Wall detector [21], which consists of 50 liquid-scintillator neutron detectors covering the forward 1π section of EUROBALL. The efficiencies for protons and for neutrons were estimated to be about 60% and 25%, respectively.

Events in the two experiments were collected on tape under the following conditions:

a) at GASP a minimum of two Compton-suppressed Ge detectors fired in coincidence with two BGO elements from the multiplicity filter, and

b) at EUROBALL a minimum of two Compton-suppressed Ge detectors and 1 element of the Neutron Wall fired in coincidence.

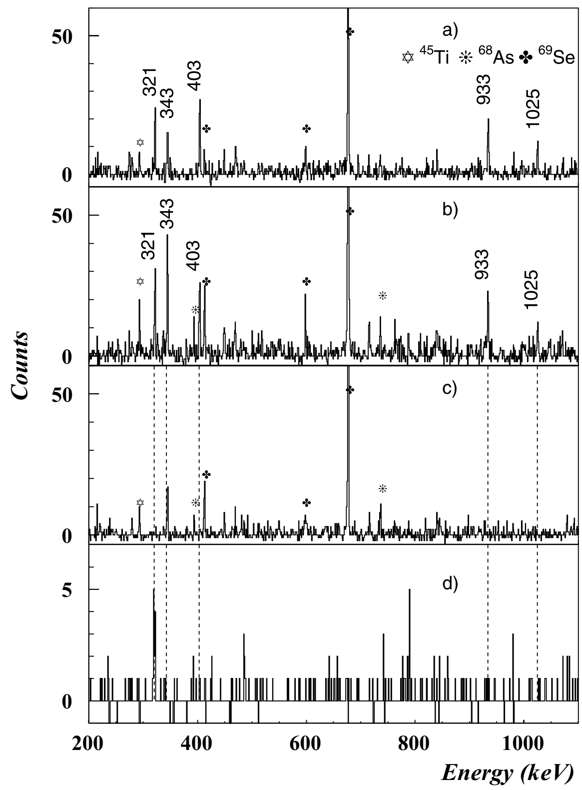

Fig. 1. Spectra of γ-γ events from the GASP experiment gated on the 933, 321 and 1025 keV lines of ^{70}Br in coincidence with a) 0 proton 1 neutron, b) 1 proton and 1 neutron, c) 1 neutron and 2 protons, d) 1 neutron and 1 α-particle. Contaminants from other reaction channels are marked.

With a beam current of ≈ 5 particle nA in both runs, the event rates were ≈ 2 and 4 kHz, respectively and the single rates in the germanium detectors were ≈ 1 kHz in the two experiments.

In the reaction used, ^{70}Br is populated following the evaporation of one proton and one neutron (pn channel). Hence in the off-line analysis γ-rays belonging to ^{70}Br were selected by requiring that only the events corresponding to the detection of one proton in the $\Delta E - E$ Si telescopes and one neutron in the neutron ring were incremented into a symmetrized E_γ-E_γ matrix. To further enhance the different structures observed, we made use of triples data by constructing E_γ-E_γ matrices in coincidence with the proper γ transitions in ^{70}Br. Figure 1 shows the γ-ray spectra obtained requiring one neutron detected in the neutron ring in coincidence with a) zero, b) one, c) two protons and d) one alpha-particle, detected in the ISIS Si telescope detectors. The reader should note the disappearance of the γ lines when coincidence with 2 protons or 1 α-particle is required. To validate the assignment we have also compared ratios of coincidence intensities of the γ-

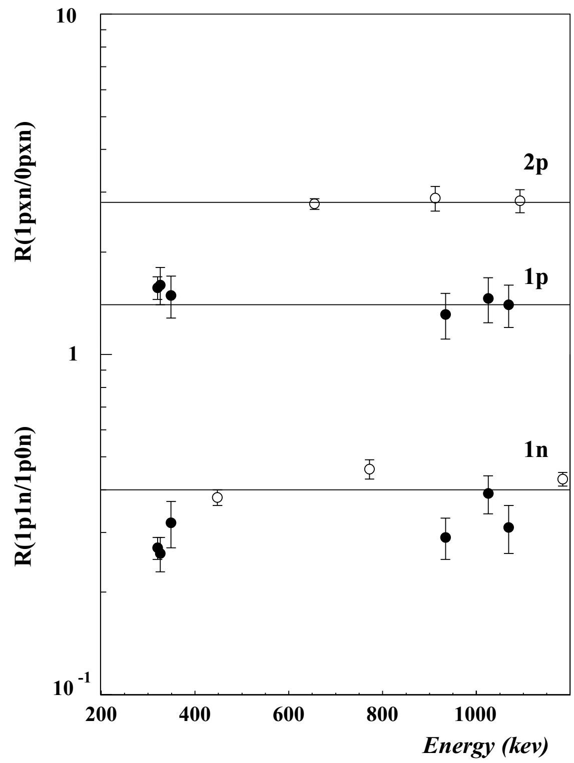

Fig. 2. γ-ray intensity ratios (EUROBALL data), for selected γ-rays (321, 326, 350, 933, 1025, 1069 keV) from the pn reaction channel ^{70}Br (filled symbols), obtained from the 0 and 1 proton gated (top) and 0 and 1 neutron gated (bottom) matrices. The open symbols in the top panel correspond to the 2p channel ^{70}Se taken as reference. The open symbols in the bottom panel correspond to the 2pn channel ^{69}Se. The three lines show the calculated values for the 1p, 2p and 1n reaction channels.

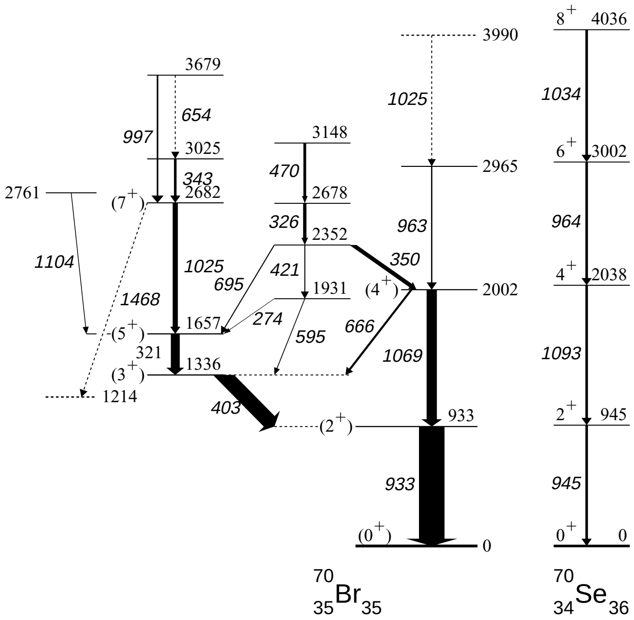

Fig. 3. Partial decay schemes of the $T_z = 0$ ^{70}Br and of ^{70}Se nuclei. Dashed transitions and levels are tentative. The width of the arrows is proportional to the intensities of the transitions. On the basis of interpretation, spin parities (9^+), (6^+) and (8^+) are tentatively assigned to the ^{70}Br levels at 1214, 2965 and 3990 keV, respectively.

rays assigned to ^{70}Br with those of γ-rays from exit channels with known proton and neutron multiplicities. Ratios of γ-γ intensities in coincidence with one proton or one neutron (pn reaction channel leading to ^{70}Br) to those without charged-particle conditions are plotted in fig. 2 (top). Similar ratios of coincidence intensities for the two proton channels leading to ^{70}Se are also shown [22]. At the bottom, ratios of γ-γ intensities in coincidence with one neutron to those without the neutron condition are shown and compared to those of the 2pn channel leading to ^{69}Se. For comparison, the intensity ratios deduced from detection probabilities calculated according to [23] are given as solid lines. Such ratios, obtained for a detection efficiency of 60% for protons and 25% for neutrons, show that the 321, 326, 350, 933 and 1069 keV γ transitions belong to the pn exit channel. In order to exclude γ-ray assignments from other pn channels coming from contaminant reactions on oxygen and carbon, we have performed a careful check of all the known γ lines. Once the identification was clear, the particle-gated γ-γ and γ-γ-γ coincidences were used to build the level scheme for ^{70}Br shown in fig. 3. The spins and parities of the levels were deduced, whenever possible, from the analysis of the directional correlation ratios from oriented states (DCO). Special attention was paid to the DCO ratio analysis using particle coincidence events. In the DCO analysis a γ-γ matrix was created with γ-rays from the Ge detectors placed at 90° with respect to the beam direction (clover detectors) on one axis and γ-rays from those at $\approx 156°$ (cluster detectors) on the other, under the condition of being in coincidence with one proton particle into the EUCLIDES Si telescopes and one neutron into the neutron wall detectors. In this way, contamination from other reaction channels was strongly reduced. In the EUROBALL geometry, if one gates on a stretched quadrupole transition, the theoretical DCO ratios $I_\gamma(156°, \text{Gate } 90°)/I_\gamma(90°, \text{Gate } 156°)$ are ≈ 1 for stretched quadrupole transitions and ≈ 0.5 for pure dipole transitions. If, on the contrary, gates are set on a pure dipole transition, the expected DCO ratios for quadrupole and dipole transitions are ≈ 2 and ≈ 1, respectively. The energies, relative intensities, DCO ratios (when possible), excitation energies and placements of the assigned γ transitions are listed in table 1.

3 Discussion

The level scheme for ^{70}Br deduced from the present work is shown in fig. 3. The observed structure might be built on either the 0^+ or 9^+ β-decaying states, but, through the comparison with the isobaric analogue states in ^{70}Se [22], we prefer to locate it on the 0^+ state. From the proposed level scheme shown in fig. 3, we can speculate about the possible configurations of the states of the odd-odd,

Table 1. Energies, relative intensities and angular correlations (DCO) or distribution ratios of γ-ray transitions assigned to ^{70}Br from the reactions used in the present experiments. The intensities are normalized to the 933 keV transition (assumed to be 100). The DCO ratios were obtained by gating on the stretched $\Delta I = 2$, 933 keV transition. Only for the 933 keV transition the angular distribution ratio was obtained from the single spectra. In all cases particle gates were used.

E_γ	Intensity	DCO or angular ratio	E_x	$I^{\rm i} \rightarrow I^{\rm f}$
274(1)	2(1)		1931	$\rightarrow (5^+)$
320.9(4)	35(4)	1.1(3)	1657	$(5^+) \rightarrow (3^+)$
326.2(5)	13(2)	0.31(14)	2678	
343.1(5)	9(2)	0.9(2)	3025	$\rightarrow (7^+)$
349.6(5)	16(2)	0.83(15)	2352	$\rightarrow (4^+)$
402.7(4)	59(6)	0.77(11)	1336	$(3^+) \rightarrow (2^+)$
421.0(6)	4(2)		2352	
470.4(6)	11(2)		3148	
595(1)	3(1)		1931	$\rightarrow (3^+)$
654(1)	2(1)		3679	
665.6(6)	8(2)		2002	$(4^+) \rightarrow (3^+)$
694.7(5)	4(1)		2352	$\rightarrow (5^+)$
933.4(4)	100	1.1(3)	933	$(2^+) \rightarrow (0^+)$
963.4(6)	5(2)		2965	
997.0(5)	6(2)		3679	$\rightarrow (7^+)$
1024.8(5)	20(2)	1.2(3)	2682	$(7^+) \rightarrow (5^+)$
1025(1)	3(2)		3990	
1069.0(5)	41(5)	1.1(3)	2002	$(4^+) \rightarrow (2^+)$
1104(1)	3(1)		2761	$\rightarrow (5^+)$
1468(1)	3(1)		2682	

$N = Z$ nucleus ^{70}Br. Here particle excitations will mainly involve the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $g_{9/2}$ orbitals as observed in neighbouring nuclei. As a result, we expect that the $T = 1$, $I^\pi = 0^+$ ground state will involve a proton-neutron ($\pi\nu$) configuration with a mixture of the subshells mentioned above. One notes that a $\pi g_{9/2}\nu g_{9/2}$ admixture will be essential here to lower the $T = 1$ $I^\pi = 0^+$ configuration below the $T = 0$ states. Since the $T = 1$ $I^\pi = 2^+$ state is expected at $\approx$ 950 keV from comparison with the isobaric analogue state in ^{70}Se, we give a (2^+) assignment to the 933 keV level. The angular distribution ratio of 1.1(3) deduced for the 933 keV transition agrees with an $E2$ assignment for the de-exciting transition. The levels at 3990, 2965 and 2002 keV (4^+) compare very well with the isobaric analogue states 8^+, 6^+ and 4^+ in ^{70}Se at 4036, 3002 and 2038 keV, respectively and therefore spin parities (8^+) and (6^+) may be tentatively assigned to the states at 3990 and 2965 keV. The 1025 keV transition de-exciting the 3990 level is observed in double-gated spectra in coincidence with the other three members of the isobaric cascade, but the weak population of the state prevents a definitive assignment. The 1336 and 1657 keV levels are assigned to be (3^+) and (5^+) from the DCO ratios and decay patterns. They are probably based on the $\pi p_{3/2}\nu p_{3/2}$ and $\pi f_{5/2}\nu f_{5/2}$ configurations. The (7^+) state at 2682 keV, more than 1 MeV higher than the (5^+) state, can be assigned to the $\pi g_{9/2}\nu g_{9/2}$ configuration. Since the

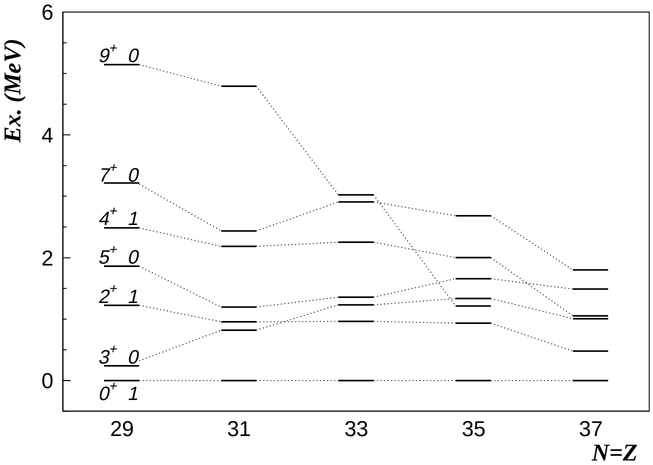

Fig. 4. Level systematics for odd-odd $N = Z$ nuclei. Levels are classified by spin, parity and isospin values. Excitation energies are normalized to the 0^+ states. Experimentally unidentified $T = 1$ energy levels —as in the case of ^{62}Ga— are taken from isobaric analogue states.

$\pi g_{9/2}\nu g_{9/2}$ two-body matrix element is strongly attractive, the stretched 9^+ state is expected, taken the 7^+ level as a reference, to be at least 1 MeV more bound [24]. We therefore propose such a two-quasiparticle 9^+ configuration for the 1214 keV state connected to the 2682 keV level by the 1468 keV transition, which is observed in coincidence with the 343 and 997 keV transitions feeding the (7^+) state. The weak 1468 keV de-excitation branch, however, prevents an experimental spin parity assignment to the level at 1214 keV. In fig. 4 the systematics of the excited states in odd-odd $N = Z$ nuclei is reported [25–29,14]. Our assignments appear to be generally consistent with the systematics. Note the low excitation energy of the proposed (9^+) β-decaying isomer which is in agreement with the expectations from β-decay studies [10,11] and consistent with the calculated oblate deformation for such a state [30]. The non observation of such a high-spin isomer at low excitation energy in the $N = Z = 37$ ^{74}Rb nucleus [26] is an indication for a transition to prolate deformation for heavier systems. Such a shape transition is clearly visible in fig. 4 from the drop in excitation energies of the 2^+ and 4^+ $T = 1$ states going from ^{70}Br ($N = Z = 35$) to ^{74}Rb ($N = Z = 37$).

It has been pointed out recently that CEDs can also probe changes in radius along the yrast band [7]. Large scale shell model calculations, performed for the ^{50}Fe, ^{50}Cr $T = 1$ states, have shown that a detailed description of the CED can be obtained taking into account the drifts in radii and the Coulomb normalization [6]. In particular the drifts in radii along the yrast band are found to be responsible for the dip in the CED at low angular momentum. Extending these considerations to odd-odd systems one notes that, if the observed $T = 1$ states with $I > 0$ were pure seniority 2 states, no significant differences would be expected between the transition energies in the $\pi\nu$ configuration of ^{70}Br and the two-neutron (ν^2) configuration

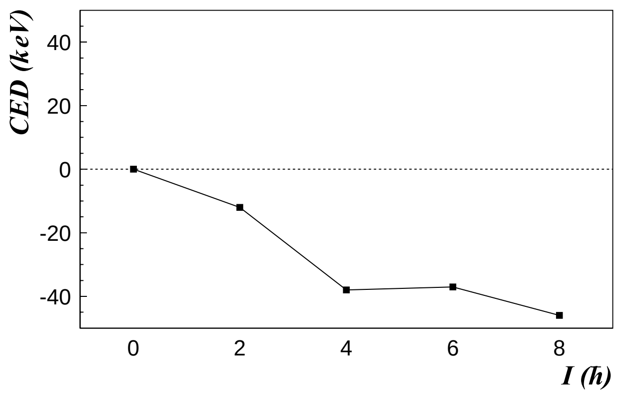

Fig. 5. Coulomb energy differences ($E_x^{I^\pi}(T_z=0) - E_x^{I^\pi}(T_z=1)$) between isobaric analogue states in ^{70}Br and ^{70}Se nuclei as a function of the angular momentum.

of ^{70}Se. Deviations from such behaviour occurring at the dripline may be related to the breaking of isospin symmetry by the increased spatial extension of the proton wave function resulting from the fact that the particle is very weakly bound. It is interesting to note that for the ^{70}Br, ^{70}Se nuclei —figs. 3 and 5— CEDs for isobaric analogue states have negative values. A compression of the energy spectrum for the $\pi\nu$ configurations can be associated with two effects, both related to the increased proton radius for dripline nuclei:
a) A reduction of the Coulomb repulsion due to the spatial extension of the proton wave function (Thomas-Ehrman shift [31,32]).
b) A decrease of the nuclear two-body residual interaction due to the different radial distributions of the wave functions for neutrons and loosely bound protons. The differences in radial distributions determine a reduction of the spatial overlap of the two orbitals. Because of the low centrifugal barriers, the radial function of the low l orbits will be more affected resulting in a compression of the energy spectrum [33]. We have calculated the $\pi\nu$ two-body matrix elements (TBME) for a delta interaction using Woods-Saxon single-particle wave functions in the $p_{1/2}$, $p_{3/2}$, $f_{5/2}$, $g_{9/2}$ model space. When the proton separation energy is close to zero, the calculations show a reduction of the values of the TBMEs, with respect to the $\nu\nu$ ones, of the order of 2–10%. The effect depends on the single-particle orbit involved, being larger for low l-values. This results in an increase of the excitation energy of the 0^+ ground state relative to the higher-spin levels and therefore in a compression of the excitation energy spectrum. A larger effect, of the order of 10–20%, is calculated for the $\pi\pi$ matrix elements. It is worth mentioning here that for ^{70}Br the proton separation energy, extracted from systematic trends, is $S_\mathrm{p} = (2600 \pm 400)$ keV [34].

4 Conclusions

In summary, we have established a level scheme for the odd-odd nucleus ^{70}Br for the first time. Negative values for the CEDs between isobaric analogue states in ^{70}Br and ^{70}Se seem to indicate a reduction in Coulomb repulsion for the dripline nucleus ^{70}Br which could be explained in terms of an extended proton radius.

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