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Short note

First identification of excited states in the N = Z nucleus ^{70}Br

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Abstract. Excited states in the $T_z = 0$ nucleus ^{70}Br have been investigated using the reaction ^{58}Ni(^{16}O,1p3n). γ rays were detected with one EUROBALL CLUSTER detector and three single HPGe detectors. Charged particles and neutrons were registered with the Rossendorf silicon ball and six modules of the EUROBALL neutron wall, respectively. The identification of γ transitions in ^{70}Br is based on the analysis of $\gamma\gamma$-proton-neutron coincidences. A level scheme of ^{70}Br has been established for the first time. It shows a multiplet-like structure of probably isospin $T = 0$ while $T = 1$ isobaric analogue states are not observed.

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

Nuclei with equal numbers of neutrons and protons ($N = Z$) offer the possibility to study the pairing correlation between neutrons and protons (n-p pairing) which is enhanced if these particles occupy the same orbitals [1]. Odd-odd $N = Z$ nuclei are of particular interest because they may give insight into the different modes of n-p pairing. In these nuclei, the valence neutron and the valence proton may couple with antiparallel spins ($J = 0$) forming an n-p pair with isospin $T = 1$ analogously to pairs of identical nucleons. Moreover, they can form an n-p pair with parallel spins and $T = 0$. Nucleon pairs of like particles with $J = 0$, $T = 1$ form usually the paired structures in medium and heavy-mass nuclei. However, in odd-odd nuclei these states may compete with $T = 0$ states. This $T = 0$ pairing predominates in the ground states of odd-odd nuclei in the *sd* shell ($A \leq 40$) with spins and parities of $J^{\pi}_{\rm gs} = 1^+, 3^+, 5^+$, whilst in heavier nuclei, except for ^{58}Cu, $T = 1$ pairing becomes dominant and is reflected in the fact that the ground states have $J^{\pi} = 0^+$ [2]. In $^{62}_{31}$Ga$_{31}$ a level sequence built on a $J^{\pi} = (1^+)$, $T = 0$ state has been found which feeds directly the $J^{\pi} = 0^+$, $T = 1$ ground state [3], while $T = 1$ isobaric analogue states of the $T_z = 1$ isobar have not been observed. Similarly, $^{66}_{33}$As$_{33}$ displays strongly populated multiplet-like sequences feeding the 0^+ ground state while the population of a possible $J^{\pi} = 2^+$, $T = 1$ isobaric analogue state is very weak [4]. In contrast to these nuclei, the $J^{\pi} = 2^+, 4^+$, $T = 1$ isobaric analogue states are clearly observed in $^{74}_{37}$Rb$_{37}$ [5]. Here, the $T = 1$ band is crossed by a $T = 0$ band which starts at $J = (5)$ and follows a regular $J(J + 1)$ pattern. Such a transition from $T = 1$ to $T = 0$ pairing, caused by rotation, is predicted in several theoretical studies [6–8]. The present study aims to investigate how $T = 0$ and $T = 1$ pairing evolve in the $N = Z = 35$ nucleus ^{70}Br, which is located between $^{66}_{33}$As$_{33}$, with a rather multiplet-like structure, and $^{74}_{37}$Rb$_{37}$, which possesses pronounced $T = 1$ and $T = 0$ rotational bands. No excited states in ^{70}Br have been reported so far. Half-lives of two states were determined from β-decay studies: $T_{1/2} = 78.5$ ms [9], assigned to the ground state and due to a fast transition to a $0^+ \rightarrow 0^+$ Fermi decay [2], and $T_{1/2} = 2.2$ s [10], assigned to an isomer. However, to date there is no firm evidence on the relative energetic locations of these states.

Excited states in ^{70}Br were populated using the reaction ^{58}Ni(^{16}O,1p3n) at a beam energy of 95 MeV. For this reaction a cross section of 0.6 mb (0.03 % of the total cross section) is predicted by the evaporation code PACE [11]. The beam, delivered by the MP tandem accelerator of the Max-Planck-Institut für Kernphysik Heidelberg, was focused onto an enriched ^{58}Ni target of 5 mg cm^{-2} thickness. γ rays were detected with one EUROBALL CLUSTER detector [12] without escape-suppression shield, placed at 90° relative to the beam direction, and three unshielded single HPGe detectors positioned at 60°, 90° and 120° to the beam.

In order to select the weak 1p3n exit channel leading to ^{70}Br, evaporated particles were measured in coincidence with γ rays. Charged particles were detected with the Rossendorf silicon ball (RoSiB) consisting of 39 detectors and covering a solid angle of about 90% of 4π. To prevent scattered ^{16}O ions from hitting the silicon detectors the target was surrounded by aluminium foils. These were shaped as a truncated cone of 50 μm thickness at forward angles, followed by a tubular part of 35 μm thickness around 90° and a 25 μm thick disc perpendicular to the beam at backward angles. For the discrimination between protons and α particles the pulse-shape discrimination technique described in [13] was applied. Neutrons were registered with six segmented modules of the EUROBALL neutron wall [14] placed at 0° to the beam and covering a solid angle of about 1π. The segments were combined to eight independent channels. A total of about 1.1×10^9 coincidence events with signals of at least two Ge detectors and of at least one silicon or one neutron detector were recorded. For each silicon or neutron detector a two-dimensional spectrum of zero-crossing time versus energy loss or versus time of flight, respectively, was created. Two-dimensional gates set in these spectra were used to create γ-γ matrices in coincidence with various numbers of protons, α particles and neutrons. These γ-γ coincidence matrices were analysed using the codes ESCL8R [15] and VS [16]. Examples of spectra of γ-γ events in coincidence with different combinations of emitted particles are shown in Fig. 1. A comparison of the top spectrum containing γ-γ events without any particle-coincidence condition with the spectra in coincidence with two α particles and one proton (2α1p) or three protons and one neutron (3p1n) shows that known γ transitions in nuclei belonging to these exit channels are clearly visible, whereas those not fulfilling the respective particle-coincidence condition are strongly suppressed. The bottom spectrum contains γ-γ events in coincidence with one proton and three neutrons (1p3n), which corresponds to the reaction channel leading to ^{70}Br. The number of events in this spectrum amounts to about 0.02 % of the number of events in the top spectrum containing the total of γ-γ events. This percentage corresponds roughly to the cross section of 0.03 % of the total cross-section estimated for this reaction channel by the code PACE. In this spectrum prominent γ rays at 392, 406, 716, 735, 751 and 754 keV are observed that are thought to belong to ^{70}Br. These γ rays are not in coincidence with α particles. With respect to the incomplete detection of protons and neutrons they could belong to exit channels like 2p3n, 2p4n or 1p4n. However, these can be ruled out because these channels lead to the known isotopes ^{69}Se, ^{68}Se [17,18] or to ^{69}Br which should be populated much weaker than ^{70}Br. Moreover, ^{69}Br was shown to be unbound in its ground state [19]. Since the number of counts in the 1p3n spectrum is very small, the coincidence relations of the observed γ rays have been analysed in a γ-γ matrix created in coincidence with no α particles, less than two protons and more than one neutron. On the basis of this analysis the level scheme of ^{70}Br was established.

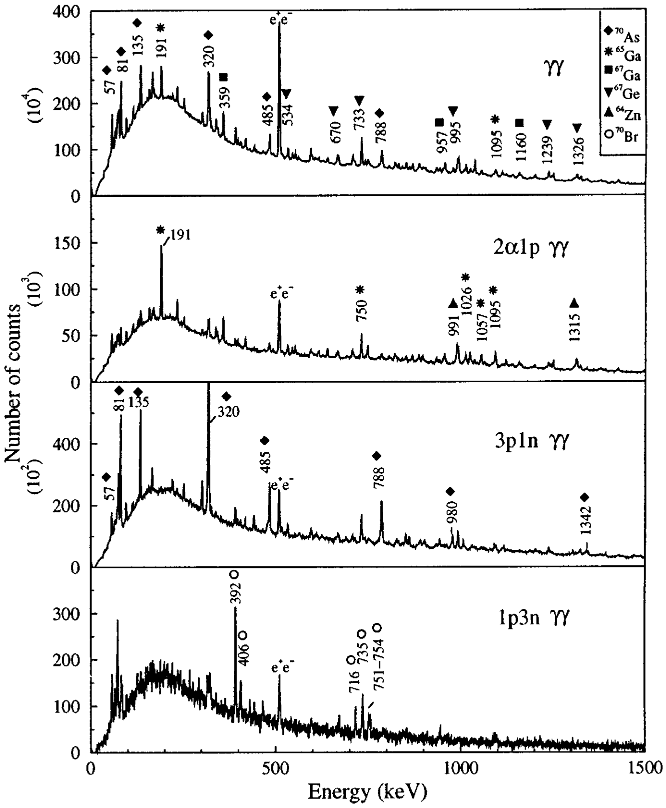

Fig. 1. Spectra of γ-γ events in coincidence with various combinations of emitted particles

In order to validate the assignment of the observed γ rays to the 1p3n exit channel we have compared ratios of coincidence intensities of these γ rays with those of γ rays from exit channels with known proton and neutron multiplicities. This technique can be used to assign γ rays to exit channels because the intensity of a γ ray in coincidence with specific evaporated particles depends on the multiplicity of these particles and on the detection efficiency, but only weakly on the individual reaction channel [20,21]. Ratios of γ-γ intensities in coincidence with at least one neutron ($I_{n\gamma\gamma}$) to those without particle-coincidence condition ($I_{\gamma\gamma}$) are plotted in Fig. 2. The intensities of γ transitions of known exit channels

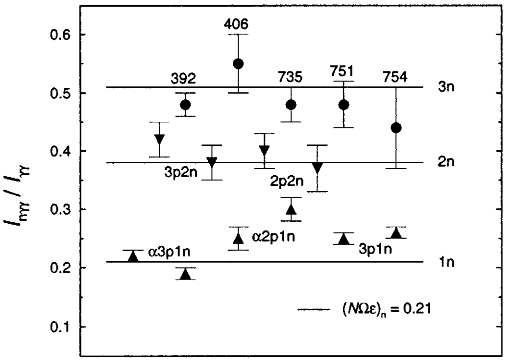

Fig. 2. Ratios of γ-γ intensities from exit channels with different neutron multiplicities in coincidence with at least one neutron to those without particle-coincidence condition. The solid lines represent calculated values (see text)

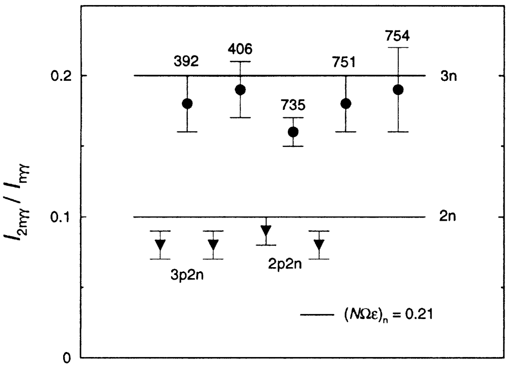

Fig. 3. Ratios of γ-γ intensities from exit channels with different neutron multiplicities in coincidence with at least two neutrons to those in coincidence with at least one neutron. The solid lines are calculated as in Fig. 2

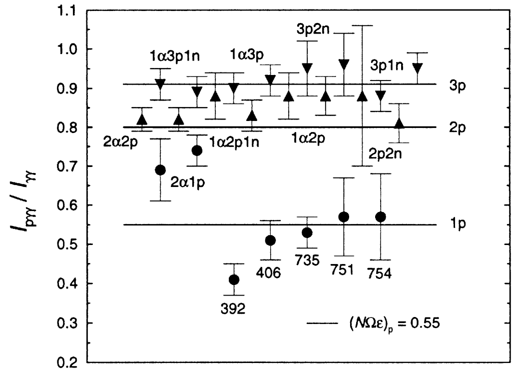

Fig. 4. Ratios of γ-γ intensities from exit channels with different proton multiplicities in coincidence with at least one proton to those without particle-coincidence condition. The solid lines represent calculated values (see text)

were obtained from γ-γ spectra gated on the ground-state transition in the respective nucleus. The intensities of the 392 keV γ ray were deduced from spectra gated on the 406 keV γ ray while the intensities of the γ rays at 406, 735, 751 and 754 keV were obtained from spectra gated on the 392 keV γ ray. The intensity ratios of γ transitions of different exit channels with a certain neutron multiplicity are roughly the same while the ratios belonging to neutron multiplicity one are well separated from those with neutron multiplicity two. The $I_{n\gamma\gamma}/I_{\gamma\gamma}$ values of the 392, 406, 735, 751 and 754 keV γ rays are greater than those of the channels with $2n$ emission, although there is a small overlap within the errors. For comparison, the $I_{n\gamma\gamma}/I_{\gamma\gamma}$ ratios deduced from detection probabilities calculated according to (6) in [22] are given as solid lines. These ratios obtained for a detector efficiency of $(N\Omega\epsilon)_n = 0.21$ (N = number of identical detectors, Ω = solid angle of one detector, ϵ = efficiency of one detector) reproduce the ratios of the exit channels with $1n$ and $2n$ emission and show that the 392, 406, 735, 751 and 754 keV γ rays are compatible with $3n$ emission. To verify this, ratios of γ-γ intensities in coincidence with at least two neutrons to those in coincidence with at least one neutron have also been deduced and are shown in Fig. 3. Here, the $I_{2n\gamma\gamma}/I_{n\gamma\gamma}$ ratios of the 392, 406, 735, 751 and 754 keV γ rays are clearly greater than those of γ rays of $2n$ channels and they are consistent with the calculated values for $3n$ emission as well. To determine the proton multiplicity of these γ rays ratios of γ-γ intensities in coincidence with at least one proton to those without particle-coincidence condition were deduced and are shown in Fig. 4. In this graph the $I_{p\gamma\gamma}/I_{\gamma\gamma}$ ratios of the 392, 406, 735, 751 and 754 keV γ rays are markedly lower than the values of exit channels with proton multiplicities two and three, which suggests that they correspond to proton multiplicity one. Calculated ratios given for $(N\Omega\epsilon)_p = 0.55$ reproduce the values of the exit channels with $2p$ and $3p$ emission and confirm the assignment of the 392, 406, 735, 751 and 754 keV γ rays to an exit channel with $1p$ emission. The ratios given for γ rays of the $2\alpha 1p$ exit channel are greater than the predicted value for $1p$ channels. This is caused by a competition of the $2\alpha 1p$ emission with the emission of $1\alpha 3p2n$ leading to the same final nucleus. By combining the neutron and proton multiplicities deduced for the γ rays at 392, 406, 735, 751 and 754 keV these can be assigned to the exit channel $1p3n$ leading to the final nucleus ^{70}Br.

The level scheme of ^{70}Br deduced from the present γ-γ-particle experiment is shown in Fig. 5. The observed structure may be built on either of the observed β-decaying states. Energies and relative intensities of the γ transitions assigned to ^{70}Br are listed in Table 1. Multipole orders of the γ transitions and thus level spins could not be determined from the present experiment.

The level scheme comprises two level sequences that resemble partners with different signature (J mod 2). In this case the 392, 323 and 412 keV γ rays are $\Delta J = 1$ transitions, while the 715, 735 and 751 keV cross-over transitions may have $\Delta J = 2$. The sequences show a multiplet-like, non-regular structure. The comparison of the level sequences in ^{70}Br with the yrast sequence of the T_z = 1 isobar ^{70}Se [23] included in Fig. 5 shows that there is no correspondence between the states in ^{70}Br and ^{70}Se. This suggests that the sequences found in ^{70}Br may be of $T = 0$ character. Thus, they are likely to be built on the $T_{1/2} = 2.2$ s state, which is expected to have $J^{\pi} = (3, 4, 5)^+$

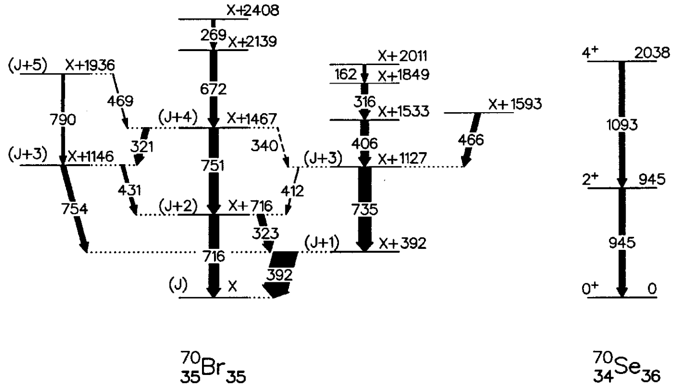

Fig. 5. Level scheme of ^{70}Br deduced from the present γ-γ-particle-coincidence experiment. Yrast states of the isobar ^{70}Se [23] are shown for comparison

Table 1. γ transitions assigned to ^{70}Br

E_γ(keV)^a	I_γ^b	E_γ(keV)^a	I_γ^b
161.5	9(1)	430.6	13(2)
268.7	12(1)	466.3	22(3)
316.2	26(2)	469.4	
320.9	23(2)	671.9	28(2)
323.4	28(2)	715.5	40(2)
392.0	100(1)	735.1	53(3)
339.5		751.4	37(3)
406.1	32(2)	754.5	20(2)
411.6		790.5	10(2)

^{a} Transition energy. The error is in the range of (0.1 - 0.5) keV.
^{b} Relative intensity of the γ transition normalised to $I_\gamma = 100$ of the 392 keV transition. This value is deduced from coincidence spectra containing γ-γ events of all Ge detectors in coincidence with no α particles, less than two protons and more than one neutron.

from systematics of isotopes, isotones and $N = Z$ nuclei. If they were built on the short-lived $T_{1/2} = 78.5$ ms, $J^\pi = (0^+)$ state, there should be visible branches from the $J + 3, 4$ states to the $J^\pi = 2^+$, $T = 1$ state, as observed in ^{66}As [4].

A deuteron-like $T = 0$ system leads to states with odd spins. Since one of the sequences in ^{70}Br is supposed to have even spins, the $T = 0$ states may consist of multi-particle structures involving more than two nucleons. The irregular structure of ^{70}Br resembles that of the light odd-odd $N = Z$ neighbours ^{62}Ga and ^{66}As rather than that of the heavy neighbour ^{74}Rb which is characterised by the appearance of rotational-like T =1 and $T = 0$ sequences.

Summarising, we have established a level scheme of the odd-odd $N = Z$ nucleus ^{70}Br for the first time. The scheme shows a multiplet-like structure suggesting that the observed states of ^{70}Br might be of nearly spherical character. These states are assigned to $T = 0$. There is no evidence however for T =1 isobaric analogue states.

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