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High-spin study of odd-A $_{49}$In isotopes beyond the neutron mid-shell

R. Lucas[1], M.-G. Porquet[2,a], Ts. Venkova[3], I. Deloncle[2], M. Houry[1,b], Ch. Theisen[1], A. Astier[4,c], A. Bauchet[2], S. Lalkovski[2], G. Barreau[5], N. Buforn[4], T.P. Doan[5], L. Donadille[6,d], O. Dorvaux[7], J. Durell[8], Th. Ethvignot[9], B.P.J. Gall[7], D. Grimwood[8], W. Korten[1], Y. Le Coz[1], M. Meyer[4], A. Minkova[2,10], A. Prévost[4], N. Redon[4], A. Roach[8], N. Schulz[7], A.G. Smith[8], O. Stézowski[4], and B.J. Varley[8]

[1] Commissariat à l'Énergie Atomique, CEA/Saclay, DSM/DAPNIA/SPhN, 91191 Gif-sur-Yvette Cedex, France
[2] CSNSM, IN2P3-CNRS and Université Paris-Sud, 91405 Orsay, France
[3] INRNE, BAS, 1784 Sofia, Bulgaria
[4] IPNL, IN2P3-CNRS and Université Claude Bernard, 69622 Villeurbanne Cedex, France
[5] CENBG, IN2P3-CNRS and Université Bordeaux I, 33175 Gradignan, France
[6] School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, United Kingdom
[7] IReS, IN2P3-CNRS and Université Louis Pasteur, 67037 Strasbourg, France
[8] Department of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, United Kingdom
[9] Commissariat à l'Energie Atomique Bruyères-le-Châtel, CEA/DIF/SPN, BP12, 91680 Bruyères-le-Châtel, France
[10] University of Sofia, Faculty of Physics, 1126 Sofia, Bulgaria

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Abstract. The ^{115,117,119,121}In nuclei have been produced as fission fragments in three reactions induced by heavy ions: ^{12}C + ^{238}U at 90 MeV bombarding energy, ^{18}O + ^{208}Pb reaction at 85 MeV, and ^{31}P + ^{176}Yb at 152 MeV. Their level schemes have been built from gamma-rays detected using the EUROBALL III and IV arrays. High-spin states of ^{117,119,121}In nuclei have been identified for the first time. Moreover, isomeric states lying around 2.5 MeV have been established in ^{119,121}In from the delayed coincidences between the fission fragment detector SAPhIR and the gamma array. Most of the observed states can be described by coupling a proton $g_{9/2}$ hole to a Sn core, while the intruder band based on an orbital from the $\pi[g_{7/2}/d_{5/2}]$ sub-shells behaves as the ground-state band of neighbouring Cd isotopes.

PACS. 21.60.Ev Collective models – 23.20.Lv Gamma transitions and level energies – 25.85.Ge Charged-particle-induced fission – 27.60.+j $90 \leq A \leq 149$

1 Introduction

A rich variety of nuclear phenomena has been noted in indium isotopes, many years ago. A lot of theoretical studies have been performed in order to describe the low-spin structures of $^{113\text{-}121}$In obtained from the study of β-decays [1–4]. Shape coexistence in odd-mass nuclei near closed shells has been reviewed a few years later [5], in which ^{115}In was chosen as an illustration.

The behaviour of high-spin states generally provides fruitful information to characterize both the motion of the odd nucleon and the motion of the underlying core. Unfortunately the high-spin study of the In isotopes has been up to now restricted to $A = 113$–115, the heaviest ones to be populated by fusion-evaporation reactions [6,7]. To study the evolution of the structure of the more neutron-rich indium nuclei, one thinks naturally to use fission as this phenomenon is known to provide a large number of neutron-rich nuclei which are, for the most part, accessible in no other manner and which are released with various excitation energies, spins and deformations. The development of high-resolution γ-ray arrays has lead to important developments in the spectroscopy of fission fragments. Since the mass distribution of fragments from spontaneous fission of actinides is highly asymmetrical, the experimental study of the $A \sim 120$ mass region is less known as com-

[a] e-mail: porquet@csnsm.in2p3.fr
[b] *Present address*: CEA-DIF, DAM/DCRE/SDE/LDN, 91680 Bruyères-le-Châtel, France.
[c] *Present address*: CSNSM IN2P3-CNRS and Université Paris-Sud 91405 Orsay, France.
[d] *Present address*: CEA/Saclay, DSM/DAPNIA/SPhN, 91191 Gif-sur-Yvette Cedex, France.

pared to the $A \sim 100$ mass region or to the $A \sim 140$ mass region [8,9]. On the other hand, induced fission exhibits a strong symmetric fission component as the shell effects are washed out by the high excitation energy of the fissioning system. In this case, the range of produced nuclei can be adjusted by choosing the fusion reaction and the projectile energy.

For the study of the indium chain isotopes presented in this paper, we used three fusion reactions in order to get a large number of In isotopes, from the stability line to the most neutron-rich nuclei as possible. High-spin states of ^{117,119,121}In nuclei have been identified for the first time. Moreover, new isomeric states lying around 2.5 MeV have been established in ^{119,121}In from the delayed coincidences between fission fragment detectors and the gamma array. Most of the observed states can be described by coupling a proton $g_{9/2}$ hole to a $_{50}$Sn core with a broken neutron pair, either $\nu h^2_{11/2}$ for the positive-parity states or $\nu h^1_{11/2}$ $\nu[d_{5/2}/g_{7/2}]^1$ for the negative-parity states. On the other hand, the intruder band based on an orbital coming from the spherical $\pi[g_{7/2}/d_{5/2}]$ sub-shells (located above the $Z = 50$ shell gap) behaves in a similar way to the ground-state band of the neighbouring $_{48}$Cd isotopes. These results show that the neutron-rich In nuclei exhibit a shape coexistence phenomenon up to spin 19/2 at least.

2 Experimental procedures and data analysis

2.1 Reactions and γ-ray detection

The ^{12}C + ^{238}U reaction was studied at 90 MeV incident energy. The beam was provided by the Legnaro XTU tandem accelerator. A 47 mg/cm^2 target of ^{238}U was used to stop the recoiling nuclei. The gamma-rays were detected with the EUROBALL III array [10]. The spectrometer contained 15 cluster germanium detectors placed in the backward hemisphere with respect to the beam, 26 clover germanium detectors located around 90° and 30 tapered single-crystal germanium detectors located at forward angles. Each cluster detector consists of seven closely packed large-volume Ge crystals and each clover detector consists of four smaller Ge crystals. The data were recorded in an event-by-event mode with the requirement that a minimum of five unsuppressed Ge detectors fired in prompt coincidence. About 1.9×10^9 coincidence events with a γ multiplicity greater than or equal to three were registered. Events were sorted by the EURO14 software [11] and analysed with the Radware package [12].

The second and third reactions were studied at the Vivitron accelerator of IReS (Strasbourg), using the EUROBALL IV spectrometer which consists of the same array of Ge crystals as EUROBALL III and an inner ball of 210 BGO crystals. For the fusion reaction, ^{18}O + ^{208}Pb at 85 MeV beam energy, the thickness of the target was 20 mg/cm^2. The third fusion reaction was ^{31}P + ^{176}Yb at 145 MeV beam energy. The 1.5 mg/cm^2 target was deposited in a 15 mg/cm^2 Au backing in order to stop the recoiling nuclei. With the requirement of a minimum of three unsuppressed Ge detectors firing in prompt coincidence, a total of 0.7×10^9 and 2.2×10^9 coincidence events were collected in the ^{18}O- and ^{31}P-induced reactions, respectively. The offline analysis consisted of both usual γ-γ sorting and multi-gated spectra using the FANTASTIC software [13] and a three-dimensional "cube" built and analysed with the Radware package [12].

2.2 Isomer selection

To identify new isomeric states in fission fragments, we have performed another experiment using a fission fragment detector to trigger the EUROBALL III array and isolate the delayed γ-ray cascades. The heavy-ion detector, SAPhIR, is made of many photovoltaic cells which can be arranged in several geometries [14]. In the present work, it consisted of 32 photovoltaic modules laying in four rings around the target. We have used the ^{12}C + ^{238}U reaction at 90 MeV with a thin target, 0.14 mg/cm^2. Fragments escaping from the target are stopped in the photovoltaic cells of SAPhIR. The detection of the two fragments in coincidence provides a clean signature of fission events. The EUROBALL III time window was 1 μs, allowing detection of delayed γ-rays emitted during the de-excitation of isomeric states.

Time spectra between fragments and γ-rays have been analyzed in order to measure the half-life of isomeric levels. The FWHM of the time distribution for prompt γ-rays was around 15 ns. In this experiment, new isomeric states have been found in ^{119,121}In nuclei, which will be detailed below.

2.3 Identification of new γ-ray cascades

More than one hundred nuclei are produced at high spin in such experiments, and this gives several thousands of γ-transitions which have to be sorted out. Single-gated spectra are useless in the majority of cases. The selection of one particular nucleus needs at least two energy conditions, implying that at least two transitions have to be known.

The identification of transitions depopulating high-spin levels which are completely unknown is based on the fact that prompt γ-rays emitted by complementary fragments are detected in coincidence [15,16]. For each reaction used in this work, we have studied many pairs of complementary fragments with known γ-ray cascades to establish the relationship between their number of protons and neutrons. The sum of the proton numbers of complementary fragments has been found to be always the atomic number of the compound nucleus. The total number of evaporated neutrons (sum of the pre- and post-fission emitted neutrons) is mainly 10 in the ^{12}C + ^{238}U reaction [17,18], and 6 in the two other reactions. These numbers have been used to identify the γ-ray cascades of ^{117,119,121}In nuclei, as explained in the next section.

The fusion reaction ^{31}P + ^{176}Yb leads to an odd-Z compound nucleus. The $_{49}$In isotopes are then associated with some even-Z $_{36}$Kr isotopes emitting well-known γ-ray cascades. The case of the $_{49}$In isotopes produced in the ^{12}C + ^{238}U reaction is not so easy to handle as complementary fragments of In isotopes are other In isotopes, $Z = 49$ being just half the atomic number of the ^{250}Cf compound nucleus. Finally, the use of three different reactions to produce the various In isotopes has turned out to be very efficient to disentangle the coincidence relationships which are often complicated by the existence of many doublets or triplets of transitions very close in energy.

3 Experimental results

The $^{113\text{-}119}$In isotopes are produced as fission fragments of $_{85}$At isotopes obtained in the fusion reaction ^{31}P + ^{176}Yb at 152 MeV beam energy. The mass interval is shifted towards the heavy-mass side when using the two other reactions (see below, fig. 9). Therefore, the high-spin states of the $^{119\text{-}121}$In isotopes have been obtained mainly from the analysis of the ^{18}O and ^{12}C induced reactions.

The high-spin states of ^{113}In observed in this work extend up to spin (27/2) and are in complete agreement with those already known from the fusion-evaporation reaction [6].

3.1 Study of ^{115}In

The high-spin states of ^{115}In had been previously studied by means of a fusion-evaporation reaction [7]. They had been arranged in two structures: the first one, built on the ground state, extends up to spin $(29/2^+)$ and the other, with negative parity, extends from spin $(15/2^-)$ at 2 MeV up to spin $(31/2^-)$ [7]. A more complete level scheme has been deduced from the present experiment (see fig. 1) using the spectra gated by all the combinations of already-known transitions and new ones identified in those spectra. Several transitions had to be shifted as their previous locations [7] do not agree with the observed coincidence relationships. The spin assignments[1] are based upon i) the already known spins of the band head states [20], ii) the assumption that in yrast decays, spin values increase with the excitation energy, iii) the analogy with the level structures of ^{113}In [6]. The levels are grouped into three structures (see fig. 1). The first structure is directly built on the $9/2^+$ ground state. Its low-spin part is characterized by high-energy transitions and a large change is observed above the $(21/2^+)$ state. One has to note that two transitions of the same energy (569 keV) have to be placed in this structure, since all the double-gated spectra with one gate on the 569 keV transition show the existence of another 569 keV line. This first structure is very similar to the one in ^{113}In, apart from the decay of the $(21/2^+)$ state (at 2878 keV), which exhibits three branches. Two of them populate the positive-parity states: a 569 keV transition to the $(17/2^+)$ level; and an unobserved 10 keV transition to the $(19/2^+)$ level at 2868 keV (required by coincidence conditions between the 559 keV and the 82, 136, 376 keV γ-rays). The third branch (339 keV) makes a link to the negative-parity structure. This has not been observed in ^{113}In.

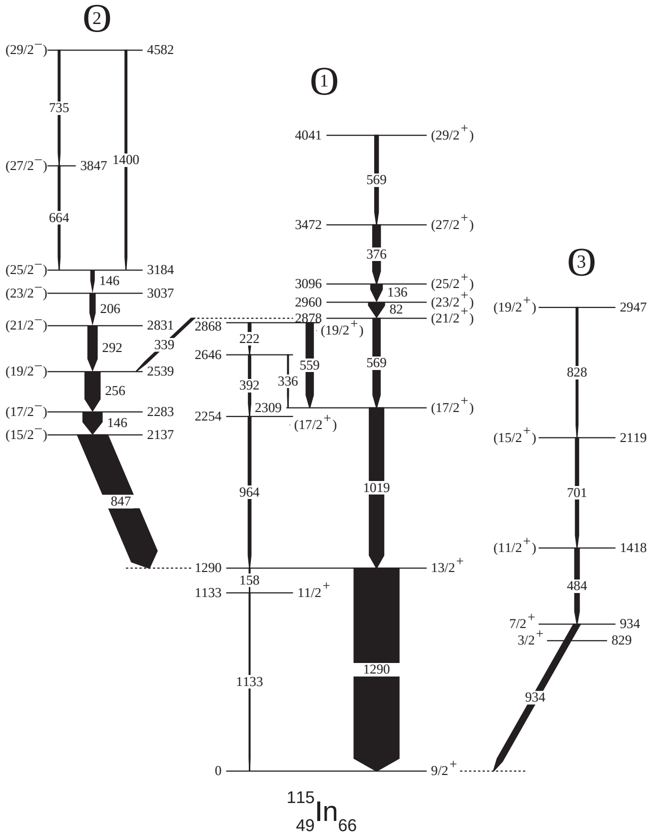

Fig. 1. Level scheme of ^{115}In obtained as a fission fragment in the fusion reaction ^{31}P + ^{176}Yb at 152 MeV beam energy. The spin and parity values, given without parenthesis, have been established from β-decay measurements [20]. The $3/2^+$ level at 829 keV, which is the first state of the band built on the $1/2^+[431]$ intruder orbital, has not been populated in this experiment.

The second structure is built on a $(15/2^-)$ level at 2137 keV excitation energy and extends up to 4582 keV excitation energy. Several other γ-rays (256[2], 345, 470 keV) have been seen in coincidence with transitions belonging to the second structure, but they could not be placed in the decay scheme. The third structure comprises three transitions and is built on the $7/2^+$ state at 934 keV. This state has been previously identified from the β-decay of the $11/2^-$ isomeric state of ^{115}Cd [2] and interpreted as a member of the band built on the $1/2^+[431]$ intruder orbital. The 1418 keV level had also been populated in the β-decay of ^{115}Cd$^{\mathrm{m}}$ and assigned as a $9/2^+$ state. We could not expect the population of such a low-spin state around 1.4 MeV excitation energy. Therefore, we propose that its

[1] In fission experiments, spin values could be assigned from angular correlation results [19]; the statistics of our present data was unfortunately too poor to perform such an analysis.

[2] Belonging to an unresolved doublet of transitions observed in self-coincidence.

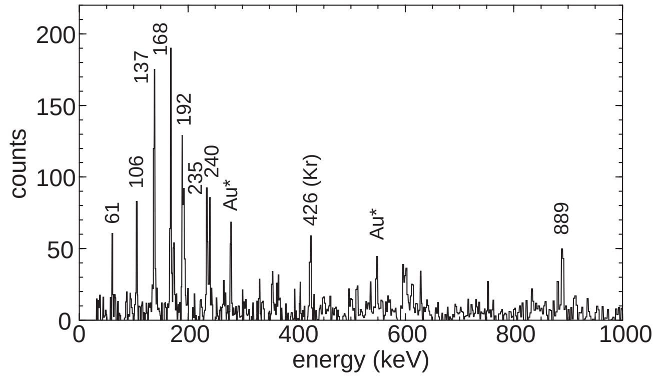

Fig. 2. Double-gated γ-ray spectrum with gates on one transition of ^{117}In (1235 keV) and one transition of ^{84}Kr (882 keV), its main complementary fragment in the fusion-fission reaction ^{31}P + ^{176}Yb.

spin value is $(11/2^+)$. The intruder band has been extended up to spin $(19/2^+)$ at 2947 keV excitation energy.

3.2 Study of ^{117}In

Prior to this work, only the $(13/2^+)$ state was known at 1235 keV [20]. It mainly decays by a 1235 keV transition to the $9/2^+$ ground state, the cascade of two transitions (169 keV + 1066 keV) being only 3% of the decay. The double-gated γ-ray spectrum with gates on these two transitions exhibits a new 889 keV transition. This transition is also observed in triple coincidence with the 1235 keV transition and the first transition of ^{84}Kr, which is the main complementary fragment of ^{117}In in the fusion-fission reaction ^{31}P + ^{176}Yb. Other new lines are also found in this double-gated spectrum (see fig. 2). They were used for further investigations of the coincidence data.

The level scheme deduced in the present work is presented in fig. 3. It displays the same features as the ^{115}In one, except the disappearance of the $(19/2^+)$ level and the stronger link of the $(21/2^+)$ state towards the $(19/2^-)$ level (240 keV γ-ray). A side band composed by at least three transitions (194, 272, and 311 keV) populates the structure 2, but its complex decay scheme could not be established.

3.3 Study of ^{119}In

The study of the β-decay of ^{119m}Cd had led to the identification of a $(9/2^+, 11/2^+, 13/2^+)$ level at 1204 keV excitation energy in ^{119}In, which had been interpreted as the $13/2^+$ state [21]. However, in the latest compilation [22], such a spin value has been ruled out because of the population of a state around 1.2 MeV excitation in the reaction ^{120}Sn(d, ^{3}He) with $L = 3$ [23].

Using the data of the fusion-fission reaction ^{18}O + ^{208}Pb, we have looked for the ^{119}In transitions using the spectrum gated by the two first transitions (119 and 136 keV) of its main complementary fragment, ^{101}Nb [24].

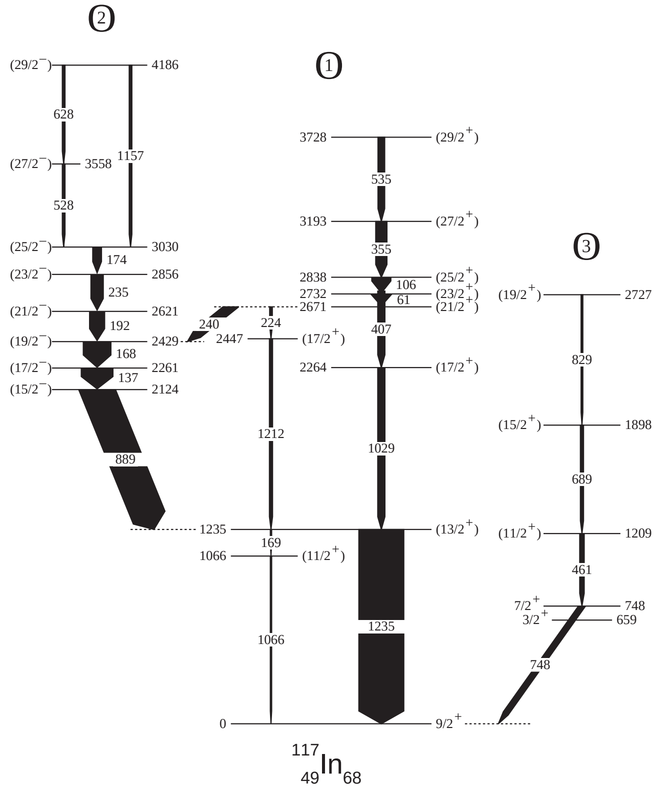

Fig. 3. Level scheme of ^{117}In deduced in the present work. The spin and parity values, given without parenthesis, have been established from β-decay measurements [20]. The $3/2^+$ level at 659 keV, which is the first state of the band built on the $1/2^+[431]$ intruder orbital, has not been populated in this experiment.

Besides the other γ-lines belonging to ^{101}Nb, this spectrum also exhibits a 1204 keV γ-transition which could be assigned to ^{119}In. Then two new γ-transitions (928 and 1020 keV) have been seen in the spectra in double coincidence with the 1204 keV transition and the 119 keV or 136 keV transition (^{101}Nb). These two new high-energy γ-transitions are also observed in triple coincidence with the 178 keV and 1025 keV transitions, which form another decay path of the 1204 keV excited state of ^{119}In (with low intensity, only 6% of the decay). From all these coincidence relationships, we propose that the 1204 keV excited level of ^{119}In is the expected $13/2^+$ state. It is worth pointing out that the population of the 1.2 MeV state in the (d, ^{3}He) reaction was very weak [23], and may not correspond to the 1204 keV state.

All the double-gated γ-ray spectra with gates on the 1204, 1020 and 928 keV transitions, using data from both the ^{18}O + ^{208}Pb and the ^{12}C + ^{238}U reactions, have been used to identify new other transitions. Then these new transitions have been used for further investigations of the coincidence data in order to establish the level scheme shown in fig. 4.

The levels are grouped into the same three structures as in ^{115,117}In. Here the $(21/2^+)$ state only decays to the $(19/2^-)$ level (218 keV γ-ray), which, in turn, decays to

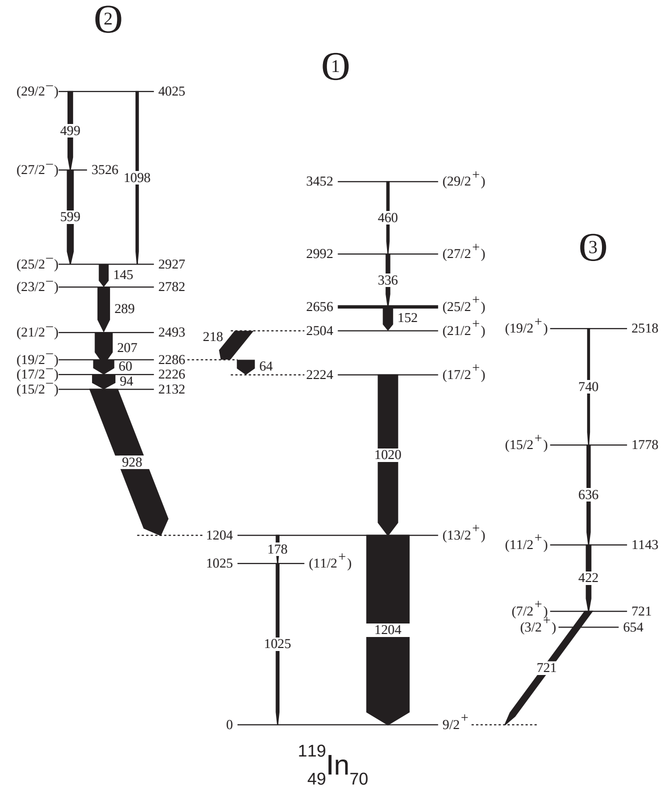

Fig. 4. Level scheme of ^{119}In deduced in the present work. The $(3/2^+)$ level at 654 keV, which is the first state of the band built on the $1/2^+[431]$ intruder orbital, has not been populated in this experiment. It has been established from β-decay measurements [20, 21]. The $(25/2^+)$ level at 2656 keV excitation energy is isomeric, $T_{1/2} = 240 \pm 25$ ns (see text).

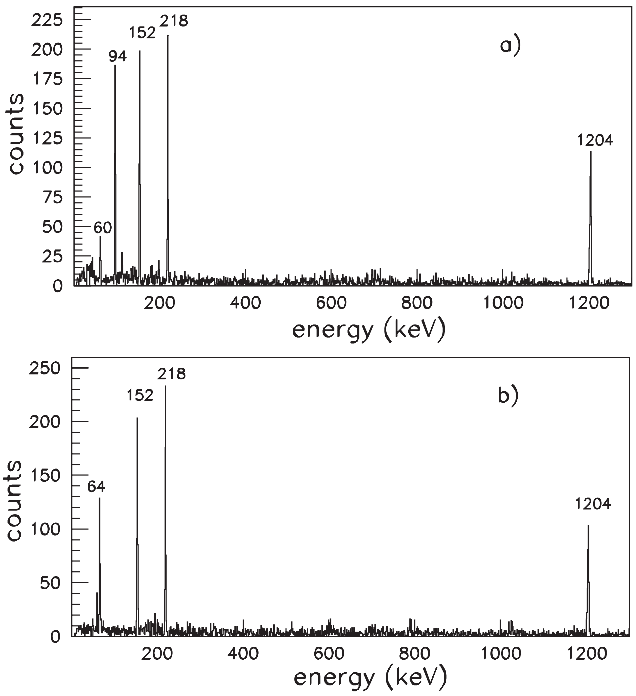

Fig. 5. Spectra of γ-rays which have been detected in the time interval 50 ns–1 μs after the detection of two fragments by SAPhIR. γ-rays in prompt coincidence with the 928 keV transition (a), with the 1020 keV transition (b).

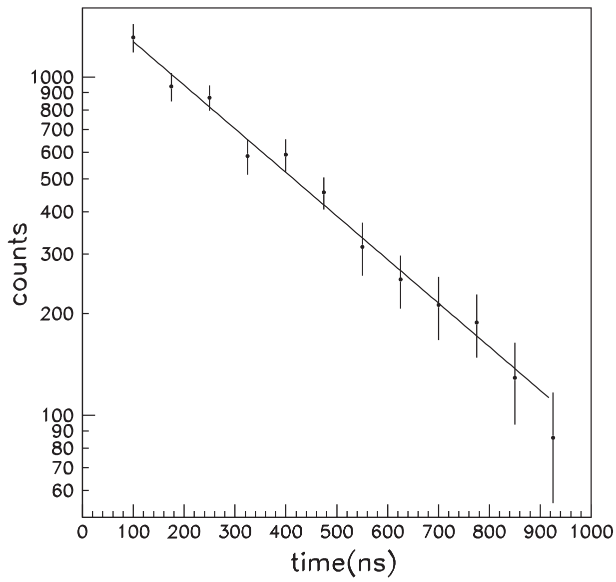

Fig. 6. Decay curve of the 152 keV transition of ^{119}In produced as a fission fragment from the ^{12}C + ^{238}U reaction. The straight line corresponds to a half-life of 240 ns.

the $(17/2^+)$ state (64 keV γ-ray). Such a path is a new feature in the In isotopes.

The analysis of delayed γ-rays in the experiment triggered by the SAPhIR fission-fragment detector has revealed the existence of an isomeric state in ^{119}In. Examples of the delayed spectra showing its two decay paths are given in fig. 5. From such spectra, we have deduced that the isomeric state is the 2656 keV state (decaying by the 152 keV transition) and that the 60 keV transition is $M1$, while the 64 keV transition is $E1$ (from the total intensity balance).

Its half-life was measured to be 240 ± 25 ns (fig. 6). Only an $E2$ multipolarity can account for such a value, with $B(E2) = 21 \pm 2\, e^2 fm^4$, a value close to those known in the neighbouring Sn nuclei. This will be discussed in the next section. This multipolarity leads to the $(25/2^+)$ assignment for the isomeric state. It is worth pointing out that the energies (336 and 460 keV) of the two transitions located above the $(25/2^+)$ state are very similar to the ones placed at the top of the structure 1 of the lighter isotopes.

A side band composed of at least four transitions (145, 313, 501 and 512 keV) populates the structure 2, but its complex decay scheme could not be established.

The intruder band (structure 3) built on the $1/2^+[431]$ orbital which was known up to spin $(11/2^+)$ [21] has been extended up to spin $(19/2^+)$ (see fig. 4).

3.4 Study of ^{121}In

The high-spin states of ^{121}In have been studied from the data of the two reactions, ^{12}C + ^{238}U and ^{18}O + ^{208}Pb. Starting from the first $13/2^+$ state known at 1181 keV [20], we have used the same method as described in the previous sections in order to identify the main transitions

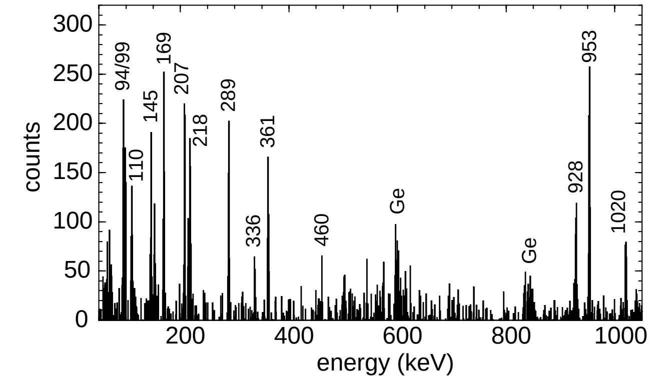

Fig. 7. Double-gated γ-ray spectrum with gates on one transition of ^{121}In (1181 keV) and one transition of ^{119}In (1204 keV), built from the data obtained in the fusion-fission reaction ^{12}C + ^{238}U. The 94, 145, 207, 218, 289, 336, 460, 928, and 1020 keV transitions have been assigned to ^{119}In (see fig. 4), whereas the other transitions (at 99, 110, 169, 207, 361, and 953 keV) can be assigned to ^{121}In.

populating the $13/2^+$ state. In the ^{12}C + ^{238}U reaction, the main complementary fragment of ^{121}In is ^{119}In. This is illustrated in fig. 7 showing the spectrum of γ-rays in coincidence with the $13/2^+ \to 9/2^+$ transitions of the two isotopes (1181 and 1204 keV), which exhibits, with similar yields, the transitions of ^{119}In (see the previous section) and new transitions which can be assigned to ^{121}In. Contrary to the lighter In isotopes, only one γ-ray with an energy around 1 MeV is observed in ^{121}In (see fig. 7). Moreover, the intensity of this new transition at 953 keV in ^{121}In is close to the sum of the intensities of the 928 keV and 1020 keV transitions which directly populate the $(13/2^+)$ level of ^{119}In.

The level scheme deduced from all the coincidence relationships is given in fig. 8. The structure 1 is much less developed than in the lighter In isotopes, as we could not identify a cascade of γ-rays to be located above the 99 keV transition. Using data from the SAPhIR experiment, four transitions have been found to have a delayed component (1181, 953, 214 and 99 keV), corresponding to the decay of an isomeric state with $T_{1/2} = 350 \pm 50$ ns. Only an $E2$ multipolarity for the 99 keV transition can account for such a value and the isomeric state has been assigned to be $(25/2^+)$, as in ^{119}In. Since the 454 keV has been observed in prompt coincidences with the 1181, 953, and 214 keV transitions, it has been placed directly above the $(21/2^+)$ state.

The bottom of structure 2 has changed as compared to the ones measured in the lighter isotopes. Starting from the hypothesis that the state decaying by the 110 keV transition is $(25/2^-)$ since the structure built on this state is similar to the one observed in all the lighter isotopes, we have concluded that two low-energy $M1$ transitions have escaped from our experimental detection. They are noted by X and Y in fig. 8. The energies of transitions from the $19/2^-$ and $17/2^-$ states strongly decrease from ^{113}In to ^{119}In and values much lower than 60 keV can be expected in ^{121}In.

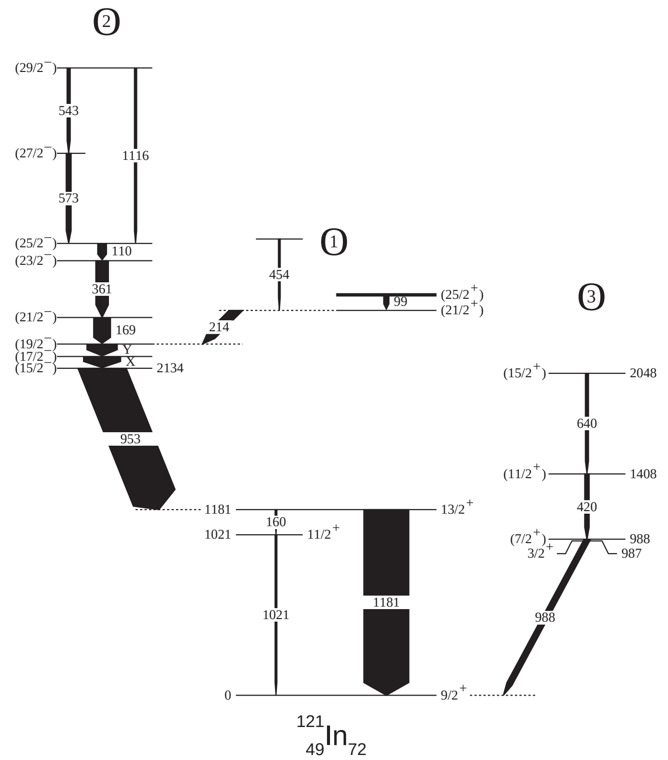

Fig. 8. Level scheme of ^{121}In deduced in the present work. Unobserved transitions located above the $(15/2^-)$ level at 2134 keV are noted by X and Y (see text). Because of these unobserved transitions, excitation energies of levels with spin values higher than 15/2 are not determined. The $(25/2^+)$ level is isomeric, $T_{1/2} = 350 \pm 50$ ns. The $(3/2^+)$ level at 987 keV, which is the first state of the band built on the $1/2^+[431]$ intruder orbital, has not been populated in this experiment. It has been established from β-decay measurements [20].

With the spin assignments reported in fig. 8, the link between the structures 1 and 2 occurs at the same spin values $(21/2^+ \to 19/2^-)$ in the three isotopes, ^{117,119,121}In, giving support to the existence of the two unobserved transitions.

3.5 Search for high-spin levels of ^{123}In

The relative yields of the odd-A In nuclei, obtained as secondary fragments from the three fusion reactions used in this work, have been calculated from the number of γ-rays populating their ground states. The results, shown in fig. 9, indicate that ^{123}In is undoubtedly populated as a fission fragment in the reactions induced by ^{18}O or ^{12}C.

We could expect to identify new transitions in ^{123}In using the γ-rays of ^{117}In which is its main complementary fragment in the ^{12}C reaction. The use of the ^{18}O data is not possible as the high-spin level scheme of ^{99}Nb (main complementary fragment of ^{123}In) remains unknown at the present time.

The double-gated γ-ray spectrum with gates on the 1235 keV and the 1165 keV transitions ($13/2^+ \to 9/2^+$ in

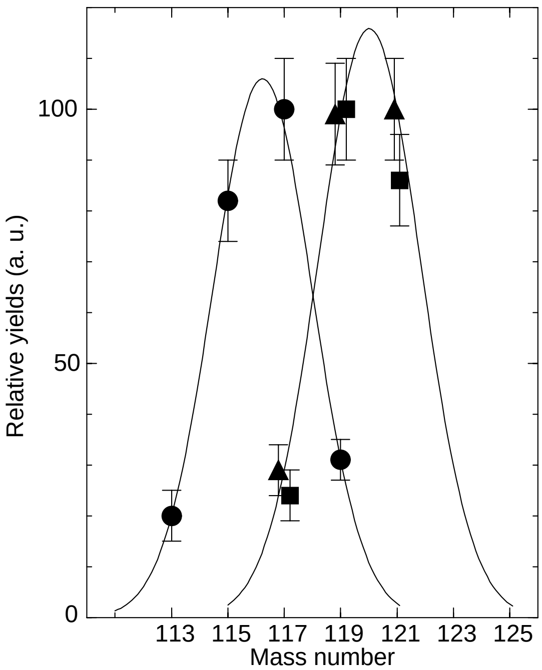

Fig. 9. Yields of the odd-A In nuclei, obtained as secondary fragments from the three fusion reactions: ^{31}P + ^{176}Yb at 152 MeV beam energy (circles), ^{18}O + ^{208}Pb at 85 MeV beam energy (squares, plotted slightly shifted to the right), and ^{12}C + ^{238}U at 90 MeV beam energy (triangles, plotted slightly shifted to the left). The maximum of each experimental distribution has been normalized to 100 (A = 117 for the ^{31}P-induced reaction, A = 119 for the ^{18}O- and ^{12}C-induced reactions). The results have been fitted using Gaussian functions.

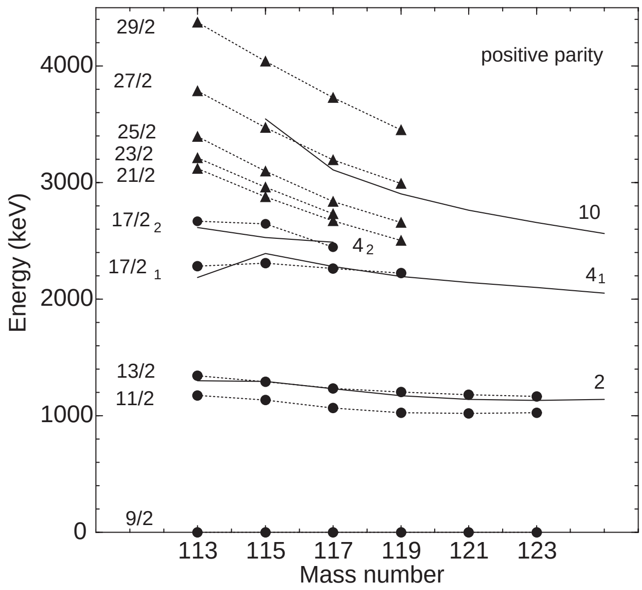

Fig. 10. Evolution of the positive-parity states in odd-mass ^{A}In isotopes (circles and triangles linked by dotted lines), and of the 2^+, 4_1^+, 4_2^+ and 10^+ states of the corresponding $^{A+1}$Sn cores (solid lines). Because of the two unobserved transitions located in the bottom of structure 2, the $21/2^+$ and $25/2^+$ states of ^{121}In could not be displayed.

^{117}In and ^{123}In, respectively) has revealed no transition, not even those of ^{117}In. This means that the correlation between the two complementary fragments has been lost. So we propose the existence of a long-lived isomeric state in ^{123}In around 2–3 MeV excitation energy, its half-life being greater than 2 or 3 μs, taking into account the timing conditions of this experiment. It is worth pointing out that long-lived isomeric states have been recently found in ^{125}In [25] and ^{129}In [26], around 2 MeV excitation energy.

4 Discussion

Most of the features of the low-spin states of $_{49}$In isotopes had been successfully described by coupling either a proton hole to a $_{50}$Sn core or a proton particle to a $_{48}$Cd core [1–4]. In the following sections, we will discuss to what extent such interpretations, which imply shape coexistence, remain valid for spin values as high as 29/2.

4.1 Structure 1

The systematics of the energies of the yrast positive-parity states (structure 1) observed in the odd-A $^{113\text{-}123}$In isotopes is drawn in fig. 10 showing also the evolution of the 2_1^+, 4_1^+, 4_2^+, and 10_1^+ of the corresponding Sn core. The similarity demonstrates that the structure 1 of $_{49}$In isotopes can be well described in terms of a $\pi g_{9/2}$ hole coupled to a $_{50}$Sn core. As the states with spin values $\geq 21/2$ show the same behaviour as that of the 10_1^+ state of Sn isotopes corresponding to a $\nu h_{11/2}$ pair breaking, the configuration $\pi g_{9/2}^{-1}\ \nu h_{11/2}^2$ can be proposed for these states. As the proposed configuration contains both particles (two neutrons) and a hole (one proton), the spin of the lowest member of the multiplet corresponds to the perpendicular coupling[3] of the proton angular momentum and of the two-neutron angular momentum, that is $\sim 21/2^+$.

In this experiment we have observed all the states of this multiplet with $I \geq 21/2^+$ in $^{113\text{-}119}$In isotopes. It is worth pointing out that the configuration of states with $I > 21/2$ is pure, whereas lower-spin states ($I \leq 21/2$) can be admixtures of other multiplets, where two neutrons are located in the $N = 4$ sub-shells (for instance, the configuration $\nu d_{5/2}\ \nu g_{7/2}$ gives a 6^+ state which has been observed in the even-even Sn isotopes).

One can notice that the reduced transition probability of the delayed 152 keV transition observed in the ^{119}In isotope, $B(E2) = 21 \pm 2\ \mathrm{e}^2\mathrm{fm}^4$, is not too far from the value of the isomeric transition $10^+ \rightarrow 8^+$ in its core, ^{120}Sn, $B(E2) = 8.7 \pm 0.2\ \mathrm{e}^2\mathrm{fm}^4$ [28], giving another support to the proposed $\pi g_{9/2}^{-1}\ \nu h_{11/2}^2$ configuration.

A detailed discussion of the evolution of this structure as a function of In mass number, from $A = 113$ to $A = 129$, will be given in a forthcoming publication [29].

[3] Typical examples of such a coupling can be found in ref. [27].

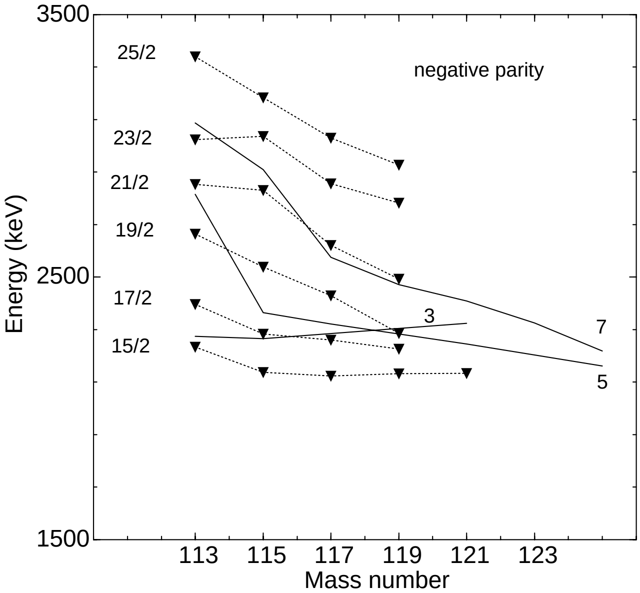

Fig. 11. Evolution of the negative-parity states in odd-mass ^{A}In isotopes (triangles linked by dotted lines), and of the 3^-, 5^-, 7^- states of the corresponding $^{A+1}$Sn cores (solid lines). Because of the two unobserved transitions located in the bottom of structure 2, the states of ^{121}In could not be displayed.

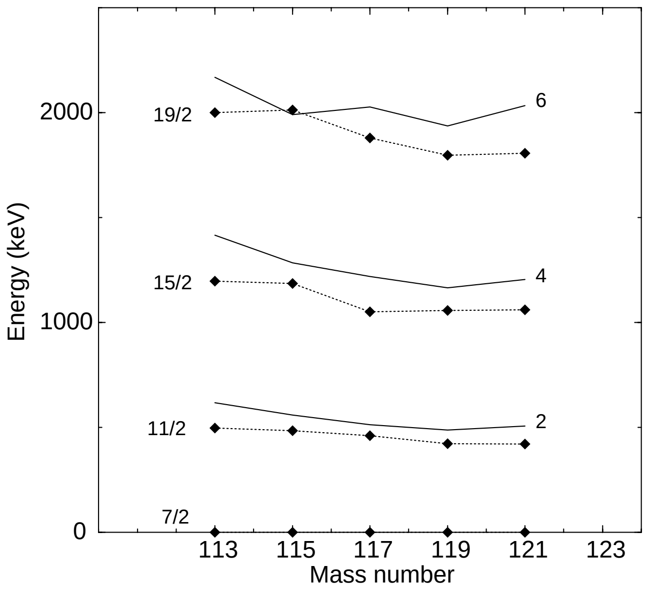

Fig. 12. Evolution of the positive-parity states of structure 3 in odd-mass ^{A}In isotopes (diamonds and dotted lines), and of the first yrast states of the corresponding $^{A-1}$Cd cores [20] (solid lines).

4.2 Structure 2

The systematics of the energies of the yrast negative-parity states (structure 2) observed in the odd-A $^{113\text{-}121}$In isotopes is drawn in fig. 11 showing also the evolution of the 3_1^-, 5_1^-, and 7_1^- states of the corresponding Sn core.

The configuration of the first negative-parity states of Sn isotopes (involving one state from the negative-parity intruder sub-shell $\nu h_{11/2}$ and another from one of the positive-parity sub-shells of the $N = 4$ shell) changes when the number of neutron increases, as the neutron Fermi level is going up into the $N = 4$ shell. This explains the crossings of the 3_1^- and 5_1^- states between ^{118}Sn and ^{120}Sn and of the 5_1^- and 7_1^- states between ^{126}Sn and ^{128}Sn (not shown in fig. 11), the negative-parity states of the heaviest Sn isotopes coming from the configuration $\nu h_{11/2}\ \nu d_{3/2}$.

The yrast negative-parity states of $^{113\text{-}121}$In isotopes behave similarly (see fig. 11). Therefore, the structure 2 of $^{113\text{-}121}$In can be interpreted as a break of a neutron pair involving the first positive-parity sub-shells of the $N = 4$ shell. This leads to the 3qp configuration, $\pi g_{9/2}^{-1}\ \nu h_{11/2}^{1}\ \nu[d_{5/2}/g_{7/2}]^{1}$.

4.3 Structure 3

The intruder orbital $\pi 1/2^+[431]$ coming from the spherical $\pi[g_{7/2}/d_{5/2}]$ sub-shells located just above the $Z = 50$ shell gap appears around and below 1 MeV excitation energy in the odd-A $^{113\text{-}121}$In isotopes. The intruder states occur at the lowest energy at mid-shell, where the Cd core should have the greatest softness against quadrupole deformation.

Several states of the band built on this intruder orbital have been already identified in ^{115,117,119}In from β-decay of ^{115,117,119}Cd$^{\rm m}$, from spin 1/2 up to spin (9/2,11/2) [20]. A good description of these states has been achieved only by taking into account all the Nilsson orbitals originating from the $N = 4$ shell [1]. From the wave functions obtained in this calculation, the predicted high-spin part of the band can be considered as formed by two decoupled bands on both the $\pi d_{5/2}$ and $\pi g_{7/2}$ orbitals (these two bands have respectively a positive and a negative signature).

We have observed, for the first time, the negative-signature states up to spin $(19/2^+)$ in the $^{115\text{-}121}$In isotopes, allowing us to check this prediction. Indeed the excitation energies of the $(11/2^+)$, $(15/2^+)$, $(19/2^+)$ states above the $7/2^+$ states in $^{113\text{-}121}$In are very similar to the first yrast states of the corresponding $^{112\text{-}120}$Cd cores, as shown in fig. 12.

Finally two shapes coexist in $^{113\text{-}121}$In up to spin $19/2^+$ at least, states of structure 1 and 2 being associated to a spherical shape and those of structure 3 to a slightly deformed shape.

5 Conclusion

Thanks to the high efficiency of the EUROBALL III and IV arrays, new band structures have been identified in the ^{115,117,119,121}In nuclei. These isotopes have been produced as fission fragments in three reactions induced by heavy ions: ^{12}C + ^{238}U at 90 MeV bombarding energy, ^{18}O + ^{208}Pb reaction at 85 MeV, and ^{31}P + ^{176}Yb at 152 MeV. The use of the fission fragment detector, SAPhIR, has allowed us to identify new isomeric states lying around 2.5 MeV in ^{119,121}In. Most of the excited states observed in these In nuclei can be interpreted in terms of a proton $g_{9/2}$ hole coupled to Sn core excitations. In addition, the intruder bands based on an orbital from the $\pi[g_{7/2}/d_{5/2}]$ sub-shells, which have been extended up to spin (19/2), behave like the ground-state bands of neighbouring Cd isotopes, showing that the shape coexistence phenomenon well known at low spin in In isotopes survives up to spin 19/2 at least.

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