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Letter

High-spin yrast and yrare structures in ^{112}In

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Abstract. The high-spin states of ^{112}In have been investigated with in-beam γ-ray spectroscopic methods using the $^{110}\mathrm{Pd}(^{7}\mathrm{Li},5\mathrm{n})^{112}\mathrm{In}$ reaction at a beam energy of 50 MeV. A level scheme with 3 band structures has been established. The backbending associated with the alignment of a pair of $g_{7/2}/d_{5/2}$ neutrons has been found in the negative-parity yrast band. The configuration for the positive-parity yrare band has been assigned to $\pi g_{9/2}\otimes\nu g_{7/2}$ for the lower-spin states, and $\pi g_{9/2}\otimes\nu h^{2}_{11/2}(g_{7/2})$ for the higher-spin levels.

The proton-rich In isotopes lie between $A\sim 90$ spherical nuclei with $Z\sim 40$, $N\sim 50$ and spherical Sn nuclei with a $Z=50$ shell closure. Their level structures are expected to exhibit moderate collectivity and to be associated with a triaxial shape [1], especially in isotopes with neutron numbers close to the middle shell $N=64$. The study of the level structure of the odd-odd In nuclei in this region can provide richful information on the nuclear shape, on the single-particle driving effects by the high-j high-Ω $g_{9/2}$ and intruder $h_{11/2}$ orbitals. ^{112}In could be an interesting case under this situation. Although some low-spin levels of ^{112}In have been studied by the reactions $^{110}\mathrm{Pd}(^{6}\mathrm{Li},4\mathrm{n})$ [2], the $^{112}\mathrm{Cd}(\mathrm{p},\mathrm{n}\gamma)$ [3] and the $^{109}\mathrm{Ag}(\alpha,\mathrm{n}\gamma)$ [3], the information of its level structure is still very limited up to now and no clear band structures were observed in their investigations. In this paper, we briefly report on the experimental investigation of high-spin states in ^{112}In, and discussion for the configurations of the newly found yrast and yrare bands.

High-spin states in ^{112}In were populated through the $^{110}\mathrm{Pd}(^{7}\mathrm{Li},5\mathrm{n})$ reaction. The target consisted of a $2.4\,\mathrm{mg/cm^2}$ foil of ^{110}Pd (isotopically enriched to 97.2%) on a $0.4\,\mathrm{mg/cm^2}$ natural gold backing. The ^{7}Li beam was delivered by the HI-13 tandem accelerator of the China Institute of Atomic Energy (CIAE). To determine the optimum beam energy for producing ^{112}In, γ-ray excitation functions were measured at beam energies of 40, 42, 46, 48, and 50 MeV; the beam energy of 50 MeV was then chosen for the γ-γ coincidence measurement. An array consisting of 12 Compton-suppressed HPGe detectors and two planar HPGe detectors was used to collect γ-γ coincidence data. The Ge detectors in the array were placed at 90°, ±37°, ±30° and ±60° relative to the beam direction, respectively. Each detector had an energy resolution of about 2 keV for 1332.5 keV γ-rays. Energy and efficiency calibrations of the detectors were performed using standard sources ^{60}Co and ^{152}Eu. In order to eliminate the contaminations from the K-X-rays of lead in the γ-spectra, a lower threshold of 90 keV was set for these detectors. Events have been collected, in event-by-event mode, when at least two Compton-suppressed Ge detectors fired in coincidence. A total of 200×10^{6} γ-γ coincidence events was recorded. The data were sorted into a fully symmetrized E_γ-E_γ coincidence matrix, as well as into an asymmetric DCO (Directional Correlation ratios of Oriented states) matrix. The DCO matrix was created by sorting the detectors at ±37° on one axis and the detectors at $\sim 90°$ on the other. These matrices were analyzed with the Radware Programs [4].

The excited states of ^{112}In have been studied previously both by M. Eibert *et al.* [2] and T. Kibédi *et al.* [3].

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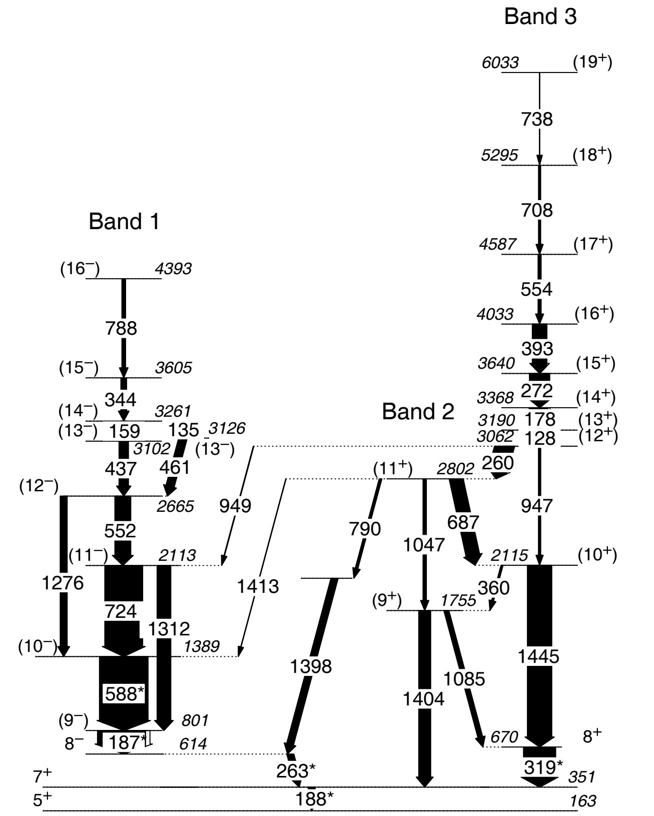

Fig. 1. Level scheme of ^{112}In obtained from the present experiment. It is built on the 5^+ state at 163 keV. The γ energies are in keV. The width of the arrows is relative to the intensity of transitions. Transitions from the previous work are indicated by asterisks.

In their work, the low-spin transitions were identified and spins were pushed up, respectively, to $10^-\hbar$ and $8^+\hbar$ for the negative and positive portion, thereof the low-lying transitions with the energies 188, 263, 187, 588 and 319 keV are confirmed in the present study. In the present work, the new transitions are placed with the coincidence with the known transitions. Based on the γ-γ coincidence relations, together with the intensity balance of transitions, energy matching and the DCO ratio analysis [5], the level scheme of ^{112}In is finally obtained, as presented in fig. 1. In our array geometry, if one gates on a stretched quadrupole transition, the expected DCO ratios are close to 1.0 for stretched quadrupole transitions and around 0.6 for pure dipole transitions. Figure 2 shows the plot of DCO ratios for the partial transitions, included in the level scheme of ^{112}In, against γ transition energies. As the low statistics of DCO data for some weak γ-rays, the DCO values could not be determined. From the DCO ratios, the previous works [2,3] and systematic comparison with its neighbouring odd-odd nuclei, we tentatively assigned the spins and parities of the levels in ^{112}In, as shown in fig. 1. The current study extends the ^{112}In level scheme considerably, both by the addition of new bands (labeled 2 and 3 in fig. 1) and the extension of the known sequence to higher spin. As an example, fig. 3 shows the

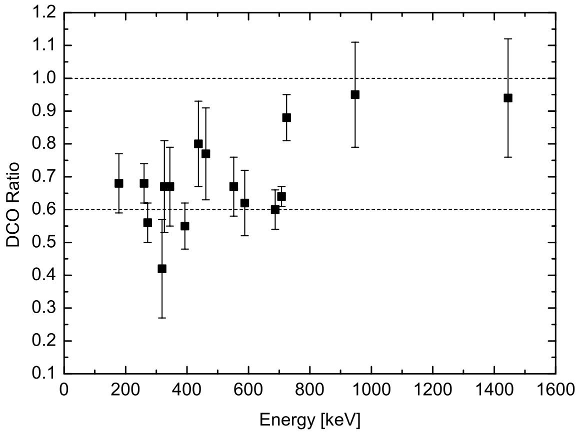

Fig. 2. DCO ratio *versus* γ-ray energies for several transitions in ^{112}In.

representative coincidence γ-ray spectra by gating on the 552 keV (a), 1312 keV (b), 260 keV (c) and 128 keV (d) γ transitions, respectively, where the stronger coincidence peaks in bands 1, 2 and 3 can be seen. In the following, we will concentrate the discussion on the structures of bands 1, 2 and 3.

The yrast states in band 1 of the odd-odd ^{112}In are built on the 8^- state located at 614 keV above the 1^+ ground state [3]. Its configuration has been assigned to $\pi g_{9/2} \otimes \nu h_{11/2}$ in previous work. The proton Fermi level is located among the high-K orbital of the $\pi g_{9/2}$ subshell, while the neutron Fermi level lies at the bottom of the $\nu h_{11/2}$ subshell. Therefore, the perpendicular coupling of the angular momenta of the deformation-aligned proton and rotation-aligned neutron leads to a large magnetic moment, then the peculiar behavior of this band is characteristic of a dipole band. In the previous work, band 1 was only observed to $10\hbar$, it is extended to $16\hbar$ and a backbend is found in the present experiment. The observed spins I in band 1 are presented in fig. 4 as functions of the rotational frequency ω, which for dipole bands is defined as $\hbar\omega(I) = [E(I+1) - E(I-1)]/2$. For comparison, $I(\omega)$ for the similar band in its adjacent isotope ^{110}In [6] is also plotted in fig. 4. It is clear from fig. 4 that both bands show a very similar behavior including the frequencies of the alignments and the corresponding gains in spin. It is suggested that this large backbend in ^{110}In is attributed to the alignment of the first pair of positive-parity $g_{7/2}/d_{5/2}$ neutrons [6]. Band 1 in ^{112}In has, therefore, been assigned to $\pi g_{9/2} \otimes \nu[h_{11/2}(g_{7/2}/d_{5/2})^2]$ after the backbend based on the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration.

Band 2 is a new band deduced from the present experiment. The levels in the yrare positive-parity band 2 are connected by $E2$ transitions as well as by intermediate $M1$ transitions. The level energy difference $E(I) - E(I-1)$ for this set of levels obviously exhibits a signature (α) splitting by analyzing the γ transition energies. The energy difference for even I values is lower ($\alpha = 0$) compared to the odd I ($\alpha = 1$) values. Considering the Fermi surface for both protons and neutrons and the β deformation ~ 0.099 [7] of the low-spin state of ^{112}In, it is evident that

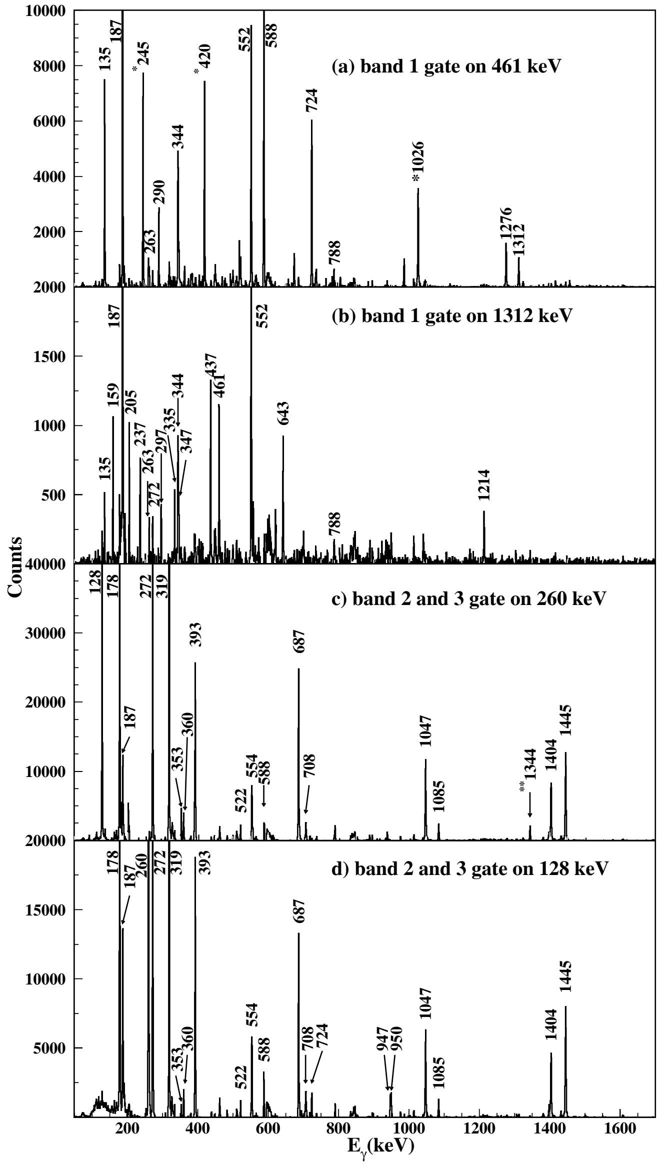

Fig. 3. Coincidence spectra obtained by (a) gating on the 724 keV, (b) gating on the 1312 keV, (c) gating on the 260 keV, (d) gating on the 128 keV in ^{112}In. The energies with single or double asterisks are infections from the reaction channels ^{7}Li + ^{197}Au → ^{200}Pb and ^{7}Li + ^{110}Pd → ^{113}In, respectively.

only the $g_{9/2}$ Nilsson orbital lies near the Fermi surface for proton, while near the neutron Fermi surface the Nilsson orbitals are generally mixed in this mass region including $g_{7/2}$, $d_{5/2}$ and $h_{11/2}$ orbitals. The neutron configuration of band 2 is probably coming from the $g_{7/2}$ or $d_{5/2}$ orbital in consideration of the positive parity. Furthermore, in an odd-odd nucleus the favored signature is defined as $\alpha_f = \frac{1}{2}[(-1)^{j_p-1/2} + (-1)^{j_n-1/2}]$ [8] and it is clear that for ^{112}In $j_p = 9/2$, thereby, the j_n only can be specified as 7/2 in order to satisfy the $\alpha = 0$ signature. Hence the configuration for band 2 is assigned as $\pi g_{9/2} \otimes \nu g_{7/2}$. The large level energy difference $E(I) - E(I-1)$ between the odd-spin sequence and the even-spin set indicates a large signature splitting in band 2. As discussed earlier, there is

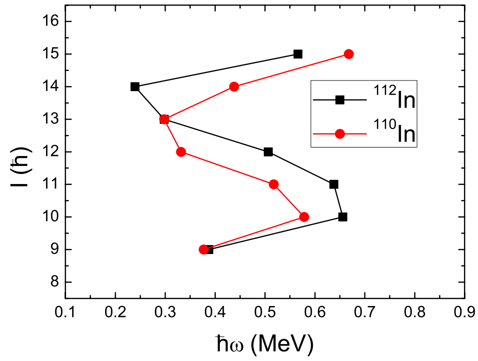

Fig. 4. Angular momentum as a function of rotational frequency for band 1 in ^{112}In and bands 1 and 2 in ^{110}In [6].

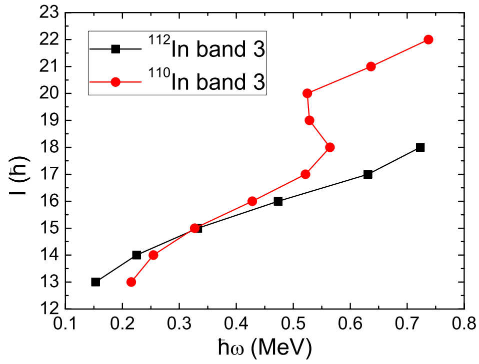

Fig. 5. Angular momentum as a function of rotational frequency for band 3 in ^{112}In and band 3 in ^{110}In [6].

a Nilsson orbitals mixing near the neutron Fermi surface, the signature splitting may be coming from the Coriolis mixing of the $\Omega = 1/2$ component (1/2[550]).

The crossover transitions 1445 and 947 keV built on the known 8^+ state [3] in band 2 favor a positive parity for the spin with the $12\hbar$ state. Furthermore, the measured transitions in band 3 are tentatively assigned as $M1$ multipolarity based on the DCO analysis, wherefore the newly observed band 3 is very possibly a positive-parity band. The observed strong $M1$ transitions (see the spectrum gated by the 260 and 128 keV transitions in fig. 2 (c) and (d)) and no $E2$ crossover transitions denote a large magnetic moment for this band. Considering the proton and neutron numbers in ^{112}In, the configuration of band 3 is probably partially coming from the valence protons occupying the upper sub-states of the $g_{9/2}$ orbital and on valence neutrons lying in the lower sub-states of the $h_{11/2}$ orbital. Moreover, apart from the rotational frequency higher than 0.6 MeV, the spin as a function of rotational frequency for band 3 plotted in fig. 5 is very similar to the band 3 in ^{110}In [6], which has been reported with the configuration of $\pi g_{9/2} \otimes \nu[h^2_{11/2}(g_{7/2}/d_{5/2})]$. Therefore, band 3 in ^{112}In may have a similar configuration to band 3 in ^{110}In. As band 3 decays only into band 2 and it is assigned as $\pi g_{9/2} \otimes \nu g_{7/2}$, the configuration for band 3 could be assigned to $\pi g_{9/2} \otimes \nu(h^2_{11/2} g_{7/2})$.

In this work a detailed level scheme for the ^{112}In nucleus has been built from a γ-ray spectroscopy study. Three band structures have been identified as belonging to ^{112}In. A backbend observed in the negative-parity band is attributed to the alignment of a pair of $g_{7/2}/d_{5/2}$ neutrons. The configuration for the newly constructed bands 2 and 3 have also been discussed and specified as $\pi g_{9/2} \otimes \nu g_{7/2}$ and $\pi g_{9/2} \otimes \nu(h^2_{11/2} g_{7/2})$, respectively.

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