LOW-LYING LEVELS IN ^{128}I EXCITED IN ^{124}SN(^{7}LI,3n) REACTION

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In-beam measurements of gamma-ray coincidences following the ^{124}Sn(^{7}Li,3n)^{128}I reaction were performed with a hybrid array of high purity germanium (HPGe) detectors, LaBr3:Ce scintillator detectors and one neutron scintillator detector. Based on the $\gamma\gamma$ concidence data and γ-n spectra, a low-spin level scheme has been built. Low-spin excited states in ^{128}I were populated for the first time in heavy-ion induced fusion-evaporation reaction.

Keywords: In-beam spectroscopy, nuclear structure

1. Introduction

Spectroscopic results on doubly odd ^{128}I structure originates from thermal neutron capture [1],[2] and deuterons or protons induced reactions studies. Properties of low-energy excited states have been studied. The most recent overview [3] of the experimental properties of low-lying levels in this nucleus shows that unique and certain spin-parity quantum numbers are set only for few levels. This work presents recent spectroscopic results on the low-spin excited states in ^{128}I populated for the first time in the heavy-ion induced ^{124}Sn(^{7}Li,3n)^{128}I fusion-evaporation reaction. The experiment was performed at the Bucharest Tandem Van de Graaff accelerator of IFIN-HH.

2. Experiment and results

Excited states in ^{128}I were populated in the heavy-ion induced ^{124}Sn(^{7}Li,3n)^{128}I reaction with a 27 MeV ^{7}Li pulsed beam (1 ns wide pulses, 200 ns apart) with intensity of about 5 nA. The cross sections of the 3n (^{128}I) channel was $\approx$ 600 mb [4]. The target was isotopically enriched ^{124}Sn, 3.4 mg/cm^2 thick deposited on 13 mg/cm^2 gold backing. The γ rays were detected with an array of eight, $\sim$ 50% relative efficiency, HPGe detectors and five $LaBr_3$:Ce scintillators. Two HPGe detectors were placed at 90°, one at 45° and the rest at 143° with respect to the beam axis. The data acquisition system was triggered either by two HPGe detectors, or by at least one HPGe detector and two $LaBr_3$:Ce detectors firing in coincidence. A 1 liter liquid scintillator detector was also used for neutrons detection. Raw data from all these detectors were recorded in "listmod" during approx. 5 days of data taking. In the offline processing different coincidence matrices were built [5]. Gamma rays were assigned to the level scheme of the ^{128}I isotope based mainly on the $\gamma\gamma$ coincidence data. The $\gamma\gamma\gamma$ matrix served only for guidelining. Fig. 1(a) shows the total projection of the

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$\gamma\gamma$ matrix built with the data acquired by the HPGe detectors. Sample γ-ray gated spectra obtained from the same matrix are displayed in Fig. 1(b-n).

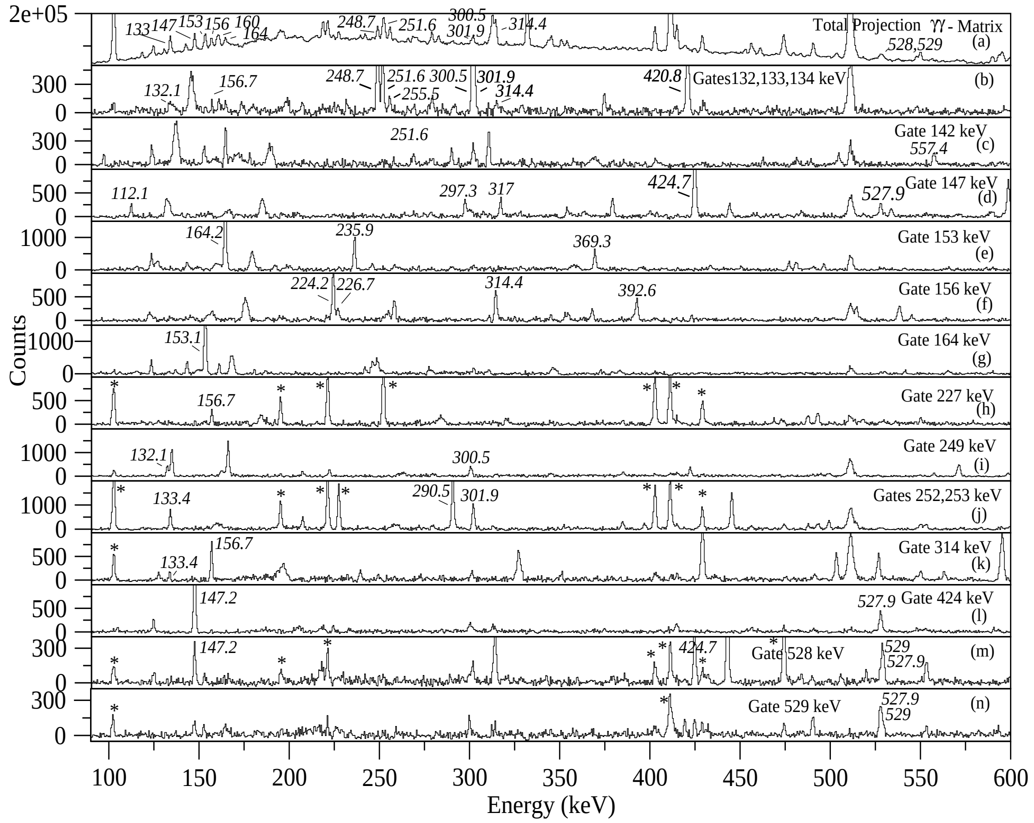

FIGURE 1. (a) Total projection of a $\gamma\gamma$ coincidence matrix; (b-n) Gated coincidence spectra showing the transitions assigned to ^{128}I. The γ rays are denoted by their energy. Peaks marked with "*" are identified as other transitions from ^{128}I when at the energy of the gating transition there are also another gammas in the high-spin region.

Most of the transitions that were assigned to ^{128}I and placed in the level scheme were highlited. In Fig. 2 sample γ-ray gated spectra obtained from a symmetric $\gamma\gamma$-coincidence matrix gated on neutrons shows that the γ rays are produced following a reaction that produces neutrons. Based on the present experiment a low-spin level scheme has been built (Fig. 3). This scheme confirm 31 levels known from previous works and add a new one at

1184.8 keV. A list of the level energies and their uncertainties is given in Table 1. Our level scheme is in good agreement with that of the (n,γ) work [2]. The level scheme is based only on coincidence results:

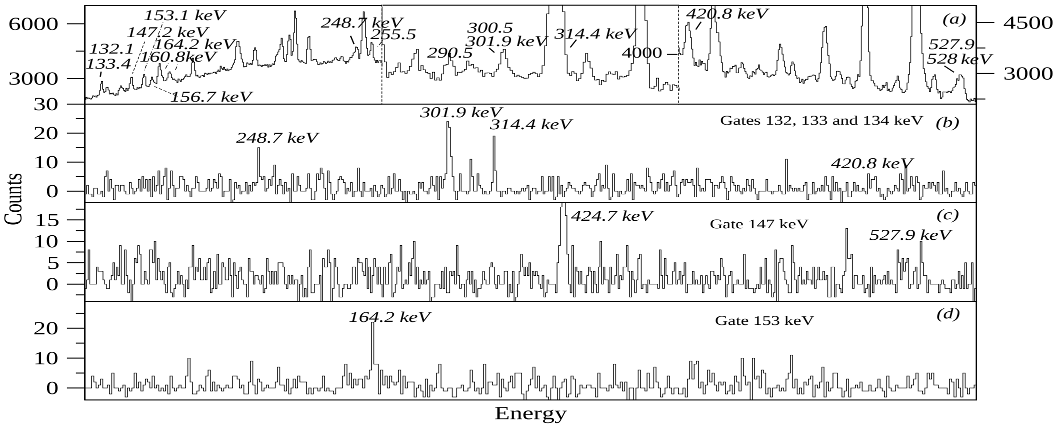

FIGURE 2. (a) Total projection of a nγ coincidence matrix; (b-d) γ-ray gated spectra obtained from a symmetric $\gamma\gamma$-coincidence matrix gated on neutrons showing transitions assigned to ^{128}I.

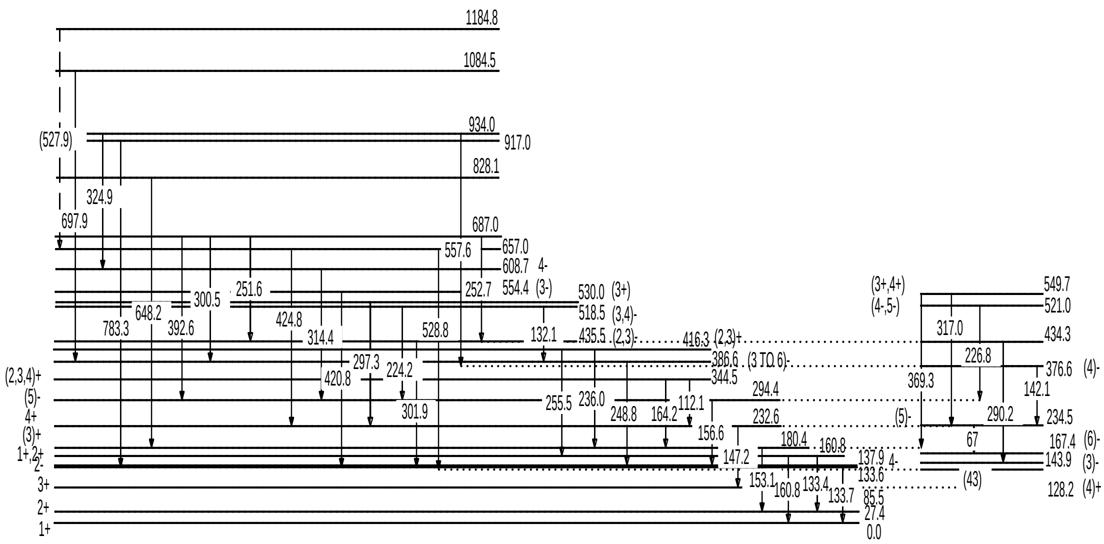

FIGURE 3. Low-spin region of the ^{128}I level scheme of as derived from the current study.

-*The 133.6 keV level* decays via the 133.6 keV transition to the ground state and is populated by the 301.9 and 420.8 keV transitions. The spectrum from Fig. 1(b) was obtained by gating on 133(+/-2) keV on one of the axis of the $\gamma\gamma$ coincidence matrix. The 132.1, 248.7, 300.6, and 314.4 keV are transitions to the 137.9 keV state [3] and are observed in

133(+/-2) keV gated spectrum. A highly converted approx. 4 keV transition, the energy difference between the 137.9 and 133.6 keV states, was already introduced in the level scheme on the basis of 248.7 and 133.6 keV coincidence [2]. The 251.6 keV transition seen in the spectrum comes from the upper cascade.

-*The 160.8 keV level* is depopulated by the 160.8 and 133.4 keV transitions and populated by the 255.5 keV transition as shown in Fig. 1(b).

-*The 180.4 keV level* feeds the 27.4 keV level via the 153.1 keV transition and is fed by the 164.2, 236.0, and 369.3 keV transitions (Fig. 3), in agreement with results shown in Fig. 1(e).

-*The 232.6 keV level* is populated mainly by the 424.8, 297.3 and 317.2 keV transitions shown in Fig. 1(d) in coincidence with the 147.2 keV transition. The neutron multiplicity of the 147.2 keV transition makes it (within error range) the best candidate for the $3n$ reaction channel as shown in Fig. 4.

-*The 294.4 keV level* decays via 156.6 kev transition and in fed by the 224.2, 226.8, 314.4, and 392.6 keV transitions shown in gated spectrum from Fig. 1(f).

Based on results shown in the gated spectra from Fig. 1(g-n) other measured gammas have been placed in the scheme. One new level was added at 1184.8 keV excitation energy. It decays via 527.9 keV transition to the 657.0 keV level which further decays via two known 424.8 and 528 keV transitions. The 527.9 keV transition was introduced in the level scheme only based on the coincidence relations of the 424.8 and 527.9 keV transitions. Since the neutron multiplicity value found for the 424.8 keV is placed in between the $3n$ and $4n$ channels, and it has a large uncertainty, the possibility of 527.9 keV to come from another reaction channel is not excluded. However, when the level energy increases it is more likely that the state is populated directly from the reaction [7]. The number of counts increases in the 528 keV peak as it shown in Fig. 2(a). Approx. 3500 counts were recorded in the 528 keV doublet (without efficiency correction which produces an exponentialy decrease with energy). Another remark on the multipolarity of 527.9 keV transition can be made: the DCO (*Directional Correlations from Oriented states*) ratio value clearely corresponds to a quadrupole character (see Table 1). At this energy and increasing spin the degree of alignment for the 1184.8 keV state is higher than for the lower states.

The ENSDF adopted spin/parity ($I_i^\pi \to I_f^\pi$) of the excited states are also present in Table 1. For few transitions previously assigned multipolarity is compared with the assignment form the present work.

The angular correlations DCO are used to discriminate between transitions of different multipolarities [6]. Fusion-evaporation reactions produce a large number of gamma-ray transitions (see Fig. 1(a)). In this case, except for clear and intense transitions, aquiring single spectra prooves unuseful for determining the gamma-rays anizotropy. Thus, it is more common to measure coincidence data. Consequently, much cleaner, angle gated spectra are obtained and anizotropy can be easily determined. Usually detection angles are fixed by the experimental set-up. In our case the angles are 143^o and 90^0 and the DCO ratio values are obtained from the asymmetric $\gamma\gamma$ coincidence matrix with the HPGe detectors placed at 143^o on one axis and the HPGe detectors placed at 90^0 on the second axis. However, the coincidence condition introduces angular correlations into the data that alter the true anizotropy. As described in Ref. [6] these correlations can be used to discriminate between different multipolarities. The following definition, particular to our geometry, was used:

$$R_{DCO} = \frac{I(\gamma_1 \text{ at } 90^\circ; \gamma_2 \text{ at } 143^\circ)}{I(\gamma_1 \text{ at } 143^\circ; \gamma_2 \text{ at } 90^\circ)} \tag{1}$$

In this way, by gating on a stretched quadrupole (Q) transition, γ_1, the value of the DCO ratio is about 0.5 if γ_2 is a stretched dipole (D) transition, and 1.0 if it is a stretched quadrupole transition, and conversely, gating on a D transition γ_1, one gets DCO ratios of about 1.0 or 2.0 if γ_2 is a D or Q transition, respectively [6].

In Table 1 (last column) for few transitions previously assigned multipolarity is compared with the tentative assignment form the present work. Good agreement is observed. The fusion-evaporation reaction is a mechanism which will impart the largest possible angular momentum to the excited nucleus, populating mainly the high spin states in the nucleus of interest [7]. Previous DCO ratios were calculated assuming that nuclear states populated following this reaction are still aligned. This assumption it is not necessary true in the low-spin region and only the relatively good agreement between the adopted γ multipolarity and the one deduced from the present work proves that a degree of alignment is still present.

The γ-rays assigned to ^{128}I in the present study can be observed in the neutron gated spectra given in Fig. 2(a). Some remarks must be made here. Not all the states are populated directly, in the fusion-evaporation reaction (especially at these spin values), many states being populated by the γ-ray cascade which follows. This way, the additional condition of coincidence with a neutron causes a dramatic decreased of the peaks intensities in the $\gamma\gamma$ neutron gated spectra presented in Fig. 2(b-d). Moreover, the neutrons kinematics and the small detection angle covered by the neutron detector can be an disadvantage. Tentative neutron multiplicities were analyized for some of the low-spin transitions in order to find out if they belong to the 3n channel. The results are summarized in Fig. 4 where the γ-ray of interest are shown in squares.

3. **Conclusions and Perspective**

In this work the level scheme of the doubly odd ^{128}I was obtained experimentally in the ^{124}Sn(^{7}Li,3n)^{128}I reaction. 31 known nuclear states were confirmed and a new one was tentatively placed in the scheme. For the first time these states have been excited in a heavy-ion induced fusion-evaporation reaction. $\gamma\gamma$, $\gamma\gamma\gamma$, γ-n coincidences were measured in a classical γ spectorscopy experiment. DCO ratios showed that a degree of alignment of the nuclear states exist even at these spin values. Neutron multiplicities associated to gamma-ray from ^{128}I were also measured. Neutron multiplicity for high-spin transitions in ^{128}I were also analyzed and will be presented in a future work concerning the high-spin level scheme of ^{128}I. Also, results on neutron multiplicity for known high-spin transitions in ^{127}I [8], coming from the most intense reaction channel (4n), are shown only as a reference.

TABLE 1. Gamma-ray transitions in ^{128}I, as found in the present work, associated to the level scheme shown in Fig. 3. The γ-ray assignment (initial level energy, spin and parity of the initial and final level) are given in columns 1, 3 and 7. The fifth column shows gamma rays used as gating transitions that determine the DCO ratio values given in the seventh column. The last column shows the adopted/assigned (from the present work) multipolarity of the transition. ([a] *adopted values are from Ref.* [3]*)*

E_{level} (keV) this work	E_{level} (keV) adopted[a]	I_i^π adopted	E_γ (keV)	I_f^π adopted	DCO gate	R_{DCO}	γ multipol. adopted/ this work
133.74(4)	133.6	2^-	133.73(2)	1^+			
160.72(11)	160.8	$1,2^+$	160.81(5)	1^+			
		$1,2^+$	133.44(7)	2^+			
180.21(14)	180.4	$(3)^+$	153.12(2)	2^+			
232.36(16)	232.6	4^+	147.23(3)	3^+			
294.64(11)	294.4	$(5)^-$	156.77(4)	4^-			
344.43(15)	344.5	$(2,3,4)^+$	164.2(3)	$(3)^+$	153/M1	1.02(8)	M1+E2/(D)
		$(2,3,4)^+$	112.05(5)	4^+			
376.31(30)	376.6	$(4)^-$	142.12(6)	$(5)^-$			
386.76(12)	386.6	$(3TO6)^-$	248.63(6)	4^-	133/E1	1.4(1)	M1,E2/(D)
416.19(14)	416.3	$(2,3)^+$	255.41(3)	$1,2^+$	161/M1	1.1(2)	M1,E2/(D)
		$(2,3)^+$	235.83(6)	$(3)^+$	153/M1	1.3(2)	-/(D)
434.57(10)	434.3		290.24(10)	$(3)^-$			
435.64(6)	435.5	$(2,3)^-$	301.79(2)	2^-	133/E1	1.4(1)	-/(D)
518.83(12)	518.5	$(3,4)^-$	224.16(3)	$(5)^-$	156/M1	1.2(1)	M1,E2/(D)
		$(3,4)^-$	132.11(3)	$(3TO6)^-$			
521.41(22)	521.0	$(4,5)^{(-)}$	227.01(9)	$(5)^-$	156/M1	0.7(1)	-/(D)
529.70(19)	530.0	$(3)^{(+)}$	297.3(1)	4^+	147/M1	1.2(2)	-/(D)
549.49(16)	549.7	$(3,4)^{(+)}$	369.26(7)	$(3)^+$	153/M1	1.5(3)	-/(Q)
		$(3,4)^{(+)}$	317.15(9)	4^+	147/M1	2.0(4)	/(Q)
554.53(5)	554.4	$(3)^{(-)}$	420.68(5)	2^-	133/E1	1.5(2)	
608.99(16)	608.7	4^-	314.13(12)	$(5)^-$	156/M1	1.2(3)	M1,E2/(D)
657.13(16)	657.0		529	$(4)^+$			
			424.7(3)	4^+	147/M1	1.3(1)	-/(D)
687.25(9)	687.0	$3,4^-$	392.55(12)	$(5)^-$	156/M1	1.6(3)	-/(Q)
		$3,4^-$	300.46(5)	$(3TO6)^-$			
		$3,4^-$	252.68(1)				
		$3,4^-$	251.5(1)	$(2,3)^-$	133/E1	1.4(2)	M1,E2/(D)
828.37(19)	828.1		647.45(5)	$(3)^+$	153/M1	1.5(5)	
917.00(15)	917.0		783.26(6)	2^-			
933.87(25)	934.0	$(3,4)^{(-)}$	557.54(15)	$(4)^-$	142/M1	2.2(9)	-/(Q)
		$(3,4)^{(-)}$	324.88(8)	4^-			
1084.65(54)	1084.5		697.89(22)	$(3TO6)^-$			
1184.99(23)			527.90(4)(new)		147/M1	2.5(6)	-/Q

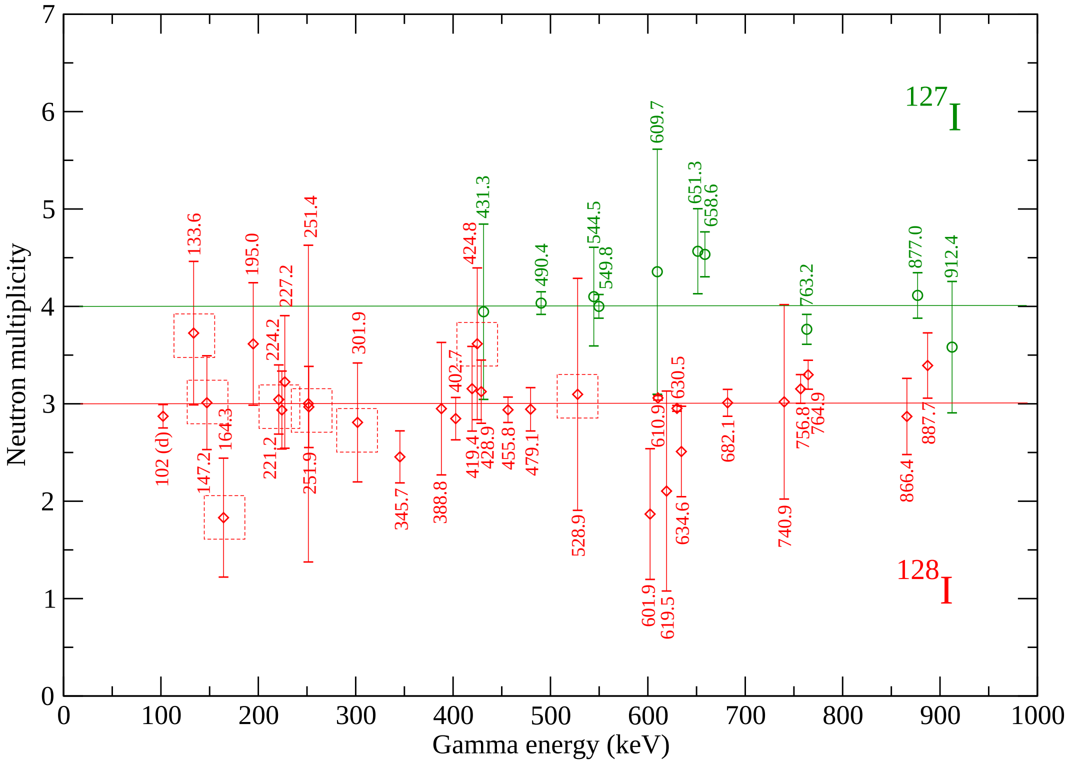

FIGURE 4. The neutron multiplicity as the number of neutrons produced by the fission-evaporation reaction channel, associated to gamma-rays from ^{127}I-(4*n* channel) and ^{128}I-(3*n* channel).

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