Medium-spin states in neutron-rich 83As and 81As

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The ^{83,81}As nuclei have been produced as fission fragments in the fusion reaction ^{18}O+^{208}Pb at 85 MeV bombarding energy and studied with the Euroball array. Medium-spin states of ^{83,81}As have been established up to $\sim$ 3.5 MeV excitation energy. From angular correlation analysis, spin values have been assigned to most of the ^{81}As excited states. The behaviors of the yrast structures identified in this work are discussed in comparison with the general features known in the mass region. Then they are compared to the results of two theoretical approaches, the 'rotor+quasi-particle' for ^{81}As and the shell model using the effective interactions JUN45 for ^{83,81}As.

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I. INTRODUCTION

The persistence of the magic numbers in the very exotic nuclei is the object of many experimental and theoretical studies (see e.g. Ref. [1]). Several magic shell gaps are so fragile as several neutron-rich nuclei (^{12}Be$_8$, ^{32}Mg$_{20}$, and ^{42}Si$_{28}$) were found to exhibit large collectivity [2–4]. As for $^{78}_{28}$Ni$_{50}$, the two magic numbers, 28 and 50, are created by spin-orbit interaction, such as 6, 14 or 82. While $^{20}_{6}$C$_{14}$ and $^{42}_{14}$Si$_{28}$ have proven to be deformed [4, 5], $^{132}_{50}$Sn$_{82}$ has the major characteristics of a doubly-magic spherical nucleus [6, 7]. Thus the actual behavior of ^{78}Ni deserves to be examined, particularly the size of the shell gaps at $Z = 28$ and $N = 50$ when approaching ^{78}Ni would be a first clue.

In order to better characterize the properties of the proton orbits located close to the $Z = 28$ gap, several studies using very different experimental approaches have been performed on some neutron-rich $_{29}$Cu and $_{31}$Ga isotopes. Spin values and magnetic moments of the ground states of ^{71,73,75}Cu establish the inversion between the $\pi f_{5/2}$ and $\pi p_{3/2}$ orbits at mid occupation of the $\nu g_{9/2}$ subshell [8], and a low-lying collective mode is observed in ^{71,73}Cu from their large $B(E2)$ values [9]. These sets of results are well accounted for by large scale shell model calculations, provided that the valence space contains the $\pi f_{7/2}$ orbital, i.e. proton excitations across the $Z = 28$ gap are allowed [10].

The spin value, magnetic moment and electric quadrupole moment of the $^{71-81}$Ga ground states are additional indicators of the evolution of the proton orbits with the occupation of the $\nu g_{9/2}$ subshell [11]. The ground states of the odd-A ^{71,75,77,79}Ga have the same spin value, $3/2^-$. On the other hand, the magnetic moment of ^{79}Ga is about two times lower than the one of ^{71,75,77}Ga, and the quadrupole moment of ^{71,79}Ga is positive while the one of ^{75,77}Ga is negative. All these results are explained if the three-proton configuration of these $3/2^-$ states evolves as a function of the number of neutrons occupying the $\nu g_{9/2}$ subshell, from $[\pi p_{3/2}]^3$ in ^{71}Ga$_{40}$, to $[\pi p_{3/2}]^1 \otimes [\pi f_{5/2}]^2$ in ^{75,77}Ga$_{44,46}$, and to $[\pi f_{5/2}]^3$ in ^{79}Ga$_{48}$. It is worth noting that the latter configuration, with I$^\pi = 5/2^-$, was suggested for the ground state of ^{81}Ga$_{50}$ [12] and confirmed by the last measurement [11]. Shell-model calculations in the f_5pg_9 valence space well reproduce the properties of the $^{71-77,81}$Ga ground states. On the other hand, they fail to explain the magnetic moment and electric quadrupole moment of ^{79}Ga$_{48}$, the effect of proton excitations across the $Z = 28$ gap, not taken into account in the valence space, would deserve to be investigated [11].

In the present work we report on the study of excited states in $^{81,83}_{33}$As$_{48,50}$ nuclei, produced as fission fragments in the fusion reaction ^{18}O+^{208}Pb at 85 MeV bombarding energy and studied with the Euroball array. The yrast states of both isotopes have been observed up to $\sim$ 3.5 MeV excitation energy and up to spin values around 21/2 for ^{81}As and 15/2 for ^{83}As. These results, strengthened by those previously obtained from the β-decay studies of ^{81,83}Ge [13, 14], allow us to discuss the behavior of the five valence protons at the end of the $\nu g_{9/2}$ filling.

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II. EXPERIMENTAL DETAILS

A. Reaction, γ-ray detection and analysis

We have used the ^{18}O + ^{208}Pb reaction at 85 MeV incident energy. The beam was provided by the Vivitron accelerator of IReS (Strasbourg). A 100 mg/cm^2 target of ^{208}Pb was used to stop the recoiling nuclei. The gamma-rays were detected with the Euroball array [15]. 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 [16] and each Clover detector consists of four smaller Ge crystals [17].

The data were recorded in an event-by-event mode with the requirement that a minimum of three unsuppressed Ge detectors fired in prompt coincidence. A set of 4×10^9 three- and higher-fold events was available for the subsequent analysis. The offline analysis consisted of both multi-gated spectra and three-dimensional 'cubes' built and analyzed with the Radware package [18].

More than one hundred nuclei are produced at high spin in such fusion-fission experiments, and this gives several thousands of γ transitions which have to be sorted out. Single-gated spectra are useless in most of the 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 [19, 20]. For the 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 [21]. The sum of the proton numbers of complementary fragments has been found to be always the atomic number of the compound nucleus, Z = 90. The total number of emitted neutrons (sum of the pre- and post-fission neutrons) is mainly 4, 5, and 6. This was taken into account for identifying the γ-ray cascades of the ^{81,83}As nuclei, as shown in forthcoming sections.

B. γ-γ angular correlations

In order to determine the spin values of excited states, the coincidence rates of two successive γ transitions are analyzed as a function of θ, the average relative angle between the two fired detectors. The Euroball spectrometer had C^2_{239} = 28441 combinations of 2 crystals, out of which only $\sim$ 2000 involved different values of relative angle within 2°. Therefore, in order to keep reasonable numbers of counts, all the angles have been gathered around three average relative angles : 22°, 46°, and 75°.

The coincidence rate is increasing between 0° and 90° for the dipole-quadrupole cascades, whereas it decreases for the quadrupole-quadrupole or dipole-dipole ones. More precisely, the angular correlation functions at the three angles of interest were calculated for several combinations of spin sequences, corresponding to typical multipole orders (see Table I). In order to check the method, angular correlations of transitions belonging to the yrast cascades of the fission fragments having well-known multipole orders were analyzed and the expected values were found in all cases.

TABLE I. Values of the angular correlation functions, R(θ), normalized to the ones calculated at 75°, computed for several combinations of spin sequences and multipole orders (Q = quadrupole, D = Dipole).

Spin sequence $2I_1 - 2I_2 - 2I_3$	Multipole orders	R(22°)	R(46°)	R(75°)
13 – 9 – 5	Q - Q	1.13	1.06	1.00
9 – 7 – 5	D - D	1.06	1.03	1.00
13 – 9 – 7	Q - D	0.92	0.96	1.00
9 – 5 – 3	Q - D+Q[a]	1.21	1.11	1.00
9 – 5 – 3	Q - D+Q[b]	0.78	0.89	1.00
7 – 5 – 3	D - D+Q[a]	0.87	0.93	1.00
7 – 5 – 3	D - D+Q[b]	1.18	1.09	1.00

[a] with a mixing ratio $\delta = +1$.
[b] with a mixing ratio $\delta = -1$.

III. EXPERIMENTAL RESULTS

A. Level scheme of ^{83}As

Many excited states of ^{83}As were identified from the study of the β-decay of ^{83}Ge (I$^\pi$=5/2$^+$), unfortunately without spin and parity assignments [13]. In the most recent issue of evaluated spectroscopic data for all nuclei with mass number A=83 [22], the ground state of ^{83}As is assumed to have I$^\pi$ = 5/2$^-$, 3/2$^-$, while the first excited state at 306.5 keV is assumed to have I$^\pi$ = 3/2$^-$, 5/2$^-$, since the two single-proton orbits located above the Z = 28 shell closure are $\pi f_{5/2}$ and $\pi p_{3/2}$. If the ground state has I$^\pi$ = 3/2$^-$, the first yrast states of ^{83}As, which should be populated in the fusion-fission reaction used in the present work, are similar to those of its neighboring isotone, ^{85}Br, already identified in our data set [23]. In that case, the main yrast cascade should comprise a 306.5 keV γ ray. Moreover we have to look for two transitions with energies between 1.2 and 1.5 MeV corresponding to the quadrupole excitation built on the I$^\pi$ = 3/2$^-$ and I$^\pi$ = 5/2$^-$ single-proton states, respectively. On the other hand, if the ground state has I$^\pi$ = 5/2$^-$, the first yrast states only involve the $\pi f_{5/2}$ orbit and we have to look for a single transition with an energy between 1.2

and 1.5 MeV, located above the ground state.

For the identification of the transitions de-exciting the yrast states of ^{83}As, we have firstly analyzed the γ-lines in coincidence with two transitions emitted by its main complementary fragment, ^{139}La [24]. We did not observe the 306.5-keV γ ray, but we have found a transition at 1543 keV. Such a transition was already identified in the β-decay of ^{83}Ge and having no coincident γ rays, it was placed directly above the ground state. We have, in a second time, analyzed spectra in double coincidence with one transition of ^{139}La and the 1543-keV transition. That gave us a new γ-line at 323 keV which does not belong to ^{139}La. Then several new transitions of ^{83}As were observed in the spectrum of γ-rays in double coincidence with the 1543- and the 323-keV transitions (see Fig. 1).

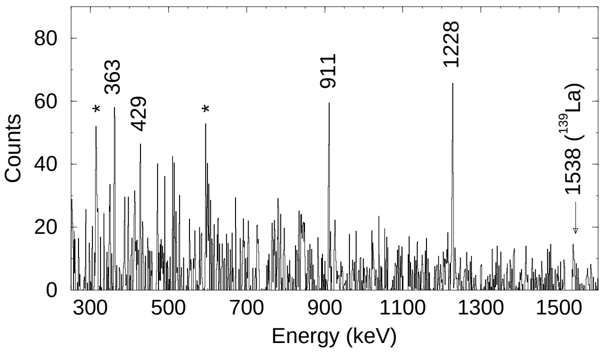

FIG. 1. Spectrum of γ-rays in double coincidence with the 1543- and the 323-keV transitions belonging to the yrast cascade of ^{83}As. The weak 1538-keV transition is emitted by its main complementary fragment, ^{139}La. The two lines marked with a star are identified contaminants.

Lastly all coincidence relationships between the new transitions of ^{83}As have been carefully analyzed in order to build the level scheme shown in Fig. 2. The properties of the transitions assigned to ^{83}As are given in Table II.

TABLE II. Properties of the transitions assigned to ^{83}As observed in this experiment.

E_γ(keV)[a]	I_γ[ab]	$J_i^\pi \rightarrow J_f^\pi$	E_i(keV)	E_f(keV)
322.8(2)	100(15)	$(11/2^-) \rightarrow (9/2^-)$	1866	1543
362.8(4)	20(7)	$(15/2^-) \rightarrow (13/2^-)$	3457	3094
429.1(3)	25(7)		3206	2777
911.1(3)	45(12)	$\rightarrow (11/2^-)$	2777	1866
1227.7(1)	55(14)	$(13/2^-) \rightarrow (11/2^-)$	3094	1866
1234(1)	<15		2777	1543
1543.3(7)	-	$(9/2^-) \rightarrow (5/2^-)$	1543	0

[a] The number in parenthesis is the error in the last digit.
[b] The relative intensities are normalized to $I_\gamma(323) = 100$.

It is worth pointing out that the 1543- and the 323-keV transitions have been observed in the ^{82}Se + ^{288}U deep-inelastic reaction at 505 MeV bombarding energy, the ^{83}As nuclei being selected into a magnetic spectrograph [25]. A level scheme of ^{83}As was proposed afterwards [26], with the 429- and the 911-keV transitions located above the two others, but in reverse order as compared to our result. In addition, the angular distribution of the 1543- and the 323-keV γ-lines were measured as respect to the angle of detection of ^{83}As nuclei, showing that the former has a quadrupole character and the latter a dipole one.

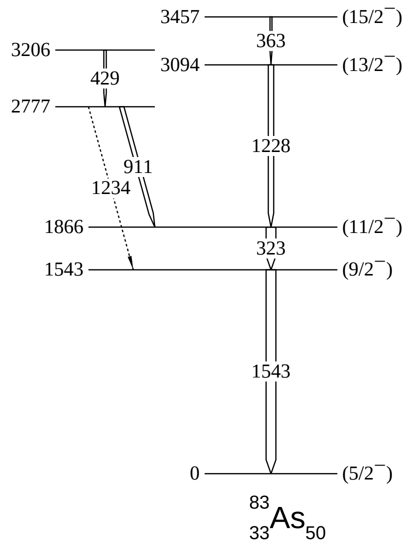

FIG. 2. Level scheme of ^{83}As obtained in this work.

The statistics of our ^{83}As data is too low to perform $\gamma - \gamma$ angular correlation analyses. Therefore the spin assignments of all the new states shown in Fig. 2 are based on the experimental results of Ref. [26] and on the close similarity with the states built on the $5/2_1^-$ level of ^{85}Br [23], the $5/2^-$ assignment for the ^{83}As ground state being discussed in Sect. IV A 1.

B. Level scheme of ^{81}As

Most of the previous information on the excited states of ^{81}As come from the β-decay studies of the two long-lived levels of ^{81}Ge [14], the ground state with I^π=9/2$^+$ and the isomeric state at 679 keV, with I^π=1/2$^+$. These two studies were very difficult because both long-lived levels possess similar half-lives. Thus the strong β-transitions cannot be easily allocated to a particular isomer, which hampers to precisely assign spin and parity values to the most populated states. The authors of Ref. [14] have used comparisons with the ^{83}Se $\rightarrow$ ^{83}Br decay. In particular, the 9/2$^+$ ground state of ^{83}Se does not populate levels in ^{83}Br below 1 MeV strongly. Thus in analogy, they assumed that all β-transitions to levels below 1 MeV belong to the low-spin isomer of ^{81}Ge and they tentatively chose low spin values for all the excited states of ^{81}As, lying below 1 MeV and directly populated by β-decay. In summary, the spin assignments of the first excited states of ^{81}As, available at the beginning of this work [24, 27], were not precise enough to know what low-lying transitions were to be used to search for new γ-rays belonging to the yrast cascades, in our data set.

Thus in order to identify the unknown transitions depopulating yrast states of ^{81}As, we have looked into spectra gated by the first transitions of its main complementary fragment, ^{141}La. Fortunately its level scheme has recently been built [28] using data set of another fusion-fission reaction, in which ^{141}La is mainly associated to ^{101}Nb. In the spectra doubly-gated by transitions of ^{141}La, we have found three transitions, at 336 keV, 738 keV, and 793 keV, which are known to be emitted by low-lying excited states of ^{81}As in the β-decay of ^{81}Ge [14]. Then these transitions have been used to build other double-gated spectra in order to analyze all the coincidence relationships. Two examples of such double-gated spectra are given in Fig. 3.

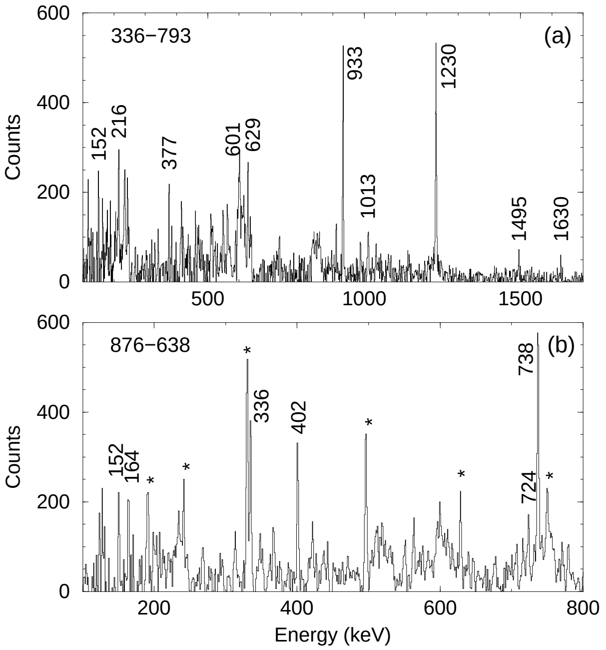

FIG. 3. Spectra of γ-rays in coincidence with two transitions of ^{81}As: (a) with the 336- and the 793-keV transitions, (b) with the 876- and the 638-keV transitions. The lines marked with a star are identified contaminants.

The obtained level scheme is shown in Fig. 4. All the transitions assigned to ^{81}As are given in Table III.

Noteworthy is the fact that the 2758-keV state, one of the most populated in the β-decay of ^{81}Ge [14], is also observed in the present work, where it is populated by a cascade of three low-energy γ-rays (216 keV, 152 keV, and 164 keV). A few γ-decay branches of the 2758-, 2624- and 2142-keV states, measured in the β-decay experiment [14], could not be identified in our spectra because of their too weak intensities.

Spin and parity values of $3/2^-$ are assigned to the ground state of ^{81}As [24, 27]. This state is strongly populated by proton transfer, as well as the 336 keV state. The angular distributions of the ejectiles associated to these two states are characterized by $l = 1$ and $l = 3$, respectively, both in the (t, α) and $(d,^3He)$ pick-up reactions [29, 30]. For $Z = 33$, a low-lying state strongly populated with a $l = 3$ proton transfer is expected to have $I^\pi = 5/2^-$ and not $7/2^-$, when taking into account the angular momenta of the proton orbits located above the $Z = 28$ gap. This choice is corroborated by a stronger argument coming from another study. Two states (at 3136 keV and 3195 keV), strongly populated by the β-decay of ^{81}Ge (allowed transitions, i.e. $\Delta I = 0$ or 1, $\Delta\pi = +$), de-excite towards the $3/2^-$ ground state [14]. This implies that they are fed from the β-decay of the $1/2^+$ isomeric state, limiting their spin value to $1/2^+$ and $3/2^+$. These two low-spin states also de-excite towards the 336-keV state, this excludes $I^\pi = 7/2^-$ and gives spin and parity assignments of $5/2^-$ for the latter.

In order to determine the spin values of the ^{81}As yrast states, we have analyzed several $\gamma - \gamma$ angular correlations. The experimental results obtained for the strongest transitions are given in Table IV. The three first series of angular correlation results would indicate that the four transitions, at 336 keV, 793 keV, 933 keV and 1230 keV, do have the same mutipole order. Moreover the presence of the 402- and 391-keV transitions in parallel to the 793-keV one would imply that the charac-

TABLE III. Properties of the transitions assigned to ^{81}As observed in this experiment.

E_γ(keV)[a]	I_γ[a b]	$J_i^\pi \rightarrow J_f^\pi$	E_i(keV)	E_f(keV)
134.0(5)	<4	$(11/2)^+ \rightarrow (9/2)^+$	2758	2624
151.6(3)	11(4)	$(15/2^+) \rightarrow (13/2^+)$	3126	2975
164.5(3)	8(3)	$(17/2^+) \rightarrow (15/2^+)$	3291	3126
216.5(3)	18(4)	$(13/2^+) \rightarrow (11/2)^+$	2975	2758
335.6(2)	53(6)	$5/2^- \rightarrow 3/2^-$	336	0
377.1(4)	6(2)	$(21/2^-) \rightarrow 17/2^-$	3669	3292
391.3(4)	3.0(15)	$9/2^- \rightarrow 7/2^-$	1129	738
401.6(3)	16(4)	$7/2^- \rightarrow 5/2^-$	738	336
482.4(4)	4(2)	$9/2^{(+)} \rightarrow$	2624	2142
602.0(4)	5(2)	$(11/2^-) \rightarrow 9/2^-$	1730	1129
628.6(4)	5(2)	$13/2^- \rightarrow (11/2^-)$	2359	1730
637.6(2)	44(5)	$13/2^{(+)} \rightarrow 9/2^{(+)}$	2251	1613
723.8(4)	10(4)	$(13/2^+) \rightarrow 13/2^{(+)}$	2975	2251
737.6(2)	47(5)	$7/2^- \rightarrow 3/2^-$	738	0
792.9(2)	37(6)	$9/2^- \rightarrow 5/2^-$	1129	336
859.2(5)	5(2)	$7/2 \rightarrow 5/2^-$	1195	336
875.8(2)	63(6)	$9/2^{(+)} \rightarrow 7/2^-$	1613	738
933.1(3)	24(6)	$17/2^- \rightarrow 13/2^-$	3292	2359
1013.4(6)	<2	$\rightarrow 9/2^-$	2142	1129
1145.0(5)	10(4)	$(11/2)^+ \rightarrow 9/2^{(+)}$	2758	1613
1171(1)	<3	$(17/2^+) \rightarrow 13/2^{(+)}$	3422	2251
1230.2(4)	30(8)	$13/2^- \rightarrow 9/2^-$	2359	1129
1429.6(8)	4(2)	$(9/2)^+ \rightarrow 7/2$	2624	1195
1495.5(7)	6(2)	$(9/2)^+ \rightarrow 9/2^-$	2624	1129
1629.7(7)	4(2)	$(11/2)^+ \rightarrow 9/2^-$	2758	1129

[a] The number in parenthesis is the error in the last digit.
[b] The relative intensities are normalized to the sum $I_\gamma(336) + I_\gamma(738) = 100$.

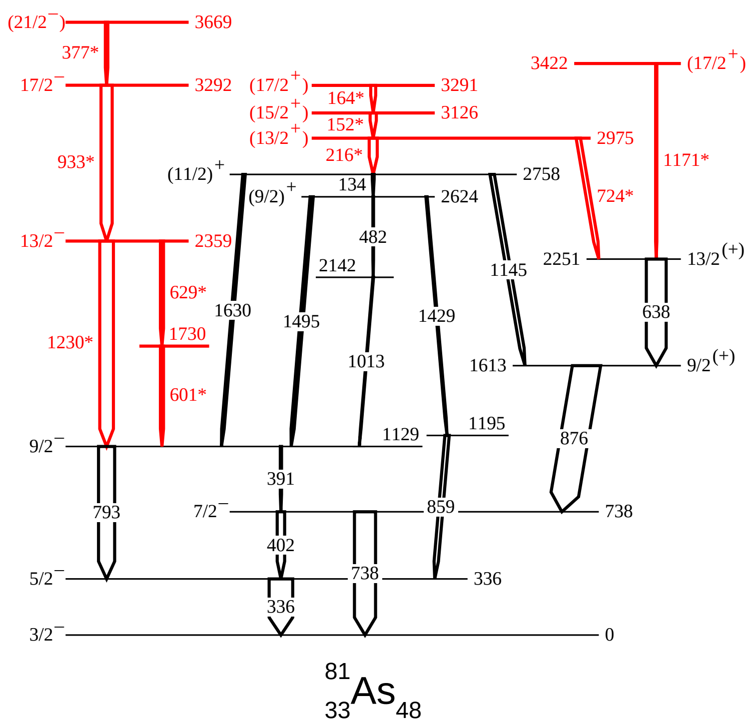

FIG. 4. (Color online) Level scheme of ^{81}As obtained in this work. Transitions drawn in black were already known from the β-decay of ^{81}Ge [27]. The new transitions (in red) are marked with an asterisk. The spin and parity values are from the present work (see text). The weak γ-decay branches of the 2142-, 2624- and 2758-keV states are not drawn for the sake of simplification.

TABLE IV. Coincidence rates between γ-rays of ^{81}As as a function of their relative angle of detection, normalized to the ones obtained around 75°.

E_γ-E_γ	R(22°)[a]	R(46°)[a]	R(75°)[a]
336 - 793	1.31(16)	1.18(10)	1.00(6)
793 - 1230	1.21(18)	1.10(10)	1.00(7)
1230 - 933	1.25(20)	1.09(10)	1.00(6)
336 - 876	0.89(13)	0.96(9)	1.00(6)
402 - 876	1.29(17)	1.15(11)	1.00(6)
738 - 876	0.94(18)	0.86(11)	1.00(8)
738 - 638	1.32(26)	1.40(18)	1.00(9)
876 - 638	0.81(17)	0.98(12)	1.00(8)

[a] The number in parenthesis is the error in the last digit.

ter of the latter is most probably quadrupole. The same argument holds for the 1230-keV transition, because of the cascade of the 629- and 601-keV transitions. Thus we would have to conclude that the 336-keV transition has a quadrupole character, with ΔI=2, implying a I=7/2$^-$ assignment for the 336-keV level. Such a result is at variance with the arguments mentioned above. Thus the 336 keV transition is a ΔI=1, strongly mixed transition, whereas both the 793-keV and 1230-keV transitions are ΔI=2 quadrupole transitions. Indeed, as shown in the bottom of Table I, a strongly mixed (Q+D) transition can give similar results as a pure quadrupole one, if the mixing ratio δ is positive. All these arguments result in the proposed spin values of 5/2$^-$, 7/2$^-$, 9/2$^-$, 13/2$^-$, and 17/2$^-$ for the levels at 336, 738, 1129, 2359, and 3292 keV, respectively.

The spin values of the states drawn in the right part of the level scheme can be deduced from the second series of angular correlation results (see Table IV): The 738- and the 638-keV transitions have a quadrupole character and the 876-keV transition a dipole one. Firstly, it is important to note that, due to its spin value, the 738-keV level cannot belong to the β-decay of the 1/2$^+$ isomeric state of ^{81}Ge, contrary to what had been chosen by the authors of Ref. [14]. It has to be placed in the decay scheme of the ^{81}Ge ground state, as well as two other levels linked to it (at 2912 keV and 3368 keV). Thus the relative γ-intensity balances of all the states of the ^{81}Ge (9/2$^+$) decay scheme given in the previous work [14] have to be changed, before computing the β intensities and the $logft$ values. The result obtained for the 738-keV state is now $logft = 6.5$, which is in agreement with a first-forbidden non-unique transition, ^{81}Ge (9/2$^+$) $\rightarrow$ ^{81}As (7/2$^-$). Secondly, the 1613-keV state has likely I$^\pi$=9/2$^+$ since (i) in our experiment, the 876-keV transition being dipole with ΔI=1, I(1613 keV) = 9/2 and (ii) in the Se(d,^{3}He) reaction, the analysis of the angular distribution [30] leads to either l = 3, i.e. I$^\pi$(1613 keV) = 5/2$^-$ or 7/2$^-$, or

$l = 4$, i.e. $\mathrm{I}^\pi(1613\text{ keV}) = 7/2^+$ or $9/2^+$. Because of the large error bars in that analysis, the positive parity of the 1613 keV state is put in parenthesis in Fig. 4.

The spin values of the states drawn in the central part of the level scheme come from the results of the β-decay of ^{81}Ge ($9/2^+$). The 2624- and 2758-keV states are strongly populated ($logft \leq 5$), so they have I^π=$7/2^+$, $9/2^+$, or $11/2^+$. The 2758-keV state has likely the largest spin value, $11/2^+$, and the 2624-keV state, one unit less, since in the yrast decays such as those observed in our experiment, spin values increase with excitation energy. Because of their low energy, the transitions located above the 2758-keV state have most likely a dipole character, this suggests that spin values of the corresponding levels are increasing by one unit each.

Finally a quadrupole character can be proposed to the 1171-keV transition which would belong to the band built on the $9/2^+$ state at 1613 keV. As for the 3669-keV state located at the top of the $5/2^-$ band, it could have $\mathrm{I}^\pi = 21/2^-$ as the energy spacings in this band is close to the ones of the yrast bands of the two even-even neighbors, ^{80}Ge and ^{82}Se. Particularly, the low energies of their $8^+ \rightarrow 6^+$ transition, 467 keV and 373 keV respectively, are similar to the one measured in ^{81}As (377 keV).

IV. DISCUSSION

A. General features of the two isotopes

1. *A five-valence-proton nucleus,* ^{83}As

Since the two proton orbits, $\pi p_{3/2}$ and $\pi f_{5/2}$, lie just above the $Z = 28$ gap and are close in energy, the configuration of the low-energy states of $^{83}_{33}$As can be simply written as $[\pi p_{3/2} \pi f_{5/2}]^5$. Such a configuration with a mid-occupation of two orbits gives rise to a lot of different states, their spin values extending from I^π=$1/2^-$ to I^π=$13/2^-$, which is the maximum spin of the $[\pi p_{3/2} \pi f_{5/2}]^5$ configuration, with two broken pairs. In order to explain the states having spin values higher than 13/2, the neutron excitation across the $N = 50$ gap has to be taken into account, as observed in many nuclei of the same region, both with even-Z values [31–34] and with odd-Z ones [23, 32].

It is now well established experimentally that the order of the two proton orbits lying above the $Z = 28$ gap, $\pi p_{3/2}$ and $\pi f_{5/2}$, changes during the filling of the $\nu g_{9/2}$ subshell [8], the $\pi f_{5/2}$ orbit becoming the first one when $N \sim 50$. Since the spin value and the magnetic moment which have been measured for the $^{81}_{31}$Ga ground state [11] demonstrate that its odd proton is located in the $\pi f_{5/2}$ subshell, the case of $^{83}_{33}$As would be straightforward: In its ground state, the odd proton is also located in the $\pi f_{5/2}$ subshell, implying $\mathrm{I}^\pi = 5/2^-$. Nevertheless, two states with $\mathrm{I}^\pi = 3/2^-$ are expected at low excitation energy, the one from the $\pi f^3_{5/2}$ configuration and the one having the odd proton in the $\pi p_{3/2}$ orbit. Their actual energies depend on the relative energy of the two orbits, and on the residual interactions between the five protons. Thus the chance that one of these two $3/2^-$ states or a mixture of both may be the ground state of ^{83}As cannot be ruled out, a priori. Several sets of residual interactions were proposed to describe some nuclei in this mass region, mainly the $N = 50$ isotones [35, 36]. It is important to note that shell-model (SM) calculations using such sets (see the Fig. 4 of Ref. [12]) do not give the same predictions, even though they get the same order of the two proton orbits. For instance, when using the set of Ref. [36], the $\mathrm{I}^\pi = 5/2^-$ value of $^{81}_{31}$Ga ground state is well reproduced, while the configuration of the ground state of $^{83}_{33}$As is predicted to be $\pi p^1_{3/2}$, thus $\mathrm{I}^\pi_{gs} = 3/2^-$ [12]. In summary, the experimental determination of the order of the $5/2^-_1$ and $3/2^-_1$ states of ^{83}As is an important issue for the fine tuning of the effective interactions between protons in this mass region.

The experimental results obtained on the yrast states of $^{83}_{33}$As show clearly that the spin value of its ground state is higher than the one of its first excited state at 306 keV (known from the β-decay), since the yrast cascade measured in the present work does not contain any 306 keV γ-transition (see Fig. 2).

The yrast states of ^{83}As measured in the present work are close to the ones of its neighboring isotone, ^{85}Br, when considering the yrast cascade located above its $5/2^-_1$ state at 345 keV [23]. As already mentioned, the maximum value of angular momentum which can be obtained from the excitation of protons in the $\pi p_{3/2}$ and $\pi f_{5/2}$ subshells is $13/2^-$. The $15/2^-$, $17/2^-$ and $19/2^-$ states of ^{85}Br were discussed [23] in terms of the coupling of proton excitation and the *neutron-core* excitation, $[\nu g_{9/2}]^{-1}[\nu d_{5/2}]^{+1}$, which is observed in the even-Z isotones. A similar proton-neutron configuration can be adopted for the highest excited state observed in ^{83}As.

2. *Onset of deformation at* $N = 48$*, the case of* ^{81}As

The energies of the first yrast states of the $N = 48$ isotones, with even-$Z \leq 38$, display a quasi-rotational behavior, with a ratio $\mathrm{E}(4^+_1)/\mathrm{E}(2^+_1) \sim 3$ in the middle of the 28-38 proton shell [34]. This can be viewed as the sign of a static deformation. The elongation parameters of ^{80}Ge and ^{82}Se computed from the experimental B(E2; $2^+_1 \rightarrow 0^+$) strengths are $\epsilon \sim 0.15$. It is noteworthy that self-consistent 'Hartree-Fock-Bogoliubov + blocking' calculations using the Gogny D1S interaction predict that the ground state of ^{81}As$_{48}$ is deformed, with an elongation parameter close to 0.15 [37].

Thus in order to discuss the properties of a $N = 48$ isotone with an odd Z value, it is tempting to use the 'rotor + quasi-particle (qp)' approach where the deformation is explicitly introduced, both in the rotor part and in the qp wave-functions which are the solutions of a deformed hamiltonian.

We have performed particle-rotor calculations in the framework of the model presented in Ref. [38]. The model hamiltonian includes the single-particle energies and the matrix elements for the core-particle couplings, both sets computed using a modified harmonic oscillator (Nilsson) potential, as well as the rotational energy of the core. The results of the first step, the energies of the single-proton orbitals as a function of the quadrupole deformation of the Nilsson potential, are shown in Fig. 5. We have determined new values of the κ and μ parameters for the $N = 3$ major shell, κ_3=0.065 and μ_3=0.60, in order to reproduce the order of the $\pi f_{5/2}$ and $\pi p_{3/2}$ orbits when $N \sim 50$. Indeed the standard values of parameters for the $N = 3$ proton shell [39] could not be used since they were fitted to reproduce the reversed order of these two orbits, as observed in lighter nuclei.

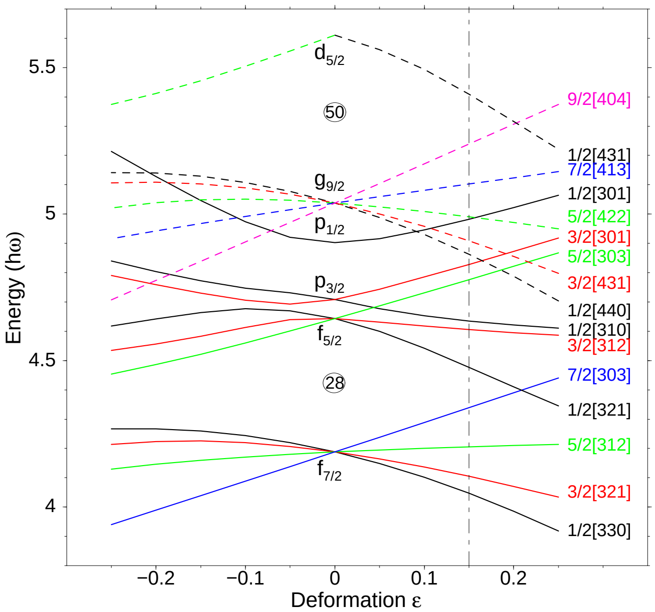

FIG. 5. (Color online) Single-particle proton levels of the modified harmonic oscillator as a function of quadrupole deformation ϵ. Values of the κ and μ parameters for the $N = 3$ major shell are adjusted to reproduce the order of the $\pi f_{5/2}$ and $\pi p_{3/2}$ orbits when $N \sim 50$ (see text). Negative (positive) parity states are marked by solid (dashed) lines. The dotted-dashed vertical line brings out the proton levels expected for $\epsilon = 0.15$, which is close to the deformation value computed for the $N = 48$ cores (see text). The spherical shell closures are indicated.

The different ingredients of the 'particle-rotor' calculation are:

- the value of the deformation parameter: $\epsilon = 0.15$, extracted from B(E2; $2_1^+ \to 0^+$) strength of the ^{80}Ge core (as said above),

- the moment of inertia of the core: Its value, $\Im = 4.55\ \hbar^2 MeV^{-1}$, is extracted from the E(2_1^+) value of ^{80}Ge,

- the states lying around the Fermi level which are taken into account: All the states shown in Fig. 5 have been considered,

- the Coriolis attenuation parameter: $\chi = 0.75$ (a standard value), which allows us to reduce all single-particle matrix elements. Otherwise the theoretical spectrum is significantly compressed with respect to the experimental one.

The low-energy part of the negative-parity level scheme predicted for ^{81}As is shown in the right part of Fig. 6, by comparison with the experimental results (from the β-decay of ^{81}Ge and the present work). First of all, the

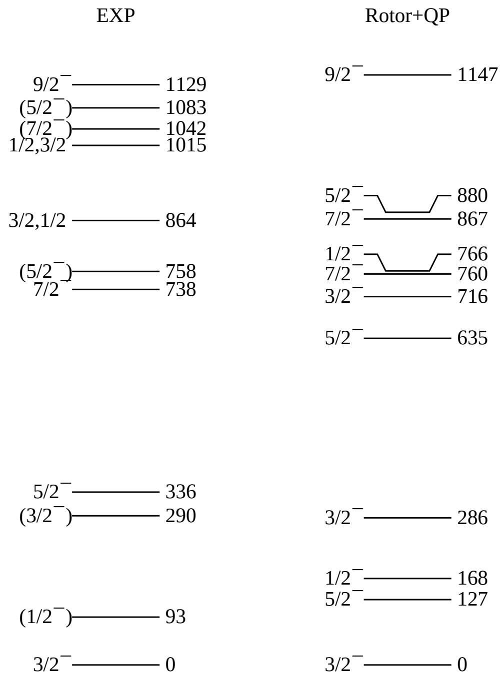

FIG. 6. Left part: All the states measured so far in ^{81}As, which are located below the $9/2^-$ level at 1129 keV (from the β-decay of ^{81}Ge and the present work). Right part: All the states predicted by the particle-rotor approach, located below the $9/2_1^-$ level.

'rotor+qp' calculations reasonably describe the experimental levels. Each experimental state located below the $9/2^-$ level at 1129 keV has a theoretical couterpart in the good energy range. Especially the gap between the first four states and the others is reproduced, even though the actual order of states is not exactly the same. We have to remind that in such calculations, there are many parameters which could be varied in order to find better agreement. This is beyond the scope of this discussion, which is to show that in such an approach which takes explicitly into account the deformation, the main properties of the low-energy level scheme of ^{81}As are well accounted for, even though its number of neutrons, close to the magic number, would let us think that only a spherical approach would do a good job.

It is instructive to look at the wave functions of some states of ^{81}As (see Table V). They exhibit large mixings which are due to the Coriolis terms in the 'rotor+qp' hamiltonian:

- The band built on the 1/2[310] deformed state is perturbed because of the value of its decoupling parameter. Thus the first state of the band, which is the ground state, has $I^\pi = 3/2^-$.
- With its main components on the 5/2[303], 3/2[312], and 1/2[321] orbits (all of them being issued from the spherical $\pi f_{5/2}$ shell, see Fig. 5), the first state with $I^\pi = 5/2^-$ can be interpreted as a 'decoupled' state, i.e. the angular momentum of the odd-proton being aligned on the rotational axis.
- The decomposition of the $9/2^-_1$ state involves the same deformed orbits than those of the $5/2^-_1$ state. Thus it likely belongs to the decoupled band built on the $\pi f_{5/2}$ shell.

TABLE V. Decomposition of the wave functions of some states of ^{81}As on the deformed basis.

E (keV)	I^π	1/2[321]	3/2[312]	1/2[310]	5/2[303]	3/2[301]
0	$3/2^-$	4%		83%		12%
127	$5/2^-$	13%	36%	5%	45%	1%
168	$1/2^-$			100%		
286	$3/2^-$	3%	93%		13%	3%
1147	$9/2^-$	30%	39%	9%	20%	2%

In addition, the 'rotor+qp' calculations gives excited states with positive parity, particularly a 'decoupled' band built on the $\pi g_{9/2}$ shell. Such a prediction was expected since the Fermi level is located just below the high-j shell and the core is weakly deformed. Thus the group of states which are experimentally observed at 1613 kev, 2251 keV and 3422 keV (see the right part of Fig. 4) likely belongs to the band built on the $\pi g_{9/2}$ shell.

It is worth noting that the largest β-decay strengths in this mass region are due to the Gamov-Teller transition, $\nu p_{1/2} \rightarrow \pi p_{3/2}$ in 'spherical' notations[1]. Thus, the strong β-decay branches of ^{81}Ge$_{49}$ ($9/2^+$) populating the states at 2624 and 2758 keV of ^{81}As [14] can be written as: $(\nu p_{1/2})^2(\nu g_{9/2})^9 \rightarrow (\pi p_{3/2})^1(\nu p_{1/2})^1(\nu g_{9/2})^9$. Therefore, the positive-parity states, drawn in the middle part of Fig. 4, have an excited two-neutron configuration involving the $\nu p_{1/2}$ and $\nu g_{9/2}$ subshells. As for the protons, the odd proton is located in the $\pi p_{3/2}$ subshell and the breaking of one proton pair in the $\pi f_{5/2}$ subshell has to be taken into account for spin values greater than $13/2^+$.

[1] or $\nu 1/2[301] \rightarrow \pi 3/2[301]$ in 'deformed' notations.

B. Results of shell model calculations

A new effective interaction for SM calculations in the f_5pg_9-shell space, JUN45, was recently published [40]. It gives a satisfactory description of a lot of experimental results (binding energies, magnetic moments, energies and spin values of excited states, ...). Nevertheless we have to stress that the nuclei having $Z < 34$ and $N \geq 46$ are less successfully described than those having more protons and less neutrons (see for instance the systematics of the 2^+_1 states for $N = 46 - 50$ in the Fig. 9 of Ref. [40]). The use of the f_5pg_9-shell space implicitly assumes that the two shell closures, at $Z = 28$ and $N = 50$, are so strong that they hinder quadrupole collectivity which could develop between the $\pi f_{7/2}$ and the $\pi p_{3/2}$ orbits on the one hand, and between the $\nu g_{9/2}$ and the $\nu d_{5/2}$ orbits on the other hand. In this section, we make a detailed comparison between the new experimental information obtained in ^{83,81}As$_{50,48}$ and the SM predictions, in order to know to what extent the f_5pg_9-shell space is a sufficient model space to give a reasonable description of these nuclei. The calculations were performed using the ANTOINE shell model code [41].

1. ^{83}As

The results of the SM calculations of ^{83}As are given in the left part of Fig. 7. The ($9/2^-$), ($11/2^-$), and ($13/2^-$) states observed in the present work are well described, as well as the $3/2^-$ state at 306 keV. On the other hand, the SM calculations fail to predict another excited state below 1 MeV, thus the state at 712 keV observed in the β-decay of the $5/2^+$ ground state of ^{83}Ge [13] has no theoretical counterpart whatever its spin value (for the drawing of Fig. 7, we have chosen $I^\pi = 3/2^-$ for the 712 keV state).

The first excited state with a positive parity, predicted at 2.61 MeV, comes from the excitation of one proton into the $g_{9/2}$ subshell, i.e. the $[\pi p_{3/2}\pi f_{5/2}]^4[g_{9/2}]^1$ configuration. Then the breaking of one proton pair in the pf subshells gives rise to the states with $I^\pi = 13/2^+_1$, $15/2^+_1$, and $17/2^+_1$, calculated at 3.76 MeV, 4.19 MeV, and 4.39 MeV (see the filled blue squares in the left part of Fig. 7). These states are unlikely to be observed in experiments such as the one of the present work, which only populates the yrast states. Indeed, they are too high in energy, as compared to negative-parity states coming from the *neutron-core excitation* which have been measured in neighboring $N = 50$ isotones, such as ^{85}Br, ^{84}Se, or ^{82}Ge [23, 31, 33]. Knowing that the size of the $N = 50$ gap is slowly decreasing with Z [1], the energy of the $15/2^-_1$ state of ^{83}As is expected to be lower than 3.71 MeV (the energy of the $15/2^-_1$ state of ^{85}Br), meaning that the calculated $15/2^+_1$ state cannot be yrast.

The configuration of the $11/2^-_2$ state, calculated at 3.17 MeV, is very different from the one of the $11/2^-_1$ state. Its two main components are $[\pi p_{3/2}]^3[\pi f_{5/2}]^2$

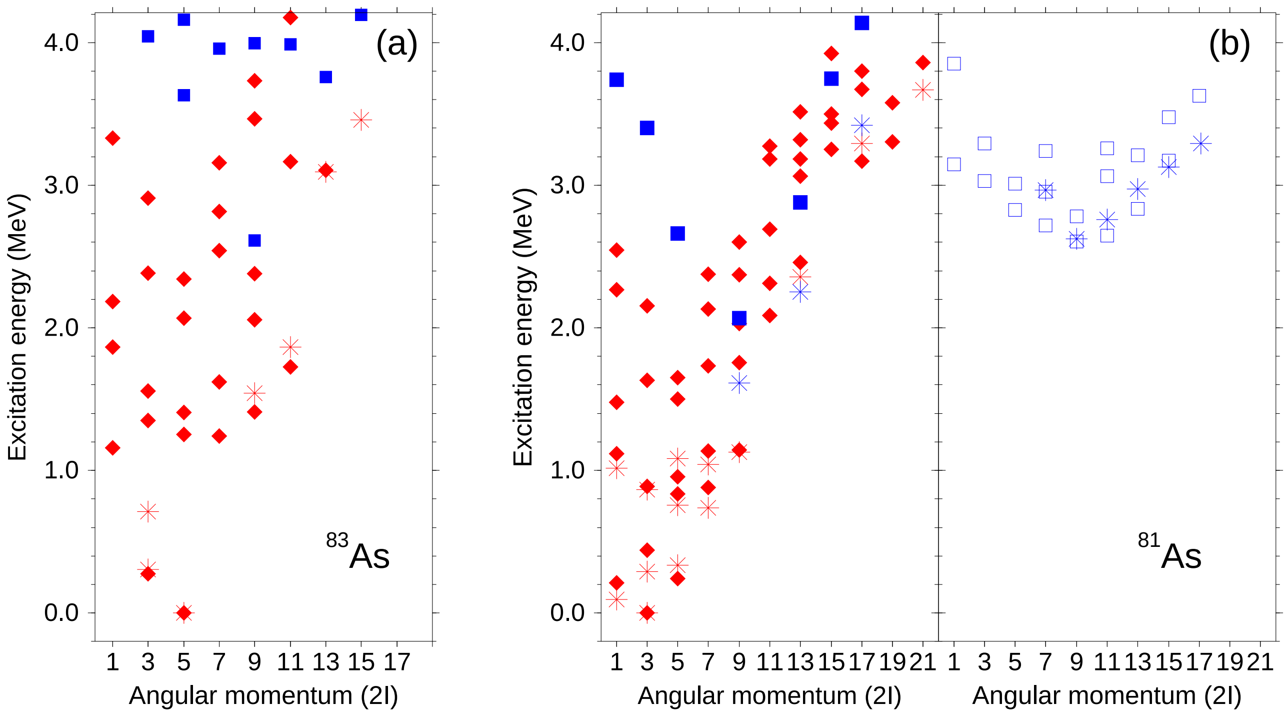

FIG. 7. (Color online) Excitation energy as a function of angular momentum of the states of ^{83}As (a) and ^{81}As (b). The experimental states (this work and Ref. [24]) having negative (positive) parity are drawn with red (blue) asterisks. The negative-parity states predicted by the SM calculations are drawn with red diamonds. The positive-parity states due to proton excitations predicted by the SM calculations are drawn with filled blue squares and those due to neutron excitations with empty blue squares. All the SM states with an excitation energy lower than 2 MeV are drawn. From 2 MeV to 4.1 MeV, we only show a few states for each value of angular momentum.

(36%) and $[\pi p_{3/2}]^2[\pi f_{5/2}]^3$ (57%), while the main configuration of the $11/2^-_1$ state is $[\pi p_{3/2}]^1[\pi f_{5/2}]^4$ (87%). The experimental level at 2777 keV (see Fig. 2) could be that $11/2^-_2$ state, and the 3206 keV level could be one of the states having that particular proton configuration coupled to the neutron-core excitation.

2. ^{81}As

The results of the SM calculations of ^{81}As are given in the right part of Fig. 7. The neutron subshell fillings of all the calculated states drawn with filled symbols are the same, $[\nu p_{3/2}]^4[\nu f_{5/2}]^6[\nu p_{1/2}]^2[\nu g_{9/2}]^8$, the breaking of one $g_{9/2}$ neutron pair providing some amount of angular momentum. The negative-parity states observed in the present work are reasonably well described, as well as those with an excitation energy lower than 1.1 MeV, measured in the β-decays of ^{81}Ge (shown in the left part of Fig. 6). It is important to note that the experimental yrast spectrum is more compressed than the theoretical one: The predicted energies of the two first quadrupole transitions located above the $5/2^-_1$ state are 904 keV and 1314 keV instead of 793 keV and 1230 keV measured in the present work.

As for the first positive-parity state coming from the excitation of one proton into the $\pi g_{9/2}$ subshell, its energy is ~450 keV higher than the measured ones (compare the filled blue square and the blue asterisk, for $I^\pi = 9/2^+$). The same discrepancy was already noted in Ref. [40] in case of several isotopes of $_{29}$Cu, $_{31}$Ga, and $_{33}$As, this was ascribed to deformation expected at mid-occupation of the neutron subshells. Moreover, the experimental spectrum linked to the $9/2^+_1$ state is more compressed than the theoretical one (for instance, the predicted energy of the $13/2^+ \rightarrow 9/2^+$ transition is 814 keV instead of 638 keV). This could be a sign of collectivity, not taken into account within the f_5pg_9-shell space.

A lot of positive parity states are predicted around 3 MeV excitation energy (they are drawn with empty blue squares in the right part of Fig. 7), their energies display a quasi-parabolic curve as a function of their spin values, with a minimum at spin 9/2. The neutron subshell fillings of all these calculated states are the same, $[\nu p_{3/2}]^4[\nu f_{5/2}]^6[\nu p_{1/2}]^1[\nu g_{9/2}]^9$, i.e. the excitation of one neutron from the $p_{1/2}$ subshell to the $g_{9/2}$ one. This is exactly the neutron configuration we have assigned to the $(9/2)^+$ and $(11/2)^+$ at 2624 keV and 2758 keV excitation energy because of their large population in the β-decay of the ^{81}Ge ground state (see the end of Sect. IV A 2). A spin and parity assignment of $7/2^+$ can be proposed for the third state strongly populated in the β-decay at 2966 keV [14] and not observed in the present work. This state, as well as those having higher spin values, measured at 2975 keV, 3126 keV, and 3291 keV in the present work (see Fig. 4), have likely the same excited neutron configuration.

3. Conclusion

The use of the JUN45 effective interaction accounts for an overall description of the excited states of ^{81,83}As, except a few problems related to values of specific interactions and/or collective effects, which also occur in the description of neighboring nuclei.

Firstly, two configurations with three valence protons in the $f_{5/2} - p_{3/2}$ subshells give a $3/2^-$ state, namely $[\pi p_{3/2}]^1 \otimes [\pi f_{5/2}]^2$ and $[\pi f_{5/2}]^3$. The SM calculations of ^{79}Ga indicates that the two configurations are mixed [11], the $[\pi p_{3/2}]^1 \otimes [\pi f_{5/2}]^2$ one being dominant in the wave function of the first $3/2^-$ state. This is at variance with measured properties of the ^{79}Ga ground state, since its magnetic moment and its electric quadrupole moment impose that the $[\pi f_{5/2}]^3$ configuration is the main part of the wave function, i.e. that of the second calculated $3/2^-$ state [11]. As for ^{83}As, its first $3/2^-$ state, predicted at 275 keV excitation energy (in good agreement with the experimental energy, 306 keV), has an odd number of protons in the $\pi p_{3/2}$ subshell. The $[\pi f_{5/2}]^3$ configuration, which could have been assigned to the second excited state measured at 712 keV, is involved at much higher energy (in the second and third $3/2^-$ states, see Fig. 7). As a result, there is no theoretical counterpart to a second excited state of ^{83}As lying below 1 MeV excitation energy. One could expect that some changes in the interactions within the $\pi f_{5/2} - \pi p_{3/2}$ orbits could decrease the energy of the $3/2^-$ state from the $[\pi f_{5/2}]^3$ configuration both in Ga and As isotopes. In addition, the energy of the 2_1^+ state is predicted too high in the $_{30}$Zn and $_{32}$Ge isotopes with $N = 46, 48$ (see the Fig. 10 of Ref. [40]). It mainly depends on the effective interactions in the $\pi f_{5/2}$ and $\pi p_{3/2}$ subshells, as well as the relative location of these two orbits. The $\pi p_{3/2}$ subshell is involved in the low energy part of the level schemes of several isotopes used in the fitting calculation of Ref. [40] ($35 \leq Z \leq 38$, with $N = 46 - 50$). On the other hand, the $\pi f_{5/2}$ subshell only dominates the structure of the nuclei having a fewer number of valence protons and $N = 46 - 50$. Since they were not included in the fitting procedure, the corresponding effective interactions could be still improved. One can surmise that the problems in the description of the $3/2^-$ states in ^{79}Ga and ^{83}As, as well as that of the low-energy levels of the heavy $_{30}$Zn and $_{32}$Ge isotopes would then be fixed.

Secondly, the calculated energies of the first $9/2^+$ states coming from the excitation of one proton to the $\pi g_{9/2}$ subshell are systematically too high whatever the number of protons (see the Fig. 13 of Ref. [40], and the right part of Fig. 7 for the case of ^{81}As). These energies could largely decrease thanks to quadrupole deformation, but the f_5pg_9 space is not enough to allow for the development of quadrupole collectivity. Such a deficiency also shows itself in the energies of the quadrupole excitation built on the $5/2_1^-$ and the $9/2_1^+$ state of ^{81}As which are predicted too high in energy as compared to the experimental results. To cure that shortcomings, the valence space should be enlarged in order to take into account the core excitation. Excitations across the $Z = 28$ gap are prerequisite to describe the low-energy collective $1/2^-$ states measured in heavy odd-N Cu isotopes [10]. Such excitations should be also investigated for the heavy Ga and As isotopes.

V. SUMMARY

^{81,83}As have been produced as fission fragments in the fusion reaction ^{18}O+^{208}Pb at 85 MeV bombarding energy, their γ-rays being detected using the Euroball array. Their medium-spin level schemes have been built up to $\sim$ 3.5 MeV excitation energy by analyzing triple γ-ray coincidence data. Using γ-γ angular correlation results, spin and parity values have been assigned to many states observed in ^{81}As. The behaviors of the yrast structures identified in this work have been firstly discussed in comparison with the general features known in the mass region and the 'rotor+quasi-particle' approach has been used to tentatively describe the low-energy states of ^{81}As. Then shell model calculations using the effective interactions JUN45 in the f_5pg_9 shells have been compared to experimental results of ^{81,83}As in order to test the predictions at one particular limit of the valence space, i.e. for Z at the beginning and N at the end of the f_5pg_9 shells.

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