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Further evidence on shape coexistence in ^{72}As

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The ^{72}As nucleus was studied via the $(\alpha,n\gamma)$ reaction at 14.2 MeV bombarding energy. Single γ-, $\gamma\gamma$-coincidence, and internal conversion electron spectra were measured with Ge(HP) γ-ray and superconducting magnetic lens plus Si(Li) electron spectrometers. On the basis of the internal conversion coefficients of ^{72}As transitions, parities of the medium-spin levels up to 1.4 MeV excitation energy were determined, resulting in unambiguous parities also for the heads of the bands observed previously. The states observed were assigned to proton-neutron multiplets on the basis of their decay properties. The energy splittings of the observed multiplets are in accordance with the prediction of the previous interacting boson-fermion-fermion model (IBFFM) calculations using a transitional core lying between the vibrational SU(5) and γ-soft O(6) limits, except that of the $\pi g_{9/2}\nu g_{9/2}$ multiplet, which was described using the deformed SU(3) core in the present IBFFM calculations. Such a core structure is in accordance with previous particle-rotor and Hartree-Fock-Bogoliubov calculations. [S0556-2813(99)03903-5]

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I. INTRODUCTION

Shape coexistence in the mass 80 region is well known; it has also been found in the odd-odd ^{74,76}Br nuclei [1–3], and it was also predicted in light odd-odd As nuclei [4]. In recent works by García Bermúdez *et al.* [5] and by Döring *et al.* [6] the band structure in ^{70,72}As has been revealed. The bands based on the $8^{(+)}$ and $9^{(+)}$ states were interpreted as rotational bands with $\beta\sim0.26$ prolate deformation on the basis of the lifetime measurements [5,6].

The aim of the present work was only to determine the parities of the bandheads, as well as of other states, so as to deduce configuration assignments for the medium-spin states, but the data allowed also spin-parity assignment for some of the medium-spin states, which complement the previous level schemes [4,6,14]. Since the energy splittings of the proton-neutron multiplets are highly sensitive to the core structure [7,8], further evidence is expected for the shape coexistence from the analysis of the proton-neutron multiplets. For a description of the multiplet states the interacting boson-fermion-fermion model (IBFFM) [9] was previously applied. It is an extension of the interacting boson model (IBM) [10,11] and of the interacting boson-fermion model (IBFM) [12,13]. In this work we rely on the same model.

II. EXPERIMENTAL METHODS AND RESULTS

The experiments were performed using the 14.2 MeV-energy α-particle beam of the Debrecen cyclotron. The $\sim$30-μg/cm^2-thick ^{69}Ga targets, isotopically enriched to 99.7%, were prepared by evaporation of metallic Ga onto 40 μg/cm^2 carbon backing foils. The γ- and $\gamma\gamma$-coincidence measurements were carried out using 20% and 25% coaxial Ge(HP) detectors having $\sim$2 keV energy resolution at 1332 keV. For energy and intensity determination the detectors were placed at 90° and at 125° to the beam direction, respectively. The $\gamma\gamma$-coincidence gate spectra made possible the energy and intensity determination even for those γ rays which were weak or unresolved in singles spectra. The energies of the strong ^{72}As γ rays obtained were in good agreement with the results of our former $(p,n\gamma)$ measurements [14].

In the $\gamma\gamma$-coincidence measurement the Ge(HP) detectors were placed at 125° and 235° relative to the beam direction. The $\sim7\times10^6$ $\gamma\gamma$-coincidence events were recorded in

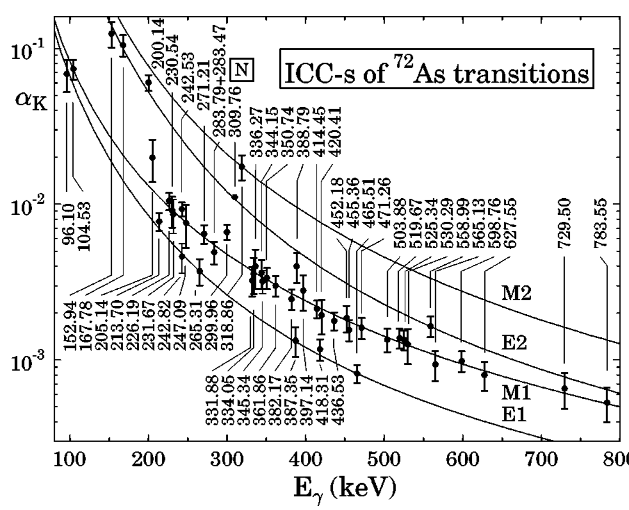

FIG. 1. Experimental (symbols with error bars) and theoretical (curves) internal conversion coefficients of ^{72}As transitions as a function of the γ-ray energy.

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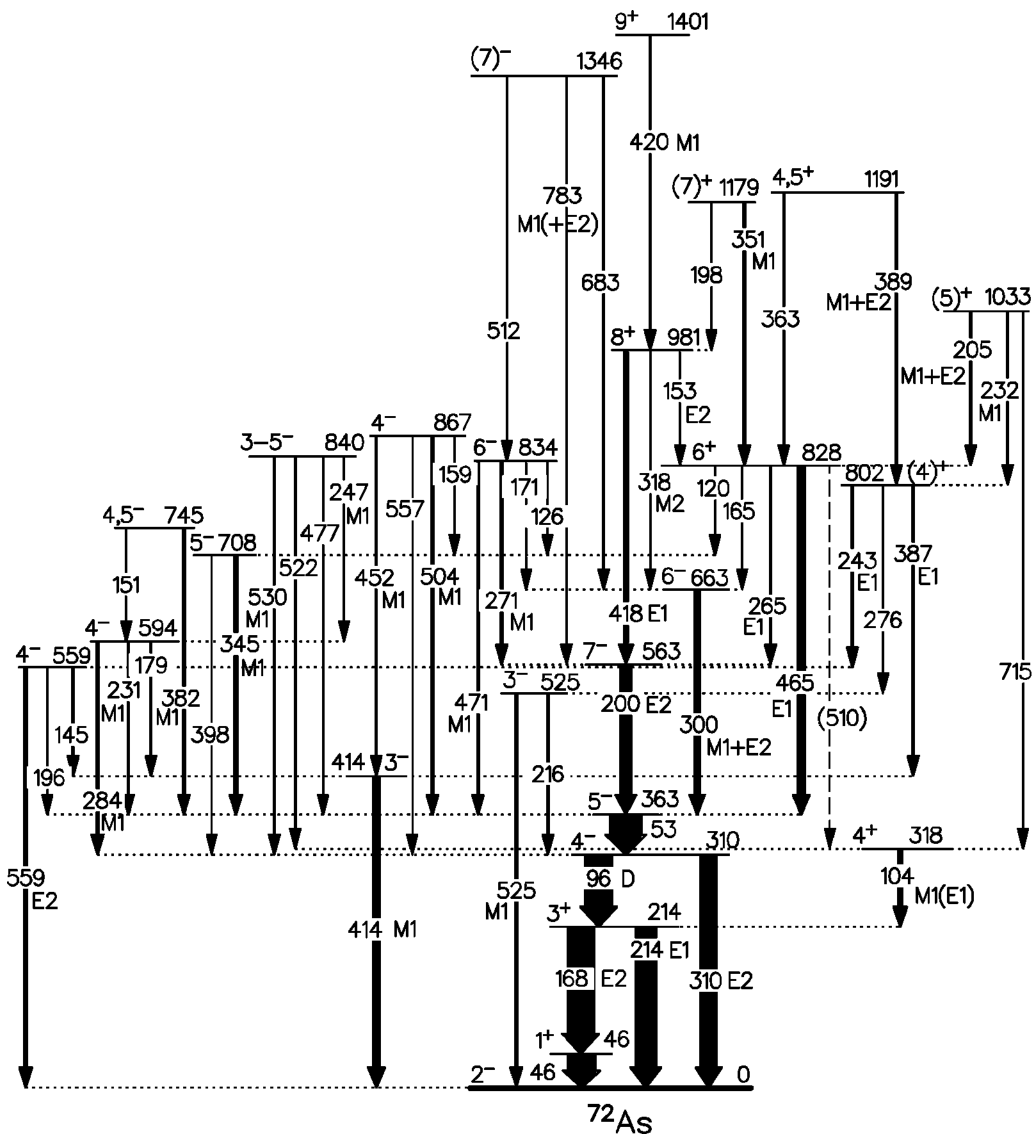

FIG. 2. The proposed level scheme for ^{72}As from the $(\alpha,n\gamma)$ reaction up to 1.4 MeV excitation energy. Only levels with unambiguous parities and spin values $I\geqslant4$ are presented. In addition to the energies of the γ rays, their multipolarities are also given.

event-by-event mode and the data processing was carried out off line. After creating a symmetrized two-dimensional coincidence matrix, a standard gating procedure was used.

Internal conversion electron spectra were measured with a superconducting magnetic lens plus Si(Li) spectrometer having ~2.4 keV energy resolution (at 917 keV) and 10% transmission (for two detectors). The estimated effect of the angular distribution of electrons on the measured internal conversion coefficients was usually much less than their statistical uncertainties. For the energy and efficiency calibration of the γ and electron spectrometers ^{133}Ba and ^{152}Eu sources were used.

Internal conversion coefficients (ICC's) were determined from the conversion electron and γ-ray spectra. For normalization of the experimental ICC's the theoretical α_K value [15] of the strong 309.76-keV stretched $E2$ transition of ^{72}As [14,16] was used. With this normalization, the internal conversion coefficients measured also in the (p,n) reaction study have been reproduced [14,16]. The theoretical curves and experimental ICC's of the ^{72}As transitions are presented in Fig. 1. In the case of the 231-, 243-, and 345-keV doublets, the ICC's of the 231.67-, 242.82-, and 345.34-keV transitions were deduced by taking the α_K values of the other members of the corresponding doublets from the results of our previous measurement [14]. To determine the ICC of the 388.79-keV transition from the 388-keV doublet, we assumed that the multipolarity of the disturbing 387.35-keV γ ray connecting the 802-keV $(4)^+$ state with the 414-keV 3^- level is a pure $E1$ transition. As a result, ICC's have been determined for 45 γ rays, and new multipolarities could be assigned to 22 transitions.

The construction of the level scheme was based on the $\gamma\gamma$-coincidence measurement and on the energy and intensity balances of the transitions, as well as on the results of our former $(p,n\gamma)$ measurement [14]. The levels of ^{72}As were observed in the present experiment up to about 2.5 MeV energy. In Fig. 2 the proposed level scheme is presented up to 1.4 MeV excitation energy containing only those states with spin $I\geqslant4$ to which unambiguous parities could be assigned. In addition, some low-lying levels through which the higher-lying levels are depopulated are also shown.

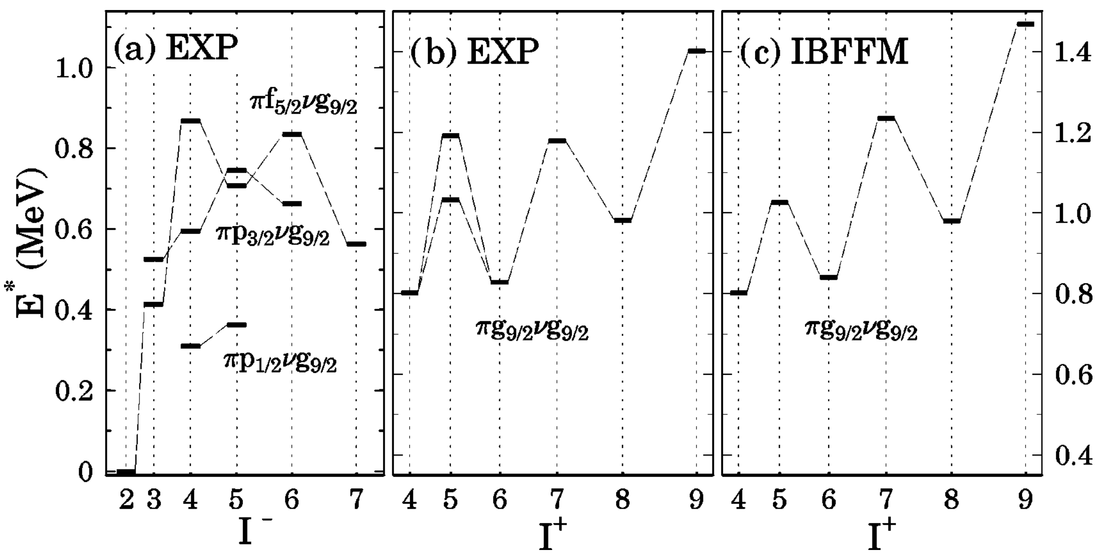

FIG. 3. Proton-neutron multiplet states in ^{72}As based on the $\nu g_{9/2}$ configuration. The spectra in (a) and (b) are the experimental negative- and positive-parity levels, respectively, obtained from the former $(p,n\gamma)$ [14] and the present $(\alpha,n\gamma)$ reaction studies. The spectrum in (c) is the $\pi g_{9/2}\nu g_{9/2}$ multiplet calculated in the IBFFM with an SU(3) prolate core. The abscissa is scaled according to $I(I+1)$, where I is the spin of the states.

The placement of all the transitions previously known is in agreement with the corresponding data of Refs. [4,6,14,17]. Our $\gamma\gamma$-coincidence measurement strengthened the placement of the 783- and 512.4-keV γ rays as the decay of the 1346-keV state reported only in Ref. [6]. Comparing our level scheme to the one given by Mariscotti *et al.* [18], two differences were found: (i) we did not observe the weak 148.8-keV transition decaying from the state at 563-keV and (ii) the 432-keV γ ray (not shown) was placed above the 418-keV transition decaying from the 981-keV state, both in agreement with Refs. [4,6,17]. In addition, we have found several new transitions between previously known states, which are also supporting the existence of the levels previously established only by a single γ transition.

The spins and parities of the low-lying states up to 600 keV have been unambiguously established from our former $(p,n\gamma)$ reaction study [14]. Using these parity values and the multipolarities of the transitions, the parities of the states given in Fig. 2 could be determined. The new multipolarities also made possible the spin determination for some states.

The levels at 828, 867, and 1033 keV are decaying via pairs of $M1+E2$ or $E1$ transitions to level pairs having $\Delta I=2$ spin differences. Because of the presence of the dipole components in these transitions, this decay mode can only be obtained by letting a spin I state decay to its $I+1$ and $I-1$ neighbors, determining the spin values of the decaying state. Thus, we propose $I^\pi=6^+,4^-$, and $(5)^+$ spins and parities to the 828-, 867-, and 1033-keV states, respectively.

We assigned $I^\pi=3-5^-$ and $4,5^+$ spin-parity values to the states at 840 and 1191 keV, respectively, based on multipolarities of the γ rays depopulating them.

The fact that the levels at 708, 745, and 1179 keV are decaying via $M1$ transitions allowed the determination of $I_i=I_f\pm1$ intervals for their possible spin values. These levels are connected to other levels also via low-energy (E_γ <200 keV) transitions. Because of the weak intensities of these low-energy γ rays, we could not assign multipolarities to them, but on the basis of the recommended upper limits for transition probabilities [19] they are expected to have dipole character. Using this assumption we proposed I^π $=5^-$, 4, 5^-, and $(7)^+$ spin and parity values to the states at 708, 745, and 1179 keV, respectively.

Two pairs of bands have been found in the ^{72}As nucleus [4,6], the parities of which were guessed on the basis of theoretical considerations. From the present measurement for the bandheads at 981 and 1401 keV the positive parity was established by the multipolarities of the depopulating γ rays. On the other hand, the pair of levels at 834 and 1346 keV were found to have negative parity. As the bands are built of stretched $E2$ cascades, knowledge of the parity of the bandheads gives also the parities of the band members. Thus, the 1875-, 2307-, and 3504-keV states, reported in Ref. [4,6], have positive parity, while the 1665-, 2517-, and 3445-keV ones, established by Ref. [6], have negative parity.

The 663-keV state is fed by the 318-keV $M2$ transition from the $I^\pi=8^+$ 981-keV state ([4,6] and discussion above), and decays via the 300-keV $M1+E2$ transition to the 363-keV state having $I^\pi=5^-$ spin parity [14]. These facts leave room only for the 6^- spin-parity assignment to the 663-keV state.

III. DISCUSSION

The low-lying states of the $^{72}_{33}$As$_{39}$ nucleus are expected to arise from the excitations of the odd proton and the odd neutron and their angular momentum coupling with each other and with core excited states. The members of the multiplets are connected via $M1$ transitions, and branching out of the multiplets is usually caused by mixing of the different multiplets. Using these selection rules, on the basis of the branching ratios, the multipolarities of the transitions, and the known configurations of the low-spin states [14], the levels observed in the present study could be arranged into proton-neutron multiplets. The proton-neutron multiplet structure of ^{72}As is shown in Fig. 3.

The $\pi f_{5/2}\nu g_{9/2}$ *multiplet*. The energy splitting of this multiplet is expected to show an open-down parabolic shape. The lowest-spin member of the multiplet, the 2^- state, is predicted to have the lowest energy. On the basis of their magnetic dipole moments [20], the $\pi f_{5/2}\nu g_{9/2}$ configuration has been assigned to the 2^- ground state and to the lowest-lying 7^- state at 563 keV [14]. The first 3^- level at 414 keV, decaying only to the 2^- ground state by an M1 transition, has also been allocated to this multiplet [14]. The 867-keV 4^-, 708-keV 5^-, and 834-keV 6^- states are connected via strong (in the I_γ/E_γ^3 scale) branches to each other, as well as to the 414-keV 3^- and 563-keV 7^- states having the $\pi f_{5/2}\nu g_{9/2}$ configuration. Hence, these levels may correspond to the 4^-, 5^-, and 6^- members of this multiplet, respectively.

The $\pi p_{1/2}\nu g_{9/2}$ *doublet*. The dominating configuration of the lowest-lying 4^- and 5^- states is expected to be the $\pi p_{1/2}\nu g_{9/2}$ one. For this doublet the $E(4^-)<E(5^-)$ energy order is predicted. Below 700 keV excitation energy the only 5^- state is the 363-keV one, which decays only to the lowest-lying 4^- state at 310 keV by an $M1$ transition. Consequently, the 310- and 363-keV states may be the experimental equivalents of the 4^- and 5^- members of the $\pi p_{1/2}\nu g_{9/2}$ doublet, as proposed in Ref. [14].

The $\pi p_{3/2}\nu g_{9/2}$ *multiplet* is the exception from the $M1$ selection rule, as in addition to the intramultiplet transitions the spin-flip $p_{3/2}\to p_{1/2}$ $M1$ transitions are also allowed with ~ 1 Weisskopf units (W.u.) strength. Thus, the low-energy intramultiplet transitions might be lost in favor of the higher-energy $p_{3/2}\to p_{1/2}$ transitions. In addition to the 525-keV 3^- and 594-keV 4^- states preferring the decay to the members of the $\pi p_{1/2}\nu g_{9/2}$ doublet, and assigned to the $\pi p_{3/2}\nu g_{9/2}$ multiplet earlier, the best candidates for the 5^- and 6^- member states are the 745-keV $4,5^-$ and the 663-keV 6^- levels. They are also strongly connected to the $\pi p_{1/2}\nu g_{9/2}$ multiplet and even the low-energy intramultiplet $5^-\to 4^-$ transition can be found. The energy splitting of the multiplet has an open-down parabolic shape in agreement with the prediction.

The experimental energies of these states are in good agreement with those predicted by the previous interacting-boson-fermion model calculations [14].

The above assignments can be considered as proposals for the strongest components of the wave functions projected onto the quasiparticle shell model space. Significant configuration mixing must be present, as can be deduced from the existence and strength of the intermultiplet transitions, and as is demonstrated in the IBFFM calculations [14]. In the case of the positive-parity states the assignment to proton-neutron multiplets is even more difficult, since both the proton and the neutron configurations can be mixed. As a result, the quantitative calculations may predict the same dominating configuration for several states of the same spin, and other configurations may completely be fragmented. Another ambiguity in grouping states into multiplets results from the uncertainty in spin determination of the lowest spin states [21,22]. A possible configuration assignment is given in Ref. [14]. Other reasonable assignments can also be imagined, but with the limitations mentioned above for the meaning of the multiplet states in the present case.

There is a set of positive-parity states, consisting of the 1401-keV 9^+, the 981-keV 8^+, the 1179-keV $(7)^+$, the 828-keV 6^+, the 1191- and 1033-keV $(5)^+$, and the 802-keV $(4)^+$ states, which are connected via $M1$ and $E2$ transitions, while their branching to the other positive-parity states is negligible, and even the lowest-energy states decay almost exclusively to negative-parity states. These properties indicate that this group of states has a similar dominant configuration, strongly different from that of the other positive-parity states. While the basic set of the positive-parity states is obtained via coupling of the protons and neutrons in the $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ configurations, a distinct group can be formed by coupling the $g_{9/2}$ proton and neutron states. The above characteristics are in agreement with the assignment of the mentioned group of states to the $\pi g_{9/2}\nu g_{9/2}$ configuration, especially if we take into account that in the populated negative-parity states the neutron is also in the $\nu g_{9/2}$ configuration. Both the 1191- and 1033-keV states have similar decay properties, making them equally good candidates for being the 5^+ member of the $\pi g_{9/2}\nu g_{9/2}$ multiplet. The decay patterns observed suggest that both states have strong $\pi g_{9/2}\nu g_{9/2}$ components. It is to be mentioned that on the basis of other arguments the 1401-keV 9^+ and the 981-keV 8^+ states were assigned to the $\pi g_{9/2}\nu g_{9/2}$ configuration by Döring *et al.* [6]. They also proposed the 1179-keV $(7)^+$ and the 828-keV 6^+ states to be the members of this multiplet, although their spins and parities were less certain. As is seen in Fig. 3, the splitting of the other multiplets can be approximated with a simple parabola, associated with the vibrational limit of the IBFFM [23], while the splitting of the $\pi g_{9/2}\nu g_{9/2}$ multiplet exhibits a signature pattern. This structure is clearly different from those expected in vibrational or γ-soft limits of the IBFFM, but it is in qualitative accordance with the limit of the IBFFM associated with a deformed SU(3) core [24]. To describe the states associated with the $\pi g_{9/2}\nu g_{9/2}$ configuration, we performed here an additional IBFFM calculation with an SU(3) boson core.

It should be noted that previous investigations of odd-odd nuclei in the $A\approx 80$ region, such as ^{74,76}Br, ^{80}Rb, ^{82,84}Y, have shown a well-deformed rotational structure starting above ≈ 0.5 MeV, associated with the $\pi g_{9/2}\nu g_{9/2}$ configuration, and was described by particle-rotor and cranking calculations [1–3,25–28]. In particular, large prolate deformations were deduced [2].

The IBFFM parameters defined according to Ref. [29] and Ref. [30] (for α and β) were taken as follows. The boson core was described by a prolate SU(3) core with $N=7$, $\alpha=1.1$ MeV, $\beta=0.35$ MeV, and, correspondingly, $\chi=-\sqrt{7}/2$. We note that in the absence of experimental information on the deformed core, we have determined the values of the SU(3) core parameters under the following assumptions: we have assumed that the 2_1^+ SU(3) core state lies 0.46 MeV above the 0_1^+ SU(3) state. This energy spacing is more than a factor of 2 smaller than the spacing between the 2_1^+ and 0_1^+ transitional core states of Ref. [14], which could be considered as a reasonable assumption. Further, the 0_2^+ SU(3) state was assumed to lie slightly above the 0_1^+ SU(3) state.

The $\pi g_{9/2}$ and $\nu g_{9/2}$ quasiparticle parameters were taken from the previous calculation for ^{72}As [14]. Boson-fermion interaction strengths included in the calculation are $\Gamma_0^\pi = \Gamma_0^\nu = 0.25$ MeV, and $\Lambda_0^\pi = \Lambda_0^\nu = 8.0$ MeV. In order to reproduce the odd-even staggering, the residual interaction strengths were adjusted to $H_\delta = 0.3$ MeV and $H_t = -0.09$ MeV. It should be pointed out that the values of the boson-fermion and residual interaction strengths associated here with the SU(3) core differ sizably from those given in Ref. [14], which were associated with a transitional core. However, this is consistent with the experience that the coexistence of IBFFM families of states associated with different types of cores [here the SU(3) and the transitional cores] involves sizable differences in other IBFFM interaction parameters.

The $\pi g_{9/2} \nu g_{9/2}$ IBFFM multiplet calculated in this way is shown in Fig. 3(c). For the calculation of the electromagnetic properties the effective charges and g factors were taken from Ref. [14], but with g_s^π and g_s^ν reduced to $g_s^\pi = 0.4\ g_s^{\pi,\mathrm{free}} = 2.234$ and $g_s^\nu = 0.4\ g_s^{\nu,\mathrm{free}} = -1.530$. Using this parametrization, the measured $B(E2)$ values [6] are well described both in the odd- and even-spin bands, as well as the relative strength of the $M1$ branching from the odd- to even-spin band, but the strength of the transitions connecting the even-spin states with the odd ones is underestimated by an order of magnitude.

We note that in this way many parameters were adjusted to the family of states having the prolate SU(3) core. We have checked, however, that these IBFFM results appear rather robust with respect to some changes of the core parameters. In particular, we have found that the assumption of the prolate SU(3) core is necessary to achieve a reasonable description of the corresponding experimental data.

In conclusion, the description within the IBFFM framework supports the assumption that the splitting of the $\pi g_{9/2} \nu g_{9/2}$ multiplet can only be associated with a prolate-deformed core, which coexists with the soft core of the five lower-lying two-quasiparticle multiplets identified in the ^{72}As nucleus. According to a good description of the electric quadrupole properties, the same $\beta_2 = 0.26$ prolate deformation can be associated with the present IBFFM calculation as was deduced from the band structure [6].

It is interesting that, although the ^{72}As nucleus has 5 valence protons and 11 valence neutrons, putting the odd neutron onto the intruding $g_{9/2}$ orbital is not enough to deform the nucleus. It becomes deformed only when a proton is also pushed to the $g_{9/2}$ orbit. According to Federman and Pittel [31], a mutual polarization between protons and neutrons leads to the deformation, resulting in an increased occupation of the deformation driving high-spin orbits. The presence of such an effect has been shown in odd-odd Sb nuclei [8]. In the present case, the need for unusually large exchange interactions (Λ_0) in the IBFFM calculations can be interpreted as a simulation of the increased $g_{9/2}$ occupation probabilities. Thus, it is expected that with decreasing neutron number the possibility for filling the intruding $g_{9/2}$ orbital is decreasing, and together with it the possibility for the polarization vanishes at some point. Looking at the level scheme of ^{68}As [32], it is seen that the $9^{(+)}$ state at 2158 keV (interpreted as the 9^+ member of the $\pi g_{9/2} \nu g_{9/2}$ multiplet) is isomeric, indicating that there are no low-spin members of the multiplet at lower energies, and hence there is no band found in this nucleus. This situation suggests that the turning point is reached at seven valence neutrons, although according to a Vampire calculation [33] the polarization can take place even at that neutron number.

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