PHYSICAL REVIEW C **82**, 044313 (2010)

Shape coexistence near the $N = 38$ shell gap: Magnetic moment of the 981.6 keV $J^{\pi} = 8^{+}$ level in ^{72}As

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(Received 27 October 2009; revised manuscript received 13 August 2010; published 20 October 2010)

We report on the first determination of the magnetic moment of the 981.1 keV, $J^{\pi} = 8^{+}$ level in ^{72}As, a nucleus that belongs to the $A \approx 70$ mass region dominated by rapidly changing deformations and shapes. The 8^{+} level is the bandhead of a collective sequence of positive parity levels coexisting with low-spin and medium-spin spherical shell-model states. The magnetic moment was measured by the time-integral perturbed angular distributions method to be $\mu = -(4.272 \pm 0.280)\mu_N$. This value is in disagreement with the presumed $[\pi(1g_{9/2}), \nu(1g_{9/2})]$ configuration and points to a more complex configuration involving two neutrons in the $1g_{9/2}$ orbital.

DOI: 10.1103/PhysRevC.82.044313 PACS number(s): 21.10.Ky, 23.20.En, 25.70.Gh, 27.50.+e

I. INTRODUCTION

Extensive investigations of the structure of neutron deficient $A \approx 60$–80, $N \approx Z = 33$–40 nuclei have revealed many interesting features. Drastic changes of properties appear for nuclei with $Z \geqslant 33$ when going from nuclei with 50 neutrons to nuclei with 36–40 neutrons [1,2]. Large quadrupole deformations $\beta \approx 0.4$ and strong collectivity are seen. Furthermore, evidence for shape coexistence at low spins, found for the first time in ^{72}Se [3], has generated a special interest in studies of the region. A striking feature is the strong variation of the shape as a function of particle number, excitation energy, and spin. The microscopic structure of the nuclei from the $A \approx 60$–80 mass region is essentially determined by the $2p_{1/2}$, $1f_{5/2}$, $2p_{3/2}$, and $1g_{9/2}$ orbitals. The strong shape variation and the shape coexistence effects may be interpreted as resulting from the competition of the stabilizing energy gaps of the deformed single-particle field at nucleon numbers 34, 36, 38, and 40. Calculations of the equilibrium configurations in this mass region were performed within the configuration-dependent shell-correction approach with deformed Woods-Saxon potentials [4].

Calculations based on the generalized Woods-Saxon potential (see Fig. 1, p. 398 of Ref. [4]) predict competing deformed gaps at nucleon numbers 34 and 36 for $\beta \approx -0.26$ and $\beta \approx -0.4$, respectively, and at nucleon numbers 34 and 38 for $\beta \approx 0.26$ and $\beta \approx 0.4$, respectively. A pronounced shell gap also exists at a nucleon number 40 for a spherical shape. The single-particle level density in the $A \approx 60$–80 nuclei is lower by a factor of 2 than in deformed heavy nuclei; therefore the single-particle deformed energy gaps that appear at similar nucleon numbers ($N, Z = 34$–38) manifest themselves in a comparatively dramatic way. Hence, adding or removing a few nucleons can have a dramatic effect on the nuclear shape. Competing prolate, oblate, and spherical shapes are even expected to coexist in the same nucleus. This is particularly true for the neutron-deficient selenium ($Z = 34$) and krypton ($Z = 36$) isotopes, where the protons appear to prefer an oblate shape, but where neutron numbers of 38–42 favor a strongly deformed $\beta \approx 0.4$ prolate shape.

The shape coexistence in ^{72}Se was explained as arising from the oblate polarizing influence of the shell gap at nucleon number 34 and the strong prolate driving influence of the gap at nucleon number 38. In recent years, nuclei near the strongly deformed shell gaps at $N = Z = 36$ and $N = Z = 38$ for large oblate and large prolate deformation, respectively, were investigated in much detail. The recently discovered $J^{\pi} = 0^{+}$ shape isomers in ^{74}Kr and, for the first time, in the $N = Z$ nucleus ^{72}Kr reinforced the evidence of the importance of both shell gaps [5]. Thus the detailed spectroscopy near the $N = 38$ deformed shell gap is still an interesting research subject.

The study of the $N = 39$ odd-odd nucleus ^{72}As is fairly interesting. Properties of low-lying, low-spin, and medium-spin states up to the 562.8 keV, $J^{\pi} = 7^{-}$ isomeric state were experimentally well investigated. The ground-state spin, magnetic dipole moment, and electric quadrupole moment were determined in an atomic beam nuclear magnetic resonance experiment [6]. Information on low-lying, low-spin, and medium-spin levels stemmed from the β decay of ^{72}Se [7,8] and from the ^{72}Ge$(p,n)^{72}$As [9–13], ^{69}Ga$(\alpha,n)^{72}$As [14], ^{70}Ge$(\alpha,pn)^{72}$As, ^{72}Ge$(\alpha,3np)^{72}$As [15], and ^{59}Co$(^{16}O,2pn)^{72}$As [16] reaction studies. The level scheme was established and two isomeric states were identified. The magnetic moments of the 2^{-} ground state and of the isomers with spins and parities 3^{+} and 7^{-} were also measured.

All experimental data, including the magnetic moments, were successfully described in terms of the nuclear shell model, without any assumption of nuclear deformation. Recently, a collective structure based on a 981.1 keV, $J^{\pi} = 8^{+}$ level was identified [14,17–20]. Information on the low-spin and high-spin levels of ^{72}As were recently summarized in Nuclear Data Sheets [21]. A relevant portion of the level scheme of ^{72}As is presented in Fig. 1.

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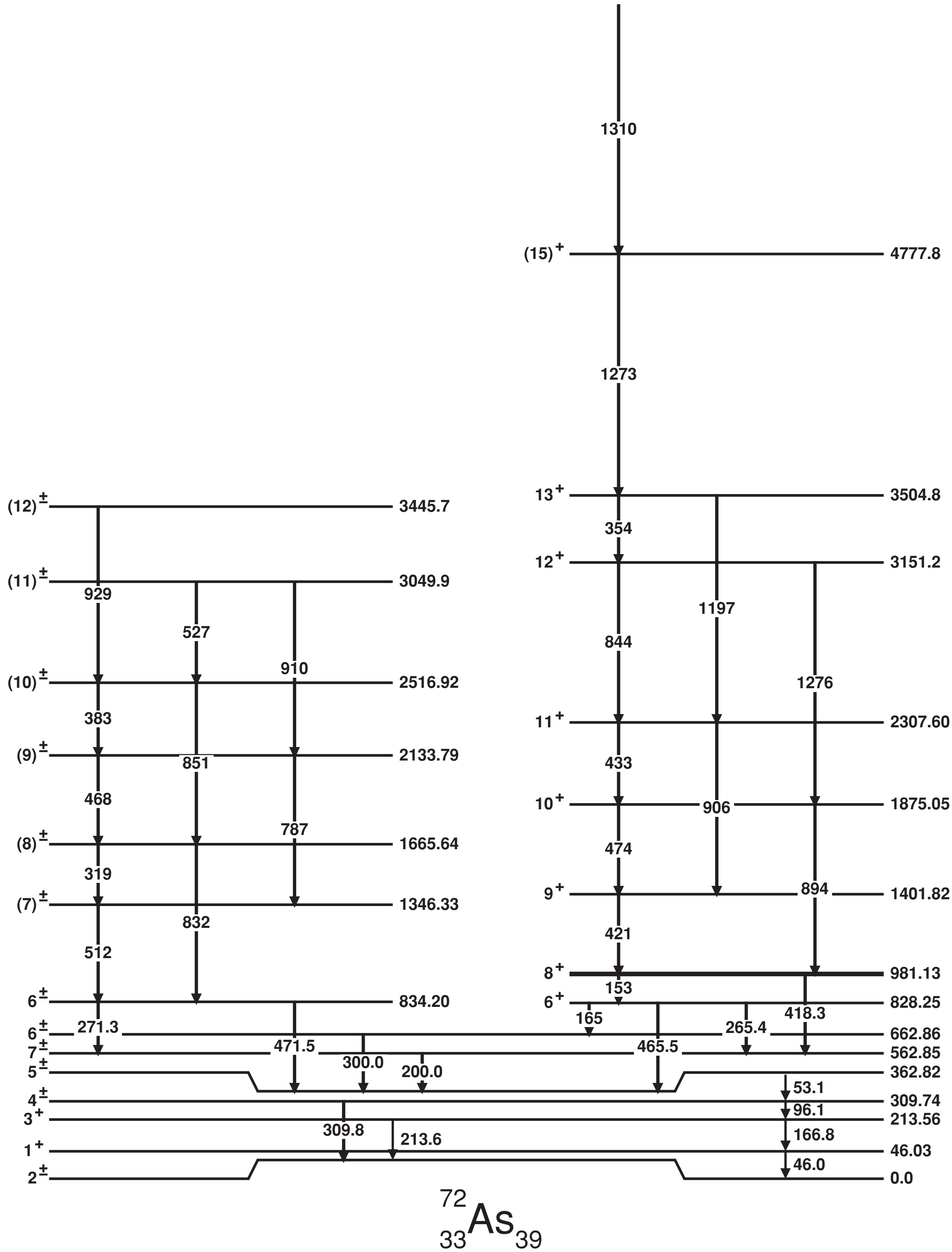

FIG. 1. Collective band built on the $J^{\pi} = 8^{+}$ level of ^{72}As.

The observed properties of the high-spin positive-parity level sequence such as rotational-like structure and enhanced $E2$ transition strengths ($B(E2) \approx 40$ W.U.) do not fit into the spherical shell model and point to a collective excitation coexisting with the low-spin and medium-spin spherical shell-model states. From the measured half-life of the 7^{-}, 562.8 keV level and the $E2$ character of the 200.3 keV transition a $B(E2) \approx 1.1$ W.U. will result.

The rotational-like positive parity band was tentatively interpreted as having a $[\pi(1g_{9/2}), \nu(1g_{9/2})]$ configuration [14,18]. To test this assumption and to investigate further the shape coexistence in ^{72}As we measured the magnetic moment of the 981.1 keV, $J^\pi = 8^+$ level using the time-integral perturbed angular distribution technique.

II. EXPERIMENTAL METHOD AND DATA ANALYSIS

The experiment was performed at the 8.5 MV Van de Graaff Tandem accelerator of the National Institute for Physics and Nuclear Engineering—Horia Hulubei (NIPNE-HH) in Bucharest, Romania. The excited states in ^{72}As were populated using the ^{56}Fe(^{19}F,$2pn$)^{72}As reaction at 60 MeV bombarding energy. The magnetic moment of the 981.1 keV, $J^\pi = 8^+$ level was measured by means of the time-integral perturbed angular distribution method. This state decays by a strong branch to the 562.8, $J^\pi = 7^-$ state and is not fed from higher-lying states with lifetimes larger than 1 ps. The experimental setup includes a special reaction chamber centered on an angular correlation turntable. To have the residual nuclei in a ferromagnetic environment, a thick (14 μm) natural iron foil was used as a target and implantation medium. To saturate the internal hyperfine field, the iron foil was placed between the poles of a small electromagnet. The gamma rays were detected by two large-volume, intrinsic Ge detectors, having resolutions of about 1.9 and 2.5 keV at 1.33 MeV. One of the detectors was placed at 270° and used as a monitor; the second one was placed successively at seven angles between 0° and 90°. Two measurements were performed: (a) an angular distribution measurement without polarizing magnetic field and (b) a measurement with the moving detector placed seven angles between 0° and 90° for the up and down directions of the polarizing magnetic field.

The measured gamma-ray spectra produced in the heavy-ion bombardment were quite complex since seven residual nuclei of comparable intensity such as $(2p)^{73}$As, $(pn)^{73}$Se, $(\alpha n)^{70}$As, $(\alpha p)^{70}$Ge, $(2pn)^{72}$As, $(p2n)^{70}$Se, and $(\alpha pn)^{69}$Ge were produced in the decay of the compound nucleus ^{75}Br.

A relevant region of a measured spectrum is presented in Fig. 2.

The spectra analysis was carried out using the interactive code LEONE [22]. For normalization we used both the intensities of some strong transitions measured with the monitor detector and the intensity of the strong isotropic 398 keV transition from ^{69}Ge, measured with the moving detector. In Fig. 3 we present the measured angular distribution for the 418.3 keV transition deexciting the 981.1 keV, $J^\pi = 8^+$ level of ^{72}As and the result of a fit with Legendre polynomials.

The extracted coefficients were $A_2 = -0.217 \pm 0.005$ and $A_4 = 0.003 \pm 0.006$. The transition is a pure dipole. The rather large A_2 coefficient shows a substantial alignment of the $J^\pi = 8^+$ level.

The perturbed angular distribution in a static magnetic field is given by

$$W(\theta, \pm H) = 1 + b_2 \cos[2(\theta \mp \Delta\theta_2)] + b_4 \cos[4(\theta \mp \Delta\theta_4)]. \quad (1)$$

For a pure dipole transition we have

$$W(\theta, \pm H) = 1 + b_2 \cos[2(\theta \mp \Delta\theta)], \quad (2)$$

where $\Delta\theta$ is the mean rotation angle. The b_2 coefficient is related to the A_2 coefficient by the relation $b_2 = (3/4A_2)/(1 + 1/4A_2)$. The Larmor frequency is obtained using $\tan(2\Delta\theta) = 2\omega\tau$, where τ is the lifetime of the level. Finally, the gyromagnetic factor is related to the Larmor frequency and to the value of the hyperfine magnetic field by $\omega = -g\mu_N H/h$.

The measured perturbed angular distribution of the 418.3 keV transition in ^{72}As for both field directions is shown in Fig. 4.

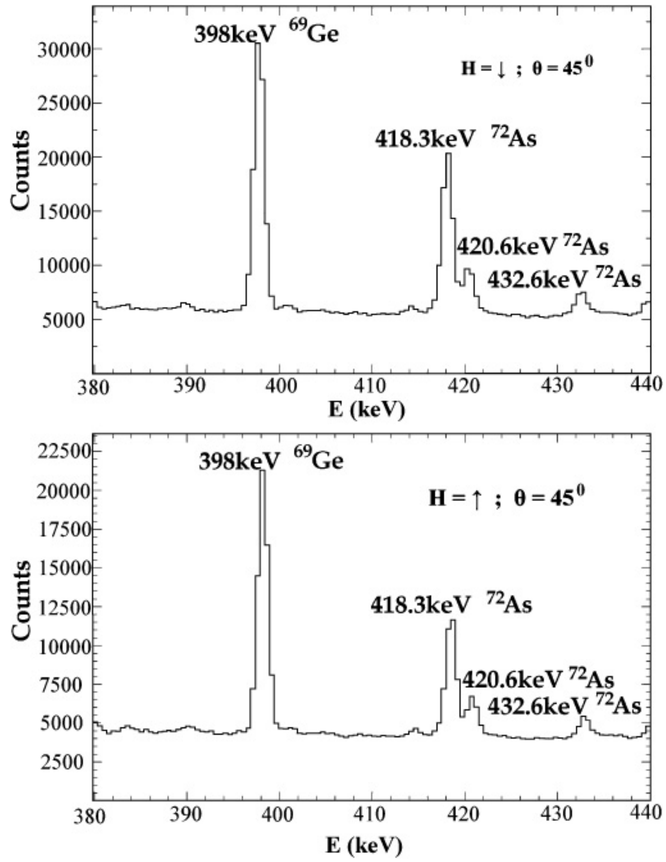

FIG. 2. Relevant portions of spectra measured at 45° with polarizing magnetic field down ($H = \downarrow$) and up ($H = \uparrow$).

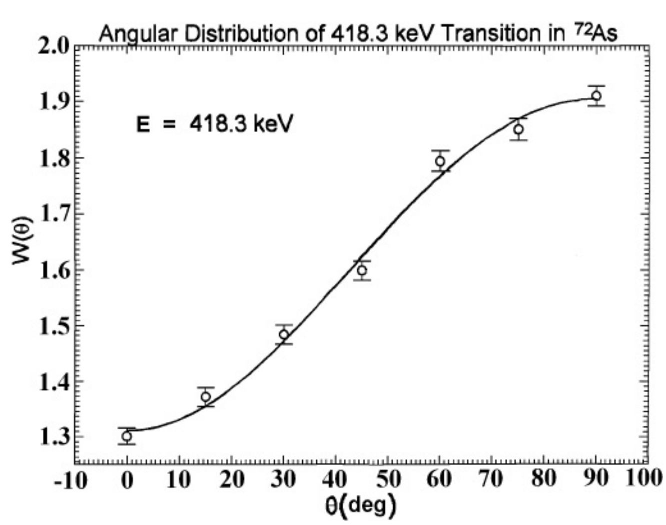

FIG. 3. Angular distribution of 418.3 keV transition.

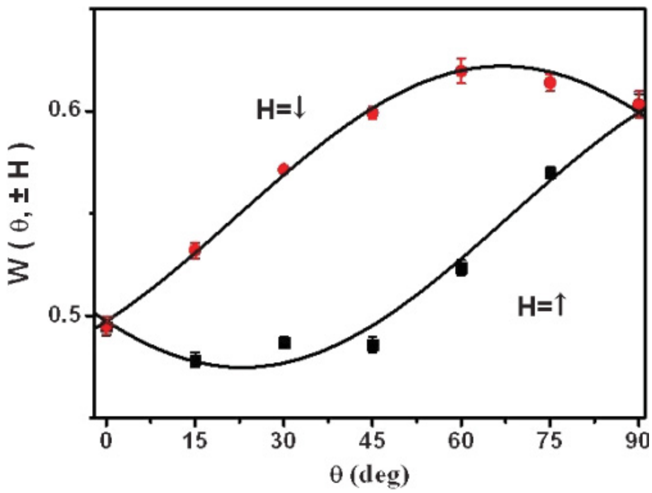

FIG. 4. (Color online) Perturbed angular distribution of the 418.3 keV transition.

The perturbed angular distribution was analyzed by fitting the expression (2) to the experimental points. The experimental precession value $\Delta\theta = (23.04 \pm 0.80)^\circ$ was obtained.

For the hyperfine field for As nuclei in Fe a value of H(As/Fe) = +342.9(3) kG was adopted [23]. Using for the lifetime of the level the value $\tau = 580 \pm 20$ ps [19], we obtained a g factor of $g = -(0.534 \pm 0.035)$. This gives for the magnetic moment a value of $\mu = -(4.272 \pm 0.280)\mu_N$.

III. RESULTS AND DISCUSSION

Nuclei in the $A \approx 70$ mass region exhibit a large variety of complex structure phenomena, including large deformations, shape transitions, and shape coexistence. The theoretical description of these nuclei is complicated because of the large number of nucleons outside the closed shells $N = Z = 28$, which lead to a variety of possible configurations. Also, because of the presence of several, rather large gaps in the Nilsson scheme for both protons and neutrons in this mass region, the nuclear structure often changes drastically by adding just a few nucleons. The proximity of the $N = 38$ prolate and $N = Z = 34, 36$ oblate shell gaps implies that nuclei exhibit different shapes at different excitation energies. All these aspects make the $A \approx 70$ mass region an interesting testing ground for different theoretical approaches. Measurements of magnetic moments of these nuclei can help determine which of the various possible configurations is realized in a certain isotope, thus providing basic tests of nuclear models.

The low-spin states of ^{72}As ($Z = 33$, $N = 39$) were interpreted using the spherical shell model or models adapted from the spherical shell model. Because $N = 38$ is sometimes considered to be a semimagic number it is expected that the low-lying states have relatively simple configurations from the point of view of the shell model. In fact, the magnetic moment of the ground state of ^{72}As as measured by Phillips *et al.* [24], Herzog *et al.* [25], and Hogerworst *et al.* [26] are very close to the value for configuration $[\pi(f_{5/2})^1, \nu(g_{9/2})^1]_{2^-}$. The appearance of this configuration as the ground state is in accordance with the predictions of Nordheim's rule.

The magnetic moments of the isomeric states 3^+ at 213.6 keV and 7^- at 562.8 keV were discussed as arising predominantly from the configurations $[\pi(f_{5/2})^1, \nu(f_{5/2})^{-1}]_{3^+}$ and $[\pi(f_{5/2})^1, \nu(g_{9/2})^1]_{7^-}$, respectively [27,28]. In all these cases the unpaired proton is thought to move in the $1f_{5/2}$ subshell. The $E1$ transitions to the ground state from the 46 keV, 1^+ state and from the 214 keV, 3^+ state are strongly hindered by factors of about 10^4 and 10^7, respectively. This shows that the 5 protons and 11 neutrons above the ^{56}Ni core fill mostly the $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, and $1g_{9/2}$ orbitals. Within this configuration space $E1$ transitions are strictly forbidden. Thus, the effect of other orbitals such as $1f_{7/2}$ or $2d_{5/2}$ is very small.

To get an insight into the structure of the low-lying ^{72}As states, calculations were performed in several articles using various models. ten Brink *et al.* [29] calculated the energy spectra and electromagnetic properties of ^{72}As using a number-conserving BCS quasiproton-quasineutron model. They used a Schiffer force for the effective proton-neutron interaction. It was supposed that the nuclear core was spherical and the phonon degrees of freedom were neglected. The experimental splitting of the $[\pi(f_{5/2}), \nu(g_{9/2})]$ multiplet is quite well reproduced by the model, which seems to suggest that phonon degrees of freedom that are not contained may be neglected.

The magnetic moments of the 2_1^-, 3_1^+, and 7_1^- levels are well reproduced by the calculations. Sohler *et al.* [13] calculated the energy spectra and electromagnetic properties of ^{72}As using the interacting boson-fermion-fermion model (IBFFM). The wave functions are rather complex, with several hundred nonvanishing components. However, in the 2_1^- ground state and the 7_1^- excited state the dominating configuration is $[\pi(f_{5/2}), \nu(g_{9/2})]$. The magnetic moments are quite well reproduced. For the 3_1^+ the wave function is more complex. The magnetic moment is well reproduced, in closer agreement with the experiment than in the calculations of ten Brink *et al.* The structure of low-spin and high-spin levels in ^{72}As has been investigated microscopically in the framework of the few determinant (FED) VAMPIR approximation [30]. General symmetry-projected Hartree-Fock-Bogoliubov (HFB) quasiparticle configurations were used as basic building blocks and the underlying mean fields, as well as the configuration mixing, were determined by chains of variational calculations. The calculations are based on complex HFB transformations allowing parity and proton-neutron mixing, but still imposing time reversal and axial symmetry. Concerning the magnetic moments, the calculations yield g factors of 0.933 for the prolate and 0.063 for the oblate yrast 7^- solution; the experimental value is 0.116(2). For the lowest 3^+ level the experiment yields a g factor of 0.525(6) in quite good agreement with the value 0.52 obtained from the oblate solution for this state while the prolate solution yields 0.38. For the 2^- ground state the experimental g factor is −1.08, while the calculation produces 0.69 for the prolate solution and 0.06 for the oblate solution. In Ref. [20] the 8^+ level and the collective sequence based on this level were tentatively interpreted as a collective structure built on the $2qp$ configuration $[\pi(1g_{9/2}), \nu(1g_{9/2})]$ from comparisons with rotational bands found in other odd-odd nuclei from the $A \approx 70$ mass region such as ^{74,76}Br. In Ref. [14] the same tentative configuration is assigned for 8^+ and 9^+ states at 981.1 and 1401.8 keV, respectively. There is no theoretical prediction for the magnetic moment of the 8^+ level in ^{72}As.

From the shell-model theory, the g factor of a doubly odd nucleus is given by

$$g = \frac{1}{2}(g_p + g_n) + \frac{1}{2}(g_p - g_n)\frac{J_p(J_p+1) - J_n(J_n+1)}{2J(J+1)},$$

where $p(n)$ indicates the odd proton (neutron), respectively. To take into account core polarization, the values of the experimental g factors from neighboring odd nuclei have to be used in the calculations. The Schmidt single-particle value for the $1g_{9/2}$ proton is $g = 1.509$ ($\mu = 6.79$). The measured values of the magnetic moments of the isomeric $(9/2)^+$ states in ^{69,71,73}As are 4.64(59), 5.108(45), and 5.234(14), respectively [31,32]. These values are somewhat lower than the Schmidt value. The Schmidt single-particle value for the $1g_{9/2}$ neutron is $g = -0.425$ ($\mu = 1.91$). An experimental g factor of $g = -0.215(10)$ can be derived as the average of the g factors of the $9/2^+$ states in even-odd Ge isotopes from Ref. [33]. If we assume that the 8^+, 981.1 keV level has a $[\pi(1g_{9/2}), \nu(1g_{9/2})]$ two-particle configuration then the calculated value of the g factor is $g = 0.460$, in disagreement with the experimental value. The lifetime of the 8^+ level yields $B(E1) = 1.22 \times 10^{-5} e^2(\mathrm{fm})^2$ for the $E1$ transition to the 562.8, 7^- state [19]. Also this $E1$ transition is strongly hindered by a factor of about 10^{-5} over the single particle unit. The negative sign of the measured g factor of the 8^+ level points on a neutron-excited configuration. On the basis of the magnetic moment the $[\pi(f_{5/2})^1, \nu(g_{9/2})^1]$ configuration was assigned to the 2^- ground state of ^{72}As. The $9/2^+$ level is at 198 keV excitation energy in the isotonic nucleus ^{71}Ge. If a second neutron is promoted into the $1g_{9/2}$ orbital, a $\nu[(1g_{9/2})^2_{8^+}(1f_{5/2})^{-1}]_J$ two-particle one-hole neutron configuration is created. The neutron states associated with this configuration couple with the proton in the $1f_{5/2}$ orbital. The experimental g factors of the protonic and neutronic $1f_{5/2}$ states are $g = +0.667$ and $g = +0.308$, respectively. If we use for the g factor of the $1g_{9/2}$ neutron the experimental value $g = -0.215(10)$ we obtain for the g factor of the 8^+ state the value $g = -0.301$, if we consider a stretched neutron state with $J = (21/2)^-$. It is interesting that, in spite of the fact that in the ground state the odd neutron is in the intruding $1g_{9/2}$ orbital, this is not enough to deform the nucleus. It becomes deformed only when a second neutron is pushed to the $1g_{9/2}$ orbital.

In summary, we measured the magnetic moment of the 981.6 keV, $J^\pi = 8^+$ level in ^{72}As for the first time. The deduced magnetic moment is in disagreement with a presumed $[\pi(1g_{9/2}), \nu(1g_{9/2})]$ two-quasiparticle configuration. In spite of the fact that in the ground state the odd neutron is in the intruding $1g_{9/2}$ orbital, this is not enough to deform the nucleus; the negative sign of the g factor points to a more complex configuration involving two neutrons in the $1g_{9/2}$orbital. Therefore the nucleus appears to become deformed only when a second neutron is pushed in the $1g_{9/2}$ orbital.

ACKNOWLEDGMENTS

We acknowledge the financial support of Romanian ANCS/MEC and UEFISCSU-CNCSIS under the Contract No. ID-293/2007.

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