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Yrast isomers in ^{95}Ag, ^{95}Pd, and ^{94}Pd

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The yrast level schemes of three neutron deficient nuclei with mass $A \approx 95$ have been studied with the reaction ^{58}Ni+^{40}Ca at 135 MeV, using the GASP γ-ray array, the ISIS silicon ball, and the n-ring neutron detector. Excited levels, including a $(23/2^+)$ spin-gap isomer, are reported for the first time in the heaviest $N=Z+1$ nucleus experimentally investigated, ^{95}Ag. In ^{95}Pd, the yrast line above the ground state has been observed and connected to states above the known isomeric level $21/2^+$, showing for the first time that this is indeed a spin-gap isomer. In ^{94}Pd, the 95.6-keV isomeric transition was confirmed, and its $E2$ character was firmly established. The experimental observations are compared with current shell-model calculations.

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New experimental information about neutron deficient nuclei with mass above 90 is of considerable interest for shell-model calculations aimed at the description of nuclei close to ^{100}Sn. Being close to the $N=Z$ line, they are expected to show enhanced neutron-proton pairing effects based on the $T=0, I=1, I_{max}$ configuration [1]. The nuclear structure in this region is mainly given by $(p_{1/2}, g_{9/2})$ hole configurations in the doubly magic ^{100}Sn, and therefore the neutron-proton pairing is dominated by the $g_{9/2}$ neutron and proton orbitals. Older shell-model calculations of Gross and Frenkel [2] in the proton $(p_{1/2}, g_{9/2})$ subshells have been performed assuming a semimagic ^{88}Sr core and a set of two-body matrix elements, which describe well many experimental data. Other sets of two-body effective interactions were deduced for this region more recently, but most of them are tuned for nuclei close to the β stability line. Going towards heavier neutron deficient nuclei, a better specification of the effective interaction becomes crucial. Experimental information concerning nuclei close to the $N=Z$ line is not so rich as for the isotopes close to stability. In many cases, such as the rp-process calculations, physics based on the properties of proton rich nuclei relies on shell-model estimates instead of unavailable experimental quantities. Thus it is very important to have reliable shell-model description for the $N \approx Z$ nuclei of this region. One of their characteristics that must be described is the occurrence of high-spin isomeric states.

In ^{95}Pd, a high-spin isomeric state with a half-life of 14 s decaying by both β^+/EC (where EC stands for electron capture) and β-delayed proton emission has been discovered, assigned as $(21/2^+)$, and placed at approximately 2 MeV excitation energy [3,4]. Shell-model calculations of Ogawa [5] have predicted that the first $21/2^+$ state in this nucleus has lower excitation energy than the first $15/2^+$ and $17/2^+$ states. This inversion would create a spin-gap isomer, since the $21/2^+$ state could be deexcited only by β decay competing with $E4\,\gamma$ decay to the first $13/2^+$ state. The calculated position of this state relative to the $17/2^+$ state was shown to depend rather critically on the value of the two-body matrix element $\langle g_{9/2}^2 | V_{pn} | g_{9/2}^2 \rangle_{J=9}$ [5]. Recent γ-ray spectroscopic investigations have assigned excited states above the isomeric level, but its real position has still remained unknown, as the excited states above the ground state could not be observed [6]. In ^{94}Pd, seven yrast transitions were identified following the decay of a 0.53(1) μs half-life of an isomeric state [7,8], which has been associated to the 14^+ isomer predicted by shell-model calculations. In a very recent study of ^{94}Ag β decay [9], some new γ rays were assigned to ^{94}Pd and placed below and above the isomeric state. Consistent information about the level structure of the $N=Z+1$ nucleus ^{95}Ag was not available in literature until the present work. Only very recently three γ rays have been attributed to this nucleus, but they could not be placed in a level scheme [10]. Shell-model calculations [5,11] predicted another possible spin-gap isomer in this nucleus. The present experimental data enrich significantly the knowledge of this nuclear region and allow a much better test for the current shell-model calculations in nuclei close to $N=Z=50$.

The ^{94}Pd, ^{95}Pd, and ^{95}Ag nuclei have been populated in the ^{58}Ni+^{40}Ca reaction performed at the Legnaro XTU Tandem accelerator with a ^{40}Ca beam of energy 135 MeV. The incident beam energy favored the two- and three-particle evaporation channels. The beam intensity during the experiment was about 8 particle nA, and a ^{58}Ni foil of thickness 6 mg/cm^2 was used as target.

The γ rays were detected with the GASP detector array [12] arranged in its standard configuration with 40 Compton-suppressed high purity Ge detectors and with the 80 BGO

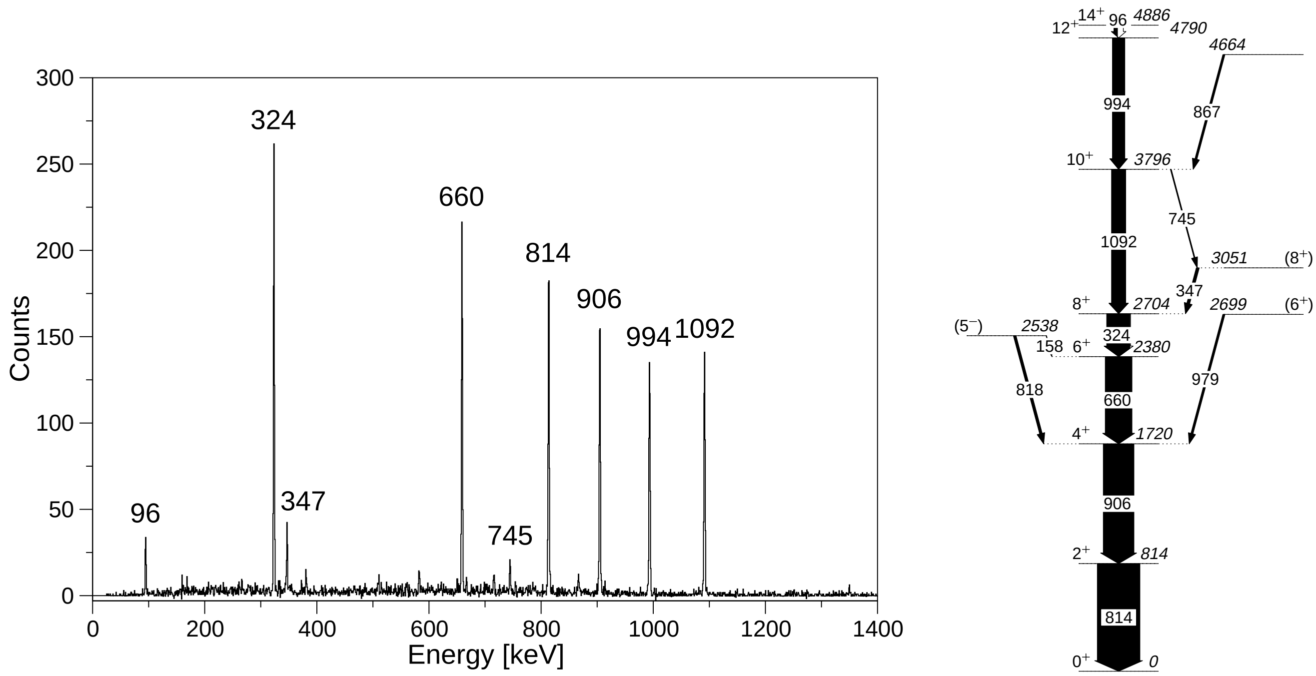

FIG. 1. Left side: γ-Ray spectrum obtained by a sum of double gates on the known yrast transitions of ^{94}Pd, on a γ-γ-γ cube anticoincident with charged particles. Right side: The level scheme of ^{94}Pd as deduced from the present experiment.

element inner ball. The six elements of the most forward ring of the BGO inner ball were replaced by the *n*-ring detector [13], which consisted of six BC501A liquid scintillator detectors for neutron-γ discrimination. The ISIS silicon ball [14,15], a 40-element $\Delta E - E$ telescope array, with a geometry similar to that of GASP, was also used. The trigger condition required at least two Ge detectors and one BGO firing in coincidence. This "low multiplicity" trigger was specially chosen to facilitate the study of isomeric states, which possibly decay by short cascades with a small number of γ rays.

Information on the charged particles was extracted from the ISIS data, and it consisted of the type and multiplicity of the detected particles. Neutron selection was performed by setting conditions on pulse shape signal, detected energy, and time of flight. The experimental values of the particle detection efficiencies were $\sim 60\%$ for detecting one proton, 38% for one α particle, and 3.5% for one neutron. About 10^9 events were collected during the experiment. Several γ-γ-γ cubes and γ-γ coincidence matrices were sorted with different conditions on the detected charged particles and neutrons. They were used to assign the γ rays emitted through the decay of excited states in the residual nuclei.

The right side of Fig. 1 presents the level scheme of ^{94}Pd populated through the $2p2n$ channel as observed in this experiment. The 96-keV transition, which is the highest one observed by us in the yrast line, was confirmed to be the previously reported isomeric transition with a half-life of 0.53(1) μs [9]. The spectrum from Fig. 1 shows a sum of double gates set onto the known yrast transitions of this nucleus [7,9] selected from a γ-γ-γ cube anticoincident with charged particles. By gating on this cube or on γ-γ matrices vetoed by the charged particles, most of the observed events come from coincidences in cascades, which are delayed with respect to the reaction. The 96-keV line was confirmed as an isomeric transition by the fact that a spectrum similar to that of Fig. 1 was obtained from a cube coincident with protons, and it has shown all lines, except the 96-keV transition. Indeed, if this transition would have came from a prompt decay, it should have been observed in coincidence with protons five times more intense because of high proton detection efficiency. It should be mentioned that the same effect has been observed for many other known long lived isomers of nuclei populated in our reaction. Generally, only isomers of up to several tens of nanoseconds can be seen in prompt coincidence with charged particles or neutrons.

Assuming a constant intensity of the decay along the cascade fed by the isomeric level, the total conversion coefficient of the 96-keV transition was estimated to be $\alpha_T = 1.9(4)$. Dipole multipolarity, which could not be excluded by the lifetime of the isomeric state, would have led to an α_T value at least three times smaller, while the theoretical value for a $14^+ \rightarrow 12^+$ transition is 1.65. So the experimental value is clearly consistent only with stretched $E2$ multipolarity. Following the isomer decay, we observed weak transitions at 347 and 745 keV. The first one was observed also in Ref. [9] but was not placed in the level scheme. In the same work, a 745-keV transition is marked as ^{52}Mn contamination. Conversely, our double-gated spectra showed the 347- and 745-keV γ rays in coincidence with each other and with the whole yrast cascade, except the 1092-keV line. These coincidence relationships validate their placement in the ^{94}Pd level scheme as shown in Fig. 1.

Besides the 347- and 745-keV lines, other transitions of 979, 818, 158, and 867 keV were found in prompt coincidence with protons and neutrons. The 979-keV line was previously reported by La Commara *et al.* [9], and its placement

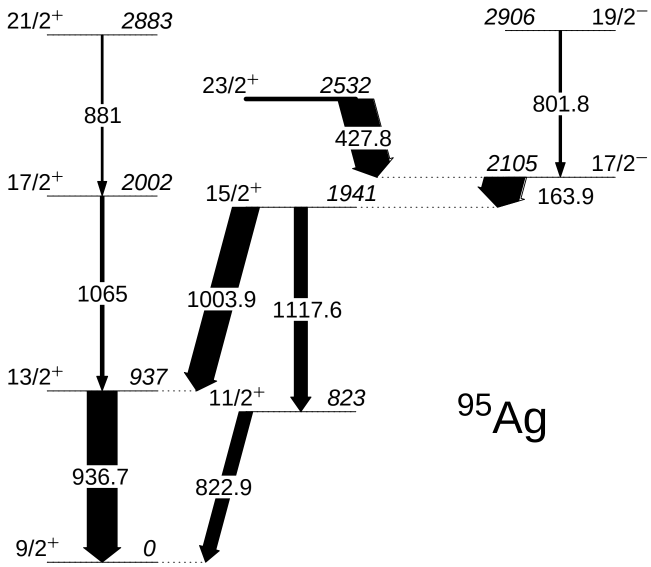

FIG. 2. Level scheme of ^{95}Ag as established in the present experiment.

in the level scheme is confirmed by our data. The angular distribution analysis has revealed a stretched quadrupole type for the 906-, 660-, 324-, 1092-, 994-, and 979-keV transitions, while the angular distribution of the 818-keV line suggests a pure dipole type. These results and the conversion coefficient of the 96-keV transition allow clear spin-parity assignments for the levels observed in the ^{94}Pd nucleus as presented in Fig. 1. For instance, the spin and parity of the isomeric state are firmly supported by our experimental data to be 14^+, as predicted by the shell model.

Figure 2 shows the level scheme of the ^{95}Ag nucleus, which was populated in the present experiment through the $1p2n$ reaction channel. In the case of this nucleus, our experimental results suggested that the level at 2532 keV is isomeric having a relatively long half-life, probably well above 1 μs. We discuss below the grounds for this assignment. Candidates for transitions from excited states in ^{95}Ag were found by comparing spectra from matrices produced setting different conditions on neutrons and charged particles. One such candidate line is the 164-keV transition. Starting from this line, the level scheme presented in Fig. 2 was constructed following the usual procedure based on the relative intensities of the observed γ transitions and the coincidence relationships between them. Figure 3 shows gated spectra that support our assignments. The first three spectra in the upper part are as follows. Figure 3(a) shows gate on the 164-keV γ ray selected from a matrix coincident with neutrons and with at least one proton, Fig. 3(b) shows gate on the same γ ray selected from a matrix coincident with neutrons and at least two protons, and Fig. 3(c) shows the same gate on a matrix coincident with neutrons and α particles. The peaks from Figs. 3(b) and 3(c) correspond to transitions in the channels $3pn$ (^{94}Rh) and αpn (^{92}Rh), respectively. One can observe that the five peaks with energies from 802 to 1118 keV are present in Fig. 3(a) while they are absent in Figs. 3(b) and 3(c). Hence they must belong to a nucleus populated through evaporation of only one proton and some neutrons. In order to identify the reaction channel, the number of neutrons was estimated from the intensities of candidate lines in coincidence with neutrons. The neutron multiplicity is proportional to the ratio of the intensity of a γ line in coincidence with neutrons versus the total intensity of the same line. Compared with that of the γ rays in channels with one neutron, this ratio is double for our candidate lines; thus two neutrons are evaporated (see Fig. 3). As a result, these five transitions have been assigned to the $1p2n$ channel corresponding to the nucleus ^{95}Ag.

One should note in Fig. 3(a) the complete absence of the 428-keV line. As in the case of ^{94}Pd, this indicates an isomer

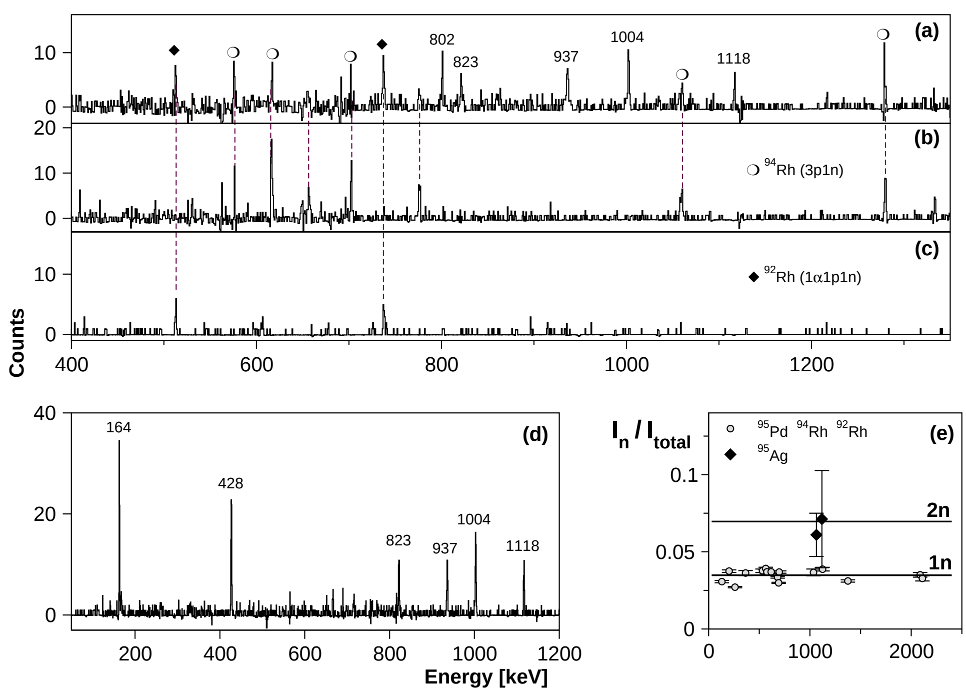

FIG. 3. Spectra demonstrating the level scheme of ^{95}Ag. (a) A gate on the 164-keV transition, on a matrix coincident with neutrons and zero or one protons; (b) a gate on the same line on a matrix coincident with neutrons and at least two protons; (c) the same gate on a matrix coincident with neutrons and α particles; (d) sum of double gates on different transitions assigned to ^{95}Ag, on a cube vetoed by charged particles (see text for details). Lower right corner: relative neutron multiplicity estimated for the 1065- and 1118-keV transitions assigned to ^{95}Ag and for transitions from channels with one evaporated neutron.

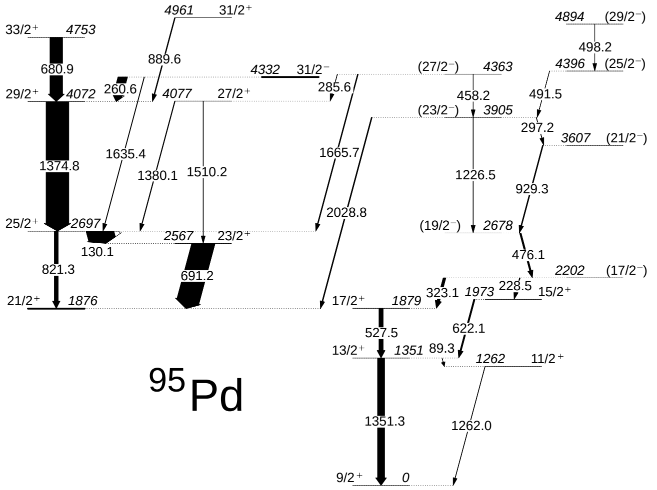

FIG. 4. Low-energy level scheme of ^{95}Pd determined in the present experiment.

decaying by this transition with a lifetime of the order of 1 μs or larger. The last spectrum [Fig. 3(d)] is a sum of triple coincidences selected from the cube vetoed by charged particles as discussed above. This spectrum was obtained by setting double gates on all combinations between the γ rays of 164 keV, 428 keV, and the group composed by the 823-, 937-, 1004-, and 1118-keV lines. It clearly shows the γ-ray cascade fed by the isomeric level at 2532 keV as presented in Fig. 2. The absence of the 802-keV transition from Fig. 3(d) is explained by the short lifetime of its initial level promptly fed in the reaction. We could not derive angular distributions or angular correlations with enough accuracy to allow multipolarity assignments since the statistical level of the experiment was very low for ^{95}Ag. The spin and parity values shown in Fig. 2 are only tentative, and they were made by comparison with shell-model calculations (Refs. [5,11] and below).

In ^{95}Pd, we found the previously unknown excitation energy of the $21/2^+$ isomer. We have also observed many new high-spin levels related to the positive- and negative-parity structures reported by Arnell *et al.* [6] above the $21/2^+$ isomeric state. We report here only on the results concerning the lower spin part of the level scheme.

From the β^+/EC decay of ^{95}Ag [11], we had some information concerning low-spin states feeding the ground state. The lowest state was proposed at 1262 keV. In Ref. [11] an intriguing transition of 1351 keV was also discussed, and it was finally thought to be a transition from ^{95}Rh [16]. We clearly deduced that a 1262-keV line belongs to the $2pn$ channel (^{95}Pd). Moreover, the 1351-keV transition is a composite line that belongs both to the $2pn$ and $3p$ (^{95}Rh) channels. The presence of a transition at 89 keV in coincidence with the 1262-keV line proves the existence of the 1351-keV level, which decays directly to the ground state. Using these observations, we have built up the level scheme of ^{95}Pd nucleus starting from the ground state, as shown in the right side of Fig. 4. The upper transitions at 285.6, 1665.7, and 2028.8 keV were found in our experiment to be in coincidence with known transitions assigned by Arnell *et al.* above the $21/2^+$ isomer [6] and shown on the left side of Fig. 4. These new transitions allowed a connection between the two parts of the level scheme, and consequently the excitation energy of the isomer was firmly established to be 1876 keV.

The multipolarities of the new transitions have been estimated from angular distributions and DCO ratios. In particular, the $11/2^+$ assignment to the 1262-keV state is in agreement with its observation in the β decay of the ^{95}Ag ground state [11]. The transitions of 1351 and 527 keV were found to be of stretched quadrupole type supporting the spin parities $13/2^+$ and $17/2^+$ for the 1351- and 1879-keV levels, respectively. Moreover, the 323-keV transition was found to be of pure nonstretched dipole type, and this fact supports the negative-parity assignments for the structure built upon the 2202-keV level. The tentative spin assignments shown in Fig. 4 are consistent with the spin values assigned in earlier experiments [6] to the isomeric state and to the states above it. It should be emphasized that the excitation energy of the $21/2^+$ isomer is 3 keV below the $17/2^+$ level. This clearly proves for the first time that the $21/2^+$ state is a real "spin-gap" isomer whose γ decay may take place only by an $E4$ transition of 525 keV unobserved by us and which must compete with the observed β^+/EC decay [3,4].

Most of the properties of the nuclei with $Z,N \leqslant 50$ are satisfactorily described by assuming a $^{100}_{50}$Sn core and placing the valence proton and neutron holes into the $g_{9/2}, p_{1/2}$ orbitals [17]. However, to account for the observed high-spin states of some $N=50$ nuclei [18] or for the distribution of the β^+ decay of ^{96}Ag [19], it is more appropriate to consider a larger configuration space. So the restriction of a rigid ^{100}Sn core is relaxed and particle-hole excitations are allowed to occur from the $g_{9/2}$ and $p_{1/2}$ orbits to the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, and $s_{1/2}$ shells above.

In order to get insight to the nuclear structure of the nuclei studied in our experiment, shell-model calculations were carried out using the model proposed by Johnstone and Skouras (JS) [17]. These calculations, shown in Fig. 5, reproduce most of the observed levels of the three nuclei within about 100 keV, including those which have still tentative spin-parity assignments. One should notice that above 2 MeV excitation energy, the calculation predicts several other levels, which will not be discussed here.

Using the JS wave functions, we have made a preliminary study of the decay of the 14^+ state of ^{94}Pd and of the $21/2^+$ state of ^{95}Pd. With an effective charge of $1.5e$ for protons and $0.75e$ for neutrons, we obtained $B(E2)=53\ e^2\,\mathrm{fm}^4$ for the $14^+ \rightarrow 12^+$ decay of ^{94}Pd, which is in satisfactory agreement with the experimental estimate of $44(6)e^2\,\mathrm{fm}^4$. On the other hand, the calculation predicts a partial half-life of about 50 s for the $E4$ decay $21/2^+ \rightarrow 13/2^+$ in ^{95}Pd. This value is 3.5 times slower than the half-life of the $21/2^+$ state corresponding to its β^+ decay [3,4].

Despite its success in reproducing the energies of the ^{95}Ag levels, the JS model is not suitable for describing the decay of the $23/2^+$ state at 2532 keV. This particular state is expected to deexcite mainly by $E3$ decay to the $17/2^-$ state at 2105 keV [11]. However, the $E3$ decay in the $N,Z \leqslant 50$ nuclei proceeds mainly by the $g_{9/2} \rightarrow p_{3/2}$ and $g_{9/2} \rightarrow f_{5/2}$ tran-

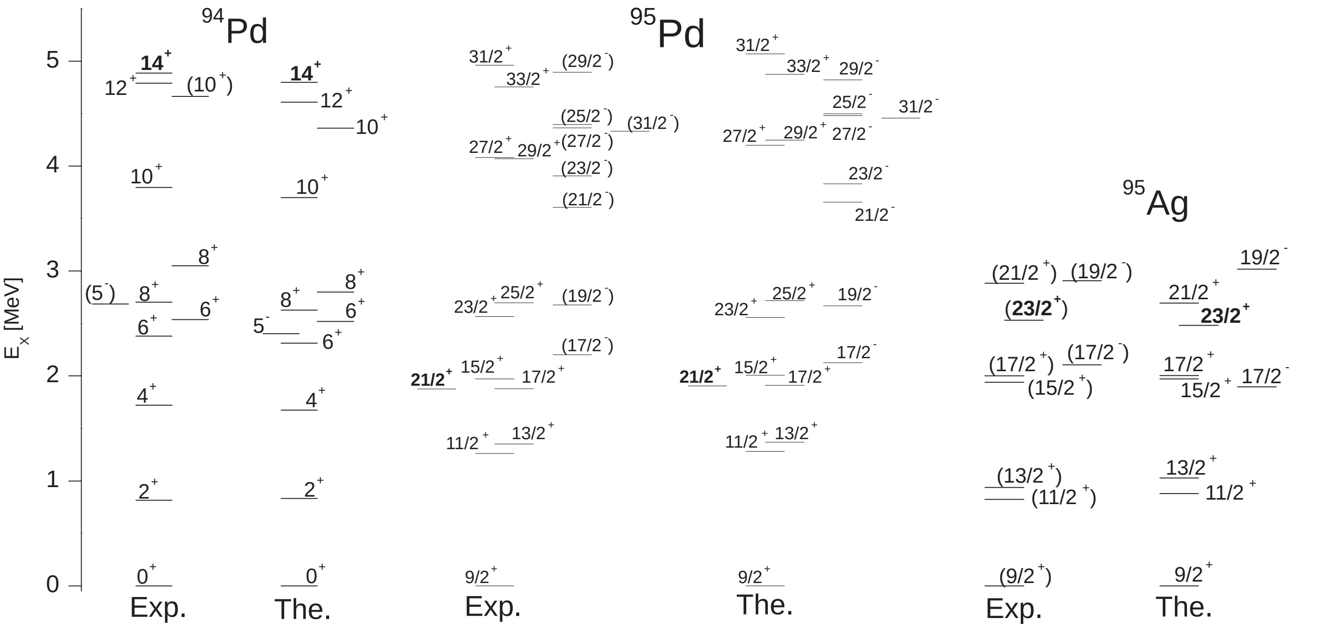

FIG. 5. Comparison of the experimental level schemes of ^{94}Pd, ^{95}Ag, and ^{95}Pd, with the JS shell-model calculations (see text for details).

sitions and, as described above, the $p_{3/2}$ and $f_{5/2}$ orbitals are not included in the JS model space. To determine the decay of the $23/2^+$ state of ^{95}Ag, Schmidt *et al.* [11] used the model of Sinatkas *et al.* [20], which employs a $\{g_{9/2},p_{1/2},p_{3/2},f_{5/2}\}$ model space. Using the latter model but the experimental energies of the ^{95}Ag levels, we estimate that the $23/2^+$ state is deexcited by about 98% to the $17/2^-$ at 2105 keV with a weak branch to the $17/2^+$ state at 2002 keV. The calculated half-life is about 3 ms, i.e., about two orders of magnitude faster than the half-life estimated for the β^+ decay of this $23/2^+$ state [11].

To summarize, in this paper are presented new experimental results for yrast isomers in ^{95}Ag, ^{95}Pd, and ^{94}Pd. A level scheme for ^{95}Ag, the heaviest $N=Z+1$ nucleus studied by γ-ray spectroscopy, was deduced for the first time. This level scheme includes a $23/2^+$ isomeric state that is deexcited by $E3$ decay. The conversion coefficient deduced for the 95.6-keV isomeric transition in ^{94}Pd demonstrated is $E2$ character. The level scheme of ^{95}Pd was completed and the excitation energy of the $21/2^+$ isomeric state was deduced. All these results are discussed in the frame of the shell model, which accounts for most of the properties of the three nuclei.

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