Proton-hole states in the $N = 30$ neutron-rich isotope ^{49}K

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Excited states in the $N = 30$ neutron-rich isotope ^{49}K have been studied using multinucleon transfer reactions with thin targets and the PRISMA-CLARA spectrometer combined with thick-target γ-coincidence data from Gammasphere. The $d_{3/2}$ proton-hole state is located 92 keV above the $s_{1/2}$ ground state, and the proton-particle $f_{7/2}$ state is suggested at 2104 keV. Three other levels are established as involving the coupling to 2^+ of two neutrons above the $N = 28$ shell. The measured or estimated lifetimes served to reinforce the interpretation of the observed level structure, which is found to be in satisfactory agreement with shell-model calculations.

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I. INTRODUCTION

Medium light nuclei are particularly for investigating changes of shell structure with isospin. They are sufficiently large to produce a well-defined mean potential, yet they can be rather easily affected by small changes of the neutron-to-proton composition. The resulting reordering of neutron shells can give rise to interesting structural phenomena such as the appearance of the so-called island of inversion near ^{32}Mg [1], or the rapid destruction of the $N = 40$ subshell closure, well-established in ^{68}Ni [2], but absent in the neutron-rich Fe isotopes [3,4].

Nuclei in the direct vicinity of doubly magic ^{48}Ca recently became the object of intense efforts to study the evolution of structure with increasing neutron excess. The $N = 32$ subshell closure [5–7] has been firmly established and reflects the energy spacing between the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ neutron orbitals above the $N = 28$ gap. It prompted new challenging experimental efforts to clarify nuclear structure at neutron number $N = 34$ [8,9] and, specifically, to verify theoretical predictions [10] for single-particle energies of these weakly bound neutron states. The adequacy of effective interactions for shell-model calculations involving active neutrons and protons above $N = 28$ and $Z = 20$ is well documented [6,11]. On the other hand, the poor knowledge of the relevant single-particle energies and corresponding two-body interactions makes it more difficult to include proton orbitals below $Z = 20$ into the shell-model space. As a consequence, the experimental yrast structures established in the closest neighbors of the ^{48}Ca core [12,13] and in the $N = 30$ isotones [14], which involve many proton excitations across the $Z = 20$ gap, can at present not be fully verified by shell-model calculations. This justifies a strong interest in the structure of neutron-rich potassium isotopes, as this may provide experimental guidance for theoretical calculations involving proton-hole states.

The presently available information on proton-hole states in potassium isotopes [15,16] already indicates an interesting evolution of nuclear structure with isospin. Starting with the $N = 20$, ^{39}K isotope, a dramatic change in the $d_{3/2}$ and $s_{1/2}$ proton-hole energies occurs when the $f_{7/2}$ neutron shell is filled. The $s_{1/2}$ state, which is initially well separated from the $d_{3/2}$ ground state, lowers its energy rapidly with increasing neutron number. Eventually both states are crossing in the $N = 28$ ^{47}K isotope, which has a $1/2^+$ ground state and 360 keV, $3/2^+$ first excited state. The main aim of the present work was to identify states in the hitherto completely unknown ^{49}K isotope in order to assert whether this evolution in proton-hole energies continues also at larger neutron excess.

Until recently, the only information available on the $N > 28$ potassium isotopes came from β-decay studies [17–19] which assigned respective ground states as 2^- and $3/2^+$ for the ^{48}K and ^{49}K isotopes. However, even these assignments should be viewed as tentative, based on the reported β-decay properties. In this work, we present results of experiments in which both isotopes were studied by in-beam γ spectroscopy using deep-inelastic transfer reactions. Earlier, we reported preliminary results concerning both the ^{48}K and ^{49}K isotopes [20]. Final results on ^{48}K will be published separately [21] and the present paper concentrates fully on the ^{49}K isotope where excited states were observed for the first time.

II. EXPERIMENTS, DATA ANALYSIS, AND RESULTS

Data from three separate experiments of different types were used to establish the ^{49}K level structure. All of them exploit deep-inelastic, heavy-ion reactions. Chronologically, the first one was performed at the Argonne National Laboratory ATLAS accelerator in the context of a series of thick-target, γ-coincidence experiments devoted to spectroscopic investigations of nuclei inaccessible in fusion evaporation reactions [12]. The 330-MeV ^{48}Ca beam was used to bombard a 50 mg/cm^2 metallic ^{238}U target placed in the center of the Gammasphere multidetector array [22] which measured indiscriminately coincidences between γ rays emitted from any excited nuclear product arising in the nuclear collisions. The high-statistics γ coincidence data collected in this run have already been successfully used to reveal extended level structures in several neutron-rich nuclei, e.g., [4,11,12], where the existing γ-ray information provided an easy isotopic assignment. In the absence of any previous knowledge of associated γ transitions, the isotopic assignment was an obvious problem for the neutron-rich K isotopes beyond the $N = 28$ line. In addition, these isotopes were expected to be produced with very small yields, making their identification more challenging. However, in the data analysis, the presence of ^{48}K and ^{49}K reaction products was inferred from off-beam coincidence events collected between the beam bursts separated by 400 ns. This analysis clearly revealed a number of strong ^{48}Ca transitions known to occur in the β decay of the ^{48}K isotope [17,18], and also of the 2023–2249 keV ^{49}Ca cascade populated with much less favorable yield in the ^{49}K decay [19]. It was thus concluded that the data from the ^{238}U + ^{48}Ca experiment contain in-beam events associated with both neutron-rich K isotopes, yet their analysis had to await initial identifications coming from another source.

With this aim, a second experiment was carried out at the INFN LNL Legnaro Tandem-ALPI Linac accelerators, using the PRISMA-CLARA spectrometer [23,24] and the same ^{238}U + 330 MeV ^{48}Ca reaction. The wide-angle PRISMA spectrometer ensured A and Z identification of the reaction products and provided precise determination of the product velocity vectors, thereby allowing proper Doppler correction of the accompanying prompt γ rays. The 0.6 mg/cm^2 ^{238}U target was located at the focus point of the CLARA γ-ray array. It was bombarded with a ^{48}Ca beam of a 0.6 pnA average intensity. The PRISMA spectrometer was placed at an angle of 52° with respect to the beam; i.e., slightly forward of the calculated grazing angle of 55°. The collected data yielded excellent isotopic identification, and the precise Doppler correction provided a γ-ray resolution ranging from 4 keV at 200 keV to 25 keV at 4 MeV energy. The inspection of γ spectra associated with several nuclei studied previously confirmed the presence of all intense transitions established in earlier thick-target experiments [13]. As expected, new lines appeared also corresponding to γ transitions associated with short-lived states that could not be observed in thick-target measurements due to large Doppler broadenings.

The selection of neutron-rich potassium isotopes is illustrated in Fig. 1(a) with thelow-energy part of the γ-ray spectrum obtained for the well-studied ^{47}K. The $N = 30$, ^{49}K nucleus was produced with a 10 times smaller yield and turned out to be the most neutron-rich potassium isotope for which meaningful γ-ray information could be obtained from this experiment. The spectrum associated with ^{49}K is shown in Fig. 1(b) with the insert picturing the selection of the $A = 49$ mass window from the distribution of potassium isotopes. The extracted energies and intensities of six γ transitions identified with ^{49}K, and marked in the figure, are listed in Table I.

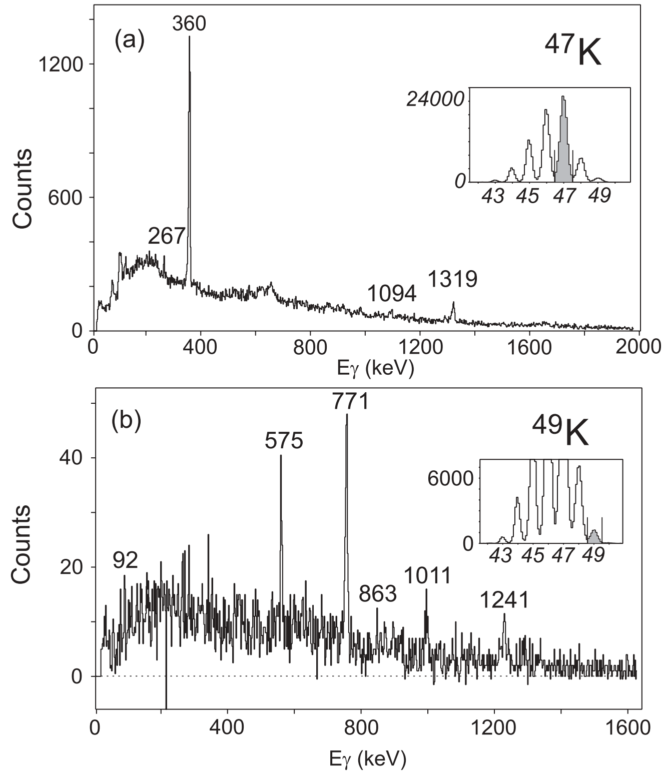

FIG. 1. γ spectra measured in coincidence with the PRISMA-CLARA spectrometer. Inserts show selection of the mass window from the distribution of potassium isotopes. (a) Low-energy part of the γ-ray spectrum obtained for ^{47}K. Indicated lines were known from thick-target experiments [12]. Note the absence of an intense 1660 keV transition due to the 7 ns half-life of the corresponding state. (b) γ-ray spectrum associated with ^{49}K. All indicated lines are observed for the first time.

TABLE I. Energies and relative intensities of γ transitions identified in ^{49}K isotope and observed in two PRISMA-CLARA experiments. The plunger experiment (expt-2) geometry compared with the standard one (expt-1) resulted in better efficiency in detecting the isomeric transition, which is reflected by an increase in the 92 keV transition intensity (see text).

Transition energy E_γ (keV)	Relative intensity I_γ		Level energy E_i (keV)
	Expt-1	Expt-2	
91.7 (3)	32(9)	51(9)	91.7
575.5 (2)	36(5)	44(8)	1438.3
771.1 (2)	100	100	862.8
862.6 (8)	8(4)	7(7)	862.8
1011.2 (8)	36(8)	38(9)	1102.9
1241.4 (4)	35(6)	33(9)	2104.2

With this initial information, the thick-target data were used to establish theg relevant coincidence relations necessary for the construction of the ^{49}K level scheme. The analysis of threefold γ coincidences was required to select rare ^{49}K events out of very complex data.

Figure 2 illustrates the quality of the data with double gates set on the crucial transitions indicated. It became apparent that the most intense 771 keV transition is in direct coincidence with the low-energy 92 keV transition, which confirmed the originally uncertain identification of this line from the low-statistics PRISMA-CLARA γ spectrum. This established firmly the existence of the 863 keV state, and other coincidence relationships settled the 575 and 1241 keV γ rays as the two relatively strong parallel transitions feeding this state from above. The low-intensity 863 keV line was placed as a cross-over transition to the ground state based on the matching energy argument. The 1011 keV transition, unambiguously identified with the ^{49}K isotope, was not in coincidence with any other transition pair and, consequently, established the presence of yet another level decaying directly to the ground state or, alternatively, to the first excited state. The resulting level scheme of Fig. 3 includes all γ transitions identified from spectrum of Fig. 1(b) and listed in Table I; the coincidence analysis did not reveal any other line.

Special care was required to clarify the ordering of the 771 and 92 keV transition, since it establishes the location of lowest excitations in ^{49}K $N = 30$ and, hence is vital to addressing the issue of the relative position of the levels with predominant $s_{1/2}$ and $d_{3/2}$ proton-hole character. The low intensity of the 92 keV line derived in the PRISMA-CLARA experiment (Table I) led us originally to locate this transition above the more intense 771 keV γ line [20]. However, this placement also posed problems since the 92 keV intensity could barely balance the intensity from the two lines at 575 and 1241 keV feeding the 863 keV level. At the same time, this 92 keV γ ray appeared with notable clarity in the coincidence spectra of Fig. 2(b). This apparent inconsistency led us to consider the possibility that the 92 keV could be the ground-state transition, and the large part of the transition intensity remained undetected in the PRISMA-CLARA thin-target experiment due to the possible longer level lifetime. Indeed, the geometry of the PRISMA-CLARA setup defines a narrow space around the target for efficient γ-ray detection. γ rays from the recoiling nuclear products emitted with delay of a few nanoseconds or more cannot be detected with their full intensity. This feature was clearly confirmed by the absence of isomeric transitions associated with, e.g., ^{47,48}K isotopes, which have strongly populated isomers with 7 ns lifetimes [21].

Confirmation that the state lifetime is indeed responsible for the substantial reduction of the 92 keV transition intensity came as a byproduct of a subsequent new experiment with the PRISMA-CLARA setup, where lifetimes in the picosecond range were measured with the plunger technique [25]. The conditions used in this experiment, i.e., the selection of the ^{48}Ca + 300 MeV ^{208}Pb reaction and, in particular, the presence of the 4 mg/cm^2 of natural Mg velocity degrader foil of the plunger resulted in much lower velocity of recoiling products. As a result, γ transitions from ns isomeric states were detected more effectively. The low-energy part of the γ-ray spectrum

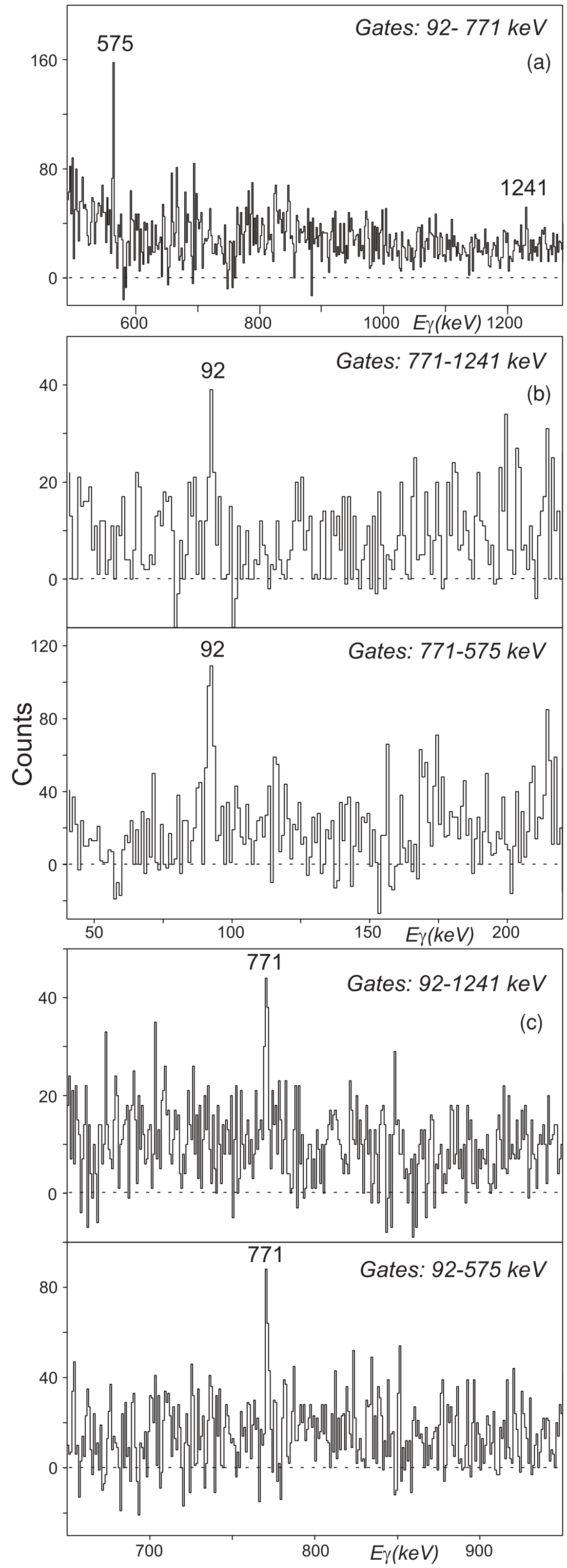

FIG. 2. Selected parts of coincidence spectra obtained from triple-γ coincidence data in thick-target experiment ^{238}U + 330 MeV ^{48}Ca. Double-gate energies are indicated.

associated with the ^{49}K isotope of Fig. 4 comes from this experiment and was obtained by summing the data from all

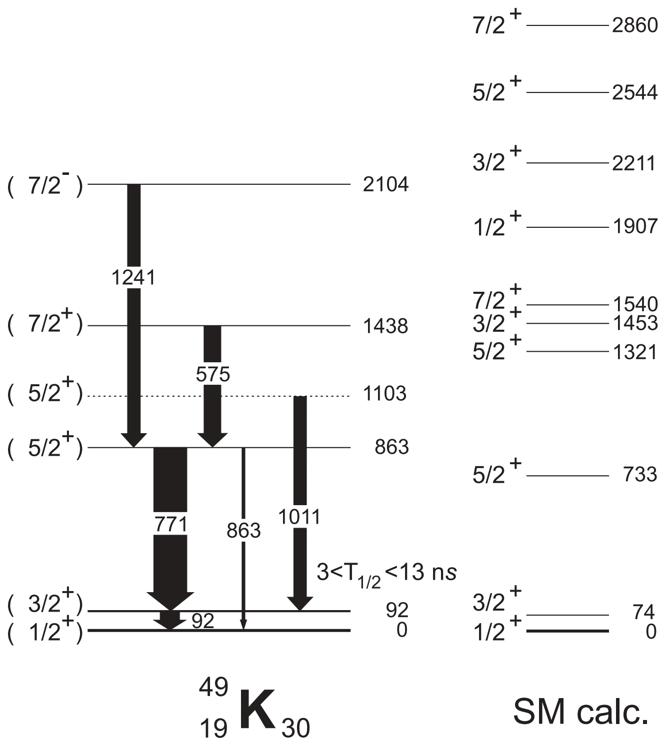

FIG. 3. ^{49}K level scheme established in the present study. For the 1011 keV transition, the alternative placement as feeding the ground state is possible. Indicated as tentative, the spin-parity assignments are strongly supported by several experimental facts as discussed in the text. The theoretically calculated level energies using the large space shell-model approach (see text) are shown to the right.

plunger runs performed for various target-degrader distances. It is apparent that the now prominently visible 92 keV line is strongly enhanced compared to the previous experiment [Fig. 1(b)]. Comparing product velocities and geometry of both experiments, one concludes that a state lifetime of at least 3 ns can provide the explanation of this enhancement. In setting this fairly conservative half-life limit, we took into account the strong intensity of the 360 keV transition observed in both PRISMA-CLARA experiments. This transition decays from the 1.1 ns 360 keV state in ^{47}K and apparently is detected with almost full efficiency. We concluded that a half-life of at least 3 ns is required to explain the strong reduction of the 92 keV transition intensity due to the escape of ^{49}K products from the γ detector's view. Moreover, from the same plunger experiment data, we were able to demonstrate short lifetimes for the states decaying by 771 and 575 keV transitions.

Parts of the γ-ray spectra appropriate for illustrating the lifetime effects observed for both transitions can be found in Fig. 5. The spectrum at the bottom was obtained for large

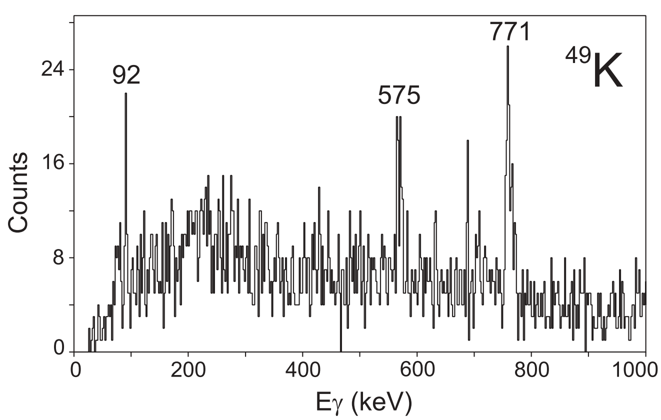

FIG. 4. γ-ray spectrum of ^{49}K obtained in plunger experiment devoted to measure lifetimes in the ps range. The spectrum was obtained by summing all runs performed with various target-degrader distances. The observed clear enhancement of the 92 keV line intensity compared to that in Fig. 1(b) indicates a state lifetime in the ns range. Broad lines at 575 and 771 keV have two components arising from decays before and after plunger degrader.

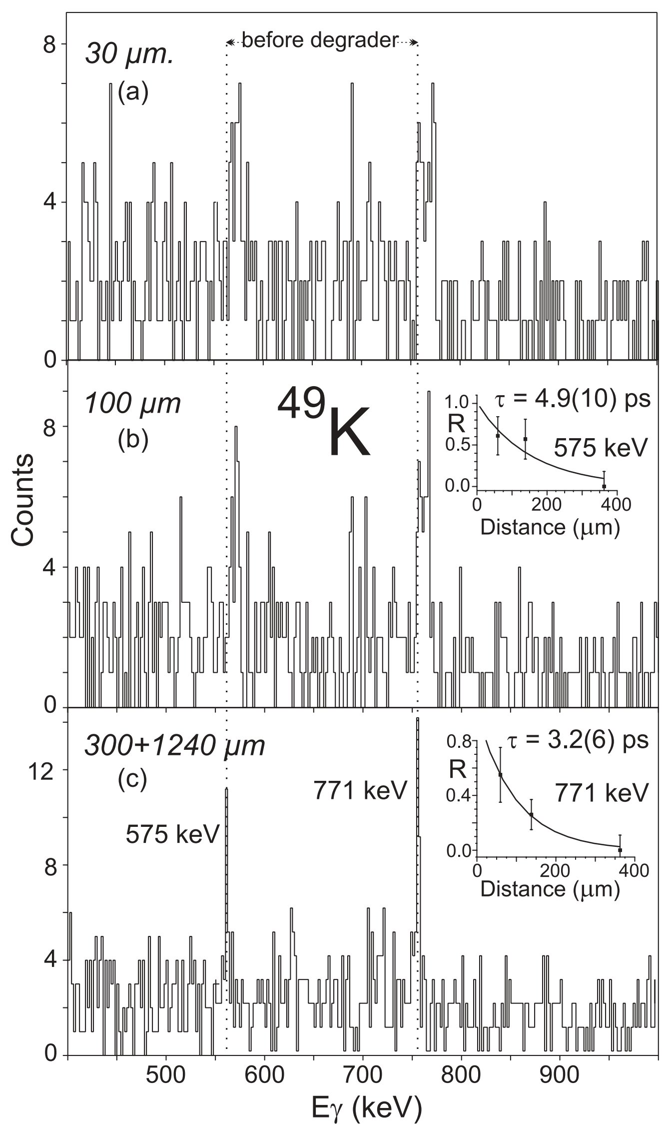

FIG. 5. Doppler-corrected γ-ray spectra showing the 575 and 771 keV lines at various target-degrader distances as indicated in (a)–(c). Separation of components arising from γ emission before (shifted to low energy) and after (properly corrected) the degrader foil served to form ratios $R = I_{\mathrm{after}}/(I_{\mathrm{before}} + I_{\mathrm{after}})$ used to determine lifetimes (see inserts).

target-degrader distances where γ emission for the 575 and 771 keV transitions occurs prior to the ^{49}K recoils reaching the degrader foil, and the two lines are fully Doppler shifted. In the two other spectra of Fig. 5 measured with target-degrader distances of 100 and 30 μm, correspondingly, both lines show clearly two components arising from decays before and after the degrader. Their relative intensities provide a means of determining the associated lifetimes. Despite the low statistics, both components could be separated, and inserts in Fig. 5 show the resulting $I_{after}/(I_{before} + I_{after})$ ratios used to extract lifetimes [25]. The statistically more significant results obtained for the 771 keV transition provided a mean lifetime value of 3.2(6) ps for the 863 keV level. However, this value corresponds to an effective lifetime which includes the strong population from higher-lying states. From the thick-target data, where the 575 and 1241 keV transitions appear as narrow lines, one may conclude that a lower limit of 0.5 ps is appropriate for both of the corresponding states. The fit of the ratios obtained for the 575 keV line (see insert) gave a somewhat longer mean lifetime of 4.9(10) ps, which could in turn imply a state lifetime much shorter than 3.2 ps for the 863 keV state fed by the 575 keV transition. Typical values for $E2$ transitions in the region are represented by energies and half-lives of the first 2^+ states in the ^{48}Ca (3832 keV, 39.7 fs [26]) and ^{50}Ca (1026 keV, 70.7 ps [25]) isotopes. Even the 2.5 times faster $E2$ transition in ^{48}Ca would require 170 and 740 ps for the mean lifetimes associated with the 771 and 575 keV transitions, correspondingly. On the other hand, the typical $M1$ transition as the 780 keV from the 4612 keV 3^+ state in ^{48}Ca yields a 1.7 ps lifetime. In any case, both measured lifetime values are well in the range expected for the 575 and 771 keV $M1$ transitions and support subsequent spin-parity assignments. The short lifetimes of higher-lying states as well as all experimental facts settle uniquely the 92 keV transition as being the ground-state transition deexciting the lowest excited state in ^{49}K with a lower limit of 3 ns for this state half-life. The unknown direct population of the state precludes a more precise lifetime estimate. However, a careful examination of the $\gamma\gamma$-time distribution for coincidence events involving the 771 and 92 keV transitions in the thick-target experiment allowed us to established a 13 ns upper limit for the half-life. For these events, no deviation could be noticed from the prompt time distribution established from intense coincidence events involving closely lying 94.6 ^{238}U target $K_{\alpha 2}$ x rays.

In conclusion, we established the first excited state of ^{49}K to be located at a 92 keV energy, and we estimated its half-life limits as $3 < T_{1/2} < 13$ ns. The tentative spin-parity assignments indicated in the ^{49}K level scheme of Fig. 3 are discussed in the following section. In the absence of direct experimental input, the expected state structure had to be considered as well to suggest the most likely spin-parity assignments for observed states.

III. DISCUSSION

The systematics of the lowest $1/2^+$, $3/2^+$, and $7/2^-$ states in a series of potassium isotopes is displayed in Fig. 6. As mentioned in the Introduction, the filling of the neutron $f_{7/2}$ shell from ^{39}K to ^{47}K results in a dramatic reordering of the energies of the $s_{1/2}$, $d_{3/2}$, and $f_{7/2}$ proton orbital. Starting with the $N = 20$ ^{39}K isotope where the $d_{3/2}$ proton-hole state is the ground state and the excitation of the $s_{1/2}$ proton-hole state requires more than 2.5 MeV, the addition of successive $f_{7/2}$ neutron pairs rapidly decreases the energy separation between these proton states located below the $Z = 20$ gap. Apparently, the $d_{3/2}$ protons gain binding energy much more effectively in the interaction with $f_{7/2}$ neutrons than do the $s_{1/2}$ protons, and, eventually, both orbital energies cross at the $N = 28$ neutron number, as observed in the ^{47}K isotope. It has been shown by Otsuka *et al.* [27] that this evolution of single-particle energies can be well understood as a monopole effect of the tensor force. Recently it was concluded that both tensor and central forces contribute to the same extent and fully account for the observed variation of the $d_{3/2}$ and $s_{1/2}$ energy spacing [28]. The presently established levels for the ^{49}K isotope, when included in the Fig. 6 systematics, suggest that this reordering of proton states holds beyond the $N = 28$ neutron number. However, the energy separation is now reduced to 92 keV.

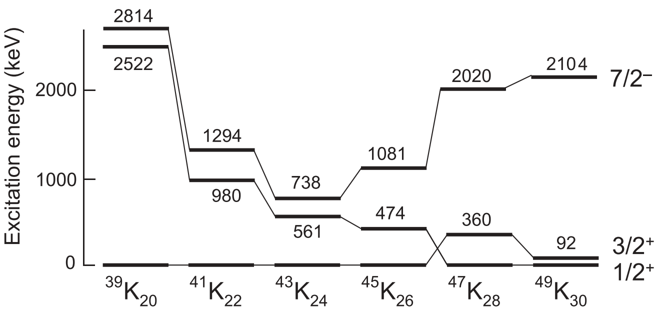

FIG. 6. Systematics of the lowest $1/2^+$, $3/2^+$, and $7/2^-$ states in a series of potassium isotopes including the presently obtained ^{49}K results.

It should be recognized that the validity of this observation rests solely on the proposed spin-parity assignments for the two states involved, and the latter point deserves further discussion. From the ^{49}K β-decay studies [19], a $3/2^+$ spin-parity assignment was tentatively suggested for the parent ground state. However, a $1/2^+$ assignment appears to be equally likely, especially considering the fact that the predominant (86%) emission of β-delayed neutrons strongly hampers the precise determination of the final ^{49}Ca state population in the very weak, direct β-decay branch. The presently established ^{49}K level scheme strongly favors the $1/2^+$ assignment for the ground state and the $3/2^+$ assignment for the 92 keV first excited state. The alternative, i.e., the reversed assignment, has to be excluded based on features of the established level scheme. First, ^{49}K is produced in deep-inelastic reactions with the well-established tendency to predominantly populate yrast states. The strong population of the 92 keV level is very much in line with the $3/2^+$ assignment [see the predominant population of the corresponding 360 keV $3/2^+$ state in ^{47}K, see Fig. 1(a)] and would be strongly inconsistent with the alternative $1/2^+$ spin-parity. An even more convincing argument comes from the observed γ decay of higher-lying states which proceeds via the 863 keV state of likely yrast $5/2^+$ assignment. This yrast level decays predominantly with an intense 771 keV transition to the 92 keV state and a much weaker 863 keV branch to the ground state. This $M1/E2$ intensity pattern would be highly unlikely with the reversed assignment. Thus, one may safely conclude that in the ^{49}K isotope, the $s_{1/2}$ proton-hole is the ground state and the $d_{3/2}$ proton-hole is located at 92 keV. The limits $3 < T_{1/2} < 13$ ns settled for the half-life of the 92 keV state appears to be consistent with this interpretation as well. In ^{47}K, a 1.1(3) ns half-life was measured for the 360 keV state, reflecting the forbidden character of the $d_{3/2} \rightarrow s_{1/2}$ $M1$ transition. The energy factor would require a half-life value of about 60 ns for the 92 keV transition of ^{49}K. However, the involvement of two additional neutrons can easily result in the acceleration of this transition by roughly one order of magnitude; the important fact remains that the observed half-life is in the expected nanosecond range. It is worth pointing out that the present conclusion regarding the relative position of the $s_{1/2}$ and $d_{3/2}$ proton-hole states also requires the reconsideration of ground-state spin-parity assignments proposed for more neutron-rich K isotopes from β-decay measurements. Specifically, at present, the ^{50}K ground state is assumed to be a 0^- level [29] requiring the involvement of a $d_{3/2}$ proton-hole in the configuration. The coupling of a $p_{3/2}$ neutron with a $s_{1/2}$ proton-hole would result in a 1^- ground state instead, which provides a more natural explanation for the presence and interpretation of a higher-lying isomer in ^{50}K, as recently reported [30].

Among the states obtained with the two additional neutrons coupled as a 0^+ pair, the only level anticipated to appear below 2.5 MeV is the one resulting from promotion of one proton across the $Z = 20$ gap to the $f_{7/2}$ proton orbital. This proton-particle state involves, then, an additional 0^+ proton-hole pair. An excellent candidate for this state is the level at 2104 keV, and we shall return to this level below with arguments supporting such an assignment. All other states established in the ^{49}K level scheme of Fig. 3 must arise from an additional degree of freedom provided by the two valence neutrons. The level structure established recently in the $N = 30$ ^{50}Ca isotope [14] suggests a particularly simple situation, since only the 1026 keV, first 2^+ state with predominant neutron $(p_{3/2})^2$ configuration needs to be considered since all other states are located at energies higher than 3 MeV.

The coupling of the $s_{1/2}$ and $d_{3/2}$ proton-holes to this 2^+ excitation gives rise to a $3/2^+$ and $5/2^+$ doublet and a $1/2^+$, $3/2^+$, $5/2^+$, and $7/2^+$ quadruplet of states, respectively. Only states with the highest spin values are expected to be observed in our experiment because these will be yrast. Taking the yrast population into account, it is natural to assign the 863 keV state as the yrast $5/2^+$ level with a most natural γ branching of a strong 771 keV $M1$ and a much weaker 863 ground-state $E2$ transition. The higher-lying 1438 keV state is then naturally the maximum spin $7/2^+$ state of the $\pi d_{3/2}^{-1} \nu p_{3/2}^2$ configuration, and the significant shift to high energy reflects the repulsive 3^- coupling of the $p_{3/2}$ neutron particle with the $d_{3/2}$ proton-hole documented in the ^{48}K isotope [20]. As mentioned earlier, the lifetimes measured for the 575 and 771 keV transitions are fully consistent with their $M1$ character and support the suggested assignments. Less certain is the assignment of the level depopulated by the 1011 keV transition which is not connected with the main yrast cascade. Furthermore, at present, it is not even clear whether it populates the ground state or the 92 keV level. Nevertheless, the yrast population considerations favor the placement above the 92 keV state and a $5/2^+$ assignment, as tentatively indicated in Fig. 3, although a $3/2^+$ assignment and alternative placement is also possible.

As indicated earlier, the highest energy state located in the present experiment is the 2104 keV level, which fits well with the $7/2^-$ assignment when taking into account the expected excitation energy for such a state. In the $N = 28$ ^{47}K isotope, this $7/2^-$ $f_{7/2}$ proton-particle state observed at 2020 keV is isomeric [21] with the 6.4 ns half-life determined by the $M2$ decay to the $d_{3/2}$ proton-hole state. In the ^{49}K isotope, the possibility of decay to the lower-lying $5/2^+$ state by an $E1$ branch destroys the isomerism. However, the 1241 keV transition was observed as a discrete line in the thick-target coincidence experiment, indicating a state lifetime longer than 0.5 ps. On the other hand, in the lifetime experiment, the counts that could be attributed to the 1241 keV transition were found predominantly at the Doppler-shifted energy, indicating a short lifetime not exceeding 2 ps. This would be consistent with a strongly forbidden $E1$ transition and, consequently, with the suggested assignment and interpretation of the 2104 keV state.

Following the above discussion based solely on experimental facts and qualitative expectations, we compare the ^{49}K levels with theoretical calculations. Recently, Nowacki and Poves [31] presented results of unrestricted $0\hbar\omega$ shell-model calculations carried out in the sd-pf valence space ($8 \leqslant Z \leqslant 20$, $20 \leqslant N \leqslant 40$) with the SDPF-NR Hamiltonian [32]. In this approach, protons fill the sd shells and neutrons occupy the pf orbitals and the effective SDPF-NR interaction consists of three parts: (a) the USD interaction two-body matrix elements (TBME) for the proton-proton interaction, (b) the KB interaction TBME for the neutron-neutron interaction, and (c) the (parametrized) G-matrix interaction of Ref. [33] for the proton-neutron interaction. The monopole part of the interaction is empirically modified to provide a correct evolution of the effective single-particle energies across the region of nuclides. The authors [31] presented only results for three states in ^{49}K, and we applied the same approach using the OXBASH code [34] to calculate a more complete set of levels. From the two possible alternatives, we used only the SPDF-NR interaction because it predicts the $1/2^+$ ground state in agreement with our experimental findings. The calculated levels are shown in the right-hand side of Fig. 6. These include the three calculated levels presented in Ref. [31] which are exactly reproduced. The good reproduction of the level ordering and the observed overall agreement between the experimental and calculated levels support our spin-parity assignments. Here, the calculated yrast sequence of $3/2^+$, $5/2^+$, and $7/2^+$ levels above the $1/2^+$ ground state matches particularly well the energies of experimental states. A somewhat larger difference is observed for the near-yrast 1103 keV state, which could correspond to the second $5/2^+$ level calculated at a 1321 keV energy. Although the alternative experimental location of this state and the $3/2^+$ assignment cannot be ruled out, the calculation gives additional weight to our preferred choice. Another important observation is that the lowest, second $7/2^+$ state was calculated at a very high energy of 2860 keV. This also provides a strong reinforcement of our suggestion that the much lower lying 2104 keV state arises from the promotion of an unpaired proton to the $f_{7/2}$ orbital above the $Z = 20$ gap.

IV. CONCLUSIONS

In summary, we established for the first time the level scheme of the neutron-rich ^{49}K isotope using data from three experiments exploiting deep-inelastic, heavy-ion reactions. The important observation is that the reordering of the $s_{1/2}$ and $d_{3/2}$ proton-hole state energies taking place in the ^{47}K isotope holds also at larger neutron excess. However, the energy separation between these states is much smaller. The sequence of observed levels can be understood well with the limited degrees of freedom defined by the coupling of proton-holes with two $p_{3/2}$ neutrons. The location of the $f_{7/2}$ proton-particle state in ^{49}K indicates also that the energy separation of the $s_{1/2}$ and $f_{7/2}$ proton states, directly related to the $Z = 20$ energy gap, remains largely unaffected by the increased neutron excess. The measured or estimated state lifetimes are consistent with the proposed interpretation. The presently available shell-model calculations are in satisfactory agreement with the observed level structure.

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[1] T. Motobayashi *et al.*, Phys. Lett. B **346**, 9 (1995).
[2] R. Broda *et al.*, Phys. Rev. Lett. **74**, 868 (1995).
[3] M. Hannawald *et al.*, Phys. Rev. Lett. **82**, 1391 (1999).
[4] N. Hoteling *et al.*, Phys. Rev. C **74**, 064313 (2006).
[5] A. Huck, G. Klotz, A. Knipper, C. Miehé, C. Richard-Serre, G. Walter, A. Poves, H. L. Ravn, and G. Marguier, Phys. Rev. C **31**, 2226 (1985).
[6] R. V. F. Janssens *et al.*, Phys. Lett. B **546**, 55 (2002).
[7] J. I. Prisciandaro *et al.*, Phys. Lett. B **510**, 17 (2001).
[8] D. C. Dinca *et al.*, Phys. Rev. C **71**, 041302(R) (2005).
[9] S. N. Liddick *et al.*, Phys. Rev. Lett. **92**, 072502 (2004).
[10] M. Honma, T. Otsuka, B. A. Brown, and T. Mizusaki, Phys. Rev. C **65**, 061301(R) (2002).
[11] B. Fornal *et al.*, Phys. Rev. C **72**, 044315 (2005).
[12] R. Broda, J. Phys. G **32**, R151 (2006).
[13] R. Broda, Acta Phys. Pol. B **32**, 2577 (2001).
[14] R. Broda *et al.*, Acta Phys. Pol. B **36**, 1343 (2005).
[15] Evaluated by John A. Cameron and B. Singh, Nucl. Data Sheets **92**, 783 (2001); **94**, 429 (2001); B. Singh and John A. Cameron, *ibid.* **107**, 225 (2006).
[16] Evaluated by T. W. Burrows, Nucl. Data Sheets **108**, 923 (2007); **109**, 171 (2008).
[17] A. Huck, G. Klotz, A. Knipper, C. Miehe, C. Richard-Serre, and G. Walter, in Proceedings of the International Conference on Nuclei Far from Stability, Helsingor, Denmark, CERN-81-09, Vol. 2, 1981 (unpublished), p. 378.
[18] L. G. Multhauf, K. G. Tirsell, S. Raman, and J. B. McGrory, Phys. Lett. B **57**, 44 (1975).
[19] L. C. Carraz *et al.*, Phys. Lett. B **109**, 419 (1982).
[20] R. Broda *et al.*, Annual Report 2006 INFN-LNL-217, ISSN 1828-8545 (Legnaro, 2007).
[21] W. Królas *et al.*, in *Proceedings of the Fourth International Conference on Fission and Neutron-Rich Nuclei, Sanibel Island, Fla., 2007*, edited by J. H. Hamilton, A. V. Ramayya, and H. K. Karter (World Scientific, Singapore, 2008), p. 531; and unpublished.
[22] I. Lee, Nucl. Phys. A **520**, c641 (1990).
[23] A. Gadea *et al.* and the EUROBALL and PRISMA-2 Collaborations, Eur. Phys. J. A **20**, 193 (2004).
[24] A. Stefanini *et al.*, Nucl. Phys. A **701**, 217c (2002).
[25] J. J. Valiente-Dobon *et al.*, Phys. Rev. Lett. **102**, 242502 (2009).
[26] Evaluated by T. W. Burrows, Nucl. Data Sheets **107**, 1747 (2006).
[27] T. Otsuka, T. Suzuki, R. Fujimoto, H. Grawe, and Y. Akaishi, Phys. Rev. Lett. **95**, 232502 (2005).
[28] Y. Utsuno, T. Otsuka, B. Brown, M. Honma, and T. Mizusaki, AIP Conf. Proc. **1120**, 81 (2009).
[29] E. K. Warburton, Phys. Rev. C **44**, 1024 (1991).
[30] H. L. Crawford *et al.*, Acta Phys. Pol. B **40**, 481 (2009).
[31] F. Nowacki and A. Poves, Phys. Rev. C **79**, 014310 (2009).
[32] S. Nummela *et al.*, Phys. Rev. C **63**, 044316 (2001).
[33] S. Kahana, H. C. Lee, and C. K. Scott, Phys. Rev. **180**, 956 (1969).
[34] B. A. Brown *et al.*, OXBASH for Windows, Report 1289, MSU-NSCL, 2004 (unpublished).