Towards the Limits of Existence of Nuclear Structure: Observation and First spectroscopy of the Isotope $^{31}$K by measuring its three-proton Decay

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The most-remote from stability isotope $^{31}$K, which is located four atomic mass units beyond the proton drip line, has been observed. It is unbound in respect to three-proton ($3p$) emission, and its decays have been detected in flight by measuring trajectories of all decay products using micro-strip detectors. The $3p$-emission processes have been studied by means of angular correlations $^{30}$S+$3p$ and the respective decay vertexes. The energies of the previously-unknown ground and excited states of $^{31}$K have been determined. This provides its $3p$ separation-energy value $S_{3p}$ of $-4.6(2)$ MeV. Upper half-life limits of 10 ps of the observed $^{31}$K states have been derived from distributions of the measured decay vertexes.

In recent experimental [1] and theoretical [2] studies of the lightest isotopes in the argon and chlorine isotope chains, limits of existence of the corresponding nuclear structure were addressed. For the issue of existence of nuclear structure, we adopt the approach used in Ref. [2]. Namely, a nuclear configuration has an individual structure with at least one distinctive state, if the orbiting valence protons of the system are reflected from the corresponding nuclear barrier at least one time. Thus the nuclear half-life may be used as a criterion here, and two extreme cases can be mentioned. The very long-lived particle-emitting states may be considered as quasistationary. For example, the half-lives of all known heavy two-proton ($2p$) radioactivity precursors (e.g., $^{45}$Fe, $^{48}$Ni, $^{52}$Zn, $^{67}$Kr) are a few milliseconds [3][4]. For such long-lived states, modifications of nuclear structure by coupling with continuum are negligible. In the opposite case of very short-lived unbound ground states (g.s.), the continuum coupling becomes increasingly important, which can be regarded as a transition to continuum dynamics. For example, the discussion of the tetra-neutron ($4n$) system has shown that its spectrum is strongly affected both by the reaction mechanism and by the initial nuclear structure of the participants [7]. In Ref. [2], the isotopes

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20\textsuperscript{Ar} and 25\textsuperscript{Cl} were predicted as the most remote nuclear configurations with identified g.s.. Similar predictions allow to expect a number of previously-unknown unbound isotopes located within a relatively broad (by 2-5 atomic mass units) area along the proton drip line. For more exotic nuclear systems beyond such a domain, no g.s. of isotopes (and thus no new isotope identification) are expected. Therefore a new borderline indicating the limits of existence of isotopes in the nuclear chart and the transition to chaotic-nucleon matter may be inspected.

In this work we continue the “excursion beyond the proton drip line” of Ref. [1] by presenting the results of additional analysis of the data obtained with a 31\textsuperscript{Ar} secondary beam [8]. In the experiment, described in detail in Refs. [1, 8], the 31\textsuperscript{Ar} beam was produced by the fragmentation of a primary 885 MeV/u 30\textsuperscript{Ar} beam at the SIS-FRS facility at GSI (Germany). The previous objectives of the experiment were studies of 2p decays of 29,30,31\textsuperscript{Ar} isotopes. We briefly repeat the general description of the experiment and the detector performance. The FRS was operated with an ion-optical settings in a separator-spectrometer mode, where the first half of the FRS was set for the detection of heavy-ion secondary beam [8]. In the experiment, described in detail in Refs. [1, 8], the 31\textsuperscript{Ar} beam was produced by the fragmentation of a primary 885 MeV/u 30\textsuperscript{Ar} beam at the SIS-FRS facility at GSI (Germany). The previous objectives of the experiment were studies of 2p decays of 29,30,31\textsuperscript{Ar} isotopes. We briefly repeat the general description of the experiment and the detector performance. The FRS was operated with an ion-optical settings in a separator-spectrometer mode, where the first half of the FRS was set for the detection of heavy-ion secondary target located at the FRS middle focal plane. In the cases addressed in Refs. [1, 8], the 29,30\textsuperscript{Ar} nuclei were produced via neutron knockout reactions from the 31\textsuperscript{Ar} ions. The decay products of unbound 29,30\textsuperscript{Ar} nuclei were tracked by a double-sided silicon micro-strip detector (DSSD) array placed just downstream of the secondary target. Four large-area DSSDs [8] were employed to measure hit coordinates of the protons and the recoil heavy ions (HI), resulting from the in-flight decays of the studied 2p precursors. The high-precision position measurement by DSSDs allowed for reconstruction of all fragment trajectories, which let us to derive the decay vertex together with angular HI-p and HI-p1-p2 correlations. For example, the trajectories of measured \(28\textsuperscript{S}+p+p\) coincidences served for the analysis, and the spectroscopic information on 30\textsuperscript{Ar} was concluded [8]. The spectra of 30\textsuperscript{Ar} were observed by using 2p angular correlations as function of their root-mean-square angle relative to \(28\textsuperscript{S}\),

\[
\rho_\theta = \sqrt{\theta_{p1-28S}^2 + \theta_{p2-28S}^2}.
\]  

A number of by-product results was obtained in a similar way from the data recorded in the same experiment. In particular, a 3p-unbound nuclear system of 31\textsuperscript{K} was populated in a charge-exchange reaction. This mechanism has lower cross section than knockout reactions, and the obtained data have smaller statistics than in the previously-mentioned case [8]. In spite of poor statistics with few events registered, we have obtained several nuclear-structure conclusions from the data. The 31\textsuperscript{K} spectrum was derived from trajectories of all decay products \(28\textsuperscript{S}+p_1+p_2+p_3\) measured in four-fold coincidence. All detector calibrations were taken from the analyses reported in Refs. [1, 8]. In Fig. 1 we present 3p correlations observed in decays of 31\textsuperscript{K} as function of their root-mean-square angle

\[
\rho_\theta = \sqrt{\theta_{p1-28S}^2 + \theta_{p2-28S}^2 + \theta_{p3-28S}^2}.
\]  

FIG. 1. Three-proton angular correlations as function of their root-mean-square angle \(\rho_\theta\) [see eq. (2)] derived from the measured trajectories of all decay products, \(28\textsuperscript{S}+3p\) (histogram), which reflect the excitation spectrum of the isotope 31\textsuperscript{K}. The peaks (i), (ii), (iii) suggest the 31\textsuperscript{K} states whose 3p-decay energies \(Q_{3p}\) are shown in the upper axis.

\(Q_{3p}\) (MeV)

\[
\rho_\theta = \sqrt{\theta_{p1-28S}^2 + \theta_{p2-28S}^2 + \theta_{p3-28S}^2}.
\] derived from the measured trajectories of \(28\textsuperscript{S}+3p\) coincident events. The kinematical variable \(\rho_\theta\) is introduced because the decay protons share the 3p-decay energy, in analogy with 2p decays [see eq. (1)]. One can see three peaks (i), (ii) and (iii) reflecting the population of states in 31\textsuperscript{K} isotope, and their respective 3p-decay energies \(Q_{3p}\) of about 4.5, 9 and 16 MeV may be estimated from the upper axis.

In order to establish decay schemes of the states in 31\textsuperscript{K}, we have produced angular \(\theta_{p-28S}\) correlations projected from the \(28\textsuperscript{S}+3p\) events which are selected by the gates around the \(\rho_\theta\)-peaks (i), (ii), (iii) in Fig. 1. These projections are shown in the respective panels in Fig. 2. In particular, the lowest-energy 4.5 MeV peak (i) may correspond to the 31\textsuperscript{K} g.s., which decays by emission of a proton first into an intermediate 30\textsuperscript{Ar} g.s., whose 2p-decay energy of 2.45(15) MeV is known [8]. Then the corresponding \(\theta_{p-28S}\) correlations in Fig. 2(i) should consist of two contributions. The firstly-emitted proton should cause a peak in the observed \(\theta_{p-28S}\) correlations. The second component should be the known broad \(\theta_{p-28S}\) distribution from the 30\textsuperscript{Ar} g.s. 2p-decay [8], which is centered at \(E_{p-28S} \geq 1.2\) MeV (because the 2 protons, which can not be distinguished, share the 2p-decay energy). We have fitted the data by a sum of
two respective components: 1) the Monte-Carlo simulation including the response of the experimental setup to 1p-emission by 31K (the simulation procedure is described in details in Refs. [10, 11]; 2) the known detector response to the 2p-decay of 30Ar g.s. (see Ref. [8]). One may see, that the small-angle region of the θp−28S distribution agrees with the 2p-decay of 30Ar g.s. (the dotted-line taken into account the literature value of the 2p-decay energy of 2.45±0.05 MeV), while the large-angle correlations can be described by the 1p-emission of 31K into 30Ar g.s. (solid line) with the best-fit decay energy of 2.15(15) MeV. The illustration of procedure of the data fit is given in Fig. 3 where the probability that the simulated response of the setup to the 1p decay of 31K into the 30Ar g.s. matches the measured angular θp−28S correlations is shown in dependence on the 1p-decay energy. The best-fit energy and its uncertainty have been derived from the distribution centroid and width, respectively. Thus we may assign the 3p-decay energy of the 31K g.s. as 2.15(15)+2.45±0.05≈4.6(2) MeV.

Similar angular θp−28S projections made with the 9 and 16 MeV gates (see Fig. 2) are less conclusive. One may see that both distributions in Fig. 2(ii) and (iii) contain no contribution from the 2p-decay of 30Ar g.s., and therefore the 9 and 16 MeV excited states in 31K should proceed via excited states in 30Ar.

The result of the data analysis, the assigned levels of 31K and their decay scheme, is shown in Fig. 4. The derived information may be improved in following experiments with higher statistics and increased resolution. The mass of the 31K g.s. may be derived by using the masses of 28S+3p and the Q1p value, which then may be compared with available theoretical predictions. The energy of the 31K g.s. has been predicted by the systematics proposed for the mass differences of mirror nuclei (the improved Kelson-Garvey mass relations [12]), and the estimates for the tentative (3/2+) and (1/2+) states based on mirror energy differences [13] are shown by the dashed lines.

FIG. 2. Angular θp−28S correlations projected from the measured 28S+3p coincidences (histograms). The data in panels (i), (ii), (iii) are selected by the respective gates around the p3-ppeaks in Fig. 1. The corresponding 1p-decay energies Ep−28S are given by the upper axis. The solid curve is the best-fit contribution from the initial 1p-decay of 31K into the 30Ar g.s. with the fitted decay energy of 2.15(15) MeV. The contribution of a subsequent 2p-decay of 30Ar with the known energy of 2.45 MeV [8] is shown by the dotted curve.

FIG. 3. Probability that the simulated response of the setup to the 1p decay of 31K into the 30Ar g.s. matches the measured angular θp−28S correlations [shown in Fig. 2(i)] as a function of assumed 1p-decay energy Q1p.

FIG. 4. Proposed decay scheme of 31K levels with a tentatively-assigned 1p-decay channel through the known 30Ar and 29Cl states [8], whose energy is given relative to the 3p, 2p and 1p thresholds, respectively. On the right-hand side, the energies of the 31K g.s. predicted by the improved Kelson-Garvey mass relations [12], and the estimates for the tentative (3/2+) and (1/2+) states based on mirror energy differences [13] are shown by the dashed lines.
observed in $Ip$-unbound nuclei. Alternatively, as the $^{31}\text{K}$ g.s. decays via the long-lived $^{30}\text{Ar}$ g.s., we may use the empirical $S_p$ systematics of $Ip$-emitting states in light nuclei based on parametrization of experimental mirror energy differences (MED) $^{13}$. The definition is $\text{MED}=S_n(\text{neutron-rich nucleus})-S_p(\text{its proton-rich mirror})$, and $\text{MED}=(Z/A^{1/3})\text{MED}'$, where the MED' value does not depend on the nuclear charge $Z$ and mass $A$ $^{13}$. This parametrization can be scaled to the presumably $d_{3/2}$ g.s. of $^{31}\text{K}$ by using the known thresholds of the $A$-2 mirror pair $^{29}\text{Cl}^*(3/2^+)-^{29}\text{Mg}_{g.s.}(3/2^+)$, which results in not much better agreement with the data (see Fig. 4 on right-hand side). The similar estimate can be done by using the $A$-2 mirror states $^{29}\text{Cl}_{g.s.}(1/2^+)-^{29}\text{Mg}^*(1/2^+)$ where excitation energy of the experimentally identified $^{29}\text{Mg}^*(1/2^+)$ is 55 keV according to Ref. $^{13}$. Then the evaluated $S_{3p}$ value is of -6.0 MeV which still disagrees with the data. Such a difference in the observed and predicted energies of the $^{31}\text{K}$ g.s. requires further investigation, for example the influence of three-nucleon forces may be studied like in Ref. $^{17}$.

The width of the $^{31}\text{K}$ g.s. derived by the fit in Fig. 2 (i) provides only the upper-limit value $\Gamma_{g.s.}<400$ keV, as it reflects the experimental resolution. For comparison, the upper-limit Wigner estimate for a single-particle $1d_{3/2}$-shell width of $^{31}\text{K}$ g.s. is about 30 keV only. The widths of the excited 9 and 16 MeV states were estimated from the $\rho_3$ distribution in Fig. 1 giving the values of 1 and 2 MeV, respectively. One should also note, that the spectrum of $^{31}\text{Mg}$, which is the mirror nucleus of $^{31}\text{K}$, displays a number of low-energy levels assigned to two rotational bands and to a spherical configuration $^{18}$, which provides an evidence of shape coexistence in this nuclear system. Most of these states de-excite by $\gamma$-ray emission with half-lives in the nanosecond range. As all $^{31}\text{K}$ states are unbound, the isospin-symmetrical rotational bands are unlikely to be excited.

Nevertheless, we have evaluated the half-life values of the observed $^{31}\text{K}$ states in the picosecond range by measuring distributions of their decay vertexes. Figure 5 (a) shows the profile of $2p$-decay vertexes of the $^{30}\text{Ar}^*$ short-lived excited states first published in $^{12}$ by using the measured $^{28}\text{S}+p+p$ trajectories. This profile serves as a reference in the evaluation of the $3p$-decay vertexes from the $^{31}\text{K}$ “ground” and “first excited” states which are shown in Fig. 5 (b) and (c), respectively. The two latter profiles are derived from the measured $^{28}\text{S}+p+p+p$ events by applying the selection gates around the peaks (i) and (ii) in the $\rho_3$-spectrum of $^{31}\text{K}$ shown in Fig. 4. The Monte Carlo simulations $^{10,11}$ of the reference case of $^{30}\text{Ar}$ short-lived excited states are shown in Fig. 5 (a). They assume $T_{1/2}=0$ ps for the $^{30}\text{Ar}$ states and take into account the experimental angular uncertainties in tracking the fragments and reconstructing the vertex coordinates. The simulations reproduce the data quantitatively. The half-life uncertainty is illustrated by the $T_{1/2}=5$ ps simulation which fails fitting the data. The asymmetry of the rising and falling slopes of the vertices is due to multiple scattering of the fragments in the thick target. Similar Monte Carlo simulations with $T_{1/2}$ of 0, 5 and 10 ps of the $^{31}\text{K}$ states are compared with the corresponding data in Fig. 5 (b). One may see that the $T_{1/2}=5$ ps simulation is the best fit for the $^{31}\text{K}$ g.s. data. However, production of few events of $^{31}\text{K}$ inside the 27-mm thick secondary target result in the $T_{1/2}$ uncertainties of 10 ps. Thus we conclude that the half-life value of the $^{31}\text{K}$ g.s. is shorter than 10 ps, which is our upper-limit estimate. For the $^{31}\text{K}$ excited-state, the best fit of its vertex profile is shown in Fig. 5 (c) giving $T_{1/2}=0$ ps. Though we found no indication on long-lived states in $^{31}\text{K}$, a dedicated experiment with improved resolution and larger statistics inspecting possible shape coexistence in $^{31}\text{K}$ may provide a strict test of isospin-symmetry conservation/violation of such exoctic nuclear systems.

In conclusion, the first spectroscopy of the previously-unknown isotope $^{31}\text{K}$, located four atomic mass units beyond the proton drip line, has revealed states whose widths are much smaller than the values of 3–5 MeV which are mandatory for the formation of a nuclear state $^{2}$. Therefore the half-lives of the observed $^{31}\text{K}$ states are much longer than those predicted at the limits of existence of nuclear structure, and one can conclude...
that a transition region to chaotic nuclear systems is not reached yet. Looking to the future, similar charge-exchange reactions with more exotic beams like $^{48}$Ni or $^{67}$Kr prospect investigations of nuclear systems located by seven mass units beyond the proton drip line, where the basic mean-field concept and Pauli principle may be ultimately tested. Last but not least, the mass of the $^{31}$K g.s. can be derived from the measured $S_{pp}$ value, which is the most challenging test of predictions of nuclear mass models.

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