

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 $^{28}\text{S}+3p$ 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 , ^{54}Zn , ^{67}Kr) are a few milliseconds [3–6]. 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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^{26}Ar and ^{25}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 dripline” of Ref. [1] by presenting the results of additional analysis of the data obtained with a ^{31}Ar secondary beam [8]. In the experiment, described in detail in Refs. [1, 8], the ^{31}Ar beam was produced by the fragmentation of a primary 885 MeV/u ^{36}Ar beam at the SIS-FRS facility at GSI (Germany). The previous objectives of the experiment were studies of $2p$ decays of $^{29,30,31}\text{Ar}$ 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 separation and focusing of the radioactive beams on a secondary target in the middle of the FRS, and the second half of FRS was set for the detection of heavy-ion decay products. The secondary 620 MeV/u ^{31}Ar beam with an intensity of 50 ions s^{-1} bombarded a 27-mm thick ^9Be secondary target located at the FRS middle focal plane. In the cases addressed in Refs. [1, 8], the $^{29,30}\text{Ar}$ nuclei were produced via neutron knockout reactions from the ^{31}Ar ions. The decay products of unbound $^{29,30}\text{Ar}$ nuclei were tracked by a double-sided silicon micro-strip detector (DSSD) array placed just downstream of the secondary target. Four large-area DSSDs [9] 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- p_1 - p_2 correlations. For example, the trajectories of measured $^{28}\text{S}+p+p$ coincidences served for the analysis, and the spectroscopic information on ^{30}Ar was concluded [8]. The spectra of ^{30}Ar were observed by using $2p$ angular correlations as function of their root-mean-square angle relative to ^{28}S ,

$$\rho_\theta = \sqrt{\theta_{p_1-^{28}\text{S}}^2 + \theta_{p_2-^{28}\text{S}}^2}. \quad (1)$$

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}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}K

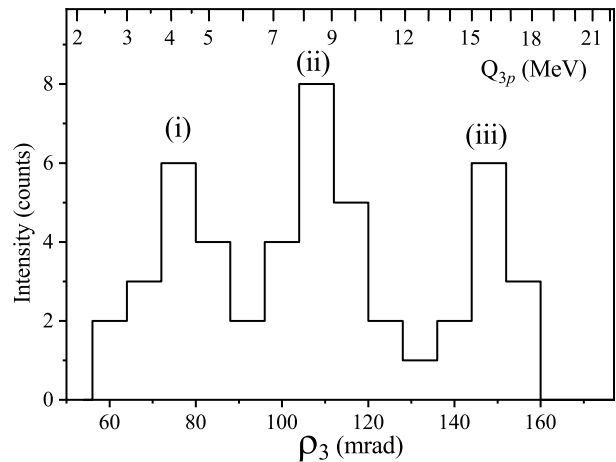


FIG. 1. Three-proton angular correlations as function of their root-mean-square angle ρ_3 [see eq. (2)] derived from the measured trajectories of all decay products, $^{28}\text{S}+3p$ (histogram), which reflect the excitation spectrum of the isotope ^{31}K . The peaks (i), (ii), (iii) suggest the ^{31}K states whose $3p$ -decay energies Q_{3p} are shown in the upper axis.

spectrum was derived from trajectories of all decay products $^{28}\text{S}+p_1+p_2+p_3$ 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}K as function of their root-mean-square angle

$$\rho_3 = \sqrt{\theta_{p_1-^{28}\text{S}}^2 + \theta_{p_2-^{28}\text{S}}^2 + \theta_{p_3-^{28}\text{S}}^2} \quad (2)$$

derived from the measured trajectories of $^{28}\text{S}+3p$ coincident events. The kinematical variable ρ_3 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}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}K , we have produced angular $\theta_{p-^{28}\text{S}}$ correlations projected from the $^{28}\text{S}+3p$ events which are selected by the gates around the ρ_3 -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}K g.s., which decays by emission of a proton first into an intermediate ^{30}Ar g.s., whose $2p$ -decay energy of 2.45(15) MeV is known [8]. Then the corresponding $\theta_{p-^{28}\text{S}}$ correlations in Fig. 2(i) should consist of two contributions. The firstly-emitted proton should cause a peak in the observed $\theta_{p-^{28}\text{S}}$ correlations. The second component should be the known broad $\theta_{p-^{28}\text{S}}$ distribution from the ^{30}Ar g.s. $2p$ -decay [8], which is centered at $E_{p-^{28}\text{S}} \simeq 1.2$ MeV (because the 2 protons, which can not be distinguished, share the $2p$ -decay energy). We have fitted the data by a sum of

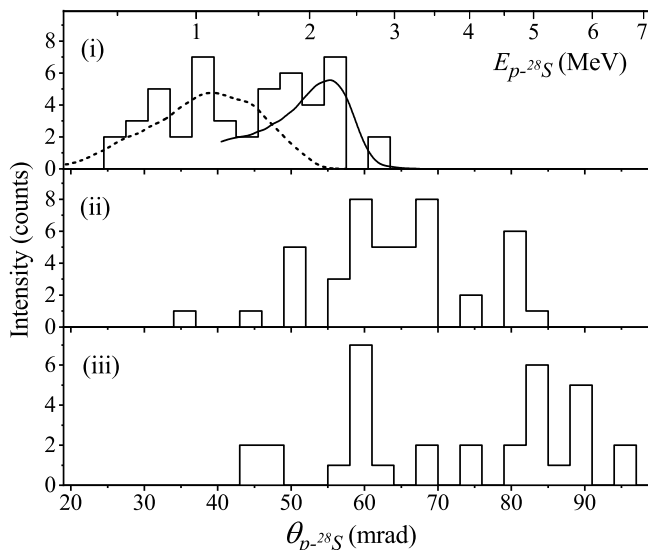


FIG. 2. Angular θ_{p-28S} correlations projected from the measured $^{28}\text{S}+3p$ coincidences (histograms). The data in panels (i), (ii), (iii) are selected by the respective gates around the ρ_3 -peaks in Fig. 1. The corresponding $1p$ -decay energies E_{p-28S} are given by the upper axis. The solid curve is the best-fit contribution from the initial $1p$ -decay of ^{31}K into the ^{30}Ar g.s. with the fitted decay energy of 2.15(15) MeV. The contribution of a subsequent $2p$ -decay of ^{30}Ar with the known energy of 2.45 MeV [8] is shown by the dotted curve.

two respective components: 1) the Monte-Carlo simulation including the response of the experimental setup to $1p$ -emission by ^{31}K (the simulation procedure is described in details in Refs. [10, 11]; 2) the known detector response to the $2p$ -decay of ^{30}Ar g.s. (see Ref. [8]). One may see, that the small-angle region of the θ_{p-28S} distribution agrees with the $2p$ -decay of ^{30}Ar 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 ^{31}K into ^{30}Ar 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 ^{31}K into the ^{30}Ar g.s. matches the measured angular θ_{p-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 ^{31}K g.s. as $2.15(15) + 2.45 \pm 0.10 \simeq 4.6(2)$ MeV.

Similar angular θ_{p-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 ^{30}Ar g.s., and therefore the 9 and 16 MeV excited states in ^{31}K should proceed via excited states in ^{30}Ar .

The result of the data analysis, the assigned levels of ^{31}K and their decay scheme, is shown in Fig. 4. The de-

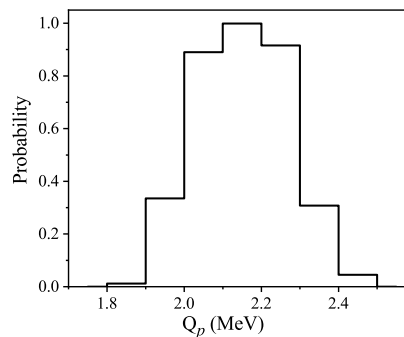


FIG. 3. Probability that the simulated response of the setup to the $1p$ decay of ^{31}K into the ^{30}Ar g.s. matches the measured angular θ_{p-28S} correlations [shown in Fig. 2(i)] as a function of assumed $1p$ -decay energy Q_p .

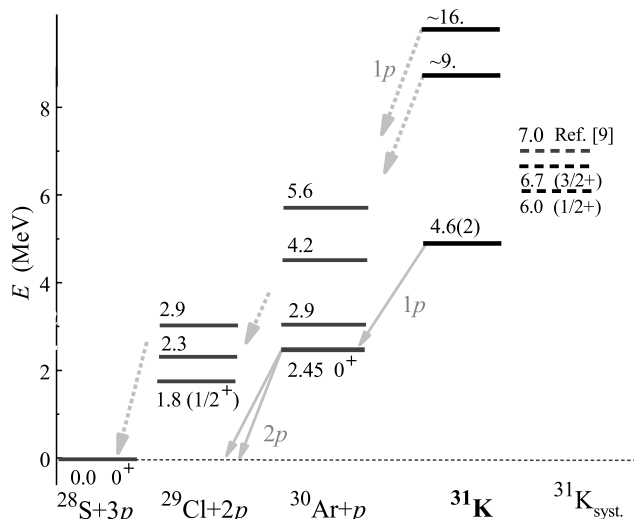


FIG. 4. Proposed decay scheme of ^{31}K levels with a tentatively-assigned $1p$ -decay channel through the known ^{30}Ar and ^{29}Cl states [8], whose energy is given relative to the $3p$, $2p$ and $1p$ thresholds, respectively. On the right-hand side, the energies of the ^{31}K g.s. predicted by the 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.

rived information may be improved in following experiments with higher statistics and increased resolution. The mass of the ^{31}K g.s. may be derived by using the masses of $^{28}\text{S}+3p$ and the Q_{3p} value, which then may be compared with available theoretical predictions. The energy of the ^{31}K g.s. has been predicted by the systematics proposed for the mass differences of mirror nuclei (the improved Kelson-Garvey mass relations [12]), which is shown in Fig. 4 on the right-hand side. One sees quite a large disagreement with the experimental value. Such a difference may be explained by the effect of Thomas-Ehrmann shift [14, 15] which is often

observed in $1p$ -unbound nuclei. Alternatively, as the ^{31}K g.s. decays via the long-lived ^{30}Ar g.s., we may use the empirical S_p systematics of $1p$ -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}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. [16]. 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}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}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}K g.s. is about 30 keV only. The widths of the excited 9 and 16 MeV states were estimated from the ρ_3 distribution in Fig. 1 giving the values of 1 and 2 MeV, respectively. One should also note, that the spectrum of ^{31}Mg , which is the mirror nucleus of ^{31}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 γ -ray emission with half-lives in the nanosecond range. As all ^{31}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}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 [19] 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}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 ρ_3 -spectrum of ^{31}K shown in Fig. 1. The Monte Carlo simulations [10, 11] of the reference case of ^{30}Ar short-lived excited states are shown in Fig. 5(a). They assume $T_{1/2} \simeq 0$ ps for the ^{30}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

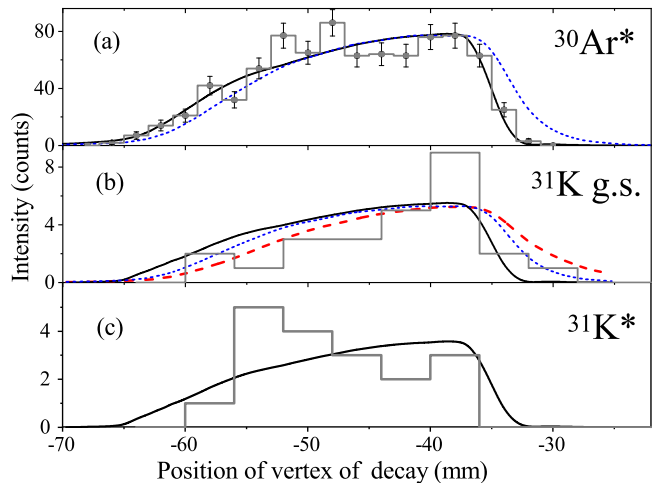


FIG. 5. (a) Profile of the $^{30}\text{Ar}^* \rightarrow ^{28}\text{S}+p+p$ decay vertices along the beam direction with respect to the microstrip detector (histogram with statistical uncertainties) closest to the reaction target. The data correspond to short-lived excited states in $^{30}\text{Ar}^*$ [19]. (b,c) Profiles of the $^{31}\text{K} \rightarrow ^{28}\text{S}+p+p+p$ decay vertexes measured under the same conditions as those shown in panel (a). In panel (b), the data with the lowest ρ_3 angles around the peak (i) in Fig. 1 are selected, where the ground state of ^{31}K is assigned. (c) The data are gated by the larger angles ρ_3 around the peak (ii) in Fig. 1, which corresponds to a short-lived excited state in ^{31}K . Solid, dotted and dashed curves show the Monte Carlo simulations of the detector response for the $2p$ -decays of ^{30}Ar and $3p$ -decays of ^{31}K with half-life $T_{1/2}$ of 0, 5 and 10 ps, respectively.

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}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}K g.s. data. However, production of few events of ^{31}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}K g.s. is shorter than 10 ps, which is our upper-limit estimate. For the ^{31}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}K , a dedicated experiment with improved resolution and larger statistics inspecting possible shape coexistence in ^{31}K may provide a strict test of isospin-symmetry conservation/violation of such exotic nuclear systems.

In conclusion, the first spectroscopy of the previously-unknown isotope ^{31}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}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_{3p} value, which is the most challenging test of predictions of nuclear mass models.

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