EXPLORATION OF NUCLEAR STRUCTURE ALONG THE PROTON-UNBOUND ARGON AND CHLORINE ISOTOPES*

D. Kostyleva

for the EXPERT/Super-FRS Experiment Collaboration of FAIR

Justus-Liebig University
Heinrich-Buff-Ring 16, 35392 Giessen, Germany
and
GSI Helmholtzzentrum für Schwerionenforschung GmbH
64291 Darmstadt, Germany

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A systematic investigation of the argon and chlorine isotopes located by two and three mass units beyond the proton drip line was performed recently at the FRS. A state-of-the-art tracking technique with silicon micro-strip detectors allowed for measurement of the trajectories of argon and chlorine in-flight decay products. These data were used to reconstruct angular correlations between decay products, which allowed to assign the energy levels to ^{31}Ar and ^{30}Cl for the first time. On the basis of the observed excited states in ^{31}Ar and a new estimation of its two-proton separation energy S_{2p} of a few keV, the prospects for further studies of low-binding effects of this nucleus are presented.

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1. Introduction

The borders separating bound and unbound nuclear systems, *i.e.* drip-lines are important landmarks of the nuclear chart. Loosely bound nuclear states are in a transition region between bound states and continuum, and they can have long enough lifetimes to be considered as quasi-stationary nuclear systems. Here, one can raise the question about the limits of existence of such nuclear structure. In order to investigate this on the neutron-deficient side of the nuclear chart, we performed detailed investigations of argon and chlorine proton-unbound isotopes [1–3]. All three articles report studies done via trajectories measurement of the in-flight decay products

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performed at the fragment-separator and spectrometer FRS at GSI, Darmstadt. In Ref. [1], we reported on ^{31,29}Ar and ^{30,28}Cl energy level assignment. In the theoretical paper [2], we perform predictions for the lightest quasi-stationary systems to be ^{26}Ar and ^{25}Cl in the corresponding isotopic chains, done on the basis of cluster models and experimental systematics obtained in [1]. The article [3] is devoted to previously unobserved ^{30}Ar and its "subsystem" ^{29}Cl. One of the interesting results of those investigations is the new estimation of the two-proton separation energy $S_{2p} = +6(34)$ keV for the ^{31}Ar ground state.

The ^{31}Ar nucleus is the most-studied in respect to β-delayed proton decays: $\beta 2p$ [4–6] and $\beta 3p$ [7, 8] experiments were performed at the ISOLDE facility at CERN and the LISE facility at GANIL. ^{31}Ar is also predicted to be a true $2p$ emitter [9]. However, no experimental evidence of such a process has been found so far. In the more recent study [10] with the Optical Time Projection Chamber at the FRS fragment-separator, the $\beta 3p$ decay branching ratio of ^{31}Ar is found to be $0.07 \pm 0.02\%$. The latter value directly relates to the upper limit of non-observation of a direct $2p$-decay branch of ^{31}Ar.

Here, on the basis of [1], the first-time observed ^{31}Ar excitation energy spectrum is reported as well as the new estimation of S_{2p} of this nucleus and possible effects of the low binding on the properties of this nucleus are elaborated.

2. Experiment and data interpretation

The experiment was conducted at fragment-separator FRS with a primary beam of 885 A MeV ^{36}Ar coming from the UNILAC linear accelerator and the SIS18 synchrotron. The details of the experimental setup can be found in Refs. [1, 3, 11], here just a brief description is given. The secondary beam of 620 A MeV ^{31}Ar with the intensity of 50 ions per second was transported by the first half of FRS to the thick ^{9}Be target. The main objective of studies was $2p$ decay of ^{30}Ar from one-neutron removal reaction, however, the process such as inelastic scattering of ^{31}Ar was also observed. The scheme of the experiment is shown in Fig. 1. An array of double-sided silicon micro-strip detectors (DSSD) was set downstream from the secondary target in order to measure the hit coordinates of ^{29}S and two protons from the corresponding in-flight decay of an excited state in ^{31}Ar. The high-precision reconstruction of the decay-product trajectories allowed to measure angular correlations of $^{29}\mathrm{S} + p$ and $^{29}\mathrm{S} + p + p$, see the scatter plot in Fig. 2 (a).

In Fig. 2 (b), one can see an illustration of the kinematics for the simple case of isotropic and mono-energetic one-proton emission from a high-energy precursor, ^{31}Ar* in our case. In laboratory system, there is a kine-

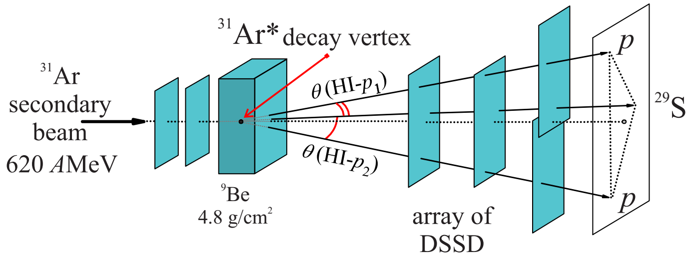

Fig. 1. Scheme of the experimental setup around the secondary ^{9}Be target at the central focal plane of the FRS. The reaction of ^{31}Ar inelastic excitation followed by the $2p$ decay occurs inside the target. Then the decay products (^{29}S and two protons) are tracked by the array of double-sided silicon micro-strip detectors (DSSD).

matic enhancement at the maximum possible angle between ^{29}S and proton $\theta_{^{29}\mathrm{S}-p}(\mathrm{max})$, where the proton is emitted orthogonally to the momentum of ^{29}S. The enhancement is represented by the peak in the corresponding angular distribution in Fig. 2 (c). Thus, one can derive spectroscopic information like the decay energy from the related peak in the data.

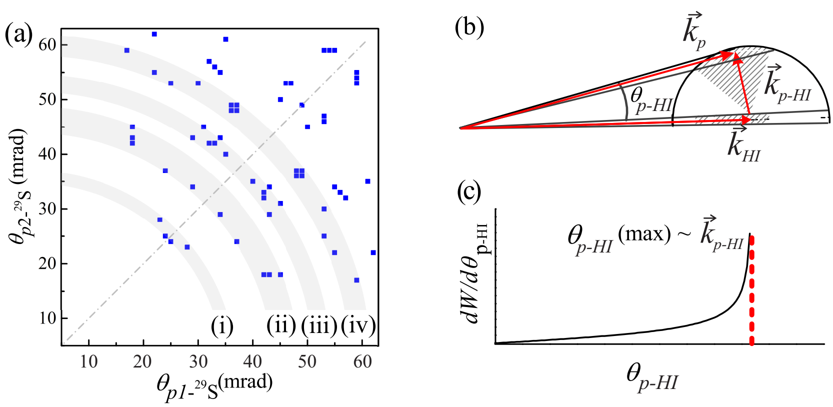

Fig. 2. (a) Angular correlation $\theta_{p1-^{29}\mathrm{S}}$–$\theta_{p2-^{29}\mathrm{S}}$ from the measured triple $^{29}\mathrm{S}+p+p$ coincidence. The states sharing the same total energy are shown by the Roman numerals and shaded arcs. (b) Schematic illustration of kinematics related to the isotropic mono-energetic proton emission. $\vec{k}_p$, $\vec{k}_{\mathrm{HI}}$ are the momenta of proton and heavy ion (HI) in the lab system, respectively, $\vec{k}_{p-\mathrm{HI}}$ is the relative momentum between them. The kinematic enhancement around the maximum angle $\theta_{p-\mathrm{HI}}$ is shown by the striped area, and the corresponding angular distribution with the peak next to $\theta_{p-\mathrm{HI}}(\mathrm{max})$ is shown in panel (c).

The experimental angular correlation derived from $^{29}\mathrm{S}+p$ double coincidences is shown in Fig. 3 in gray color, where one can see peaks corresponding to different energy states in $^{30}\mathrm{Cl} = {}^{29}\mathrm{S}+p$ subsystem. In order to quantitatively reproduce the data, the Monte-Carlo simulation of the setup response was performed. By fitting each peak from the data by the corresponding simulation, one can deduce the decay energy of a state and its uncertainty. In Fig. 3, the Monte-Carlo simulation curve for the first state is shown. The positions of other peaks were deduced from triple-coincidence spectra, the corresponding procedure is described in Ref. [1] in detail. An agreement between double- and triple-coincidence spectra was observed, *i.e.* peak-like structures were found at the same positions in both histograms. Thus, the data are reproduced by the simulation. Each peak is assigned its energy and uncertainty. The reconstructed level scheme of ^{31}Ar and its subsystem ^{30}Cl is shown in Fig. 4.

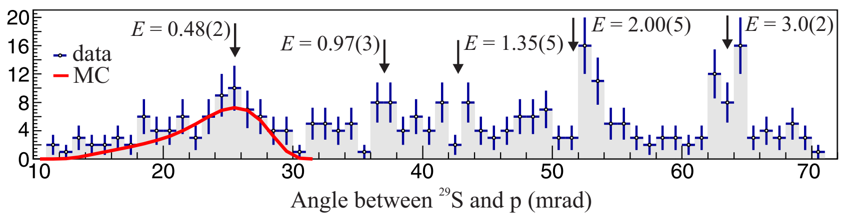

Fig. 3. (Color online) Experimentally obtained angular correlation of ^{29}S and one of the protons is shown by the gray-filled histogram and dots with statistical uncertainties. This spectrum reflects the states in the ^{30}Cl subsystem. Monte-Carlo simulation curve for the first state in ^{30}Cl is shown in dark gray/red. The positions of the other states identified by the analysis of the triple-coincidence data [1] are shown by the black arrows coupled with the assigned energies of the states.

3. Estimation of location of ^{31}Ar ground state and conclusions

The decay energies for five states in ^{30}Cl and six excited states in ^{31}Ar and the transitions between them have been assigned. There is no sign of ^{31}Ar ground state in the data. However, the obtained excitation spectrum of ^{31}Ar shows a very high level of isobaric symmetry with its mirror nucleus — ^{31}Al, thus one may deduce the S_{2p} value of the ^{31}Ar ground state. It is done by comparing four aligned low-lying energy levels in both mirror partners. Namely, the states in ^{31}Ar with the decay energy Q_{2p} of 0.95(5), 1.58(6), 2.12(7) and 2.62(13) MeV are in high correspondence with the sequence of known states in ^{31}Al [12] with excitation energies of 0.9467(3), 1.61297(24), 2.090(11) and 2.676(28) MeV. Thus, one can assume that the g.s. of both nuclei are separated by the same energy from their first excited states. If one calculates a weighted average of the differences between four S_{2p} of the excited states, the $S_{2p} = +6(34)$ keV for ^{31}Ar ground state is obtained. This evaluation is illustrated in Fig. 4.

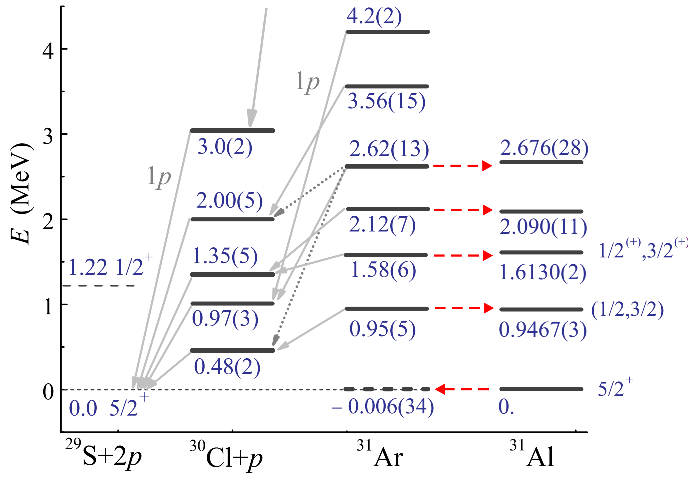

Fig. 4. (Color online) The energy level scheme for ^{31}Ar and ^{30}Cl from [1]. Assigned decay transitions are shown by the gray arrows. The red dashed arrows point to the corresponding states in ^{31}Al, the isobaric mirror of ^{31}Ar.

This new estimation is in agreement with the previous ones, performed during studies of $\beta 2p$ decay of ^{31}Ar: $S_{2p} = -3(110)$ keV from [4] and the estimation +100(210) keV from AME2016 [13]. In all three cases, the experimental errors do not allow to determine the sign of separation energy. Thus, it is unclear whether ^{31}Ar is beyond the proton dripline or not. For the *sd*-shell nuclei, a shift of the energy levels in neutron-deficient systems in respect to their mirror nuclei (Thomas–Ehrman shift [14, 15]) is a common feature, but it was not observed in this case. Thus, by assuming high isobaric symmetry reported here, ^{31}Ar is likely a bound system. In order to clarify this issue, one has to directly measure the mass of this nucleus with high accuracy and precision.

4. Prospects for further studies

For a $2p$-radioactivity case, the precursors values $S_p > 0$ and $S_{2p} < 0$, which means that $1p$ emission is not possible and thus two valence protons are emitted simultaneously. For the case of $S_p < 0$ and $S_{2p} > 0$, a weakly bound system of two nucleons might form a halo-like structure. In general, halo structures are characterized by very small binding energy and unusually large radius. In the recent theoretical paper [16] on the emergence of halos and Efimov states for systems with low three-body binding energy, it is shown that there is an abrupt increase of their r.m.s. radius around binding energies of 100 keV. In our case, S_{2p} of ^{31}Ar is of the order of tens of keV, thus one might consider this system a possible candidate for a proton-halo structure.

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