PROBING THE STRUCTURE OF NEUTRON-DEFICIENT ACTINIUM ISOTOPES IN JYFL-ACCLAB*

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Excited states of the $^{207-213}$Ac nuclei were studied by employing fusion–evaporation reactions at the RITU and MARA separators of the Accelerator Laboratory of the University of Jyväskylä, Finland. In three of the four conducted experiments prompt γ-ray transitions were measured by employing the JUROGAM3 spectrometer, while the fourth experiment focused on delayed spectroscopy of ^{207}Ac. Level schemes were established for odd-A isotopes, and those are compared to the systematics set by nearby astatine and francium nuclei, as well as to the excited states of the respective even–even isotone cores.

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1. Introduction

In JYFL-ACCLAB (Accelerator Laboratory of University of Jyväskylä, Finland) the nuclei in the so-called beyond-lead region ($Z \geq 82$ and $N \leq 126$) have been studied extensively over the past decade. For example, a number of new isotopes have been discovered [1–6], as well as a large variety of different isomeric states [7–11] and coexisting nuclear shapes [12–14]. Shape coexistence, together with the evolution of nuclear shapes, is a central topic in the studies of nuclei in the beyond-lead region. In neutron deficient odd-A isotopes of astatine and francium the $9/2^-(\pi h_{9/2})$ ground state remains nearly spherical in heavier isotopes. However, when moving towards the proton dripline the ground state first becomes weakly oblate, and while this happens, the proton intruder $s_{1/2}$ orbital approaches the Fermi surface rapidly. In heavier isotopes a $1/2^+$ $(\pi s_{1/2})$ state is observed as a metastable isomeric state (see, for example, Refs. [7–10] and references therein), but it

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becomes the ground state starting from ^{195}At [15] and possibly from ^{199}Fr [2, 16], and while this change happens, the ground states become more deformed [17]. Another sign of developing deformation in At and Fr nuclei is the reduction in the excitation energy of a $13/2^+$ ($\pi i_{13/2}$) isomeric state as the neutron number is reduced [4]. This is due to the $i_{13/2}$ proton coupling to the $2p$–$2h$ excitation of the underlying even–even core, leading into oblate deformation. Such coupling can result in rotational structures built on this state [9, 10].

Recently, we have expanded these studies into neutron-deficient actinium isotopes through in-beam γ-ray spectroscopy and decay-spectroscopy techniques. The purpose of this article is to summarize the results of our four recent experiments. Out of the four experiments, the first two focused on the structure of the ^{211,213}Ac isotopes, and detailed results are already published elsewhere [18]. The latter two studied the structure of ^{209}Ac via in-beam spectroscopy and that of ^{207}Ac through decay spectroscopy techniques, and the full details of those studies will be published in the near future [19].

2. Experimental methods

The nuclei of interest were produced through fusion–evaporation reactions, see Table 1 for the used reactions, primary beam details, as well as the used experimental setups. Around the target chamber the JUROGAM3 [20] germanium-detector array was placed to detect promptly emitted γ rays in three of the experiments. The fusion–evaporation residues, referred to as recoils hereafter, recoiling out of the target were separated from the unreacted primary beam and other unwanted ions either by the MARA (Mass-Analyzing Recoil Apparatus [21, 22]) or by RITU (Recoil-Ion Transport Unit [23, 24]) separators. The former operates in vacuum mode, whereas the latter was filled with ≈1 mbar of He gas. The focal-plane spectrometers of both devices are nearly identical, and in those the recoils first pass through a Multi-Wire Proportional Counter (MWPC) before implantation into a Double-Sided Silicon Detector (DSSD). An event was considered as a recoil if an implantation energy — time-of-flight (from MWPC to DSSD) condition was satisfied. Additionally, an event in the DSSD was considered as a radioactive decay if no coincident MWPC signal was present. In ^{207,209}Ac studies, a BOX-like silicon-detector array of 28 PIN diodes was placed along the circumference of the DSSD to detect micro-second scale emission of internal conversion electrons and to allow adding back α-particles escaping the DSSD. Outside the focal-plane vacuum chamber three Broad-Energy Germanium detectors (BEGe) and one coaxial detector were placed to detect delayed γ-ray transitions. Data from all detector channels were recorded independently and time-stamped with a 100 MHz metronome, and subsequently, those were analysed via the Grain [25] software package.

Table 1. Experimental details of the actinium studies performed recently in JYFL-ACCLAB.

Experiment	^{213}Ac	^{211}Ac
Reaction	^{180}Hf(^{37}Cl, $4n$)^{213}Ac	^{175}Lu(^{40}Ar, $4n$)^{211}Ac
Cross section	50 μb	50 μb
$E_{\rm beam}$ [MeV]	170	182
$I_{\rm beam}$ [pnA]	10	17
t [hours]	142	167
Separator	MARA	MARA
Spectrometer(s)	Focal plane	Focal plane
	JUROGAM3	JUROGAM3
Experiment	^{209}Ac	^{207}Ac
Reaction	^{180}Hf(^{35}Cl, $6n$)^{209}Ac	^{175}Lu(^{36}Ar, $4n$)^{207}Ac
Cross section	420 nb	3 nb
$E_{\rm beam}$ [MeV]	190	184
$I_{\rm beam}$ [pnA]	28	200
t [hours]	150	64
Separator	RITU	RITU
Spectrometer(s)	Focal plane	Focal plane
	JUROGAM3	—

3. Results and discussion

All isotopes of actinium studied over this campaign are relatively short-lived α-decaying nuclei. This allowed us to use the extremely selective method of Recoil-Decay Tagging (RDT [26, 27]) that is particularly suitable to reliably identify events arising from very weak production channels. For an example of the RDT method the reader is referred to Figs. 1 and 4 of Ref. [18] and the related discussion. Through the RDT method we identified prompt γ-ray transitions belonging to $^{209-213}$Ac isotopes with the main focus on the odd-A nuclei. Level schemes were build based on γ-ray energies and intensities, their coincidence relationships and angular distributions, which support the proposed spin and parity assignments of ^{211}Ac and ^{213}Ac. Owing to the very small production cross section, only γ-ray singles data were available for the ^{209}Ac isotope, in which case the level scheme was based on similarities with the neighbouring isotope ^{211}Ac and with that of the even–even isotone core ^{208}Ra. For the list of observed transitions, detailed analyses, and the obtained level schemes, see Refs. [18, 19].

In Fig. 1 we summarize the main outcome of this campaign by comparing the lowest $^{13}/_{2}^{-}$, $^{17}/_{2}^{-}$, and $^{21}/_{2}^{-}$ states of Ac nuclei to the 2^+, 4^+, and 6^+ states of their even–even isotone cores. In addition, the same comparison is shown for francium and astatine isotopes and their even–even cores. In the beyond-lead region it has been well established (see, for example, Refs. [9, 10, 28, 29] and references therein) that the lowest negative parity states of astatine and francium nuclei have a strong tendency to follow the energies of the 2^+, 4^+, and 6^+ states of the underlying even–even core, as is also apparent in Fig. 1 (b) and (c). Owing to this, the negative parity states in At and Fr are commonly interpreted as the odd $h_{9/2}$ valence proton coupled weakly to the respective states of the even–even core. Our newly obtained data for actinium isotopes show no sign of divergence from the systematic pattern set by At and Fr isotopes. This indicates that there are no abrupt changes in nuclear structure or deformation when one moves from At and Fr isotopes to heavier Ac nuclei, and that the odd $\pi h_{9/2}$ remains mainly as a "spectator" in the sense that it has little impact on the excitation energies of the negative parity states, but it only brings the additional angular momentum of $^{9}/_{2}$ units.

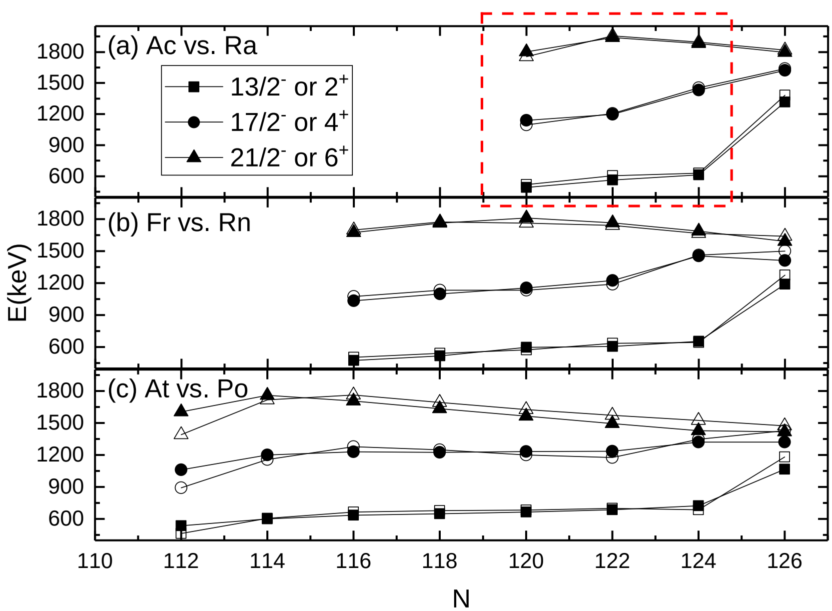

Fig. 1. Energies of the lowest negative parity $^{13}/_{2}^{-}$, $^{17}/_{2}^{-}$, and $^{21}/_{2}^{-}$ states in the (a) Ac, (b) Fr, and (c) At isotopes compared to the energies of the 2^+, 4^+, and 6^+ states of the even–even isotone core. The solid symbols are for the odd-Z nuclei, while the open symbols denote the yrast states in the (a) Ra, (b) Rn, and (c) Po core nuclei. The negative parity data obtained in this campaign are highlighted in dashed red/gray, while the other data points were extracted from NuDat3.0 [30].

Another result was obtained in the fourth experiment focusing on the decay spectroscopy of ^{207}Ac when altogether 8 internal conversion events were observed to rapidly follow an implantation event of ^{207}Ac. Out of these, four events were observed in the BOX detector, while the other four were seen in the traces recorded from the x-side of the DSSD, see Fig. 2 for an example. Additionally, a few γ-ray events were observed in the focal plane germanium-detector array under identical tagging conditions as those used to identify the internal conversion electrons. These internal transition events can be interpreted as a sub-microsecond M2 transition depopulating a $13/2^+$ ($\pi i_{13/2}$) isomeric state in ^{207}Ac. These interpretations are supported, for example, by the extracted internal-conversion coefficient and B(M2) value, and by the level energy systematics of other $13/2^+$ states in the beyond-lead region. The details of the analysis and full discussion will be published shortly [19].

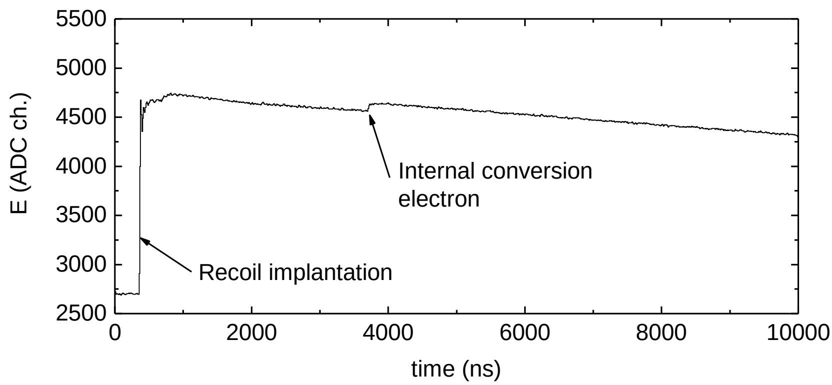

Fig. 2. Waveform sample ("trace"), recorded from the x-side of the DSSD, showing an implantation event rapidly followed by an internal conversion electron event. The event sequence was identified as an implantation of ^{207}Ac as it is correlated with a subsequent α-decay event of ^{207}Ac in the same pixel of the DSSD.

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