Article ID: 1007-4627(2016) 02-0141-05

Spectroscopy of Low-lying States in Odd-Z Odd-A Nuclei Beyond Lead

U. Jakobsson[1], J. Uusitalo[2], K. Auranen[2], H. Badran[2], B. Cederwall[1], D. M. Cox[2],
T. Grahn[2], P. T. Greenlees[2], R. Julin[2], S. Juutinen[2], A. Herzáň[2], J. Konki[2],
M. Leino[2], M. Mallaburn[2], J. Pakarinen[2], P. Papadakis[2], J. Partanen[2], P. Rahkila[2],
M. Sandzelius[2], J. Sarén[2], C. Scholey[2], J. Sorri[2], S. Stolze[2]

(1. KTH, The Division of Nuclear Physics, AlbaNova University Center, SE-10691 Stockholm, Sweden;
2. University of Jyvaskyla, Department of Physics, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland)

Abstract: Low-lying states in odd-Z odd-mass nuclei at the proton drip-line beyond lead have recently been studied through fusion-evaporation reactions using a gas-filled recoil separator. Isomeric $1/2^+$ and $13/2^+$ states have been observed in odd-mass astatine and francium nuclei. The systematic behaviour of the level energies of these states have been studied and a similarity between the $1/2^+$ state in astatine and francium has been found. Furthermore, the $13/2^+$ state has been observed in the francium nuclei with an oblate behaviour suggesting a coupling of the $i_{13/2}$ proton to the $2p-2h$ intruder excitation.

Key words: Nuclear spectroscopy; isomeric states; $Z > 82$

CLC number: O571.2　　**Document code:** A　　**DOI:** 10.11804/NuclPhysRev.33.02.141

1 Introduction

During the recent years progress has been made in the study of low-lying states in odd-Z nuclei beyond lead. Laser-spectroscopic studies have been performed for the ground states in francium nuclei[1–2]. Alpha-decay as well as prompt and delayed gamma-ray spectroscopy have been used in studying low-lying states in neutron-deficient astatine and francium nuclei[3–9]. These studies include the discovery of previously unobserved isomers and the investigation of the properties of already discovered ones. Two new isotopes of francium have recently been observed, namely ^{197}Fr[7] and ^{198}Fr[7–8], with neither of them showing signs of proton emission. To date the only proton emitter known above lead is thus ^{185}Bi[10]. There is only this one known proton emitter, although recent spectroscopic results in this region have been extended to nuclei beyond the proton drip-line. For instance, the new francium isotopes are proton unbound in their ground state by close to 1 MeV and in-beam spectroscopy has been performed for nuclei where all excited states are proton unbound, see for instance Ref. [3]. Fig. 1 presents proton separation energies for odd-Z nuclei in the region above lead. The filled circles indicate nuclei where low-lying states have recently been studied.

A main topic of study in this region is nuclear deformation and consequently shape coexistence. Deformation in this region is based on the intruder picture associated with excitations across the $Z = 82$ shell closure. Such intruder excitations include the $2p-2h$ and the $4p-4h$ excitation that in even-Z nuclei are associated with oblate and prolate deformation, respectively. In the odd-Z nuclei a $1/2^+$ state is created by a $1p-1h$ excitation. This state will have an “intruding” down-sloping trend when moving away from the neutron shell closure, that is with an increasing number of neutron holes. Such a behaviour is typical for a state based on an intruder configuration. Moreover, structures based on this configuration will experience deformation. The odd proton in odd-Z nuclei may also couple to an intruder configuration. For instance the coupling of the $i_{13/2}$ proton to the $2p-2h$ excitation will result in a deformed $13/2^+$ state, with a strongly-coupled rotational band built on it. Alternatively a coupling of the odd proton to the $4p-4h$

Received date: 2 Sep. 2015;

Foundation item: Academy of Finland under the Finnish Center of Excellence Programmes (2006-2011, 2012-2017); EURONS (European Comissiom) (RII3-CT-2004-506065); EU 7th Framework Programme (262010) (ENSAR)

Biography: Ulrika Jakobsson (1983–), female, Kuusankoski, Finland, Ph.D., working on experimental nuclear physics; E-mail: ulrjak@kth.se.

excitation will create a prolate deformed $13/2^+$ state, with a decoupled rotational structure built on it. The level energy of the state will furthermore have a downsloping behaviour. The $h_{9/2}$ proton can also couple to an intruder excitation, but thus far such a coupling has not been observed and the $9/2^-$ state, that is the ground state in heavier isotopes, is suggested to remain spherical. A motivation for the study of intruder-based states in these nuclei, is the question how far beyond the $Z = 82$ proton shell closure the intruder picture can be found as the shell closure moves further below the Fermi surface.

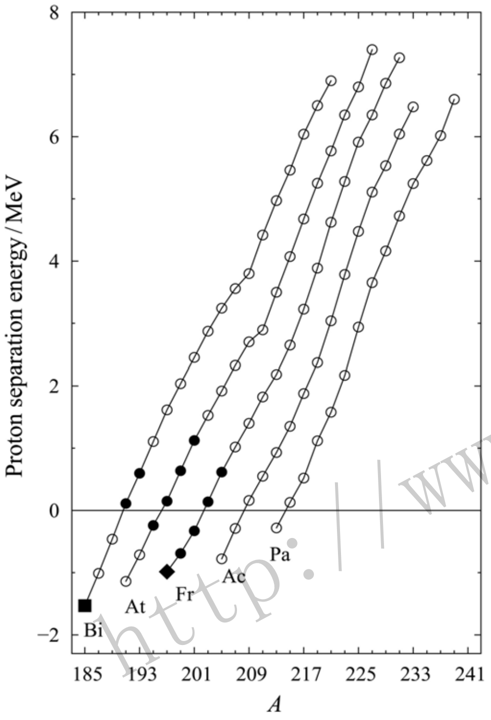

Fig. 1 Proton separation energies for odd-Z odd-A isotopes of elements above the $Z = 82$ proton shell closure. The nuclei most recently studied are indicated with filled circles. Of these the new francium isotope ^{197}Fr is shown with a filled diamond. The only know proton emitter above lead ^{185}Bi is indicated with a filled square. The data points are taken from Refs. [11-12] and for ^{197}Fr derived from Refs. [7, 13].

Here we present results from our recent studies in the astatine and francium nuclei. For further information please see the Refs. [3-4, 8-9] together with references therein.

2 Experimental techniques

The nuclei were studied at the accelerator laboratory at the University of Jyväskylä, Finland. Stable heavy-ion beams provided by an ECR ion source were accelerated with the K-130 cyclotron and impinged on a rotating thin target. The studied nuclei were produced through fusion-evaporation reactions generally in the xn or the pxn evaporation channel. The forward-focused fusion-evaporation projectiles (later called recoils) were separated from primary beam particles and other unwanted reaction products by the gas-filled recoil separator RITU (Recoil Ion Transport Unit)[14–15]. After exiting RITU the recoils were deposited in the GREAT spectrometer[16–17] at its focal plane. When arriving in GREAT the recoils passed through a MWPC and were implanted in a highly-granular double-sided silicon strip detector (DSSD), where their particle emission was observed. Upstream from the DSSD a silicon PIN-detector array is mounted to detect particles that have escaped from the DSSD. The DSSD is, furthermore, surrounded by clover HPGe-detectors mounted outside the GREAT chamber for gamma-ray detection and a thin planar Ge-detector is placed inside the GREAT chamber behind the DSSD in order to detect low-energy gamma rays. See Fig. 2 for a schematic drawing of the GREAT spectrometer. All data channels are read out independently using the total data readout technique TDR[18].

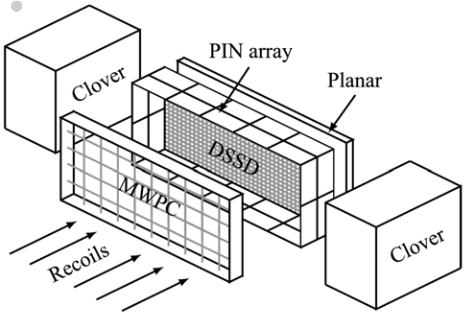

Fig. 2 A schematic drawing of the GREAT spectrometer. The clover Ge-detector facing the GREAT chamber from the top has been omitted for visual purposes.

The decay of the recoils, and that of their daughter nuclei, was observed in the same DSSD pixel as the recoil implantation. With the help of temporal correlations recoil-decay chains could be reconstructed within the DSSD. Consequently, with the help of the known decay properties of the daughter nucleus, the decay properties of the parent nucleus could be extracted. For more information on the technique see for instance Ref. [8].

If the recoil arrived in GREAT in an isomeric state, the decay or the de-excitation of the state could be observed. If the half-life of the isomer was sufficiently long to overcome the processing time of the ADC of the DSSD channel, the isomeric transition could be observed within the same DSSD pixel as the recoil implantation and the possible subsequent ground-state decay had taken place. In the case where the isomer decays via particle emission, recoil-decay chains can be constructed as discussed above. If this is not the case, the transition from the long-lived isomer is often highly converted, and the conversion electrons leave an energy deposit in the DSSD that can be observed. If the isomer de-excites via intermediate states to the ground state, a prompt cascade of conversion electrons can be emitted. In this case the DSSD serves as a calorimeter detecting the energy deposit of the absorbed electrons together with the energy released in the relaxation of the electron cloud. As the implantation depth of the recoils in the DSSD is in general quite shallow, maximally 10 μm, roughly half of the conversion electrons will escape the DSSD without an energy deposit. Together with the fact that part of the transitions in the cascade may not be converted, the resulting electron spectrum depicting the multistep de-excitation of the isomer can be quite complex. The "end-point" of this spectrum, however, represents the excitation energy of the isomer. In this scenario all transitions in the cascade have been converted and all conversion electrons have been observed. We observed such a spectrum associated with the decay of the $1/2^+$ isomer in the nuclei ^{199}At, ^{201}At, ^{203}Fr and ^{205}Fr. With the knowledge of the available proton orbitals in this region, the structure generating the cascade of electrons could be reconstructed. In the astatine cases gamma rays coincident with the cascade were furthermore observed, confirming the assignment of the level energy of the isomer and the structure below it. In the francium cases the statistics were too sparse to observe coincident gamma rays and GEANT4[19–20] simulations were used in the interpretation. For further information on the experimental details see Ref. [3-4, 9].

When the half-life of the isomer is shorter than tens of microseconds, the energy deposit cannot be detected within the DSSD. If the transition from the isomer is not converted, the emitted gamma ray can be observed in the Ge-detectors surrounding the DSSD and the corresponding conversion electron can be observed with the PIN-array if it escapes the DSSD. In this case use of the recoil-decay tagging technique (RDT)[21–23] was made to observe the isomer. As the properties of the recoil had been deduced with the information gained by its decay in the DSSD, temporal correlations between the recoil implantation and the detection of an isomeric event in the GREAT Ge-detectors or the PIN-array could be performed. In this way the gamma rays and conversion electrons were assigned to the corresponding nuclide. Based on the comparison of the gamma-ray peaks with the corresponding conversion-electron peaks, the properties of the isomers could be extracted. Such spectra were collected in the case of the $13/2^+$ isomer in the nuclei ^{203}Fr and ^{205}Fr. For further experimental details see Refs. [3-4].

3 Results and discussion

The $1/2^+$ state is relatively well-known in neutron-deficient bismuth isotopes, where it is observed to have a down-sloping behaviour when moving away from the neutron shell closure, a trend that is typical to an intruder state. Moreover, it is observed to become the ground state in ^{185}Bi[10] close to the neutron mid-shell. In the neutron-deficient astatine isotopes the information available of the $1/2^+$ state is more scarce. Prior to our studies it had been observed in ^{191}At, ^{193}At[24] and ^{195}At[25], where it is the ground state, and in ^{197}At at an excitation energy of only 52 keV[26]. Our recent studies have extended the knowledge of the systematics of the $1/2^+$ state in astatine to heavier isotopes. We observed this state at approximately 240 keV in ^{199}At with very low statistics through the internal conversion of the isomeric transition in the DSSD subsequent to the alpha decay of the parent nucleus ^{203}Fr[3]. An upward sloping behaviour could then be anticipated to occur for the $1/2^+$ state when moving toward the neutron shell closure. We later revisited this isotope producing it directly in the fusion-evaporation reaction, with high statistics, and confirmed our previous results with a considerable improvement in the accuracy of the level energy of 244 keV and the half-life of the isomer of 273(9) ms[9].

In the same study we observed the $1/2^+$ state in ^{201}At at a level energy of 459 keV and with a half-life of 45(3) ms. With these new results the upward rising trend of the $1/2^+$ state could be confirmed. Both in ^{199}At and ^{201}At the isomer de-excites through a cascade consisting of an $E3$ transition to a $7/2^-$ $(\pi f_{7/2})$ state followed by a $M1$ transition to the $9/2^-$ ground state. Furthermore, a $3/2^+$ and a $5/2^+$ state were observed to feed the $1/2^+$ state in both nuclei. These two states are suggested to originate from a $(\pi d_{3/2})^{-1}$ and $(\pi d_{5/2})^{-1}$ configuration, respectively. In that case the resulting states would be based on the intruder mechanism similarly to that of the $1/2^+$ state. In the neutron-deficient francium isotopes the information available for the $1/2^+$ state was previously even more scarce than in the astatine isotopes. The state had been observed in ^{201}Fr at a level energy of 146 keV through the observation of its alpha decay to the $1/2^+$ state in ^{197}At. In the heavier isotope ^{203}Fr the alpha decay from the state had been observed, but as the level energy of the corresponding state in the daughter nucleus was not known, the level energy could not be determined[27]. In our recent study[3] this state was observed at a level energy of approximately 360 keV. With our new results for the level energy of 244 keV of the corresponding state in the daughter nucleus ^{199}At, the level energy can, however, now be updated to a value of 362 keV in ^{203}Fr. For this state both an alpha-decay branch of 20(4)% and an internal-transition branch was observed, whereas in the heavier isotope ^{205}Fr no alpha-decay branch was observed for this state[4]. In this case the $1/2^+$ state observed at close to 610 keV de-excites solely to the ground state via intermediate states. In both nuclei this decay path consists of a three-step cascade, where a $M2$ transition to a $5/2^-$ $(\pi h_{9/2}\otimes 2^+)$ state is followed by a $M1$ transition to a $7/2^-$ $(\pi h_{7/2})$ state[3–4] which in turn is followed by a second $M1$ transition to the $9/2^-$ ground state. In the lighter isotope ^{199}Fr the $1/2^+$ state is suggested to become the ground state, resulting in a deformation of the ground state[3, 8]. With the new information available for the isotopes ^{199}Fr, ^{203}Fr and ^{205}Fr of the behaviour of the level energy of the $1/2^+$ state a trend very similar to that of the astatine nuclei can be observed. See Fig. 3(a) for a comparison of the systematic behaviour of the $1/2^+$ state in bismuth, astatine and francium isotopes. A similarity in the systematics between astatine and francium isotopes is clearly visible, and the $1/2^+$ state reaches the ground state earlier in the astatine and francium isotopes than in the bismuth isotopes.

Fig. 3(b) presents the systematic behaviour of the $13/2^+$ state in neutron-deficient bismuth, astatine and francium isotopes. The filled data points denote the nuclei where recent studies have been made. As can be seen in the figure, we have observed the $13/2^+$ state in the francium isotopes for the first time[3–4]. The down-sloping trend of the level energies can be anticipated to follow that of the astatine and bismuth nuclei. In our studies we also observed a strongly-coupled rotational structure to be built on this state in both isotopes, indicating that the $13/2^+$ state is oblate deformed in this case. A coupling of the odd $\pi i_{13/2}$ proton to the oblate $2p-2h$ excitation could be the cause for the deformation.

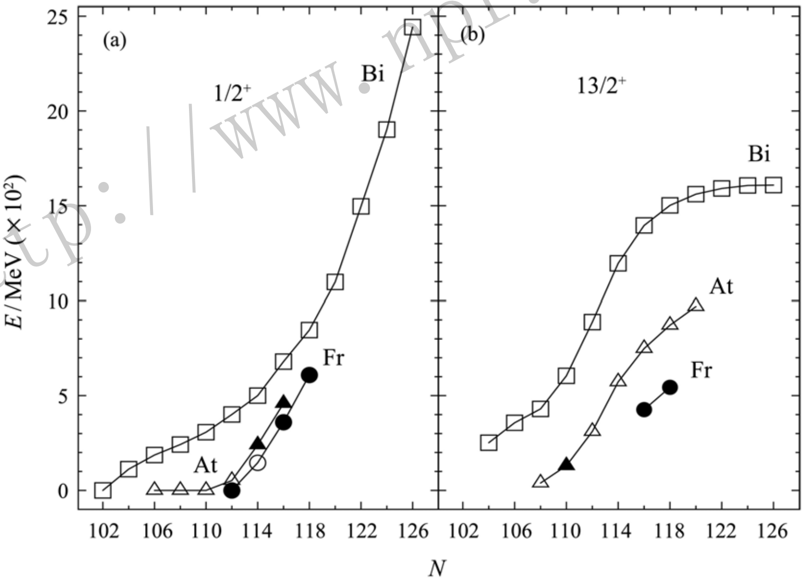

Fig. 3 Systematics of level energy of (a) the $1/2^+$ state and (b) the $13/2^+$ state in odd-mass bismuth, astatine and francium isotopes. The filled symbols indicate isotopes where the state in question has recently been discovered or studied. For further information see Ref. [3] and references therein.

4 Outlook

At the moment the only known proton-emitting nucleus above lead is ^{185}Bi. We are slowly reaching the limits of the usage of stable heavy-ion beams together with fusion-evaporation reactions to produce new isotopes and to search for proton emitters in this region. By using high-intensity ion beams and gas-filled recoil separators to separate the reaction products, there exist still subjects of study. For instance, the nucleus ^{189}At can be reachable and the proton separation energy is expected to be low enough for proton emission to be observable. In heavier nuclei such as francium, actinium and protactinium isotopes the production cross sections already become too low for fusion-evaporation reactions to be used in search of proton emission. In these cases production through the alternative fragmentation reactions may, however, be feasible. Nevertheless, beyond protactinium proton emitters are no longer expected to be reached.

The study of the properties of low-lying states in the already known isotopes that lie at the proton dripline still provides interesting topics of study. Shape coexistence between these states still requires further in-beam studies in several astatine and francium isotopes. For instance, the onset of prolate deformation in astatine isotopes has not yet been observed, although it has been reported in the lighter bismuth isotopes. New low-lying states have been observed in neutron-deficient astatine isotopes but the level energy systematics of these states is still sparse.

Acknowledgements This work has been supported by the Academy of Finland under the Finnish Center of Excellence Programmes (2006-2011 and 2012-2017) and through EURONS (European Comissiom Contract No. RII3-CT-2004-506065). The authors would also like to thank the GAMMAPOOL European Spectroscopy Resource for the loan of the detectors for the JUROGAM and JUROGAM2 arrays. Support has also been provided by the EU 7th framework programme, Project No. 262010 (ENSAR). U. J. acknowledges support from the Finnish Academy of Science and Letters and the Vilho, Yrjö and Kalle Väisäla Foundation.

References:

[1] VOSS A, PEARSON M R, BILLOWES J, *et al.* Phys Rev Lett, 2013, **111**: 122501.

[2] FLANAGAN K T, LYNCH K M, BILLOWES J, *et al.* Phys Rev Lett, 2013, **111**: 212501.

[3] JAKOBSSON U, JUUTINEN S, UUSITALO J, *et al.* Phys Rev C, 2013, **87**: 054320.

[4] JAKOBSSON U, UUSITALO J, JUUTINEN S, *et al.* Phys Rev C, 2012, **85**: 014309.

[5] KALANINOVÁ Z, ANTALIC S, ANDREYEV A N, *et al.* Phys Rev C, 2014, **89**: 054312.

[6] NYMAN M, JUUTINEN S, DARBY I, *et al.* Phys Rev C, 2013, **88**: 054320.

[7] KALANINOVÁ Z, ANDREYEV A N, ANTALIC S, *et al.* Phys Rev C, 2013, **87**: 044335.

[8] UUSITALO J, SARÉN J, JUUTINEN S, *et al.* Phys Rev C, 2013, **87**: 064304.

[9] AURANEN K, UUSITALO J, JUUTINEN S, *et al.* Phys Rev C, 2014, **90**: 024310.

[10] ANDREYEV A N, ACKERMANN D, HEβBERGER F P, *et al.* Phys Rev C, 2004, **69**: 054308.

[11] National Nuclear Data Center, information extracted from the NuDat 2 database, http://www.nndc.bnl.gov/nudat2/.

[12] ZHANG Z Y, GAN Z G, MA L, *et al.* Phys Rev C, 2014, **89**: 014308.

[13] WANG M, AUDI G, WAPSTRA A H, *et al.* Chin Phys C(HEP & NP), 2012, **36**: 1603.

[14] LEINO M, AYSTO J, ENQVIST T, *et al.* Nucl Instr Meth B, 1995, **99**: 653.

[15] SARÉN J, UUSITALO J, LEINO M, *et al.* Nucl Instr Meth A, 2011, **654**: 508.

[16] PAGE R D, ANDREYEV A N, APPELBE D E, *et al.* Nucl Instr Meth B, 2003, **204**: 634.

[17] ANDREYEV A N, BUTLER P A, PAGE R D, *et al.* Nucl Instr Meth A, 2004, **533**: 422.

[18] LAZARUS I H, APPELBE E E, BUTLER P A, *et al.* IEEE Trans Nucl Sci, 2001, **48**: 567.

[19] AGOSTINELLI S, ALLISON J, AMAKO K, *et al.* Nucl Instr Meth A, 2003, **506**: 250.

[20] ALLISON J, AMAKO K, APOSTOLAKIS J, *et al.* IEEE Trans Nucl Sci, 2006, **53**: 270.

[21] PAUL E S, WOODS P J, DAVINSON T, *et al.* Phys Rev C, 1995, **51**: 78.

[22] SCHMIDT K H, SIMON R S, KELLER J G, *et al.* Phys Lett B, 1986, **168**: 39.

[23] SIMON R S, SCHMIDT K H, HEβBERGER F P, *et al.* Z Phys A, 1986, **325**: 197.

[24] KETTUNEN H, ENQVIST T, GRAHN T, *et al.* Eur Phys J A, 2003, **17**: 537.

[25] KETTUNEN H, ENQVIST T, LEINO M, *et al.*, Eur Phys J A, 2003, **16**: 457.

[26] COENEN E, DENEFFE K, HUYSE M, *et al.* Z Phys A, 1986, **324**: 485.

[27] UUSITALO J, LEINO M, ENQVIST T, *et al.* Phys Rev C, 2005, **71**: 024306.