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Decay studies of neutron-deficient odd-mass At and Bi isotopes

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Abstract. Alpha-decay properties of the isotope ^{191}At were investigated for the first time and the decay properties of ^{193}At and ^{195}At were studied with improved accuracy. The nuclei were produced in fusion-evaporation reactions of ^{54}Fe and ^{56}Fe ions with ^{141}Pr and ^{142}Nd targets. The fusion products were separated in-flight using the gas-filled recoil separator RITU and implanted into a position-sensitive silicon detector. The isotopes were identified using position, time and energy correlations between the implants and subsequent alpha decays. New information concerning the low-lying states in the corresponding alpha-decay daughter nuclei ^{187}Bi, ^{189}Bi and ^{191}Bi was also gained using alpha-gamma coincidences.

PACS. 23.60.+e α decay – 27.80.+w $190 \leq A \leq 219$ – 23.20.Lv γ transitions and level energies – 21.10.Dr Binding energies and masses

1 Introduction

The region of neutron-deficient nuclei far from stability around the closed $Z = 82$ proton shell and the $N = 104$ neutron mid-shell offers an interesting challenge for various theoretical models as well as experimental instruments. A variety of nuclear phenomena, like shape coexistence and development of intruder states, can be observed in this limited region of the nuclear chart and understood by the coupling of the particles and particle holes to the proton-magic Pb core. In addition, the vicinity of the proton drip line in odd-Z nuclei offers an opportunity to observe proton emission in this region.

More detailed discussions about the analysis and the results of the present article are published in references [1,2]. A summary of fusion-evaporation reactions used in the present work along with the measured production cross-sections of the primary products is presented in table 1.

Table 1. Measured production cross-sections of the reactions used in the present work. Beam energies in the middle of the target are given. The ^{195}At experiment was dedicated to the production of a new radon isotope ^{195}Rn [3] and the astatine isotope was obtained as a side-product. A transmission of 40% for the evaporation residues in the RITU separator was assumed.

Reaction	Cross-section	E_{beam}
^{142}Nd(^{56}Fe, p2n)^{195}At	200 nb	262 MeV
^{141}Pr(^{56}Fe, 4n)^{193}At	40 nb	266 MeV
^{141}Pr(^{54}Fe, 4n)^{191}At	300 pb	260 MeV

2 Results

Three alpha-decaying states were identified for ^{193}At, and two for both ^{191}At and ^{195}At nuclei. For each of these isotopes the $1/2^+$ intruder state was observed to be the ground state. The alpha decays of the $7/2^-$ states in ^{195}At and ^{193}At were observed to feed the excited $7/2^-$ states at 148.7(5) keV and 99.6(5) keV in the corresponding daughter nuclei ^{191}Bi and ^{189}Bi, respectively. The spin, parity and excitation energy of these final states, observed for the first time, were determined using the properties of gamma-ray transitions observed in coincidence with the alpha decay of the ^{195}At and ^{193}At isotopes. The identification of the $13/2^+$ state in ^{193}At was also based on alpha-gamma coincidences. In ^{187}Bi the existence of the excited $7/2^-$

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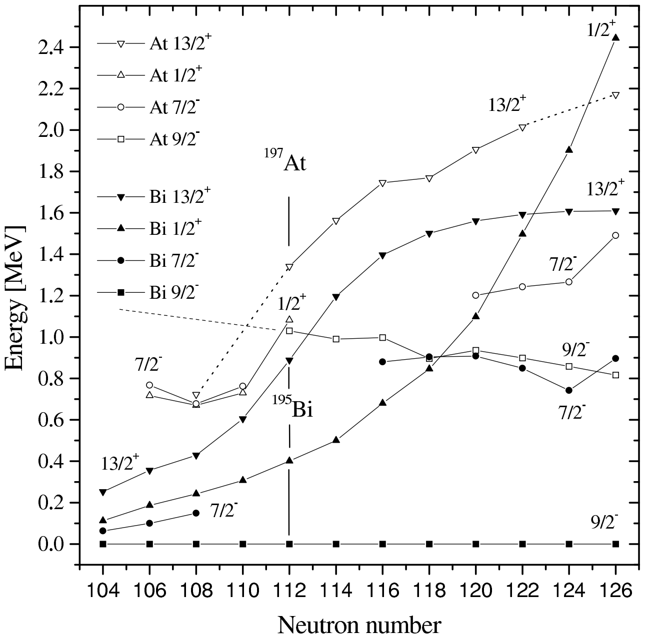

Fig. 1. Level systematics of odd-mass Bi and At isotopes. Level energies are normalised to the $9/2^-$ ground state in bismuth isotopes using the proton binding energies [2].

state at 63(10) keV was deduced based on the shape of the alpha-decay energy spectrum of ^{191}At. The spin and parity assignments of the initial states in the astatine isotopes were based on the unhindered alpha decays.

The level systematics of the odd-mass bismuth and astatine isotopes are shown in fig. 1. For astatine isotopes the systematics are obtained by using proton binding energies and normalising them to the ground state of the bismuth isotopes. The mass values needed for the proton binding energies were taken from the recent atomic mass measurements [4,5,6], updated with the new results for ^{191}At, ^{193}At, ^{195}At and ^{187}Bi [1,2].

The level schemes suggested for ^{191}At, ^{193}At and ^{195}At were observed to differ from those observed in heavier odd-mass astatine isotopes. The intruder $1/2^+$ state, having a $\pi(4p-1h)$ configuration becomes the ground state in ^{195}At. In the heavier odd-mass astatine isotopes, the ground state is the $9/2^-$ state. In addition, a $7/2^-$ state rather than a $9/2^-$ state is suggested to represent the first excited state in these light astatine isotopes. The emergence of the $7/2^-$ state over the $9/2^-$ state can be understood by assuming a change in deformation between the ^{197}At and ^{195}At isotopes. According to the Nilsson diagram a $7/2^-$ state, associated with an oblate $7/2^-[514]$ Nilsson state, becomes available for the 85th proton in odd-mass astatine isotopes if sufficient oblate deformation is assumed. Based on the results of the present work it is proposed that in light $A < 197$ odd-mass astatine isotopes the deformed three-particle configuration, driving the last proton to the $7/2^-[514]$ Nilsson state, is energetically more favoured than the nearly spherical $(\pi h_{9/2})^3$ configuration. Correspondingly, the existence of a low-lying $7/2^-$ state in bismuth isotopes can be understood by a $7/2^-[514]$ Nilsson proton state associated with oblate deformed structures.

The recent potential energy calculations [7,8] support the $7/2^-$ assignment of this low-lying state observed in ^{189,191}Bi and deduced to exist in ^{187}Bi. Based on these calculations this state in ^{189,191}Bi was associated with the oblate $7/2^-[514]$ configuration as deduced also in the present work. At the mid-shell nucleus $^{187}Bi_{104}$ the excitation energy of the $7/2^-$ state was still observed to come down (see systematics in fig. 1). However, according to the calculations [8] the excitation energy of the oblate structure should already increase in ^{187}Bi. The downward behaviour was explained by a prolate $7/2^-$ state, originating from the $1/2^-[530]$ orbital, which crosses the oblate configuration between ^{189}Bi and ^{187}Bi. In addition, similar crossing of the oblate and prolate structures is most likely occurring in the $1/2^+$ and $13/2^+$ states [8].

Proton separation energies of $-240(130)$ keV, $-560(140)$ keV and $-1020(140)$ keV were determined for ^{195}At, ^{193}At and ^{191}At, respectively. This indicates that ^{195}At is the first proton unbound astatine isotope. Using the WKB barrier transmission approximation [9] and assuming a spectroscopic factor of one, the proton separation energy obtained for ^{191}At would correspond to a partial half-life of approximately 57 s for an unhindered proton emission from the $\pi s_{1/2}$ orbital. This rough estimation suggests that the branching ratio of the proton emission compared to the alpha-decay would be too small to be detected. The proton separation energy of the next odd-mass astatine isotope ^{189}At can be estimated to be approximately -1500 keV by extrapolating the systematics of the heavier At isotopes. Based on the WKB calculation this value would correspond to a half-life of approximately 50 μs for a proton emission from the $\pi s_{1/2}$ orbital assuming a spectroscopic factor of one. An energy of 7900 keV can be extrapolated for the alpha decay of $1/2^+$ state in ^{189}At to the $1/2^+$ state in ^{185}Bi corresponding to a partial half-life of 400 μs for an unhindered alpha decay. Thus, the ^{189}At nucleus is a good candidate for the observation of proton emission. For more details see references [1,2].

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