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DECAY SPECTROSCOPY STUDIES OF THE TWO NEW ISOTOPES OF ASTATINE[*]

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Decay properties of two new isotopes of astatine, ^{188}At and ^{190}At, were studied in the Accelerator Laboratory of the University of Jyväskylä, Finland. The nuclei were produced in fusion–evaporation reactions, and those were separated from the primary beam and target-like products by employing the RITU (Recoil-Ion Transport Unit) recoil separator. Decay-spectroscopy studies were performed for the produced nuclei resulting in information about the decay properties of ^{188}At and ^{190}At. The ^{188}At isotope was found to be the heaviest proton emitter to date. Additionally, the ^{190}At isotope was observed to decay via α decay. The results were compared with the systematics and with non-adiabatic quasiparticle calculations. In ^{188}At, a deviation in the one-proton separation energy was observed, indicating the first possible sign of the Thomas–Ehrman shift in heavy nuclei.

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1. Introduction

The search for new isotopes has been a subject of study throughout the decades of nuclear physics research. Thus far, around 3000 nuclei are known, whereas approximately 4000 species are estimated to remain undiscovered to date [1]. The most common decay mode of the neutron-deficient heavy nuclei is α decay. However, the decay characteristics become more complex in the most neutron-deficient odd-Z nuclei due to the increasing possibility for the nucleus to decay via proton emission. Proton emission has been observed for approximately 50 cases from ^{108}I to ^{185}Bi [2]. The proton emission becomes energetically possible as the proton dripline is crossed, *i.e.*, one-proton separation energy becomes negative. Astatine represents the next odd-Z element beyond what was long observed to be the heaviest

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proton emitter, ^{185}Bi. The one-proton separation energy becomes negative in ^{195}At, thus the proton emission can be expected in the lightest astatine nuclei. In spite of the possibility for the proton emission, it has so far not been observed in astatine nuclei. This arises from the significant decrease in the half-lives and the production cross sections as the astatine nuclei get lighter, causing challenges for the experimental studies aiming to expand the chart of known nuclei. As the half-lives and the production cross sections decrease, γ or laser spectroscopy techniques are no longer possible. An efficient tool for probing these nuclei is decay spectroscopy, through which it is possible to measure the particle energies and half-lives. These can then be used to address some of the fundamental questions, such as the mass of the decaying species. In addition to the proton emission, odd-Z nuclei are interesting in a perspective of a phenomenon called the Thomas–Ehrman effect [3, 4]. The effect refers to a phenomenon where the wave function of a proton-unbound nucleus with an $s_{1/2}$-proton component extends outside the nuclear core reducing the repulsive Coulomb energy. The effect has been observed in light and medium mass nuclei [5, 6], however, not yet in heavy nuclei but a possible sign of it is discussed in this work and also in Ref. [7].

The area of trans-lead nuclei has been studied widely in the Accelerator Laboratory of the University of Jyväskylä (JYFL-ACCLAB) and other laboratories. During the past decades, many new isotopes and structure studies have been published, see, for example, Refs. [8–12]. The present conference proceedings article will summarise the studies of the two new astatine isotopes [7, 13], extending the long-standing research.

2. Experimental methods

The experiment was performed in the JYFL-ACCLAB. A 1 mg/cm^2 thick $^{\mathrm{NAT}}$Ag target was irradiated with an ^{84}Sr beam. The nuclei of interest were produced in the $^{107}\mathrm{Ag}(^{84}\mathrm{Sr}, 3n)^{188}$At and $^{109}\mathrm{Ag}(^{84}\mathrm{Sr}, 3n)^{190}$At fusion–evaporation reactions. A K-130 cyclotron was used to accelerate the beam of ^{84}Sr ions with an average intensity of 12 pnA over a total irradiation time of 181 h. The used beam energies were 380 MeV and 390 MeV. Additionally, 100 and 200 μg/cm^2 thick degrader foils were varied in front of the target to modify the beam energy. To separate the fusion–evaporation residues (recoils) from the unreacted primary beam, a gas-filled recoil separator RITU (Recoil-Ion Transport Unit [14, 15]) was employed. The recoils were transported to the focal plane of RITU where the GREAT (Gamma Recoil Electron Alpha Tagging [16]) spectrometer was used to identify the events. At GREAT, the recoils first passed through a MWPC (Multi-Wired Proportional Counter) and were subsequently implanted into a DSSD (Double-sided Silicon Strip Detector). These detectors were used to distinguish the recoils and decays from scattered beam and target-like particles. The recoil events were separated based on the time-of-flight between the MWPC and DSSD and on their energy loss in the MWPC. The decays were required to be measured only in the DSSD (no MWPC signal present). Additionally, a separate calibration reaction of ^{78}Kr+^{92}Mo was run to calibrate the DSSD energy response for α and proton activities. The proton-emitting activities of ^{166}Ir, ^{166m}Ir, ^{167}Ir, and ^{167m}Ir [17, 18], and α-decaying isotopes of ^{150}Dy, ^{162}W, ^{163}W, ^{166}Os, ^{167}Os, and ^{167m}Ir [19–23] were used to perform the calibration. The total irradiation time for the calibration reaction was 40 h and beam energy of 365 MeV was used. A total Data Readout (TDR) acquisition system collected the data, a 100 MHz clock was used for time stamping and the data were analysed with a Grain software package [24].

3. Results

Decay spectroscopy provides extreme selectivity which is achieved by measuring correlations between genetic decays. A DSSD pixel was required to record at least two subsequent decays after the implantation of a recoil. Moreover, the first decay was required to occur within 2 ms and 10 ms time windows after the implantation for ^{188}At and ^{190}At, respectively. These methods provided correlation matrices remarkably clean from the randomly correlated background events. The details of the analysis and decay schemes are reported in Refs. [7, 13]. The experiment resulted in the identification of two new neutron-deficient astatine isotopes, ^{188}At and ^{190}At.

The ^{188}At was observed to decay via proton emission, resulting in the identification of the heaviest proton emitter to date. Two decay chains were observed, and those were interpreted as proton emission and as α decay. The decay path is shown in Fig. 1 (a). The extracted proton-particle energy and half-life of the decaying state are 1.50(4) MeV and 190^{+350}_{-80} μs, respectively. The half-life was determined based on the observed two decays and it was derived using the maximum-likelihood method [25]. The full energy of the α-decay was not recorded as the α particle escaped from the DSSD. Nevertheless, the rest of the decay chain was successfully measured with α energies which are in good agreement with the literature values of the daughter species, thus supporting the reported interpretations. Despite the escaped α particle, the Q_α value can be calculated based on energy conservation for the new isotope from the measured proton energy, and by assuming a ground-state-to-ground-state decay. The calculated value is $Q_\alpha = 7.90(20)$ MeV.

For ^{190}At, only α-decay events were observed, and the observed decay path is shown in Fig. 1 (b). Altogether four α-decay chains were detected, resulting in an α-particle energy and half-life of 7.75(2) MeV and $1.0\,^{+1.4}_{-0.4}$ ms, respectively. The probability of the observed decays to originate from the same radioactive species was probed using Schmidt's radioactive decay probability test [26]. Per the test, the measured decay-time distribution is consistent with that expected for the decay of a single radioactive species. The α decay of ^{190}At was independently observed by Andreyev *et al.* [27]. The measured values are in agreement with our results. More discussion can be found in Ref. [27].

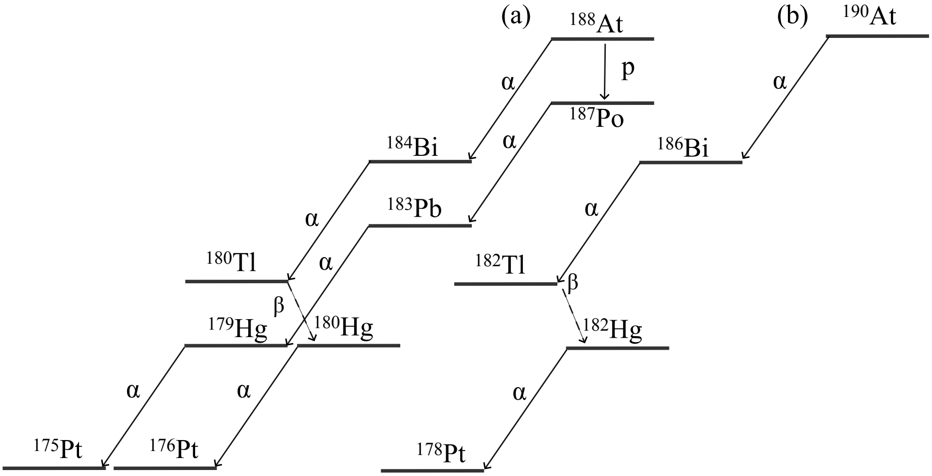

Fig. 1. The decay chains of the isotopes ^{188}At (a) and ^{190}At (b) constructed based on the measured data.

4. Discussion

The non-adiabatic quasiparticle model [29] was expanded to nuclei beyond the lead region to interpret the ^{188}At data. Within the model, the proton-emitting state was probed by calculating the rotational energies of the candidate states, and then by comparing to the measured partial proton-decay half-life. In the model, a 2^- state was found to be the lowest in energy at the expected quadrupole deformation of 0.24–0.3, and to reproduce the measured proton-decay rate. In the model, the proton component of the 2^- state wave function is $s_{1/2}$, which is consistent with the systematics of other light astatine isotopes, as well as with the only other proton emitter in the region, ^{185}Bi [30].

The results are compared with the systematics of other light astatine nuclei in Fig. 2, where the Q_α values are shown as a function of the mass number. The uncertainty for ^{188}At is large, which arises from the uncertainty of the mass excess of the daughter nucleus ^{184}Bi. The ^{190}At isotope follows the systematics rather well, however, a decrease in Q_α value is indicated

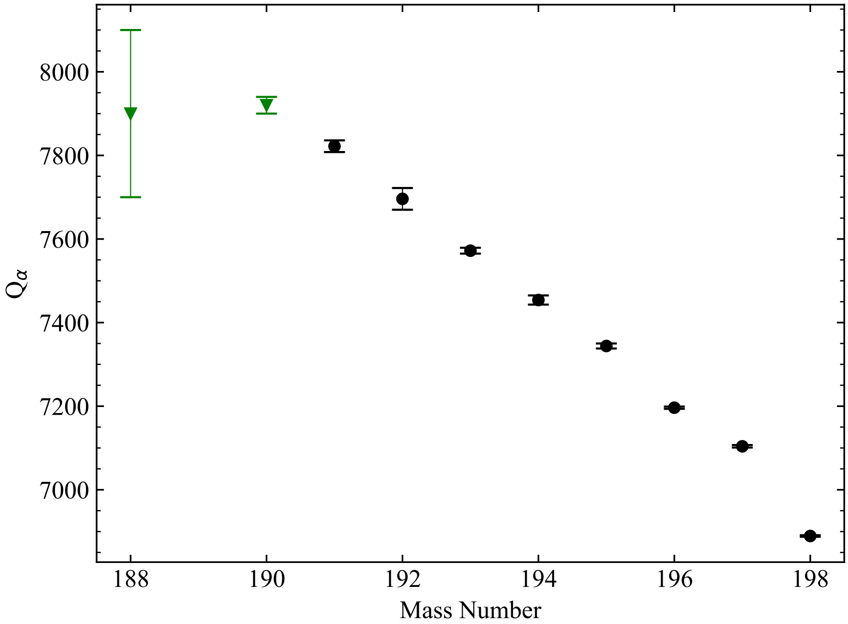

Fig. 2. (Color online) The systematics of the Q_α-values of astatine nuclei. From the ^{191}At to ^{198}At, the data [28] are marked with black circles, whereas the data [7, 13] of the new isotopes ^{188,190}At are marked with green triangles.

for ^{188}At. This is another possible sign of the Thomas–Ehrman effect, since the decrease in the proton-decay energy is seen as the decrease of the Q_α value as well. To set further confidence on this, one should narrow down the uncertainty of $Q_\alpha(^{188}\mathrm{At})$ by measuring the mass excess of ^{184}Bi with improved precision, or by measuring more ^{188}At α-decay events, and look for decays where the α particle did not escape the implantation detector. The deviation in the one-proton separation energy systematics of astatine and also of bismuth isotopes has been discussed in [7]. The common factor with these two elements is the $\pi s_{1/2}$ component in the wave function of the ground states of the lightest nuclei, which makes them prone to the Thomas–Ehrman effect. More discussion can be found in Ref. [7].

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