Mass and half-life measurements of neutron-deficient iodine isotopes

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Abstract Neutron-deficient iodine isotopes, $^{116}$I and $^{114}$I, were produced at relativistic energies by in-flight fragmentation at the Fragment Separator (FRS) at GSI. The FRS Ion Catcher was used to thermalize the ions and to perform highly accurate mass measurements with a Multiple-Reflection Time-of-Flight Mass-Spectrometer (MR-TOF-MS). The masses of both isotopes were measured directly for the first time. The half-life of the $^{114}$I was measured by storing the ions in an RF quadrupole for different storage times and counting the remaining nuclei with the MR-TOF-MS. The measured half-life was used to assign the ground state to the measured $^{114}$I ions. Predictions on the possible $\alpha$-decay branch for $^{114}$I are presented based on the reduced uncertainties obtained for the $Q_\alpha$-value. Systematic studies of the mass surface were performed with the newly obtained masses, showing better agreement with the expected trend in this mass region.

1 Introduction

Nuclear masses are basic properties of the nuclei; they reflect the forces between the nucleons. The $Q$-values, which can be obtained from the masses, define which spontaneous decay modes are energetically possible. In the case of $\alpha$-decay, the $Q$-value has a direct correlation to the partial half-life ($T_{1/2}$) of the decaying nuclei, known as the Geiger-Nuttall law [1]. Above the double-magic nucleus $^{100}$Sn ($Z = N = 50$) there is a special mid-shell region which forms an island of nuclei with an $\alpha$-decaying branch. This $\alpha$-decay island is composed of neutron-deficient isotopes of Te, I, Xe, Cs and Ba [2,3]. Reduced uncertainties in the masses of the nuclides involved in the $\alpha$-decay can constrain the half-life and, thereby, the expected branching ratio of this decay.

The trend of observables derived from the masses along isotopic or isobaric chains, such as two-proton or two-neutron separation energies ($S_{2p}, S_{2n}$), can reveal information about nuclear structure [4–6]. These observables can also be used to crosscheck the masses since unexpected changes in the trend of the observables can point towards errors or deviations in the extrapolations of the mass surface. In the $\alpha$-decaying mid-shell region, the observable calculated from the masses as the double difference of the two-proton separation energy in the $Z$ direction ($d_{ZZ}[S_{2p}(N, Z)]$, see Eq. 1), shows some irregularities if the presently known and extrapolated mass values [7] are used.
\[
d_{2Z}[S_{2p}(N, Z)] = \frac{S_{2p}(N, Z + 2) - 2 \cdot S_{2p}(N, Z) + S_{2p}(N, Z - 2)}{4}
\]

(1)

This indicates that inaccuracies may be present in the mass surface in this region. The masses of the iodine isotopes with \( N = 61 \) (114I) and \( N = 63 \) (116I) have not been measured directly before, and for the case of 114I only an extrapolated value is available in the literature [7]. Moreover, the decay scheme for the ground and isomeric states of 114I is not well known and has not been published in a primary publication [8].

In this work, we present the first direct mass measurement of 116I and 114I and the half-life measurement of 114I which is used to determine the state of the measured mass distribution. Based on the obtained mass of 114I, an updated value of the \( Q_\alpha \)-value with an uncertainty reduced by a factor of 10 is calculated, tightly constraining the \( \alpha \)-decay partial half-life of 114I using the Geiger-Nuttall law. Also, a study of the (FRS) at GSI [9] and delivered to the FRS Ion Catcher [10] via projectile fragmentation at the Fragment Separator a beryllium production target of 1.622 g/cm² was used. The ions per spill and a typical spill length of 4 s impinging in 114I, a 600 MeV/u projectile beam of 124Xe of up to 1.238U projectile beam in a beryllium production target of 5.043 Page 2 of 6 Eur. Phys. J. A           (2020) 56:143

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The nuclides 116I and 114I were produced at relativistic energies via projectile fragmentation at the Fragment Separator (FRS) at GSI [9] and delivered to the FRS Ion Catcher [10] where the ions were slowed down and thermalized in a gas-filled Cryogenic Stopping Cell (CSC) [11–13]. Subsequently, the ions were extracted and transported via a Radio Frequency Quadrupole (RFQ) beamline to a Multiple-Reflection Time-of-Flight Mass Spectrometer (MR-TOF-MS) [14,15] to perform mass measurements and ion counting [16]. The nuclide 116I was produced via fragmentation of a 300 MeV/u 238U projectile beam in a beryllium production target of 0.270 g/cm² with intensities up to 2 \times 10^8 ions per spill and a typical spill length of 1 s. The CSC was operated at a helium pressure of 64 mbar at a temperature of 77 K, corresponding to an areal density of 4.2 mg/cm². For the production of the 114I, a 600 MeV/u projectile beam of 124Xe of up to 1 \times 10^9 ions per spill and a typical spill length of 4 s impinging in a beryllium production target of 1.622 g/cm² was used. The CSC was operated at 75 mbar and 82 K, which corresponds to an areal density of 4.6 mg/cm². In both cases, an extraction time about 4 times longer than expected was measured due to non-properly working electronics in the RF-Carpet, 200 ms [17,18]. To analyze the data and obtain the masses, the drifts of the time-of-flight data were corrected performing a time-resolved calibration using a well-known mass. The peak shape was obtained from a high-count reference and used for fitting the ion of interest. The analytical function describing the peaks is the Hyper-EMG [19], a weighted maximum likelihood estimate is then used to fit this function to the data. All the measured species reported in this paper are ions singly positively charged. Details of the data analysis procedure are presented in [16].

2.2 Mass of 116I

Previous mass measurements of 116I were performed indirectly [20,21]. The isomeric state of 116I cannot be measured in the MR-TOF-MS due to its short half-life \((t_{1/2} = 3.27 \mu s)\). The 116I ions underwent 570 isochronous turns (IT) in the analyzer of the MR-TOF-MS. They were then ejected from the analyzer, passed through the Time Focus Shift (TFS) reflector [22] and impinging on the detector. The total time-of-flight amounted to about 19 ms with a resolving power at FWHM of 350.000. The mass range selector (MRS) [15] was used to isolate ions with the mass number \( A = 116 \) from a total of about 30 species detected in the MR-TOF-MS. A total of 427 counts were recorded for this isotope. The reference ion used for the precision calibration and for the time resolved calibration (TRC) was the molecule \( ^{86}\text{Kr}^{14}\text{N}_2 \) \((A = 114)\), which was formed in the CSC and ionized by the beam. It underwent 575 IT in the analyzer of the MR-TOF-MS. This reference ion was included in the spectrum by temporally switching off the MRS. Due to an unfavorable operation of the MRS in this measurement, the MRS shift error [16] is the main source of uncertainty in this mass measurement. Other individual components of the total uncertainty are: peak shape, statistical, calibrant, time-resolved calibration and non-ideal ejection uncertainty (see [16] for more information about the individual contributions).

The mass value for 116I measured in this work, its uncertainty and the deviation from the literature are shown in Table 1. The mass value lies on the upper limit of the uncertainty range reported in the literature for indirect measurements.

2.3 Mass and half-life of 114I

Although the mass of some iodine isotopes with a smaller number of neutrons have already been measured directly [23, 24] or indirectly [25,26], the mass of 114I has remained unmeasured, and only extrapolated values are available in the literature [7]. The long-lived isomeric state with \( t_{1/2} = (6.2 \pm 0.5) \) s [27] and an excitation energy of 265.9 keV [28] lies almost within the uncertainty range of the extrapolated ground state mass given in the literature, i.e. \( \pm 150 \) keV [7]. Therefore, if only a single state is detected for this nuclide, the assignment to ground or isomeric state can not be made solely based on its mass.
The mass resolving power at FWHM of the MR-TOF-MS during the measurement with the FRS Ion Catcher was 350,000, enough to distinguish between both states, following the data evaluation method presented in [16]. A detailed investigation of the smallest detectable isomeric ratio was performed by generating and analyzing synthetic data for the given measurement conditions of mass resolving power, distance between the peaks of ground and isomeric state (in this case the excitation energy of the isomer), and the total number of events. The analysis shows that only a single state can be detected if the relative abundance of one of the states is smaller than 10%. For the mass measurement of the nuclide $^{114}$I, data with two different numbers of IT were obtained (574 IT and 575 IT) with a total time-of-flight of about 19 ms. The MRS was always on and set to isolate the mass number $A = 114$. A total of 2775 counts were recorded for the mass measurement of this nuclide. The reference ion for the precision calibration and for the TCR was the same ion as for $^{114}$I, namely the isobaric molecule $^{86}$Kr$^{14}$N$_2$ ($A = 114$), which was formed in the CSC and ionized by the beam. The rate of this ion was adjusted by the isolation-dissociation-isolation (IDI) method [29]. A mass-to-charge ratio spectrum including the calibrant ($^{86}$Kr$^{14}$N$_2$) and the ion of interest ($^{114}$I) is shown in Fig. 1. The fitting function determined was a Hyper-EMG with one exponential on each side, the shape parameters of which were calculated from the calibrant data. The result of the data evaluation is represented by the (red) solid line which is the sum of the two Hyper-EMG functions fitted to the unbinned data of the calibrant and ion of interest separately. The areas of the functions were normalized to the measurement with the average storage time of 0 s with the highest $^{114}$I counts. The (red) dashed curve represents a fit with an exponential decay function, yielding a half-life of (1.89 ± 0.23) s.

![Counts per 21μ]

**Fig. 1** Measured mass-to-charge ratio spectrum including the calibrant $^{86}$Kr$^{14}$N$_2$ ($A = 114$) and the ion of interest $^{114}$I. The square points represent the histogram of the unbinned data. Hyper-EMG functions with one exponential on each side were used for fitting the data, the shape parameters of which were obtained from the calibrant data. The (red) continuous line represent the sum of the two Hyper-EMG functions obtained after fitting the unbinned data. The inset shows the normalized counts of the $^{114}$I peak measured for different average storage times in the RFQ. The data points (squares) were normalized to the measurement with the average storage time of 0 s with the highest $^{114}$I counts. The (red) dashed curve represents a fit with an exponential decay function, yielding a half-life of (1.89 ± 0.23) s.

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tion period and used as a normalization factor for the number of $^{114}$I nuclei produced. The number of $^{114}$I ions after storage was determined via high-resolution mass measurement using the MR-TOF-MS. An exponential function was fitted to the normalized counts for the different average storage times in order to determine the half-life (see inset in Fig. 1). The uncertainty of the half-life was calculated as the quadratic sum of the statistical uncertainty of the fit ($\pm 0.21\ s$) and the propagated uncertainty from the spill length ($\pm 0.1\ s$). The obtained value for the half-life of $(1.89 \pm 0.23)\ s$ is in good agreement with the literature value for the ground state. Thus, the measured mass value could be assigned to the ground state. The results of the mass, half-life and their uncertainties are shown in Table 1.

2.4 Partial half-life of $\alpha$-decaying iodine isotopes

The island of $\alpha$-decaying nuclei in the medium-heavy neutron-deficient region comprises iodine ($Z = 53$) isotopes close to the proton drip line, with the lightest reported isotope to have an $\alpha$-decay branch being $^{108}$I [26]. The heaviest iodine isotope with a reported $\alpha$-decay branch is $^{113}$I, with a branching fraction of $3.31 \times 10^{-5}\%$ [2]. For the next iodine isotope ($^{114}$I), no $\alpha$-decaying branch has been reported and only estimates have been made from the $Q_\alpha$-value obtained with masses from the droplet-model [2,33].

The coefficients of the Geiger-Nuttall law [1] for the iodine isotopes were obtained from the existing data on $\alpha$-decay, from $^{108}$I to $^{113}$I, obtaining a linear function with a slope of 76.7 and an intercept value of $-39.25$. The $Q_\alpha$-value of $^{114}$I, calculated with the literature masses has a large uncertainty, mainly due to the uncertainty of the $^{114}$I mass. The $\pm 1\sigma$ uncertainty of the $Q_\alpha$-value translates in the Geiger-Nuttall law into 3 orders of magnitude uncertainty in the partial half-life of the $^{114}$I $\alpha$-decay. This is shown in Fig. 2. A more precise determination of the $Q_\alpha$-value for $^{114}$I allows to pin down the partial half-life and, therefore, the branching ratio of the $\alpha$-decay for this isotope. The $\alpha$-decay branching ratio for $^{114}$I, calculated with the mass values of this work is $7.70 \times 10^{-9}\%$ with a $\pm 1\sigma$ uncertainty below one order of magnitude. This can accurately predict the expected count rate of $^{114}$I $\alpha$-decay and also establish the end of the island of $\alpha$-emitters in the medium-heavy range of neutron-deficient isotopes, reflected in the low value of the $\alpha$-decay branching ratio.

2.5 Systematic studies of the binding energies

The calculation of the double difference of the two-proton separation energy observable $d_{2Z}[S_2p(N, Z)]$ (see Eq. (1)) performed with the masses reported in the literature [7] presents anomalies in the trend in those nuclei where the binding energy of the iodine isotopes ($^{114}$I and in particular $^{116}$I) is included (top panel of Fig. 3). The trend of the $d_{2Z}[S_2p(N, Z)]$ values affected by the new mass measurements of the iodine isotopes ($Z = 51$, $Z = 53$, $Z = 55$ and

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**Table 1** Mass and half-life results for the two measured iodine isotopes ($^{116}$I and $^{114}$I) compared with the literature [7,30]. The extrapolated values given in the literature are marked with the symbol #.

| Nuclei | Half-Life$_{MR}$/s | Half-Life$_{FRS}$IC/s | Reference | $ME_{FRSIC}$-IC/keV | $ME_{AME16}$/keV | $ME_{FRSIC}$-$ME_{AME16}$/keV | Number of events |
|--------|--------------------|----------------------|-----------|---------------------|----------------|-----------------------------|-----------------|
| $^{116}$I | 2.91 ± 0.15 | - | $^{86}$Kr$^{14}$N$_2$ | -77318 ± 117 | -77490 ± 100 | 172 ± 154 | 427 |
| $^{114}$I | 2.1 ± 0.2 | 1.89 ± 0.23 | $^{86}$Kr$^{14}$N$_2$ | -72639 ± 20 | # - 72800 ± 150 | 161 ± 151 | 2775 |
Fig. 3 Double difference of the two proton separation energy in the $Z$ direction $d_{2Z}[S_{2p}(N, Z)]$ (see Eq. (1)) for different isotopic chains calculated with: top: literature mass values [7], middle: literature values including the mass measurement of $^{114}$I and $^{116}$I presented in this work and bottom: common mass models values (FRDM12 [35], UNEDF1 [36] and HFB-24 [37]) and with the same data as the middle panel for the iodine isotopes for a clear comparison. The filled/empty symbols in the middle panel represent the points which are/are not affected by the new measured masses. The trend of the $d_{2Z}[S_{2p}(N, Z)]$ for the iodine and cesium isotopes is smoother when calculated with the new masses presented in this work (middle panel). The HFB model shows a sudden change at $N = 63$. The UNEDEF model describes best the general trend of the experimental data and all models agree in the trend if a substantial uncertainty is taken into account.
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