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Half-life measurements of stored fully ionized and hydrogen-like ^{122}I ions

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Abstract. The half-lives of fully ionized and hydrogen-like (H-like) ^{122}I ions have been measured in a heavy-ion storage ring. The β^+-decay constants for both charge states and the electron capture (EC) decay constant of H-like ions have been determined. The EC-decay constant in H-like ^{122}I ions $\lambda_{\mathrm{EC}}^{\mathrm{H\text{-}like}} = 7.35(33) \cdot 10^{-4}\,\mathrm{s}^{-1}$ is, within the uncertainty, the same as the one in neutral atoms. This result is in agreement with the estimates of recent theoretical considerations on the EC-decay of few-electron ions that explicitly take into account the conservation of the total angular momentum of the nucleus plus lepton(s) system and its projections. No firm confirmation could be concluded from our results on the predicted effect that allowed Gamow-Teller transitions become forbidden if the initial and final total angular momenta are not equal.

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1 Introduction

The advent of radioactive ion beam facilities enabled investigations of β-decay in highly charged ions [1]. Such investigations are interesting, since highly charged ions offer the unique possibility to study β-decay under "clean" conditions. For instance, the parent ions can be prepared in a simple, well-defined quantum state, as fully ionized (bare), hydrogen-like (H-like) or helium-like (He-like) ions. In this way, the complicated corrections, which arise in neutral atoms due to the effects of many particles [2], like partial screening of the nuclear charge by the electron cloud, can be disentangled. Furthermore, some decay channels that are not present in neutral atoms can be opened up when the atoms are highly ionized, such as the bound-state β-decay [3,4]. And, vice versa, some decay modes known in neutral atoms can become forbidden in highly charged ions like, *e.g.*, the electron conversion decay of nuclear excited states is disabled in bare nuclei [5,6].

The dependence of the β-decay probabilities on the atomic charge states can affect the pathways of nucleosynthesis in stars, since atoms are highly ionized in the corresponding high-temperature and high-density stellar environments [7,8].

Studies of β-decays in highly charged ions require dedicated experimental facilities since the radioactive nuclides in high atomic charge states have to be produced, purified from contaminants and stored for extended periods of time. Up to date, all studies of β-decay in highly charged ions have been conducted at the experimental storage ring ESR at GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany. For a comprehensive review the reader is referred to ref. [1].

In this work we report on the half-life measurements of fully ionized and H-like ^{122}I ions. More specifically, the orbital electron capture (EC) decay constant in H-like ^{122}I ions as well as β^+-decay constants in fully ionized and H-like ^{122}I ions have been accurately determined. These measurements are a continuation of the experimental program on β-decay studies of bare and few-electron nuclides. Previously, EC- and β^+-decay constants have been obtained for H-like and He-like ^{140}Pr [9–11] and ^{142}Pm [11,12] ions. Ground states of ^{140}Pr and ^{142}Pm nuclei have spin-parity $I^\pi = 1^+$ and decay mainly (more than 95% of the decay strength) by a single allowed Gamow-Teller transition to the ground states of the corresponding daughter ^{140}Ce and ^{142}Nd nuclei which have spin-parity 0^+ [13]. As in the cases of ^{140}Pr and ^{142}Pm, the spin-parity of the ground state of ^{122}I nuclei is 1^+. We note that the data given in ref. [13] correspond to data for neutral atoms. However, only about 82% of the decay strength goes to the ground state of the stable daughter ^{122}Te nuclei ($1^+ \rightarrow 0^+$) and the remaining decay strength is distributed over several excited states in the ^{122}Te nuclei.

In this work, we also attempt to study ($1^+ \rightarrow 2^+$) EC transition in H-like ions, where a significant reduction of the decay strength is expected [14–17].

2 Experiment

The GSI facility represents a worldwide unique combination of the heavy-ion synchrotron SIS, the in-flight fragment separator FRS and the experimental storage ring ESR [18], which makes the study of the decays of highly charged ions possible[1] [1]. In the experiment described here, the primary beams of stable ^{132}Xe ions with intensities of up to $5 \cdot 10^8$ ions/spill have been accelerated by the SIS to relativistic energies of $593\,\mathrm{MeV}/u$. The secondary beams of ^{122}I ions have been produced by projectile fragmentation reaction of the primary beams in a $2.5\,\mathrm{g/cm}^2$ thick ^{9}Be production target placed in front of the FRS [22]. At such high kinetic energies, the ^{122}I reaction products emerge from the target predominantly as fully ionized ions [23], which have been used for an efficient in-flight separation from the β-decay daughter ^{122}Te ions. For this purpose, we have set up the FRS up to its middle focal plane [22], where a $737\,\mathrm{mg/cm}^2$ thick homogeneous aluminium energy degrader was installed, to transmit the bare $^{122}\mathrm{I}^{53+}$ nuclei. Since it is not possible to form ^{122}Te in the charge state 53+, *no* ^{122}Te ions were transmitted up to the degrader. The energy of the primary beam has been chosen such that the ^{122}I ions have the energy of exactly $400\,\mathrm{MeV}/u$ after passing through the degrader. Then, the second half of the FRS up to the ESR has been tuned to transmit alternatively pure beams of H-like or fully ionized ^{122}I ions. The employed Al material is much thicker than the equilibrium thickness of about $60\,\mathrm{mg/cm}^2$. The equilibrium charge state distributions have been calculated with the GLOBAL code [23]. Thus, the ^{122}I ions emerging from the degrader were present to about 97.3% as bare nuclei, to 2.7% as H-like and to less than 0.02% as He-like ions. The latter yield turned out to be too small for performing any half-life measurements of He-like ^{122}I ions in the present experiment.

The H-like or fully ionized ^{122}I ions transmitted through the FRS have been injected and stored in the ESR. The rest gas pressure in the ESR is about 10^{-11} mbar which is an indispensable condition for the present measurements. The inevitable —due to the nuclear reaction process— velocity spread of stored ions has been reduced by stochastic [24] and electron [25] cooling, which allowed achieving a velocity spread as low as $\delta v/v \approx 5 \cdot 10^{-7}$ in about 6 s. The former cooling method is switched on for about 4 s for fast pre-cooling of the ions. It is designed to operate at the fixed energy of the stored beam of $400\,\mathrm{MeV}/u$, the energy of ^{122}I ions after the energy degrader. The electron cooler was on during the entire measurement time.

The revolution frequency of cooled ions is a measure of their mass-over-charge ratio [26] and can be used for the unambiguous identification of parent and daughter nuclides. The revolution frequencies have been measured by

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[1] We note that a secondary ion beam facility at the Institute of Modern Physics in Lanzhou, China, has been commissioned recently and will soon become capable of conducting similar experiments (for more details see refs. [19–21] and references cited therein).

applying the Schottky mass spectrometry (SMS), which is routinely employed at the ESR for direct mass measurements of exotic nuclei [27–33].

Ions at $400\,\mathrm{MeV}/u$ circulate in the ESR, which has a circumference of $\sim 108.4\,\mathrm{m}$, with frequencies of about 2 MHz. Every highly charged ion induces mirror charges at each revolution on a couple of electrostatic pick-up electrodes placed inside the ESR aperture. Since the induced signals are periodic in time, the Fourier transform of the digitized noise from the pick-up yields the revolution frequency spectrum (noise-power density spectrum). Typically in our experiments, we analyze the 29–30th harmonic of the revolution frequency, that is frequencies around $f = 60\,\mathrm{MHz}$. At these harmonic numbers the entire frequency acceptance of the ESR is about 320 kHz [29]. In the present experiment we have employed a commercial real-time spectrum analyzer Sony-Tektronix 3066. A 5 kHz frequency bandwidth centered at the frequency of the parent ^{122}I ions has been recorded. The spectrum analyzer was capable of storing one spectrum per second, where each spectrum had a frequency resolution of about 8 Hz per channel corresponding to 128 ms acquisition time. More details on the data acquisition system can be found in refs. [11,34].

In the EC-decay, the mass of the ion is changed by the Q_{EC}-value but the charge stays unchanged [35]. Thus, the EC-decay causes a sudden change in the revolution frequency of about 200 Hz (at the 30th harmonic). In the β^+-decay the charge changes by one unit which leads to a change of revolution frequency by about 150 kHz at the 30th harmonic. Since the β^+-decay followed by an electron-stripping reaction populates the fully ionized daughter ions as the EC-decay, we have restricted the ESR acceptance with mechanical slits such that no β^+-decay daughter ion can be stored (see also ref. [36]).

3 Data analysis

In total, 5 measurements with bare $^{122}\mathrm{I}^{53+}$ nuclei and 9 measurements with H-like $^{122}\mathrm{I}^{52+}$ ions were conducted. The data have been independently analyzed by two groups which have developed different data analysis packages.

The measurement time after each injection of the ions into the ESR was about 1200 s. For each measurement we produced 100 spectra by averaging 12 recorded spectra of 128 ms length. The averaging reduces the amplitudes of the random noise by a factor $\sqrt{12}$, thus improving the signal-to-noise characteristics of the produced spectra. The relative error of the amplitudes of the noise power density A is defined [37–39] as follows:

$$\frac{\sigma_A}{A} = \frac{1}{\sqrt{N_{av}}}, \tag{1}$$

where $N_{av} = 12$ denotes the number of averaged spectra.

While the revolution frequencies of the ions provide an unambiguous isotope identification, the intensities of the frequency peaks reflect directly the corresponding number of stored ions [35,37]. In addition to the number of particles, the areas of the frequency peaks depend also linearly on the revolution frequency and quadratically on the ionic charge. Since the frequency difference of the parent and EC-decay daughter ions is approximately 200 Hz (at 60 MHz) and the ionic charge is identical, these contributions are negligible in our context.

H-like ^{122}I ions decay by the two-body EC- and the three-body β^+-decay. Therefore, the total decay constant of the H-like ^{122}I is given by the sum

$$\lambda = \lambda_{\beta+} + \lambda_{\mathrm{EC}} + \lambda_{loss}, \tag{2}$$

where $\lambda_{\beta+}$ is the β^+-decay constant, λ_{EC} is the EC-decay constant and λ_{loss} is the loss constant which accounts mainly for the ion losses due to atomic interactions with the residual gas in the ring or with electrons in the ESR cooler.

The evolution of the number of stored parent $^{122}\mathrm{I}^{52+}$ ions, $N_{\mathrm{I}}(t)$, is described as follows:

$$N_{\mathrm{I}}(t) = N_{\mathrm{I}}(0) \cdot e^{-\lambda t}, \tag{3}$$

where $N_{\mathrm{I}}(0)$ is the number of parent ions at the time $t = t_0$, the starting time of the measurement.

It is probable that by picking up an electron from the Al degrader the H-like ^{122}I ions are produced in both hyperfine states with total angular momenta $F_i = I_i - \frac{1}{2} = \frac{1}{2}$ and $F_i = I_i + \frac{1}{2} = \frac{3}{2}$, where i indicates the initial (parent) state. The magnetic moment of ^{122}I ground state has been measured to be $\mu = +0.94(3)\mu_{\mathrm{N}}$ [40], where μ_{N} is the nuclear magneton. Because it is positive, the hyperfine ground state is $F_i = \frac{1}{2}$.

Following [14], we have calculated the hyperfine splitting energy to be about $\Delta E_{hf} \approx 0.28\,\mathrm{eV}$, which corresponds to a half-life ($F_i = \frac{3}{2} \to F_i = \frac{1}{2}$) of $t_{1/2} \approx 2.0\,\mathrm{s}$. Therefore, in order to have all ^{122}I ions in the hyperfine ground state prior to the start of the analysis, we have used data only for $t > 24\,\mathrm{s}$ after injection. We note, that *no* repopulation of the upper hyperfine states has been observed in the experiments conducted up to now at the ESR, see, *e.g.*, ref. [41].

As mentioned above, the orbits of the daughter ions from the β^+-decay lie outside the acceptance of the ESR. Due to the small frequency difference between the parent and EC daughter ions, the latter remain stored in the ESR. Hence, the number of stored EC-decay daughter $^{122}\mathrm{Te}^{52+}$ ions can be measured simultaneously. The evolution of the number of stored daughter $^{122}\mathrm{Te}^{52+}$ ions, $N_{\mathrm{Te}}(t)$, can be written as [12,34]

$$\begin{aligned} N_{\mathrm{Te}}(t) = {} & N_{\mathrm{I}}(0)\frac{\lambda_{\mathrm{EC}}}{\lambda - \lambda_{loss}}(e^{-\lambda_{loss}t} - e^{-\lambda t}) \\ & + N_{\mathrm{Te}}(0) \cdot e^{-\lambda_{loss}t}, \end{aligned} \tag{4}$$

where $N_{\mathrm{Te}}(0)$ is the number of EC-decay daughter ions at $t = t_0$.

Examples of a decay curve of H-like ^{122}I ions and a growth curve of bare ^{122}Te ions are shown in the lower part of fig. 1.

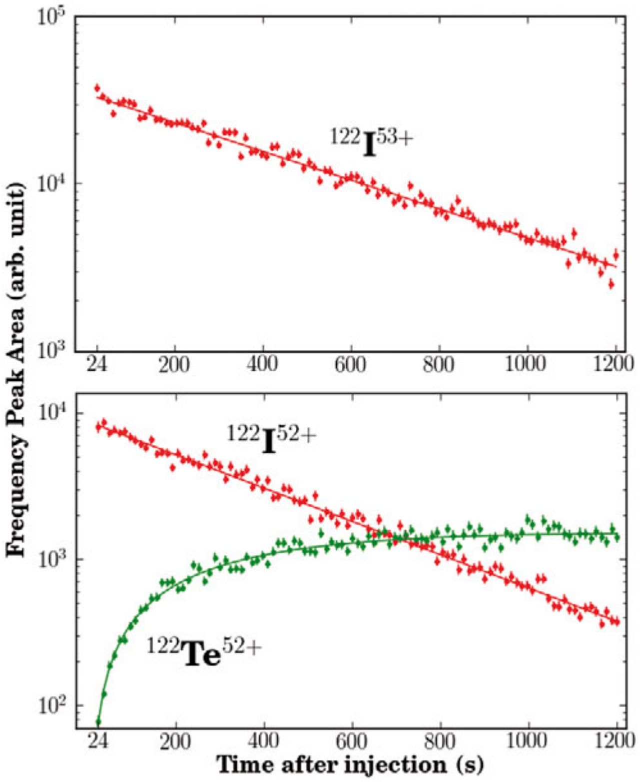

Fig. 1. The evolution of Schottky peak areas for $^{122}\mathrm{I}^{53+}$ (upper panel) and $^{122}\mathrm{I}^{52+}$ and $^{122}\mathrm{Te}^{52+}$ (lower panel) ions. The fits are illustrated according to eqs. (3) and (4).

Table 1. EC- and/or β^+-decay constants for neutral atoms (estimated using the data from ref. [13]), fully ionized and H-like ^{122}I ions (this work). The values from this work were converted to the rest frame of the ions by using the Lorentz factor $\gamma = 1.42941$.

Ion	λ_{β^+} [s^{-1}]	λ_{EC} [s^{-1}]
$^{122}\mathrm{I}^{0+}$	$2.48(23) \cdot 10^{-3}$	$7.0(6) \cdot 10^{-4}$
$^{122}\mathrm{I}^{52+}$	$2.80(15) \cdot 10^{-3}$	$7.35(33) \cdot 10^{-4}$
$^{122}\mathrm{I}^{53+}$	$2.63(17) \cdot 10^{-3}$	–

Bare $^{122}\mathrm{I}^{53+}$ ions can undergo only the three-body β^+-decay ($\lambda_{\mathrm{EC}} = 0$) and only the reduction of the number of stored $^{122}\mathrm{I}^{53+}$ ions has therefore been measured. The measured data points were fitted using eq. (3) by setting $\lambda = \lambda_{\beta^+} + \lambda_{loss}$. The loss constant, λ_{loss}, has been obtained from the evolution of the number of the stored $^{122}\mathrm{Te}^{52+}$ daughter ions given by eq. (4) and amounts to $\langle\lambda_{loss}\rangle = 1.5(5) \cdot 10^{-4}\,\mathrm{s}^{-1}$. An example of the decay curve of bare $^{122}\mathrm{I}^{53+}$ nuclei is illustrated in the upper part of fig. 1.

The χ^2 minimization procedure has been employed for determining the fit parameters in eqs. (3) and (4). The reduced χ^2-values of the fits lie in the range of $1.6 < \chi^2 < 3$. These values are larger than unity and, thus, give a hint that our uncertainties might be underestimated. To account for the latter, we have used the standard procedure and increased the uncertainties of the fit parameters by a factor $\sqrt{\chi^2}$.

Data analyses performed by two independent groups provided consistent results. Furthermore, the decay constants deduced from different measurements are consistent for bare and H-like ions. The final decay constants for fully ionized and H-like ^{122}I ions, obtained by weighted averaging, are given in table 1.

4 Discussion

The estimated EC/β^+ branching ratios for the decays to different states in ^{122}Te are tabulated in ref. [13]. From this it follows that neutral ^{122}I atoms decay by $22 \pm 2\%$ via EC-decay and by $78 \pm 2\%$ via β^+-decay. Taking into account the measured half-life of neutral atoms $T_{1/2}(^{122}\mathrm{I}^{0+}) = 3.63(6)\,\mathrm{min}$ [13], the corresponding EC- and β^+-decay constants were calculated and are listed in table 1. The β^+-decay constants agree within 2σ for all listed charge states, which is expected since the effect of the electron screening and the modified Q_{β^+}-value on the β^+-decay probability should be smaller than a few percent, well below the experimental uncertainties.

The measured EC-decay constant of H-like $^{122}\mathrm{I}^{52+}$ ions $\lambda_{\mathrm{EC}}^{\text{H-like}} = 7.35(33) \cdot 10^{-4}\,\mathrm{s}^{-1}$ is within the error bars the same as the EC-decay constant of neutral ^{122}I atoms $\lambda_{\mathrm{EC}}^{\text{neutral}} = 7.0(6) \cdot 10^{-4}\,\mathrm{s}^{-1}$, though the number of bound electrons in H-like ions is just one, which has to be compared to 53 electrons in neutral atoms. It is obvious that, similar to the previously measured EC-decay probabilities of H-like ^{140}Pr and ^{142}Pm ions, the simple scaling of the EC-decay rate being just proportional to the density of all bound (s)-electrons at the nucleus does not hold.

We note that the effects due to hyperfine interaction have been observed in μ-capture in muonic atoms [42] and also in EC-decay of neutral atoms, where shifts in the energies of K X-rays following the EC-decay were measured [43]. The necessity to take into account the conservation of total angular momenta of the nucleus-lepton system in the EC-decay of highly charged ions has been noted in ref. [44]. The obvious advantage of employing highly charged ions is that a decay of a parent ion prepared in a pure hyperfine state can be investigated. First investigations of EC-decay of H-like ^{140}Pr and ^{142}Pm ions [9,12] have shown that this is indeed essential. In these two cases it was found that the main transitions $(F_i = \frac{1}{2},\ I_i = 1^+) \to (F_f = \frac{1}{2},\ I_f = 0^+)$, where f indicates the final (daughter) state, are by about 50% faster in H-like ions than in the corresponding He-like ions.

In the present case, the EC-decay strength of ^{122}I nuclei is distributed over several states in the daughter ^{122}Te nuclei, where $74.3 \pm 7.0\%$ and $22.5 \pm 5.2\%$ of the EC-decays correspond to $(I_i = 1^+) \to (I_f = 0^+)$ and $(I_i = 1^+) \to (I_f = 2^+)$ Gamow-Teller transitions, respectively. For the remaining $3.1 \pm 0.6\%$ of the decays, several I_f values are tentatively assigned in ref. [13].

Since we started our measurements 24 s after the injection of the ions into the ESR and since the number of injected ions was kept below 1000 ions, we can safely assume that *all* H-like $^{122}\mathrm{I}^{52+}$ ions are stored in the ESR in the hyperfine ground state $F_i = \frac{1}{2}$. The transitions $(F_i = \frac{1}{2},\ I_i = 1^+) \to (F_f = \frac{1}{2},\ I_f = 0^+)$ conserve the total angular momentum and, analogously to the cases ^{140}Pr and ^{142}Pm ions, we can assume that they are 1.5 times faster than the corresponding transitions in He-like ions (for the theoretical explanation of this effect, the reader is referred to refs. [14,15,17]). However, we expect that *allowed* Gamow-Teller transitions $(I_i = 1^+) \to (I_f = 2^+)$, become forbidden in our case since it is impossible to form a state with $F_f = \frac{1}{2}$. We note that any contribution of forbidden EC-decays can safely be neglected in our context.

Since the production yield of He-like $^{122}\mathrm{I}^{51+}$ ions was too small for a successful measurement of $\lambda_{\mathrm{EC}}^{\text{He-like}}$, it has to be deduced theoretically. For this purpose, we performed relativistic Dirac-Fock calculations [45] to estimate the total electron densities at the nucleus for the neutral ($\rho_{\mathrm{tot}}^{\mathrm{neutral}}$) and He-like ions ($\rho_{\mathrm{tot}}^{\text{He-like}}$). The ratio of these densities $\rho_{\mathrm{tot}}^{\text{He-like}}/\rho_{\mathrm{tot}}^{\mathrm{neutral}} = 0.87$ and thus the estimated $\lambda_{\mathrm{EC}}^{\text{He-like}} = 6.1(4) \cdot 10^{-4}\,\mathrm{s}^{-1}$. The validity of such an estimate has been verified by numerous $\lambda_{\mathrm{EC}}^{K}$ measurements [2] as well as by our previous results on $\lambda_{\mathrm{EC}}^{\text{He-like}}$ of ^{140}Pr and ^{142}Pm ions. Thus, assuming only the $(F_i = \frac{1}{2},\ I_i = 1^+) \to (F_f = \frac{1}{2},\ I_f = 0^+)$ transitions, we obtain $\lambda_{\mathrm{EC}}^{\text{H-like}} = 1.5 \times P(1^+ \to 0^+) \times \lambda_{\mathrm{EC}}^{\text{He-like}} = 6.8(8) \cdot 10^{-4}\,\mathrm{s}^{-1}$, where $P(1^+ \to 0^+) = 0.743(70)$. This result is in good agreement with our measured value (see table 1).

However, due to the relatively large uncertainties of the experimental values as well as of the theoretical estimates, no clear conclusion can be drawn on the contribution of $(I_i = 1^+) \to (I_f = 2^+)$ transitions to the EC-decay of H-like $^{122}\mathrm{I}^{52+}$ ions.

Putting all values together, the measured EC-decay constant of H-like $^{122}\mathrm{I}^{52+}$ ions, $\lambda_{\mathrm{EC}}^{\text{H-like}}(\mathrm{exp})$, can be written as

$$\lambda_{\mathrm{EC}}^{\text{H-like}}(\mathrm{exp}) = \lambda_{\mathrm{EC}}^{\text{He-like}} \times \left(1.5 \cdot P(1^+ \to 0^+) + x \cdot P(1^+ \to 2^+)\right), \tag{5}$$

where $P(1^+ \to 0^+) = 0.743(70)$, $P(1^+ \to 2^+) = 0.225(52)$, and $\lambda_{\mathrm{EC}}^{\text{He-like}} = 6.1(4) \cdot 10^{-4}\,\mathrm{s}^{-1}$. Thus, the relative contribution of $(I_i = 1^+) \to (I_f = 2^+)$ transitions in H-like ions can be estimated and amounts to $x = 0.44 \pm 0.66$. This result allows for the same strength of these transitions in H-like and in He-like ions, and at the same time it is compatible with the hypothesis of the forbidden $(I_i = 1^+) \to (I_f = 2^+)$ transitions in H-like ions. We note that we neglected in the above calculations the $3.1 \pm 0.6\%$ of the decay strength to the states in ^{122}Te ions with tentatively assigned spins, which correspondingly increase the final uncertainties.

5 Summary and outlook

EC- and/or β^+-decay constants of fully ionized and H-like ^{122}I ions have been measured at the experimental storage ring ESR. The obtained results show that the EC-decay rate of H-like $^{122}\mathrm{I}^{52+}$ ions, that is with a single bound electron, is comparable to the EC-decay of neutral $^{122}\mathrm{I}^{0+}$ atoms with 53 bound electrons. This result confirms previous observations in H-like ^{140}Pr and ^{142}Pm ions, that the allowed Gamow-Teller transitions $(F_i = \frac{1}{2},\ I_i = 1^+) \to (F_f = \frac{1}{2},\ I_f = 0^+)$, conserving the total angular momentum, $F_i = F_f$, are by 50% faster in H-like ions compared to the respective He-like ions.

In addition to the above result, in this paper we addressed for the first time the $(1^+ \to 2^+)$ allowed Gamow-Teller transitions in H-like ions. It was predicted [14–16] that such transition would become forbidden, if the parent ions are stored in the $F_i = \frac{1}{2}$ hyperfine state, since *no* state with $F_f = \frac{1}{2}$ can be formed and thus *no* transitions conserving the total angular momentum F are possible. The accuracy of our experimental data and of theoretical decay rate estimations, however, were not sufficient to draw a definite conclusion supporting or refuting this prediction.

In this context, more suitable nuclei have to be investigated. The case of the EC-decay of H-like ^{111}Sn is briefly discussed in ref. [16]. Another interesting case can be the EC-decay of H-like ^{143}Sm ions [46]. This nucleus decays mostly (about 92%) by a single Gamow-Teller transition from the ground state with $I^\pi = \frac{3}{2}^+$ to the ground state $\frac{5}{2}^+$ of the daughter ^{143}Pm nucleus. The nuclear magnetic moment is positive $\mu = +1.01(2)\mu_N$ [40]. Accordingly, the hyperfine ground state of ^{143}Sm ions with one bound electron has a total angular momentum $F_i = 1$. Since the possible total angular momenta of the daughter ion and the emitted neutrino can only be $F_f = 2$ and $F_f = 3$, there is no allowed transition possible which conserves the total angular momentum, and thus only a very weak EC-decay is expected. It is planned to test this hypothesis by measuring the EC-decay constants in H-like and He-like ^{111}Sn and/or ^{143}Sm ions in the storage ring ESR at GSI or in the Experimental Cooler-Storage Ring (CSRe) at IMP in Lanzhou [46].

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