

Studies at the border between nuclear and atomic physics: Weak decays of highly charged ions

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Abstract. Present status of experimental studies of weak decays of highly charged ions is presented. The paper closely follows the progress-report presentation given at the conference. Due to the limited space an emphasis is given to an exhaustive bibliography.

Highly charged ions (HCIs) offer unparalleled opportunities for studying the interplay of atomic structure and nuclear decay properties [1–6]. On the one side, such studies are important for understanding radioactive decay processes. The ions with none or a few bound electrons, hydrogen- (H-like) or helium-like (He-like), represent well-defined – nucleus plus lepton(s) – quantum mechanical states. In HCIs, the complicated corrections, which arise in neutral atoms due to effects of many bound electrons, like partial screening of the nuclear charge by the electron cloud [7], can be decoupled. On the other side, the decay properties of HCIs can be essential for modelling nucleosynthesis processes in stars [8–10], where the high temperature-density conditions lead to high ionisation degree of the involved nuclides. Indeed, significant modifications of nuclear half-lives ($T_{1/2}$) are expected in HCIs [11–13]. The latter is obviously true for fully-ionised atoms, where the decay branches involving atomic electrons are disabled.

Single-pass measurements of fast decay channels (lifetimes shorter than a few hundreds of ns), like internal conversion or particle decays, can be performed without storage [14]. For instance, the measurements in highly charged Fe and Te ions led to a discovery of a new decay mode, bound-state internal conversion (BIC) [15,16]. In this work we concentrate on the experimental studies of electroweak decays. Since typical weak lifetimes are longer than about a ms, single-pass measurements are not feasible. Therefore, in order to study weak decays of HCIs, it is necessary to create radioactive nuclei in a nuclear reaction, remove a number of bound electrons producing the required atomic charge state, and then preserve this charge state for an extended period of time sufficient for the ions to decay. Apart from the recent studies in the Electron Beam Ion Trap (EBIT) at TRIUMF [17,18], all other investigations of weak decays of HCIs were performed in the experimental storage ring ESR at GSI Helmholtz Center [19].

The high energy part of the GSI facility consists of an 18-Tm heavy-ion synchrotron SIS-18, the projectile fragment separator FRS and the cooler-storage ring ESR [19]. HCIs are produced at relativistic energies of a few hundreds A MeV through the projectile fragmentation or in-flight fission nuclear reactions [20]. The electrons are efficiently stripped away from energetic particles while passing through target material [21–23]. Fully-ionised and up to 4-electron ions are routinely produced at energies of about 100 – 400 A MeV [24–35]. The selection of the atomic charge state is done by optimising the primary projectile energy, target material and its thickness [36]. Secondary beams are separated in flight in the FRS within about 300 ns and are injected into the ESR [37]. By employing the magnetic rigidity analysis the cocktail beams can efficiently be transmitted to the ESR, which has a maximum magnetic rigidity $B\rho = 10$ Tm [38]. By using energy-loss degraders, also the separation of mono-isotopic beams is possible [20]. The cocktail beams are ideally suited for precision mass measurements [39–50].

The essential prerequisite for half-life measurements is the reduction of their momentum spread in order to obtain sufficient resolving power for their unambiguous identification. This is achieved by beam cooling. Stochastic [51] and electron [52] cooling methods allow for reducing the initial relative momentum spread of about 10^{-2} to $10^{-5} - 10^{-7}$ within a few seconds. The latter number depends critically on the number of stored ions [53]. For electron-cooled ions, the mass resolving power of about 750000 is reached, which is sufficient to separate isobars and even low-lying isomers by their revolution frequencies in the ring. The intensities of stored ions are continuously monitored with non-destructive time-resolved Schottky spectrometry [54–58]. In addition, the decay/reaction products can be intercepted by dedicated particle detectors [59,60].

Studies of weak decays in HCIs were among the main scientific motivations for the construction of the ESR [61]. In the three-body β_c^+ and β_c^- decays, the energy and momentum

are shared between the generated leptons and the recoiling daughter ion. The first measurement of a pure three-body β_c^+ decay channel was conducted already at the commissioning of the FRS-ESR in 1992. A beam of fully-ionised ^{19}Ne was stored in the ESR and the decay constant of $^{19}\text{Ne}^{10+}$ was measured [37]. Later, in a dedicated study, the β_c^+ decay rates of fully-ionised $^{52,53}\text{Fe}^{26+}$ nuclei were measured and compared to theoretical expectations [62]. Following the first experiments, several measurements of β_c^+ and β_c^- decays were conducted [63, 64].

However, the main interest lies in the studies of two-body beta decays: orbital electron capture (EC) and bound-state β^- -decay (β_b^-). These decays can be described with: $n + \nu_e \leftrightarrow p + e_b^-$, where p , n , e_b^- , ν_e are proton, neutron, bound electron and electron neutrino, respectively.

In the β_b^- , one of the neutrons in the nucleus is transmuted into a proton with an emission of an electron and an electron antineutrino. However, different from an ordinary β_c^- decay, the electron is not emitted to the continuum but occupies one of the bound orbitals [11]. Thus, there are two bodies in the final state. Since the inner orbitals in neutral atoms are Pauli-blocked, β_b^- is restricted to very weakly bound electron states of the daughter atom and is, therefore, only a marginal decay branch in neutral atoms. The consequence of the fact that the electron is not emitted to continuum, is that the neutral-atom Q -value is enhanced roughly by the binding energy of the generated bound electron. In particular along the stability line where the nuclei have very small Q -values, removing bound electrons may lead to dramatic modifications of β -decay rates. One example is the fully-ionised $^{163}\text{Dy}^{66+}$ nucleus which decays within ~ 50 days while the neutral ^{163}Dy atom is stable [65]. The experiment on the bound-state β -decay of $^{163}\text{Dy}^{66+}$ took place in 1992 and was the first experimental verification of the existence of this decay mode. Furthermore, the temperature T for the branching point of the s -process at $A = 163$ could be deduced [1]. Another striking example is ^{187}Re atom, which has a very long half-life of 42 Gy. However, the increased Q -value in $^{187}\text{Re}^{75+}$ ions enables the decay to the first excited state in ^{187}Os . The $T_{1/2}$ is then reduced to merely 33 years [66], causing a dramatic consequence for a possible application of the $^{187}\text{Re}/^{187}\text{Os}$ pair as a nuclear cosmo-chronometer [67].

Fully-ionised $^{206,207}\text{Tl}^{81+}$ nuclei have sufficiently large decay Q -value (> 1 MeV) and it was possible to directly resolve the parent and daughter ions and measure both β_b^- - and β_c^- -decay branches [68]. Recently the β_b^- - and β_c^- -decays have also been measured in bare $^{205}\text{Hg}^{80+}$ [69]. In contrast to numerous measurements of EC/ β_c^+ branching ratios, the β_b^-/β_c^- ratio was determined for the first time, in fair agreement with theoretical estimations [12, 69].

The measurement of β_b^- decay of $^{205}\text{Tl}^{81+}$ was proposed more than 20 years ago [70, 71]. Accurate knowledge of the matrix element of the transition between the ground state of ^{205}Tl and the 2.3 keV first excited state in ^{205}Pb is required to estimate the neutrino capture cross-section on ^{205}Tl . This reaction is essential for Solar neutrino physics [72] as well as for a better understanding of the very end of the s -process nucleosynthesis [73–76].

Concerning the time-mirrored decay mode, EC, it is obvious that it is disabled in fully-ionised nuclei. The first EC studies of H- and He-like ions were conducted for ^{122}I , ^{140}Pr , and ^{142}Pm ions [77–79]. It was observed that the allowed $1^+ \rightarrow 0^+$ Gamow-Teller decay in H-like $^{140}\text{Pr}^{58+}$ and $^{142}\text{Pm}^{60+}$ ions is by a factor ~ 1.5 faster than in the He-like $^{140}\text{Pr}^{57+}$ and $^{142}\text{Pm}^{59+}$ ions. Although seems counterintuitive, this result is explained by the conservation of the total angular momentum of the nucleus plus lepton system [80–83]. The effect of the latter is best illustrated by the disabled Gamow-Teller $1^+ \rightarrow 2^+$ transitions in EC decay of H-like $^{122}\text{I}^{52+}$ ions [79]. By selecting specific nuclei and transitions, forbidden decays and other subtle effects in beta decay can be addressed in the future [84–86]. The above results are an excellent example of the influence of atomic structure on nuclear weak decay.

However, the most intriguing measurement remains the observation of the modulated EC decays in H-like $^{140}\text{Pr}^{58+}$ and $^{142}\text{Pm}^{60+}$ ions [87, 88]. The observed phenomenon can not be explained within the present understanding of the electro-weak interaction and could not be reproduced in implanted atoms [89, 90]. It therefore caused intensive discussions in literature,

see, e. g., [91–93]. The electron capture decay of $^{142}\text{Pm}^{60+}$ ions was remeasured in 2010 [94] and in 2014. The experimental data have been analysed and the publication is in preparation.

In summary, heavy-ion storage-cooler rings have proven to be excellent tools to perform high-precision decay experiments on HCIs. Left outside of the present work are the results on the decay studies of nuclear isomeric states in HCIs [95–101].

The ESR at GSI is the only facility where weak decays of HCIs have been addressed. However, there are two more storage rings coupled to radioactive ion beam facilities [102]. These are the experimental cooler-storage ring CSRe at Institute of Modern Physics (IMPCAS) in Lanzhou, China and the rare-ion storage ring R3 at RIKEN in Wako, Japan. The storage ring complex at IMPCAS is organised in a similar way as the one at GSI. Here, the CSRe is coupled to the heavy-ion synchrotron CSRm with a fragment separator RIBLL2. The successful research program at CSRe concentrates on direct mass measurements of exotic nuclides, see Refs. [103–112]. At RIKEN, the R3 storage ring is located behind the BigRips fragment separator. RIKEN offers presently the maximal intensities of the primary beams worldwide. However, since the driver accelerator is a cyclotron, the injection into the R3 could only be done on a particle by particle basis [113, 114]. Although to date no lifetime measurements of HCIs were performed in the R3, they are being planned. An obvious task is to measure still unknown half-lives.

The future scientific programs are rich and include investigations of exotic decay channels such as two-photon and internal pair de-excitation [115], bound electron-positron decays [116], nuclear excitations by electron capture or electron transitions [117], α -decays [118], as well as EC decay of lithium-like ions and forbidden EC decays [82, 85]. Last but not least, proton and neutron radioactivity as well as β -delayed particle emission [119] are interesting topics.

As an outlook it is essential to note new storage ring projects launched worldwide. The CRYRING has been installed behind the ESR [117]. HCIs decelerated to energies down to a few hundreds of A keV will be available, thus allowing unique experiments at the interface between nuclear structure, atomic and astrophysics. The TSR@ISOLDE project at CERN [120] has been postponed. The TSR will probably be installed behind CSRm at IMPCAS. Studies of β -decays is one of the physics cases for the TSR, with $^7\text{Be}^{2+,3+}$ ions being among the main targets [120].

Necessary to mention are the two next-generation radioactive-ion beam facilities FAIR in Germany and HIAF in China, both containing complexes of storage rings. The detailed discussions on the perspectives of research with HCIs at FAIR and HIAF can be found in [121, 122]. After the completion of FAIR, the facility will offer flexible experimental conditions for experiments with stored radioactive HCIs. For instance they will be available in the energy range spreading over 10 orders of magnitude from nearly at rest to about 5 A GeV [123, 124, 126].

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