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Radioactive decays of highly-charged ions

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Abstract. Access to stored and cooled highly-charged radionuclides offers unprecedented opportunities to perform high-precision investigations of their decays. Since the few-electron ions, e.g. hydrogen- or helium-like ions, are quantum mechanical systems with clear electronic ground state configurations, the decay studies of such ions are performed under well-defined conditions and allow for addressing fundamental aspects of the decay process. Presented here is a compact review of the relevant experiments conducted at the Experimental Storage Ring ESR of GSI. A particular emphasis is given to the investigations of the two-body beta decay, namely the bound-state β-decay and its time-mirrored counterpart, orbital electron-capture.

1 Introduction

Nuclear decay rates can significantly be modified in highly-charged ions (HCI) [1, 2, 3, 4]. It is obvious that orbital electron capture (EC) and internal conversion (IC) decays are disabled if the number of bound electrons is reduced to zero in fully-stripped atoms. Bare nuclei or hydrogen-like (H-like), helium-like (He-like) or lithium-like (Li-like) ions can be considered as well-defined quantum mechanical systems in which the influences and corrections due to many bound electrons are just absent or feasible to handle [5, 6]. Such systems offer clean conditions for the investigations of the effects of the electron shell on the nuclear decay characteristics. Furthermore, it can happen that decay modes known in neutral atoms turn out to be forbidden in HCI and vice versa new decay modes may open [7]. Last but not least, knowledge of weak decays of HCIs is important for the understanding of stellar nucleosynthesis processes since they typically proceed at high temperature and density conditions at which the atoms are highly ionised [7, 8, 9, 10, 11, 12, 13].

On the one side the experimental investigations of radioactive decays of HCIs require the capability to produce and separate exotic nuclei in a well-defined high atomic charge state. On the other side, it is indispensable to be able to preserve this high atomic charge state for a sufficiently long period of time to allow the ions to β-decay [14, 15, 16, 17, 18]. Due to these experimental challenges, decay studies of radioactive HCIs are conducted routinely only at GSI Helmholtz Center in Darmstadt (GSI). In this contribution we briefly review the relevant experiments. More details can be found in Refs. [3, 4, 17, 19].

2 Experiment

The heart of the high-energy part of the GSI accelerator complex is the heavy-ion synchrotron SIS18 [20], which can deliver intense primary beams of any stable isotope accelerated up to a maximum magnetic rigidity of $B\rho =$

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18 Tm. Secondary beams are produced via projectile fragmentation and, in the case of uranium primary beam, also projectile fission reactions [21, 22, 23, 24] using the targets placed in front of the fragment separator FRS [25]. The produced secondary beams are separated in flight with the FRS [25, 26] and are injected into and stored in the experimental storage ring ESR [27]. Owing to relativistic energies, the fragments are present as highly-charged ions already after the production target [28, 29]. The production of a specific ionic charge state can be optimised by varying the primary beam energy, the target thickness and target material. By employing the atomic slowing down of ions in special energy degraders, it is possible at the FRS to prepare clean mono-isotopic beams [25, 30, 31, 32].

The ESR has a circumference of 108 m. It is an ultrahigh vacuum (UHV) machine with a rest gas pressure of $\sim 10^{-11}$-10^{-12} mbar [27], which is essential for preserving the high atomic charge state of the stored ions. In the ESR the velocity spread of the HCI is reduced by stochastic [33, 34, 35] and/or electron [36, 37, 38] cooling. For beam intensities of below a few thousands ions, the initial velocity spread is reduced by first stochastic pre-cooling and then electron cooling to about $\delta v/v \sim 10^{-7}$ [37, 39] within a few seconds [40, 41]. Ions with sharp velocity distributions can unambiguously be identified by their revolution frequencies. This is the basis of the so-called Schottky Mass Spectrometry (SMS) [42], which is successfully applied at the ESR for high-precision mass measurements of exotic nuclides [43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62]. The frequencies and intensities of the stored ions are measured with nondestructive Schottky detectors [63, 64]. Dedicated particle detectors blocking specific orbits in the ring can be employed to measure the intensities of the decay products [65, 66]. Schottky detectors have no restrictions on the numbers of stored ions and can detect single ions as well as beams of milli-Ampere currents [67]. Furthermore, they allow for redundant measurements of the decay of the parent ions and the growth of the number of the daughter ions at the same time [56].

The destructive detectors are employed to detect decay or reaction products and are often used in the cases when the orbits of the corresponding ions lie outside the storage acceptance of the ring [68, 69]. In 2014, a new silicon detector was constructed to detect and count the number of daughter ions in the ESR [70]. Due to the UHV environment, special pockets were designed and be installed after one of the dipoles of the ring. These pockets accommodate the particle detectors and can be moved close to the coasting beam. To achieve the position and charge-resolved measurements, the new design of the detector includes: a stack of 8 silicon pad detectors, a double-sided silicon strip detector (DSSD), and a CsI scintillator. The DSSD has 60 × 40 strips on the p and n sides, respectively. The total thickness of the detectors is sufficient to stop bare heavy ions ($Z > 80$) with energies up to 400 MeV/u. The detector can combine different methods of ion identification, namely, the position information from the DSSD and the energy deposit from the silicon pads [71], or the multiple sampling of the energy deposit [68, 72]. For the stopped ions one can use the ΔE/E method.

A complementary technique, Isochronous Mass Spectrometry (IMS), can be applied to measure the frequencies of uncooled stored ions [19, 41, 73, 74, 75, 76, 77, 78], which is ideally suited to investigate the shortest-lived nuclei with half-lives as short as a few tens of microseconds. The frequencies of each individual stored ion are measured with dedicated secondary-electron detectors [79, 80, 81, 82]. Due to the energy loss in the detector, the ions can survive in the ring for only a few hundreds of revolutions. With novel highly-sensitive Schottky detectors [63], nondestructive measurements on single ions became also possible also in the IMS [64]. The IMS technique is successfully applied not only at the ESR but also at the experimental cooler-storage ring CSRe [83, 84] at the Institute of Modern Physics in Lanzhou [85, 86, 87, 88, 89, 90, 91, 92, 93, 94] and will become the main operation mode of the RI-RING at RIKEN [95, 96].

3 Results

The results obtained in various experiments at the ESR are summarised in the 2011 Nuclear Wallet Cards and can be found at http://www.nndc.bnl/gov/.

3.1 Half-lives of long-lived isomeric states

Isomers are metastable nuclear states [97, 98], which can de-excite to the corresponding ground states by either internal conversion (IC) or internal transition (IT). Isomers can also decay to different nuclides through α, β-decay or fission. In fully ionised atoms, all bound electrons are removed and the de-excitation through IC is impossible resulting in an increase of the isomer half-lives. This could experimentally be shown in the ESR on the examples of ^{144m}Tb, ^{149m}Dy and ^{151m}Er isomers [99]. Such measurements provide accurate conversion coefficients and also weak gamma decay branches can be investigated.

The single particle sensitivity of the storage ring spectrometry can be used to search for yet unknown isomers. Several isomers were discovered in the ESR using both IMS and SMS techniques [100, 101, 102, 103, 104, 105]. A clear advantage is that very long-lived isomers with very small production yields can unambiguously be identified, which was demonstrated by the identification of many long-lived isomers in heavy neutron-rich nuclides [106, 107, 108].

The decay channels can not only become disabled in HCIs but also new decay modes can open up in few-electron ions, like, e.g., bound internal conversion (BIC). The BIC process was observed in HCIs in single pass experiments [109, 110, 111]. In a storage ring, the repopulation of the upper hyperfine states was not observed [112, 113], and if the storage time is long enough for the hyperfine states to relaxate, the ions will be stored in the ground hyperfine states thus having a well-defined total angular momentum. The conservation of the total angular momentum has to be considered and the transitions allowed in neutral atom may become forbidden in HCIs [114].

In the future one can consider investigations of bound electron-positron decay, where the created electron is captured on a free orbital while the positron is emitted to continuum. Also interesting are $0^+ \rightarrow 0^+$ de-excitations, which, e.g., connect the ground and the first excited states in neutron-deficient lead nuclei [115]. Such decays are highly converted and in the absence of bound electrons are significantly hindered. For instance, in the rapid proton capture process (rp-process) in Novae, such excited 0^+ states in bare nuclei may have sufficiently long lifetimes and thus significantly modify the processing speed [116].

3.2 Alpha-decay of highly-charged ions

Investigations of α decay of HCIs was proposed several years ago [117, 118, 119]. It is suggested to address possible tiny variations in the α-decay Q-values and half-lives of fully-ionised α emitters arising due to the effect of electron screening. So far only a few preparatory tests were conducted at the ESR.

3.3 Beta decay of highly-charged ions

Importance of precision experiments on β decay of HCIs was recognised very early and was one of the main motivations for the team led by Paul Kienle for the construction of the ESR. Already in 1992 beta decay of bare ^{19}Ne was addressed in the ESR where a pure three-body β^+ decay channel was measured in the absence of electrons [14, 25]. Presently the decays of several fully-ionised systems were studied on both sides of the valley of β-stability.

Over the past two and a half decades, the most attention at the ESR was given to investigations of two-body decays. Here the storage rings offer unprecedented experimental conditions. A well-known example is the bound state beta decay, β_b-decay [13, 120, 121]. This is a β^- decay in which one of the neutrons in the nucleus is transmuted into a proton accompanied by the emission of an electron and an electron antineutrino. Different from the continuum β^- decay mode, the electron is not emitted to the continuum but occupies one of the bound orbitals. It is clear that any significant decay probability is only existent in highly-charged ions which offer electron vacancies in the inner shells. Some decay energy is "saved" in the decay thus modifying the rate as compared to the one in the neutral atom. One example is the fully-ionised ^{163}Dy^{66+} nucleus which decays within ~ 50 days while the neutral ^{163}Dy atom is stable [122, 123]. Another example is ^{187}Re: Neutral atoms have a very long half-life of 42 Gy, which reduces to 33 years if all electrons are removed [71]. This dramatic modification of the half-life makes it difficult to employ ^{187}Re/^{187}Os as a galactic clock [124, 125, 126]. Last but not least, simultaneous measurements of the three-body β^--decay and the two-body bound state beta decay channels in ^{207}Tl^{81+} and ^{205}Hg^{80+} nuclei were conducted. These measurements allowed for the determination of β_b/β^- ratios, the analogs of the EC/β^+ ratios on the neutron-rich side of the nuclidic chart [68, 72, 127, 128].

The measurement of the bound state beta decay of ^{205}Tl^{81+} nuclei [129, 130], proposed since the nineties, is still pending. Accurate knowledge of the matrix element of the $^{205}\mathrm{Tl} + \nu_e$ ($E_{\nu_e} > 52$ keV) $\rightarrow$ $^{205}\mathrm{Pb}^*$ (2.3 keV) + e^- transition is essential for neutrino physics [130] as well as for better understanding of the nucleosynthesis prior to the the birth of the Solar system [8, 131, 132, 133].

The two-body beta decay mode on the neutron-deficient side of the nuclidic chart is orbital electron capture, EC [134]. It is obvious that EC is disabled in bare nuclei. Recently, EC of H- and He-like ions was accurately measured in ^{122}I, ^{140}Pr, and ^{142}Pm ions [56, 135, 136, 137]. It was observed that H-like ^{140}Pr^{58+} and ^{142}Pm^{60+} ions decay by a factor ~1.5 faster than the corresponding He-like ^{140}Pr^{57+} and ^{142}Pm^{59+} ions, and even neutral atoms. This result is explained by the conservation of the total angular momentum and by the fact that the ions in the ESR are stored in the ground hyperfine state [117, 138, 139, 140]. The latter selectivity of the ESR can be used to address forbidden decays and other subtle effects in beta decay [114, 141, 142, 143]. We note, that similar effects were seen in muon capture [144]. However, the most intriguing result remains the observation of the modulated EC decays in H-like ^{122}I^{52+}, ^{140}Pr^{58+} and ^{142}Pm^{60+} ions [145, 146, 147]. If the ~7 s modulations on top of the exponential decay are confirmed in future experiments, this result can lead to new interesting physics, since such modulations are not expected within the present understanding of the electro-weak interaction (see Refs. [146, 147] for more details).

4 Summary and Outlook

Heavy-ion storage-cooler rings employed for storing highly-charged radioactive ions have proven to be excellent tools to perform high-precision decay experiments. The ESR at GSI remains still the only facility to perform such kinds of measurements. Another facility of this sort is the CSRe in Lanzhou. In addition to the successful mass measurements program at the CSRe in Lanzhou, also the lifetime spectroscopy is being commissioned now [148, 149]. Furthermore, several new storage ring projects were launched which will soon be able to study properties of highly-charged exotic nuclei. One of them is the TSR@ISOLDE at CERN [150] where the measurements of β-decays of HCIs is one of the main physics cases. Other projects are the Rare-RI Ring at RIKEN [95, 96, 151], and HIAF in China [152]. Last but not least, the future FAIR facility [153] accommodates several dedicated storage rings. We note that decay studies of HCIs were foreseen in electron-ion beam traps [154] as well as in ion traps, like, e.g., HITRAP at the ESR [155, 156].

At FAIR, exotic nuclei will be produced and separated at the new superconducting fragment separator Super-FRS [157, 158] and transported to new storage rings. The physics program at the rings is rich and goes beyond investigations of nuclear ground-state properties, see, e.g., [159, 160, 161, 162, 163, 164, 165, 166]. Decays of highly-charged ions will be studied within the ILIMA experiments [167, 168]. Short-lived nuclei will be investigated in the collector ring with the IMS technique, new Schottky detectors or particle detectors [169]. For longer-lived species, it was planned to stochastically pre-cool them in the CR and then transport to the new storage ring NESR for precision investigations. However, the NESR is presently out of the scope of the initial version of FAIR and will thus be delayed. Therefore, instead of the NESR, the ions will be sent to the high-energy storage ring HESR [170, 171]. It was shown, that the HESR can store HCIs, and, e.g., EC or β_b-decay experiments can be conducted there. Since the FRS and ESR will remain operational until they are surpassed by the Super-FRS and NESR, a connection between FRS-ESR and the HESR is of a clear advantage [171]. For instance, the beams of long-lived HCIs, e.g., ^{205}Tl^{81+} ions, could be purified and pre-cooled in the ESR, transmitted and accumulated in the HESR, which is then ideally suited to measure long half-lives. Furthermore, since a low energy storage ring CRYRING is being constructed downstream the ESR [170] a backwards connection of the FAIR facilities with the ESR-CRYRING would offer a great potential for physics with slow cold ion or antiproton beams. With CRYRING, ESR, CR, and HESR, FAIR will offer stable and radioactive HCIs in a broad and continuous range of energies from a few hundreds keV/u (CRYRING) until 5-6 GeV/u (HESR) thus allowing for unique atomic and nuclear physics experiments (see, e.g., [172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183]).

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