

Electroweak Decays of Highly Charged Ions

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Abstract. In this contribution we review the present status of experimental studies of electroweak decays of highly charged ions. A particular focus will be given on the bound state beta decay measurement of ²⁰⁵Tl.

1 Introduction

Investigations of decays of highly charged radionuclides (HCR) have been among the physics motivations for the construction of the Experimental Storage Ring (ESR) at GSI Helmholtz Center in Darmstadt, Germany [1]. The very reason for the interest in such studies is that HCRs with none or a few bound electrons, like, for instance, hydrogen-like (H-like), helium-like (He-like) or lithium-like (Li-like) ions, represent well-defined nucleus plus lepton(s) systems with well-defined quantum numbers. Owing to the latter, HCRs offer unparalleled opportunities for studying the interplay of atomic structure and nuclear decay properties [2–9]. Apart from basic understanding of decay phenomena, such studies are essential for nuclear astrophysics where the nuclei involved into nucleosynthesis are highly ionized in hot and dense stellar environments [10–12].

The question on whether the nuclear decay probability is a fundamental constant or can be modified is addressed since the beginning of nuclear physics [13]. Only minor modifications of below about 1% have been observed by varying temperature, pressure, chemical environments, etc. [14–16]. However, it has been realized that nuclear half-lives ($T_{1/2}$) can change dramatically in HCRs [17–19]. On the one hand, this is straightforward for fully-ionized atoms where the decay branches involving atomic electrons, such as orbital electron capture (EC) or internal conversion (IC), are disabled. On the other hand, new decay channels disabled in neutral atoms can open up. One example of such exotic decay modes is the bound-state internal conversion (BIC) [20–22]. In the BIC process, an excited nuclear state resonantly transfers its excitation energy to a bound electron which is excited to a higher energy, but still bound, atomic level. This process has been discovered in single-pass experiments which are suitable for fast decays ($T_{1/2} < \sim 500$ ns).

Since typical weak lifetimes are longer than about a ms, for their investigations one requires facilities which are capable to store the produced radionuclides in a preserved high charged state for a sufficiently long time. Apart from the recent studies in the Electron Beam

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Ion Trap (EBIT) at TRIUMF [23, 24], very recent measurements of weak decays of fully-ionized $^{49}\text{Cr}^{24+}$, $^{53}\text{Fe}^{26+}$ atoms [25] and the de-excitation of the $^{94m}\text{Ru}^{44+}$ isomeric state [26] at the experimental cooler storage ring CSRe at Institute for Modern Physics (IMP), Lanzhou, all other investigations of decays of HCRs were performed in the ESR of GSI [2–4, 27].

2 Heavy-Ions Storage Rings

There are three storage ring facilities in the world which allow for storing highly charged exotic nuclei [28]. These are the ESR at GSI [29], the CSRe at IMP [30] and the R3-storage ring at RIKEN Nishina Center in Wako [31–33].

Magnetic rigidity is defined $B\rho = mv\gamma/q$, where m/q is mass to charge ratio of a particle, v its velocity, and γ relativistic Lorentz factor. The high energy part of the GSI facility consists of an 18-Tm heavy-ion synchrotron SIS, the in-flight projectile fragment separator FRS [34] and the 10-Tm cooler-storage ring ESR [35]. Exotic nuclei are produced at relativistic energies of a few hundreds MeV/u through projectile fragmentation or in-flight fission nuclear reactions [36]. The FRS is employed to select and transport the ions of interest to the ESR [37]. The flight time through the FRS is merely 300 ns. In general the FRS can transport all produced exotic nuclei, the “cocktail” beam, lying within its $B\rho$ acceptance. By adding specially shaped degraders, one employs the atomic energy loss, ΔE , in the so-called $B\rho - \Delta E - B\rho$ separation method to achieve the separation of mono-isotopic beams [38].

Due to the high kinetic energies, orbital electrons are efficiently stripped off the fragments emerging from the target material [39–42]. By tuning the projectile energy, target material and thickness, ion beams in a specific charge state of interest can selectively be produced and stored in the ESR. Fully-ionised and up to 4-electron ions are routinely produced at energies of about 100 – 400 MeV/u, see, e.g., Refs. [43–54].

The storage ring mass spectrometry makes use of cocktail beams and is applied successfully at the ESR [56–67] and CSRe [68–77]. The R3 is being commissioned now and is expected to begin with mass measurements already in 2018.

3 Decay studies of highly charged radionuclides

The decay studies are typically conducted with mono-isotopic beams to avoid contaminations or secondary feedings. Furthermore, mono-isotopic beams are often needed in reaction studies with internal targets or electron cooler (see, e.g., [43, 78–80]).

The ESR has a circumference of 108 m. This is an ultra-high vacuum machine with an average residual gas pressure of about $10^{-10} - 10^{-11}$ mbar. The latter is an essential prerequisite for experiments with highly charged ions. The beam cooling is needed to reduce the inevitable momentum spread of the ions, $\Delta p/p$, which is mainly due to nuclear reaction process. This is of utmost importance to achieve sufficient resolving power for an unambiguous identification of parent and daughter ions. Stochastic [81] and electron [82] cooling methods are used to reduce $\Delta p/p$ to $\approx 10^{-5} - 10^{-7}$ within a few seconds. The achievable minimum $\Delta p/p$ depends critically on the number of stored ions and is determined by the balance between the cooling force and the intra-beam scattering effects. For electron-cooled ions, a transition to ordered beams is observed at low particle intensities of below about 2000 ions [83, 84]. In this mode, 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 [85–89]. In addition, the decay/reaction products can be intercepted by dedicated particle detectors [90–93].

Numerous experiments have been performed at the ESR and since recently also at the CSRE for investigations of continuum beta decay and de-excitation of nuclear isomers [25, 26, 94–103]. In the last years a special attention is given to two-body beta decays. These are the orbital electron capture (EC) and bound-state β^- -decay (β_b^-), which can be described in a general form $n + \nu_e \leftrightarrow p + e_b^-$, where p , n , e_b^- , ν_e are proton, neutron, bound electron and electron neutrino, respectively. Concerning the experiments on EC, the reader is referred to Refs. [104–121]. Here we focus on the β_b^- decay studies.

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 [17]. This decay was first predicted by Daudel *et al.* [122] in 1947 and then discussed in detail by Bahcall [123]. Similar to EC, in which the electron from any shell can be captured, the created electron in the β_b^- -decay can occupy different shells in a daughter ion. The scaling of the probabilities to capture (generate) s-electron from (in) electron shells with different principal quantum number n scales as $1/n^3$ [124]. Since the inner orbitals in neutral atoms are Pauli-blocked, β_b^- is only a marginal decay branch in neutral atoms.

The first direct observation of the bound-state beta decay (β_b decay) was done in the ESR in 1992 [125] with the use of bare $^{163}\text{Dy}^{66+}$ ions. Neutral ^{163}Dy is stable. However, without electrons its half-life is merely ~ 50 days. This result yielded the temperature T for the branching point of the s-process at $A = 163$ [2]. Another 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 measured $T_{1/2}$ is merely 33 years [126], which constrains the applicability of the $^{187}\text{Re}/^{187}\text{Os}$ pair in cosmo-chronometry [127].

Fully-ionised $^{205}\text{Hg}^{80+}$ and $^{206,207}\text{Tl}^{81+}$ nuclei have sufficiently large decay Q -values. The parent and daughter ions could thus be directly resolved by their revolution frequencies in the ESR. Both β_b^- - and β_c^- -decay branches were measured [128, 129]. In contrast to numerous measurements of EC/β_c^+ branching ratios, these are the only measured β_b^-/β_c^- ratios, which are in fair agreement with theoretical estimations [18, 129].

4 Bound-State Beta Decay of $^{205}\text{Tl}^{81+}$

The measurement of the bound-state beta-decay rate of fully-ionized ^{205}Tl has been proposed more than 20 years ago [130, 131]. Its decay rate is needed to determine the matrix element for the EC of the 2.3 keV excited state in ^{205}Pb to the ground state of ^{205}Tl . This matrix element is important for the determination of the pp-solar neutrino capture probability into the 2.3 keV state of ^{205}Pb [132, 133]. It can also be used to constrain the very end of the s-process nucleosynthesis [134–137]. The proposal for this measurement has been approved at GSI.

A projectile beam of enriched ^{206}Pb will be accelerated by SIS to ~ 700 MeV/u. The intensity of $2 \cdot 10^9$ particles/spill on target is expected. The production target will be ^9Be . The masses of parent $^{205}\text{Tl}^{81+}$ and daughter $^{205}\text{Pb}^{81+}$ ions differ by ~ 31 keV. This tiny difference does not allow to separate them by revolution frequencies in the ESR. Therefore, the essential condition for this experiment is that the amount of $^{205}\text{Pb}^{81+}$ ions directly injected into the ESR is as small as possible. For this purpose we will employ the $B\rho - \Delta E - B\rho$ separation. The thicknesses of all matter in the FRS will be optimized such that the final energy of $^{205}\text{Tl}^{81+}$ ions equals 400 MeV/u. The ESR stochastic cooling system is matched to this energy. Beam stacking will be applied to accumulate about 10^6 parent ions.

In order to count the number of produced β_b^- -daughters, the bound electron will be stripped from ^{205}Pb by employing a strong Ar gas-jet. The gas jet has a density of about 10^{13} argon atoms/cm². It will be turned-on for a fixed period of time. The change of the

atomic charge state causes a significant alteration in the trajectory and hence the revolution frequency. The number of daughter ions can be counted in two ways either by Schottky diagnosis or by a particle detector on the corresponding orbit.

For the design number of 10^6 stored bare ^{205}Tl ions and a very cautiously estimated bound-state beta decay half-life of 1 year, we expect about 40 bound-state beta decays within a storage time of 1 hour. A waiting time is therefore necessary to accumulate daughter ions before the start of the gas-jet. We plan to have several waiting times of up to several hours. During the waiting time, the electron current in the cooler will be set to the minimum to reduce the recombination rate. The intensity of the parent ions will constantly be monitored by the Schottky analysis. This is essential to account for various beam losses.

The amount of the $^{205}\text{Pb}^{81+}$ ions directly injected from the FRS will be measured by switching the gas-jet immediately after injection. The primary beam of ^{206}Pb in charge states $82+$ and $81+$ will be used to calibrate the efficiency of the gas-jet stripping and beam losses.

5 Outlook

Heavy-ion storage-cooler rings have proven to be excellent tools for performing high-precision decay experiments on HCRs. There are many ideas for unique investigations of decays of HCRs which guarantee the rich perspectives of the field, see [112, 116, 138–142].

New storage ring projects are launched worldwide. The CRYRING has been installed behind the ESR [143], where HCRs decelerated to energies down to a few hundreds of A keV will be available. This will enable unique experiments at the interface between nuclear structure, atomic and astrophysics. Since the TSR@ISOLDE project at CERN [144] has been postponed, the TSR will probably be installed at IMP. Decays of HCRs belong to major physics cases for the TSR [144]. New storage rings are in the focus of the next-generation radioactive-ion beam facilities FAIR in Germany and HIAF in China. At FAIR, the stored HCRs will be available at energies covering 10 orders of magnitude from nearly at rest to about 5 A GeV [145–147]. Some discussions on the research with HCRs at FAIR and HIAF can be found in [148, 149].

This short paper is dedicated to our friends Paul Kienle and Fritz Bosch who made indispensable contributions to this field of research. This review is based on previous publications of our colleagues from several storage ring collaborations. To all of them we are deeply obliged. This work is in part supported by the Helmholtz/CAS Joint Research Group (HCJRG-108), and by the European Research Council (ERC) under the EU Horizon 2020 research and innovation programme (ERC CG 682841 “ASTRUM”).

References

- [1] P. Kienle *Forschung im Focus* (Interfrom, 1993).
- [2] Yu. A. Litvinov and F. Bosch, *Rep. Prog. Phys.* **74**, 016301 (2011).
- [3] Yu. A. Litvinov *et al.*, *Phys. Scripta T* **144**, 014001 (2011).
- [4] F. Bosch *et al.*, *Prog. Part. Nucl. Phys.* **73**, 8 (2013).
- [5] F. Bosch *et al.*, *Phys. Scripta T* **156**, 014025 (2013).
- [6] D. R. Atanasov *et al.*, *Phys. Scripta T* **156**, 014026 (2013).
- [7] F. Bosch and Yu. A. Litvinov, *Int. J. Mass Spectrom.* **349-350**, 151 (2013).
- [8] D. R. Atanasov *et al.*, *J. Phys. B* **48**, 144024 (2015).
- [9] D. R. Atanasov *et al.*, *J. Phys. Conf. Series* **875**, 012008 (2017).
- [10] E. M. Burbidge *et al.*, *Rev. Mod. Phys.* **29**, 547 (1957).
- [11] H. Schatz, *Int. J. Mass Spectrom.* **349-350**, 181 (2013).

- [12] K. Langanke and G. Pinedo, *Phys. Scripta T* **166**, 014001 (2015).
- [13] E. Rutherford and F. Soddy, *J. Chem. Soc. Trans.* **81**, 837 (1902).
- [14] G. T. Emery, *Ann. Rev. Nucl. Sci.* **22**, 165 (1972).
- [15] B. Wang *et al.*, *Eur. Phys. J. A* **28**, 375 (2006).
- [16] T. Ohtsuki *et al.*, *Phys. Rev. Lett.* **98**, 252501 (2004).
- [17] J. N. Bahcall, *Phys. Rev.* **126**, 1143 (1962).
- [18] K. Takahashi and K. Yokoi, *Nucl. Phys. A* **404**, 578 (1983).
- [19] K. Takahashi and K. Yokoi, *At. Data Nucl. Data Tables* **36**, 375 (1987).
- [20] W. R. Phillips *et al.*, *Phys. Rev. Lett.* **62**, 1025 (1989).
- [21] W. R. Phillips *et al.*, *Phys. Rev. A* **47** 3682 (1993).
- [22] F. Attallah *et al.*, *Phys. Rev. C* **55**, 1665 (1997).
- [23] K. G. Leach *et al.*, *Nucl. Instr. Meth. A* **780**, 91 (2015).
- [24] K. G. Leach *et al.*, *Atoms* **5**, 14 (2017).
- [25] X. L. Tu *et al.*, *Phys. Rev. C* **97**, 014321 (2018).
- [26] Q. Zeng *et al.*, *Phys. Rev. C* **96**, 031303(R) (2017).
- [27] D. Atanasov *et al.*, *J. Phys. Conf. Series* **875**, 012008 (2017).
- [28] Y. H. Zhang *et al.*, *Phys. Scripta* **91**, 073002 (2016).
- [29] B. Franzke, H. Geissel and G. Münzenberg, *Mass Spectrometry Reviews* **27**, 428 (2008).
- [30] J. W. Xia *et al.*, *Nucl. Instr. Meth. A* **488**, 11 (2002).
- [31] Y. Yamaguchi *et al.*, *Nucl. Instr. Meth. B* **266**, 4575 (2008).
- [32] A. Ozawa *et al.*, *Prog. Theor. Exper. Phys.* **2012**, 03C009 (2012).
- [33] T. Yamaguchi *et al.*, *Int. J. Mass Spectrom.* **349-350**, 240 (2013).
- [34] H. Geissel *et al.*, *Nucl. Instr. Meth. B* **70**, 286 (1992).
- [35] B. Franzke, *Nucl. Instr. Meth. B* **24/25**, 18 (1987).
- [36] H. Geissel, *Progress Part. Nucl. Phys.* **42**, 3 (1999).
- [37] H. Geissel *et al.*, *Phys. Rev. Lett.* **68**, 3412 (1992).
- [38] G. Münzenberg, *Nucl. Instr. Meth. B* **70**, 265 (1992).
- [39] C. Scheidenberger *et al.*, *Nucl. Instr. Meth. B* **142**, 441 (1998).
- [40] H. Ogawa *et al.*, *Phys. Rev. A* **75**, 020703(R) (2007).
- [41] I. Tolstikhina *et al.*, *Phys. Usp.* **56**, 213 (2013). [2013 *Usp. Fiz. Nauk* **183** 225]
- [42] V. P. Shevelko *et al.*, *Nucl. Instr. Meth. B* **421**, 45 (2018).
- [43] C. Brandau *et al.*, *J. Phys. Conf. Series* **194**, 012023 (2009).
- [44] C. Brandau *et al.*, *J. Phys. Conf. Series* **388**, 062042 (2012).
- [45] W. Nörtershäuser *et al.*, *Phys. Scripta T* **156**, 014016 (2013).
- [46] C. Brandau *et al.*, *Phys. Scripta T* **156**, 014050 (2013).
- [47] S. Tashenov *et al.*, *Phys. Rev. Lett.* **113**, 113001 (2014).
- [48] M. Lochmann *et al.*, *Phys. Rev. A* **90** 030501(R) (2014).
- [49] P-M Hillenbrand *et al.*, *Phys. Rev. A* **91**, 022705 (2015).
- [50] P-M Hillenbrand *et al.*, *Phys. Rev. A* **93**, 042709 (2016).
- [51] H. Beyer *et al.*, *J. Phys. B* **48**, 144010 (2015).
- [52] J. Ullmann *et al.*, *J. Phys. B* **48**, 144022 (2015).
- [53] R. Sanchez *et al.*, *J. Phys. B* **50**, 085004 (2017).
- [54] J. Ullmann *et al.*, *Nature Comm.* **8**, 15484 (2017).
- [55] A. Gumberidze *et al.*, *Nucl. Instr. Meth. B* **408**, 27 (2017).
- [56] T. Radon *et al.*, *Nucl. Phys. A* **677**, 75 (2000).
- [57] Yu. N. Novikov *et al.*, *Nucl. Phys. A* **697**, 92 (2002).

- [58] J. Stadlmann *et al.*, *Phys. Lett. B* **586**, 27 (2004).
- [59] Yu. A. Litvinov *et al.*, *Phys. Rev. Lett.* **95**, 042501 (2005).
- [60] H. Geissel and Yu. A. Litvinov, *J. Phys. G* **31**, S1779 (2005).
- [61] Yu. A. Litvinov *et al.*, *Nucl. Phys. A* **756**, 3 (2005).
- [62] H. Geissel *et al.*, *Eur. Phys. J Special Topics* **150**, 109 (2007).
- [63] Yu. A. Litvinov *et al.*, *Nucl. Phys. A* **787**, 315c (2007).
- [64] B. H. Sun *et al.*, *Nucl. Phys. A* **812**, 1 (2008).
- [65] B. H. Sun *et al.*, *Int. J. Mod. Phys E* **18** 346 (2009).
- [66] L. X. Chen *et al.*, *Phys. Rev. Lett.* **102**, 122503 (2009).
- [67] D. Shubina *et al.*, *Phys. Rev. C* **88**, 024310 (2013).
- [68] M. Wang *et al.*, *Int. J. Mod. Phys. E* **18**, 352 (2009).
- [69] X. L. Tu *et al.*, *Nucl. Instr. Meth. A* **654**, 213 (2011).
- [70] X. L. Tu *et al.*, *Phys. Rev. Lett.* **106**, 112501 (2011).
- [71] Y. H. Zhang, *Phys. Rev. Lett.* **109**, 102501 (2012).
- [72] H. S. Xu *et al.*, *Int. J. Mass. Spectr.* **349-350**, 162 (2013).
- [73] X. L. Yan *et al.*, *Astrophys. J. Lett.* **766**, L8 (2013).
- [74] X. L. Tu *et al.*, *J. Phys. G* **41**, 025104 (2014).
- [75] P. Shuai *et al.*, *Phys. Lett. B* **735**, 327 (2014).
- [76] X. Xu *et al.*, *Phys. Rev. Lett.* **117**, 182503 (2016).
- [77] P. Zhang *et al.*, *Phys. Lett. B* **767**, 20 (2017).
- [78] N. Kalantar-Nayestanaki *et al.*, *Int. J. Mod. Phys. E* **18**, 524 (2009).
- [79] B. Mei *et al.*, *Phys. Rev. C* **92**, 035803 (2015).
- [80] H. Moeini *et al.*, *Nucl. Instr. Meth. A* **634**, 77 (2011).
- [81] F. Nolden *et al.*, *Nucl. Instr. Meth. A* **532**, 329 (2004).
- [82] M. Steck *et al.*, *Nucl. Instr. Meth. A* **532**, 357 (2004).
- [83] M. Steck *et al.*, *Phys. Rev. Lett.* **77**, 3803 (1996).
- [84] J. P. Schiffer and P. Kienle, *Z. Phys. A* **321**, 181 (1985).
- [85] Yu. A. Litvinov *et al.*, *Nucl. Phys. A* **734**, 473 (2004).
- [86] H. Geissel *et al.*, *Nucl. Phys. A* **746**, 150c (2004).
- [87] H. Geissel *et al.*, *Eur. Phys. J. Special Topics* **150**, 109 (2007).
- [88] F. Nolden *et al.*, *Nucl. Instr. Meth. A* **659**, 69 (2011).
- [89] X. C. Chen *et al.*, *Nucl. Instr. Meth. A* **826**, 39 (2016).
- [90] M. A. Najafi *et al.*, *Nucl. Instr. Meth. A* **836**, 1 (2016).
- [91] B. Mei *et al.*, *Phys. Rev. C* **94**, 044615 (2016).
- [92] O. Klepper *et al.*, *Nucl. Instr. Meth. B* **70**, 427 (1992).
- [93] O. Klepper and C. Kozhuharov, *Nucl. Instr. Meth. B* **204**, 553 (2003).
- [94] H. Irnich *et al.*, *Phys. Rev. Lett.* **75**, 4182 (1995).
- [95] F. Attallah *et al.*, *Nucl. Phys. A* **701**, 561c (2002).
- [96] Yu. A. Litvinov *et al.*, *Phys. Lett. B* **573**, 80 (2003).
- [97] B. H. Sun *et al.*, *Eur. Phys. J. A* **31**, 393 (2007).
- [98] B. H. Sun *et al.*, *Phys. Lett. B* **688**, 294 (2010).
- [99] M. W. Reed *et al.*, *Phys. Rev. Lett.* **105**, 172501 (2010).
- [100] L. X. Chen *et al.*, *Phys. Lett. B* **691**, 234 (2010).
- [101] M. W. Reed *et al.*, *Phys. Rev. C* **86**, 054321 (2012).
- [102] L. X. Chen *et al.*, *Phys. Rev. Lett.* **110**, 122502 (2013).
- [103] A. Akber *et al.*, *Phys. Rev. C* **91**, 031301(R) (2015).

- [104] L. M. Folan and V. I. Tsifrinovich, *Phys. Rev. Lett.* **74**, 499 (1995).
- [105] Yu. A. Litvinov *et al.*, *Phys. Rev. Lett.* **99**, 262501 (2007).
- [106] Z. Patyk *et al.*, *Phys. Rev. C* **77**, 014306 (2008).
- [107] Yu. A. Litvinov, *Nucl. Phys. A* **805**, 260c (2008).
- [108] Yu. A. Litvinov *et al.*, *Phys. Lett. B* **664**, 162 (2008).
- [109] P. A. Vetter *et al.*, *Phys. Lett. B* **670**, 196 (2008).
- [110] A. N. Ivanov *et al.*, *Phys. Rev. C* **78**, 025503 (2008).
- [111] T. Faestermann *et al.*, *Phys. Lett. B* **672**, 227 (2009).
- [112] Yu. A. Litvinov, *Int. J. Mod. Phys. E* **18**, 323 (2009).
- [113] N. Winckler *et al.*, *Phys. Lett. B* **679**, 36 (2009).
- [114] C. Giunti, *Nucl. Phys. B (Proc. Suppl.)* **188**, 43 (2009).
- [115] A. Merle, *Phys. Rev. C* **80**, 054616 (2009).
- [116] N. Winckler *et al.*, *Nucl. Phys. A* **834**, 432c (2010).
- [117] F. Bosch and Yu. A. Litvinov, *Prog. Part. Nucl. Phys.* **64**, 435 (2010).
- [118] K. Siegien-Iwaniuk *et al.*, *Phys. Rev. C* **84**, 014301 (2011).
- [119] D. R. Atanasov *et al.*, *Eur. Phys. J. A* **48**, 22 (2012).
- [120] P. Kienle *et al.*, *Phys. Lett. B* **726**, 638 (2013).
- [121] A. Gal, *Symmetry* **8**, 49 (2016).
- [122] R. Daudel *et al.*, *J. Phys. Radium* **8**, 238 (1948).
- [123] J. N. Bahcall, *Phys. Rev.* **124**, 495 (1961).
- [124] W. Bambynek *et al.*, *Rev. Mod. Phys.* **49**, 77 (1977).
- [125] M. Jung *et al.*, *Phys. Rev. Lett.* **69**, 2164 (1992).
- [126] F. Bosch *et al.*, *Phys. Rev. Lett.* **77**, 5190 (1996).
- [127] F. Bosch *et al.*, *AIP Conf. Proc.* **477**, 344 (1999).
- [128] T. Ohtsubo *et al.*, *Phys. Rev. Lett.* **95**, 052501 (2005).
- [129] J. Kurcewicz *et al.*, *Acta Phys. Polonica B* **41**, 525 (2010).
- [130] W. F. Henning *et al.*, *AIP Conf. Proc.* **126**, 203 91985).
- [131] M. K. Pavićević, *Nucl. Instr. Meth. A* **271**, 287 (1988).
- [132] M. K. Pavićević *et al.*, *Nucl. Instr. Meth. A* **621**, 282 (2010).
- [133] M. K. Pavićević *et al.*, *J. Phys. Conf. Series* **888**, 012192 (2017).
- [134] J. B. Blake, T. Lee and D. N. Schramm, *Nature Phys. Sci.* **242**, 98 (1973).
- [135] J. B. Blake and D. N. Schramm, *Astroph. J.* **197**, 615 (1975).
- [136] G. Huss *et al.*, *Geoch. Cosmoch. Acta* **73**, 4922 (2009).
- [137] R. Baker *et al.*, *Earth and Planet. Sci. Lett.* **291**, 39 (2010).
- [138] C. Scheidenberger *et al.*, *Hyperf. Interact.* **173**, 61 (2006).
- [139] F. Bosch *et al.*, *EPJ Web Conf.* **123**, 04003 (2016).
- [140] C. Nociforo *et al.*, *Phys. Scripta T* **150**, 014028 (2012).
- [141] Ch. J. Cerjan *et al.*, *J. Phys. G* **45**, 033003 (2018).
- [142] I. Dillmann and Yu. A. Litvinov, *Prog. Part. Nucl. Phys.* **66**, 358 (2011).
- [143] M. Lestinsky *et al.*, *Eur. Phys. J. Special Topics* **225**, 797 (2016).
- [144] M. Grieser *et al.*, *Eur. Phys. J. Special Topics* **207**, 1 (2012).
- [145] P. M. Walker *et al.*, *Int. J. Mass Spectrom.* **349-350**, 247 (2013).
- [146] T. Stöhlker *et al.*, *Hyperf. Interact.* **227**, 45 (2014).
- [147] T. Stöhlker *et al.*, *Nucl. Instr. Meth. B* **365**, 680 (2015).
- [148] Yu. A. Litvinov *et al.*, *Nucl. Instr. Meth. B* **317**, 603 (2013).
- [149] P. J. Woods *et al.*, *Phys. Scripta T* **166**, 014002 (2015)