First approach to half-life measurements around N=126

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Abstract. The present piece of work reviews recent progress on β-decay half-life measurements around the neutron shell N=126. The production of heavy neutron-rich nuclei is discussed, including the present status of the experimental data available for this region of the chart of nuclides. The impact of the theoretical calculations used to model the properties of nuclei involved in the r-process nucleosynthesis is discussed.

1. Introduction
The half-life, a fundamental property of radioactive nuclei, plays a decisive role in several astrophysical processes, being the r-process nucleosynthesis [1] one remarkable example. In the r-process, the abundance pattern presents pronounced peaks around the mass numbers A~ 80, 130 and 195 that clearly reflect the influence of the nuclear structure at the magic neutron numbers N= 50, 82 and 126. As the half-lives of nuclei at magic neutron numbers are relatively long, they determine the dynamical time scale of the r-process and build-up the abundance peaks at the waiting points.

For the vast majority of nuclei on or close to the r-process path, no experimental information is available. This is remarkably critical for the region around the neutron shell N=126, associated to the waiting point A=195, which has remained over the years as a practically unexplored territory, since the nuclei involved are so neutron-rich that their production in the laboratory becomes a real challenge. These nuclei represent the last bottleneck for proceeding into the actinide region, and become an important normalisation point for the r-process models, for determining the end-point and time scale of the r-process, and the production of trans-bismuth elements.

While the synthesis in the laboratory of all such nuclei for half-life measurements will be out of reach, the study of the ones which are closer to stability, and therefore expected to be the major contributors to the overall timescale of the r-process, as the key r-nuclei $^{192}Dy$, $^{193}Ho$, $^{194}Eu$, $^{195}Tm$, $^{196}Yb$ and $^{197}Lu$, will probably be within reach in the future. In fact, a first approach for measuring half-lives around the neutron shell N=126 has been performed at GSI [2] based on the event-by-event particle identification and implantation-β-decay time correlation of a mixed beam produced by cold fragmentation [3]. This work represents a first step towards the study of the r-process waiting-point nuclei.

In the following sections, a review of the different experimental approaches for producing and studying nuclei around the neutron shell N=126 will be presented, including the most recent
experimental half-life data available. Also the comparison between the data and the different theoretical calculations used to model the nuclear properties of the r-nuclei will be discussed, including their implications on the r-process nucleosynthesis.

2. Production of heavy neutron-rich nuclei
In order to study experimentally this region of the chart of nuclides, the first challenge we have to face is the production of such nuclei in the laboratory. In general there exists two complementary methods to produce and separate heavy neutron-rich nuclei: the in-flight \[4\] technique and the isotope-separation on-line (ISOL) technique \[5\]. Both methods have extensively been used for $\beta$-decay studies of r-process-relevant nuclei at different regions of the chart of the nuclides.

The ISOL technique suffers from specific difficulties for heavy neutron-rich nuclei. Elements between Hf ($Z = 72$) and Pt ($Z = 78$) are difficult to extract from the production target due to their low volatility, and for neutron-rich isotopes of the adjacent heavier elements, the ISOL technique suffers from an overwhelming isobaric contamination of isobars with higher $Z$, which are produced with much higher cross sections. Background suppression can be achieved by combining resonant-laser ionisation and the specific condition that the isotope of interest is longer lived than the unwanted species. But these conditions are not generally applicable.

The in-flight separation is universal, offering the advantage of fast ($< 1\mu s$), highly efficient, chemistry-independent separation. This technique allows to select the desired region on the chart of nuclides and to perform experiments focusing either on one nucleus or on a cocktail beam, by the adequate tuning of the magnetic fields of the separator. The nuclei to be studied are then implanted in a detection setup, and the contaminants due to the small fraction of inevitable secondary reactions, produced during the stopping process, are eliminated by a further range selection at the implantation stage. As a consequence, the clean particle identification for each implanted nucleus permits the direct correlation of an individual fragment with its subsequent $\beta$ decay on an event-by-event basis.

3. Experimental approaches to measure $\beta$-decay half-lives
The experimental approach of choice for measuring half-lives will depend on the lifetimes themselves and on the production of the nuclei investigated. These approaches can be subdivided mainly into two groups: Activation method and delayed-coincidence method.

- Activation method
  In the first case, it is feasible to produce a large number of nuclei, in a given time period, which is short compared to their half-life. The experiment thus consists of an activation phase and a recording phase. These phases might be repeated several times.
  There exists some variants of the activation-type experiment. First, the decays are registered; secondly, the number of nuclei still present in the probe is determined as a function of time. In both cases, the spectrum follows an exponential function.
  For very long half-lives, the decay rate is approximately constant during the experiment, and the value of the half-life can be obtained directly from the ratio of the number of detected decays per time unit over the total number of nuclei in the sample.
  In all these cases, the background may consist of nuclei with other half-lives (contaminations, daughter nuclei) or a constant rate of parasitic events.

- Delayed-coincidence method
  In this second case, the experiment is characterised by short half-lives and/or low production rates. If the rate of produced nuclei is lower than the inverse of its half-life, it is convenient to record the time of production and look for the time of the consecutive decay. These time differences are sorted into a spectrum.
  The data can be recorded as follows:
All decay-like events, after any produced nucleus,
all decay-like events, after the last produced nucleus,
only the first decay-like event, after the last produced nucleus.

Several methods have been developed to extract half-lives of radioactive species from experimental data and to determine their statistical uncertainties. A review on these methods is given in Ref. [2]. In general, if the average production rate is constant, there is no time structure in the production rate, and the standard analytical methods can be used to extract the half-lives. However, if the source intensity is not constant, that is, if it is modulated with a periodic function, the recorded time-correlation spectra do not directly reflect the decay properties of the nuclei involved but also show signatures of the time structure of the beam. In this case, the standard analytical methods cannot be used and a new numerical method has been developed in Ref. [2] to deal with the determination of the half-lives from such spectra with a complex time-dependent structure.

The statistical analysis to deduce the decay constant $\lambda$ can be a complex task since the radioactive decays can only be observed in a limited time range, and in addition, events of other species which decay with different decay constants or background events may be mixed in. Also if daughter nuclei produced in the primary decay are also radioactive, an even more complex situation appears.

4. Status of half-lives around the neutron-shell N=126
Along the N=126 neutron shell, south of lead, only five isotones have been identified, and the half-life of only three of them has been already measured. Figure 1 shows the present status of the chart of nuclides in this region, and Table 1 shows a summary of the experimental half-life information available for these nuclei. Colour boxes in the figure indicate the known half-lives [6], while empty boxes mark nuclei identified with no experimental half-life information available.

| Isotope | $T_{1/2}$       | Reference |
|---------|----------------|-----------|
| $^{207}Tl$ | 4.77(2) min | [7]       |
| $^{206}Hg$ | 8.32(7) min | [8]       |
| $^{205}Au$ | 31(2) s     | [9]       |
| $^{204}Pt$ | —            | [10]      |
| $^{203}Ir$ | —            | [10]      |

The half-life given for $^{207}Tl$ is the weighted average of 4.76(2) min [11], 4.77(5) min [12], 4.79(2) min [13] and 4.77(3) min [14]. For $^{206}Hg$, the value listed in Table 1, is the weighted average of 8.5(1) min [15], 8.1(4) min [16] and 8.15 (10) min [17]. The half-life of $^{205}Au$, 31(2) s, is taken from [18]. This last one is the most recent experimental half-life information at the neutron shell N=126, and dates from 1994. As can be seen, few progress has been obtained over the last years in studying the properties of nuclei in this region. The reason for this situation is that the production in the laboratory of heavy neutron-rich nuclei is a real challenge. However, a recent experiment performed at GSI [10] in 2003 allowed for the production and identification of $^{204}Pt$ and $^{203}Ir$ by means of cold fragmentation of a $^{208}Pb$ beam at 1 GeV/A, opening a way...
Figure 1. Chart of the nuclides around N = 126. The colour indicates the known half-lives [6], while empty boxes mark nuclei identified with no experimental half-life information available.

towards the study of heavy nuclei around the shell N=126 (see Figure 2). This work allowed the production and identification of more than 190 heavy neutron-rich nuclei, 25 of which were synthesised for the first time. Figure 3 shows the region of the chart of nuclides covered in this experiment. The solid line represents the limits of the chart of nuclides before that work, and the dashed line, the limits of the known half-lives. Also in this work the half-life of 7 nuclei was measured for the first time. The values are listed in Table 2.

Table 2. β-decay half-lives measured in [19] compared with different model calculations. See text for details.

| Nuclide | $T_{1/2}$ | DF3+QRPA | FRDM+QRPA |
|---------|----------|----------|-----------|
|         | (s) [19] | (s) [20] | (s) [21]  |
| $^{202}$Ir | 11 ± 3   | 9.8      | 68.4      |
| $^{199}$Ir | 6$^{+5}_{-4}$ | 46.7    | 370.6     |
| $^{198}$Ir | 8 ± 2    | 19.1     | 377.1     |
| $^{200}$Os | 6$^{+4}_{-4}$ | 6.9     | 187.1     |
| $^{199}$Os | 5$^{+4}_{-2}$ | 6.6     | 106.8     |
| $^{196}$Re | 3$^{+1}_{-2}$ | 1.4     | 3.6       |
| $^{195}$Re | 6 ± 1    | 8.5      | 3.3       |
| $^{194}$Re | 1 ± 0.5  | 2.1      | 70.8      |
2.56 2.58 2.6 2.62 2.64

Atomic number (Z)

Figure 2. Two-dimensional cluster plot of Z vs. A/Z, including the identification of $^{204}\text{Pt}$ [19]

Figure 3. Fragments residues in the reaction $^{208}\text{Pb}$ (1 A GeV) + Be. [19]. The solid line represents the limits of the chart of nuclides before this work. The dashed line shows the limit of the known half-lives.

5. Nuclear properties of the nuclei at N=126 and their implication in the r-process
As pointed out before, there is no experimental data for r-nuclei at N = 126 on the r-process path ($Z \approx 65 - 72$). As a consequence, r-process simulations still rely on theoretical models for the $\beta$-decay half-lives. When comparing the experimental data available close to N=126 with the model calculations available in this region, it can be seen, as shown in Table 2, that the DF3+QRPA model agrees, in general, rather well with the experimental half-lives. On the other
hand, the FRDM+QRPA half-lives are for most nuclei more than one order of magnitude longer than the data.

The DF3+QRPA model is the only one that includes Gamow-Teller (GT) and first-forbidden (FF) transitions on the same footing. Therefore, the good agreement of the experimental half-lives with this model gives strong evidence for important contributions of FF transitions to the total half-lives, arising from $\nu 3p_{1/2} \rightarrow \pi 3d_{3/2}$ and $\nu 1i_{13/2} \rightarrow \pi 2h_{11/2}$ neutron-proton transitions, and hence it seems that pure GT estimates of the half-lives of the $N = 126$ waiting points are insufficient. Since the differences between these two models qualitatively persist up to the $N = 126$ waiting-point nuclei around $Z = 65$ as shown in Ref. [22], the r-process matter flow to the heavier fissioning nuclei [23] may be faster than currently expected.

6. Summary and outlook

In summary, half-lives of nuclei approaching the r-process waiting point at $N = 126$ have been measured for the first time after many years of no progress in this region of the chart of nuclides. This work may be considered as the starting point of a new era in exploring the properties of heavy neutron-rich nuclides. It relies on the production of the nuclides of interest by cold fragmentation and the application of a novel very efficient analysis method.

The prospects for extending this experimental approach to more neutron-rich isotopes of elements below lead and reaching r-nuclei such as $^{192}$Dy, $^{195}$Ho, $^{194}$Eu, $^{196}$Tm, $^{196}$Yb and $^{197}$Lu, are very promising, in particular when higher beam intensities become available in the new-generation facilities around the world as GSI-FAIR[24], NSCL/FRIB[25] at MSU and RIBF/RIKEN[26].

References

[1] E.M. Burbidge et al. 1957 Rev. Mod. Phys. 29, 547.
[2] T. Kurtukian-Nieto et al. 2008 Nuc. Instr. and Meth. A 589, 472.
[3] J. Benlliure, et al. 1999 Nucl. Phys. A 660, 87.
[4] D. Morrissey, B. M. Sherrill, 2004 Lect. Notes Phys. 651, 113.
[5] P. Van Duppen, 2006 Lect. Notes Phys. 700, 37.
[6] National Nuclear Data Center. http://www.nndc.bnl.gov/chart.
[7] M. J. Martin 1993 Nuclear Data Sheets 70, 315.
[8] F.G. Kondev 2008 Nuclear Data Sheets 109, 1527.
[9] F.G. Kondev 2004 Nuclear Data Sheets 101, 521.
[10] T. Kurtukian-Nieto et al. 2006 Progress in the investigation of nuclei approaching the r-process waiting point $A = 195$. Proceedings of Science POS(NIC-IX)008.
[11] M. Curie et al. 1931 Rev. Modern Phys. 3, 427
[12] K. Fajans, A. F. Voigt 1940 Phys. Rev. 58, 177.
[13] B. W. Sargent, L. Yaffe, A. P. Gray. 1953 J. Phys 31, 253.
[14] J. M. Trischuck, E. Kankeleit. 1967 Nucl. Phys. A 90, 33.
[15] P. Kauranen. 1962 Ann. Acad. Sci. Fennicae, Ser. A VI 96.
[16] G. K. Wolf. 1968, Nucl. Phys. A 116, 387.
[17] G. K. Wolf. 1968, Nucl. Phys. A 116, 387.
[18] Ch. Wennemann et al. 1994 Z. Phys. A 347, 185.
[19] T. Kurtukian-Nieto, Ph.D. Thesis, University of Santiago de Compostela, 2006. http : //www – wnt.gsi.de/charmns/DoktorArbeiten/Teresa – Kurtukian/PhDThesis7KN.pdf
[20] T. Kurtukian-Nieto et al. 2009 Nucl. Phys. A 827 587.
[21] P. Möller, B. Pfeiffer, and K.-L. Kratz, 2003 Phys. Rev. C 67, 055802.
[22] J. N. Borzov et al., 2008 Nucl. Phys. A 814, 159.
[23] G. Martínez-Pinedo et al., 2007 Prog. Part. Nucl. Phys. 59, 199.
[24] http://www.gsi.de/fair
[25] http://www.frib.msu.edu
[26] http://www.rarf.riken.go.jp/rbf