Ion implant-$\beta$-decay correlation half-lives in a pulsed beam for isotopes beyond N=126

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Abstract. Half-lives and $\beta$-delayed neutron emission probabilities of several isotopes of Au, Hg, Tl, Pb and Bi, in the neutron-rich region around and beyond N=126, were determined in an experiment performed at the RIB facility of GSI [1]. These are decay properties that are directly related to the final abundance distribution of the elements due to their contribution during the freeze-out of the $r$-process nucleosynthesis. This contribution summarizes the main aspects of the analysis methodology followed for the determination of $\beta$-decay half-lives. The main particularities of the present analysis concern the characterization of the $\beta$-background, as well as the effect of the pulsed-beam in the ion-$\beta$ time correlations.

1. Introduction

$\beta$-delayed neutron emission plays a fundamental role in astrophysics for the understanding of the rapid neutron capture process in explosive stellar environments. This effect is more important in the heavy mass region around N=126, where practically all nuclei along the $r$-process path are expected to be $\beta$-delayed neutron emitters. In order to provide new information in this mass region we carried out an experiment at GSI with an $^{238}$U beam at 1 GeV/u impinging onto a 1.6 mg/cm$^2$ Be target. The fragments of interest were selected and identified by means of the Fragment Separator (FRS) [2]. The Silicon Implantation Beta Absorber (SIMBA) [3, 4] was used to measure both ion implants and $\beta$-decays. Neutrons were detected by means of the BEta deLayed Neutron (BELEN) detector [5]. The methodology implemented for building the implant-$\beta$ correlation diagrams is described in section 2. An experimental validation of the analysis technique is reported in section 3. Finally, section 4 summarizes the main results and conclusions.

2. Analysis methodology for the determination of $\beta$-decay half-lives

In this work we have followed the analytical approach employed in several previous works at both isol- and fragmentation facilities [3, 6, 7] to analyze the implant-$\beta$ time-correlation diagram. However, in order to do so, we had to quantify and carry out a systematic study of several aspects involved in the experiment, such as the characterization of the $\beta$ background, the correlation area inside the silicon layers of SIMBA, between the implantation position of the ions and the position of the decays, and the effect of the beam characteristics used in the measurement.
2.1. Analytical model for implant-β correlations

Several approaches of the Bateman equations [8] were studied in order to determine the value of the half-life. Since all granddaughters of the analyzed species are stable, or very long lived isotopes, in all cases all β decays contributing to the activity decay curve were considered emitted by the parent and the direct daughter, an approximation which is given by equation 1:

\[
\sum_{i=1}^{N} \lambda_i N_i(t) = (\lambda_1 N_1(t) + \lambda_2 N_2(t))
\]

where \(N_i(t)\) is the number of nuclei for each isotope \(i\) at certain time \(t\), \(\lambda_1 = \ln(2)/T_{1/2}\) is the decay constant for the implanted nucleus with an unknown half-life \(T_{1/2}\) and \(\lambda_2\) is the decay constant for the daughter nucleus. Following the time-dependency of the correlation distributions presented in [9], there are two strategies to study the implant-β time-correlations in a certain region around the implants. One is using the first β-decay after the implant, which has a strong dependency with the β efficiency, \(\varepsilon_\beta\). This case, \(\varepsilon_\beta\) is not constant along the energy range, it changes according to the Q-value of each isotope, the result is biased when the β-background rate is high and also by the time-dependent β-background characteristic of the pulsed beam-structure of the SIS synchrotron used in this experiment at GSI. On the other hand, the correlation of each implant with all-β events, over a sufficiently broad time-window \((\gg T_{1/2})\), gives a better solution for the present experiment. In this case the dependency on \(\varepsilon_\beta\) is affecting by the same amount all terms of the expression which describes the time-correlation probability function, \(\rho(\lambda, t)\), and it can be left as a free parameter in the analysis [9]. In this case, the accumulated distribution is described by equation (2),

\[
N^\text{All}_\beta(t) = N_1(0)\rho(\lambda, t)\Delta t = (\varepsilon_\beta \lambda_1 N_1(t) + \varepsilon_\beta \lambda_2 N_2(t) + \varepsilon_\beta b) \cdot \Delta t
\]

\[
= \varepsilon_\beta \cdot (\lambda_1 N_1(t) + \lambda_2 N_2(t) + b) \cdot \Delta t
\]

where \(N^\text{All}_\beta(t)\) is the total number of detected decays at a time \(t\), \(N_i\) the number of nuclei of each isotope in the chain, \(b\) is the β-background corrected by \(\varepsilon_\beta\) and \(\Delta t\) corresponds to the bin time-width used in the implant-β time-correlations. The factor \(N_1(0) \cdot \varepsilon_\beta\) is determined by the content of the first bin in the time correlation curve. For each distribution, this latter factor is included within the Maximum-Likelihood (ML) analysis and thus, the time dependent factor of the adjusted expression, \(\lambda_1 N_1(t) + \lambda_2 N_2(t) + b\) does not depend on the β-efficiency.

3. \(^{213}\text{Tl}\) analysis as method benchmark

To analyze the elements present in the analysis affecting the sensitivity and the accuracy of the half-life result, a systematic study based on the decay of \(^{213}\text{Tl}\) was carried out. This particular isotope was chosen because its implant statistics were large (1015 implants) and there exist previous half-life measurements in the literature obtained independently using other methods [10, 11].

3.1. Background characterization

The main contribution to the β-background was related to the pulsed beam-structure. It induced a different background level during beam extraction from the SIS-synchrotron (spill width of 1 s) and after it (the spill-off time interval, which was of 3 s). The background was characterized with time-reversal (or time backward) implant-β correlations using only the pixels within the assigned correlation area. This can be observed in figure 1 for both methods, all-beta (left) and all-β-off-spill (right) events, over a time window of ±360 s for each implant event. The negative time-interval of these diagrams represents the backward (uncorrelated) background contribution. The
average background is of $b = 2$ counts/s for the all-$\beta$ events and the $b = 1.4$ counts/s in the off-spill correlation mode. The higher background rate in the first case indicates the aforementioned effect of enhanced $\beta$-like background during the beam-spill interval. The background level thus determined allows one to adjust the parameter $b$ in the equation 2, which has a flat dependency in time. Once determined, the background parameter $b$ was kept fixed in the ML analysis over the whole time-window, and the unknown parameter $\lambda_1$ was derived.

3.2. Effect of the beam structure with all-$\beta$ and all-$\beta$-off-spill correlations

Due to the limited statistics for most of the implanted isotopes the binned Maximum-Likelihood (ML) algorithm [12] was used. It was implemented by including the expression presented in equation 2 in a ROOT/C++ code. Figure 1 shows the result of the analysis after the convergence of the ML algorithm for both distributions with all-$\beta$ and all-$\beta$-off-spill methods. It is worth to discuss the large amount of counts in the first bin of the all-$\beta$ correlation distribution (figure 1-left). This is an effect related to the in-beam mode when the bin time-width is larger or equal to the spill time width. It can be avoided by excluding the first bin from the fit-range, as shown in the analysis presented in figure 1-left. Indeed, the half-life value obtained using both correlation approaches are in perfect agreement within the quoted statistical uncertainty. The goodness of the analytical model in both cases is indicated by the reasonable reduced $\chi^2$-value ($\chi^2$/NDF) obtained, which is of 2.21 and 1.40, respectively.

3.3. Implant-$\beta$ correlation area

The position of each implanted nucleus is typically determined with an accuracy of $\pm 1$ mm$^2$, i.e. one pixel in a silicon layer of SIMBA. Selecting $\beta$-events detected in SIMBA in a correlation region around the implant position, it was possible to build time correlations like those shown in figure 1. Contributions from decays of other nuclei implanted before or right after the isotope of interest, in the same correlation region can be neglected thanks to the low implantation rate of 0.114 ions/s. Depending on the average range of $\beta$-particles in SIMBA and the rate of $\beta$-like background events, an optimal correlation area can be determined, which maximizes the peak-to-background $P/B$ ratio. In order to determine it, $^{213}$Tl implant-$\beta$ correlations were performed for several symmetric correlation areas of 9 mm$^2$, 25 mm$^2$ and 49 mm$^2$ around the implant location and for both types of correlation, all-$\beta$-events and spill-off $\beta$-events (case of 9 mm$^2$ shown in figure 1-left and right, respectively). These correlation areas correspond to the one-,
two- and three-closest pixels around the implant location. Table 1 summarizes the evaluation of each correlation area according to the $P/B$ ratio together with the reduced $\chi^2$-value ($\chi^2$/NDF) obtained for each case. In summary, it can be concluded that a correlation area of 9 mm$^2$ (3×3 pixels, 1 pixel around the implant) seems the most convenient in terms of sensitivity to the decay curve. In this case the $P/B$-ratio becomes a factor about 20% larger than areas of 25 mm$^2$ and 49 mm$^2$. The case of 1 mm$^2$ was also evaluated but the limited statistics of many isotopes makes this, in general, a worse option.

### 4. Results and conclusions

To summarize the systematic method for the analysis of the isotopes in this experiment, the half-lives were obtained following these characteristics:

- A constant background value $b$ determined using the backward $\beta$-events, with the same time-range and area-correlation as for the forward $\beta$-events.
- Implant-$\beta$ correlation area of 9 mm$^2$, i.e. one pixel around the implantation pixel.
- Off-spill correlations are better suited for the half-life determination than all $\beta$-events approach, mainly due to the lower $\beta$-like background rate and generally better $\chi^2$-values.

Finally, it is worth emphasizing the consistency of the result obtained for the half-life of $^{213}\text{Tl}$ for all possible analysis conditions within the quoted statistical uncertainties [1].

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