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Progress in the investigation of nuclei approaching the r-process waiting point A = 195

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Heavy neutron-rich nuclei approaching the r-process waiting point A=195 were produced by cold-fragmentation reactions induced by ^{208}Pb projectiles at 1 A GeV on a beryllium target at the Fragment Separator at GSI. Moreover, a new technique has been developed to measure β-decay half-lives in complex background conditions. Around 30 heavy neutron-rich nuclei have been synthesized for the first time and the half-lives of some of them have been determined.

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1. Introduction

The astrophysical r-process is responsible for the synthesis of approximately half of the heavy nuclei in the Universe. The abundance distribution of this process clearly shows a dominant feature: large peaks at the nuclear mass numbers A = 80,130,195. The location of these peaks is related to neutron shell closures, which clearly reflects the influence of the nuclear properties in the stellar nucleosynthesis.

One of the main problems we have to overcome to fully understand the observed r-process abundances is the lack of information on the nuclei participating in this process, in particular for the heaviest ones. The main reason for this is that heavy neutron-rich nuclei involved in the r-process were until now far from any experimental access.

During the last years promising results have been obtained investigating the properties of medium-mass neutron-rich nuclei close to the waiting points A=80[1] and 130 [2] while the waiting point around A=195 remained as an almost unexplored territory. However, the possibility to accelerate heavy ions at relativistic energies made it possible to investigate during the last years reaction mechanisms leading to the production of heavy neutron-rich nuclei such as cold-fragmentation reactions [3].

The interpretation of the observed r-process abundances requires detail knowledge on the structure and gross properties of the involved nuclei. In particular masses, β half-lives and neutron-capture cross sections are relevant. In this work we concentrate on the measurement of β half lives of heavy neutron-rich nuclei. β-decay half-lives are of importance not only because they play an important role in the understanding of the progress and time scale of the stellar nucleosynthesis processes and consequently in the final abundance patterns, but also because they can be used to benchmark nuclear models far from stability.

In the next sections we will present new experimental data corresponding to heavy neutron-rich nuclei approaching the waiting point A=195 from an experiment performed at the FRS at GSI to explore the production and β half-lives of heavy neutron-rich nuclei close to the neutron closed shell N=126.

2. Experimental setup and data analysis

The experimental technique used for the production of heavy neutron-rich nuclei is the in-flight fragmentation of relativistic heavy projectiles. The data presented in this paper correspond to an experiment performed at SIS/FRS [4] facility of the Gesellschaft für Schwerionenforschung (GSI). The beam used was ^{208}Pb at 1 A GeV impinging on a beryllium target. The beam intensity was 10^7 ions/s, the spill length was 2 s and a repetition cycle 10 s. In these collisions, the fragmentation process can populate the so called cold-fragmentation reaction channel[3], where only protons are removed from the projectile and the excitation energy of the resulting projectile pre-fragment is so low that no neutron evaporation follows fragmentation. When using a ^{208}Pb beam, this reaction mechanism allows to produce heavy neutron-rich nuclei along the closed shell N=126.

To study the decay properties of a subset of projectile residues, these nuclei must be identified and isolated from the other reaction products. In this experiment the isotopic identification was achieved by determining both the atomic number Z and the mass-over-charge ratio A/Z of each fragment passing through the FRS by measuring their magnetic rigidities, time-of-flight (ToF) and energy loss. In order to separate different elements with enough resolution and to disentangle the different ionic charge states, we used *the degrader energy-loss method [3]*, which takes into account the difference in magnetic rigidity between the two sections of the FRS. A detailed description of the production and identification method can be found in Ref [3]. Figure 1 presents all nuclei produced during the experiment with a production cross-section larger than 1 nb. The solid line in the figure represents the present limit of known nuclei and the dashed line, the limit of known half-lives. In the present work we were able to synthesize around 35 heavy neutron-rich nuclei with unknown half-lives, being 25 of them produced for the first time.

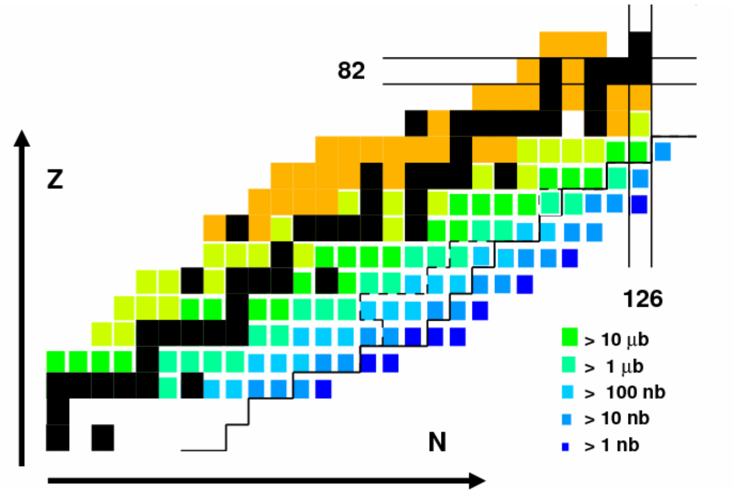

Figure 1: Cluster plot of the chart of nuclides representing all nuclei produced in the present experiment. The colour scale indicates the production cross section.

In order to measure the half-lives, the nuclei of interest were implanted into an active catcher. Half-lives were deduced from position-time correlations between the implanted fragments and the subsequent β-decays. The left panel of figure 2 shows a schematic view of the experimental setup used for measuring β half-lives. The FRS was operated in monoenergetic mode [4]. An aluminium degrader at the exit of the FRS was used to slow down the nuclei in order to guarantee their implantation into a stack of the four Micron Semiconductor Ltd double-sided silicon strip detector (DSSD) with a surface of 5x5 cm^2, 1 mm thickness and 16 x 16 strips of 3.3 mm pitch. This array of DSSD was used as fragment catcher and as monitor of the β-decay activity. The DSSD array was placed between two scintillation detectors acting as veto for the implantation. Moreover, an ionization chamber was used to eliminate secondary reactions induced in the degrader. In figure 2 (right) we report on a two-dimensional cluster plot the atomic number as a function of the mass-over-charge ratio of the nuclei measured in one magnetic setting of the FRS optimized to transmit ^{198}Ir (a) and the corresponding implanted nuclei in the DSSD array (b).

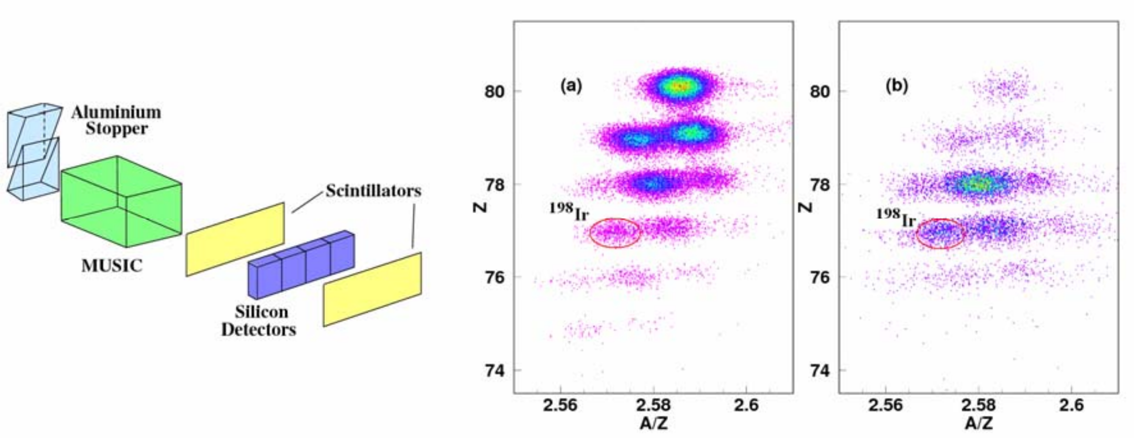

Figure 2: (Left panel) Schematic view of the experimental setup used for β half-life determination. (Right panel) Identification matrix of produced (a) and implanted nuclei (b) in one magnetic setting of the FRS centred on ^{198}Ir.

The half-life of the nuclei was deduced from time-position correlations between the implanted fragments in the DSSD and the subsequent β-decays. Due to the pulsed structure of the beam, the event rates of implantation and decay were modulated with a periodic time structure. In addition, we had to face a beam-induced background contamination in the recorded decay curves, coming from the time structure of the previously implanted nuclei and δ or atomic electrons coming during the beam spill.

The key of the time correlation analysis is to disentangle the background from the real events. In order to evaluate the background, we established the shape of the uncorrelated events by evaluating the time difference of a given implantation to a previous β, that is, making the fragment-β correlations in a time reversed sequence.

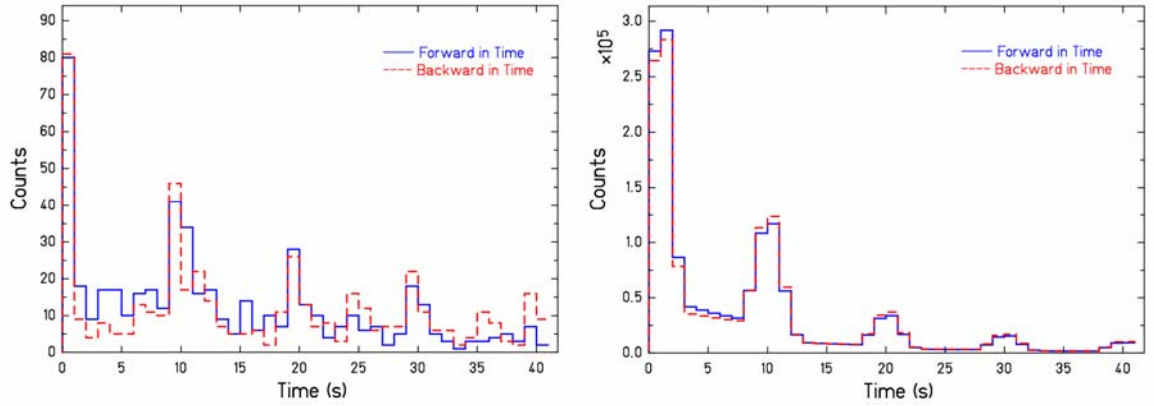

Figure 3: Measured implantation-β forward and backward time distributions for ^{195}Re (left) and an example of the same distributions simulated with a Monte-Carlo code assuming τ = 8 s and 50 % β detection efficiency (right).

Forward time spectra contain the information of the 'true' fragment-β correlations (See left panel of figure 3). For the interpretation of these complex time-correlation spectra, we developed a Monte Carlo code simulating the time sequence of nuclei implantation and electron detection. In this code the time sequence of fragment implantation and electron detection are simulated according to the experimental conditions (spill sequence, fragment implantation rate during the spill and electron detection rate during spill and pause). Moreover, β decays with a given lifetime (τ) were randomly generated. All simulated electrons were then filtered by the β-detection efficiency of our DSSD array (ε). In these simulations only the β lifetimes and the β-detection efficiencies are free parameters. All other parameters were obtained from the measured data. The simulated fragment-electron events were then forward and backward time correlated using the same procedure as for the analysis of the measured data. The right panel in figure 3 shows an example of simulated fragment-electron time correlations in both, forward (solid line) and backward (dashed line) time sequence for ^{195}Re.

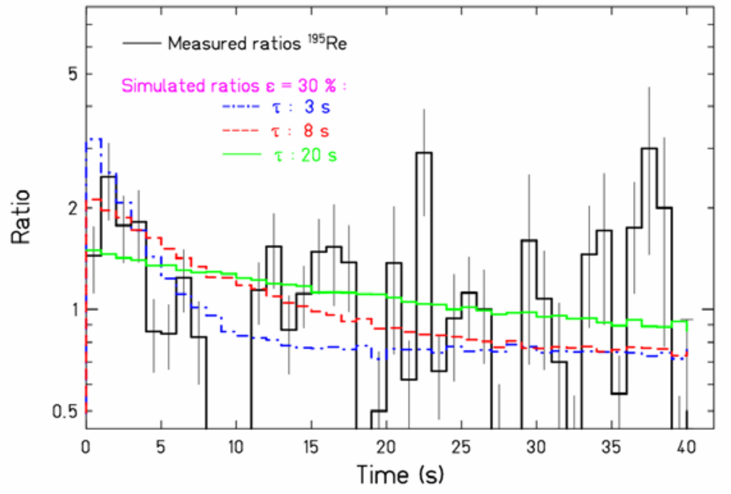

Figure 4: Measured ratio of forward and backward fragment-β time correlations of ^{195}Re compared with tree different Monte-Carlo simulations with a fixed detection efficiency of 30% and different values of lifetime.

Figure 4 shows the ratio between the forward and backward time correlation of measured events for ^{195}Re (a heavy neutron-rich nucleus synthesized for the first time in this experiment), compared with the same ratios obtained in different simulations using a fixed value of the β-detection efficiency (ε = 30 %) and 3 different lifetimes τ = 3, 8, and 20 s. In this plot we appreciate that a τ = 3 s fits quite well to the experimental data, using a 10 s time window, but if we extend the time window up to 40 s, then it is clear that a longer lifetime, as for instance, τ = 8 s fits better the experimental data. This let us to the conclusion that we have to use a time window that includes several beam pulses in order to determine the half-life.

Taking into account Figure 4, half lives were obtained from two-dimensional fits of the measured and simulated ratios of time correlations in forward and backward time direction by applying the least-squares method being the lifetime (τ) and the β-detection efficiency (ε) the two-fitting parameters. In Figure 5 we show as example the two-dimensional (lifetime-efficiency) χ^2 distribution obtained for ^{195}Re using this procedure. The minimum of this two-dimensional distribution was obtained from parabolic fits in both dimensions. The interval defined by the minimum χ^2 plus one unit defined our error bars [5] as shown in the right panel of Figure 5.

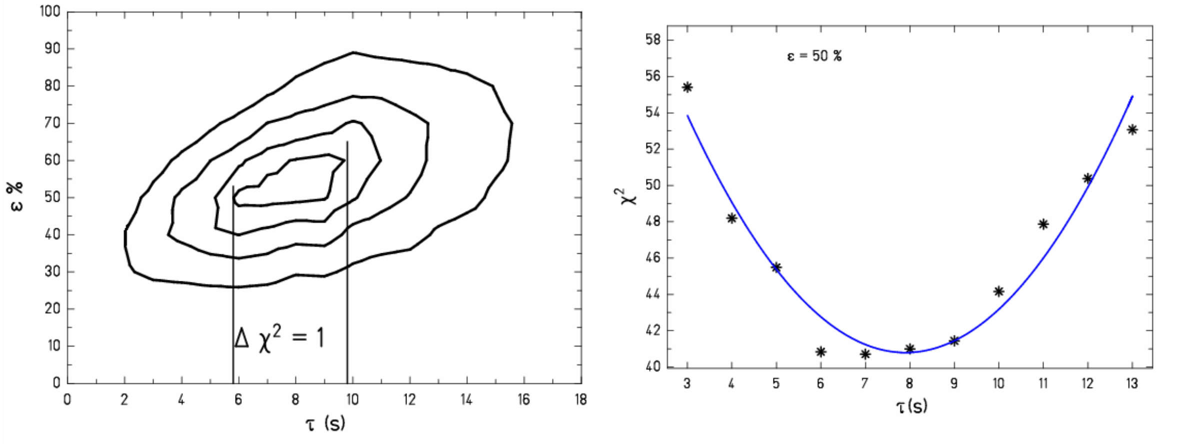

Figure 5: (Left panel) χ^2 two-dimensional distribution (lifetime-efficiency) obtained with our fitting procedure for ^{195}Re. (Right panel) χ^2 projection into the lifetime coordinate for a 50% detection efficiency

3. Results

In order to validate the proposed method of analysis we studied the ^{198}Ir nucleus which has a previously measured half-life of 8 ± 3 s [6]. The minimum χ^2 of the fit for the ratio of the forward and backward time correlations between the experimental and simulated data corresponds to a $T_{½} = 8 \pm 2$ s which is in a good agreement with the previous measurement.

We perform the same kind of analysis for different nuclei produced and implanted during the experiment. Table 1 show a summary of the experimental measurements and a comparison with the Gross-Theory calculations [7], the hybrid-model with Gamow-Teller decays in RPA and fist-forbidden decays in the Gross-Theory [8], and the self-consistent QRPA approach [9,10].

Table 1 Measured $T_{½}$ compared with theoretical calculations

Nuclei	Exp. $T_{1/2}$ (s)	Gr.Th. [7]$T_{1/2}$ (s)	RPA(GT)+f(Gr.Th.)[8]	DF3+ CQRPA[10]
^{194}Re	1.0 ± 0.5	16.1	70.8	2.6
^{195}Re	6 ± 2	10.3	3.3	11.6
^{196}Re	3 ± 2	5.1	3.6	1.9
^{198}Ir	8 ± 2		377.1	19.1
^{202}Ir	11 ± 3	8.5	68.4	9.8

We found that CQRPA [9][10] seems to works better in reproducing the experimental data close to the shell and that first-forbidden transitions seems to be a key issue to describe β-decay close to N=126. The differences observed between the experimental half-lives and the model calculations for nuclei far from the closed-shell, could be attributed to deformation effects. Indeed, nuclear deformation is an important input parameter for the QRPA calculations of Gamow-Teller (GT) strength function, and a 'wrong' GT-decay pattern finally results in a 'wrong' half-life.

4. Conclusions

The results shown in this work represent a first step achieved towards the study of heavy neutron-rich nuclei approaching the r-process waiting point at A=195. A new technique has been developed to measure the β-decay half-lives of exotic nuclei in complex background conditions using position and time correlations between the implantation of the fragment and the subsequent β-decay. The β-decay half-lives predicted within the DF+CQRPA framework are in a better agreement with experimental data than the RPA (GT)+ff(Gr.Th.) and Gross Theory results. Systematic DF+CQRPA calculations in this region will be used for planning new experiments. Further experimental progress will be obtained including β–γ coincidences. Cold-fragmentation is a promising reaction mechanism to extent the limits of the chart of nuclides in the region of heavy neutron-rich nuclei, provided that enough primary beam intensities are available. In a few years the new FAIR [11] facility will offer a tremendous potential to further investigate the r-process path around the waiting point A = 195.

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