New half-lives in the polonium isotopic chain

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Abstract. The astrophysical rapid-neutron capture process (r-process) of explosive nucleosynthesis is responsible for the formation of half of the heavy nuclei above Fe. Actinides are produced towards the end of this process, when the neutron flux is expected to be minimal. Given that, in this heavy region of the chart of nuclides, the r-process path runs far away from the accessible species, experimental inputs on β decay for nuclei beyond N=126 are particularly useful to test predictions of global nuclear models. In this paper, results from a recent experiment performed by the HISPEC-DESPEC collaboration are discussed. The experiment populated 220<A<230 Po-Fr nuclei in a relativistic fragmentation reaction induced by a 1 GeV/u ^{238}U beam. The species were selected and identified using the FRagment Separator (FRS) and implanted in the DEcay SPECtroscopy (DESPEC) station to study their subsequent β decay. The β-decay half-lives in the polonium isotopic chain are discussed with the help of recent theoretical models, to assess the impact of the measured values on the predictions of the r-process.

1 Introduction

The astrophysical rapid-neutron capture process (r-process) of explosive nucleosynthesis is responsible for the formation of half of the heavy nuclei above Fe [1]. Several astrophysical sites have been identified as possible hosts for this process, involving high temperatures and strong fluxes of neutrons [2]. Despite the high interest, both theoretical and experimental, there is still no consensus on the dominant site for r-process nucleosynthesis and, in addition, the large deviations among different theoretical predictions, related to the properties of neutron-rich nuclei involved, introduce a significant source of uncertainty in r-process nucleosynthesis simulations.

Experimental nuclear structure ingredients, such as masses, decay rates and neutron-capture cross sections, are at the basis of r-process abundance predictions. However little is known for the heavy elements beyond ^{208}Pb, where the actual experimental reach is limited to few isotopes beyond the stability line.

Lying beyond the N=126 and Z=82 shell closures, the decay of heavy nuclei is expected to show a sizable contribution coming from non-allowed decays, in particular first-forbidden

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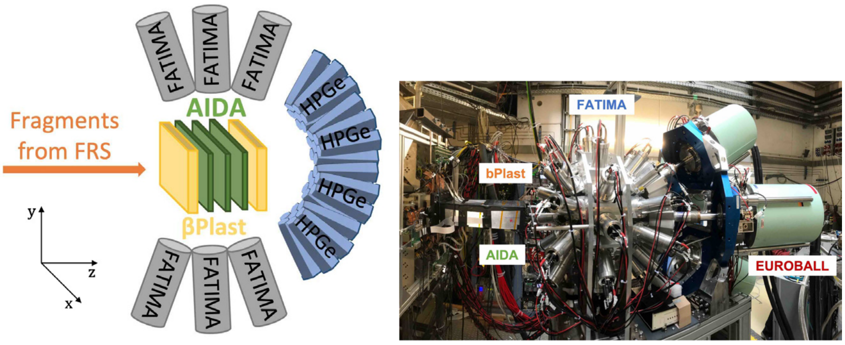

Figure 1. 2-D rendering (left panel) and real picture (right panel) of the DESPEC decay station used in the experiment S460 at GSI.

transitions. The setting in of such decays is expected to shorten the half-lives, giving rise to a faster flux towards heavier systems, for which the fission channel is open. This would then result in an increased abundance of lanthanides, accompanied by a decreased abundance of actinides [3].

Moreover, the region of the nuclear chart north-east of ^{208}Pb contains a series of short-lived isotopes with very fast α decays, showing half-lives in the ns-to-ms range. The polonium (Z = 84) isotopes are the lightest nuclei following this pattern. Going towards the most neutron-rich members of the chains, β decay takes over becoming the dominant, and then the only, decay mode. In the polonium isotopes, the changeover occurs around ^{218}Po, even if a possible, very weak, α-decay branch is expected up to ^{220}Po.

The half-lives of the nuclei in this boundary region have been studied in some recent works, however with large error bars.

All these aspects were at the basis of a recent experiment performed at GSI-FAIR (Darmstadt, Germany) within the HISPEC-DESPEC experimental campaign, as part of the FAIR Phase-0 program. The experiment has been designed to study the heavy isotopic chains of Po, At, Rn and Fr in particular, with a focus on the determination of decay properties and on the internal structure of the daughter nuclei. First results from this experimental run are here discussed.

2 The experiment

The experiment S460 employed a relativistic fragmentation reaction, induced by a ^{238}U beam on a 1.6 g/cm^2 thick Be target, to populate nuclei in the Po-Fr isotopic chains, with masses in the range $220<A<230$.

The primary beam, with an average intensity of $\sim10^9$ pps (particle per second), was accelerated to 1 GeV/u on a cycle of 4 s by the FAIR-GSI accelerators complex. The beam was delivered over a cycle of 4 s with a 2 s extraction time. The species were selected and identified using the FRagment Separator (FRS), used in achromatic mode, thanks to an Al degrader of 2.47 g/cm^2 thickness and a 3.36 mrad tilt, placed in the intermediate focal plane. After passing through two MUSIC Ionisation chambers, the cocktail beam was slowed down in a passive Al degrader, in order to be stopped in the active volume of our implantation stack.

The final focal plane of the FRS was equipped with the DEcay SPECtroscopy (DESPEC) station [4] to study the incoming nuclei and their subsequent β decay. The DESPEC station is composed of a stack of two layers of Double Sided Silicon-Strip Detectors (DSSD),

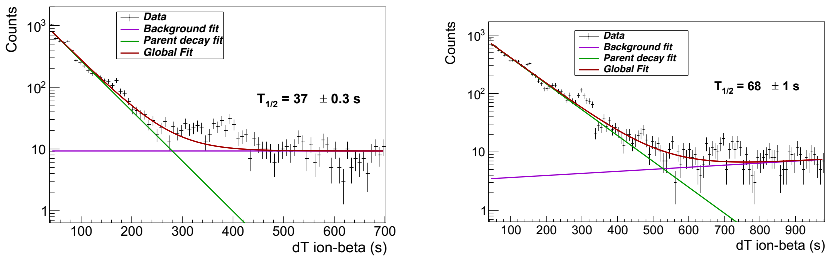

Figure 2. Decay curves for ^{221}Po (left panel) and ^{222}Po (right panel) extracted in the current experiment, together with the fitting functions (see legend).

named AIDA (Advanced Implantation Detector Array) [5], sandwiched between two plastic scintillator detectors. The active stopper is surrounded by a hybrid γ-detection array consisting of high-resolution HPGe and fast timing LaBr$_3$(Ce) detectors, having a full-energy peak efficiency at $\sim$ 1 MeV of 2% and of 2.9% [6], respectively.

Once the components of the cocktail beam have been identified in terms of charge (Z) and mass-over-charge ratio (A/Q), correlations between the implantation of the ions to their subsequent decays could be performed, on an event-by-event basis.

The AIDA stack of detectors, in fact, is able to distinguish between very energetic signals, coming from the implantation of a heavy ion, and the low-energy ones arising from the detection of an α or β particle. Thanks to its high segmentation, 128×128 strips on an area of 8×8 cm^2, AIDA can precisely define the position in X, Y and Z (beam direction) of each implant. Decays occurring in the same (X,Y, Z) position can then be correlated to each implant. The two types of events provide separate signals which are flagged as "implants" or "decay", in case they trigger the low or high gain branches.

Since the impact of the arrival of an energetic ion flashes a high number of strips, recorded as high-gain signals, only decay events occurring out of spill have been taken into consideration in our analysis. Several conditions have been applied to the data to disregard fission events, as well as contributions arising from secondary reactions in the materials surrounding the active area, and signals produced by light particles punching through the system. This is done on an event-by-event basis by setting software conditions on the reconstructed mass, zed and A/Q spectra.

Once clean conditions have been identified, we could reconstruct decay patterns for the decay of the ions contained in our cocktail beam, by matching an implant to its subsequent decays in a pre-defined time window covering several half-lives.

3 Results

In this proceedings, we report results concerning the decay of some of the polonium isotopes populated in the experiment. Data on the decay of other nuclei are being collected for future publications.

Half-lives for the decays ^{221}Po $\rightarrow^{221}$At and ^{222}Po $\rightarrow^{222}$At have been extracted. The decay curves, together with their fitting function, are shown in Fig. 2. The value in the table includes also systematic errors.

As reported in Fig. 3 and in Tab. 1, the newly measured half-lives are shorter than the previously reported values. In literature, values for ^{221}Po $\rightarrow^{221}$At, ^{222}Po $\rightarrow^{222}$At decays have

	Experimental values $T_{1/2}$ [s]		Theory [s]		
Ion	Present work	Literature	FRDM	NEY	D3C*
^{218}Po→^{218}At		185.9(1) [7]	100		1760
^{219}Po→^{219}At		620(59) [8]	80.9		313
^{220}Po→^{220}At			100	48.6	91.4
^{221}Po→^{221}At	37.1 ± 1.4	112^{+58}_{-28} [9]	85.5	219	35
^{222}Po→^{222}At	68.7 ± 2.1	145^{+694}_{-66} [9]	36	211	15.9

Table 1. Experimental values for the β-decay half-lives extracted from this work (col. 2), compared to literature values (col. 3) and to the three theoretical models described in the text. (cols. 4-6).

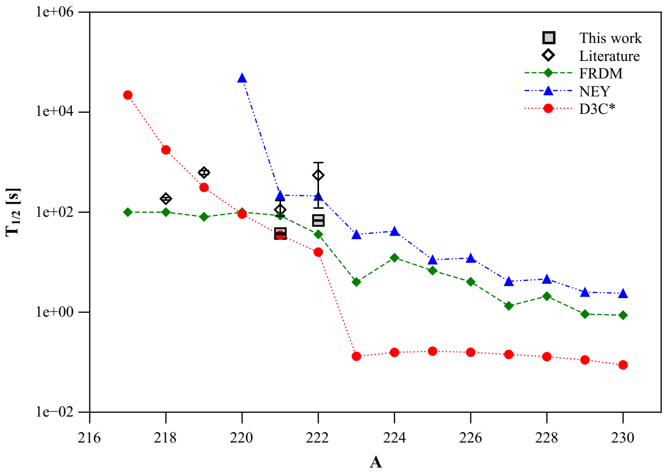

Figure 3. Open symbols represent experimental values for the half-lives of polonium isotopes extracted from the current experiment (open squares) and from literature (open diamonds, se Tab. 1 for detailed references) . Filled symbols are predictions from three different models, as reported in the caption and described in the text.

been extracted using the Schottky mass measurement approach at storage rings, resulting in $T_{1/2} = 112^{+58}_{-28}$ s, $T_{1/2} = 145^{+694}_{-66}$ s [9]. In general, The Schottky approach tends to extract longer half-lives than those found using custom-made ion-β correlations as in the experiment here described [10]

Our results are compared to state-of-the-art global models: the first one is the Finite Range Droplet Model (FRDM) by Möller et al.[11], describing the decays on the basis of Quasi-particle Random-Phase Approximation (QRPA) description of the decays; the second model (NEY), by Ney et al. [12], is a self-consistent microscopic description based on the Relativistic Hartree-Bogoliubov (RHB) model for ground states of open- and closed-shell nuclei with the proton-neutron relativistic quasiparticle random phase approximation (pn-RQRPA); the third approach (D3C*), derived by Marketin and collaborators [13], treats first-forbidden transitions on an equal footing as the Gamow-Teller transitions.

As shown in Fig. 3, the three models give a rather different description of the Po isotopic chain: Möller et al. predict a smooth behaviour with half lives slowly decreasing but remaining on the second to tens-of-seconds scale, in the mass range here considered. Ney et al., instead, predict an abrupt drop of the half-lives at mass A=221, followed, as in the model before, by a rather smooth trend. Half-lives are expected to be slightly longer than in the previous case, but the overall features agree quite well. The description of Marketin et al., where first-forbidden transitions have a higher weight, predict a sudden drop of the half-lives at mass A=223, followed by a rather smooth trend onward. Half-lives predicted by Marketin are, however, an order of magnitude lower than those obtained using the other two approaches. The comparison between data and theory points to a delayed onset of first-forbidden contributions to the decay in this mass region.

The data are under evaluation to search for a possible α-decay branch for the decay of $^{218-220}$Po, not seen in the most exotic species here described.

The data extracted in the heavier isotopic chains of Rn and At show a similar behaviour to what has been described in this proceedings, and the full set of data will help in better elucidating the impact of heavy nuclei in nucleosynthesis processes.

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