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β-decay systematic trends of nuclei beyond ^{208}Pb

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Abstract. The β decay of several nuclei beyond ^{208}Pb has been investigated using the FRS+RISING set up at the GSI accelerator facilities, in Darmstadt. This contribution provides a compilation of the β-decay information obtained for neutron-rich Tl, Pb and Bi isotopes. On the basis of the new data, a general overview on the β-decay systematics in this mass region is provided. The study reveals the impact of the microscopic structure of these nuclei on the descriptive power of standard theoretical models. These are used to extrapolate gross properties towards the neutron-drip line, where the nuclei that concur in the formation of the third r-process abundance peak reside. Deficiencies in their predictive power are discussed.

1. Introduction

Since the beginnings of the 20th century, the β decay has been a powerful tool to obtain structural information on new exotic nuclei. This mechanism has also attracted great attention in astrophysics, since the abundance patterns and time scales of the nucleosynthesis processes leading to the formation of heavy nuclei, namely the s- and r-processes [1], are determined by gross β-decay properties, such as half-lives, Q_β values, and delayed emission probabilities. z In this work special attention is payed to the third r-process abundance peak. Since direct experimental access to r-process nuclei –lying near the neutron-drip line– is still not possible, r-process calculations must rely on nuclear theories. While their descriptive power near stability has already been tested and confirmed, their predictive power in nuclei at extreme conditions of isospin might be depleted by microscopic structural effects, such as deformation or shell quenching. Therefore information on more moderately neutron-rich nuclei is of extreme importance to probe their extrapolation capabilities.

2. Experimental technique and data analysis

The neutron-rich $^{211--213}$Tl, ^{215}Pb and $^{215--219}$Bi were produced in inverse kinematics, exploiting the in-flight fragmentation of a ^{238}U primary beam colliding with a thick Be target. The 1 GeV/nucleon beam was delivered by the UNILAC-SIS accelerator system at GSI. The heavy nuclei were sent to the FRagment Separator (FRS), a high-resolution magnetic spectrometer that separates the heavy nuclei and their atomic charge states following the Bρ-ΔE-Bρ method [2]. At the exit of the spectrometer a decay station, consisting of an active stopper detection system surrounded by the RISING γ array in its "Stopped Beam Configuration" [3], was set up. The energy, time, and position of all the nuclear species implanted in the active

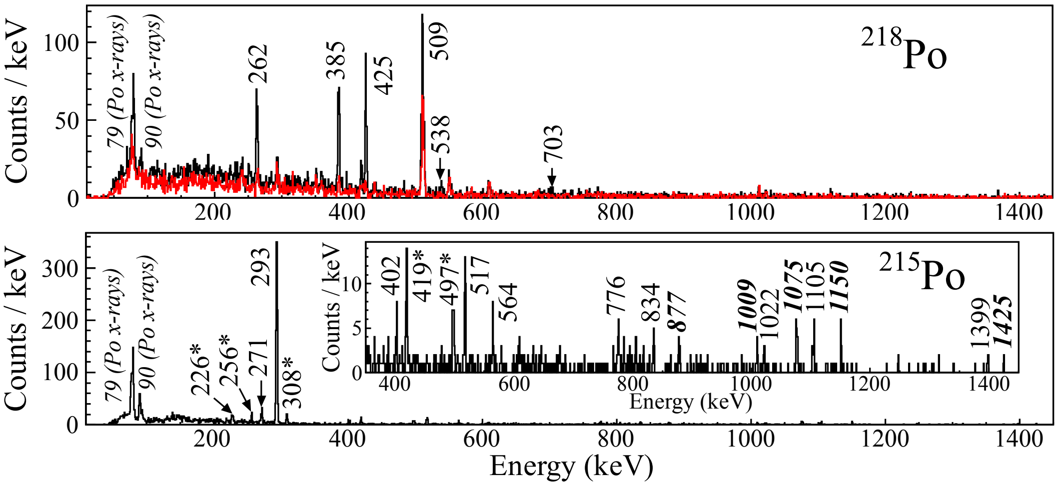

Figure 1. *(Color online) β-delayed γ spectra of the decays $^{218}Bi \to ^{218}Po$ (upper panel) and $^{215}Bi \to ^{215}Po$ (lower panel). The upper panel includes the ion-β correlations where the electron was detected in the implantation pixel. The background is shown in red. The ion-β correlations included in the lower panel, instead, are labeled with the α particle emitted by ^{215}Po.*

stopper were recorded on an event-by-event basis. This information was also collected for α and β particles, and for coincident γ rays.

Different types of time and position correlations were defined for the extraction of β-decay information. Depending on the background conditions, only ion-β correlations or additional tags to the subsequent α particles were applied. As an illustration, Fig. 1 shows the γ spectra of the decays ^{218}Bi$\to$^{218}Po and ^{215}Bi$\to$^{215}Po. In the first case, the γ spectrum includes the ion-β correlations where the electron was detected in the implantation pixel. Due to the long correlation times involved, the reverse-time background technique was applied [4, 5]. In the second case, the γ spectrum incorporates correlations with an additional tag on the α particle emitted by the daughter ^{215}Po. The short half-life of this α emitter, 1.78(5) ms [6], allowed for the extension of the β-α correlations to a greater area in the active stopper, including also the neighboring cells. In both cases, the extracted γ-rays agree with previous β-decay studies [7, 8], thus confirming the correlation procedures. Further half-life measurements were performed exploiting these α and β correlations. Ad-hoc techniques of data analysis, explicitly developed for experiments with complex background conditions [9, 10, 4], were employed. Half-lives for $^{211-213}$Tl, ^{215}Pb, $^{215-219}$Bi, $^{215-217}$Po and ^{217}At could be extracted [10, 6].

Partial β-decay level schemes have been built from β-γ and β-γ-γ spectra. The level orderings and proposed spin-parities are supported by systematics and, where possible, by shell-model calculations. As an example, Fig. 2 shows the level schemes of $^{211-213}$Pb. The newly observed states and γ rays are indicated in bold red fonts. β feedings expressed as % are also shown in the figure. These have been obtained assuming $E2$ multipolarities for all transitions, except for the 362-, 438-, 1190-, and 1395-keV γ rays, for which an $M1$ character has been considered [5]. In general, the feeding patterns show a strong population to final levels of equal parity, thus indicating an allowed Gamow-Teller nature for the decay of this isotopic chain. This behavior can be understood in terms of the shell-model structures of mother and daughter nuclei: Direct single-particle β decays are completely blocked since the ground states of the $N > 126$ Tl isotopes have a proton hole in the $s_{1/2}$ orbital, while the valence neutrons lie within the $g_{9/2}$ and $i_{11/2}$ sub-shells. Such large spin differences imply that the β transitions must be driven by the Gamow-Teller ($\nu i_{11/2}, \pi i_{13/2}$) and first-forbidden ($\nu g_{9/2}, \pi h_{9/2}$) single-particle components.

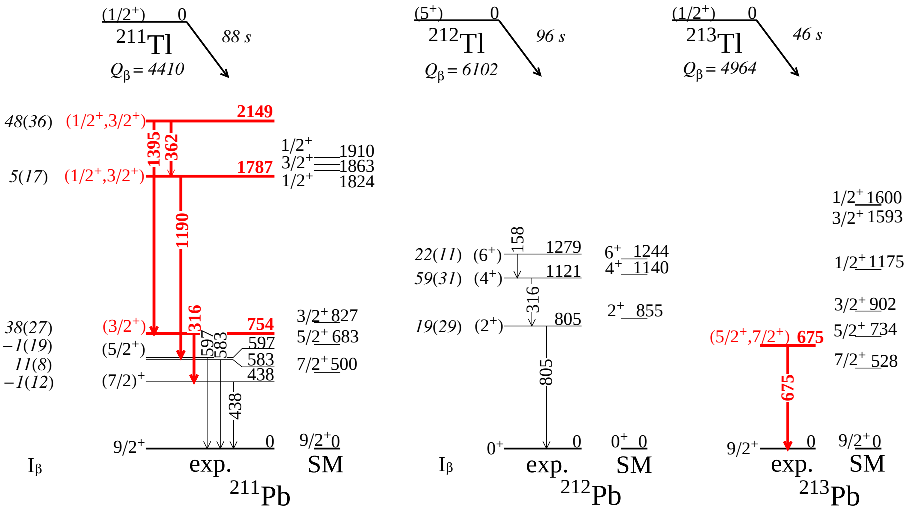

Figure 2. *(Color online) Experimental level schemes (exp.) of the* $Z = 82$ *isotopes* $^{211-213}$*Pb. Shell-model calculations (SM) are show on the right-hand side for each nucleus.*

Shell-model calculations show that the allowed part of the β-decay strength function is favored: On the one hand, the occupation number of the $i_{11/2}$ neutron sub-shell is nearly one for the Tl ground states, and, on the other, the calculations indicate that the $\pi i_{13/2}$ single-particle orbital is fragmented over several states in the Pb daughters due to correlations between nucleons, with an increasing presence for larger excitation energies. This leads to strong allowed β transitions to higher-lying states, in line with the β-decay feeding patterns observed. For instance, in the decay ^{211}Tl$\rightarrow$^{211}Pb, a 38% of the strength spreads to the first $(3/2^+)$ 754-keV state, while a 48% of β transitions populate the higher-lying $(1/2^+, 3/2^+)$ 2149-keV candidate. The situation reverses once the $Z = 82$ magic shell is filled, i.e., for the Pb and Bi nuclei with $N > 126$. Here, the main sub-shells mediating in the β decay are the $\pi h_{9/2}$ and $\nu g_{9/2}$ orbitals. As a consequence, strong first-forbidden β-decay transitions, mainly driven by the single-particle $(\nu g_{9/2}, \pi h_{9/2})$ configuration, appear.

3. β-decay systematics of trans-lead nuclei

The nuclei here discussed are of special interest to trace the systematics of β-decay half-lives in nuclei beyond ^{208}Pb. Though not extremely neutron-rich, these are important probes for the nuclear models, needed of experimental constraints that can help to strengthen their predictive power towards the exotic nuclei lying in the unexplored r-process region. Indeed, predictions of r-process time scales and production rates can vary over orders of magnitude depending on the nuclear framework employed. Whereas standard microscopic-macroscopic models emphasize the importance of the allowed Gamow-Teller β-decay strength [11], self-consistent microscopic treatments stress the role of first-forbidden transitions in the reduction of predicted lifetimes [12, 13]. The latter are expected to influence significantly the low-energy spectra of the r-process nuclei due to the presence of intruder single-particle states with different parity near the Fermi surface. The stringent constraints found in the $Z < 82$, $N < 126$ quadrant of the nuclear chart [14, 4] already provide evidence of the importance of first-forbidden transitions in the modeling of the underlying nuclear structure.

The aim of this work is to extend the former systematic studies of β-decay half-lives to the $N > 126$ region. Comparison of measured and predicted half-lives in neutron-rich Tl and Bi isotopic chains is shown in Fig. 3. For the sake of clarity, the experimental-to-theoretical ratios

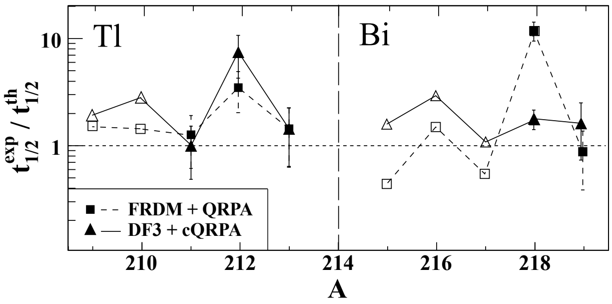

Figure 3. *Ratio between experimental and theoretical β-decay half-lives for the neutron-rich Tl and Bi nuclei studied in this work. The predictions shown by squares are obtained using the FRDM+QRPA approach while the ones shown by triangles by the DF3+cQRPA model.*

are displayed. Two models are discussed here. The first is the FRDM+QRPA approach [11], based on the microscopic Quasi-particle Random Phase Approximation upon the macroscopic Finite Range Droplet Mass model to account for the Gamow-Teller part of the β-strength function. The first-forbidden contribution, instead, is treated as a perturbation of the main Gamow-Teller strength, and thus is inserted macroscopically, employing the Gross Theory framework. The second is the DF3+cQRPA model, a full microscopic approach that implements the first-forbidden strength within the continuum Quasi-particle Random Phase Approximation, thus giving an equal treatment of Gamow-Teller and first-forbidden decays. Predictions of these models are consistent with the decay-feeding pattern derived from the γ-spectroscopy analysis: Whereas the hybrid theory gets closer to the measured values for the one-proton-hole Tl nuclei (whose β decay is mainly driven by Gamow-Teller transitions), predictions deviate up to a factor ten in the Bi isotopic chain (for which the first-forbidden transitions dominate the low-energy part of the β-decay strength distribution). Consistently, the fully microscopic model gets a better description of this isotopic chain. In general, both models underestimate the measured half-lives by an average factor of two, and predict an odd-even staggering that is not seen in the experimental data [12, 5].

The results extracted from this work have paved the way to model the underlying nuclear structure in the region spanned by the r-process during the freeze-out stage. They provide an important guide for the theoretical approaches used to extrapolate β-decay inputs in nucleosynthesis calculations. This study already represents a breakthrough in the understanding of the r-process matter flow to heavier fissioning nuclei, however, further measurements will be needed to confirm the persistence of the observed tendencies in the unexplored r-process region.

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