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Competition between allowed and first-forbidden β decays and the r-process

Zsolt Podolyák[1,*]

[1]Department of Physics, University of Surrey, Guildford, GU2 7XH, UK

Abstract. β^- decay lifetimes are essential ingredients for r-process yield calculations. In N≈126 r-process waiting point nuclei first-forbidden and allowed β decays are expected to compete. Recent experiments performed at CERN/ISOLDE showed that ^{207,208}Hg decay predominantly via first-forbidden decays. In addition, following on a high statistics study of the β^+/EC decay of ^{208}At, it is suggested that the Z>82, N<126 nuclei provide an excellent testing ground for global calculations addressing the competition between first-forbidden and allowed β decays.

1 Introduction

Half of the nuclei heavier than iron were synthesised in the r process. This process is based on a succession of neutron captures and β^- decays. Since heavy (A>150) r-process path nuclei still cannot be produced in laboratories, yield calculations have to rely on β decay half-lives predicted by theoretical calculations. In contrast to lighter mass regions, around neutron-number N=126 there is competition between (parity conserving) allowed and (parity changing) first-forbidden β decays [1, 2]. First-forbidden (FF) transitions can be dominant, with profound implications on their half-lives and therefore on the r-process, specifically on the third r-process peak at A∼195 [3]. However, FF transitions are notoriously difficult to calculate. Here we present results obtained in β-decay studies on nuclei around ^{208}Pb in experiments performed at the ISOLDE Decay Station at CERN.

2 First-forbidden β decays

An ideal atomic nucleus to study the competition between allowed and forbidden β decays should have a small number of both positive and negative parity levels which could be populated in β decay, and they should have simple and well-understood wave functions. Quantum excitations in nuclei in the vicinity of doubly magic numbers have well defined wave functions. In addition, the ^{208}Tl nucleus (with one proton-hole and one neutron-particle outside the closed shells) is expected to have a small number of both positive and negative parity low-energy states. Indeed, shell model calculations predict two 0^+, five 1^+, as well as one 0^- and three 1^- states at excitation energies below the Q_β=3.48 MeV value [4] (note, that in addition, a number of collective octupole states with negative parity are also expected above 2.6 MeV, however these could not be calculated within the used model space). Therefore, the

*e-mail: z.podolyak@surrey.ac.uk

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Table 1. Experimentally determined lifetime and first-forbidden beta decay contribution for the β decays of ^{208}Hg and ^{207}Hg, compared with theoretical predictions.

Nucleus		Exp	Theory					
			[6]	[7]	[8]	[9]	[2]	[1]
^{208}Hg	$T_{1/2}$ (s)	135(10) [5]	168.9	8.1	12.1	5.3	0.9	70
	FF/total	≈1 [5]				0.040	0.87	1
^{207}Hg	$T_{1/2}$ (s)	174(12) [11]	40.1	9.1		313.2	4.0	61
	FF/total	≈1 [10]				0.986	0.77	1

decay of ^{208}Hg into ^{208}Tl provides an ideal testing ground for the study of the competition between allowed and FF β decays. This was studied at ISOLDE at CERN [5]. Three negative parity excited states, one 0^- and two 1^-, were populated directly in β decay. The FF decay probabilities with $\log ft$ values in the range of 5.2-6.0 are in line with systematics in this region, however at present these cannot be reliably calculated. In contrast none of the positive parity states were populated. This latter can be understood by considering the properties of the single proton and neutrons involved. The half-life of the ^{208}Hg ground-state was measured as $T_{1/2}$=135(10) s [5]. There are several published global calculations covering the region of interest for the *r*-process. Since shell-model calculations are not feasible far from closed shells, all global calculations use mean field approaches, and all recent ones include first-forbidden decays. These are based on FRDM+QRPA [6], KTUY5 [7], DF3+cQRPA [8], FRDM+QRPA [9], RHB+RQRPA [2] and FAM [1] methods, and their results are compared with the experimental value in table 1. From a similar, but much higher yield experiment it was established that ^{207}Hg (Q_β=4.55 MeV [4]) also decays predominantly (several observed states have no firm parity assignment) via FF β decays [10]. The experimental and theoretical values for the ^{207}Hg decay are also listed in table 1.

None of the existing calculations can reproduce the experimental lifetimes of N≈126 nuclei in the region [12–16]. This is not surprising, as even such state-of-the-art calculations are not expected to provide accurate single-particle energies, essential for nuclei close to closed shells where the β-decay strength is dominated by few transitions. There are some shell-model calculations available for N=126 nuclei [17, 18], however these do not consider neutrons above the N=126 shell closure, therefore cannot provide a reliable lifetime estimate for ^{207,208}Hg.

It is difficult to populate heavy neutron-rich nuclei in the laboratory. It is much easier to produce proton rich ones. Recently, the β^+/EC decay of ^{208}At into ^{208}Po was studied within a high statistics experiment [19]. A roughly equal role of allowed and FF decays were found. This can be understood considering the relevant shell model orbitals in the region. Since the FF decays populate mainly excited states at high energies, some older experiments suffered from the pandemonium effect. The role of the FF β decays in the region is illustrated in figure 1. Note that some nuclei have very low Q_{EC} values and consequently there are few excited states in their daughter nuclei within the available energy window. The decays of ^{208}Po and ^{209}Po are peculiar; all β decays proceed via larger degree of forbiddenness due to the lack of daughter states with spin-parities consistent with FF and allowed β decays. The indicated small experimentally determined FF contribution for some Rn and At isotopes with larger Q_{EC} values are most likely due to the pandemonium effect, with the real value expected to be much larger.

It is suggested that the neutron-deficient region "north-west" of ^{208}Pb provides an excellent testing ground for the competition between allowed and first forbidden β-decay calculations [19]. However, presently very few global calculations for β^+/EC decays exists on this

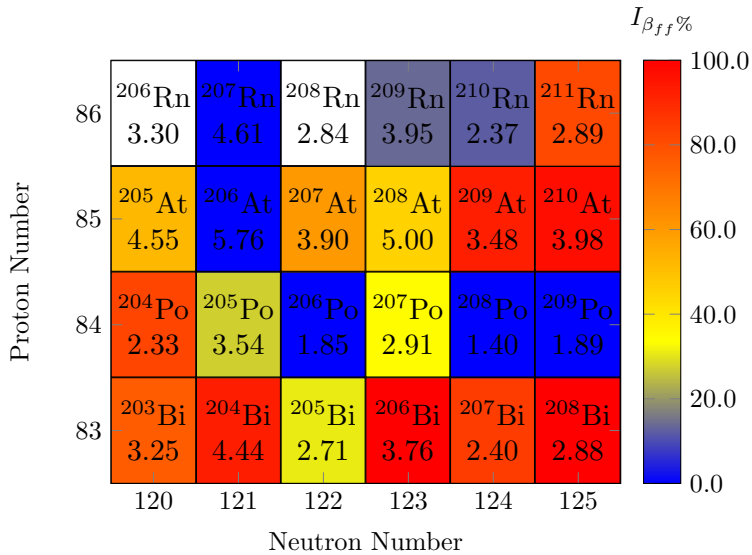

Figure 1. Role of first forbidden decays for nuclei 'north-west' of ^{208}Pb. The colour code refers to the $I_{\beta\ FF}/I_{\beta\ TOTAL}$ value. The parent nuclei are indicated. Q_{EC} values, in MeV, are also given. Figure modified from [19].

part of the nuclide chart. These predict half-lives of 105.7 s [7] and 2412 s [20], as compared to the experimental $T_{1/2}$=5900(1100) s [21]. Note that [20] considers only allowed decays.

3 The Δn=0 selection rule

The well-known selection rules for allowed β decay are: angular momentum change ΔI=0,1 and no parity change. However, there is one additional selection rule: the number of nodes in the radial wave function, n, of the parent and daughter states must be equal. The validity of this less known Δn=0 selection rule in Gamow-Teller β decay was recently investigated [22] by studying the β decay of ^{207}Hg into ^{207}Tl. The level of forbiddenness of the Δn=1 $\nu 1g_{9/2} \rightarrow \pi 0g_{7/2}$ transition has been determined. From the non-observation of this decay at the level of <3.9×10^{-3}%, corresponding to logft>8.8 (95% confidence limit), one can conclude that the selection rule holds. This is the most stringent test of the Δn=0 selection rule to date. Without this rule the lifetime of ^{207}Hg would be approximatively 7% shorter, while in the case of ^{209}Pb the effect is about ≈20%. This selection rule has little importance for nuclei close to stability, but is essential for the Z<82, N>126 r-process waiting point nuclei, lengthening their lifetimes.

4 Conclusions and outlook

In conclusion, recent ISOLDE results addressing the competition between allowed and first-forbidden β decays were reported. In particular it was found that both ^{207}Hg and ^{208}Hg decay via first-forbidden β decays into negative parity daughter states, despite the availability of positive-parity states. These were understood by examining the properties of individual neutrons and protons within the shell model approach. Following the study of the β^+/EC decay of ^{208}At, it is suggested that the Z>82, N<126 nuclei, which can be studied in high

yield experiments provide an excellent testing ground of the competition of FF and allowed decays. This region would merit modern global β decay calculations.The presented results on β decays are important for the detailed understanding of the nucleosynthesis of heavy elements produced in the rapid neutron-capture process.

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