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Nuclear physics in the N≈126 region relevant for the *r* process

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Abstract. Understanding how the heavy chemical elements are made in the astrophysical *r*-process requires information on both the properties of the nuclei involved and that of the environment. The availability of experimental information on the neutron-rich N∼126 nuclei is discussed, with emphasis on phenomena specifically relevant to this region: the large role of first-forbidden β decays, and that of the Δn=0 selection rule in Gamow-Teller decays. The development of nuclear data bases by combining different theoretical approaches is suggested.

1 Introduction

The rapid neutron-capture (*r*) process is known to synthesise about half of the nuclei heavier than iron [1]. The observational data on the *r*-process is scarce. Only the solar system provides us with elemental and isotopic abundances. Here the *r*-process abundances are determined as the difference of the total observed, minus the slow neutron-capture (*s*) process abundances. Since in the case of the *s*-process both the astrophysical site and the majority of the nuclear data are known, these calculations are robust. The such obtained *r*-process abundances, exhibit wide peaks at around masses A∼80, 135, 190, connected to the magic neutron numbers at N=50, 82, 126. This abundance pattern became a *de facto* definition of the *r*-process. This is what individual *r*-process calculations aim to reproduce, independently whether this originates from a single process, from a single site, or is a mixture of these. The single event scenario seems rather unlikely. It was suggested that the long-lived ^{182}Hf and ^{26}Al isotopes have different origins in the early solar system [2]. Another illustration of the (in)probability of a single event: it was advocated that the plasma in Local Bubble in which the solar system is embedded originated from 14-20 supernovae explosions from the last 13M years [3]. Despite all these, the fact that a single dataset is available, justifies the present approach, with single astrophysical event adopted in the *r*-process abundance calculations.

Observational information is available also from a large number of stars, for which the abundances of (some) elements were determined. Around a dozen of them, all very old, as judged by their very low metallicity, exhibit similar abundance patterns than that of the solar system *r*-process [1]. This is considered as proof of the universality of the *r*-process. However, there are other low metallicity stars in which the abundance decreases drastically with atomic number, pointing toward an incomplete *r*-process [4], with large number of intermediate cases; or the opposite of this, stars which have too much actinide nuclei (Th, U) [5].

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These observational data suggest that the *r*-process abundance distribution is dependent on the environment (neutron density, temperature), and possibly also on the site (SNe, merger); conclusion supported by the astrophysical calculations. Most likely, different sites, with different neutron density conditions, contribute to the production of *r*-process elements [1]. Additional information on the *r*-process can be gained from the chemical evolution of elements (changes in abundances as function of metallicity), pre-solar grains, meteorites carrying long lived isotopes (^{129}I, ^{247}Cm [6]), or the observation of long lived isotopes on Earth and Moon (^{60}Fe, ^{244}Pu, ^{53}Mn), see e.g. [7].

The largest uncertaintiy in the *r*-process is due to the uncertain site(s) where it happens. The site(s) needs to provide high neutron densities, with the most discussed candidate being supernovae of several types and mergers. The recent observation in 2017 of the kilonova remnant of the first observed gravitational wave event attributed to a neutron-star merger provided evidence for this scenario. The evolution of the remnant's luminosity in different wavelengths is consistent with the synthesis of heavy neutron-rich nuclei [8]. While no individual heavy elements could be observed, some properties of the spectrum were linked to strontium [9].

2 Nuclear data

The abundance calculations, as input, need information about environment, as well as nuclear data. The nuclear data clearly has an effect an the *r*-process yield calculations, as attested by the numerous studies accompanying the reporting of new lifetime and mass values (e.g. [10, 11]). As a general statement, shorter lifetimes for the N$\sim$126 (82) nuclei shift the predicted A$\sim$195 (130) *r*-process peak to higher masses. At the same time β-delayed neutron emission moves the peak to lighter masses, widening it (more exotic nuclei emit more neutrons) and smoothening it (largely removing the odd-even mass staggering) [12].

Sensitivity tests are used to identify nuclei and their properties which are particularly important for the quantitative understanding of the *r*-process yields. These are often biased towards the progenitors of final products with high abundance [13, 14]. It seems that there are no really special nuclei, but the understanding of whole regions are needed. This conclusion seems to be supported by the fact that the $\sim$130 abundance peak is not better understood than the $\sim$195 one, despite that the mass and lifetimes of several N=82 *r*-process path nuclei were already measured [15] (uncertainties due to fission recycle provide an alternative explanation).

3 Nuclear structure in the N$\sim$126 region

The neutron-rich N$\sim$126 region is different in two ways when compared to lighter nuclei. First-forbidden (FF) β decays are expected to compete against allowed ones, and even to dominate. In addition, this is the region where the effect of the so called Δn=0 β decay selection rule for Gamow-Teller transitions becomes important. We discuss these two aspects one by one.

3.1 Competition between first-forbidden and allowed beta decays

Global β-decay calculations show that allowed beta decay (with selection rules ΔI=0, $\pm$1 and $\Delta\pi$=No) dominate over first-forbidden ones (ΔI=0,$\pm$1,$\pm$2 and $\Delta\pi$=Yes) on the large part of the nuclide chart [16, 17]. But in the case of heavy nuclei, starting around N=126, first-forbidden transition compete and can become dominant, in stark contrast with the N$\sim$82 and N$\sim$50 regions. Since the calculation of FF transitions is notoriously difficult, the differencies in the predicted lifetimes are large. Table I, comparing lifetimes and FF contributions obtained from recent ISOLDE experiments on ^{207,208}Hg [18] demonstrates this.

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

Nucleus		Exp	Theory						
			[19]	[20]	[21]	[22]	[17]	[16]	[23]
^{208}Hg	$T_{1/2}$ (s)	135(10) [24]	168.9	8.1	12.1	5.3	0.9	70	
	FF/total	≈1 [24]				0.040	0.87	1	
^{207}Hg	$T_{1/2}$ (s)	174(12) [25]	40.1	9.1		313.2	4.0	61	
	FF/total	≈1 [26]				0.986	0.77	1	1

3.2 The Δn=0 selection rule

A less well-known selection rule for the otherwise allowed β-decays is that the number of nodes (n) in the radial wave functions of the initial and final states has to be the same. This Δn=0 requirement plays a major role in the β decay of heavy neutron-rich nuclei as there are several pairs of single particle Δn=0 orbitals for N>126 and Z<82. If the selection rule is strictly obeyed, β decay between them is forbidden, resulting in longer lifetimes than otherwise. The greatest impact is on nuclei where the Fermi level lies high above N=126 and/or much below Z=82, e.g. nuclei on the astrophysical r-process pathway, influencing the nucleosynthesis of heavy elements. This selection rule has little effect on isotopes which are proton-rich or close to the stability line, making the experimental investigation of its validity difficult. The most stringent test was provided by the β decay of ^{207}Hg, where the level of forbideness of the Δn=1 $\nu 1g_{9/2} \rightarrow \pi 0g_{7/2}$ transition was recently investigated at ISOLDE. An upper limit of 3.9x10^{-5} was obtained for the probability of this decay, corresponding to a logft>8.8 (95% confidence limit) [27]. This selection rule is based on the fact that the overlap integral between the Δn=0 orbitals vanishes, which is valid only if the proton and neutron feel the same potential. This is not stricly true due to the Coulomb force and the different spin-orbit couplings (parallel and antiparallel). While in ^{207}Hg the selection rule was upheld, global lifetime calculations suggest that in heavy nuclei about 20% of the decay is via these Δn=0 transitions [17]. In order to really understand the relevance of this selection rule, experimental information from much more exotic nuclei is needed, as the two available examples (^{207}Hg and ^{209}Tl) are strongly relyant on small components of the wave functions, obtained from shell model calculations. For example, in the case of the ^{207}Hg decay, the probability that there are two holes in the $\pi g_{7/2}$ orbital in its ground-state is rather low at ~10^{-4} [27].

4 Which experimental data is relevant for the r process?

The nuclear data needed for the abundance calculations are mainly masses (used to calculate Q values and, crucially, reaction cross sections) and lifetimes. Properties of excited states, unless these are long lived isomers which are included as separate nuclides, are not used in the network calculations. Figure 1 summarises the data available in the neutron-rich N≥126 region. Lifetimes along N=126 are only known for four nuclei below ^{208}Pb, down to ^{204}Pt [28]. Mass values are published only down to ^{206}Hg [29]. These properties are the ones directly compared with the global nuclear calculations. Information on ground-state poperties which are less used to constrain calculations are β-delayed neutron-emission probabilities [30] and charge radii [31]. However, there is a much wider knowledge on properties of excited states. Information on them, such as energies and spin-parities of yrast states are available down to ^{203}Ir [32], five protons from ^{208}Pb. Often there are transition strength information as well (because of the high sensitivity of the isomeric decay technique), which are used to obtain information on the wave functions. These considerable knowledge on excited states usually

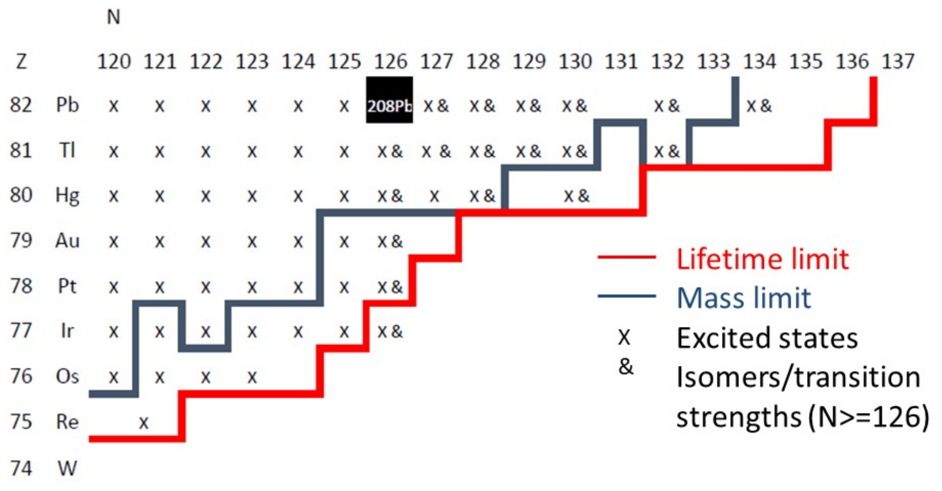

Figure 1. Status of experimental knowledge on the neutron-rich N 126 nuclei.

is not taken advantage of when testing nuclear theories. This is a shame, as excited states in less exotic nuclei, especially transition strength information, can provide knowledge on the ground state of the more exotic ones. The reason for this omission is that global calculations are somewhat simplified when compared to the more microscopic ones, and cannot be used to predict the details of the nuclear structure. On the other hand, while the shell model could predict all properties of ground- and excited states, these are computationally prohibitive for nuclei with large number of valence nucleons. Models such as the particle-vibrational coupling try to provide the bridge between these two, global and localised, type of calculations. For now, when creating nuclear databases it would be advantageous to combine (for lifetimes and masses) predictions from different theoretical frameworks, always using the one considered more reliable for a given region. In a sense such mixing is what is done, when measured values (like in the N~82 region) are combined with theoretical ones. One would need to check and smoothen discontinuities at the boundaries of different calculations. The such obtained database would be more reliable than the existing ones relying on individual global calculations.

5 Outlook

Multimessenger astronomy observations, similar to the pioneering one which followed the GW17017 event [8], will help to understand how similar/different such events are and therefore provide information on the universality of the *r* process. There is a possibility that light-curve studies will prove the production of ^{254}Cf, whose decays has a large impact after 100 days [13]. More data on the difficult to determine abundances of Th or U, the only two elements produced exclusively in the *r* process would be important for similar reasons. From experimental point of view, the radioactive beam facilities coming online will allow to measure directly the properties of some of the N=126 *r*-process path nuclei for the first time. This will help to determine how much material goes into the fission region, and get better understanding of the importance of fission recycling (for a given astrophysical scenario). This, together with experimental nuclear data might clarify the origin of the rare-earth *r*-process peak, weather it is related to discontinuities of nuclear properties (mass, neutron capture rate) or is the result of fission.

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