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r Process (n,γ) Rate Constraints from the γ Emission of Neutron Unbound States in β-Decay

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Total absorption gamma-ray spectroscopy is used to measure accurately the intensity of γ emission from neutron-unbound states populated in the β-decay of delayed-neutron emitters. From the comparison of this intensity with the intensity of neutron emission a constraint on the (n,γ) cross section for highly unstable neutron-rich nuclei can be deduced. A surprisingly large γ branching was observed for a number of isotopes which might indicate the need to increase by a large factor the Hauser-Feshbach (n,γ) cross-section estimates that impact on *r* process abundance calculations.

KEYWORDS: total absorption gamma-ray spectroscopy, beta-delayed neutron emitters, neutron-capture rates, r-process

1. Introduction

The cross-section for radiative neutron capture on very neutron-rich nuclei is a key ingredient in the description of element production during the astrophysical *r* process [1]. It is relevant during the non-equilibrium conditions that prevail if the *r* process takes place at low temperatures (cold *r* process) when the successive neutron captures are terminated by β decay rather than by photodisintegration [2]. It is also relevant in the hot *r* process after exhaustion of the neutron burst, during the freeze-out, when late captures take place with the remaining neutrons or with newly injected neutrons in the system from the β delayed neutron emission process [3].

However (n,γ) cross section values for these highly unstable isotopes are not accessible to direct experimental determination using either neutron beams or radioactive beams due to the impossibility of fabrication of suitable targets and/or the limitation on beam intensity. Thus, the input values in the *r* process network calculations are theoretical estimates. Such estimates are mostly based [4] on the statistical model of nuclear reactions using the Hauser-Feshbach formalism (HFF). The formalism uses average quantities, the partial neutron width Γ_n and the partial gamma width Γ_γ, to describe the entrance and exit reaction channels for compound states (resonances) of a given spin-parity. The energy dependency of the $\sigma_{n\gamma}$ cross-section includes the sum of terms proportional to $\Gamma_\gamma\Gamma_n/(\Gamma_\gamma+\Gamma_n)$. Conventionally the partial widths are expressed in terms of other average quantities, the nuclear level density (NLD), the photon strength function (PSF) and the neutron transmission coefficient (NTC) which are isotope dependent. Several alternative parameterizations exist for these quantities, but in general the parameters are adjusted to reproduce the available experimental information. Since this information is constrained to nuclei on or very close to the β-stability valley, the relevant question arises: how reliable are the extrapolation of these estimates to nuclei very far away from stability?

The process of β-delayed neutron (βDN) emission takes place for neutron-rich nuclei when they are far enough from stability. Then the decay can populate resonances, with excitation energy E_x above the neutron separation energy S_n, that decay by neutron emission or by electromagnetic de-excitation. The branching for γ emission is given by the ratio of γ to total widths: $\Gamma_\gamma/(\Gamma_\gamma + \Gamma_n)$. Thus a measurement of the β intensity distribution preceding γ emission $I_{\beta\gamma}(E_x)$ above S_n provides information on these partial widths that is otherwise not accessible. For that we need in addition data on the β intensity distribution with neutron emission $I_{\beta n}(E_x)$ which must be obtained independently.

In some sense one can consider the β decay as a surrogate reaction for (n,γ). However it should be noticed that in general resonances with different spin and parity J^π are populated in the two processes. This limitation is also present [5] for other (n,γ) surrogate reactions, in particular at the relevant neutron energies (up to few hundred keV). One needs models for both processes in order to convert the information obtained. The decay is governed by the β strength distribution S_β and several theoretical models are available for its calculation. In most cases, at such excitation energies, the Gamow-Teller (GT) selection rule applies and the decay populates states with the same parity and up to one unit of spin difference from the parent ground state. Capture is dominated by low angular momentum transfer, $l = 0, 1$, and the optical model (OM) can determine the population of states with different J^π.

One should consider also that since $\Gamma_n \gg \Gamma_\gamma$, the capture cross-section is basically only sensitive to Γ_γ, while the γ emission from unbound states in the decay is sensitive to both. Another difference between decay and reaction is that, as we have found, the width fluctuation corrections required by the statistical model are typically much larger for $I_{\beta\gamma}$ than for $\sigma_{n\gamma}$. This correction takes into account the fluctuation of individual transition strengths when averaging the ratios [6].

The main difficulty in this experimental approach is the accurate measurement of the weak $I_{\beta\gamma}(E_x)$ above S_n. Only a few γ transitions in a handful of isotopes have been observed with HPGe detectors. We have shown recently [7] for the first time that total absorption gamma-ray spectroscopy (TAGS) has the sensitivity and accuracy needed to provide data for exotic nuclei in the energy region of interest. The TAGS technique uses 4π scintillation detectors to absorb the full energy released in the decay from which the β-intensity distribution is reconstructed by deconvolution with the spectrometer response.

Here we report on an updated analysis of previous data together with new preliminary results for additional isotopes which confirm the results of [7].

2. Measurements

We have performed two measurements, each using a different spectrometer. The first measurement [7] used *Rocinante*, a compact 12 BaF_2 crystal spectrometer with cylindrical geometry. It is the first TAGS detector with segmentation designed for β-decay studies, which provides improved accuracy in the deconvolution through the measurement of γ-cascade multiplicities. In addition BaF_2 material was chosen in order to reduce the sensitivity of the spectrometer to β-delayed neutrons. Neutrons interact by inelastic scattering and capture producing background γ-rays. The second measurement was performed with *DTAS*, a modular 18 NaI(Tl) crystal spectrometer developed for measurements at the future FAIR/NUSTAR facility [8]. The geometry, based on rectangular crystals, is easily reconfigurable. It allows the use of large ancillary detectors, for example a DSSSD implantation detector or HPGe high-resolution γ-ray detectors. The new spectrometer provides a larger detection efficiency and has a better energy resolution but is affected by one order-of-magnitude larger neutron capture background. Background reduction and characterization is a key ingredient of the TAGS technique. We use coincidences with a β detector to eliminate the large ambient background. β signals were registered in a thin Si detector (first experiment) or a thin plastic scintillator (second experiment).

Both measurements were performed at the IGISOL on-line mass separator [9] in the JYFL Cyclotron Laboratory of the University of Jyvaskyla. Fission products were produced by protons in a thin uranium target inside the separator ion-guide source. A key feature of this installation is a double Penning trap system [10] which we use to eliminate the isobaric contamination from the fission product of interest. The purified radioactive beam was implanted on a tape at the centre of the spectrometer. The tape moved cyclically in order to remove the contamination from decay descendants. In the first experiment data were obtained for ^{87,88}Br and ^{93,94}Rb, while in the second experiment we measured ^{95}Rb and ^{137,138}I. All of them are well known β-delayed neutron emitters.

The largest sources of spectrum contamination were the decay of descendants, in particular the βDN decay, and the electronic pulse pileup. Special procedures were developed [7] to calculate the shape and magnitude of these background components.

The spectrometer response to decays was obtained by means of Geant4 [11] Monte Carlo simulations, and was calibrated with dedicated measurements. The decay response calculation requires assumptions on the de-excitation pattern that were obtained from the statistical nuclear model. The deconvolution procedure follows the methodology developed by the Valencia group [12], which allows the control of systematic uncertainties associated with this technique.

3. Results

A new extended evaluation of systematic uncertainties was performed [13] for the ^{87,88}Br and ^{94}Rb data published in [7], which now includes uncertainties in the Geant4 simulated responses. Nevertheless the updated uncertainty values do not differ much from previous ones. The evaluation of uncertainties for the case of ^{93}Rb [14] has not been completed, but the preliminary value of P_γ, the integrated β-intensity followed by γ emission above S_n, is 0.7%, which is large. It is half of the probability for neutron emission P_n.

The analysis of the second experiment is still ongoing. Particularly challenging is the correction of the contamination from the βDN branch that dominates the background. We found that the reproduction of this background is sensitive to the time sequence of signals and requires a careful choice of simulation parameters. A preliminary analysis for ^{95}Rb gives a value $P_\gamma = 1.9\%$ to be compared with $P_n = 8.9\%$. It is a remarkably large γ/neutron branching (18%) for a nucleus which has eight neutrons more than the last stable Rb isotope. In the case of ^{137}I the preliminary value of P_γ is 6.6% somewhat smaller that the value we reported in [8] but still very large compared to $P_n = 7.8\%$.

We summarize below our results on the γ/neutron competition obtained so far. We observe that, except for ^{94}Rb, the γ branching for states above S_n is large, ranging from 18% to 59%. In all these cases, ^{87,88}Br, ^{93,95}Rb and ^{137}I, we find that the large branchings can be explained in terms of the hindrance of neutron emission for one or more of the J^π groups populated in the daughter nucleus by an allowed GT decay. They require the emission of a neutron with large angular momentum ($l > 1$) in order to reach the states energetically available in the final nucleus. HFF calculations of the branching $\Gamma_\gamma/(\Gamma_\gamma + \Gamma_n)$ as a function of E_x are consistent with the measured distribution. The magnitude can be reproduced assuming a spin statistical population of the three J^π groups, proportional to $2J + 1$, or some reasonable modification of this intensity. In these calculations we use NLD, PSF and NTC obtained from standard parameters as recommended in the RIPL-3 reference input parameter library [15]. It should be noted that for these cases, since Γ_n is small, the branching is not very sensitive to the actual value of Γ_γ. The data for ^{138}I is still being analyzed but, considering the spin-parity of states in the different isotopes involved in the decay, we can anticipate a large γ branching.

The situation is different, however, for the decay of ^{94}Rb $J^\pi = 3^-$. Here the density of levels in the final nucleus ^{93}Sr, within the energy window $Q_{\beta n} = Q_\beta - S_n = 3.45$ MeV, is relatively large incrementing the number of possible neutron branches. As a consequence all three GT J^π groups in the daughter nucleus can decay by p-wave neutrons, and neutron emission is not particularly hindered. Indeed the observed γ branching in this case is only 5%. This situation maximizes the sensitivity of the branching to Γ_γ. It is also the best case to extract this information because the sensitivity to the spin distribution in the decay is minimized, since the $\Gamma_\gamma/(\Gamma_\gamma + \Gamma_n)$ ratio is similar for the three J^π groups. The comparison with HFF calculations shows that although the measured branching is small it is still much larger than the calculation using standard parameters. Assuming that the value of Γ_n is fixed we have estimated that Γ_γ has to be increased by a factor of 20 in order to match the experiment.

It is difficult to accommodate such an increase in current models for the PSF. We attempted several modifications of the PSF including the addition of low lying dipole resonances, of the pygmy E1 or scissor M1 type, and low energy dipole enhancements of E1 or M1 character, but all have a relatively modest impact. We also verified that the effect on Γ_n of variations of the OM parameters is limited. Note that changes in the NLD affect the absolute values of both Γ_γ and Γ_n but have no impact on $\sigma_{n\gamma}$ or $I_{\beta\gamma}$. On the other hand an increase of Γ_γ of such magnitude, if confirmed and generalized to very neutron-rich nuclei, will have an impact on abundance calculations for the *r* process. We plan to extend this type of measurement to other relevant isotopes in order to study this issue.

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