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β-decay measurements of $A \simeq 70 - 110$ r-process nuclei at the National Superconducting Cyclotron Laboratory

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Abstract. The present paper reports on several r-process motivated β-decay experiments undertaken at the National Superconducting Cyclotron Laboratory. β-decay half-lives and β-delayed neutron-emission probabilities were measured for nuclei around the r-process $A = 70-80$ and $A = 90 - 110$ mass regions. The data are discussed on the basis of quasi-random phase approximation calculations. The emphasis is made on the impact of these data upon calculations of r-process abundances.

1. Introduction

Despite 40 years of intensive effort, the astrophysical scenario where the r-process occurs remains as one of the major open questions in the understanding of Nucleosynthesis [1, 2]. R-process abundances constitute a typical *observable* to test theoretical models. They can be deduced by subtracting the calculated s- and p-process contributions to the total observed abundances in the Solar System. Observations of elemental distributions in metal-poor Eu-enriched stars, MPEES ([Fe/H]<-1, [Ba/Eu]<0, [Eu/Fe]>1), can also shed light on the Nucleosynthesis in the early Galaxy. Small amounts of these abundances could also be explained by contribution from additional processes beyond the standard r-process [1, 3–5].

Guided by recent observations of r-process abundances in low-metallicity stars [6], astrophysical models are being developed to infer r-process site(s). Such calculations are sensitive to both, the astrophysical conditions associated with the assumed scenario (entropy, neutron density, electron-fraction Y_e) and the properties of the nuclei involved [7, 8]. Among the different nuclear physics inputs with significant impact in these models, β-decay properties of very neutron-rich nuclei play a crucial role. β-decay half-lives ($T_{1/2}$) determine the distribution of the pre *freeze-out* isobaric abundances and speed of the process towards heavier elements. β-delayed neutron emission probabilities (P_n values) define the decay path followed by r-process nuclei during *freeze-out*, and the potential re-capture of β-delayed neutrons at late times.

With some remarkable exceptions, β-decay properties of r-process nuclei have to be calculated with nuclear models, or extrapolated from measurements in less exotic nuclei. These data also provide a probe for nuclear structure analysis in regions where more detailed spectroscopic studies are scarce [9–12].

The present paper reports on β-decay data measured at the National Superconducting Cyclotron Laboratory (NSCL) for nuclei involved in the r-process. A short summary of the experimental technique employed is presented in the first section, followed by the discussion of the data obtained for the different cases.

2. Measurement of β-decay properties of nuclei produced at NSCL

In the different experiments discussed below, the accelerated ^{86}Kr and ^{136}Xe primary beams impinged onto a Be target located at the entrance of the achromatic in-flight separator A1900 [13]. The fragmentation nuclei were forward-emitted, separated and implanted in the β-decay station, consisting of the NSCL Beta Counting System (BCS) [14] and the Neutron Emission Ratio Observer (NERO) [15]. The BCS includes a stack of Si PIN detectors, followed by a 40×40-pixel doubly-sided Si strip detector (DSSD), where the nuclei of interest are implanted, and a set of single-sided Si strip detectors to veto punch-through events. Implantation and β-decay signals from any of the DSSD strips are processed by a set of dual-gain preamplifiers, enabling the determination of position-correlated implantation/decay sequences. In addition, a 50 MHz clock is used to time-stamp each event, so that time correlations can be deduced. β-decay half-lives of the nuclei implanted in the DSSD were determined from multi-parameter χ^2-fits of the correlated β-decay time distributions. In cases of poor statistics, a maximum-likelihood fit analysis was used.

The BCS was embedded into the NERO matrix (a 60×60×80 cm^3 polyethylene block), with the DSSD located at the center of its symmetry axis as shown in Fig. 1. Besides the BCS-housing cavity, the polyethylene matrix includes sixty cylindrical holes organized in three concentric rings around the NERO symmetry axis. The holes of the innermost ring contain sixteen ^{3}He gas proportional counters; the intermediate and external rings include twenty and twenty-four B_3F counters, respectively. The use of polyethylene as neutron moderator maximizes the neutron-capture reaction cross-sections in the gas detectors (which increases with the inverse of the neutron velocity). According to MCNP simulations, such detector arrangement is optimum in terms of an energy-independent and maximum neutron-detection efficiency (about 40%). This was also verified empirically at the Institute of Nuclear Structure (Univ. of Notre Dame, Indiana, US) by measuring neutrons produced at different energies in different resonant and non-resonant reactions.

Neutron signals from the gas proportional counters were recorded in scalers and in a 64-channel multi-hit (VME) TDC. The TDC was programmed to work in start-gate mode, in which a gate signal—generated by a correlated β decay detected in the DSSD—enables the

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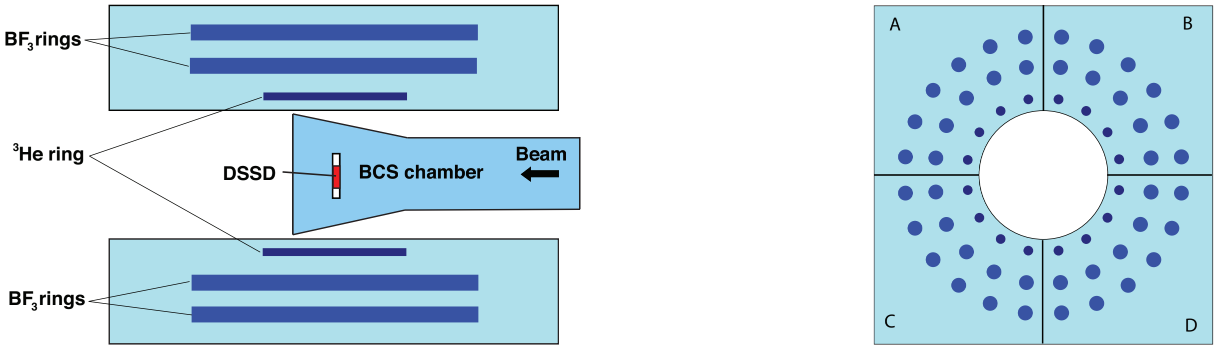

Figure 1. Schematic drawings of the NERO detector. Left: Side view showing the BCS chamber located inside of NERO with the DSSD at the central position. Right: backside showing the cylindrical cavity to house the BCS and the three concentric rings of gas-filled proportional counters. The labels A, B, C and D designate the four quadrants.

module to accept multiple stop signals in each channel from any of the sixty gas counters. The duration of this gate (200 μs) was chosen to account for the time needed to moderate and detect the neutrons. The P_n value of a given nucleus was extracted from the number of stops-signals registered in the TDC (i.e., neutrons correlated with β decays) relative to the number of β decays detected in the BCS.

Further details on the analysis techniques can be found in Ref. [12].

3. β-decay properties of r-process in the region $A = 90 - 110$

Neutron-rich nuclei in the region $A = 90 - 110$ are particularly important for the r-process. The failure of r-process models to reproduce the observed r-process abundances in the $A \simeq 110$ is a long-standing problem in Nuclear Astrophysics. As suggested by Kratz *et al.* [16], the underestimated abundances could be related with the nuclear physics inputs needed by r-process models. If, for instance, the P_n values of r-process nuclei in the region $A \sim 130$ were higher than predicted, part of them could contribute to the filling of the $A = 110$ abundance trough after the neutron freeze-out. Furthermore, the quenching of the $N = 82$ shell for neutron-rich nuclei [17] would provide the right abundance pattern prior to the $A = 130$ peak, as discussed in Refs. [16, 18, 19].

On the basis of these arguments, new β-decay half-lives were measured at NSCL for ^{90}Se, ^{105}Y, ^{106,107}Zr and ^{111}Mo, along with β-delayed neutron emission probabilities of ^{104}Y, ^{109,110}Mo and upper limits for ^{105}Y, $^{103-107}$Zr and ^{108,111}Mo [12]. The measured $T_{1/2}$ and P_n upper limits of $^{104-106}$Zr were calculated using HF+QRPA [20] and macroscopic-microscopic [21] models, as a function of quadrupole deformation. It was found that, in the case of ^{104}Zr, the data could be reproduced for deformations $|\beta_2| \simeq 0.3$ with both, oblate and prolate configurations. Beyond this value, the calculated half-lives raised monotonically. At a first glance, this finding seems to disagree with the large prolate $\beta_2 \simeq 0.4$ deformation of ^{104}Zr obtained, for instance, from spectroscopic analysis of the quadrupole moment Q_0 of the yrast band [22, 23] and from measurements of $B(E2; 2_1^+ \rightarrow 0_1^+)$ [24]. However, $T_{1/2}$ and P_n are "integral" nuclear-structure probes that are sensitive to not only the ground-state but any other intruder level with different deformations. Thus, our result points to the possible presence of spherical or weakly-deformed low-lying intruder state coexisting with a highly-deformed ground state of ^{104}Zr$_{64}$. Similar coexisting weakly-deformed states were found in ^{100}Zr$_{60}$ by Mach *et al.* [25], and, perhaps in ^{102}Zr$_{60}$ [26]. The emergence of weakly-deformed intruder states may reflect the "tailing effect" of the predicted re-occurrence of the Z=40 sub-shell, together with a new sub-shell N=70 very far from stability [7, 17]. Interestingly enough, the mechanism responsible for the emergence of a doubly semi-magic ^{110}Zr—the smoothing of the neutron density and the swallowing of the corresponding nuclear potential—governs also the quenching of the $N = 82$ shell.

The onset of triaxiality was also investigated for Nb and Mo isotopes by comparing their measured $T_{1/2}$ and P_n with the macroscopic-microscopic QRPA model of Möller *et al.* [21]. In its latest version, the model includes, besides quadrupole deformations, the triaxial degree of freedom calculated with the Finite-Range Liquid-Drop model (FRLDM) [27, 28]. The results were far closer to the data when triaxiality was included, as compared with results calculated using pure quadrupole deformations only [12] (see Fig. 2).

4. Measured $T_{1/2}$ and P_n of nuclei around the r-process waiting-point ^{78}Ni

Another r-process motivated experiment was focused on nuclei around ^{78}Ni [29, 30]. The origin of elements in this mass region is particularly challenging since, besides the r-process, contributions from the weak and strong s-process, along with charge-particle reaction sequences must be taken into consideration. In the case of the r-process, it is known that, in some models, this region represents the first bottle-neck in the flow of neutron-capture reactions occurring in the r-process. β-decay properties were measured for several Ga, Zn, Cu, Ni and Co isotopes. The data include new half-lives for ^{75}Co, ^{77,78}Ni and ^{80}Cu, along with new P_n values for ^{78}Ni and ^{80}Cu.

As shown in Fig. 3, the inclusion of the new data in classical r-process models leads to a better agreement of the calculations with observed abundances in the $A = 78 - 80$ region; in particular, the strong odd-event effect between $A = 78$ and $A = 79$ is now well reproduced. In addition, when the previously used theoretical $T_{1/2}$ of ^{78}Ni [31] is replaced by the new measured half-life in classical models, the predicted abundance pattern changes significantly, even at the $A = 195$ peak.

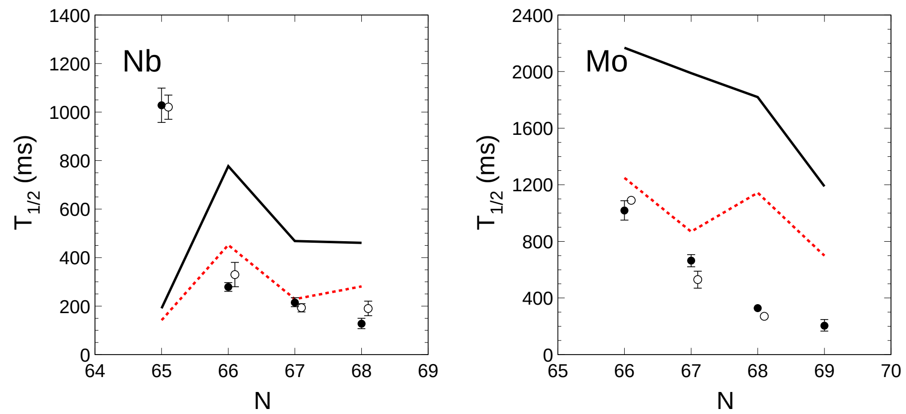

Figure 2. Measured β-decay half-lives of Nb and Mo isotopes (filled circles), compared with results from previous experiments (see [12] and references therein) (open circles). For the sake of clarity, the latter were shifted to the right by 0.1 units. The data are compared with QRPA result obtained using deformations calculated with FRDM (solid line), and FRLDM (dashed line).

5. Conclusions

A series of r-process motivated β-decay experiments have been undertaken at the National Superconducting Cyclotron Laboratory for the last years. New $T_{1/2}$ were measured for ^{75}Co,

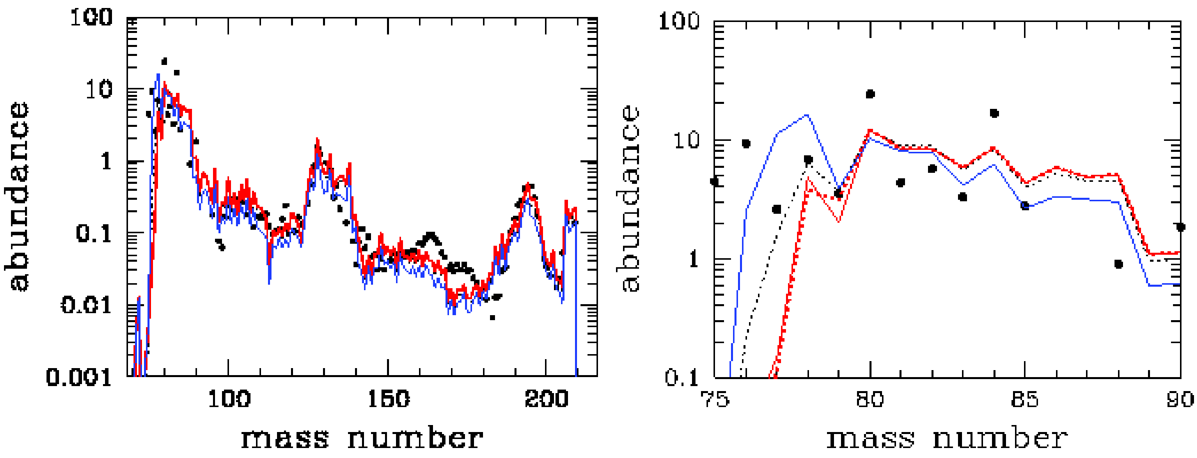

Figure 3. Solar-System r-process abundances (black solid points) compared with calculations using: old β-decay data (black dotted line); new $T_{1/2}$ and P_n data from this work (red solid line); and new β-decay half-lives, but old P_n values (red dashed line). The thin solid blue line corresponds to a calculation with the ^{78}Ni half-life calculated by [31].

^{77,78}Ni, ^{80}Cu, ^{90}Se, ^{105}Y, ^{106,107}Zr and ^{111}Mo, along with new P_n of ^{78}Ni, ^{80}Cu, ^{104}Y, ^{109,110}Mo and P_n upper limits for ^{105}Y, $^{103-107}$Zr and ^{108,111}Mo.

The measured $T_{1/2}$ and P_n upper limits of $^{104-106}$Zr were studied, using QRPA-based calculations as a function of quadrupole deformation. The calculated $T_{1/2}$ and P_n were found to increase monotonically as a function of quadrupole deformation. In the case of ^{104}Zr, the data could be reproduced for deformations significantly smaller than the values obtained from spectroscopic analysis. This finding points to the possible presence of spherical or weakly-deformed low-lying intruder state coexisting with a highly-deformed ground state of ^{104}Zr. The persistence of such intruder states for these mid-shell isotopes may be related with the emergence of a new $(Z = 40, N = 70)$ doubly semi-magic isotope ^{110}Zr. The mechanism responsible for the magic character of ^{110}Zr leads also to the quenching of the $N = 82$ shell for r-process nuclei.

As for the measurements in the $A = 70 - 80$ region, the measured $T_{1/2}$ of ^{78}Ni turned out to be significantly smaller than the theoretical value typically used in r-process models. The replacement of the old value by the new measured data in these models had a strong impact in the calculated r-process abundance pattern, even at the $A = 195$ peak. In addition, the inclusion of the new $T_{1/2}$ and P_n in classical r-process models led to a better agreement of the calculations with observed abundances in the $A = 78 - 80$ region. No significant influence of the new data was found in the $A = 160 - 180$ double-peak region, though.

Further studies of the nuclei investigated in the present experiments have to wait until β-delayed γ-spectroscopic measurements are possible with the advent of new high-intensity fragmentation-beam facilities based on FRIB/FAIR/RIBF concept. These facilities will also enable the measurement of $T_{1/2}$, P_n and nuclear masses for most of the r-process nuclei involved in the synthesis of the $A = 130$ peak.

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