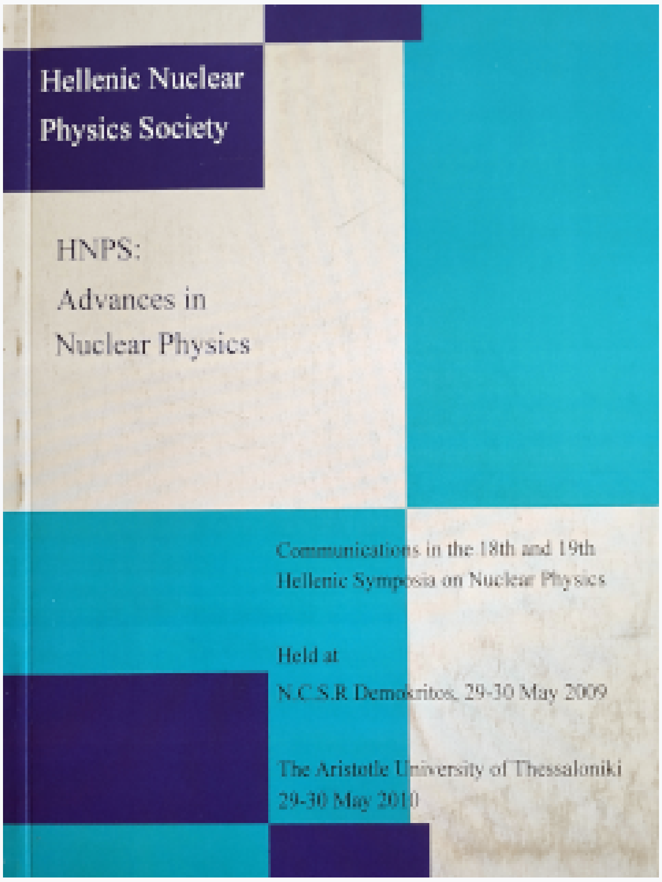
HNPS Advances in Nuclear Physics

Vol 18 (2010)

HNPS2010



β− -Decay Half-lives Using the ANN Model: Input for the R-Process

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doi: 10.12681/hnps.2537

β^--Decay Half-lives Using the ANN Model: Input for the R-Process

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Abstract

Full understanding of nucleosynthesis via the r-process continues to be a major challenge for nuclear astrophysics. Apart from issues within astrophysical modeling, there remain significant uncertainties in the nuclear physics input, notably involving the β-decay halflives of neutron-rich nuclei. Both the element distribution on the r-process path and the time scale of the r-process are highly sensitive to β^- lifetimes. Since the majority of nuclides that lie on the r-process path will not be experimentally accessible in the foreseeable future, it is important to provide accurate predictions from reliable models. Toward this end, a statistical global model of the β^--decay halflife systematics has been developed to estimate the lifetimes of nuclides relevant to the r-process, in the form of a fully-connected, multilayer feedforward Artificial Neural Network (ANN) trained to predict the halflives of ground states that decay 100% by the β^- mode. In predictive performance, the model can match or even surpass that of conventional models of β-decay systematics. Results are presented for nuclides situated on the r-ladders $N = 50$, 82 and 126 where abundances peak, as well as for others that affect abundances between peaks. Also reported are results for halflives of interesting neutron-rich nuclides on or towards the r-process path that have been recently measured. Comparison with results from experiment and conventional models is favorable.

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1. Introduction

Nucleosynthesis through the r-process produces more than half of the heavy elements beyond iron. Command of the quantitative details of this process is one of the most exciting and challenging goals of modern nuclear astrophysics [1, 2]. Its astrophysical site as well as the necessary nuclear physics input are yet to be unambiguously identified. A knowledge of β^--decay halflives T_{β^-} of heavy neutron-rich nuclides are of primary importance for a full understanding of the r-process, since they play a crucial role in determination of the time scale for matter flow and of the abundances of heavier nuclei. In the classical waiting-point approximation, T_{β^-} values are particularly important for the r-ladder isotones $N = 50$, 82, and 126 where abundances peak. In the latter dynamical r-process models T_{β^-} of all nuclides are involved.

In recent years, significant progress has been made experimentally toward determination of β^- halflives of r-process nuclides, and there are ambitious plans for further measurements at existing and new-generation facilities such as FAIR/GSI, FRIB/NSCL, and RIBF/RIKEN [1]. Still, the majority of the neutron-rich nuclides involved will remain inaccessible in the near future. Thus, continued progress rests on reliable predictions from models of nuclear systematics, based on fundamental theory or otherwise. A number of useful approaches to modeling β^- lifetimes have been proposed and applied to different regions of the nuclear chart. These include the shell-model calculation of Ref. [3] and models based on the proton-neutron Quasiparticle Random-Phase Approximation (*pn*QRPA). Important among the latter are the hybrid model by Möller et al., which combines the *pn*QRPA model with the statistical Gross Theory of *ff* decay (*pn*QRPA+*ff*GT) [4], the model by Borzov et al. in which the continuum QRPA is based on a self-consistent density-functional description of the ground-state properties (DF3+CQRPA) [5], and the relativistic *pn*QRPA model of Ref. [6] (*pn*RQRPA+*ff*). Although there is continuing improvement, the predictive power of these "theory-thick" models is rather limited far from stability. This being the case,"theory-thin," data-driven statistical modeling based on artificial neural networks (ANNs) and other adaptive techniques of statistical inference presents a potentially effective alternative for global modeling of β^--decay lifetimes, as it does for other nuclear properties. Here we apply our recently developed ANN statistical global model of T_{β^-} systematics [7] to nuclides relevant to the r-process. The essentials of this model are sketched in Sec. 2. Results are presented and discussed in Sect. 3, with concluding remarks in Sec. 4. (Further details can be found in Ref. [8].)

2. The Model

The fully-connected feedforward Artificial Neural Network (ANN) of Ref. [7] with architecture symbolized by [3-5-5-5-5-1—116] has been employed to generate T_{β^-} values for r-process nuclides. Based on existing lifetime data, this network has been taught with the Levenberg-Marquardt backpropagation optimization algorithm, supplemented by a combination of two well-established techniques, namely Bayesian regularization and cross-validation to avoid overfitting effects. The activation functions of the processing units (model neurons) of the network are taken to be of hyperbolic-tangent sigmoid form in the four intermediate (hidden) layers, a saturated linear function being chosen for the single neuron of the output layer. Inputs to the network consist of the proton and neutron numbers Z and N of the parent nucleus, together with an extra parity input coding the δ-parameter, defined as the mean of the parities of Z and N. Implementation of this parity unit helps to soften the discrepancies in performance induced by pairing gaps. The experimental data used in our β^--decay modeling have been taken from the Nubase2003 evaluation of nuclear and decay properties [9]. We restrict attention to the ground states of parent nuclei that decay 100% by the β^- mode. Additionally, we apply a cut-off at 10^6 s. Without detriment to the prediction of β^- halflives, this creates a more homogeneous collection of nuclides, which facilitates training of the network. We arrive at a data set called NuSet-B consisting of 838 nuclides, which is divided randomly into three subsets, with 503 nuclides (60%) used for training the network (learning set) and 167 (20%) used to assess the training procedure (validation set), the residual 168 (20%) being reserved to evaluate the accuracy of prediction (test set). In direct comparison with the experimental data, the ANN performance measured by the root-mean-square error $\sigma_{\rm rms}$ attains the values 0.53 (learning), 0.60 (validation) and 0.65 (test).

3. Results and Discussion

We now present some results for β^--decay halflives of nuclides relevant to the r-process, obtained by implementation of the ANN model described in the preceding section. As mentioned in the introduction, knowledge of T_{β^-} values for nuclides with $N = 50$, 82 and 126 plays a key role in understanding the process. Fig. 1 displays results for these isotones in interesting Z regions, together with the available experimental results [9, 10] and T_{β^-} values given by the *pn*QRPA+*ff*GT [4], DF3+CQRPA [5], and shell-model calculations [3]. In most cases our values are smaller than those provided by the *pn*QRPA+*ff*GT model, which would imply a corresponding speedup of the r-process. Information on β^- decay of other neutron-rich nuclides is also important for studies of r-process nucleosynthesis. Accordingly, Fig. 1 presents halflife results from our model for known and unknown nuclides of the isotopic chain of Ir, in comparison with the available experimental values [9, 14] and results from the *pn*QRPA+*ff*GT [4] and DF3+CQRPA [5] calculations. The predictive performance of the ANN model can be further assessed in terms of recently measured β^--decay lifetimes of neutron-rich nuclides [8-12]. The corresponding halflife results are included in Table 1, along with those given by the *pn*QRPA+*ff*GT [4] and DF3+CQRPA [5] models. For these nuclides, the $\sigma_{\rm rms}$ for the ANN and *pn*QRPA+*ff*GT models are 0.45 and 0.77, respectively.

4. Conclusion and Prospects

Our data-driven, theory-thin, statistical global model of β^--decay halflives, and its successors, can provide a robust tool that complements the conventional r-process clock and matter-flow studies. We plan further statistical modeling of nuclear properties relevant to the r-process, including masses and neutron-capture cross sections, based on existing artificial neural network (ANN) techniques and support vector machine (SVM) approaches [15]. Refinement of current treatments will be sought through committee-machine strategies, in which different ANNs are built to process input patterns and vote on the proper output.

5. Acknowledgments

The authors thank I. N. Borzov and T. Marketin for communicating with theoretical data and for helpful discussions. This research has been supported in part by the University of Athens under Grant No. 70/4/3309.

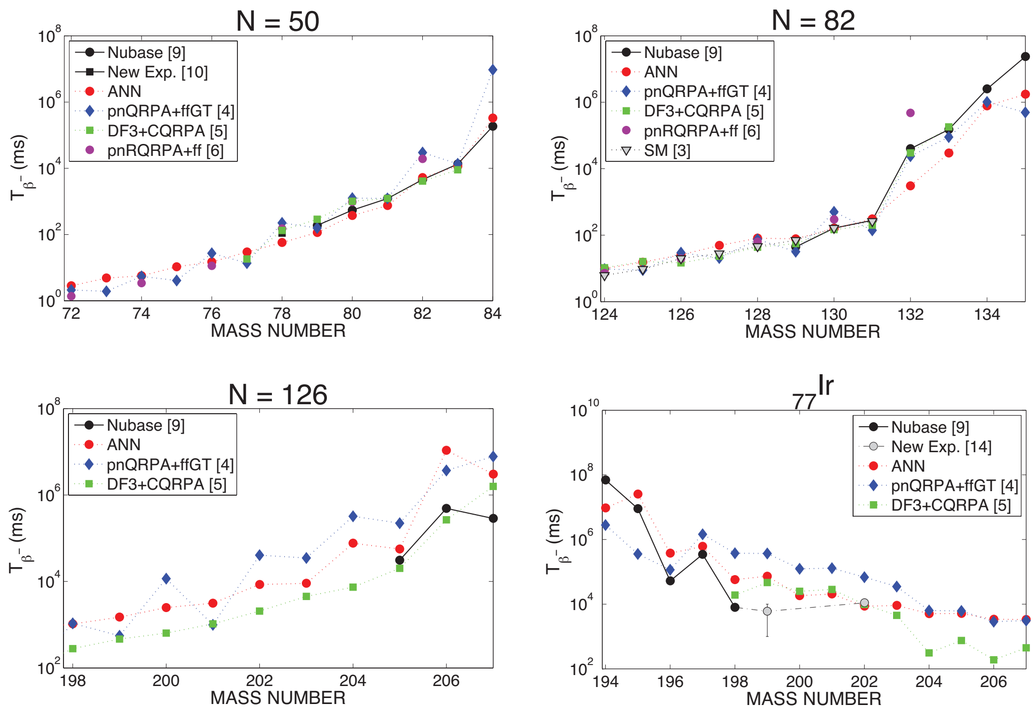

Figure 1: β^--decay halflives given by the ANN model for the r-ladder isotonic chains at $N = 50$, 82 and 126 and for the isotopic chain of Ir, in comparison with experimental and theoretical data.

		$T_{\beta^-}(ms)$		
Nucleus	**Exp. Data**	**ANN Model**	***pn*QRPA+*ff*GT**	**DF3+CQRPA**
a.) $N = 50$ **- P. T. Hosmer et al. (NSCL, MSU) 2005 [10]**				
^{78}Ni	110^{+100}_{-60}	57	224	108
b.) $N \simeq 66$ **- J. Pereira et al. (NSCL, MSU) 2009 [11]**				
^{105}Y	$160 \pm 15^{+85}_{-60}$	58	46	-
^{106}Zr	$260 \pm 20^{+35}_{-30}$	106	322	-
^{107}Zr	$150 \pm 5^{+40}_{-30}$	75	177	-
^{111}Mo	$200 \pm 10^{+40}_{-35}$	145	808	146
c.) $N \simeq 82$ **- F. Montes et al. (NSCL, MSU) 2006 [12]**				
^{115}Tc	73^{+32}_{-22}	84	71	134
^{116}Ru	204^{+32}_{-29}	188	540	193
^{117}Ru	142^{+18}_{-17}	129	163	127
^{118}Ru	123^{+48}_{-35}	69	212	95
^{119}Rh	171 ± 18	209	108	146
^{120}Rh	136^{+14}_{-13}	196	83	-
^{121}Rh	151^{+67}_{-58}	91	62	87
^{121}Pd	285 ± 24	334	1275	262
^{122}Pd	175 ± 16	227	951	184
^{123}Pd	174^{+38}_{-34}	149	397	143
^{124}Pd	38^{+38}_{-19}	124	289	105
d.) $N \simeq 82$ **- K.-L. Kratz et al. (ISOLDE, CERN) 2005 [13]**				
^{133}Cd	57 ± 10	57	185	47
^{138}Sn	150 ± 60	113	336	240
e.) $N \simeq 126$ **- T. Kurtukian-Nieto et al. (FRS, GSI) 2009 [14]**				
^{194}Re	$1^{+0.5}_{-0.5}$ (s)	20.8 (s)	70.8 (s)	2.1 (s)
^{195}Re	6^{+1}_{-1} (s)	23.9 (s)	3.3 (s)	8.5 (s)
^{196}Re	3^{+1}_{-2} (s)	8.8 (s)	3.6 (s)	1.4 (s)
^{199}Os	5^{+4}_{-2} (s)	13.6(s)	106.8 (s)	6.6 (s)
^{200}Os	6^{+4}_{-3} (s)	21.7 (s)	187.1 (s)	6.9 (s)
^{199}Ir	6^{+5}_{-4} (s)	73 (s)	370.6 (s)	46.7 (s)
^{202}Ir	11^{+3}_{-3} (s)	8.6 (s)	68.4 (s)	9.8 (s)
	$\sigma_{\rm rms}^{Log_{10}T_{\beta^-}}$	**0.45**	**0.77**	**-**

Table 1: β^--decay halflives of newly measured r-process nuclides beyond Nubase as given by the ANN model, in comparison with experimental values and results from the *pn*QRPA+ffGT [4] and DF3+CQRPA [5] calculations.

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