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A. Aprahamian

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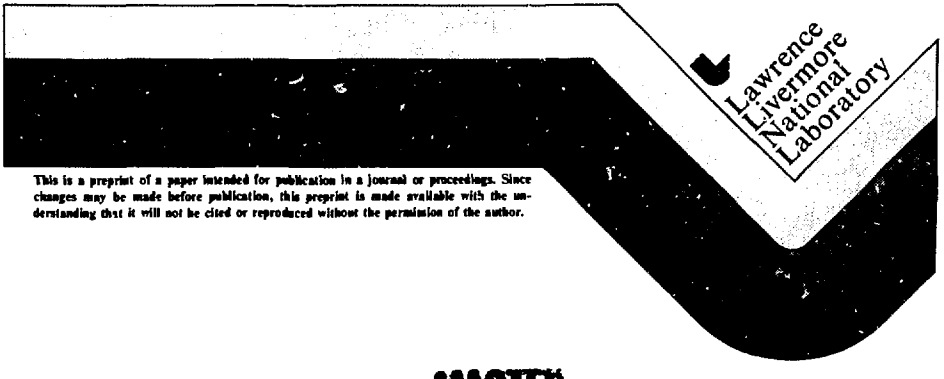

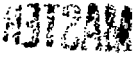

Nuclear Properties Along the r-Process Path

A. APRAHAMIAN
Lawrence Livermore National Laboratory
Livermore, California 94550
USA

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ABSTRACT

The uniformity of different nuclear regions as a function of the number of valence protons and neutrons (counted from the nearest closed shell) has been exploited for the parameterization of calculations for nuclei far from stability within the IBA model. Predictions are given for low lying levels, E2 transition rates, and binding energies for nuclei in the r-process path in the A ≈ 150 and A ≈ 190 mass regions

An important component of the present ambiguity on the site and path of the r-process is due to the uncertainties in the required input of nuclear properties.[1] The nuclei involved in the r-process are generally far from stability on the neutron-rich side and therefore not easily accessible to measurements. In these cases, crucial information on nuclear binding energies excited states, β decay rates, fission barriers and yields have to be determined by extrapolation from the known properties of nuclei closer to stability or by predictions resulting from model calculations. Both approaches have their inherent limitations since the parameters of the models or the actual measured values provide only a crude guide to unknown nuclei. This is easily seen in comparisons of calculated nuclear masses and newly measured values where disagreements can easily be in the order of 3 MeV.[2]

Recently, it has been shown[3] that complex nuclear systematics can be enormously simplified when viewed as a function of the valence neutron-proton product (N_pN_n) instead of N, Z, or A. One of the most important features of the N_pN_n scheme is the conversion of the extrapolation process into a more reliable one of interpolation. The purpose of this paper is to exploit this idea in parametrizing collective model calculations by N_pN_n and thereby predict the properties of nuclei along the r-process path near the abundance peaks at A=150 and 190.

The N_pN_n scheme is based on the role of the neutron-proton interaction in determining nuclear structure in heavy nuclei. A number of recent studies[3,4,5] have shown that the n-p interaction is the controlling agent for the onset of deformation, the development of collectivity, and the structure of nuclear phase transitions. A simple illustration of the idea is shown in Fig. 1. A traditional plot of the first 2^+_1 energies for a series of nuclei in the A = 150 region are shown to the left sides of the figure. What

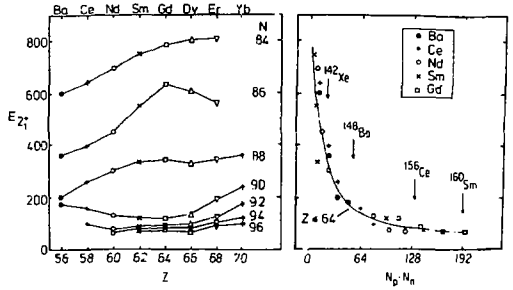

Fig. 1 Systematics of the $E_{2_1^+}$ ratios in the A = 150 region.

is observed is a complicated function of Z. The right side of Fig. 1 shows the same data as one smooth function of N_pN_n, the product of the number of valence protons and neutrons (counted as holes past midshells or midsubshells where appropriate). Similar simplifications also occur in the A = 100, A = 130, A = 190, and A = 230 nuclear regions. Furthermore, comparisons of N_pN_n plots for all of the above transition regions behave in a similar way. A collection of the curves for five mass regions is shown in Fig. 2 for the $E_{4_1^+/2_1^+}$ ratios. There are only small differences in slope, otherwise the curves are nearly identical. These results have two very significant implications.

First, the existence of a single smooth curve for a given region greatly facilitates making predictions even if only a few points are

known. Often, the N_pN_n values of many nuclei far off stability are less than those of some well known nuclei close to stability. For example the ^{166}Ba nucleus is 28 neutrons away from the last Ba isotope but it has an N_pN_n value of 96 which lies in well defined regions of both N_pN_n curves shown in Figs. 1 and 2. In this way, the properties of unknown nuclei far off stability can be determined by interpolation of known values.

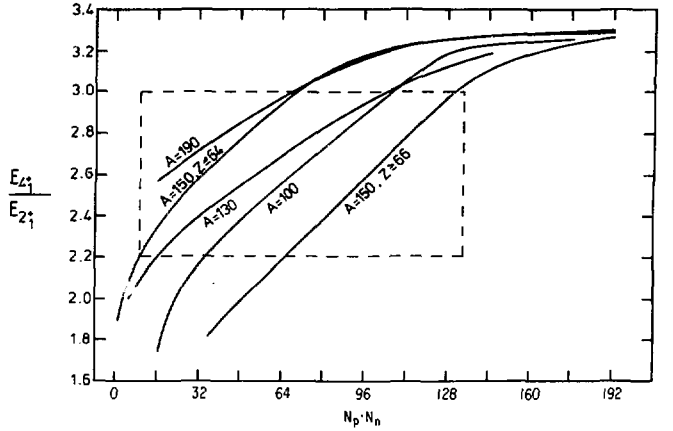

Fig. 2 Plot of the five N_pN_n curves associated with the labelled amss regions.

The second effect of the N_pN_n approach is in the parameterization of model calculations. If a nuclear region can be described so simply, then the parameters of a given model may be written as a function of N_pN_n and allow a unified description of a whole region. This idea was demonstrated in the calculations of 70 known nuclei in the A = 150 mass region within the IBA[4] framework with a set of five fixed parameters with excellent agreement.

Figure 3 shows the empirical and calculated vales for the $E_{4_1^+/2_1^+}$ ratio in the A = 150 region. The calculations clearly reproduce the empirical behavior within the region.

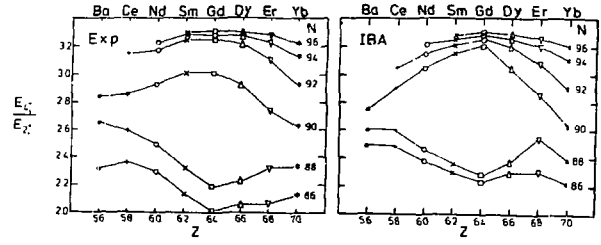

Fig. 3 Empirical and calculated $E_{4_1^+}/E_{2_1^+}$ ratios for the A = 150 region.

Therefore, for select regions of nuclei which are well reproduced by these calculations, the extrapolation-interpolation inversion can be used to yield predictions for unknown nuclei. These calculations have been carried out within the framework of the Interacting Boson Approximation for approximately 50 nuclei in the regions near the r-process abundance peaks at A = 150 and A = 190. Figure 4 shows the sequences of unknown nuclei that have been calculated.

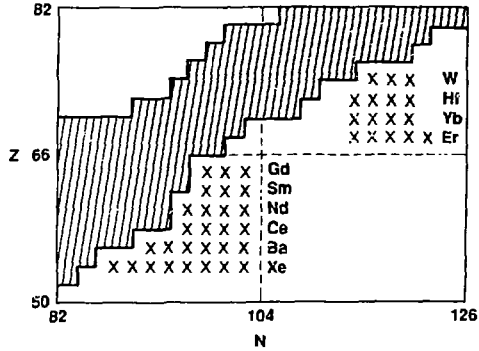

Fig. 4 The relevant portion of the N-Z plane. The shaded parts indicate known nuclei. The x's show the calculated nuclei.

Both of the chosen regions are spherical → deformed in character or in terms of the IBA, U(5) → SU(3) transition regions. The Hamiltonian for such a transition region in the IBA is simply written as

$$H = \varepsilon n_d - \kappa Q.Q \qquad (1)$$

where

$$Q = (s^+\tilde{d} + d^+s) + \sqrt{\frac{1}{5}}\,\chi\,(d^+\tilde{d})^2. \qquad (2)$$

The U(5) or vibrational limit results if $\kappa = 0$ and the SU(3) or rotor limit results when $\varepsilon = 0$. The parameterization of the ε as a function of N_pN_n is written in the following way[4]

$$\varepsilon = \varepsilon_0\, e^{-\theta(\frac{N_pN_n}{4} - N_0)}\,. \qquad (3)$$

with the parameters ε, θ, and N_0. In each region, the calculations were performed by keeping all of the 5 parameter (κ, χ, ε_0, θ, and N_0) constant and simply varying the ε as a function of N_pN_n.

The predicted results yield the complete spectrum of energies and spins of excited states, B(E2) transition strengths and binding energies. Some samples of the results for both A = 150 and A = 190 are shown in Figs. 5a, b where unknown nuclei are plotted as data points on a solid N_pN_n curve which is determined by known nuclei.

The total binding energy of a nucleus is conventionally expressed as a sum of macroscopic and microscopic contributions. The macroscopic component is well understood since it results mainly from the "liquid drop-like" properties of the nucleaus. The microscopic part is typically 10-15 MeV in magnitude and it is due to nuclear structure effects which have been to date very difficult to predict. The present calculations essentially give the microscopic contribution to the total binding energy. The total binding energy for an isotopic chain is written as,

$$\text{Binding Energy} = C + AN_n + BE_{IBA}$$

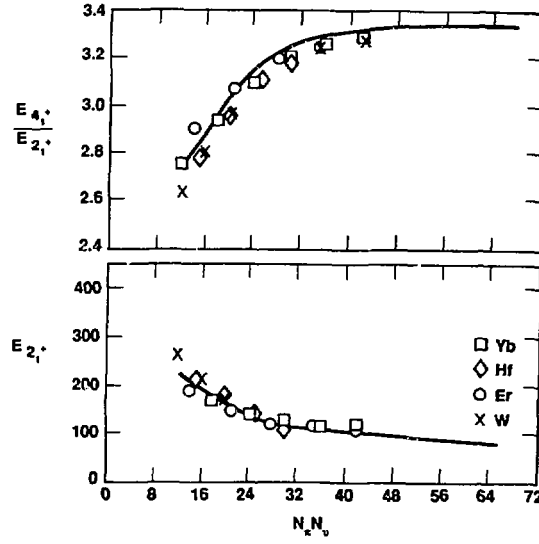

Fig. 5a,b The calculated $E_{2_1^+}$ energies and $E_{4_1^+}/2_1^+$ ratios for unknown nuclei in the A=190 region. The solid lines represent the N_pN_n systematics of known nuclei in the same region.

where C and A are constants, N_n is the number of valence neutrons and BE_{IBA} is the calculated structure contribution. The parameters C and A are determined from measured binding energies and then used along with the calculated BE_{IBA} to yield the binding energies of isotopes far from stability. The results for A = 150 region are shown in Fig. 6.

The calculated and measured values for this region are in excellent agreement. These predictions however represent only a preliminary attempt at calculating crucial nuclear properties along the r-process path. The N_pN_n approach is worthy of further investigation since it represents a unique tool for parametrization of nuclear models and therefore a reliable

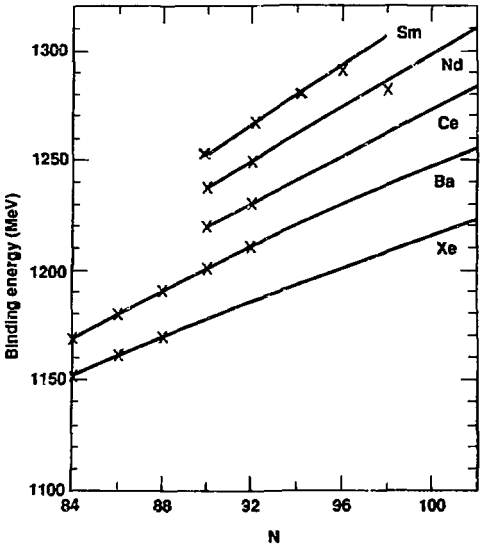

Fig. 6 The total binding energies for select nuclei from the A=150 region. The x's indicated measured values while the solid lines are the predictions.

method for predictions of nuclear properties far from stability. Also, the use of the IBA model allows calculations of the complete nuclear excitation structure, and decay strengths as as well as the binding energies.

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