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Brief Reports

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than $3\frac{1}{2}$ printed pages and must be accompanied by an abstract.*

Level structure of ^{148}Ba: A test of the N_pN_n scheme far off stability

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The deformed nucleus ^{148}Ba (populated in ^{148}Cs decay) is the heaviest $Z=56$ and the lightest $N=92$ nucleus known; thus its levels are extrapolations of both Z and N systematics. Values for $E(2_1^+)$, $E(4_1^+)/E(2_1^+)$, and $E(2_2^+)$ are in excellent agreement with interpolative predictions from systematics of the valence-nucleon product N_pN_n.

It was recently shown[1–3] that a remarkable simplification in the systematics of low-lying collective energy levels in nuclei could be achieved by displaying the data in terms of the valence-nucleon product N_pN_n rather than the usual parameters Z, N, or A. The simplification provided by this scheme was shown to work well in diverse nuclear regions[1–3] and gives added significance to the underlying concept of the importance, in all nuclear regions, of the neutron-proton interaction in determining the characteristic collective structure. More recently, other tests[4–6] of the N_pN_n scheme have reiterated its usefulness, at least as far as known nuclei are concerned.

A concept of such potentially great predictive power for nuclear structure, however, needs to be tested in heretofore unknown nuclei in order to refine and extend it. For many nuclei far from stability, level structure can be predicted[7] via *interpolation* in N_pN_n rather than *extrapolation* in Z, N, or A. The purpose of this paper is to present new data on ^{148}Ba, which enables us to test the N_pN_n scheme in a heretofore unknown region of the nuclide chart. Since ^{148}Ba is the heaviest $Z=56$ isotope and lightest $N=92$ isotone known, it is an extrapolation of both Z and N systematics. In contrast, its N_pN_n value of 60 places it near the middle of known $A\sim150$ nuclei, for which $0\lesssim N_pN_n\lesssim200$.

The levels in ^{148}Ba have been determined from recent studies of the decay of ^{148}Cs at the TRISTAN on-line mass separator[8] at Brookhaven National Laboratory. The measurements included γ singles, γ-γ coincidences, and time-sequential γ spectra. The latter were used to identify ^{148}Cs γ rays and to measure a ^{148}Cs half-life of 158 ± 7 ms. Prior to this work no information on ^{148}Ba had been published, except for the inclusion of an $E(2_1^+)$ value in a contribution[9] on the mass dependence of relative fission fragment yields. The assignments for the negative parity levels are based on their decay pattern and systematics in the $A\sim150$ region. A level scheme for ^{148}Ba is given in Fig. 1, which includes complete information on the positive parity states. The present discussion will concentrate on positive parity levels and their relation to the N_pN_n scheme.

The N_pN_n scheme was introduced and applied to transitional nuclei in mass regions $A\sim100$, $A\sim130$, and

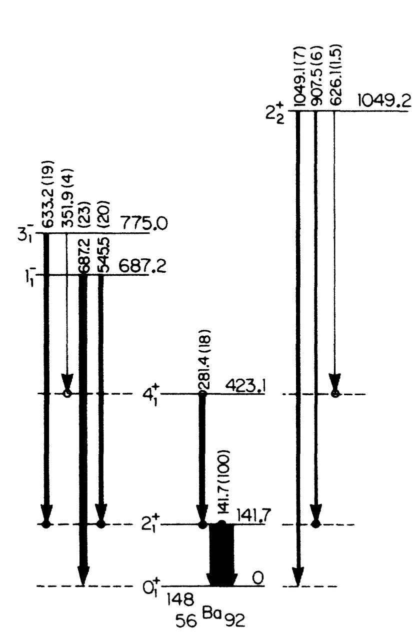

FIG. 1. Partial level scheme of ^{148}Ba, showing low-lying members of the ground and excited bands. Relative γ-ray intensities are shown in parenthesis. Coincidences are indicated by solid circles and possible coincidences by open circles.

$A \sim 150$ in Ref. 1. It was shown in Ref. 2 to also apply to the $A \sim 190$ region. In Ref. 3 a more detailed discussion of all regions is given. The contrast between interpolations in N_pN_n and extrapolations in Z, N, or A is discussed in Ref. 7. In the following we briefly review the main ideas.

The importance of the proton-neutron interactions has long been emphasized, in particular by Talmi[10] and Federman and Pittel.[11] In Ref. 11 the sudden and abrupt onset of deformation for $A \sim 100$ nuclei was explained as a consequence of strong p-n interactions. In Ref. 12 this idea was used to reinterpret the $A \sim 150$ region in light of the proton shell closure at $Z=64$. The N_pN_n concept recognizes the importance of the p-n interaction and assumes that the valence-nucleon product N_pN_n provides a qualitative measure of its strength.[1]

The valence nucleons N_p or N_n are simply the number of particles (or holes if past midshell) relative to the closed shells. For particularly strong subshells, it is necessary to include subshell closure in determining the valence nucleons. This was shown[1–3] to be of crucial importance for certain mass regions. For example, in the $A \sim 100$ region the remarkable unification in the N_pN_n systematics of $E(2_1^+)$, $E(4_1^+/2_1^+)$, $E(2_2^+)$, and $B(E2, 2_1^+ \rightarrow 0_1^+)$ results from the simple assumption that a $Z=38$ shell closure exists for $N<60$ but vanishes for $N \geq 60$. (The major shell closures at $Z=28$ and 50 are valid for all N.) With this simple assumption for the N_pN_n plots, the data points of each plot fell on a well-defined smooth curve. The smooth curves, and the slight deviations from them at $N=60$, are discussed in Ref. 3.

The $A \sim 150$ region is the most widely studied and best known of all the regions to which the N_pN_n scheme has been applied. The extensive series of nuclei in this region can be considered to comprise two distinct groups corresponding to elements below and above the proton midshell at $Z=66$. For the $Z \leq 64$ group, shell closure at $Z=64$ must be recognized. (Similarly, in Ref. 4, the behavior of the $Z=64$ subshell for $N<78$ was demonstrated in an N_pN_n analysis.) As in the $A \sim 100$ case, there is a well-known change in proton subshell structure as a function of neutron number. The $Z=64$ shell closure exists for $N<90$ but vanishes for $N \geq 90$. (Major shell closures at $Z=50$ and 82 are valid for all N.) However, for the proton-hole group with $Z \geq 66$, no shell closure at $Z=64$ was assumed, as discussed in Ref. 3. Thus the N_pN_n scheme for $A \sim 150$ nuclei results in a pair of smooth curves: one for $Z \leq 64$ and one for $Z \geq 66$. Such changes must be taken into account in counting the number of valence protons. However, this has no effect for Ba, since in this case $Z=56$ is closer to $Z=50$ than to $Z=64$.

Figures 2–4 present, for $A \sim 150$ nuclei, systematics of $E(2_1^+)$, $E(4_1^+)/E(2_1^+)$, and $E(2_2^+)$. These figures were taken from Ref. 3 and our new ^{148}Ba points added. Our Fig. 4 corrects some plotting errors for Ce in the 2_2^+ figure of Ref. 3 and also includes inadvertently omitted data points for ^{146}Ba and ^{152}Nd.[13] When plotted correctly, the Ce points are much closer to the smooth 2_2^+ curve than they were in Ref. 3. Features of the smooth curves for the N_pN_n parts of these figures as well as deviations at $N=90$, 92, and 94 are discussed in detail in Ref. 3. For the present, the most important point to note is that smooth curves are well established by many data points in Figs. 2–4.

Predicting properties, such as energy levels or transition probabilities, of unknown nuclei is fraught with uncertainty, especially if the prediction requires an extrapolation from known nuclei. In the recent past, reliance was placed upon structure indicators, such as $E(2_1^+)$, plotted as systematic functions of Z, N, or A. If transitional regions were not involved, such plots (which could differ markedly from region to region in the nuclear chart)

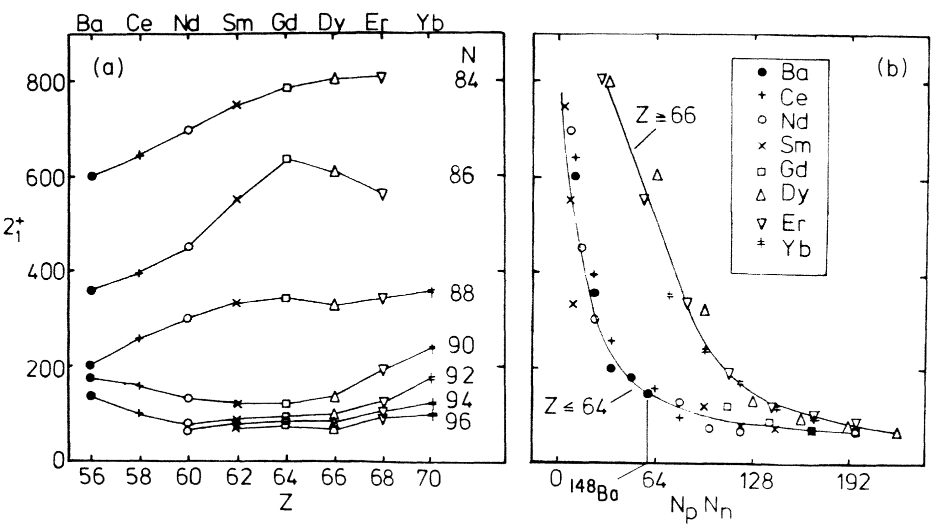

FIG. 2. $E(2_1^+)$ systematics for even-even nuclei in the $A \sim 150$ region plotted against (a) proton number Z and (b) the valence-nucleon product N_pN_n. Points for ^{148}Ba are indicated in (b) and in the following figures by a vertical line projected to its N_pN_n value of 60.

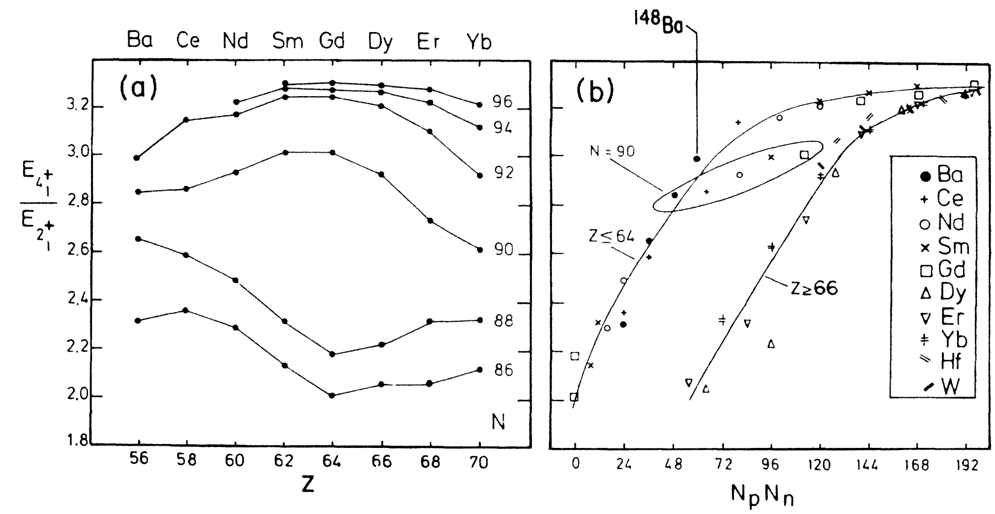

FIG. 3. $E(4_1^+)/E(2_1^+)$ systematics for even-even $A \sim 150$ nuclei. (See Fig. 2 caption.)

could be successful predictors, but have generally been found to be reliable only in hindsight. In contrast, the N_pN_n systematics smoothly span vibrational and rotational nuclei in a similar manner for diverse nuclear regions;[1–3,7] thus more accurate predictions should be expected from N_pN_n systematics.

We present here the *first test* of an extension of the N_pN_n scheme into an unexplored region of the nuclide chart. In this case extrapolations in N, Z, or A are quite uncertain, as can be seen from the left-hand sides of Figs. 2–4. $E(2_1^+)$ could easily range from 100 to 170 keV, $E(4_1^+)/E(2_1^+)$ from 3.0 to 3.2, and $E(2_2^+)$ from 1000 to 1600 keV. Indeed, a prediction by extrapolation for $E(2_2^+)$ is particularly uncertain for ^{148}Ba since the nearest isotone (^{150}Ce) does not have a known 2_2^+ level. In contrast to this difficult situation, Figs. 2–4 show that the important structure characteristics of ^{148}Ba are accurately predicted by the N_pN_n curves. Furthermore, the predictions are made by *interpolations* of the N_pN_n systematics rather than *extrapolations* in N, Z, or A. It is interesting to comment that the measured value for $E(4_1^+)/E(2_1^+)$ of 2.99 is, in fact, a rather unlikely extrapolation of Z,N systematics.

Further tests of the accuracy of prediction via the N_pN_n scheme are urgently needed. Ideal candidates would be other nuclei far from stability. Lower-Z neutron-rich nuclei far from stability are particularly desirable, since they would also be interpolations in the N_pN_n systematics instead of extrapolations in Z or N systematics. (See Ref. 4 for candidates with $50 \le Z \le 82$ and $82 \le N \le 126$.) Such additional tests would certainly probe the generality of the N_pN_n systematics and should also

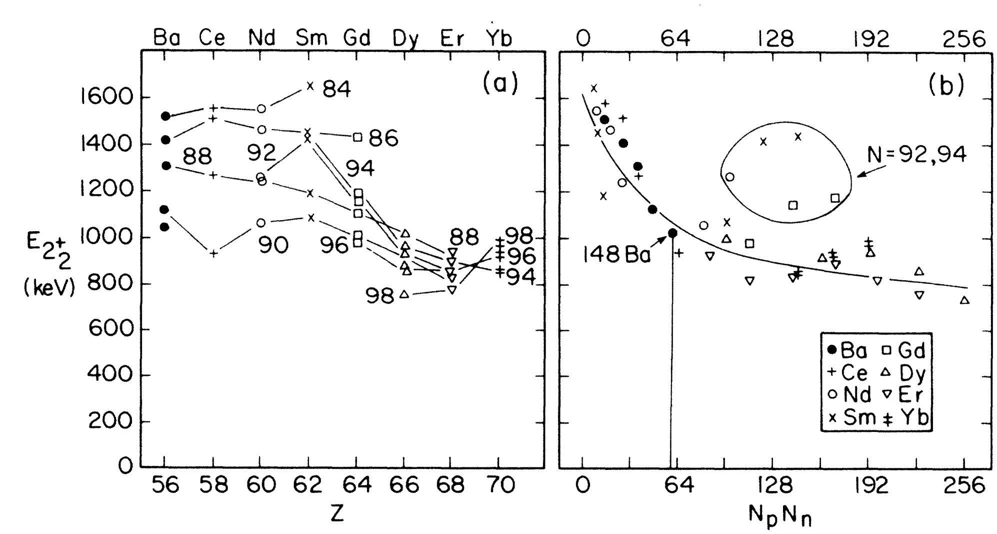

FIG. 4. $E(2_2^+)$ systematics for even-even $A \sim 150$ nuclei. (See Fig. 2 caption.)

lead to further refinements in the application of this remarkably simple indicator of collective nuclear structure. Finally, successful tests that demonstrate the predictive power of the N_pN_n scheme for more nuclei are of great interest in astrophysical calculations of *r*-process nucleosynthesis.

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