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Author

Firestone, R.B.

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R.B. Firestone

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Complex Beta-Decay Schemes:
Pandemonium Lost and Paradise Regained

R.B. Firestone

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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Abstract

The beta decay of ^{145}Gd has been studied in sufficient detail for comparison with the decay of its fictional analogue Pandemonium. It is shown that >98% of the ^{145}Gd decay intensity was observed. This result casts doubt on the value of decay schemes determined solely by statistical techniques.

The decay of the fictional nucleus Pandemonium has been described by Hardy, Carraz, Jonson, and Hansen⁽¹⁾ (hereafter HCJH). This nucleus was proposed to decay in such a complicated manner, with numerous β -decay branches and γ -ray transitions, that it could not be experimentally studied. Despite the fact that the simulated Pandemonium decay scheme was constructed using a statistical model, without any experimental confirmation, the authors concluded that we "need to reevaluate the usefulness of a whole class of experiments". In view of the gravity of that conclusion, the actual decay of Pandemonium has recently been experimentally investigated⁽²⁾, in detail, to test the arguments put forth by HCJH. It will be shown here that those arguments were too simplistic to describe real decay schemes and that the death knell for such studies is unwarranted.

The decay of the nucleus Pandemonium was based on the decay of ^{145}Gd , which had been incompletely investigated at that time⁽³⁾. HCJH correctly noted that substantial decay-scheme information remained to be observed. To estimate the amount of missing ^{145}Gd β -decay intensity, HCJH applied statistical procedures, adapted from neutron capture resonance studies, to generate the Pandemonium decay scheme. Pandemonium was chosen, like ^{145}Gd , to have $J^\pi = 1/2^+$, and the ^{145}Eu daughter levels were assumed to be $1/2^+$ or $3/2^+$. The $1/2^+$ levels in ^{145}Eu were required to deexcite by single γ -ray transitions through a level at 0.8 MeV (0.808 MeV in ^{145}Eu), and the $3/2^+$ levels by direct transitions to the $5/2^+$ ground state. A decay scheme was generated by Monte Carlo techniques, taking average level densities from Gilbert and Cameron, level separations obeying the Wigner law, and β -transition probabilities generated in a random Porter-Thomas distribution assuming a constant β -decay strength function⁽⁴⁾. This last point was significant in that a constant β -decay strength would effectively remove all nuclear structure from the analysis.

The resulting decay scheme was used to generate a theoretical γ -ray singles spectrum for Pandemonium. This spectrum appeared very realistic and was conventionally analyzed to discover how much experimental information could be extracted from various amounts of data. HCJH concluded that, with "more complete data than most experiments can produce" only 81 of ~ 1000 γ rays would be observed representing 94% of the total γ -ray intensity. They further proposed that this problem would be compounded if additional complexity in the γ -ray deexcitation pattern were included. For the earlier ^{145}Gd decay scheme, HCJH concluded that $\sim 20\%$ of the decay intensity went undetected.

The recent study of ^{145}Gd decay⁽²⁾ has resulted in the placement of 326 γ rays deexciting 136 levels in ^{145}Eu . This decay scheme was constructed primarily from the analysis of a γ -ray singles spectrum with 2×10^9 events and from coincidence data consisting of 1.3×10^7 γ - γ coincidence pairs. These experimental γ -ray singles statistics roughly corresponded to HCJH's best case (10^6 events in the strongest peaks). The actual decay-scheme drawing is too large to be included in this letter and will only be referred to in the following discussion. Four times the number of predicted γ rays were observed and that result was consistent with a very complex γ -ray deexcitation pattern. Indeed, the number of γ rays observed is a meaningless figure because *all* transitions between *every* level will occur with some finite intensity. It is more important that the γ rays observed represent a substantial portion of the total γ -ray intensity. HCJH estimated that 6% of the transition intensity should remain unobserved.

It was possible to measure the efficiency for detecting the γ rays associated with ^{145}Gd decay directly. About 5% of the total β -decay feeds 54 separate transitions that deexcite to $7/2^+$ states at 330- and 1600-keV in

^{145}Eu . Since those states could not be fed directly by any measurable β -decay, the intensity balance through them is a sensitive indicator of the γ -ray detection efficiency. The ratio of γ rays feeding to those deexciting the $7/2^+$ states from ^{145}Gd decay was measured to be 1.01 ± 0.03 indicating that substantially more intensity had been observed than that predicted by HCJH.

The assumed γ -ray deexcitation pattern of HCJH was also found to be incorrect. Only 12% of the deexcitation intensity from the known $3/2^+$ states above 3.0 MeV goes to the ground state, 9% to the $1/2^+$ state at 808 keV, and the remainder scattered to numerous other excited states. No states above 3 MeV were definitely assigned $J^\pi = 1/2^+$; but, for those unassigned levels between 3 and 4 MeV, 50% of the deexcitation intensity goes to the ground state and 25% to the $1/2^+$ state. Unassigned states above 4 MeV deexcite with 16% of their total intensity to the ground state and 17% to the $1/2^+$ state. This deexcitation pattern is far more complex than that assumed by HCJH and is completely opposite in manner from their pattern.

The increased complexity of ^{145}Gd decay should have made it difficult, following the argument of HCJH, to see even as much as 94% of the predicted intensity. Nevertheless, >98% of the decay intensity was actually observed. Therefore, the statistical model chosen by HCJH must in some way have been incorrect. The assumptions they made concerning level densities and separations are generally accepted, although possibly they were not applicable here due to the proximity of closed shells. More important, the assumption of a constant β -decay strength function for the Porter-Thomas distribution appears to have been overly simplistic. In figure 1, the experimental β -strength function for ^{145}Gd ($S(\beta) = I_\beta/ft$ averaged over 200 keV intervals) is plotted. A constant β -strength, even with the broad

topographical features suggested by HCJH, was not observed. Instead, nearly 70% of the total β -strength is directed to a narrow 'resonance' region near 4.5 MeV in ^{145}Eu . This β -strength resonance contains 21 levels with $\log ft < 6.5$ and is fed by $\sim 5\%$ of the total decay despite its high excitation energy in ^{145}Eu . The resonance feeding intensity nearly equals the proposed missing intensity of HCJH. It is likely that the large resonance in the β -strength corresponds to the opening of a neutron shell at 4 MeV⁽²⁾. Thus, the 'missing intensity' was apparently concentrated in a few, strongly fed levels and was not spread evenly over the continuum.

The simple predictions of HCJH have been shown to be incorrect for two major reasons. First, since the experimental spectrum was dominated by simple nuclear structure through which the β -decay intensity was largely funneled, the statistical arguments failed. Analogous behavior has previously been observed for the decay of lighter nuclei in the β -delayed neutron studies of Kratz et al.^(5,6). It was also observed in low-resolution continuum γ -ray studies by Duke et al.⁽⁷⁾, who noted a substantial decrease in the magnitude of the β -strength near $N=126$. Second, the experimental assumptions inherent in the HCJH analysis were extremely pessimistic. Decay schemes cannot be analyzed from γ -ray singles spectra alone. The coincidence data are the primary source of most level-scheme information, especially for complex decay schemes. In these cases many γ rays, poorly resolved in singles, can be uniquely placed into the level scheme using coincidence information. It is often advantageous, in the unraveling of decay patterns, to work with a complex scheme since numerous interlocking coincidences limit the possible level patterns. For ^{145}Gd decay, many γ rays were seen only in the coincidence spectra.

The concept of using statistical analyses to generate decay information is fatally flawed. The assumption that useful knowledge about nuclear structure can be obtained using purely statistical constructs is a dangerous one. Attempts have been made to use statistically generated beta spectra for the analysis of delayed-particle decay⁽⁸⁾ data without any allowance for the effects of nuclear structure. Such an analysis can easily err by many keV, when structure dominates the decay, and should not be used as a substitute for direct measurements.

The statement of HCJH that "every complex β -decay scheme that is based on γ -ray peak analysis and intensity balances must now be regarded as doubtful" does a considerable disservice to the advancement of nuclear science. Their denigration of "the usefulness of a whole class of experiments" fails to acknowledge that, in general, measured γ -ray intensities, energies, multipolarities, and level properties are correct irrespective of the statistical accuracy of the data. Only relative β -feedings were actually questioned by HCJH, and these have been shown here to present tractable problems. An important purpose of nuclear spectroscopy is to study the underlying structure of the nucleus, and it is neither interesting nor necessary to study every level and transition in order to obtain valuable insight. Those who deny the significance of a class of experiments with the expedience of a theoretically derived artifact are indeed doomed to find the hell that is Pandemonium.* Through the initiation of difficult experiments,

**"Let none admire
That riches grow in hell; that soil may
best
Deserve the precious bane."*

John Milton in Paradise Lost I, line 690

such as complex decay studies, the goal of unlocking the mysteries of nuclear structure can be reached and the dawn of a Paradise of knowledge approached.**

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****"And now the herald lark
Left his ground-nest, high tow'ring to descry
The morn's approach and greet her with his song."*

Paradise Regained II, line 161

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Figure Caption

Fig. 1. β -strength function for ^{145}Gd decay summed over all levels at 200 keV intervals. The indicated logft values correspond to the total decay rate to the underlying resonance.

Fig. 1

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