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A COMMENT ON PANDEMONIUM

by

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ABSTRACT

In contradiction with a recent publication, we demonstrate that data on the β -decay of ^{145}Gd confirm in all respects the statistical conclusions derived in 1977 from a computer-simulated decay of the fictional nucleus, Pandemonium. Complex β -decay schemes based on singles spectra of β -delayed γ rays must still be regarded as doubtful.

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Five years ago, we published a letter describing the decay of a fictional nucleus, Pandemonium [1]. Its purpose was to test some of the standard techniques used in the analysis of complex β -decay schemes. We first generated a "realistic" decay scheme using Monte Carlo methods constrained by broad statistical principles known to circumscribe nuclear excitation and decay [2,3]. Next we produced, also by computer, a corresponding spectrum of β -delayed γ -rays, which was then analysed as if it were real experimental data. Finally, the results of this analysis were compared with the known properties of the input decay scheme.

We concluded that a significant fraction of the γ -ray intensity is actually undetectable in a typical β -delayed γ -ray spectrum since it occurs in a multitude of weak, often unresolved peaks. As a consequence, it was suggested that β -transition rates derived by balancing γ -ray intensities cannot be trusted in cases where the decay scheme is potentially complex.

As an illustration, the properties of Pandemonium were chosen to resemble a simplified version of ^{145}Gd , a nucleus whose decay had been determined experimentally via its spectrum of β -delayed γ -rays [4]. The stimulus was a claim by Firestone et al. [5] that several of the β -transitions from ^{145}Gd exhibited very anomalous EC/β^+ ratios. Our analysis of facsimile γ -ray spectra indicated that $\approx 20\%$ of the γ -ray intensity above 1.7 MeV (the assumed safe threshold for statistical behaviour) from ^{145}Gd had likely been missed when the real data were analysed. We asserted [1] that the missing intensity was sufficient to remove the EC/β^+ anomalies.

More detailed experiments [6,7] have confirmed our assertion. Most recently, Firestone et al. have themselves reinvestigated ^{145}Gd decay, and - just as we predicted [1] - have resolved the EC/β^+ anomalies through "the discovery of numerous, weaker EC-fed levels at high excitation in (the daughter) ^{145}Eu " [7]. Indeed, the number of new γ -ray lines and their total intensity agreed remarkably well with our computer simulation.

This agreement seems to have escaped the notice of Firestone, who has now published a stirring attack on our work accusing it, among other things, of doing "a considerable disservice to the advancement of nuclear science" [8]. If his misunderstandings were restricted to the ^{145}Gd decay,

a reply would hardly be warranted since by now the EC/β^+ anomalies are resolved to everyone's satisfaction. However, the study of Pandemonium [1] was aimed more generally at all complex β -decay schemes, and the uncertainties it revealed have not been removed by Firestone's data [7] nor by his impassioned prose [8]. To the extent that his claims falsely detract from the broad applicability of the Pandemonium studies, they must be discounted. It is the purpose of this letter to do so.

The foundations upon which we based our Pandemonium calculations [1,9] are statistical theories originally derived to explain the behaviour of nuclear level spacings and transition probabilities near the neutron binding energy. The original works, which are reprinted in ref. 2 and summarized in ref. 3, are associated with the names of Wigner, Porter, Thomas, Dyson, Mehta and many others. Applications and extensions of nuclear statistical theory to the radiations following complex β -decays have been reported on a number of occasions [11-16].

In applying these theories to the decay of Pandemonium we made only one simplification. Although we required the β -transition intensities from Pandemonium itself to scatter according to a Porter-Thomas number distribution, the subsequent β -decay of each level populated in the daughter was assumed to proceed by a unique branch to the ground or a nearby state. This was intended to account for the expected predominance of nuclear structure over statistical behaviour for low-lying states, and to approximate the experimental results for ^{145}Gd as they were then known [4]. We acknowledged that "actual decay schemes are rarely so simple" [1], but pointed out that greater complexity would only tend to enhance our conclusion by making even less of the γ -ray strength visible as peaks. That the current experimental decay scheme [7] shows an average of 2.5 γ -ray branches from each level, should therefore be regarded neither as a surprise nor as an invalidation of our thesis. This is further demonstrated by the following quantitative tests.

The accuracy of the Pandemonium calculations can now be tested by a comparison of the original ^{145}Gd results [4], which our calculations were meant to simulate, and the more complete results [7] that are now available. Table I of ref. 4 and table II of ref. 7 list the γ -rays (with inten-

sities) observed in each experiment, from which it can be established that 14% of the γ -ray intensity now seen above 1.7 MeV was not observed in the earlier work. Even if we assume that ref. 7 now accounts for all the true γ -ray intensity - an assumption, as we shall see, that is by no means certain - this 14% difference is in fine agreement with our prediction [1] that $\approx 20\%$ of the true intensity had been missed in ref. 4. If the recent data are still incomplete, the agreement is even better.

Superficially, however, the agreement appears less satisfactory when we consider the number of γ -rays instead of their total intensity. Our calculations [1] indicated that a singles γ -ray spectrum with the counting statistics of ref. 6 would yield ≈ 80 peaks above 1.7 MeV, which compares unfavourably with the 262 peaks recorded in table II of that reference. Two factors serve to remove this apparent disagreement. First, the γ -rays listed in ref. 7 were not observed exclusively in singles data, as our calculations assumed; indeed "many of the γ -rays are only observed in coincidence spectra" [7], a statement confirmed by examination of the singles spectrum of fig. 2 in that reference, where ≤ 200 peaks are identifiable above 1.7 MeV. Second, the multiple γ -ray branching, already noted to be 2.5, causes an increase in our calculated number of observed γ -rays by approximately the same factor, thus bringing it into agreement with observation at ≈ 200 lines.

Finally, we turn to the question of completeness of the data in ref. 7. Our calculations [1] indicated that singles spectra of that statistical precision would leave $\approx 6\%$ of the γ -ray intensity still unobserved. Since coincidence data are used extensively in ref. 7, one would therefore expect that even less intensity is missed. Firestone [7,8], nevertheless, makes a strong point out of an experimental test that involves the observed ratio of the total intensity of 54 γ -transitions that populate two $7/2^+$ states (at 330 and 1600 keV) in ^{145}Eu , to the intensity of the two γ -transitions through which they de-excite. Since spin-selection rules forbid the β -feeding of either state, the ratio should equal one if no γ -ray intensity is missed, and be less than one otherwise. He presents the measured ratio as 1.01 ± 0.03 , from which he concludes that $> 98\%$ of the decay intensity was actually observed. Unfortunately, comparison with

the primary data (table II of ref. 7) shows that the ratio should actually be [10] 1.01 ± 0.06 . The corollary, that the data are only demonstrated to be $> 95\%$ complete, now agrees entirely with the Pandemonium calculations.

Even that reduced confidence in the recent data is eroded if we consider the γ -ray feeding-to-decay intensity ratios for the two $7/2^+$ states individually. The 330 keV state is fed by 33 γ -transitions while the state at 1600 keV is fed by 21 transitions; the respective ratios are 1.14 ± 0.09 and 0.87 ± 0.08 . The lower ratio could be interpreted to mean that considerable γ -ray intensity is missing; but the higher ratio, to the extent that it is significantly greater than unity, is quite unphysical. These discrepancies, not mentioned by Firestone [7,8], tend to cancel in the average ratio that he does quote. They leave little cause for confidence in that average, suggesting at best that experimental uncertainties are underestimated and at worst that significant γ -ray intensity has been missed or misassigned.

It should now be evident that, far from discrediting our Pandemonium calculations, the recent data on the decay of ^{145}Gd confirm in every respect the statistical predictions published five years ago. That is not to say that the physical assumptions we made in the absence of good experimental data are all correct in detail. We have already discussed the multiple γ -decay of each level, a possibility we acknowledged at the time; as anticipated, it is seen only to enhance the thrust of our original message. Of even less significance to that message is our assumption of a constant β -strength function. Using his recent data [7], Firestone concludes [8] that the β -strength function exhibits a broad resonance near 4.5 MeV in ^{145}Gd . In general, it is expected that nuclear structure leads to features in the strength function (see footnote 2 in ref. 1) but the statistical scatter of transition probabilities about that function must remain unchanged. The statistical predictions are consequently little affected. To suggest as Firestone does [8], that our predicted 6% missing γ -ray intensity has somehow been found in the strength-function resonance, is to misunderstand the nature of our simulation entirely. We did not measure the strength function and miss the resonance, we created an artificial decay that simply had no resonance. We argued, and still argue, that simple case is sufficient

to prove our point.

The Pandemonium calculation is completely analogous to many other applications of Monte Carlo calculations in physics. It served to test the response and bias of a particular detection method, and we have here shown that the conclusions are confirmed by independent experiments [6-8]. Why then the indignant outcries of which Firestone's found its way into print and others have reached us as private communications ? The answer could be that in matters statistical, the nuclear physicist's intuition remains Gaussian in nature and thus ill suited for comprehending very skew distributions. This difficulty is familiar to neutron physicists, who have not complained about Pandemonium, but who in their hearts probably accuse us of belabouring the obvious. They will most likely concur if we re-state our essential point :

"Conclusions regarding total strength and number of transitions are suspect if based on the analysis of peaks in a complex spectrum unless proper allowance is made for unobserved transitions."

Although here we state it more generally, our original concern [1] was with conclusions specifically regarding γ -decay transition rates. In that context, if our statement needs further verification, the reader can compare the β -decay branchings as they appeared in 1971 (fig. 6 of ref. 4), based on γ -ray singles data, with those that are now quoted in 1982 (fig. 10 of ref. 10) : the differences are drastic.

To end on a more positive note, we cite a few examples to demonstrate that fluctuation analysis has other applications to β -decay and that, although devoid of structural information, it remains an indispensable tool to the experimentalist. Fluctuation phenomena manifest themselves in delayed particle spectra, from which level densities have been deduced [12-14], in average level lifetimes [15] and in particle branching ratios [16], where for the isotopes $^{113,115}\text{Xe}$ the gross ratios of delayed alphas to delayed protons are increased by factors of 2-5 by this effect. Indeed, it is possible to derive [12] an expression for the peak density in a "nuclear noise spectrum"; if we apply that expression to the upper part of the singles spectrum of ref. 8, we obtain 0.22 keV^{-1} , which gives an idea of the number

of peaks that some future reinvestigation of ^{145}Gd might hope to detect.

In short : it may happen, but does not seem likely, that nuclear theory one day will be able to calculate all properties of every level. Until then, we shall need to know statistical nuclear theory. We wholeheartedly agree with R.B. Firestone that "it is neither interesting nor necessary to study every level and transition", but for this approach to work, we must deal with the observed averages in a statistically correct way.

REFERENCES

- [1] J.C. Hardy, L.C. Carraz, B. Jonson and P-G. Hansen, Phys. Lett. 71B (1977) 307.
- [2] C.E. Porter, Statistical Theories of Spectra : Fluctuations (Academic Press, New York, 1965).
- [3] J.E. Lynn. The Theory of Neutron Resonance Reactions (Clarendon Press, Oxford, 1968).
- [4] R.E. Epply, W.C. McHarris and W.H. Kelly, Phys. Rev. C3 (1971) 282.
- [5] R.B. Firestone, R.A. Warner, W.C. McHarris and W.H. Kelly, Phys. Rev. Lett. 33 (1974) 30 and 35 (1975) 401.
- [6] P. Hornshøj, H.L. Nielsen and N. Rud, Phys. Rev. Lett. 39 (1977) 537.
- [7] R.B. Firestone, R.C. Pardo, R.A. Warner, W.C. McHarris and W.H. Kelly, Phys. Rev. C25 (1982) 527.
- [8] R.B. Firestone, Phys. Lett. 113B (1982) 129.
- [9] J.C. Hardy, B. Jonson and P.G. Hansen, Nucl. Phys. A305 (1978) 15.
- [10] This is confirmed by R.B. Firestone, private communication.
- [11] P.G. Hansen, Adv. Nucl. Phys. 7 (1973) 159.
- [12] B. Jonson, E. Hagberg, P.G. Hansen, P. Hornshøj and P. Tidemand-Petersson, Proc. 3rd Int. Conf. on Nuclei Far From Stability, Cargèse, France 1976 (CERN 76-13) p. 277.
- [13] T. Elmroth, H. Hagberg, P.G. Hansen, J.C. Hardy, B. Jonson, H.L. Ravn and P. Tidemand-Petersson, Nucl. Phys. A304 (1978) 493-502.
- [14] P.G. Hansen, Annual Rev. of Nucl. and Part. Science 29 (1979) 69.
- [15] J.C. Hardy. Proc. 4th Int. Conf. on Nuclei Far From Stability, Helsingør, Denmark 1981 (CERN 81-09) p. 217.
- [16] G.T. Ewan, E. Hagberg, P.G. Hansen, B. Jonson, S. Mattsson, G. Nyman, E. Roeckl, D. Schardt and P. Tidemand-Petersson, Phys. Lett. 84B (1979) 173.