STRAIGHTFORWARD ELUCIDATION OF COMPLEX SHELL-MODEL STATES BY THE β DECAY OF NUCLEI FAR FROM STABILITY

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1. PREAMBLE

Because the decay energy increases rather rapidly as nuclei progress farther and farther from stability, the β decay of nuclei somewhat removed from stability can populate a veritable myriad of states in their daughter nuclei. Unfortunately, such decay schemes are inherently quite complex and one cannot rely on systematics to the same extent as for, say, α decay. The result is that relatively little use has been made of the potential wealth of information available from the β decay of nuclei far from stability.

Recently, however, we have found a number of nuclei moderately far from stability but close to (just below) the major closed shell at N = 82 that exhibit complex but straightforward decay patterns which can be explained with simple shell-model arguments. The configurations of these (odd-mass) nuclei, involving one or more high-spin states, are such that their β^+/ε decay is forced to populate unique and well-defined three-quasiparticle states in the daughter nuclei. Thus, here one can obtain information about the structures of states lying near 2 MeV that often is not available for states much closer to the ground state. We have thus far characterized only three such systems, viz., $_{60}Nd^{139}$-$_{59}Pr^{139}$, $_{62}Sm^{141}$-$_{61}Pm^{141}$, and $_{64}Gd^{145}$-$_{63}Eu^{145}$. Nevertheless, even these three systems have enabled us to follow energy trends and occupations of shell-model orbits in this region fairly quantitatively, something previously reserved for stripping and pick-up reactions.

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2. EXPERIMENTAL RÉSUMÉ

The parent nuclei could in each case be prepared by a number of different methods, allowing one to cross-check the mass assignments. Most of our sources were prepared using the p, τ, and α beams furnished by the Michigan State University Sector-Focused Cyclotron. Some confirming bombardments were also made with the C^{12} beam from the Yale University Heavy-Ion Accelerator. The nuclides studied are listed in Table 1 along with the methods used to prepare them. Excitation functions were run in every case. Details on the individual methods of preparation can be found in the references cited in the table.

Table 1

Nuclides exhibiting β^+/ε decay to three-quasiparticle states

Nuclide	3-QP decay?	Ref.	$t_{\frac{1}{2}}$	Reactions
Nd^{139m}	yes	1	5.5 hr	$Pr^{141}(p,3n)$ $Pr^{141}(\tau,p4n)$ $Nd^{142}(\tau,\alpha 2n)$
Nd^{139g}	no	1	30 min	same as Nd^{139m}, plus $Pr^{141}(\tau,5n)Pm^{139} \to (\beta^+/\varepsilon)$
Sm^{141m}	yes	2	22.1 min	$Nd^{142}(\tau,4n)$ $Sm^{144}(\tau,\alpha 2n)$
Sm^{141g}	no	2	11.3 min	same as Sm^{141m}, plus $Sm^{144}(p,4n)Eu^{141} \to (\beta^+/\varepsilon)$
Gd^{145m}	no	3	85 sec	$Sm^{144}(\tau,2n)$ $Sm^{144}(\alpha,3n)$ $Nd^{142}(C^{12},\alpha 5n)$ $Sm^{144}(C^{12},2\alpha 3n)$
Gd^{145g}	yes	4	21.8 min	same as Gd^{145m}

The experimental techniques used to study these nuclides were quite varied. They involved Ge(Li) and NaI(Tl) [including an 8×8-in. split annulus] γ-ray detectors in a wide variety of singles, coincidence, anti-coincidence, Compton suppression, pair ($\gamma^{\pm}$) coincidence, and two-dimensional ("megachannel") coincidence arrangements; also, Si(Li) x-ray and electron detectors. Because of space they cannot be discussed here, but some of the details can be found in the published references[1,3,4].

3. RESULTS FOR Nd^{139m} and Sm^{141m}

The decay schemes that we were able to construct for Nd^{139m} and Sm^{141m} are shown in Figs. 1 and 2. Each of these odd-mass N = 79 isotones has two isomers similar to the N = 81 isomers, a $3/2^+$ ground state and an $11/2^-$ metastable state. From the $M4$ transition probabilities they appear to differ from each other only by the exchange of a $\nu d_{3/2}$ hole for a $\nu h_{11/2}$ hole, so the major active components of their respective wave functions are most likely $(\pi d_{5/2})^2(\nu d_{3/2})^{-3}$ and $(\pi d_{5/2})^2 \times(\nu d_{3/2})^{-2}(\nu h_{11/2})^{-1}$.

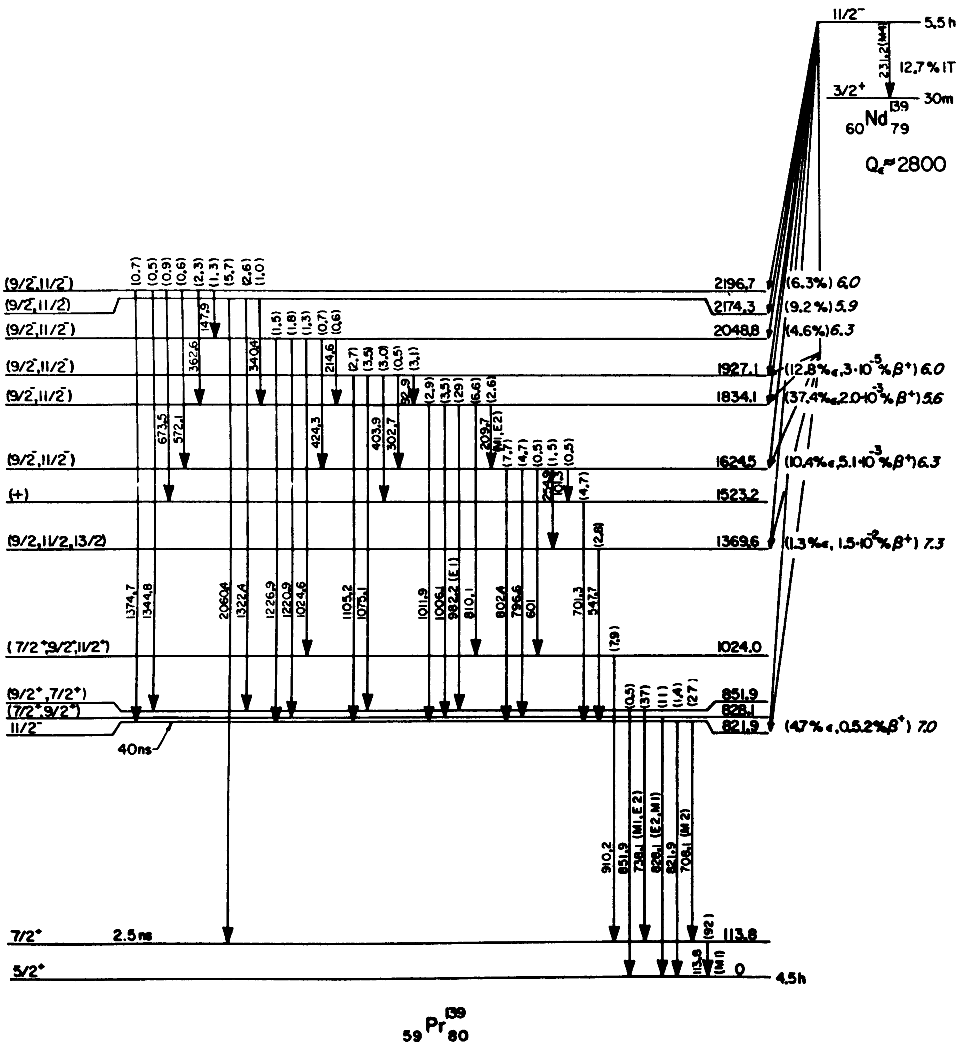

Fig. 1. The decay scheme of Nd^{139m}.

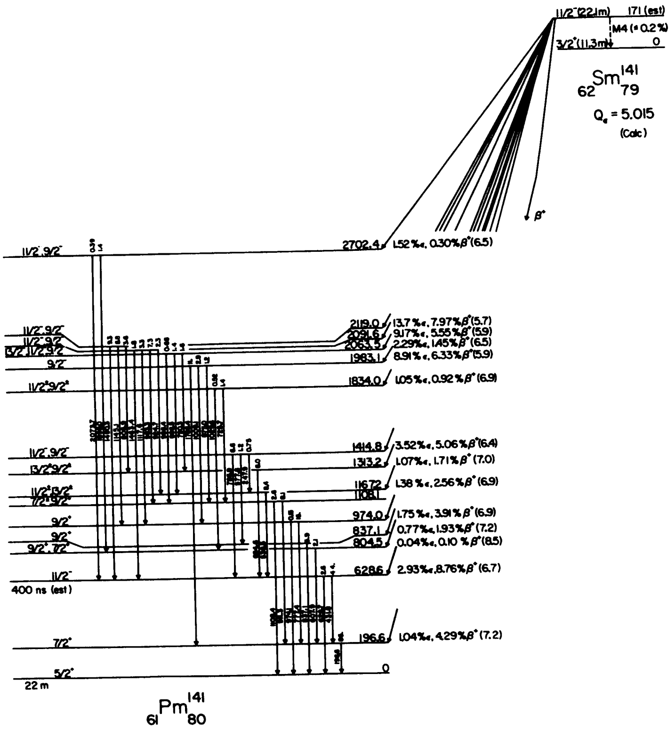

Fig. 2. The decay scheme of Sm^{141m}.

The decays of Nd^{139g} and Sm^{141g}, although formidably difficult experimentally (especially Sm^{141g}) because of the interference from the metastable state decays, present nothing really new or out of the ordinary and are similar to the decays of other $3/2^+$ nuclei in this region such as Nd^{141g} [5] and Sm^{143g} [6]. Indeed, most of their decay goes directly to the $5/2^+$ ground states of their daughters.

The decays of Nd^{139m} and Sm^{141m} are quite unusual, however. First, because of the relatively small energy between the metastable and ground states, the *M4* isomeric transitions are slow. Nd^{139m} decays only 12.7% via the isomeric transition, and we have been unable to detect any Sm^{141m} decay via this path. Instead, each decays primarily to a multiplet of high-lying states in its daughter nucleus, Nd^{139m} to six states between 1624.5 and 2196.7 keV in Pr^{139} and Sm^{141m} to seven states (if the 1834.0-keV state be included) between 1414.8 and 2702.4 keV in Pm^{141}.

In both daughters the $\pi h_{11/2}$ isomeric state is also known, lying at 821.9 keV in Pr^{139} and at 628.6 keV in Pm^{141}. The β^{+}/ε decay from $11/2^{-}$ Nd^{139m} and Sm^{141m} to these states, although allowed transitions, appears to be hindered, for the log *ft* values are 7.0 and 6.7, respectively. Thus, the decay to the high-lying multiplets, having considerably lower log *ft*'s, must also be allowed and further must be more straightforward than the decay to the $\pi h_{11/2}$ isomeric states. We present our interpretation of the Nd^{139m} behavior in a stylized form in Fig. 3 -- the diagram for Sm^{141m} is quite similar.

Consider first the rapid decay of Nd^{139g} to the ground state of Pr^{139}. It involves only the converting of a $d_{5/2}$ proton [from the $(\pi g_{7/2})^{8}(\pi d_{5/2})^{2}$ configuration above Z = 50] into a $d_{3/2}$ neutron, a very favorable transition. Now, starting with Nd^{139m}, we see that exactly the same $\pi d_{5/2} \rightarrow \nu d_{3/2}$ transition can take place. The overall decay can be represented as

$$(\pi d_{5/2})^{2}(\nu d_{3/2})^{-2}(\nu h_{11/2})^{-1} \rightarrow (\pi d_{5/2})(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}.$$

Thus, the multiplet of six high-lying states can be characterized

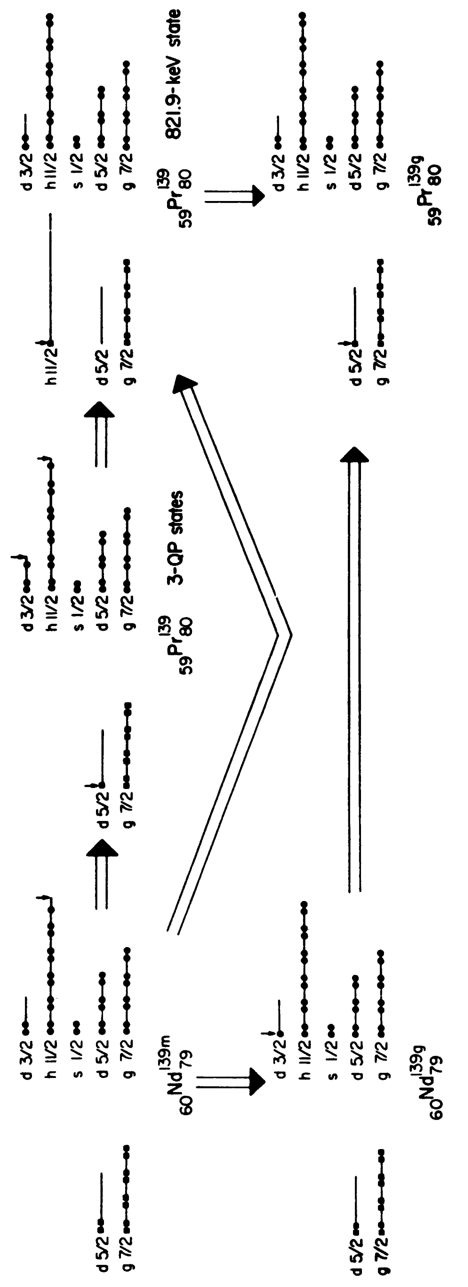

Fig. 3. Stylized representation of the decay of Nd^{139m} to three-quasiparticle states in Pr^{139}.

as three-quasiparticle states. This picture also explains the hindrance of the β^+/ε decay to the 821.9-keV state. The latter would require the conversion of a $d_{5/2}$ proton into an $h_{11/2}$ neutron, either directly or perhaps through an intermediate $d_{3/2}$ state, plus a simultaneous promotion of the remaining $d_{5/2}$ proton to the $h_{11/2}$ orbit. That the states in the high-lying multiplet are indeed fundamentally different in structure from the lower states is also evidenced by the many enhanced γ transitions between members of the multiplet contrasted with the hindrance of the γ transitions between states in the multiplet and lower states. There are many cases where 100- or 200-keV $M1$ or $E2$ transitions proceed much more rapidly than $\approx$2-MeV $E1$'s. In fact, when investigated closely it is found that the γ-transition ratios out of the multiplet are very poorly predicted by single-particle estimates. We take this to indicate that these γ transitions proceed primarily via small admixtures in the wave functions. The net result is that the state energies and particularly the β transition probabilities to the multiplet and γ transition probabilities between states in the multiplet yield information about the major components of the wave functions, while the γ transition probabilities to lower states should provide a key to some of the minor components.

We have made some preliminary shell-model calculations[7)] on the states in the multiplet using the interaction proposed by True[8)]. Of the four $9/2^-$ and four $11/2^-$ states formed by the $(\pi d_{5/2})(\nu d_{3/2})^{-1} \times(\nu h_{11/2})^{-1}$ configuration, two are forced up to higher energies (a $9/2^-$ and an $11/2^-$), while the other six lie quite nicely in the vicinity of the observed states. Transition probabilities, which are more sensitive indicators, present more problems, and it appears that the configuration, $(\pi g_{7/2})^{-1}(\pi d_{5/2})^2(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}$, plays a considerable role and needs to be included. Improved calculations are presently underway.

The decay of Sm^{141m} to the multiplet of seven high-lying, high-spin states in Pm^{141} is very similar, except that there is an additional proton pair, so the overall decay can be represented as

$$(\pi d_{5/2})^4(\nu d_{3/2})^{-2}(\nu h_{11/2})^{-1} \rightarrow (\pi d_{5/2})^3(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}.$$

Presumably the extra pair of $d_{5/2}$ protons is coupled to zero, so the essential structures of the states in the multiplet are the same as for Pr^{139}.

One striking difference between the multiplets in Pr^{139} and Pm^{141} is immediately apparent, however: the γ transitions from the states in the Pm^{141} multiplet lead to lower-lying states and not to other states in the multiplet. An explanation for this was suggested by the behavior of the N = 81 isomers, especially Gd^{145m} (cf. below for more details). The energy of the $\pi h_{11/2}$ orbit drops very rapidly with increasing Z in this region[9], and the decays of the N = 81 metastable states show that by Z = 62 there is some occupation of this orbit by proton pairs. Now, if one examines the Fig. 3 diagram for a transition from the three-quasiparticle states in Pr^{139} to the 821.9-keV state, it is apparent why such a transition is retarded. The simultaneous $\nu d_{3/2} \to \nu h_{11/2}$ and $\pi d_{5/2} \to \pi h_{11/2}$ conversions are formally required, and, as we mentioned above, these transitions probably proceed mostly via admixtures. If, however, there is some $(\pi h_{11/2})^{2n}$ occupancy in the states in Pm^{141}, the corresponding transition is only a single-particle transition and should go much faster. At present this explanation for the difference is suggested merely as a hypothesis, although, as we shall see in the next section, there is indeed evidence for the drop in energy of the $\pi h_{11/2}$ orbit and its occupancy by pairs.

It is worth noting that here we have a somewhat unique mechanism for populating three-quasiparticle multiplets in a number of nuclei in this region. The requirements are a high-spin nucleus, such as the $h_{11/2}$ isomers, and one with sufficient decay energy to populate states above the pairing-energy gap in its daughter nucleus. Additionally, the parent nucleus must be hung up with respect to decay by other modes; e.g., an isomeric transition, if present, must be of low enough energy to allow the β decay to compete. Finally, the nucleus must have a relatively unique intrinsic configuration that forces the preferred decay path to lead into the three-quasiparticle states. Specific configurations of the type we have seen here should occur only below N = 82, viz., at N = 77 and 79, with the possibility of N = 75, depending on the relative spacing of the $h_{11/2}$ and $s_{1/2}$ states. (Below N = 50 the correct type of configuration occurs at Kr^{83} and Sr^{85}, but these are too close to stability for populating high-lying states. Below N = 126 a crude extrapolation puts the proper configuration in the unbound region near Pu^{211}.) The next logical candidate to investigate is $Nd^{137(m)}$.

4. RESULTS FOR Gd^{145m} AND Gd^{145g}

A slightly different type of β decay into three-quasiparticle states is exhibited by Gd^{145g}. It is quite consistent with our previous deductions about the trends in shell-model orbits, however, and extends some of these deductions to higher Z. Essential to the arguments is the behavior of the $\pi h_{11/2}$ orbit, which is elucidated by the decays of Sm^{143m} and Gd^{145m}, so they will be discussed first. Our decay schemes for Gd^{145m} and Gd^{145g} are presented in Figs. 4 and 5.

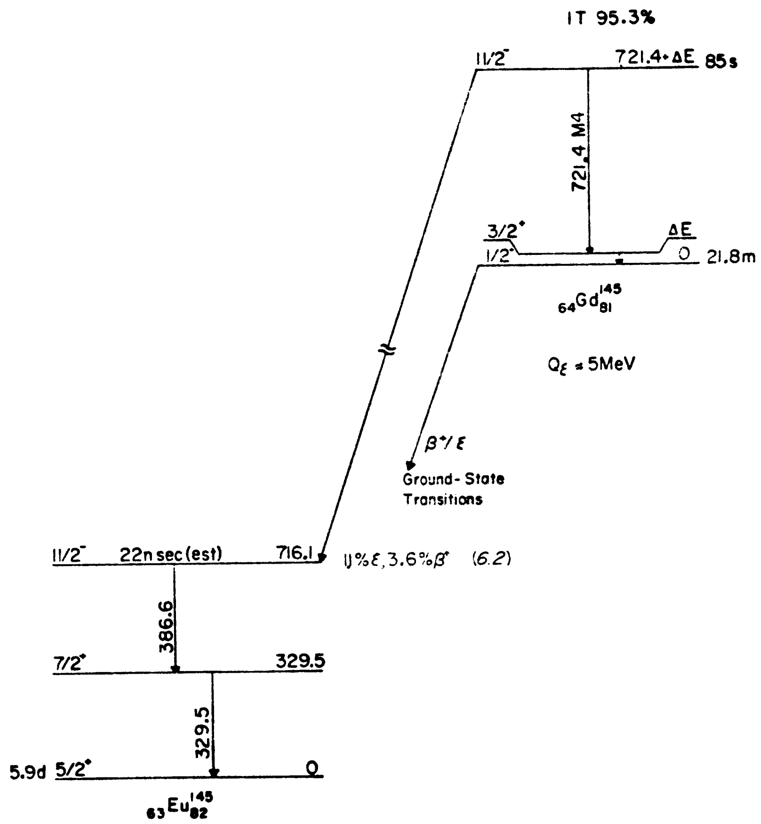

Fig. 4. The decay scheme of Gd^{145m}.

It can be seen from Fig. 4 that there is a direct β^+/ε branch from Gd^{145m} to the $h_{11/2}$ state in Eu^{145}. It occurs in 4.7% of the decays with a resulting log ft of 6.2. A similar direct branch to the $h_{11/2}$ state in Pm^{143} from the decay of Sm^{143m} has an intensity of only 0.2% and a log ft of 6.7[10]. And we have been able to set an upper limit of 0.01%

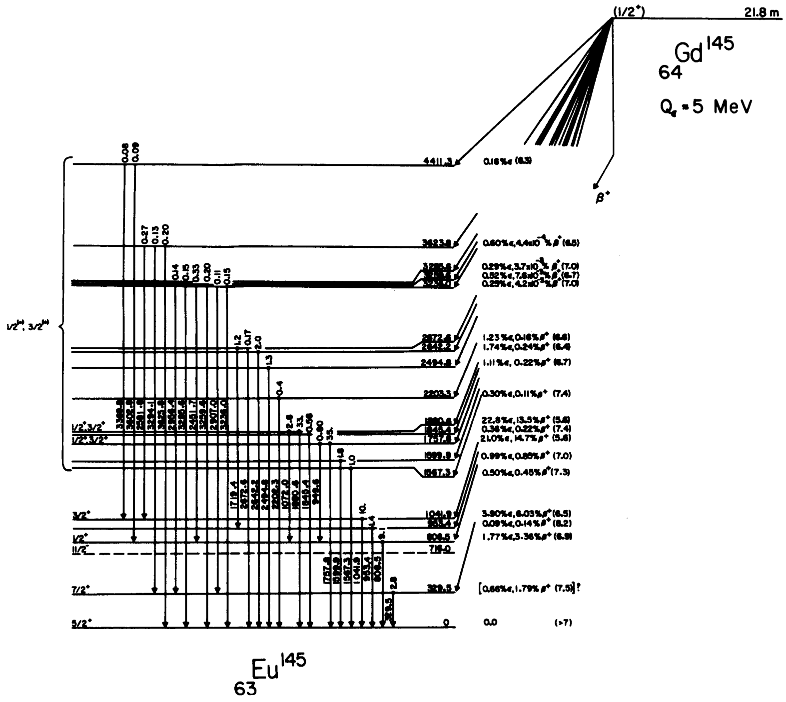

Fig. 5. The decay scheme of Gd^{145g}.

on the corresponding branch from Nd^{141m} decay, so the log ft must be greater than 7. What we are seeing in this series is evidence for the increase in occupation of the $\pi h_{11/2}$ orbit by pairs as it drops in energy with increasing Z. Each of the N = 81 metastable isomers has a single hole in the $\nu h_{11/2}$ orbit, which is the only hole available to be filled in going to the N = 82 daughters. There is essentially no $(\pi h_{11/2})^{2n}$ occupation in Nd^{141}, so the direct β branch would necessarily be $\pi d_{5/2} \rightarrow \nu h_{11/2}$ or $\pi g_{7/2} \rightarrow \nu h_{11/2}$ plus the promotion of the remaining proton from the broken pair to the $h_{11/2}$ orbit. As the $(\pi h_{11/2})^{2n}$ becomes appreciable, on the other hand, the β branch becomes simply $\pi h_{11/2} \rightarrow \nu h_{11/2}$ and the transition probabilities increase rapidly.

Armed with this information, we can explain the sudden break in the decay properties of the N = 82 ground-state isomers that occurs with Gd^{145g}. These isomers all have a single $\nu d_{3/2}$ hole in the N = 82 closed shell, and the lighter members of the series decay rapidly to the $\pi d_{5/2}$ ground states of their daughters. As can be seen from Fig. 5, however, no detectable direct β^+/ε population of the Eu^{145} ground state has been found. Instead, Gd^{145g} decays primarily to the two states at 1757.8 and 1880.6 keV. The log ft's for the decays to these states (5.6 each) are much lower than the log ft's for decay to the 808.5- and 1041.9-keV states, which from (τ,d) stripping experiments[9] were shown to be relatively pure $\pi s_{1/2}$ and $\pi d_{3/2}$ states. The 1757.8- and 1880.6-keV states were not populated in the stripping reactions to any appreciable extent, which might be taken to imply that they are complex states, at least more complex or different from what would result from dropping a single proton into a vacant or semi-vacant Sm^{144} orbit.

We consider the 1757.8- and 1880.6-keV states again to be three-quasiparticle states, although our arguments for this must necessarily be somewhat more tenuous than those we presented in the previous section. Two assumptions about the Gd^{145} structure are necessary: 1) the $\pi h_{11/2}$ orbit has appreciable occupation by pairs, and 2) the ground state of Gd^{145} is a $(\nu s_{1/2})^{-1}$ state rather than a $(\nu d_{3/2})^{-1}$ state. The second assumption is less well established than the first. It agrees with the general behavior of the neutron orbits in this nuclear region (cf. Refs. [4] and [9]), but in our experiments with Gd^{145m} decay we looked for the low-energy (<10-keV) transition that would be necessary (Fig. 4) if these orbits had crossed, and we could neither confirm nor deny its existence. A $(\nu s_{1/2})^{-1}$ ground-state assignment is really necessary, however, to explain away the absence of appreciable direct population to the Eu^{145} ground state.

With these assumptions we see that the $\nu s_{1/2}$ hole is not likely to be filled by any of the Gd^{145} protons from orbits occupied by pairs, i.e., $h_{11/2}$, $d_{5/2}$, or $g_{7/2}$ above $Z = 50$. Looking about for a vacant neutron orbit that could receive such a proton, we find the $h_{9/2}$ orbit from above $N = 82$. Crude extrapolations down from the Pb-Bi region place it somewhere between 1.5 and 2.5 MeV in Gd. If so, the β^+/ε transition could be $\pi h_{11/2} \rightarrow \nu h_{9/2}$, or written out in detail,

$$(\pi h_{11/2})^{2n}(\nu s_{1/2})^{-1} \rightarrow (\pi h_{11/2})^{2n-1}(\nu s_{1/2})^{-1}(\nu h_{9/2}).$$

This model also explains the hindrance of the decay to the $\pi s_{1/2}$ and $\pi d_{3/2}$ states in Eu^{145}. Each would require an unfavorable proton-neutron conversion followed by a proton promotion; thus, each surely goes via admixtures.

Although appealing, this explanation for the decay of Gd^{145g} must at present remain hypothetical, for we have no *direct* evidence for the $(\nu s_{1/2})^{-1}$ nature of Gd^{145g} or that it is specifically the $\nu h_{9/2}$ orbit that participates in the three-quasiparticle structure. Information would be desirable on Dy^{147}, the next member of the series, but it is far enough away from stability to cause formidable production and identification difficulties. The same is true of Tb^{145}, which could populate states in Gd^{145}. Perhaps most imminently promising is a study of Gd^{145} states via the $Sm^{144}(\tau,2n\gamma)$ reaction.

5. CONCLUSION

We have presented three examples of how complex β decays of nuclei somewhat removed from stability can be explained quite neatly in simple shell-model terms. These are only a few examples of what will undoubtedly become a fertile field of inquiry. For β decay with its rather stringent selection rules will tend to populate very specific states having well-defined structures, providing only that suffient decay energy be available. And what start out as isolated, unrelated cases, can, as with the present three, very likely be linked together in an overall picture that explains a great deal about the energies and occupations of orbits over an entire nuclear region.

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