Confirmation of the Systematic Population of
Three-Quasiparticle Multiplets by Nuclides Below

$N=82$: A Multiplet in ^{141}Pm

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Abstract:

The ϵ decay of ^{141m}Sm preferentially populates a multiplet of six (possibly seven) $9/2^-$ and/or $11/2^-$ states lying between 1414.8 and 2702.4 keV in ^{141}Pm . In simple shell-model terms this decay can be represented as $(\pi d_{5/2})^2 (\nu d_{3/2})^{-2} (\nu h_{11/2})^{-1} \rightarrow (\pi d_{5/2}) (\nu d_{3/2})^{-1} (\nu h_{11/2})^{-1}$, confirming the systematic population of three-quasiparticle multiplets by certain $N=79$ and $N=77$ nuclides.

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Several years ago that comparatively rare class of states in nuclei, well-characterized three-particle states, had its numbers swelled significantly when a multiplet of six three-quasiparticle states in ^{139}Pr populated by the ϵ decay of $^{139\text{m}}\text{Nd}$ was reported.^{1,2} The $11/2^-$ isomer, $^{139\text{m}}\text{Nd}_{79}$, was characterized as having the configuration, $[(\pi d_{5/2})^2(\nu d_{3/2})^{-2}(\nu h_{11/2})^{-1}]_{11/2^-}$ in relation to the $^{140}\text{Ce}_{82}$ core, as the principal component of its wave function. The most probable β transition, $\nu d_{5/2} \rightarrow \nu d_{3/2}$, thus would result in the three-particle configuration, $[(\pi d_{5/2})(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}]_{J^-}$, where J^- can take on values from $3/2^-$ to $19/2^-$ but for allowed transitions is limited to $9/2^-$, $11/2^-$, or $13/2^-$. γ -ray branchings narrowed the assignments to $9/2^-$ or $11/2^-$, four of each being possible from the three-particle configuration.

Subsequently, shell-model calculations were performed³ for negative-parity states in ^{139}Pr , using as simple and truncated a basis set as possible. Only the basic three-particle configuration and $[(\pi h_{11/2})(\nu d_{3/2})^{-2}]$, the basic configuration of the 821.9-keV $11/2^-$ metastable state in ^{139}Pr were used. With an exchange mixture postulated by True,⁴ good agreement was obtained — one $9/2^-$ and one $11/2^-$ state move up while the other three $9/2^-$ and three $11/2^-$ states come down to lie nicely where the experimental three-particle states had been found. Transition probabilities still were somewhat of a problem and indicated that configurations of the sort, $[(\pi d_{5/2})^2(\pi g_{7/2})^{-1}(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}]$, need to be added to the basis set. Still, the agreement was remarkable considering the simplifications and approximations involved and it pointed up the importance of the three-quasiparticle multiplets: Here, at excitations near 2 MeV in heavy nuclei we have considerable information about a number of complex but clearcut states that often is not available for states much closer to the ground state.

The work on ^{139}Pr from ^{139m}Nd decay led to the prediction^{1,2} that other $N=79$ or $N=77$ nuclides might also possess the requisite configurations for similar ϵ or β^+ decay into similar three-quasiparticle multiplets. In addition to the configuration, such a nuclide must also have sufficient decay energy to populate states above the pairing gap(s) in its daughter, and it must be "hung up" with respect to other modes of decay — for example, if it is a metastable state the energy for the isomeric transition must be low enough to make that transition quite slow. Working ones way out from β stability, he finds that ^{141m}Sm and ^{137m}Nd are the next likely candidates. In this Letter we report on our work on ^{141m}Sm decay and our finding that it does indeed populate a similar three-quasiparticle multiplet in ^{141}Pm , a multiplet whose similarities to and differences from the ^{139}Pr multiplet tell us much about the behavior of single-particle orbits in this region of the nuclidic chart.

The two isomers of $^{141}_{62}\text{Sm}_{79}$ follow the trend of the $N=79$ isomers, making six pairs now known in that series. There is a 22.1-min $11/2^-$ metastable state^{5,6} and an 11.3-min $3/2^+$ ground state^{6,7}, which should differ only by the promotion of a $d_{3/2}$ neutron hole to the $h_{11/2}$ orbit. Because the energy between them (≈ 171 keV est) is even smaller than that between the other $N=79$ isomers, the $M4$ transition between them is indeed slow and undetectable ($<0.2\%$). Thus, the two isomers decay independently. We prepared the isomers by the $^{142}\text{Nd}(\tau, 4n)^{141m+g}\text{Sm}$ and $^{144}\text{Sm}(p, 4n)^{141}\text{Eu} \xrightarrow{\epsilon} ^{141(m+g)}\text{Sm}$ reactions, using 40-MeV τ and 40-MeV p beams on separated isotope targets. The beams were provided by the MSU Sector-Focused Cyclotron. We have studied their γ -ray spectra with $\text{Ge}(\text{Li})$ and $\text{NaI}(\text{Tl})$ detectors in various singles, coincidence, pair coincidence, two-

dimensional "megachannel" coincidence, and anticoincidence configurations. A simplified version of the ^{141m}Sm decay scheme is shown in Fig. 1; the complete decay scheme and details on its construction are given in Ref. 5 and in semi-final form in Ref. 6. The decay scheme of ^{141g}Sm , which is quite ordinary and similar to that² of ^{139g}Nd and many other nuclides in this region, will be presented in Ref. 7 and can also be seen in semi-final form in Ref. 6.

The peculiar nature of ^{141m}Sm decay is readily apparent from Fig. 1. The $11/2^-$ state at 628.6 keV in ^{141}Pm is almost certainly a $\pi h_{11/2}$ single-particle state, lying almost exactly where such a state would be predicted by systematics of the region. The γ branching ratios depopulating it are in very good agreement with what would be expected for single-particle $M2$ and $E3$ transitions. The $M2$ is retarded by approximately the expected factor (≈ 100) over single-particle estimates and the $E3$ is enhanced by a factor of ≈ 3.6 — this is now the fifth enhanced $E3$ in this nuclear region,² the analogous transition in ^{139}Pr being one of these. As in ^{139m}Nd decay, however, the β^+/ϵ transition feeding it is appreciably hindered; it receives only 11.7% of the decay and the $\log ft$ is 6.7. This, of course, is fairly high for an allowed transition, but it should be compared with the analogous transition from ^{139m}Nd to ^{139}Pr , which has a $\log ft$ of 7.0. The explanation can be found in stylized form in Fig. 2, which shows symbolic shell-model representations of some of the important transitions in the ^{141}Sm - ^{141}Pm system. In this over-simplified approximation the transition would require converting a $d_{5/2}$ proton into an $h_{11/2}$ neutron, either directly or through some intermediate state, and the simultaneous promotion of a remaining $d_{5/2}$ proton up to the $h_{11/2}$ orbit.

The transition must really proceed through small admixtures in the wave functions, and this is reflected in the large $\log ft$.

The straightforward β^+/ϵ decay, $\pi d_{5/2} \rightarrow \nu d_{3/2}$, results in the three-particle configuration, $[(\pi d_{5/2})(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}]9/2^-, 11/2^-$, which we postulate for the six states at 1414.8, 1983.1, 2063.5, 2091.6, 2119.0, and 2702.4 keV. Together these receive 65.8% of the β^+/ϵ decay, and the $\log ft$ values range from 5.7 to 6.5. (If the tentatively placed state at 1834.0 keV is included, the number of states in the multiplet is increased to seven, receiving 67.7% of the decay.) These transitions are also represented in stylized form in Fig. 2. (Decay to states at 1982.6, 2091.6, and 2119.0 keV, the three states receiving the most intense population, has also been reported in an abstract by Arl't et al.,⁸ who recognized their three-particle nature. Hesse⁹ also published a skeletal decay scheme, but he gives no interpretation of his results.) * The gradation in properties of the six three-quasiparticle states in ^{141}Sm is remarkably similar to those in ^{139}Pr , with most of them decaying to the $\pi h_{11/2}$ 628.6-keV state and to the states in the vicinity of 1 MeV, many of which have considerable collective character. In each nucleus only one of the three-quasiparticle states decays to anything lower than the $\nu h_{11/2}$ state and that to the $(\pi g_{7/2})^{-1}$ first-excited state. In each nucleus this appears to be the only one having a fairly large $[(\pi d_{5/2})^2(\pi g_{7/2})^{-1}(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}]$ component.

In one respect the three-quasiparticle multiplets in ^{139}Pr and ^{141}Pm differ strikingly. In ^{139}Pr there are many enhanced low-energy γ transitions between the members of the multiplet, while the γ transitions to lower lying states all appear to be severely retarded. In ^{141}Pm , on the other hand, there appear to be fewer transitions between members of the

multiplet, and the transitions out of the multiplet do not seem to be quite so retarded. Actually, this is more or less what one would expect from the known behavior of the shell-model orbits in this region. The retardation of the transitions to the 628.6-keV state, for example, is depicted in Fig. 2. With only $g_{7/2}$ and $d_{5/2}$ proton states available, the transitions would be formally two-particle transitions, having to proceed instead by small admixtures in the wave functions. Such happens in ^{139}Pr . However, it is known both from reaction studies¹⁰ and from the β^+/ϵ decay of $N=81$ nuclei that the $h_{11/2}$ orbit drops in energy rather rapidly with increasing Z in this region. (The $\log ft$ values for the $11/2^- \rightarrow 11/2^-$ transitions in $^{141}\text{Nd} \rightarrow ^{141}\text{Pr}$, $^{143}\text{Sm} \rightarrow ^{143}\text{Pm}$, and $^{145}\text{Gd} \rightarrow ^{145}\text{Eu}$ are 7.0, 6.7, and 6.2, respectively - Refs. 11-13.) At ^{141}Sm it has acquired enough population by proton pairs to allow the γ transitions to proceed via this component and be less retarded than in ^{139}Pr . This is also consistent with the $\log ft$ for direct β^+/ϵ population of the $h_{11/2}$ state being 6.7 in ^{141}Pm instead of 7.0 as in ^{139}Pr .

The decay of ^{141}Sm thus is important in two respects. 1) Taken by itself it provides information on a whole multiplet of high-lying states in ^{141}Pm . Simple shell-model calculations should provide information on the major components of their wave functions, and a closer scrutiny of the transition probabilities should provide much information about the smaller components. 2) In the context of this region below $N=82$, it provides corroboration of the systematic population of low-lying three-quasiparticle multiplets by the β^+/ϵ decay of some of the $11/2^-$ isomers of the $N=79$ and 77 isotones. One should next look for this behavior from $^{137(m)}\text{Nd}$ and perhaps $^{143(m)}\text{Gd}$. In a wider context it also shows that the decay of nuclei far

from β stability not only can provide significant information on the positions of shell model orbits and on the properties of complex states, but also can provide information about the occupancies of these various orbits, something previously reserved for reactions studies.

References

- ¹Wm. C. McHarris, D. B. Beery, and W. H. Kelly, Phys. Rev. Letters 22, 1191 (1969).
- ²D. B. Beery, W. H. Kelly, and Wm. C. McHarris, Phys. Rev. 188, 1851 (1969).
- ³R. Muthukrishnan and A. Kromminga, Phys. Rev. C 3, 229 (1971).
- ⁴Given in R. J. Philpott and P. P. Szydluk, Phys. Rev. 153, 1039 (1967).
- ⁵R. E. Eppley, R. R. Todd, R. A. Warner, Wm. C. McHarris, and W. H. Kelly, Bull. Am. Phys. Soc. 16, 129 (1971); also, to be submitted to Phys. Rev. C (1971).
- ⁶R. E. Eppley, Ph.D. Thesis, Michigan State University, CDO-1779-32 (1970).
- ⁷R. R. Todd, R. E. Eppley, R. A. Warner, Wm. C. McHarris, and W. H. Kelly, work in progress.
- ⁸R. Arlt, G. Beyer, G. Musiol, E. S. Rydina, S. Seidler, and H. Strusny, *International Conference on the Properties of Nuclei Far from the Region of Beta-Stability, Leysin, Switzerland, August 31-September 4, 1970 - Proceedings* (CERN, Geneva, Report 70-30, 1970), p. 435.
- ⁹K. Hesse, Z. Phys. 220, 328 (1969).
- ¹⁰B. H. Wildenthal, E. Newman, and R. L. Auble, Phys. Rev. C 3, 1199 (1971).
- ¹¹D. B. Beery, W. H. Kelly, and Wm. C. McHarris, Phys. Rev. 171, 1283 (1968); also Wm. C. McHarris, R. E. Eppley, and W. H. Kelly, to be published.
- ¹²J. Felsteiner and B. Rosner, Phys. Letters 31B, 12 (1970).
- ¹³R. E. Eppley, Wm. C. McHarris, and W. H. Kelly, Phys. Rev. C 2, 1929 (1970).

Figure Captions:

- Fig. 1 Simplified and stylized decay scheme of ^{141m}Sm . Energies and J^π assignments are given only for the states pertinent to the present discussion. For more details about this decay scheme and its construction, see Refs. 5 or 6.
- Fig. 2 Symbolic shell-model representation of some of the important transitions between ^{141}Sm and ^{141}Pm states. We have given a stylized picture of the proton (squares) and neutron (circles) states between the closed shells at 50 and 82, neglecting any smearing out of occupation due to the pairing force. The arrows point to the nucleons or holes of primary interest in each state. The dashed $\pi h_{11/2}$ orbit is shown nearing the $\pi d_{5/2}$ orbit and is expected to contain some occupation by proton pairs.

Figure 1.

Figure 2.