*Work supported in part by the U. S. Atomic Energy Commission under Contract No. AT(30-1)-2098.

†On leave from Institut de Physique Nucléaire, Lyon, France.

‡On leave from CERN, Geneva, Switzerland.

[1] M. Camac, A. D. McGuire, J. B. Platt, and H. J. Schulte, Phys. Rev. 99, 897 (1955); M. Stearns and M. B. Stearns, Phys. Rev. 103, 1534 (1956).

[2] M. Krell and T. E. Ericson, to be published. This article refers to recent experimental material.

[3] M. Ericson and T. E. Ericson, Ann, Phys. (N.Y.) 36, 323 (1966).

[4] A. Partensky and M. Ericson, Nucl. Phys. B1, 382 (1967).

THREE-QUASIPARTICLE MULTIPLET IN Pr^{139}

Wm. C. McHarris
Department of Chemistry* and Cyclotron Laboratory,† Department of Physics,
Michigan State University, East Lansing, Michigan 48823

and

D. B. Beery‡ and W. H. Kelly
Cyclotron Laboratory,† Department of Physics, Michigan State University, East Lansing, Michigan 48823

(Received 24 February 1969)

Nd^{139m} in its ϵ decay preferentially populates a multiplet of six high-lying, high-spin, odd-parity states in Pr^{139}. We interpret this as $(\pi d_{5/2})^2(\nu d_{3/2})^{-2}(\nu h_{11/2})^{-1} \rightarrow (\pi d_{5/2})(\nu d_{3/2})^{-1} \times (\nu h_{11/2})^{-1}$, with the Pr^{139} states being three-quasiparticle states.

Well-characterized three-particle states in nuclei are comparitively rare, and recognizing them most often has depended on the isomeric properties of a few high-spin states. Consequently, the excitation of a multiplet of such states in one nucleus, each state decaying to a number of lower lying states, has many interesting theoretical implications. Here we report our identification of the relatively unique population of a multiplet of six high-spin, negative-parity levels in Pr^{139} by the electron-capture decay of Nd^{139m}. We interpret this as the configuration of Nd^{139m} being peculiarly suited for populating three-quasiparticle states.

The two isomers of Nd^{139} follow the trend of $N=79$ isomers, there being a 30-min $\frac{3}{2}^+$ ground state and a 5.5-h $\frac{11}{2}^-$ metastable state. Because the spacing between them is fairly small (231.2 keV) and the energy available for electron-capture decay is large (≈3 MeV), only 12.7% of the decay of the $\frac{11}{2}^-$ state proceeds via the $M4$ isomeric transition, and the two isomers decay almost independently. We prepared the isomers by the $\mathrm{Pr}^{141}(p, 3n)\mathrm{Nd}^{139m+g}$ reaction, using a 29-MeV proton beam from the Michigan State University sector-focused cyclotron, and have studied the γ-ray spectra following their decay with Ge(Li) and NaI(Tl) detectors in various singles, coincidence, and anticoincidence configurations. The resulting decay scheme of Nd^{139m} is given in Fig. 1; the details on how this was constructed and the decay scheme of Nd^{139g} will be presented in another publication.[1]

The decay of Nd^{139g} is more or less straightforward and much like the decay of many similar nuclei in this region,[2] which have most of their decay going directly to the ground state of the daughter nucleus. However, it can easily be seen

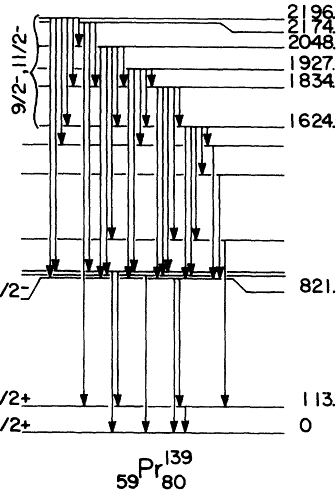

FIG. 1. Simplified level scheme of Pr^{139} showing the states that are populated in the decay of Nd^{139m} and the γ-ray transitions that de-excite them. Energies and spin-parity assignments are listed only for states pertinent to the present discussion. For more details about this scheme and its construction and for the Nd^{139g} decay scheme, see Ref. 1.

that the decay of Nd^{139m} is not so straightforward. In particular, 80.7% of its decay goes to six high-lying states at 1624.5, 1834.1, 1927.1, 2048.8, 2174.3, and 2196.7 keV in Pr^{139}, with only ≈6.5% going directly to lower lying levels. The log*ft* values for decay to these six states lie between 5.6 and 6.3, whereas for decay to an $\frac{11}{2}^-$ state at 821.9 keV, the value is 7.0. Further, the six states appear to have some common internal structure that is significantly different from the lower states—this is demonstrated by the many enhanced low-energy γ transitions within the multiplet and the scarcity of transitions to the lower states.

We measured the half-life of the 821.9-keV state to be 40 ± 2 nsec,[3] which means that the $M2$ (708.1-KeV)[4] and $E3$ (821.9-keV) transitions deexciting it have partial half-lives of ≈42 and ≈600 nsec, compared with straightforward single-particle estimates[5] of 1.2×10^{-9} and 1.3×10^{-6} sec, respectively. Thus, the $M2$ is retarded to approximately the same degree that many $M2$'s are retarded, and the $E3$ is somewhat enhanced—this is now the fourth enhanced $E3$ that has been found in this same nuclear region.[6] The implication is that these are good single-particle transitions and the 821.9-keV state is essentially a $\pi h_{11/2}$ state.

The problem, then, is in the determination of the nature of the multiplet of six high-lying states. Log*ft* values by themselves are not overly trustworthy as indicators of the types of β decay, but it is much more common for the values for allowed decay to be too high than for those for first-forbidden decay to be too low.[7] The conclusion is that the multiplet consists of high-spin, negative-parity states—various γ-ray branchings allow this to be narrowed down for most of the states to $\frac{9}{2}^-$ or $\frac{11}{2}^-$. But how can such states be constructed; especially, how can they be constructed so as to be favored for population over the 821.9-keV $\frac{11}{2}^-$ state?

In Fig. 2 we present a simple stylized version of our answer. The ground state of Nd^{139}, with three holes in the $N=82$ shell and two protons outside the $(g_{7/2})^8$ subshell, undoubtedly has as the major component of its wave function the configuration $(\pi d_{5/2})^2(\nu d_{3/2})^{-3}$. Its β^+/ϵ decay can be represented as converting a $d_{5/2}$ proton into a $d_{3/2}$ neutron, resulting in $(\pi d_{5/2})(\nu d_{3/2})^{-2}$, the ground-state configuration of Pr^{139}. This representation is consistent with the log*ft* value of 5.1. Nd^{139m}, as demonstrated by the reduced transition probability of the $M4$ transition[8] and the systematics of $N=81$ and $N=79$ isomers, differs from Nd^{139g} only in the promotion of an $h_{11/2}$ neutron to the $d_{3/2}$ orbit, resulting in $(\pi d_{5/2})^2(\nu d_{3/2})^{-2} \times (\nu h_{11/2})^{-1}$. Upon converting a $d_{5/2}$ proton into a $d_{3/2}$ neutron we get $(\pi d_{5/2})(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}$, a "three-quasiparticle state." This can be contrasted to direct population of the 821.9-keV state, which would require the transformation of a $d_{5/2}$ proton into an $h_{11/2}$ neutron, either directly or perhaps through an intermediate $d_{3/2}$ state, and a simultaneous promotion of the remaining $d_{5/2}$ proton to the $h_{11/2}$ orbit. Hence the relatively large log*ft* value of 7.0.

Although the above interpretation qualitatively explains most of the γ-ray branchings between members of the negative-parity multiplet, there are several places involving very highly hindered transitions where it runs into difficulties. We

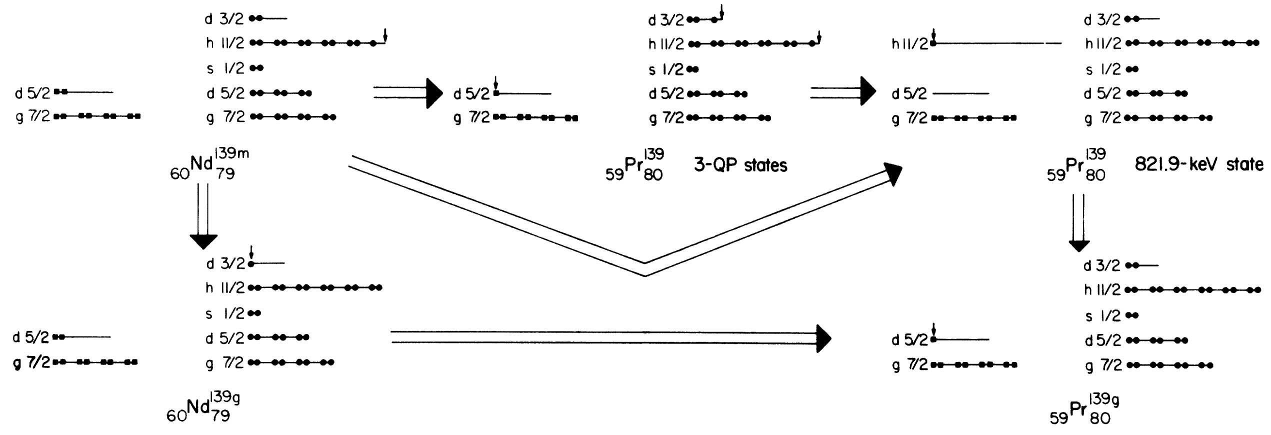

FIG. 2. Symbolic shell-model representations of some important transitions between Nd^{139} and Pr^{139} states. We have given a stylized picture of the proton (squares) and neutron (circles) states between 50 and 82 nucleons. The arrows point to the nucleons or holes of prime interest in each state.

take this to mean that small admixtures in the states are very important in determining these transition rates, but it is instructive to consider specifically one of the more extreme examples —the 1011.9-keV γ (2.9%) from the 1834.1-keV state to the $\frac{11}{2}^-$ 821.9-keV state versus the unobserved (<0.5%) 1834.1-keV γ to the $\frac{5}{2}^+$ ground state. With an $\frac{11}{2}^-$ assignment for the 1834.1-keV state one would not expect to see the 1834.1-keV γ, but with a $\frac{9}{2}^-$ assignment the arguments are not so clear. Single-particle estimates[5] for the $t_{1/2}$'s of the 1011.9-keV ($M1$) and 1834.1-keV ($M2$ or $E3$) γ's are 2.4×10^{-14} and 8×10^{-12} or 4×10^{-9} sec, respectively. According to our above description the missing $M2$ or $E3$ would involve an apparently very simple $\nu d_{3/2}\rightarrow\nu h_{11/2}$ transition (the $M2$ would be l forbidden); there may also be some hindrance from uncoupling and recoupling the states. On the other hand, the observed 1011.9-keV $M1$ γ requires the more complex simultaneous changes $\nu d_{3/2}\rightarrow\nu h_{11/2}$ and $\pi d_{5/2}\rightarrow\pi h_{11/2}$, each of which is twice l forbidden. However, l forbiddenness loses much of its meaning in multiparticle transitions and would depend on the relative phases of the transforming states; also, core polarization in multiparticle states tends to obviate the l selection rules.[9] Still, multiparticle γ decay is formally absolutely forbidden, and although there are known cases where such transitions take place at enhanced rates (e.g., the 63-keV $E1$ γ in Bk^{250} following Es^{254} α decay[10]), these are not common. When such involved rearrangements are compared, clearly the single-particle estimates lose all meaning, and minute admixtures could easily be the deciding factors.

In this multiplet of three-quasiparticle states we thus have two different and potentially very rewarding sources of information: (1) The enhanced transitions between the various members of the multiplet. These should give information on the gross features of the states and should allow one to perform calculations on states at several MeV that normally can be done only near the ground state. (2) The very retarded transitions to states not in the multiplet. These should allow one to determine some of the admixtures in the states.

It is worth noting that here we have a somewhat unique mechanism for populating three-quasiparticle "multiplets" in a number of nuclei. 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 ϵ decay to compete. Finally, the nucleus must have a relatively unique intrinsic configuration that forces the preferred decay path to be into the three-quasiparticle states. Such arrangements would appear to be present only for β^+/ϵ decay; further, they are likely to occur only below $N=82$—specifically, at $N=79$ and $N=77$, 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 configuration occurs at Kr^{83} and Sr^{85}, but these are too close to β stability for populating high-lying states. Below $N=126$ the configuration is projected to occur around Pu^{211}, a region that is not even particle stable.) Nd^{139m} appears to be the nucleus closest to β stability with the requisite properties, although among currently known nuclei other possible candidates are $\mathrm{Sm}^{141(m)}$ and $\mathrm{Nd}^{137(m?)}$. These additional cases are now being investigated.

---

*Work supported in part by the U. S. Atomic Energy Commission.

†Work supported in part by the U. S. National Science Foundation.

‡Present address: Manchester College, North Manchester, Ind. 46962.

[1] D. B. Beery, W. H. Kelly, and W. C. McHarris, to be published.

[2] Ce^{135}: A. Abdul-Malek and R. A. Naumann, Phys. Rev. 166, 1194 (1968); Ce^{137}: D. B. Beery, W. H. Kelly and W. C. McHarris, to be published; Nd^{141}: D. B. Beery, W. H. Kelly, and W. C. McHarris, Phys. Rev. 171, 1283 (1968); Sm^{143}: D. de Frenne, K. Heyde, L. Dorikens-Vanpraet, M. Dorikens, and J. Demuynck, Nucl. Phys. A110, 273 (1968).

[3] D. B. Beery, W. C. McHarris, J. J. Kolata, and W. H. Kelly, Bull. Am. Phys. Soc. 13, 1467 (1968).

[4] This multipolarity was determined from the conversion electron data of K. Ya. Gromov, A. S. Danagulyan, L. N. Nikityuk, V. V. Murav'eva, A. A. Sorokin, M. Z. Shtal', and V. S. Shpinel', Zh. Eksperim. i Teor. Fiz. 47, 1644 (1964) [translation: Soviet Phys.—JETP 20, 1104 (1965)]; and J. Gilat and W. J. Tretyl, University of California Lawrence Radiation Laboratory Report No. UCRL-17299, 1967 (unpublished), p. 20.

[5] S. A. Moszkowski, Phys. Rev. 89, 474 (1953); also in A. H. Wapstra, G. J. Nijgh, and R. van Lieshout, Nuclear Spectroscopy Tables (North-Holland Publishing Company, Amsterdam, The Netherlands, 1959).

[6] J. R. Van Hise, G. Chilosi, and N. J. Stone, Phys. Rev. 161, 1254 (1967).

[7] C. E. Gleit, C.-W. Tang, and C. D. Coryell, Nuclear Data Sheets, compiled by K. Way et al. (Printing and Publishing Office, National Academy of Sciences—Na-

tional Research Council, Washington, D.C., 1963).

[8] R. E. Eppley, W. C. McHarris, D. B. Beery, and W. H. Kelly, to be published; K. Kotajima and H. Morinaga, Nucl. Phys. 16, 231 (1960).

[9] M. Gmitro, J. Hendeković, and J. Sawicki, Phys. Rev. 169, 983 (1968).

[10] W. C. McHarris, F. S. Stephens, F. Asaro, and I. Perlman, Phys. Rev. 144, 1031 (1966).

PHENOMENOLOGICAL APPROACH TO FOUR-PARTICLE, FOUR-HOLE STATES IN O^{16}

S. Das Gupta and N. de Takacsy
Institute of Theoretical Physics, McGill University, Montreal, Canada

(Received 21 April 1969)

It is shown that a phenomenological approach to the four-particle, four-hole band in O^{16} gives reliable predictions for the level spacings and the electromagnetic transition probabilities.

The purpose of the present note is to point out that the Stephenson-Banerjee[1] description of the four-particle, four-hole (4p-4h) band in O^{16} leads readily to a model in which the positions and the lifetimes of the energy levels in the 4p-4h band can be calculated from the known positions and lifetimes of some energy levels in C^{12} and Ne^{20}. Calculations based on the model are in satisfactory agreement with known experimental data.

Hartree-Fock calculations indicate that C^{12} has an oblate intrinsic state and that Ne^{20} has a prolate intrinsic state. Stephenson and Banerjee pointed out that the most favored configuration for the 4p-4h band is the one in which one takes the 4p density from Ne^{20} and places the symmetry axis of this cigar-shaped distribution perpendicular to the symmetry axis of the pancake-shaped 4h distribution taken from C^{12}.

Let us assume that the symmetry axis of the four particles in the *s-d* shell is the *z* axis and that of the four holes is the *x* axis. The four particles then cannot rotate about the *z* axis and the four holes cannot rotate about the *x* axis, but both the densities can rotate around the *y* axis. We now use the classical law of addition of moments of inertia to obtain for the 4p-4h band

$$I_z = I(C^{12}),\quad I_x = I(Ne^{20}),\quad I_y = I(C^{12}) + I(Ne^{20}).$$

The point is that these simple relations are appropriate for the 4p-4h band. This is because (a) the orbitals in the 1*p* shell have opposite parity from those in the 2*s*-1*d* shell and (b) the particle-hole force is much weaker than either the particle-particle or the hole-hole force (from binding energy data, certainly less than 20% of either the p-p or the h-h contribution). The above relations can then be confirmed by falling back on a deformed Hartree-Fock description and using either the Inglis or Thouless method[2] for moments of inertia.

We now deduce $I(C^{12})$ and $I(Ne^{20})$ from the excitation energy of the first 2^+ state in each nucleus and then calculate the spectrum of the 4p-4h states in O^{16} treated as a triaxial rotator. The results are compared with experiment in Fig. 1, where the first excited 0^+ level is arbitrarily located at its experimental position. From binding energy data and neglecting p-h interaction one would find the 0^+(4p-4h) state at 1.4 MeV.

The intraband *E*2 transition rates can also be calculated from this model. For example, the *B*(*E*2) for the decay 6.92 → 6.06 is given in the rotational model[3] by

$$\tfrac{1}{5}[a_0\langle Q_{20}\rangle + a_{20}\langle \tfrac{1}{2}(Q_{22}+Q_{2\,-2})\rangle]^2.$$

The coefficients a_0 and a_2 are obtained from the matrix diagonalization of the rotational Hamilto-

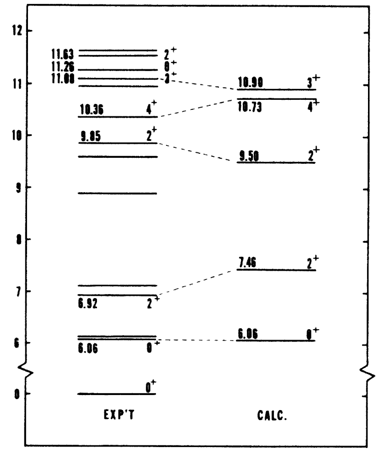

FIG. 1. A comparison of the experimental spectrum with the theoretically calculated spectrum.