Systematic Behavior of Quasirotational Bands in Odd-*A* Pd Nuclei

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Quasi-rotational bands built on the $\frac{7}{2}^+$ and $\frac{11}{2}^-$ states in ^{101}Pd, ^{103}Pd, and ^{105}Pd and the $\frac{5}{2}^+$ state in ^{101}Pd have been excited by (heavy-ion, xn) reactions. (d,p) and (d,t) reactions have been used to show that the absence of the $\frac{5}{2}^+$ band in ^{103}Pd and ^{105}Pd is related to the fragmentation of the $d_{5/2}$ quasiparticle strength in these nuclei. An unusual relation has been found between the type of reaction used and the detection of quasirotational bands in odd-*A* nuclei.

Striking systematic effects have been seen for γ-ray cascades in ^{101}Pd, ^{103}Pd, and ^{105}Pd. (Heavy-ion, $xn\gamma$)[1] and single-nucleon transfer experiments[2] have shown that the observation of the cascades is related to the single-particle purity of the bandhead rather than its spin.[3,4] In addition we have found an unexpected relation between the detection of the cascades and the type of reaction used. These experiments provide motivation for a new treatment of decoupled bands in odd-*A* nuclei.

Evidence for well-developed band structure in ^{101}Pd has been previously reported.[6] Following the production of ^{101}Pd by (heavy-ion, $xn\gamma$) reactions three strong γ-ray cascades were observed. The γ transitions in the cascades were very intense relative to the few transitions between cascades, giving credence to the band interpretation. The measured spin sequences led to assignment of three $\Delta I = 2$ bands built on $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{11}{2}^-$ states, as is seen in Fig. 1. The similarity of energy spacings between the odd-*A* bands and the band observed in the ^{100}Pd core argues forcefully that the odd-*A* bands result from excitations of the core which are relatively independent of the odd particle. There have been several previous reports of "decoupled" bands built on high-j states of unique parity, such as the $\frac{11}{2}^-$ state in La nuclei[3] and the $\frac{13}{2}^+$ state in rare-earth nuclei.[6] The surprising thing here is that bands are built on low-j states ($\frac{7}{2}^+$ and $\frac{5}{2}^+$) which have the same parity as the majority of states in this major shell ($N=4$).

In order to determine whether these bands were unique to ^{101}Pd, in-beam studies of ^{103}Pd and ^{105}Pd have been carried out.[1] The reactions used were ^{100}Ru$(\alpha, n\gamma)^{103}$Pd, ^{101}Ru$(\alpha, 2n\gamma)^{103}$Pd, ^{94}Zr$(^{12}$C, $3n\gamma)^{103}$Pd, ^{102}Ru$(\alpha, n\gamma)^{105}$Pd, and ^{96}Zr$(^{12}$C, $3n\gamma)^{105}$Pd. Excitation functions were used to identify γ rays from ^{103}Pd and ^{105}Pd, γ-γ coincidence measurements were used to place transitions into level schemes, and γ-ray angular distributions were used for angular momentum assignments.

The deduced level scheme for ^{103}Pd is shown in Fig. 2. The relative γ-ray intensities shown are all from the (^{12}C, $3n\gamma$) reaction at 47 MeV incident energy. Two bands were observed, built on states at 244 and 785 keV. The state at 244 keV was known[7] to be $j^\pi = \frac{7}{2}^+$, while the j^π for the 785-keV state was unknown. The 785-keV state

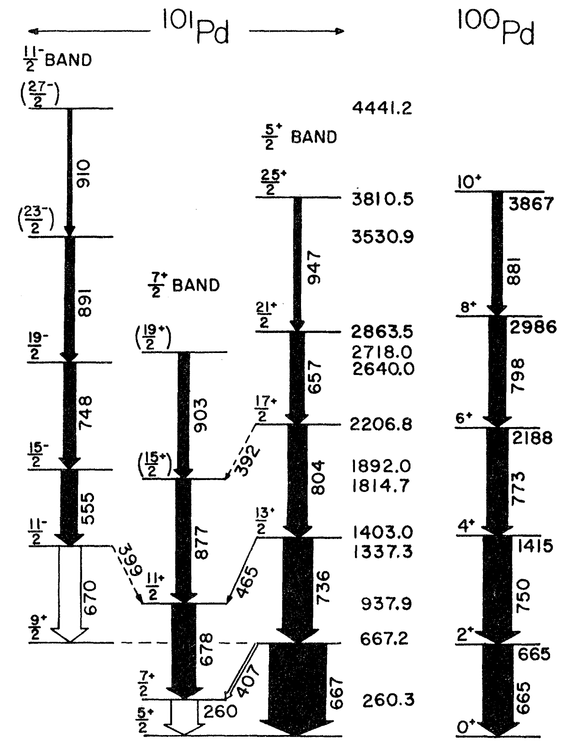

FIG. 1. The level scheme for ^{101}Pd, showing $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{11}{2}^-$ bands. Solid arrows represent $E2$ transitions, and open arrows are dominantly dipole transitions. The uncertainty in the angular momentum assignments given in brackets is caused by unresolved lines in the background which interfere with the angular distributions. The main cascade in the ^{100}Pd core is shown for comparison.

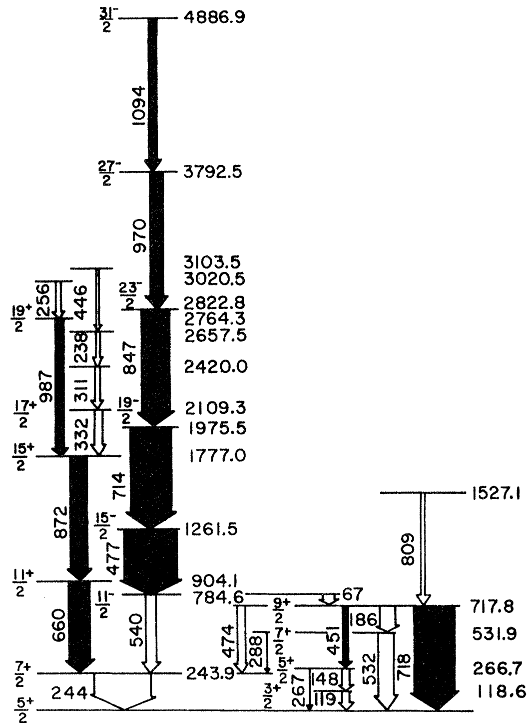

FIG. 2. The level scheme for ^{103}Pd, showing $\frac{7}{2}^+$ and $\frac{11}{2}^-$ bands. Solid arrows represent $E2$ transitions, and open arrows represent other multipolarities.

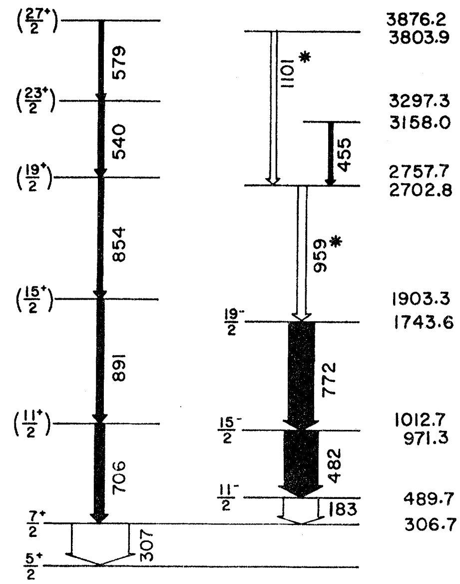

FIG. 3. The level scheme for ^{105}Pd, showing $\frac{7}{2}^+$ and $\frac{11}{2}^-$ bands. Solid arrows represent $E2$ transitions, and open arrows represent other multipolarities. The uncertainty in the angular momentum assignments given in brackets is caused by unresolved lines in the background which interfere with the angular distributions. The 959- and 1101-keV γ rays appear to come from $M1$-$E2$ mixed transitions; however, there is so much background interference that probably assignments cannot be made.

was populated with an l transfer of 5 in both of the reactions ^{102}Pd$(d,p)^{103}$Pd and ^{104}Pd$(d,t)^{103}$Pd,[2] suggesting an $\frac{11}{2}^-$ assignment. (The 625-keV state, previously thought[8] to be the $\frac{11}{2}^-$ state, was populated by l transfer of 2.) Thus $\frac{7}{2}^+$ and $\frac{11}{2}^-$ bands have been established in ^{103}Pb. No $\frac{5}{2}^+$ band could be detected. Several strong transitions were observed leading to the $\frac{5}{2}^+$ ground state, but they certainly do not constitute a band.

In the reaction ^{96}Zr$(^{12}$C$, 3n\gamma)^{105}$Pd two strong cascades were observed. One cascade was in coincidence with the previously known[7] 307-keV γ depopulating the $\frac{7}{2}^+$ state, so the cascade could be identified as a $\frac{7}{2}^+$ band. The second cascade was not in prompt coincidence with any known transition. The $\frac{11}{2}^-$ state is known[7] isomeric state with a half-life of 37 μsec. A delayed-coincidence experiment was performed to show that the second cascade led to the $\frac{11}{2}^-$ state, so it could be identified as an $\frac{11}{2}^-$ band. The resulting level scheme is shown in Fig. 3. Again no $\frac{5}{2}^+$ band was observed.

The cascades in these odd-A Pd nuclei can be satisfactorily described by using the variable-moment-of-inertia (VMI) model.[9] (In the VMI fits we assumed that the energy of the excited states was determined by the nuclear core independent of the odd particle.) Our VMI calculations suggest that at the top of the band the nucleus is significantly deformed. As the nucleus loses energy, the deformation is reduced until the nucleus is essentially spherical at the bandhead.

Investigation of ^{100}Pd,[10] ^{102}Pd,[11] and ^{104}Pd[12] show that all three core nuclei demonstrate similar stretched cascades with spin sequence 0^+, 2^+, 4^+, etc., and that these cascades can be described within the VMI framework. Thus the disappearance of the $\frac{5}{2}^+$ and in ^{103}Pd and ^{105}Pd probably is not due to differences in the core, but rather is caused by a change in the $\frac{5}{2}^+$ state. The single-particle nature of the low-lying states was accordingly investigated[2] using the reactions ^{102}Pd$(d,t)^{101}$Pd, ^{102}Pd$(d,p)^{103}$Pd, ^{104}Pd$(d,t)^{103}$Pd, ^{104}Pd$(d,p)^{105}$Pd, and ^{106}Pd$(d,t)^{105}$Pd. These were counter-telescope experiments, with an energy resolution of approximately 25-keV full width at half-maximum. Angular distributions were compared with DWUCK reaction calculations to extract l transfers and spectroscopic factors. A significant correlation was observed between the single-particle strength of the states and the band structure. In ^{101}Pd one $\frac{5}{2}^+$ and one $\frac{7}{2}^+$ state were observed with single-particle strength near unity. The $\frac{11}{2}^-$ state was not populated in the (d, t) reaction, but it certainly is expected to be a rather pure single-particle state because of its high spin and negative parity. In ^{103}Pd one $\frac{7}{2}^+$ and one $\frac{11}{2}^-$ state were observed, but three $\frac{5}{2}^+$ states were populated. Most of the $d_{5/2}$ strength remains in the ground state, but an appreciable fraction goes to two higher $\frac{5}{2}^+$ states. In ^{105}Pd again one $\frac{7}{2}^+$ and one $\frac{11}{2}^-$ state was observed, but four $\frac{5}{2}^+$ states were populated. The $d_{5/2}$ strength is thus fragmented in ^{103}Pd and ^{105}Pd, but is concentrated in one state in ^{101}Pd. There is then a one-to-one correspondence between the purity of the low-lying single-particle state and the existence of a band built on the state.

One relatively simple way to understand why we did not see the $\frac{5}{2}^+$ band in ^{103}Pd and ^{105}Pd is that a band is built on each of the low-lying $\frac{5}{2}^+$ states. Since all of these bandheads have common components (the $d_{5/2}$ orbital, etc.), there would be many transitions between the bands. Thus the available strength would be shared among so many different γ rays that it would be very difficult to recognize any band structure. Our experimental results and interpretation suggest the following summary. When a quasirotational band is present in a core nucleus, then quasirotational bands can be built on any low-lying state in the corresponding odd-A nucleus; but the band will be observed only if the bandhead is a relatively pure single-particle state.

If the preceding interpretation is correct, the Pd nuclei present a more complete picture of quasirotational bands in odd-A nuclei than do the La nuclei studied by Stephens, Diamond, and Leigh.[3] In the La nuclei only $h_{11/2}$ bands were observed, so Stephens, Diamond, and Leigh developed a coupling scheme which used the high spin and unique parity of the $h_{11/2}$ state. In the light of our experimental results, these bands appear to be a much more general feature of nuclei, so the coupling scheme proposed by Stephens, Diamond, and Leigh may not be sufficiently general.

Next we consider the unexpected relation between the observation of the bands and the type of reaction used. Previous experiments[1,11] on even-even nuclei have shown that the maximum angular momentum observed in the ground-state quasirotational band is simply related to the energy brought in by the incident projectile. For example, in ^{102}Pd and ^{104}Pd the (α, n) reaction excited states up to 10^+, and the (C, $3n$) reaction excited states up to 16^+. (The maximum excitation energy of the residual nucleus is approximately 8 MeV for the α particles and 14 MeV for the carbon ions.)

When an additional neutron is added to either of these even-even core nuclei, the situation is quite different. The bands in ^{103}Pd and ^{105}Pd were observed following (C, $3n\gamma$) reactions. The $\frac{11}{2}^-$ and $\frac{7}{2}^+$ bands in ^{105}Pd and the $\frac{11}{2}^-$ band in ^{103}Pd were not seen following $(\alpha, n\gamma)$ reactions. Only the first two states in the $\frac{7}{2}^+$ band of ^{103}Pd were seen with the $(\alpha, n\gamma)$ reaction. All even-odd nuclei are not equally difficult to excite, because all three bands were clearly evident in ^{101}Pd following $(\alpha, xn\gamma)$ reactions. Thus it appears that for the even-odd nuclei there is some critical value of energy or angular momentum which must be exceeded before the bands can be seen, and the critical value increases with number of neutrons in the Pd isotopes. This "threshold" effect suggests a simple picture for the mechanism involved in populating bands in even-odd nuclei.

The highly excited states which are produced in the residual nucleus by the (heavy-ion, xn) reaction may be separated into two categories. First there are states where quasiparticles are excited in an incoherent fashion so as to preserve the equilibrium shape of the core. There also may be states where the high excitation energy is absorbed by deforming the core. In the deformed state high angular momentum can easily be obtained by rotation, while the angular momentum of a particle state is limited by the number of available quasiparticles. (Heavy-ion, xn) reactions preferentially populate states whose angular momentum is approximately equal to the angular momentum brought in by the reaction. There will be many different paths to the ground state from any highly excited, multi-quasiparticle state. If a large number of these states are populated by the (heavy-ion, xn) reaction, there would be so many γ rays emitted that it would be very difficult to distinguish features of the decay scheme. As was noted previously, the bands which we have observed appear to be associated with significant deformation of the core at higher excitation energies. Thus the threshold effect can be explained as the result of competition between quasiparticle and deformed states. That is, in ^{101}Pd there may not be a sufficient number of particles outside the closed 50-neutron shell to produce many quasiparticle states with high angular momenta, so the deformed type of state is preferentially excited, and the bands are observed Since ^{103}Pd and ^{105}Pd have more neutrons, higher angular momenta can be attained by the quasiparticle states; so even higher angular momentum must be brought into the nucleus before the deformed states can be preferentially selected.

Another important result of the threshold effect is that the absence of bands in $(\alpha, xn\gamma)$ reactions does *not* necessarily mean that the bands do not exist, but simply that the proper reaction may not have been used. Thus the existence of quasirotational bands in odd-A nuclei may be more widespread than previously believed.

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Upper Limits to Flare-Produced Deuterium and Tritium

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Using satellite data obtained over the polar regions during the solar active period of 30 October through 2 November 1972, we obtain upper limits to the ^{2}H/^{1}H and ^{3}H/^{1}H ratios: 1.4×10^{-5} (3.1–30.6 MeV/nucleon) and 9×10^{-6} (2.4–23.0 MeV/nucleon), respectively.

This paper describes the results of a satellite-borne electronic experiment specifically designed to measure deuterons and tritons (^{2}H and ^{3}H) during solar events. Waddington and Freier,[1] using emulsions in a high-altitude balloon flight over Minneapolis, measured H:^{2}H:^{3}H as $1{:}\leq 2\times10^{-3}{:}\leq 6\times10^{-4}$ at $E>50$ MeV/nucleon during the 18 July 1961 solar event. Previously Fireman, DeFelice, and Tilles[2] had set the ^{3}H/H ratio at 4×10^{-3} which is in clear disagreement with that of Waddington and Freier. Some arguments have been advanced by Lal, Rajagopalan, and Venkatavaradan[3] that Fireman's results represent an upper limit. The present results indicate that this is indeed the case, and that the actual H:^{2}H:^{3}H ratios have not yet been measured during solar events.

The S72-1 (1972-076B) satellite was launched on 2 October 1972 into a polar orbit with an inclination of 98.4°, an apogee of 749 km, and a perigee of 731 km. The H:^{2}H:^{3}H ratios measured over the poles during the solar event of 30 October through 2 November 1972 are discussed in this paper.

The particle identifier experiment flown on board the S72-1 satellite was designed to measure H, ^{2}H, ^{3}H from 5 to 70 MeV in five energy bins for each particle species. The detector assembly consists of four solid-state detectors with a plastic-scintillator anticoincidence shield.