Observation of collective behavior in ^{110}Sn

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New levels at high excitation in ^{110}Sn have been determined using a γ-ray multiplicity filter and the reaction $^{94}_{42}$Mo(^{19}F, p2nγ)$^{110}_{50}$Sn at 83 MeV. Evidence is presented for a $\Delta J=2$ band with spins from 10^+ to 20^+. The behavior of this band suggests that it arises from the $\nu(h_{11/2})^2$ configuration in ^{110}Sn rather than the known 2p2h proton configuration structure present in other even heavier tin isotopes.

INTRODUCTION

Previous results from the β decay of $^{110}_{51}$Sb (Ref. 1) and the reactions $^{108}_{48}$Cd(α,2n)$^{110}_{50}$Sn (Ref. 2) and $^{98}_{42}$Mo(^{16}O,4n)$^{110}_{50}$Sn (Ref. 3) show no evidence for collective properties in the proton closed-shell nucleus $^{110}_{50}$Sn. In the heavier even isotopes of tin, $A=112-118$, strongly-coupled collective bands have been observed[4] which arise from proton excitation above the closed shell. These nuclei have a small positive deformation ($\epsilon\simeq 0.1$) according to the calculations of Bron *et al.*[4]

The lighter isotones of $^{110}_{50}$Sn$_{60}$, $^{106}_{46}$Pd$_{60}$, and $^{108}_{48}$Cd$_{60}$ show well-developed ground state bands which form the low-lying yrast states.[5,6] Several levels of probable $\Delta J=2$ decoupled and semidecoupled bands based on $\nu(h_{11/2},g_{7/2})$ and $\nu(h_{11/2},d_{5/2})$ configurations have been observed[7] in both ^{106}Pd and ^{108}Cd. In ^{108}Cd a decoupled band dominated by the $\nu(h_{11/2})^2_{10^+}$ configuration becomes yrast at the 10^+ level.

Prior to the present work, none of the above types of collective structure had been observed in ^{110}Sn. The low-lying collective structure exhibited by ^{106}Pd and ^{108}Cd is clearly suppressed at the closed proton shell of ^{110}Sn. Nevertheless collective structure could still occur at higher excitation in ^{110}Sn due either to proton-based collective excitations as in the heavier tin isotopes or to the $(h_{11/2})^2$, $(h_{11/2},g_{7/2})$, and $(h_{11/2},d_{5/2})$ neutron configurations. We have used the reaction ^{94}Mo(^{19}F,p2nγ)^{110}Sn to search for possible collective behavior at high spin excitation in ^{110}Sn.

EXPERIMENTAL PROCEDURE

The ^{110}Sn was formed using the reaction $^{94}_{42}$Mo(^{19}F,p2nγ)$^{110}_{50}$Sn at a bombarding energy of 83 MeV. The target was a 3 mg cm^{-2} layer of molybdenum enriched to 91.59% in ^{94}Mo on a 6 mg cm^{-2} backing of lead. The γ rays from the reaction were detected in an array of five hyperpure germanium (HPGe) detectors and seven NaI(Tl) detectors arranged as a multiplicity filter.[8] The system was used for two experiments.

In the first experiment events were stored on magnetic tape when at least three HPGe detectors or when at least two HPGe and two NaI(Tl) detectors registered events. The outputs of the HPGe detectors were then matched for gain and zero position and all the coincidence events sorted into a 1024×1024 coincidence matrix. The whole matrix was subjected to a background subtraction using the method of Palameta and Waddington.[9] Gamma-gamma coincidence spectra were then projected from the matrix for gates on one or more channels of the photopeaks. In this experiment, using a beam current of about 3.5 nA, about 1.5×10^8 events were collected.

In the second experiment triple coincidences were required between one HPGe and two NaI(Tl) detectors. A separate spectrum was stored for each HPGe detector. The five HPGe detectors were located at angles of 90°, 60°, 43°, 30°, and $-10°$ with respect to the beam direction. The five stored spectra thus provided γ ray angular distributions. In order to correct for the different efficiencies and geometries of the five HPGe detectors, a spectrum of the isotropic γ rays from the residual radioactivity was taken at the end of the irradiation using the HPGe detectors in singles mode. From these radioactivity spectra anisotropy correction factors were derived for the reaction γ rays in the energy range 200–1500 keV.

EXPERIMENTAL RESULTS

The first experiment revealed that a large number of reactions occurred in addition to ^{94}Mo(^{19}F,p2nγ)^{110}Sn. In particular the following product nuclei were observed to be present relatively strongly: ^{109}Sn, ^{109}In, ^{107}Cd, ^{107}In, and ^{106}Cd. A few additional reactions contributed very weakly. As a consequence, the gamma ray spectra were very complex; about 50% of the lines were attributable to ^{110}Sn. By gating on well-known ^{110}Sn γ rays, it was possible to identify new γ rays belonging to ^{110}Sn.

The most prominent new feature of the ^{110}Sn γ ray spectrum was a cascade of γ rays with energies 808.8, 741.4, 808.8, 904.4, and 1004.4 keV. These transitions have been found to populate a level at 5226.4 keV in ^{110}Sn, which in turn deexcites to a 9^- level at 3932.2

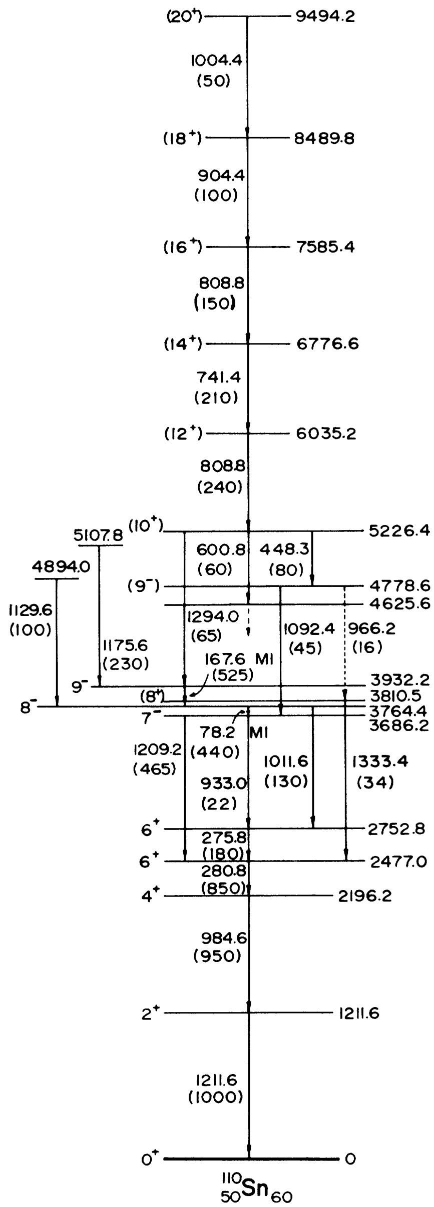

FIG. 1. Partial level scheme of ^{110}Sn showing the proposed collective cascade terminating at the 5226.4 keV level. All energies are in keV. Energy uncertainties are $\sim$0.5 keV; intensity uncertainties $\sim$10%. Conversion factors for the 78.2 and 167.6 keV transitions have been included in the quoted intensities.

keV. In addition, it deexcites through a level at 4778.6 keV, which in turn decays to a well-known 7^- level at 3686.2 keV and possibly to an 8^+ level at 3810.5 keV. A partial level scheme of ^{110}Sn, including the new cascade, is shown in Fig. 1. Figure 2 shows some of the spectral evidence for the new cascade. A common section of five coincidence spectra is shown, each of which was obtained with a single channel gate of width 1.5 keV. The fact that the cascade contains two transitions of almost the same energy at 808.8 keV is evident from the 808 keV gate spectrum which shows a strong 808.8 keV line.

The relative intensities shown in Fig. 1 were derived from the coincidence probabilities of the γ transitions. These were obtained from the peak areas in various coincidence spectra by normalizing to the known coincidence probabilities of the 985- and 280-keV γ rays. This procedure allowed the separation of the intensities of the two components of the 808 keV line, since if there are no extra-band transitions, the area of the 808 keV peak in the 808 keV gate spectrum is proportional to the intensity of the upper 808 keV transition alone. The transitions were ordered in the cascade to give monotonically decreasing intensity with increasing level energy. Alternative orderings of the two 808.8-keV and the 741.4-keV γ rays do not give a monotonic intensity change.

Angular distributions were measured for a number of the stronger components of the ^{110}Sn γ ray spectrum. The Legendre polynomial coefficients for nine spectral lines are shown in Table I and some representative angular distributions are shown in Fig. 3. The data are consistent with stretched quadrupole transitions for the 741.4, 904.4, 1004.4, and 1092.4 keV rays. For the degenerate 808.8 keV γ rays the data are consistent, with both transitions being quadrupole in character. By contrast, the angular distributions for the 1294.0 and 448.3 keV transitions indicate a stretched dipole character. For comparisons Table I includes the measured coefficients for the known[2] quadrupole ($2^+ \rightarrow 0^+$) 1212 keV and dipole ($7^- \rightarrow 6^+$) 1209 keV γ rays.

The dipole character of the 1294.0 keV transition to the 9^- state at 3932.2 keV suggests $J^\pi = 10^+$ as the spin parity of the 5226.4 keV level. If this assignment were correct, the quadrupole character of the 808.8, 741.4, 808.8, 904.4, and 1004.4 keV transitions further suggests spin assignments of 12^+, 14^+, 16^+, 18^+, and 20^+ for the 6035.2, 6776.6, 7585.4, 8489.8, and 9494.2 keV levels, respectively, as indicated in Fig. 1.

The suggested dipole and quadrupole characters of the 448.3-keV and 1092.4-keV transitions, respectively, favor a spin assignment of 9^- for the 4778.6 keV level over the other possible assignment, 8^+. This is further supported, as described in the next section, by a comparison with the level structure of the isotone $^{108}_{48}Cd_{60}$.

In addition to the features shown in Fig. 2, our coincidence spectra show a 600.8 keV γ ray in coincidence with the 741.4- and 808.8-keV γ rays, but not with the 1294.0-, 448.3-, and 1092.4-keV γ rays. This indicates that the 600.8-keV γ ray deexcites the 5226.4 keV level. However, it has not been possible to establish the subsequent decay of the level populated by the 600.8-keV γ

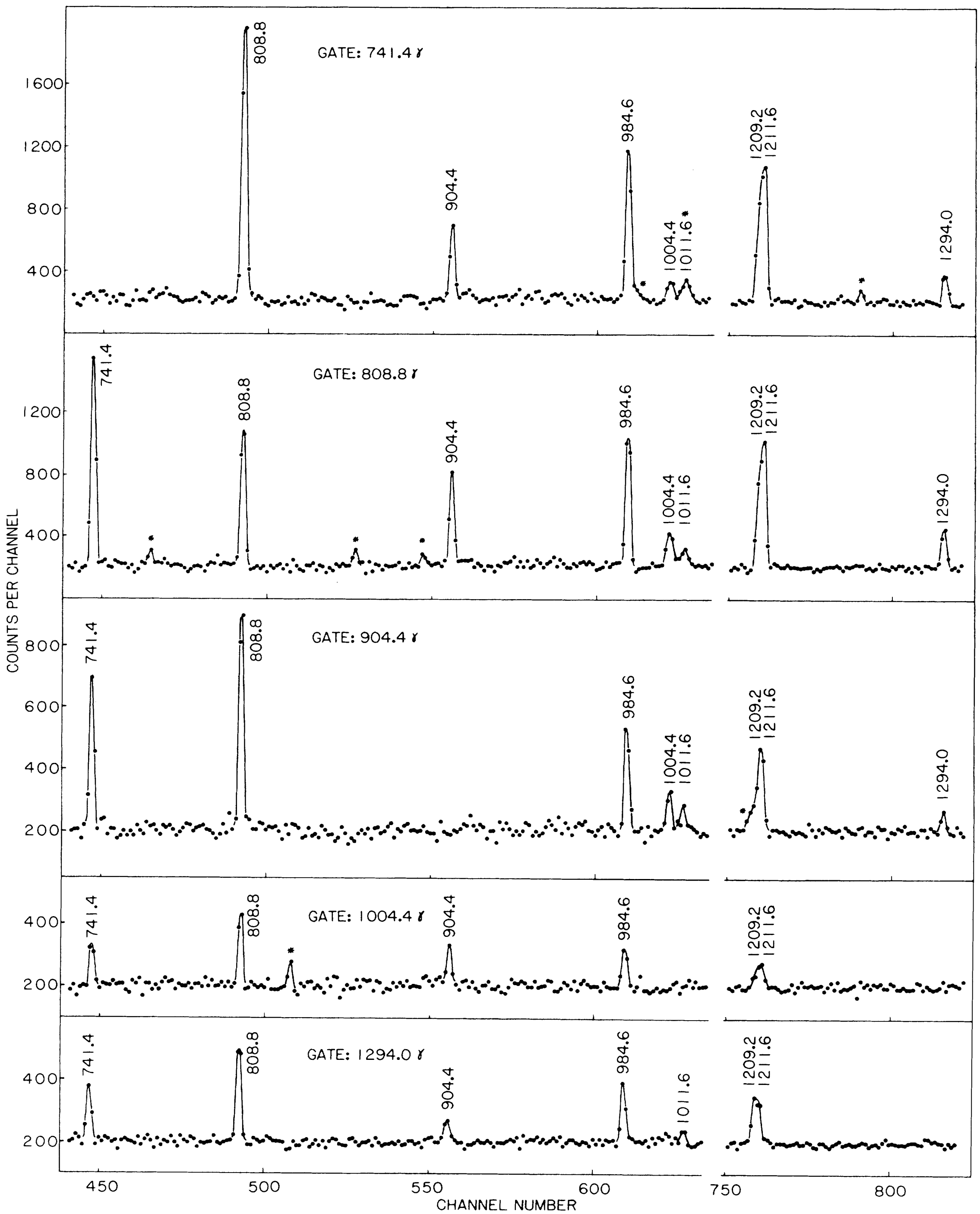

FIG. 2. Sections of selected coincidence spectra presenting the evidence for the collective cascade of Fig. 1. Features marked with an asterisk are wholly or partly due to isotopes other than ^{110}Sn.

ray. The level is probably not isomeric since the 600.8-keV γ ray is in coincidence with the 1211.6 keV γ ray which deexcites the 2_1^+ excited state. It is likely therefore that the 600.8 keV γ ray intensity is shared among a number of weak transitions which proceed to excited states of lower energies. An intensity imbalance at the 5226 keV level suggests that there are also additional weak unobserved branches from this level.

DISCUSSION

The cascade of quadrupole transitions in $^{110}_{50}$Sn described above strongly suggests a collective behavior for

TABLE I. Gamma ray angular distribution coefficients of the function $W(\theta)=1+a_2P_2+a_4P_4$.

E_γ (keV)	a_2	a_4	Proposed spin change $J_i^\pi \rightarrow J_f^\pi$
448.3[a]	−0.58 5	0.37 7	$(10^+)\rightarrow(9^-)$
741.4	0.34 3	−0.13 4	$(14^+)\rightarrow(12^+)$
808.8	0.36 3	−0.18 3	$(12^+)\rightarrow(10^+)$ $(16^+)\rightarrow(14^+)$
904.4	0.34 8	−0.12 10	$(18^+)\rightarrow(16^+)$
1004.4	0.19 10	−0.08 10	$(20^+)\rightarrow(18^+)$
1092.4	0.40 12	−0.25 14	$(9^-)\rightarrow7^-$
1209.2	−0.29 3	−0.01 3	$7^-\rightarrow6^+$
1211.6	0.31 2	−0.09 2	$2^+\rightarrow0^+$
1294.0	−0.29 10	0.05 15	$(10^+)\rightarrow(9^-)$

[a]Line not well separated from the 449.2 keV line; negative a_2 is consistent with dipole assignment.

the yrast states of $^{110}_{50}$Sn above the 10^+ state at 5226.4 keV. This does not appear to be structurally analogous to the (2p2h) proton bands observed[4] in the heavier tin isotopes, $A=112-118$. The 10^+ state of a 2p2h proton band would be expected at about 5 MeV, but its decay would be very different from that of the 5226.4 keV state. The (2p2h) proton bands in the heavier tin isotopes have no out-of-band transitions above the 6^+ state, and all the out-of-band transitions from the 6^+, 4^+, and 2^+ members go to low-lying 2^+ and 4^+ states. However, the 5226.4 keV state in ^{110}Sn decays directly to the 3932.2 keV 9^- state and indirectly to the 3686.2 keV 7^- state.

A comparison of the decay scheme of the 5226.4 keV state in $^{110}_{50}$Sn$_{60}$ with the decay of the yrast 10^+ state in $^{108}_{48}$Cd$_{60}$ suggests a possible interpretation of these data. Figure 4 shows a partial decay scheme of ^{108}Cd starting with the yrast 10^+ level, and also the decay of the (10^+) 5226.4 keV level in ^{110}Sn. The ^{108}Cd data are from the work of Samuelson *et al.*[6] The unbracketed spins and the (8^+) assignment for the 3810.5 keV level in ^{110}Sn are taken from van Poelgeest *et al.*;[2] the (9^-) and (10^+) assignments for the 4778.6 keV and 5226.4 keV states, respectively, in ^{110}Sn are from the present work. The similarity between the ^{108}Cd and ^{110}Sn decay schemes is striking, and it suggests that the (10_1^+) state in ^{110}Sn should be regarded, as in ^{108}Cd, as a predominantly $\nu(h_{11/2})^2$ state.

The higher excitation energy of the (10_1^+) level in ^{110}Sn compared to the ^{108}Cd case is consistent with the calculation of van Poelgeest *et al.*[2] They predicted an energy of about 5200 keV for the $\nu(h_{11/2})^2_{10^+}$ state using a single-particle energy for the $h_{11/2}$ neutron orbital which was derived from the $\frac{11}{2}^+$ excitation energy in ^{109}Sn.

The absence of a $10_1^+\rightarrow8_1^+$ transition in ^{110}Sn is also consistent with the calculations of van Poelgeest *et al.*[2] In that work the 8_1^+ state in ^{110}Sn was dominated by the $g_{9/2}^{-1}\otimes g_{7/2}$ proton configuration. Decay of a $\nu(h_{11/2})^2_{10^+}$ state to this 8_1^+ state is highly unlikely. In ^{108}Cd, however, the 10_1^+ state, although having a strong decoupled $(h_{11/2})^2$ component which leads to 67% branching to the 9^- states, still has an admixture of the ground state

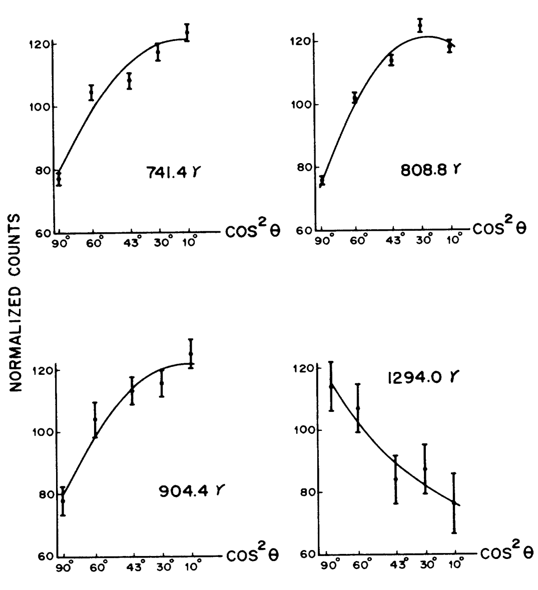

FIG. 3. Angular distributions for the 741.1, 808.8, 904.4, and 1294.0 keV gamma transitions.

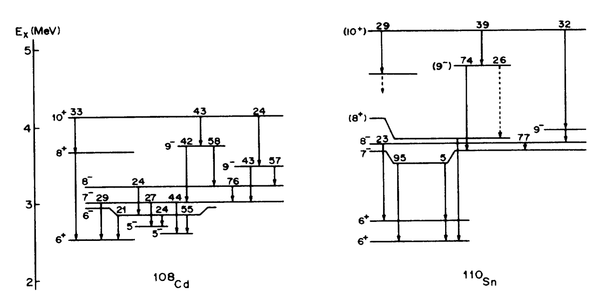

FIG. 4. Partial level schemes of ^{109}Cd and ^{110}Sn showing the similarities in level ordering.

band which allows an additional decay to the 8^+.

In summary, the comparison of ^{108}Cd and ^{110}Sn suggests that the quadrupole cascade observed in the present experiment and shown in Fig. 1 arises from a $\Delta J = 2$ collective yrast band in ^{110}Sn based on a 10^+ $\nu(h_{11/2})^2$ state at 5226.4 keV and extending in spin parity to at least $J^\pi = 20^+$.

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