THE DOUBLY CLOSED SHELL NUCLEUS $^{132}_{50}\text{Sn}_{82}$

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ABSTRACT

The structure of excited states in ^{132}Sn , fed in the β -decay of ^{132}In , has been investigated. Absolute intensities were deduced from γ -singles measurements. From multi-spectrum analysis of γ -lines the half-life of ^{132}In was determined to be 186 ± 22 ms. A level scheme based on γ - γ and β - γ coincidences is presented. The conversion electron spectrum has been studied and internal conversion coefficients deduced for two low-energy transitions. The total decay energy of ^{132}In was determined, from γ -gated β spectra, to be $Q_\beta = 13.6 \pm 0.4$ MeV. A lower limit of 6.968 MeV for the neutron separation energy in ^{132}Sn was deduced from the β -delayed neutron spectrum. The experimental results on the level structure of the doubly closed shell nucleus ^{132}Sn show that the shell model is applicable even far from the valley of stability.

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RADIOACTIVITY ^{132}In (β^-) [from U(p,fission)]; measured E_γ , I_γ , E_e , I_e , E_n , $T_{1/2}$, Q_β , γ - γ , β - γ . ^{132}Sn deduced level scheme, $B(E2)$, neutron separation energy, conversion coefficients. Uranium carbide target. Ge(Li), Si(Li), ^3He ion chamber, plastic scintillator telescope detectors. On-line mass separation.

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1. INTRODUCTION

Nuclei with closed major shells of both protons and neutrons should be well described in terms of the shell model. The nucleus ^{132}Sn , which has a closed proton shell $Z = 50$ and a closed neutron shell $N = 82$, is one of the very few species of this type. It is situated very far from the valley of stability and it is thus of special interest to determine whether or not the shell model, based on magic numbers near stability, is applicable in this region. Earlier work^{1,2)} showed that the first excited state was at ~ 4 MeV and systematics suggested that it was a 3^- state. This was also consistent with the spins and parities of the first excited states of some other doubly magic nuclei. We have shown that the first excited state is a 2^+ level at 4.041 MeV and the 3^- level is at 4.351 MeV. This is consistent with recent shell-model calculations^{3,4)}. It is of interest to test, in as much detail as possible, the predictions of these calculations, which are similar to those done for ^{208}Pb using different single-particle and hole states.

The decay of a metastable state in ^{132}Sn produced in fission has been studied by Sistemich et al.^{5,6)}, using the JOSEF separator at Jülich. They suggest that this is an 8^+ level which decays by stretched E2 transitions via the 2^+ level at 4041 keV to the ground state. Lifetime measurements by the Jülich group and conversion coefficient measurements reported in this paper are consistent with this interpretation.

The results reported here are based on a study of the levels in ^{132}Sn fed in the β -decay of ^{132}In ($T_{1/2} = 186$ ms). The isotope separator ISOLDE at CERN was used to separate mass-132 products from a uranium carbide target bombarded by 600 MeV protons. The ion-source conditions were optimized to give the best yield of ^{132}In , which was 500 atoms/s. This yield was sufficient to study the decay of ^{132}In by the techniques of nuclear spectroscopy, although in some coincidence experiments the statistical accuracy is low. Gamma-ray measurements and γ - γ coincidences have been made with Ge(Li) detectors. Beta-ray spectra, both direct and in coincidence with γ -rays, have been studied. The conversion electron spectrum has been studied and internal conversion coefficients deduced for two of the low-energy transitions. The delayed neutron spectrum has also been observed. As a result of the measurements described in this paper, we propose a decay scheme for ^{132}In and a level scheme for ^{132}Sn . The level scheme and the β -decay strengths for ^{132}In are described in terms of a shell-model calculation.

2. EXPERIMENTAL METHOD

Sources of short-lived ^{132}In were produced by directing the extracted (~ 2 μA) proton beam from the CERN Synchro-cyclotron onto a uranium carbide target containing ~ 10 g/cm² of ^{238}U . The target was maintained at a temperature of 2200 °C. Volatile fission products are released⁷⁾ from the target matrix into the ion source of the ISOLDE isotope separator. The surface ionization source used in these experiments optimized the yield of In and Cs ions and provided high selectivity against other elements within the same isobaric mass chain. The presence of ^{132}Cs ($T_{1/2} = 6.5$ d) was a serious source of background as ^{132}Cs is near the maximum of the Cs yield curve and the neutron-rich isotope ^{132}In is far from the maximum of the In yield curve. The measured yield of ^{132}In was 500 atoms/s and that of ^{132}Cs 10^{10} atoms/s. Short collection times were used to enhance the ^{132}In activity, but the presence of ^{132}Cs was a serious problem. After mass separation the activity was collected on a movable tape so that the ^{132}Sn ($T_{1/2} = 40$ s) daughter activity and the ^{132}Cs contamination were removed.

The sources produced in the separator were studied using spectroscopic techniques. The γ -ray spectra were studied with Ge(Li) detectors, the β -ray spectra with a large plastic scintillator, the conversion electron spectrum with a Si(Li) detector, and the neutron spectrum with a ^3He spectrometer. Gamma-ray spectra were recorded both in singles and in coincidence with β - and γ -rays. Because of the presence of the contaminants the singles β -ray spectra were not used in the

final analysis. The conversion electron spectra were recorded by collecting on the tape and moving the activity in front of the Si detector. Only singles spectra were measured. The neutron spectra did not have the background problems due to ^{132}Cs and ^{132}Sn which are not precursors for β -delayed neutron emission.

3. EXPERIMENTAL RESULTS

3.1 Gamma-ray measurements

Sources of ^{132}In were collected on a movable tape in front of a Ge(Li) detector and the direct γ -ray spectrum was recorded in an energy range up to 8 MeV. The highest energy γ -ray observed in other experiments associated with the decay of ^{132}In was 4.416 MeV. The tape was periodically moved into a shielded position to reduce the build-up of γ -rays from the contaminant 6.5 d ^{132}Cs and the daughter products of ^{132}In , in particular 40 s ^{132}Sn . The γ -ray spectrum observed under these conditions is shown in figs. 1 and 2. Based on half-life analysis, the lines whose energies are given have been assigned to the decay of ^{132}In . The half-life was determined to be 186 ± 22 ms using a multispectrum-analysis technique for the lines listed in table 1. The lines assigned to contaminants are marked with letters and all these lines had a half-life much greater than 186 ms. They arise from the decay-chain daughters (b) ^{132}Sn , (c) ^{132}Sb , and from (a) ^{132}Cs .

A second method of identifying lines associated with the decay of ^{132}In made use of the high Q_β value (~ 14 MeV) for this decay compared to the low values (< 4 MeV) for the principal contaminants. Gamma-ray spectra in coincidence with β -rays above 2 MeV were measured, confirming that the lines assigned to ^{132}In were in coincidence with high-energy β -rays.

The intensities of γ -rays assigned to the decay of ^{132}In were determined from the direct γ -ray spectrum. The results of these measurements are given in table 1 normalized to a value of 96 for the total feeding to the ground state. This normalization gives γ -ray intensities per 100 disintegrations since the β -decay of ^{132}In ($I^\pi = 7^-$) does not feed the 0^+ ground state of ^{132}Sn directly and because there is a 4% delayed neutron branch. The errors given for the intensities include those due to the efficiency calibration of the detector. The large error on the intensity of the 479.1 keV line is due to the difficulty in correcting for the Compton edge of the 668 keV contaminant (^{132}Cs) line which occurs at this energy. In the lower part of the table are given lines whose probable assignment is ^{132}In but whose half-life could not be measured accurately. No γ -rays were observed with energy greater than 4.416 MeV. In the energy region 600–2100 keV (not shown in the figures) no transitions assigned to ^{132}In -decay were observed. There are many contaminant lines and our experiments cannot rule out weak transitions from ^{132}In of intensities $\leq 3\%$ per disintegration.

3.2 Conversion electron measurements and internal conversion coefficients

A cooled Si(Li) detector was used to study the electron spectrum from ^{132}In up to 600 keV. Since the conversion electron lines are on top of the continuous β -ray spectrum it was only possible to observe the most intense lines of the low-energy transitions. The ^{132}In activity was collected for 0.5 s and moved to a point where it could be observed simultaneously by both the electron detector and a Ge(Li) detector placed on opposite sides of the tape. The source was counted for 0.5 s (2.5 half-lives of ^{132}In) and then moved so that the electron detector was totally shielded from low-energy electrons. In this position the γ -ray detector was not well shielded and could still detect γ -rays from the long-lived contaminants.

The results of these measurements are shown in fig. 3, in the region 240–380 keV where conversion lines were observed. Below 120 keV the background prevented observation of conversion lines. In the energy region 120–500 keV two conversion lines were observed, corresponding to the K-conversion of the 299 and 375 keV transitions. The γ -ray measurement in

this energy region is shown in the upper half of fig. 3. In addition to the lines at 299 and 375 keV from ^{132}In , background lines are seen at 280 and 340 keV. These are due to long-lived contaminants which were not shielded from the γ -ray detector.

In order to determine the internal conversion coefficients, the system was calibrated in this energy region. This was done by studying the 246 and 340 keV transitions from ^{124}Xe , whose conversion coefficients are known. The calibration was checked using the 340 keV transition from ^{132}Sn . The experimental internal conversion coefficients are given in table 2 and fig. 4 where they are compared with theoretical predictions for different multiplicities. The results are consistent with an assignment of E2, or M1, or an (M1 + E2) mixture to both the 299 and 375 keV transitions. They rule out a pure E1 assignment. This implies that the parities of the levels joined by the transitions are the same and are consistent with those assigned in the level scheme of ^{132}Sn as $6^+ \rightarrow 4^+$ and $4^+ \rightarrow 2^+$ transitions.

Kawade et al.⁶⁾ have measured the conversion coefficient of the 132 keV transition and find it to be consistent with an E2 transition and an $8^+ \rightarrow 6^+$ assignment to this transition. The spin assignments, which are also based on lifetime measurements, are discussed later.

3.3 β -ray spectrum

The Q_β value for the decay of ^{132}In is estimated from mass tables⁸⁾ to be ~ 14 MeV. In order to measure such high energies a large β -ray telescope was used. It consisted of two Ne 110 plastic scintillators, a $1\text{ mm} \times 1\text{ cm}^2$ area ΔE detector followed by a 15 cm thick $\times 10$ cm diameter E detector. The energy window on the ΔE counter was set to accept the minimum ionization peak from high-energy electrons. The telescope system helped to reduce the background due to high-energy γ -rays, which would not trigger the ΔE counter, and helped to assure that the observed β -rays came from the source position. The spectrometer was calibrated by use of a ^{207}Bi source and a ^{106}Ru source ($E_{\beta\text{max}} = 3.5$ MeV) and extrapolated to higher energies.

The singles β spectrum observed with this telescope had an end point of 9.0 ± 0.3 MeV. A Fermi plot indicated additional components, but these were difficult to resolve. In order to study these components β - γ coincidence measurements were made and these revealed the two dominant components. Figure 5 shows Fermi plots of the β -ray spectra in coincidence with gates set in the Ge(Li) spectrum from 2.2–2.4 MeV and 3.0–4.5 MeV. The lower gate emphasizes the 2269 and 2380 keV transitions and the upper gate the 4041, 4351, and 4416 keV γ -rays and their escape peaks. The end point of spectrum A is 6.0 ± 0.3 MeV and spectrum B has two components with end points 6.2 ± 0.3 MeV and 8.8 ± 0.3 MeV. This experiment would not resolve components, near the end point, separated by less than 0.3 MeV. These results are consistent with the decay scheme proposed for ^{132}In and imply a total decay energy $Q_\beta = 13.6 \pm 0.4$ MeV. The error includes an allowance for possible error in the extrapolation from our calibration spectrum.

3.4 γ - γ coincidence measurements

In order to establish the relationship between γ -transitions, coincidence measurements were made using two Ge(Li) detectors. The source was deposited on a movable tape between the detectors and periodically moved into a shielded position to reduce the long-lived contaminants, principally ^{132}Cs whose 668 keV γ -ray would otherwise have given an unacceptably high counting rate in the Ge(Li) detector coincidence system. The data were recorded event by event on magnetic tape and subsequently analysed by setting gates on all the strong γ -transitions. The contributions from the Compton distributions under the peaks were subtracted by setting windows below and above each peak. The statistical accuracy of these measurements was low for the higher-energy γ -rays but was sufficient to reveal the main features. The results of these

measurements for gates set on six of the transitions are shown in figs. 6 and 7. Coincidences are observed between the transitions of 2268 and 2380 keV and γ -rays in the 4 MeV region, thus implying the existence of levels in ^{132}Sn of at least 6.7 MeV excitation energy. This is consistent with the observed β - γ coincidence results reported in the previous section.

The coincidence relations and the relative intensities are given in table 3. The relative intensities do not include possible angular correlation effects, which in our geometry would be less than the quoted errors. The analysis of transitions adding up to ~ 668 keV was very difficult owing to strong coincidence events arising from scattering of the intense 668 keV contaminant line from one detector to the other. Within the statistical accuracy the results of the γ - γ coincidence measurements confirm the level scheme proposed in this paper.

3.5 Beta-delayed neutron measurements

The β -delayed neutron spectrum observed in the decay of ^{132}In was measured using ^3He -filled neutron spectrometers. The observed counting rate of non-thermal neutrons was very low (~ 0.5 per minute) as the P_n value⁹⁾ is only $(4.2 \pm 0.9)\%$ and the efficiency of the spectrometer for energetic neutrons (0.2–2 MeV) is in the range 10^{-3} to 10^{-4} . The apparatus was placed in an enclosure having walls of polyethylene covered with cadmium sheets. This effectively suppressed the fast neutron background, principally from the ISOLDE target area, to an acceptable level. The ^3He spectrometers are sensitive to γ -rays, which give low-energy pulses. To reduce the intense γ -radiation, mainly due to ^{132}Cs , which seriously affects the energy resolution owing to pile-up effects, a 4 mm thick lead shield was introduced between the source and the neutron spectrometer. The spectrum observed during a run of 17 hours is shown in fig. 8. There are two statistically significant peaks, separated by (100 ± 15) keV, and evidence for some higher-energy neutrons. The energies of the two peaks, including an estimate of the calibration error, are (230 ± 10) keV and (330 ± 10) keV.

Beta-delayed neutrons can arise from levels in ^{132}Sn which are at higher energy than $^{131}\text{Sn} + n$ and the present data can be used to place a lower limit on the neutron separation energy S_n in ^{132}Sn . The 6^- level at 7.210 MeV (see section 4) decays by γ -emission. If s-wave neutron emission were possible, this would completely dominate the γ -decay. In ^{131}Sn , Fogelberg and Blomqvist report¹⁰⁾ on an $11/2^-$ level at 241.8 keV. The total energy of ^{131}Sn in this state plus a neutron must exceed that of ^{132}Sn in the 7.210 MeV state, as otherwise an s-wave neutron would be emitted. This places a lower limit of 6.968 MeV on the neutron separation energy. This is consistent with recent mass formulae^{8,11,12)} which predict S_n in the range (6.89–7.31) MeV. We tentatively assign the 230 keV neutrons to the transition between the 6^- state in ^{132}Sn and the ground state of ^{131}Sn . The simplified decay scheme, shown as an inset in fig. 8, represents a possible interpretation of the β -delayed neutron data (see also section 4.2.1).

4. DISCUSSION

4.1 Level scheme of ^{132}Sn

The decay scheme of ^{132}In and the level scheme of ^{132}Sn are shown in fig. 9. This scheme is based on energy relationships, γ - γ and β - γ coincidence measurements, and the intensity balance of transitions feeding and de-exciting the levels. The β feedings and log ft values indicated in the text are also based on intensity balance. The γ -ray intensities are given in per cent per disintegration of ^{132}In . Since 4% of the decays proceed by delayed neutron emission, the relative intensities measured in the γ -ray spectrum were normalized to the 96% γ feeding to the ground state.

The level scheme shown in fig. 9 accounts for the dominant transitions observed in the decay of ^{132}In . Unfortunately, because of weak sources and a strong contamination from ^{132}Cs , the

statistics in the γ - γ coincidence measurements were not sufficiently good to resolve an ambiguity regarding the 4942 keV level. The level scheme is the most probable one based on theoretical considerations, but the data, however, do not exclude a slight modification. The γ - γ coincidences between the 526 and 2268 keV transitions would be equally consistent with a level at 6684 keV. In our figure we have chosen the 4942 keV alternative as it appears to be consistent with the theoretical discussion given below.

4.2 A shell-model interpretation

The doubly closed shell nucleus ^{208}Pb has been studied in detail and many calculations have been made of its properties. The second case of a heavy nucleus with two major closed shells for which spectroscopic information is available is that of ^{132}Sn . In recent theoretical work the energies of shell-model states in ^{132}Sn and the neighbouring nuclei have been calculated. Recent experimental work on the valence nuclei around ^{132}Sn has established the energies of single-neutron hole states in ^{131}Sn and single-proton states in ^{133}Sb . In our discussion of the level scheme of ^{132}Sn we shall compare our results with calculations which are similar to those for ^{208}Pb but using appropriate shell-model states for the $Z = 50, N = 82$ region. The single-particle states obtained in the calculations¹³⁾ by Blomqvist are shown in fig. 10. These states can be used to predict level and decay properties in ^{132}Sn , and in this section we compare our proposed level scheme with the general predictions of the shell-model calculations. The available spectroscopic information is not sufficient to allow the type of detailed comparison that has been done for ^{208}Pb .

4.2.1 The β -decay of ^{132}In

The nucleus ^{132}In has one proton hole and one neutron particle added to the double-magic nucleus ^{132}Sn . In order to find out the most probable assignment for the β -decaying ground state of ^{132}In , we first consider the ordering of the relevant single-nucleon states.

The lowest few proton-hole states in ^{131}In , and the corresponding neutron-particle states in ^{133}Sn , are not well known experimentally, except that the ground states are consistent with the shell-model assignments¹⁰⁾ $\pi g_{9/2}^{-1}$ for ^{131}In , and¹⁴⁾ $\nu f_{7/2}$ for ^{133}Sn . Theoretical calculations^{13,15)} support these ground-state assignments, and indicate that the first excited states are $\pi p_{1/2}^{-1}$ and $\nu p_{3/2}$, both well separated by about 1 MeV from the ground states. Extrapolations of experimental excitation energies, from ^{107}In , ^{109}In , ^{111}In , ^{113}In , ^{115}In , ^{117}In , ^{119}In , ^{121}In , ^{123}In to ^{131}In for the proton hole, and from ^{147}Gd , ^{145}Sm , ^{143}Nd , ^{141}Ce , ^{139}Ba , ^{137}Xe to ^{133}Sn for the neutron particle, give the same assignments for the first two orbitals of each kind, but favour somewhat lower excitation energies, ~ 0.3 MeV for $\pi p_{1/2}^{-1}$ in ^{131}In and ~ 0.6 MeV for $\nu p_{3/2}$ in ^{133}Sn .

The ordering of the single-nucleon states implies that the ground-state configuration of ^{132}In probably is $\nu f_{7/2} \pi g_{9/2}^{-1}$. The alternatives $\nu f_{7/2} \pi p_{1/2}^{-1}$ and $\nu p_{3/2} \pi g_{9/2}^{-1}$ can be excluded with some confidence on the basis of their larger single-particle energies. The splitting of the multiplets due to the neutron-proton particle-hole interaction is not expected to change this conclusion.

The lowest member of the $\nu f_{7/2} \pi g_{9/2}^{-1}$ multiplet, which becomes the ground state of ^{132}In , is most likely the $J^\pi = 7^-$ level. This follows from general properties of the proton-neutron effective interaction^{16,17)}, and is supported by experimental data on similar particle-hole excitations built on double-magic nuclei. In cases where the particle and the hole both occupy orbitals with $j = \ell + 1/2$ (or $j = \ell - 1/2$) the lowest level of the multiplet has invariably the spin $J = j_p + j_h - 1$. Examples of such cases are the $(\pi f_{7/2} \nu f_{7/2}^{-1})6^+$ state in

^{48}Sc , the $(\pi g_{9/2} \nu g_{9/2}^{-1})8^+$ state in ^{90}Nb , the $(\pi g_{7/2} \nu d_{3/2}^{-1})4^+$ state in ^{132}Sb , and the $(\pi h_{9/2} \nu f_{5/2}^{-1})6^+$ state in ^{208}Bi .

Accepting the ground-state assignment $(\nu f_{7/2} \pi g_{9/2}^{-1})7^-$, the Q_β value for the decay of ^{132}In can be estimated by connecting it to the known Q_β values^{10,14,18)} for the decays of ^{131}In , ^{133}Sn , and ^{132}Sn . If the particle-hole interaction energies can be neglected in ^{132}In and ^{132}Sb the Q_β values should be related by

$$\begin{aligned} Q_\beta(\nu f_{7/2} \pi g_{9/2}^{-1} \rightarrow 0) &= Q_\beta(\pi g_{9/2}^{-1} \rightarrow \nu d_{3/2}^{-1}) + Q_\beta(\nu f_{7/2} \rightarrow \pi g_{7/2}) - Q_\beta(0 \rightarrow \pi g_{7/2} \nu d_{3/2}^{-1}) \\ &= 8.93(15) + 7.83(7) - 3.08(4) = 13.68(17) \text{ MeV}. \end{aligned}$$

In fact, this equation is equivalent to the transverse Garvey-Kelson relation¹⁹⁾ between the six masses of $^{131,132}\text{In}$, $^{131,133}\text{Sn}$, and $^{132,133}\text{Sb}$. The particle-hole interaction energies in the $(\nu f_{7/2} \pi g_{9/2}^{-1})7^-$ and $(\nu g_{7/2} \nu d_{3/2}^{-1})4^+$ states are both expected to be small and positive, ≤ 0.1 MeV. Since they occur with opposite signs in the relation above, their contributions to the Q_β value should not be significant compared to the experimental errors. Our measured value

$$Q_\beta = 13.6(4) \text{ MeV}$$

agrees well with the calculated value.

The decay of the $(\nu f_{7/2} \pi g_{9/2}^{-1})7^-$ state can basically proceed in three different ways, i.e. by transitions involving the proton hole, the neutron particle, or the core. The final states in these transitions are of the types $\nu \nu^{-1}$, $\pi \pi^{-1}$ and $\nu \pi \nu^{-1} \pi^{-1}$, respectively. A useful comparison can be made with the simpler decays of the $\pi g_{9/2}^{-1}$ state in ^{131}In , the $\nu f_{7/2}$ state in ^{133}Sn , and the 0^+ ground state of ^{132}Sn . In the approximation that interactions with the spectator nucleon(s) only cause small energy shifts, and that the different types of final states do not mix very much, the ^{132}In decay should appear as a superposition of the ^{131}In , ^{133}Sn , and ^{132}Sn decays.

The total decay rate of ^{132}In is in accordance with this simple picture. The known half-lives^{10,14,18)}

$$\begin{aligned} T_{1/2}(\pi g_{9/2}^{-1}, ^{131}\text{In}) &= 0.28(3) \text{ s} \\ T_{1/2}(\nu f_{7/2}, ^{133}\text{Sn}) &= 1.5(1) \text{ s} \\ T_{1/2}(0, ^{132}\text{Sn}) &= 40(1) \text{ s} \end{aligned}$$

imply the half-life $(0.28^{-1} + 1.5^{-1} + 40^{-1})^{-1} = 0.24(3) \text{ s}$ for ^{132}In , in fair agreement with the measured value $0.186(22) \text{ s}$. By similar arguments, the detailed pattern of β^- feeding into excited states of ^{132}Sn may be related to the decay modes of the neighbouring nuclei. The half-lives given above imply that the main part of the decay ($\sim 85\%$) should proceed by hole transitions to $\nu \nu^{-1}$ states, and the rest ($\sim 15\%$) by particle transitions to $\pi \pi^{-1}$ states. The decay by core transitions is negligible ($< 1\%$) and will not be considered further.

The strongest decay¹⁰⁾ of ^{131}In proceeds by the Gamow-Teller (GT) transition $\pi g_{9/2}^{-1} \rightarrow \nu g_{7/2}^{-1}$. The equivalent decay of ^{132}In should produce the $(\nu f_{7/2} \nu g_{7/2}^{-1})6^-, 7^-$ states in ^{132}Sn with the intensity ratio 8:1. The observed level at 7210 keV clearly corresponds to the 6^- state of this type. The value for $\log ft$ is 4.4 ± 0.1 (6^- , ^{132}Sn) and agrees very well with $\log ft = 4.4$ ($7/2^+$, ^{131}Sn). The 7^- level is more weakly fed and if at higher energy would lie above the neutron separation energy and could decay by neutron emission to levels in ^{131}Sn . The observed P_n value⁹⁾ of 4.2% indicates that the β feeding to neutron unstable levels is relatively weak but could be $\sim 8\%$ of the feeding to the 6^- level. The delayed neutron spectrum (fig. 8) shows peaks

at 230 and 330 keV. A possible explanation is that these correspond to transitions from the 6^- level at 7210 keV to the $3/2^+$ ground state and from a 7^- level to the $11/2^-$ first excited state of ^{131}Sn . Assigning the 330 keV peak to neutrons from the 7^- level would give an energy for this level of 7552 keV. There is no evidence for the γ -decay of such a level, which would imply that it is neutron unstable. The arguments for its existence must be regarded as very tentative.

The second strongest decay from ^{131}In should be the first-forbidden transition $\pi g_{9/2}^{-1} \rightarrow \nu h_{11/2}^{-1}$. The intensity of this decay branch has not been directly measured, but a branching ratio of $\leq 20\%$, corresponding to $\log ft \geq 5.5$, has been considered possible¹⁰⁾. The equivalent transition from ^{132}In should form the states $(\nu f_{7/2} \nu h_{11/2}^{-1})6^+, 7^+, 8^+$, with the main intensity fraction (87%) going into the 8^+ state. The intensity balance for the 4847 keV level, which has largely this configuration, then requires that $\leq 50\%$ of the feeding comes by direct β^- -decay, and the rest by unobserved γ transitions from higher levels. In our experiment we observe an appreciable intensity to the 6^+ level which does not agree with this prediction and probably indicates an admixture of another configuration in this 6^+ level. There could be appreciable feeding to a 7^+ level. We have no strong evidence for such a level but have placed a very tentative level at 4917.8 keV on the basis of the 203 keV transition and this could possibly be the 7^+ member of the configuration.

Some of the known¹⁰⁾ weaker decay branches from ^{131}In to levels in ^{131}Sn around 4 MeV probably feed $\nu g_{7/2}^{-1}$ fragments mixed into various one-particle-two-hole $7/2^+$ states. The corresponding 6^- strength in ^{132}Sn should occur at ~ 9 MeV and decay by emitting neutrons of ~ 1.5 MeV. The observed structure in the high-energy part of the neutron spectrum (fig. 8) may be related to the decay of these states.

The neutron-particle decay¹⁴⁾ of ^{133}Sn is dominated by the first-forbidden transition $\nu f_{7/2} \rightarrow \pi g_{7/2}$. The transition operator contains both 0^- and 1^- terms. Detailed analyses^{20,21)} of the analogous $\nu g_{9/2} \rightarrow \pi h_{9/2}$ transition from ^{209}Pb show that the pseudoscalar operator contributes mostly to the decay. The corresponding decay of ^{132}In should therefore go to the $(\pi g_{7/2} \pi g_{9/2}^{-1})7^+$ state in ^{132}Sn at about 5.4 MeV. The energy estimate is based upon known proton separation energies and a comparison with the energy of the analogous $(\pi h_{9/2} \pi h_{11/2}^{-1})9^+$ state²²⁾ in ^{208}Pb . The $\log ft$ value¹⁴⁾ of 5.4 implies a feeding intensity of about 15%. The γ -decay of this level with such intensity should have been seen in the γ - γ coincidence spectra, unless the decay proceeds to the long-lived 8^+ isomer at 4847 keV. Gamma feeding of the 8^+ level with about this intensity was also suggested by an independent argument above.

4.2.2 Excitation energies and γ -decays of levels in ^{132}Sn

The most striking feature of the ^{132}Sn level scheme is the absence of excited states below 4 MeV, which is a consequence of the shell closures at $Z = 50$, $N = 82$. Above this energy gap one expects to find a region extending up to about 8 MeV, which is dominated by one-particle-one-hole excitations. The first few levels in this region (2^+ , 3^- , 4^+) can be described as vibrational excitations, corresponding to coherent mixtures of many one-particle-one-hole configurations²³⁾. Consequently there should occur about 100 levels in the interval $4.5 \text{ MeV} < E_{\text{ex}} < 7.5 \text{ MeV}$, most of which may be characterized by one or a few leading configurations. Only 5 or 6 of these levels have been identified in the present experiment, owing to the selectivity of the β -decay and the following γ -decay processes. We now discuss the observed levels individually regarding their configuration assignments, energies, and γ -decay properties.

The 7210 keV level is firmly identified as the $(\nu f_{7/2} \nu g_{7/2}^{-1})6^-$ state. The fact that the observed strong β feeding with a $\log ft$ value of 4.4 for the GT transition is practically equal to the $\log ft$ value for the single-particle transition $\pi g_{9/2}^{-1} \rightarrow \nu g_{7/2}^{-1}$, and that no GT strength is observed to neighbouring levels, implies that the configuration is fairly pure. This conforms with theoretical

expectations, since only four other 6^- levels should occur within ± 1 MeV from 7.2 MeV, and their interaction matrix elements with $\nu f_{7/2} \nu g_{7/2}^{-1}$ are all estimated to be < 0.1 MeV in magnitude.

The excitation energy of the 6^- level can be calculated as follows. The energy gap in the neutron single-particle spectrum at $N = 82$,

$$\delta_n = \epsilon(\nu f_{7/2}) - \epsilon(\nu d_{3/2}) = S_n(^{132}\text{Sn}) - S_n(^{133}\text{Sn}) ,$$

can be obtained from measured Q_β values and an estimated particle-hole interaction energy

$$\begin{aligned} \delta_n &= Q_\beta(^{133}\text{Sn}) - Q_\beta(^{132}\text{Sn}) - \Delta(\pi g_{7/2} \nu d_{3/2}^{-1}; 4^+) \\ &= 7.83(7) - 3.08(4) - 0.05(5) \\ &= 4.70(10) \text{ MeV} . \end{aligned}$$

Adding the single-particle energy difference¹⁰⁾ $\epsilon(\nu d_{3/2}) - \epsilon(\nu g_{7/2})$ from ^{131}Sn , and the particle-hole interaction energy in the 6^- state, gives

$$\begin{aligned} E_{\text{ex}} &= \delta_n + E_{\text{ex}}(\nu g_{7/2}^{-1}; ^{131}\text{Sn}) + \Delta(\nu f_{7/2} \nu g_{7/2}^{-1}; 6^-) \\ &= 4.70(10) + 2.434 + 0.00(5) \\ &= 7.13(11) \text{ MeV} , \end{aligned}$$

in excellent agreement with the experimental excitation energy, 7.210 MeV.

The γ -decay of the 6^- level may be compared with that of the $\nu g_{7/2}^{-1}$ level in ^{131}Sn , which decays mainly by a 2.434 MeV E2 transition to the $\nu d_{3/2}^{-1}$ ground state. In ^{132}Sn the corresponding E2 transition probability from $(\nu f_{7/2} \nu g_{7/2}^{-1})6^-$ should be divided between final $\nu f_{7/2} \nu d_{3/2}^{-1}$ states with $J^\pi = 4^-$ and 5^- in the ratio 0.6 : 0.4. There are indeed two transitions observed from the 6^- state, with energies 2.380 MeV and 2.268 MeV, and with γ intensities of the ratio 1.6(2). The final states at 4830 keV and 4942 keV are therefore with confidence interpreted as the $\nu f_{7/2} \nu d_{3/2}^{-1}$ states with $J^\pi = 4^-$ and 5^- , respectively. The γ intensity alone does not give a strong preference for this spin assignment compared to the reversed one, since a small M1 admixture ($\sim 10^{-2}$ Weisskopf units) in the $6^- \rightarrow 5^-$ transition would make the decay to 5^- strongest. However, combined with the intramultiplet energy spacing

$$E(5^-) - E(4^-) = + 111 \text{ keV} , \quad \nu f_{7/2} \nu d_{3/2}^{-1} , \quad \text{in } ^{132}\text{Sn},$$

which may be compared with the analogous case

$$E(7^-) - E(6^-) = + 118 \text{ keV} , \quad \nu g_{9/2} \nu d_{5/2}^{-1} , \quad \text{in } ^{208}\text{Pb},$$

and considering the calculated purity of these states²⁴⁾, the spin assignments are reasonably reliable.

The 4^- state γ -decays to the 3^- state at 4351 keV, which is the analogue of the thoroughly studied collective 3^- state in ^{208}Pb at 2615 keV. The 4351 keV level decays to the 0^+ ground state and, based on energy considerations, weakly to the 2^+ level at 4041 keV. Gamma-gamma coincidence measurements establish feeding from higher energy levels at least 2380 keV above this level. The position of the level is well established but direct experimental proof of the $I^\pi = 3^-$ assignment is lacking. The energy of the low-frequency octupole mode depends on detailed features of the shell structure²⁵⁾. An RPA calculation²³⁾, with the effective interaction strength

adjusted to reproduce the energy of the 3^- state in ^{208}Pb , gave good energy agreement for ^{132}Sn . The ground-state transition strength in ^{132}Sn should be of similar magnitude to that in ^{208}Pb , $B(E3) \approx 34$ Weisskopf units.

The positive parity states, 2^+ , 4^+ , 6^+ , and 8^+ , are well established by studies of the 8^+ isomeric decay⁶⁾. The lifetimes of the 4^+ , 6^+ , and 8^+ levels have been measured⁶⁾ as well as the conversion coefficient of the $8^+ \rightarrow 6^+$ transition, allowing a sensitive test of the description of these states. The present measurements, including the conversion coefficient measurements of the $6^+ \rightarrow 4^+$ and $4^+ \rightarrow 2^+$ transitions, are in agreement with the suggested spin assignments. The relative transition intensities observed in the study of the decay of ^{132}In are different from those of Sistemich et al.⁵⁾ owing to feeding from the negative parity levels and direct β feeding into the 6^+ and 8^+ levels. The comparison between experiment⁶⁾ and theory, assuming pure $\nu f_{7/2} \nu h_{11/2}^{-1}$ configurations and the neutron effective charge $e_{\text{eff}} = e$, is shown in table 4. There is fair agreement for the E2 transition rates between the higher-spin states, but the $4^+ \rightarrow 2^+$ transition rate is observed to be enhanced by a factor of 2. This may be explained by a small admixture (about 3%) of $\nu p_{3/2} \nu h_{11/2}^{-1}$ into the 4^+ state. The 2^+ and 4^+ states are also expected to contain some configuration admixtures of collective nature, in particular proton excitations involving the $\pi g_{9/2}^{-1}$ hole orbital.

5. SUMMARY AND CONCLUSIONS

In this paper we have presented the experimental information obtained in a study of the decay of ^{132}In at the ISOLDE facility at CERN. A major experimental problem was the much larger production of ^{132}Cs , which caused severe background problems. We have reported results that can clearly be identified with the decay of ^{132}In into levels in ^{132}Sn . Additional weak transitions $\lesssim 3\%$ per disintegration might not have been observed owing to the background.

Preliminary reports of these results have appeared earlier. The new data in this paper include details of the γ - γ and β - γ coincidence experiments, and delayed-neutron measurements not previously reported. All previous data have been combined with more recent measurements to give the values quoted in this paper.

The assignments of spins and parities to the levels are based on γ -decay branching ratios, β -decay feeding from the 7^- ground state of ^{132}In , level systematics, and—for the positive parity levels—on lifetime and conversion coefficient measurements. The 6^- assignment to the 7210 keV level is based on the observed strong β transition to this level.

Our results show evidence for very strong shell closure effects at $Z = 50$ and $N = 82$. The first excited state is at 4041 keV, considerably higher than that in ^{208}Pb after allowing for the $A^{-1/3}$ dependence. This state has a spin 2^+ rather than 3^- observed as the first excited state in other double-magic nuclei. In ^{132}Sn the 3^- state lies at slightly higher energy than the 2^+ state.

The proposed level scheme is consistent with the shell-model calculations by Blomqvist¹²⁾ and existing information on single-particle levels in neighbouring nuclei. This information has been used to help in making spin assignments to some of the levels. Clearly, further work is required under cleaner experimental conditions to enable a detailed comparison to be made between experiment and theory. The present results establish the general features of the level scheme and that the shell model is applicable even in a region far from the valley of stability.

REFERENCES

- 1) A. Kerek, G.B. Holm, L.-E. De Geer and S. Borg, Phys. Lett. **44B** (1973) 252.
- 2) W.-D. Lauppe, K. Sistemich, T.A. Kahn, H. Lawin, G. Sadler, H.A. Selic and O.W.B. Schult, Proc. Int. Conf. Nuclear Structure, Tokyo, 1977, in J. Phys. Soc. Japan Suppl. **44** (1978), p. 335.
- 3) T. Björnstad, L.E. De Geer, G.T. Ewan, P.G. Hansen, B. Jonson, K. Kawade, A. Kerek, W.-D. Lauppe, H. Lawin, S. Mattsson and K. Sistemich, Phys. Lett. **91B** (1980) 35.
- 4) T. Björnstad, J. Blomqvist, G.T. Ewan, B. Jonson, K. Kawade, A. Kerek, S. Mattsson and K. Sistemich, Z. Phys. A **306** (1982) 95.
- 5) K. Sistemich, W.-D. Lauppe, T.A. Khan, H. Lawin, H.A. Selic, J.P. Bocquet, E. Mounand and F. Schussler, Z. Phys. A **285** (1978) 305.
- 6) K. Kawade, K. Sistemich, G. Bathistuzzi, H. Lawin, K. Shizuma and J. Blomqvist, Z. Phys. A **308** (1982) 33.
- 7) T. Björnstad, L.C. Carraz, H.Å. Gustafsson, J. Heinemeier, B. Jonson, O.C. Jonsson, V. Lindfors, S. Mattsson and H.L. Ravn, Nucl. Instrum. Methods **186** (1981) 391.
- 8) A.H. Wapstra, G. Audi and K. Bos, Nucl. Phys. A **432** (1985) 55.
- 9) E. Lund, P. Hoff, K. Aleklett, O. Glomset and G. Rudstam, Z. Phys. A **294** (1980) 233.
- 10) B. Fogelberg and J. Blomqvist, Phys. Lett. **137B** (1984) 20; Nucl. Phys. A **429** (1984) 205.
- 11) W.D. Myers, Droplet model of atomic nuclei (Plenum, New York, 1977).
- 12) S. Liran and N. Zeldes, Atomic Data Nucl. Data Tables **17** (1976) 431.
- 13) J. Blomqvist, Proc. Int. Conf. on Nuclei far from Stability, Helsingör, 1981, CERN 81-09 (1981), p. 536.
- 14) J. Blomqvist, A. Kerek and B. Fogelberg, Z. Phys. A **314** (1983) 199.
- 15) G.A. Leander, J. Dudek, W. Nazarewicz, J.R. Nix and Ph. Quentin, Phys. Rev. C **30** (1984) 416.
- 16) A. de Shalit and J.D. Walecka, Nucl. Phys. **22** (1961) 184.
- 17) J.P. Schiffer and W.W. True, Rev. Mod. Phys. **48** (1976) 191.
- 18) K. Aleklett, E. Lund and G. Rudstam, Nucl. Phys. A **281** (1977) 213.
- 19) G.T. Garvey, Annu. Rev. Nucl. Sci. **19** (1969) 433.
- 20) A. Bohr and B.R. Mottelson, Nuclear Structure (W.A. Benjamin, New York, 1969), Vol. I, p. 350.
- 21) F. Krmpotik, K. Ebert and W. Wild, Nucl. Phys. A **342** (1980) 497.
- 22) G. Mairle, K. Schindler, P. Grabmayr, G.J. Wagner, U. Schmidt-Rohr, G.A.P. Berg, W. Hürlimann, S.A. Martin, J. Meissburger, J.G.H. Römer, B. Styczen and J.L. Tain, Phys. Lett. **121B** (1983) 307.
- 23) J.S. Dehesa, W.D. Lauppe, K. Sistemich and J. Speth, Phys. Lett. **74B** (1978) 309.
- 24) J. Blomqvist and T.T.S. Kuo, unpublished.
- 25) A. Bohr and B.R. Mottelson, Nuclear Structure (Benjamin, New York, 1975), Vol. II, p. 556.

Table 1
 γ -rays assigned to the decay of ^{132}In

Energy (keV)	Intensity (% per decay)
a) Measured $T_{1/2} = 186 \pm 22$ ms	
132.0 ± 0.7	19 ± 2
203.1 ± 0.7	5 ± 1.5
299.2 ± 0.7	50 ± 6
374.7 ± 0.7	63 ± 7
479.1 ± 0.7	30 ± 6
526.4 ± 0.7	21 ± 4
2268.3 ± 1.0	19 ± 3
2379.7 ± 1.0	30 ± 4
4040.6 ± 0.7	62 ± 7
4351.3 ± 0.7	25 ± 4
4415.8 ± 0.7	8.5 ± 1.5
b) Short $T_{1/2}$ but not measured	
64.6 ± 1.0	weak < 3
88.9 ± 1.0	weak < 3
111.5 ± 1.0	4.5 ± 1.5
310.8 ± 1.0	5 ± 2
413.4 ± 1.0	weak < 3

Table 2
Internal conversion coefficients

γ -ray energy (keV)	K-conversion coefficient				
	Experimental	Theoretical			Assignment
		E1	M1	E2	
299	0.028 ± 0.005	0.007	0.025	0.030	E2 or M1 + E2
375	0.020 ± 0.005	0.005	0.019	0.019	E2, M1 or M1 + E2

Table 3
 γ - γ coincidence results

γ -ray gate (keV)	Coincident γ -rays (keV)	Relative intensity (within gate)
4041	2380	2 ± 1
	2268	4.5 ± 1.5
	526	3 ± 1.5
	479	1.5 ± 1
	375	10 ± 2
	299	8.5 ± 2
	132	3 ± 1.5
2380	4351	3 ± 1.5
	479	5 ± 1.5
2268	4351	3 ± 1.5
	4041	10 ± 3
	526	7 ± 2.5
	(479)	(~ 2)
	375	8 ± 3
526	4041	2 ± 1
	2268	3 ± 1
	375	4 ± 1.5
479	4351	10 ± 3
	4041	2 ± 1
	2380	10 ± 3
375	4041	7 ± 2
	2268	3 ± 1
	526	3 ± 1
	299	(B.G. subtraction problem) ^{a)}
	132	2 ± 1
299	4416	2 ± 1
	4041	10 ± 3
	375	(B.G. subtraction problem) ^{a)}
	132	3 ± 1.5

a) label a as in fig. 6.

Table 4

Comparison of the measured transition probabilities $B(E\lambda)$ with theoretical values
[$B(E2)$ in units of $e^2\text{fm}^4$ and $e_{\text{eff}} = e$]

Transition	Experimental	Theoretical values ($\nu f_{7/2} \nu h_{11/2}^{-1}$) configuration
132, $8^+ \rightarrow 6^+$	5.2 ± 0.6	4.4
299, $6^+ \rightarrow 4^+$	11.3 ± 0.3	9.6
374, $4^+ \rightarrow 2^+$	16.3 ± 1.1	7.8

Figure captions

- Fig. 1** Low-energy part of the γ -ray spectrum following the β -decay of ^{132}In . The upper part of the spectrum shows the singles spectrum and the lower part shows the β -coincident spectrum. The strong reduction of the intensity of the 132 keV line is due to the long lifetime ($1.7\ \mu\text{s}$) of the 8^+ state. Peaks assigned to contaminants are labelled as follows: (a) ^{132}Cs , (b) ^{132}Sn , and (c) ^{132}Sb .
- Fig. 2** High-energy part of the β -coincident γ -ray spectrum following the decay of ^{132}In .
- Fig. 3** The upper part of the figure shows the γ -ray spectrum in the energy region 260–400 keV. Peaks labelled (a) and (b) originate from long-lived contaminants. The corresponding conversion electron spectrum is shown in the bottom part.
- Fig. 4** Experimentally determined conversion coefficients for the 299 and 375 keV transitions. The theoretical predictions imply E2 or M1 assignments or an (M1 + E2) mixture for both transitions.
- Fig. 5** Fermi plots of β spectra in coincidence with γ -rays in the energy ranges (A) 2.2–2.4 MeV and (B) 3.0–4.5 MeV.
- Fig. 6** Gamma–gamma coincidence spectra with gates on low-energy transitions. Peaks labelled (a) could arise from scattering of the intense 668 keV contaminant line.
- Fig. 7** Gamma–gamma coincidence spectra with gates on high-energy transitions. These coincidence relations imply the existence of levels in ^{132}Sn at excitation energies of at least 6.7 MeV.
- Fig. 8** Beta-delayed neutron spectrum of ^{132}In measured with a ^3He filled neutron spectrometer. The simplified decay scheme shown as an inset represents a possible interpretation of the data. S_n denotes the neutron separation energy in ^{132}Sn .
- Fig. 9** Level scheme of ^{132}Sn . Transition energies are given in keV with the corresponding intensities within brackets.
- Fig. 10** Single-particle energies in the major shells around ^{132}Sn .

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10