Single-Neutron States in ^{133}Sn

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The location of several single-neutron states in ^{133}Sn has been identified. The $p_{3/2}$, $h_{9/2}$, and $f_{5/2}$ states were found at 853.7, 1560.9, and 2004.6 keV, respectively, by measuring γ rays in coincidence with delayed neutrons following the decay of ^{134}In. Crucial for obtaining the new data were the improved yields at the mass-separator facility ISOLDE-PSB at CERN. A semiempirically adjusted Woods-Saxon calculation, based on parameters from the Pb region and normalized on the mass data at ^{132}Sn, reproduces the new single particle energies with good precision. [S0031-9007(96)00824-1]

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The properties of the four valence single particle (SP) and single hole (SH) nuclides at a doubly closed shell (DCS) are essential both for tests of the nuclear shell model and as input values in realistic nuclear structure calculations. Indeed, none of the potentials currently used in *ab initio* calculations of the nuclear shell structure is capable of properly reproducing the ordering and spacing of the SP or SH states on a global scale over the nuclear chart. Experimentally determined energies of such states are therefore important parameters in order to accurately predict the nuclear structure. Current knowledge is strongly limited, since only at the DCS nuclei ^{16}O, ^{40}Ca, and ^{208}Pb all four SP and SH nuclei are reasonably well characterized experimentally. Data for other heavy DCS nuclei and for the highly important valence nuclei must therefore be sought in exotic regions far from the stability line. New developments and strongly improved yields at the ISOLDE PS-Booster (PSB) mass-separator facility [1] at CERN now offer new possibilities for experiments in these regions. In the following we describe a study of the $N = 83$ single-neutron states of ^{133}Sn, populated in the decays of ^{133}In and ^{134}In. The latter nuclide was obtained with sufficient intensity to permit measurements of γ rays in coincidence with delayed neutrons, which proved to be of decisive importance for the identification of the single-neutron states.

The unstable DCS nucleus ^{132}Sn is intermediate in mass between the light DCS regions near Ca-Ni and the only known heavy stable DCS region at ^{208}Pb. Thus it is a potential source of important data for bridging the gap between these regions. The structures of ^{131}Sn (neutron hole) and ^{133}Sb (proton particle) are fairly well known; see Refs. [2,3]. The neutron particle and proton hole nuclei, ^{133}Sn and ^{131}In, have so far only been revealed by their β-decay properties [3,4]. We note that the single-neutron states of ^{133}Sn are the $f_{7/2}$, $p_{3/2}$, $h_{9/2}$, $p_{1/2}$, $f_{5/2}$, and $i_{13/2}$ orbits of the 82–126 shell.

Very neutron-rich nuclei can presently be studied only through the β decays of precursors which are even more unstable and therefore difficult to produce. Some of the present authors attempted to determine the structure of ^{133}Sn at the ISOLDE facility at the CERN SC, more than a decade ago. By using "traditional" β-decay spectroscopy of ^{133}In, no single particle states of ^{133}Sn could be identified at that time. The delayed neutron emission probability, P_n, was determined to $(85 \pm 10)\%$. Also a delayed neutron energy spectrum was recorded and will be discussed later. Although two β-decaying states, $g_{9/2}^{-1}$ and $p_{1/2}^{-1}$, were expected, only one half-life of 180 ± 15 ms was observed.

The limited success of the early experiments was due to low nuclide production yields, aggravated by

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the selection rules of the β decay. The very high decay energy of nuclides far from stability opens a large number of possible final states. The $9/2^+$ ground state of ^{133}In (Q_β is estimated as 13.5 MeV [5]) will thus preferentially decay by strong allowed transitions to two-particle–one-hole states above about 3.5 MeV in ^{133}Sn, and to a much lesser extent by the possible first forbidden transitions to the $2f_{7/2}$, $1h_{9/2}$, and $2f_{5/2}$ SP states. As the neutron separation energy of ^{133}Sn is only $S_n = 2.45(5)$ MeV [4], the strongly populated states will decay by delayed neutron emission and not by the noncompetitive γ transitions that otherwise could populate the lower lying SP states. The situation is similar for the decay of the expected $1/2^-$ isomer.

However, there is an alternative way of populating the low lying single-neutron states in ^{133}Sn. While a strong delayed neutron branch for the ^{133}In decay represents a clear disadvantage, a similar high P_n value for ^{134}In could be advantageous, because the emission of a delayed neutron following the β decay of ^{134}In leads, with some probability, to the population of the states of interest in ^{133}Sn. The γ rays deexciting them can thus be identified by coincidence with neutrons.

The neutron-rich isotopes of In were obtained at ISOLDE-PSB by fission reactions in a target of uranium carbide, induced by a pulsed beam of 1 GeV protons. As compared with the ISOLDE-SC ($E_p = 600$ MeV) facility, where ^{134}In was barely detectable, the yields of many very short-lived nuclides have been drastically improved at ISOLDE-PSB ($E_p = 1$ GeV). This is mainly due to the rapid release from the target caused by a thermal shock from the intense proton pulses [1]. The beam of mass 134 was collected on a tape-transport system used to periodically remove the longer lived activities. The collection point was surrounded by a cylindrical thin plastic scintillator, with only a small hole for beam inlet and close to 100% efficiency for β particles. A coincident β-particle signal in this scintillator was required for all accepted data events. Outside of the vacuum, the source point was surrounded by two liquid scintillation cells detecting neutrons by means of pulse shape discrimination, as well as by two 70% Ge detectors for the γ-ray spectroscopy. This detector system allowed the measurement of neutron-coincident γ-ray spectra and of $\gamma\gamma$-coincidence relations. Each data event included a reading from a time-to-digital converter, started by the beam pulse, for determination of the β-decay half-lives.

The neutron-coincident γ-ray spectrum shown in Fig. 1 was obtained in about 22 h of beam time. Some distinct transitions in ^{133}Sn are clearly visible, in particular, those at 854, 1561, and 2005 keV. An analysis of their time dependence with respect to the beam pulses gave the half-life of ^{134}In as 138 ± 8 ms. The 962 keV transition from the daughter decay, ^{134}Sn$(\beta n)^{133}$Sb, is also present with the expected 1.0 s half-life. The γ transitions assigned to ^{133}Sn are listed in Table I, as observed with and without

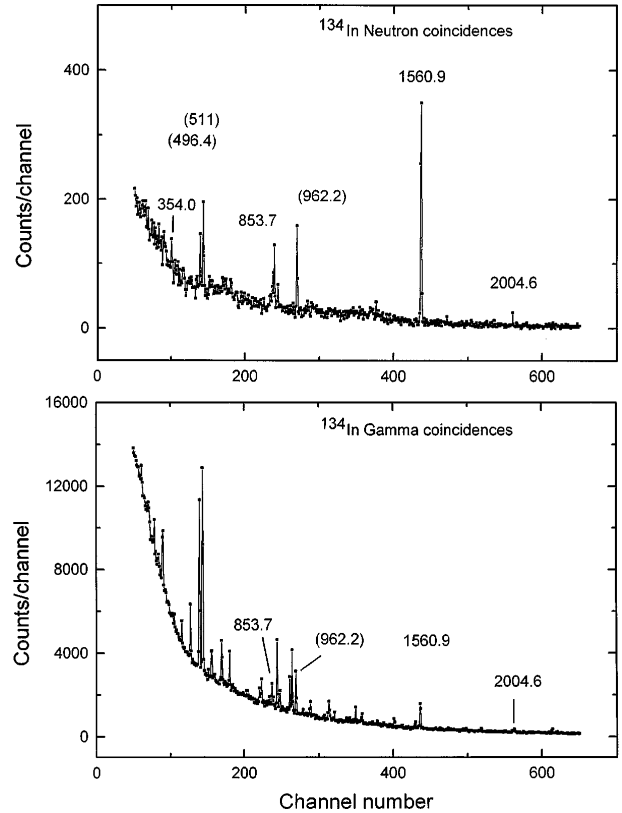

FIG. 1. Spectra of γ rays from the ^{134}In decay recorded in coincidence with signals from a pair of liquid scintillator neutron detectors. The top and bottom panels show data obtained by selecting windows, respectively, on neutron events and on γ-ray events, in the scintillator pulse-shape discrimination spectra. Labels without parentheses give the energies in keV of well visible transitions in ^{133}Sn. The 962.2 keV line follows the βn decay of the ^{134}Sn daughter product, thereby also being coincident with neutrons. The lines near channel 150 in the top panel are due to random coincidences caused by the decay of a contaminant, ^{134}Pm.

the neutron coincidence requirement. In a separate experiment, the β decay of ^{133}In was studied using the same equipment. With the correct γ-ray energies already identified, it was possible to observe very weak transitions at 854, 1561, and 2005 keV with half-lives consistent with the known value of 180 ms of ^{133}In. Their intensities are included in Table I. We could not positively identify any γ transitions in ^{134}Sn, perhaps due to a too restricted $\beta\gamma$ coincidence time window.

The $\gamma\gamma$-coincidence data excluded coincidences between any pair of the strongest transitions, at 854, 1561, and 2005 keV. These γ rays are therefore taken to represent transitions to the ground state from excited single-neutron states in ^{133}Sn.

Previous experimental results [3] are only compatible with a $2f_{7/2}$ assignment for the ground state of ^{133}Sn. Guidance regarding the nature of the new excited states at 853.7, 1560.9, and 2004.6 keV, shown in Fig. 2, is given by the known level systematics of the $N = 83$

TABLE I. Data for γ transitions in ^{133}Sn.

Energy (keV)	^{134}In decay Neutron gated	Relative intensity ^{134}In decay β gated only	^{133}In decay β gated only
354.0(10)	2.3(7)	< 2	< 10
802.0(10)[a]	2.1(10)	9(2)	Obscured
853.7(3)	13(2)	23(2)	43(15)
1560.9(5)[b]	100(5)	100(4)	100(10)
2004.6(10)	5.1(10)	26(3)	19(6)

[a]Some contribution from the 803.1 γ line from ^{206}Pb(n, n') is possible in the data for the ^{134}In decay. Note that threshold effects in the neutron detectors may influence the intensities of gated transitions.
[b]The absolute intensity of this transition is (5–10)% per decay of ^{134}In, and about 0.5% per decay of ^{133}In.

nuclides [6], and also by shell model calculations specific for the neutron-rich Sn region. The work by Chou and Warburton [7] predicts the order of the SP states partly by using experimental data from the heavier isotones. A different approach, presented below, is an update of a previous calculation [8] including semiempirical adjustments estimated from data in the Pb region. Both sources suggest strongly that the three proposed excited states should be assigned $3p_{3/2}$, $1h_{9/2}$, and $2f_{5/2}$ in order of excitation energy.

Our experimental data support these assignments based on systematics. The spin of the ^{134}In parent is not known, but the particle-hole interactions favor a high angular momentum for the β-decaying state of this nucleus. In

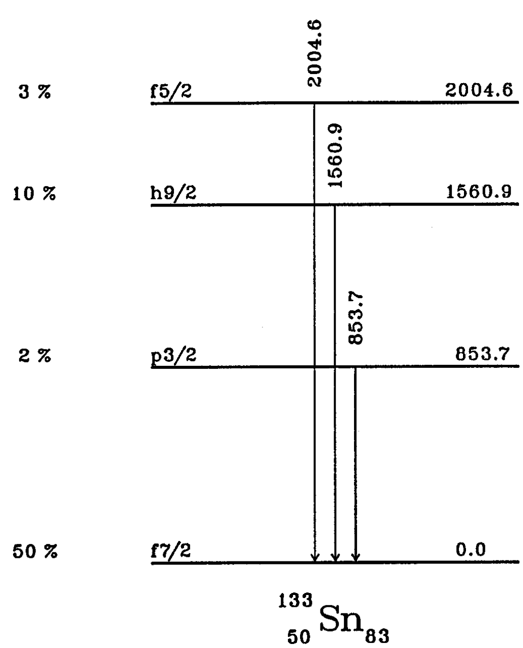

FIG. 2. The low lying levels of ^{133}Sn substantially populated by delayed neutrons following the decay of ^{134}In. The total population of the individual final states is given in units of percent per β decay of the parent nucleus.

^{132}In, the 7^- member of the $\pi g_{9/2}^{-1} \nu f_{7/2}$ multiplet is the lowest lying one. An analogous situation is expected also in ^{134}In, although a 4^--6^- ground state assignment is not completely excluded. The β-delayed neutron decay process, starting from a high J state should thus favor population of the $7/2^-$, $9/2^-$, and $5/2^-$ final states, in agreement with the intensities given in Fig. 2.

Data from the ^{133}In decay support these assignments further. The ^{133}In samples should mainly contain nuclei in the $9/2^+$ ground state, with only a minor proportion in the $1/2^-$ isomeric state. The stronger β feeding of the 1560.9 keV level as compared to the level at 2004.6 keV thus favors the $1h_{9/2}$ assignment of the former. These observations on the βn and β decays, combined with the observation that the γ-ray decays of the excited ^{133}Sn levels lead to the ground state, actually give little room for other interpretations than the one proposed in Fig. 2. Note that the 854 keV level is populated also in the ^{133}In decay. The assignment of this level as $3p_{3/2}$ has a firm basis in the systematics [6]. The observed population is therefore a strong indication that the $1/2^-$ isomer of ^{133}In indeed was present in our samples. The observed intensity of the 854 keV γ ray may correspond to several percent of the total isomer β intensity.

Table I includes two additional, so far unplaced, γ transitions observed in coincidence with the delayed neutrons following the decay of ^{134}In. Our calculations, discussed below and illustrated in Fig. 3, show that only the single-neutron states can be expected to be bound in ^{133}Sn. It is therefore suggested that the 802 keV γ line could be the $p_{1/2}$ to $p_{3/2}$ transition. The other unplaced transition, at 354 keV, has a too low energy to correspond to the expected p-state spin-orbit splitting unless rather strong interactions with higher lying states are introduced. Additional experimental work is needed to clarify the nature of these transitions.

The new experimental SP energies are compared in Fig. 3 to the results of a calculation using a Woods-Saxon potential. The parameters of the potential were optimized on the known SP and SH data at ^{208}Pb, and the absolute energy scale was normalized to the experimental mass [4] of ^{133}Sn. The calculation also included semiempirical modifications of the positions of the $p_{1/2}$ and $i_{13/2}$ states. The former has been placed relative to the $p_{3/2}$ level using an estimate of the spin-orbit splitting. The latter has been shifted down by about 0.5 MeV, in accordance with the expected interaction with higher lying core-coupled states. The magnitude of the shift was estimated by a comparison with the corresponding situation for the $j_{15/2}$ single-neutron state in ^{209}Pb. One may remark that the energies of SP states having low angular momenta become substantially lowered with decreasing binding energies. The $3p$ states thus occur much lower in ^{133}Sn than in ^{147}Gd, the latter also having $N = 83$.

Figure 3 also includes the estimated positions of the lowest neutron hole states and of the $f_{7/2} \times 3^-$

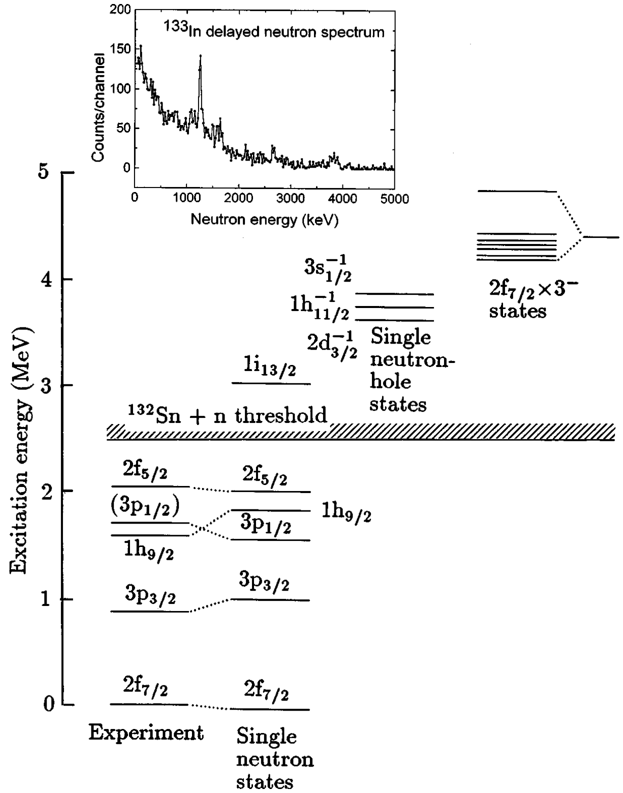

FIG. 3. A comparison of the experimental results (left) with a semiempirically adjusted Woods-Saxon calculation of the ^{133}Sn SP states. Estimated positions of other types of states are also illustrated. See the text for a discussion. The inset shows the pulse-height spectrum of the delayed neutrons following the decay of ^{133}In as obtained with ^{3}He ionization chambers. The main peak, near 1.26 MeV in this spectrum, is tentatively related to the transition from the neutron hole $1h^{-1}_{11/2}$ state to the neutron threshold.

septuplet, corrected by expected interaction displacements. Other two-particle–one-hole levels have energies of about 4.5 MeV or higher, thus they are present far above the region occupied by the SP states.

As mentioned earlier, the main part of the β strength in the ^{133}In decay leads to delayed neutron emission. The inset of Fig. 3 shows the spectrum of these delayed neutrons, as obtained with ^{3}He filled ionization chambers. Distinct lines in the spectrum represent neutron transitions, most probably to the ground state of ^{132}Sn, from resonances in ^{133}Sn populated by strong β transitions. By analogy with the decay of ^{132}In to ^{132}Sn [9], we expect the $\pi g^{-1}_{9/2} \rightarrow \nu h^{-1}_{11/2}$ transition to be the strongest one feeding the levels below about 4 MeV. The main peak near 1.26 MeV in the delayed neutron spectrum is quite likely due to the decay of the neutron hole $1h^{-1}_{11/2}$ state populated by this β transition.

On the basis of the present experiment, three out of the five excited single-neutron states in ^{133}Sn have been determined, i.e., the $3p_{3/2}$ state at 853.7 keV, the $1h_{9/2}$ at 1560.9 keV, and the $2f_{5/2}$ at 2004.6 keV. Additionally, we tentatively propose the $3p_{1/2}$ state at 1655.7 keV, and identify the neutron hole $1h^{-1}_{11/2}$ state at about 3700 keV, as discussed above.

The results demonstrate that β-decay studies continue to be the main source of important information in regions far from stability, although the strong selectivity of the β-decay process itself may need to be circumvented by using appropriate experimental approaches. The further away from stability, the smaller becomes both the energy window comprising the bound final states and the probability to populate these by a direct β transition. The reason is that a given level seldom is significantly populated from a given parent state. Although kinematically favored, the transitions to a small number of bound low lying states are very likely to be hindered by the differences in spatial symmetry between parent and daughter states. On the other hand, the delayed particle emission process, where the β-decay selectivity is modified by the dispersion of neutron l values, becomes a more general and versatile instrument for the population of bound final states as the total decay energy increases. Indeed, spectroscopy based on delayed particle coincidences may become the method of choice in the progressively more demanding studies of very exotic nuclei.

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