# Detailed Spectroscopy of the Doubly Closed Shell Nucleus $^{132}$Sn: First Observation of Octupole Collectivity

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The angular momenta and parities of the low-lying states of $^{132}$Sn have been firmly determined through studies of the $\beta$ decay of $^{132}$In. The lowest lying state with a negative parity is shown to have a collective octupole character. Several particle-hole multiplets have been identified, including the lowest lying proton excitation. More than about 20% of the theoretically estimated bound states of $^{132}$Sn have been identified.

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The properties of the nuclei at a double closure of both proton and neutron shells are of fundamental importance for the understanding and systematization of nuclear structure. The valence nuclei, possessing or lacking *one* nucleon in otherwise empty or filled shells, give direct information on the basic single particle (SP) structure. The energies of the SP states, the SP transition matrix elements, and the SP static moments are experimental observables which are crucial ingredients in any theoretical systematization of nuclear structure. The nuclei having or lacking *two* nucleons with respect to the double shell closure will in a similar manner give directly observable information on the interactions between various pairs of nucleons occupying the valence states. The doubly closed shell nuclei (DCSN) themselves are of special interest. The simplest excitations consist here of particle-hole (p-h) states in which the particle by necessity must be excited across the energy gap defining the closed shell. The p-h states of DCSN form level multiplets where the individual states often have a very simple structure with regard to admixtures of configurations. The degeneracy of the multiplets is lifted as a consequence of the p-h interaction. The mapping and identification of such multiplets may give immediate information on the nuclear two-body matrix elements (provided that perturbations can be neglected). The static moments of the levels as well as the transition rates within and in between the multiplets are likewise crucial observables linked to the underlying SP structure in a relatively transparent way. At present, the structure of a DCSN can be reasonably well predicted provided that the SP data are sufficiently well known. Conversely, the observed properties of a DCSN may be used to derive otherwise inaccessible information on a particular SP system.

The occurrence of DCSN is a rare phenomenon. In the wide region $A > 56$, the only well-studied nucleus of this type is $^{208}$Pb. Additionally, only the unstable DCSN $^{78}$Ni and $^{132}$Sn are expected to be sufficiently strongly bound to permit a study of their excited states. The present work is focused on the structure of the intermediate mass DCSN $^{132}$Sn. As this nuclide is located several steps away from the stability line on the neutron rich side, its excited states can presently be populated only in fission reactions or in the $\beta$ decay of the precursor $^{132}$In. We have studied the latter decay in a series of experiments which have led to a manyfold increase in the known data on $^{132}$Sn and which constitutes one of the single largest contributions of structure data on any DCSN. Previous experimental information on the properties of $^{132}$Sn mainly comes from $\beta$-decay spectroscopy at ISOLDE [1] and from studies of isomers populated in fission [2], although the first structure information was obtained in an experiment [3] at our laboratory about 20 years ago.

The present work has almost tripled the number of known particle-hole multiplets and excited states in $^{132}$Sn. The number of known electromagnetic transition rates has increased from 4 to about 20, and the known $\beta$-transition rates now number more than one dozen compared to the single datum available before. Perhaps of more importance, firm experimental verification now exists of the angular momenta and parities of many of the lower lying states. A detailed discussion of the new results will be given elsewhere [4]. Here we will give an overview of the information obtained and discuss in some detail only one particularly significant item; the identification of a collective octupole vibration in $^{132}$Sn.

The experiments were performed at the OSIRIS fission product mass separator facility [5] at Studsvik. A relatively pure beam of $^{132}$In, produced through thermal neutron induced fission of $^{235}$U, was obtained by operating the ion source in a surface ionization mode [5]. A miniarray consisting of five Ge spectrometers and six BGO detectors was used to study $\gamma\gamma$ coincidences and $\gamma$-ray angular correlations. A total of about $10^8$ coincidence events were collected, most of them between pairs of Ge detectors. This data set was the main source of information for the construction of the $^{132}$Sn level scheme shown in Fig. 1. The multipolarities of the stronger transitions below an energy of 0.6 MeV were deduced from conversion coefficient data obtained in a second experiment, in which conversion electron and $\gamma$-ray spectra were recorded simultaneously. Results of the best quality, see Fig. 2, were obtained in a data set that had been gated by $\beta$-particle events in a plastic scintillator placed near the sample position. The half-lives of several levels in $^{132}$Sn were determined using a triple coincidence $\beta\gamma\gamma(t)$ method [7,8]. The time delay between $\beta$ particles and $\gamma$ rays was measured using a well-calibrated system of two small scintillators (one plastic and one $BaF_2$) mounted on

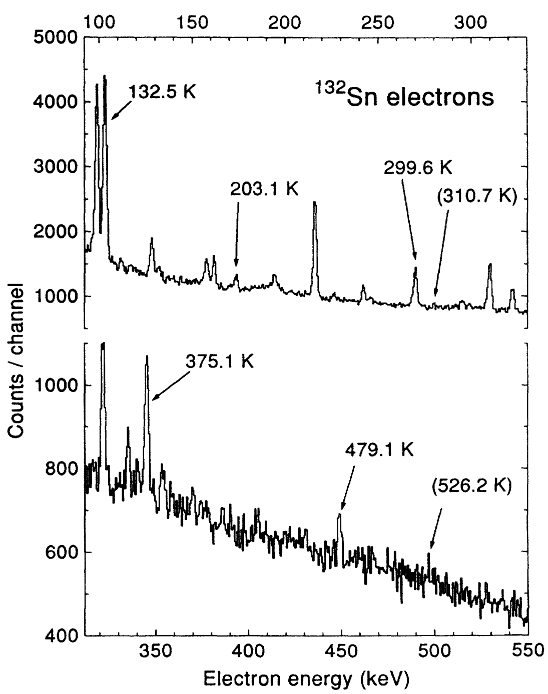


FIG. 1. Levels and transitions in the DCSN $^{132}$Sn as deduced from the present work. Note that the figure is not drawn to scale. The 22 states shown here likely represent more than about 20% of all bound states of this nucleus. The neutron separation energy is 7.404 MeV according to Ref. [6], which also gives the $Q\beta$ value of $^{132}$In. The three positive parity states near 5.5 MeV are identified as members of the $\pi g_{7/2}g_{9/2}^{-1}$ multiplet, thus representing the first observation of proton p-h states in $^{132}$Sn. Their energies are significantly shifted, by both Coulomb and nuclear interactions, from the unperturbed value of 6.13 MeV of the proton shell gap. Some properties of the lowest lying excited states are discussed in the text. A discussion of the full set of the new experimental data on this DCSN will be given elsewhere [4].

ultrafast photomultiplier-tubes (Philips XP2020 URQ). A third coincidence with a $\gamma$ ray detected in a Ge spectrometer served to unambigously select the decay path in the level scheme. The half-life data obtained are presented in Table I.

Before discussing the octupole collectivity of $^{132}$Sn, it should be remarked that the structure, in terms of a specific dominating p-h excitation, can be identified for most of the observed states in this DCSN. The identification is based mainly on the modes of feeding and decay of the levels and on the SP energies. As proposed before [1], the lowest positive parity states and the negative parity ones above 7 MeV belong with certainty to the $\nu f_{7/2}h_{11/2}^{-1}$ and the $\nu f_{7/2}g_{7/2}^{-1}$ multiplets, respectively. Our new observation also of odd-spin members in these multiplets is of significant interest as discussed elsewhere [4]. The three positive parity states near 5.5 MeV can only belong to the $\pi g_{7/2}g_{9/2}^{-1}$ multiplet. Other observed levels, with one or two exceptions, most likely represent neutron excitations. Further comments on the p-h structure are given below regarding the low-lying negative parity states and in the caption of Fig. 1.

It has been pointed out [9] that $^{132}$Sn shows the strongest shell closure of any nucleus. Taking the energy of the first excited state as a measure of of this strength and allowing for an $A^{-1/3}$ dependence on the nuclear size, $^{132}$Sn is actually found to be about 35% more rigid, in this respect, than $^{16}$O or $^{208}$Pb. All other DCSN or closed subshell nuclei have considerably smaller gaps in their level spectra. (The lightest DCSN $^4$He is not included in this or the following discussion, as it represents a special case in many ways.) In view of the exceptional "stiffness" of $^{132}$Sn, it is particularly interesting to investigate the presence of collective excitations among the first few excited states. Very general considerations [10] suggest that an octupole surface vibrational mode should be present at a relatively low energy in all DCSN. Collective states of this type have actually been observed in four of the six known DCSN, $^{56}$Ni and $^{132}$Sn being the exceptions. There exists massive theoretical support for a collective nature of the lowest lying $3^-$ state also in $^{132}$Sn, including the results of two different [11,12] calculations within the random phase approximation (RPA). On the other hand, the empirical evidence for octupole collectivity in heavier DCSN is scanty, to say the least, with the 2615 keV state of $^{208}$Pb being the single known such case for DCSN having $A > 48$.

The previous experimental study of $^{132}$Sn by Björnstad *et al.* [1], discussed the level at 4351.9 keV as the collective $3^-$ state, although the parity assignment then was based on the theoretical expectation of a low-lying octupole state. The present, considerably more detailed experimental data provide a unique identification of the spins and parities of all states below 5 MeV, in addition to the two high-lying ones near 7.2 MeV. The

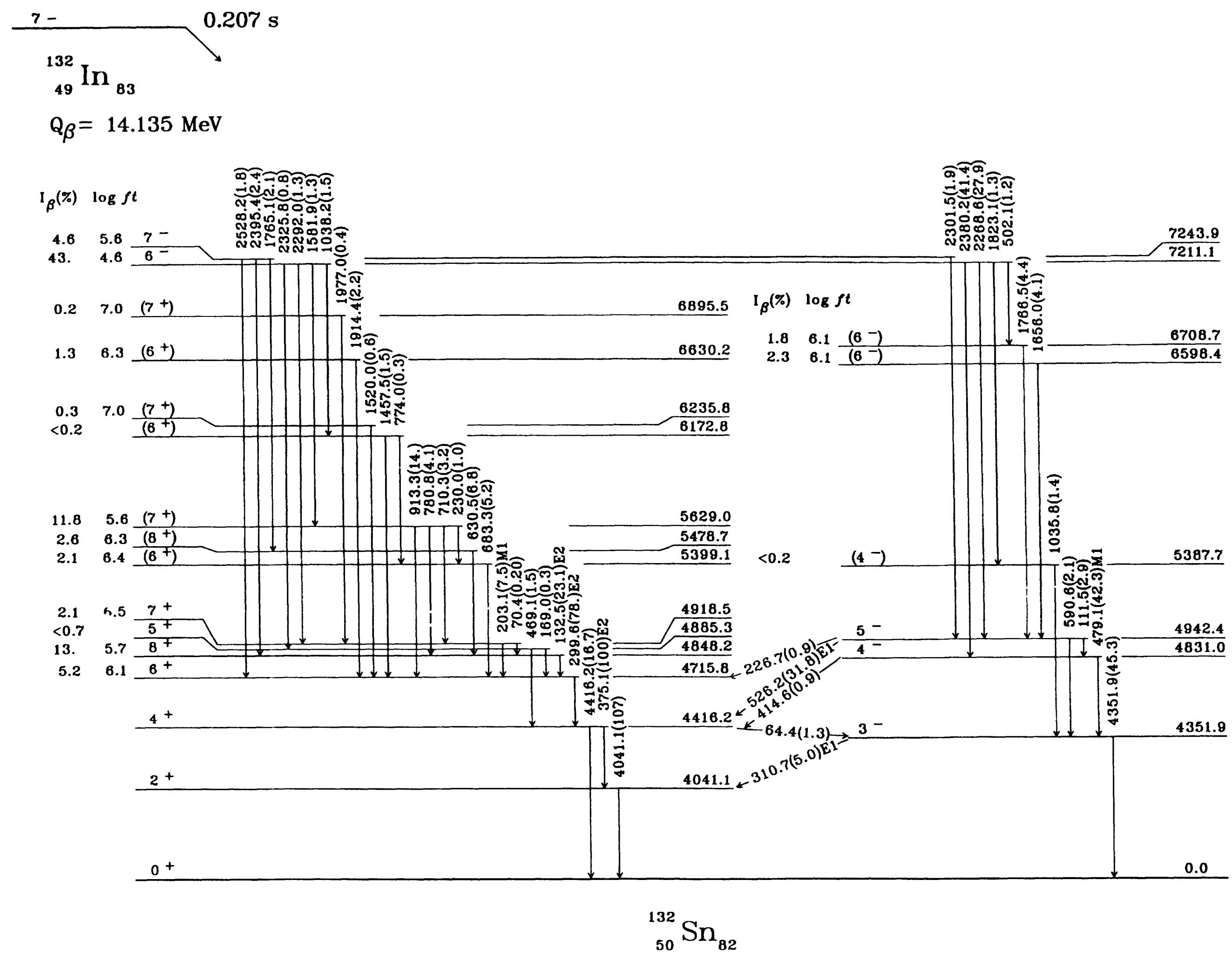


FIG. 2. The relative parities of the lower lying states of $^{132}$Sn were firmly determined from conversion electron data. In particular, the weakness of the hardly visible electron lines corresponding to the 310.7 and 526.2 keV transitions show that both are of parity changing $E1$ character. Both would have been clearly detectable if they were of $M1$ or $E2$ multipolarity. The 310.7 keV transition connects the first excited $2^+$ and $3^-$ levels of $^{132}$Sn, see Fig. 1.

4351.9 keV level can now be firmly assigned a negative parity, due to the presence of a parity changing $E1$ transition to the previously [12] well-known $2^+$ state at 4041.1 keV.

Having established with certainty that the 4351.9 keV level has $J^\pi = 3^-$, we may begin to investigate the nature of this state. The lowest lying p-h $3^-$ state should belong to the $\nu f_{7/2}d_{3/2}^{-1}$ multiplet, where the particle and hole states correspond to the ground state configurations of $^{133}$Sn and $^{131}$Sn, respectively. The unperturbed energy of the multiplet would thus equal the neutron shell gap of 4.94 MeV [6]. The $4^-$ and $5^-$ members were (tentatively) identified near this energy by Björnstad *et al.* [1] on grounds of strong systematic evidences. We can now empirically confirm the negative parity of these states, see Figs. 1 and 2. To find the excitation energy of the $3^-$ state belonging to this configuration, one needs to investigate the p-h interaction energies within the multiplet. This may simply be performed by a comparison with the analogous and well-known $\nu g_{9/2}f_{5/2}^{-1}$ multiplet in $^{208}$Pb. The comparison shows that the $3^-$ and $5^-$ levels of $^{132}$Sn should both be only slightly displaced by the interaction and should both be present within about 100 keV from each other near 4.94 MeV. The observed energy of the $5^-$ level is 4942.4 keV. As there are no reasonable physical processes that may depress the energy of this p-h $3^-$ state by several hundred keV (to agree with that of the 4531.9 keV level), we conclude that the $(\nu f_{7/2}d_{3/2}^{-1})_{3^-}$ state remains undetected due to a weak population, and that the 4351.9 keV level must contain a mixture of many p-h configurations, lowered in energy by the coherent effect of diagonal and nondiagonal interaction matrix elements.

TABLE I. Half-lives of excited states in $^{132}$Sn.

| Level (keV) | $J^{\pi}$ | Half-life[a,b] |
|---|---|---|
| 4351.9 | $3^-$ | <5.0 ps |
| 4416.2 | $4^+$ | 3.95(13) ns |
| 4715.8 | $6^+$ | 20.1(5) ns |
| 4831.0 | $4^-$ | 26.0(5) ps |
| 4848.2 | $8^+$ | 2.03(4) μs |
| 4885.3 | $5^+$ | <40.0 ps |
| 4918.5 | $7^+$ | 62.0(7) ps |
| 4942.4 | $5^-$ | 17.0(5) ps |
| 5629.0 | $(7^+)$ | 13.0(ps) |

[a]All data from the present work.
[b]Uncertainties are given in units of the last digit.

The main empirical characteristic of an octupole vibrational state is the presence of an enhanced $E3$ transition connecting the $3^-$ level with the ground state. The presently obtained upper limit of 5 ps for the half-life of the 4351.9 keV level shows that the $E3$ transition strength in $^{132}$Sn is at least 7 Weisskopf units (W.u.). To put this number into perspective, one should compare it to the known data on collective $E3$ transitions in other DCSN. The four previously known collective $B(E3)$ values range from 9 to 34 W.u., as shown in Table II (in which Refs. [13] and [14] are cited). Additionally, there are three known cases in nuclei with major subshell closures, all having strengths of 30 W.u. or more. These data may suggest an expected enhancement factor of about 30 also in $^{132}$Sn, although the results of the RPA calculations (included in Table II) give values about a factor of 2 lower than this. Although not conclusive with respect to the magnitude of the $B(E3)$, our lower limit of 7 W.u. for the deexciting $E3$ transition rate is nevertheless a sufficient indicator of collectivity to classify the 4351.9 keV level as a surface octupole vibrational state.

The present lifetime determinations are limited in accuracy partly as a consequence of a limited number of recorded delayed coincidence events. A considerably improved beam intensity will overcome this problem. A possibility for a direct determination of the $3^-$ level half-life, in the near future, is thus offered by using the expected high intensity beams from the planned PIAFE project [15].

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TABLE II. $E3$ transition rates in doubly closed shell or subshell nuclei.

| Nuclide | Energy (keV) | $B(E3)$[a] (W.u.) |
|---|---|---|
| | Collective $3^-$ levels, DCSN | |
| $^{16}$O | 6130 | 14 |
| $^{40}$Ca | 3737 | 31 |
| $^{48}$Ca | 4507 | 9 |
| $^{132}$Sn | 4352 | >7[b] |
| $^{208}$Pb | 2615 | 34 |
| | Collective $3^-$ levels, nuclei with closed subshells | |
| $^{90}$Zr | 2750 | 32 |
| $^{96}$Zr | 1897 | 47[c] |
| $^{146}$Gd | 1579 | 37 |
| | Theory, RPA | |
| $^{132}$Sn | 4352 | 12–20[d] |

[a]The $B(E3)$ values are from Ref. [13] unless otherwise noted.
[b]Present work.
[c]Ref. [14].
[d]Ref. [12].

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