First Identification of the $d_{3/2}$ State and Measurements of Single Proton Transition Rates in ^{133}Sb

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Detailed structure information on ^{133}Sb has been obtained in a high-sensitivity study of the ^{133}Sn decay. The $d_{3/2}$ single proton state was found at 2439.5 keV. The γ-ray branching gives $B(M1; d_{3/2} \rightarrow d_{5/2})/B(E2; d_{3/2} \rightarrow g_{7/2}) = 0.037(3)$ in W.u. For the $h_{11/2}$ state, a half-life of 11.4(4.5) ps was measured for the first time, giving $B(M2; h_{11/2} \rightarrow g_{7/2}) = 0.55(22)$ W.u. and $B(E3; h_{11/2} \rightarrow d_{5/2}) = 22(13)$ W.u. The single proton transition strengths in ^{133}Sb and ^{209}Bi are found to be remarkably similar. In contrast, the spin-orbit splitting in these nuclei show important differences. [S0031-9007(98)06391-1]

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Single particle states are the basic elements of any microscopic description of atomic nuclei. Yet, despite the fact that the wave functions are rather well known, there is at present no nuclear potential capable of reproducing in detail the ordering of single particle energies all over the nuclear chart. For an accurate theoretical or systematical work, it is necessary to use the empirical single particle energies rather than calculated ones. Experimentally determined energies of the single particle states are thus of considerable importance. Similarly, the electromagnetic matrix elements between the single particle states are crucial observables that cannot in general be accurately obtained from model calculations.

The nuclides having one nucleon outside doubly closed shells (DCS) give the most direct information on the single particle properties. At present, these properties are reasonably well determined experimentally only for light nuclei ($A \leq 56$) and at ^{208}Pb. The DCS region at ^{132}Sn with $Z = 50$ and $N = 82$ is the best accessible candidate for detailed studies of single particle properties in the wide intermediate region $56 < A < 208$. Nuclides in this region are neutron-rich and unstable and therefore not presently amenable to reaction spectroscopy. The bulk of the known data has been obtained from β-decay spectroscopy on mass-separated fission products. Recent examples of such work include the identification [1] of single neutron states in ^{133}Sn, the determination [2] of effective charges in the region, and a measurement [3] of the $g_{7/2}$ single proton magnetic moment. New data are also emerging from fission studies using large γ-ray detector arrays [4,5].

This Letter presents new experimental results on the single proton states in ^{133}Sb ($Z = 51, N = 82$) obtained at the fission-product mass separator OSIRIS [6] at Studsvik in a study of the β^- decay of ^{133}Sn. Since the higher-lying single proton states are very weakly populated in this β decay [7,8], a series of high sensitivity measurements were performed in order to detect the weak γ-ray transitions. Apart from a high statistics $\gamma\gamma$-coincidence measurement, the radioactive $A = 133$ sources collected on-line were studied via time sequential multispectra recorded using a Compton suppressed Ge spectrometer, in order to identify the γ rays following the characteristic half-life of ^{133}Sn and to provide accurate information on γ-ray energies and intensities. Both types of measurements were able to detect γ rays having intensities down to about 10^{-5} per decay of the ^{133}Sn parent. More than 75 excited states were established in ^{133}Sb, most of them for the first time (for details see Ref. [9]). Our new data show very clearly the presence of a state at 2439.5 keV in ^{133}Sb, which decays to the previously established $d_{5/2}$ state [7] at 962.1 keV and to the $g_{7/2}$ ground state; see Fig. 1. We conclude that this new level is the $d_{3/2}$ single proton state for the following reasons.

In contrast to the situation in the ^{208}Pb region, the single proton states ($g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$) are clearly separated from other states in ^{133}Sb. The large shell gaps at ^{132}Sn cause more complex configurations to occur at energies of about 4 MeV and higher. Any levels found up to ~3 MeV in ^{133}Sb must therefore be of single proton character. Theoretical predictions [10–12] place the highest lying single proton state near or below 3 MeV. The observed γ-ray branching from the 2439.5 keV state is compatible with a $d_{3/2}$ assignment, but not with $s_{1/2}$, which is the only alternative. Our new data do not support the previously suggested [8] level at 2707 keV, then thought to be the $d_{3/2}$ state. (Given about 2 orders of magnitude higher sensitivity of the current study over our previous work [8], the 2707.7 keV transition would have been easily confirmed if present in the decay of ^{133}Sn.) The theoretical works [10–12] predict the $d_{3/2}$ and $s_{1/2}$ levels to be located at energies of about 2.5–3.0 MeV.

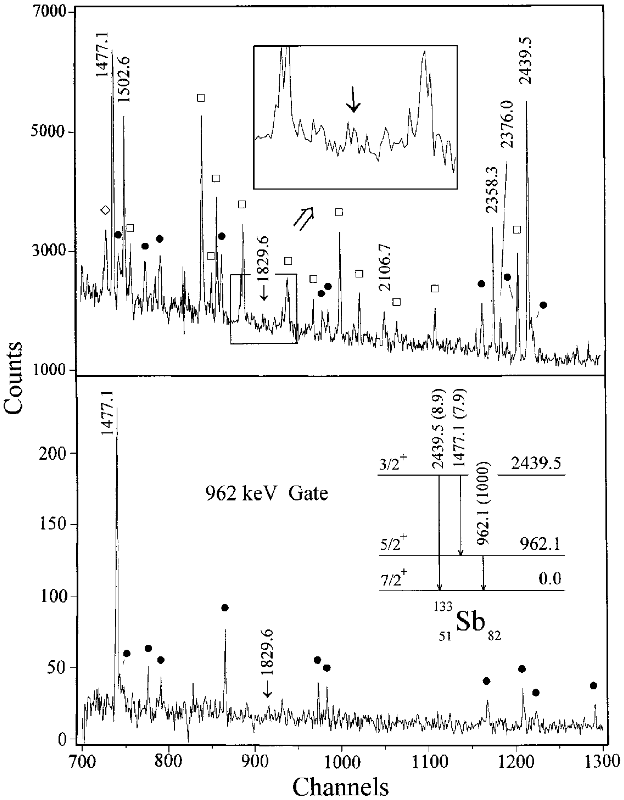

FIG. 1. Sections of the γ-singles (top) and $\gamma\gamma$-coincidence (bottom) spectra that established the $d_{3/2}$ level in ^{133}Sb via the 1477.1 and 2439.5 keV γ transitions. Lines from the decay of ^{133}Sn were identified using a multispectrum technique and are marked by energies given in keV. The impurity lines include the decay of ^{133}Sb (●), ^{133}Te (□), and the background (◇). The main contribution from isobaric impurities has been subtracted from the singles spectrum.

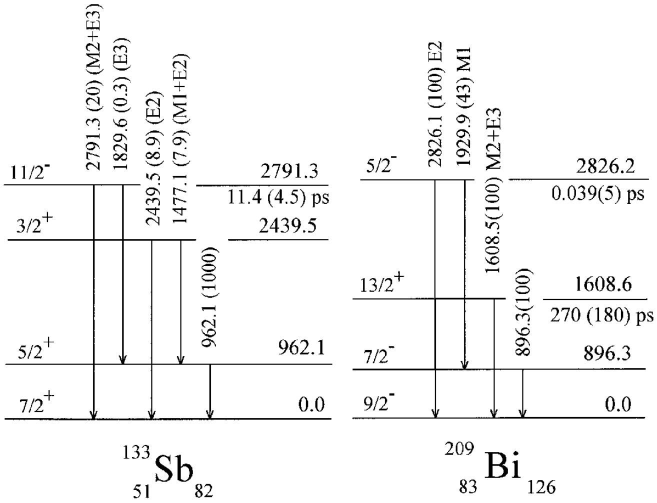

FIG. 2. Partial level schemes comparing the corresponding single proton states and their properties between the ^{132}Sn and ^{208}Pb regions. The relative intensity of 1000 units for the 962.1 keV transition corresponds to 12% per decay of ^{133}Sn. Only γ-ray branchings are given for ^{209}Bi. See the text for details.

We have no evidence for any γ ray that could represent the decay of the expected $s_{1/2}$ state. The total population of this state appears to be smaller, by at least a factor of 20, than that of the $d_{3/2}$ state, which may be reasonable in view of the relatively high angular momentum, $7/2^-$, of the parent ^{133}Sn.

Our results corroborate the previously proposed $h_{11/2}$ state [13] at 2791.3 keV. Both the singles and coincidence γ-ray data show consistent evidence for a weak $E3$ γ-ray branching to the $d_{5/2}$ state at 962.1 keV; see Figs. 1 and 2. The coincidence spectrum gated on the 2791.3 keV transition revealed that the $h_{11/2}$ level is populated by four main γ rays (E_γ = 1502.6, 2358.3, 2821.1, and 3275.7 keV) from higher-lying levels. (A direct population by a β transition would be of second forbidden type and therefore of insignificant intensity.) This γ-ray population has made it possible to use the sensitive fast-timing $\beta\gamma\gamma(t)$ method [14] for a measurement of the level half-life. The method is based on triple coincidences between two fast scintillators and a high resolution Ge detector.

The lifetime measurement of the $h_{11/2}$ single proton level at 2791.3 keV followed a classical case of a two γ-ray cascade [14]. When the γ-ray transition deexciting the level, γ_{2791}, is gated in the Ge detector and the feeding γ ray, γ_{2821}, is gated in the BaF$_2$ crystal, the centroid shift of the fast timing β-γ_{2821} spectrum provides a reference point. If one inverts the gates and selects γ_{2821} in the Ge detector and γ_{2791} in BaF$_2$, then the fast timing β-γ_{2791} spectrum is time delayed with the shift from the reference point equal to the mean life of the 2791.3 keV level. Any influence from the mean life of the higher-lying level is canceled in the comparison. The details of the analysis are illustrated in Fig. 3. The reference points (open circles) were obtained with the 2791.3 keV transition selected in the Ge detector, and with gates in the BaF$_2$ detector set on the full energy peaks and parts of the Compton response of the main γ-ray transitions feeding the $h_{11/2}$ level from states at >4 MeV. The time-delayed point (open square) represents an averaged centroid of four time spectra, β-γ_{2791}, gated in Ge by the main transitions of energy 1502.6, 2358.3, 2821.1, and 3275.7 keV, respectively, directly feeding the $h_{11/2}$ state, and further gated by the 2791.3 keV transition selected in BaF$_2$. In order to improve the statistics, we have selected in BaF$_2$ the full energy peak and part of its Compton continuum in the energy range above 1 MeV. Standard $\gamma\gamma$ coincidences using Ge detectors have certified that in the selected range there are no impurity contributions. Since the average energy of the transitions feeding the level is exceptionally close to the energy of 2791.3 keV for the deexciting transition, no corrections are required in the centroid shift analysis. Thus the mean life of the 2791.3 keV level is precisely equal to the shift of the time-delayed and reference points. As a consistency check, and to improve the statistical accuracy, the parallel

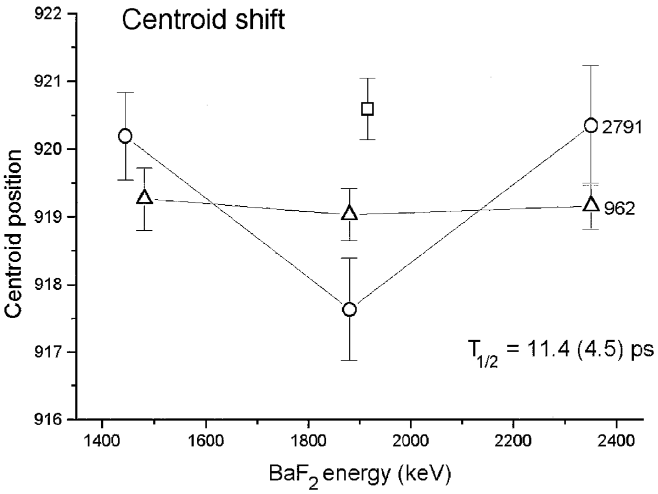

FIG. 3. Centroid shift analysis of the time-delayed spectra related to the $h_{11/2}$ level at 2791.3 keV. The mean life of the $h_{11/2}$ level is given by the shift of the time-delayed point (□) from the reference points (○ and △). The horizontal scale refers to the energy gates selected in BaF$_2$; the vertical time scale is 13.1 ps/channel. The BaF$_2$ gate for the time-delayed point includes the full energy peak at 2791 keV and part of its Compton continuum above ~1 MeV. See text for details.

γ transitions feeding the $d_{5/2}$ level at 962.1 keV were also used to provide independently the time reference points (triangles). As a result the half-life of the single proton $h_{11/2}$ state was deduced for the first time as $T_{1/2} = 11.4(4.5)$ ps.

The new data give the first possibility to directly compare transition probabilities between the basic single proton states in the heavy DCS regions at ^{132}Sn and ^{208}Pb. This is of particular interest since the regions correspond to each other in the sense [10] that each single particle state (n, l, j) at ^{132}Sn has a corresponding state $(n, l + 1, j + 1)$ at ^{208}Pb, with a similar ordering and spacing (with some exceptions). As a result there is a close similarity of selected properties in the two regions [10,15] extending also to include electromagnetic transition rates [2]. The present data on the decays of the $d_{3/2}$ and $h_{11/2}$ levels in ^{133}Sb should thus be compared to the decay properties of the previously known $f_{5/2}$ and $i_{13/2}$ states [16] in ^{209}Bi.

The half-life of the presently found $d_{3/2}$ level of ^{133}Sb is not known; consequently, we consider the relative transition rates. Inspecting Fig. 2, we find the $d_{3/2}$ state and its corresponding $f_{5/2}$ state in ^{209}Bi are deexcited by a spin-flip $M1$ ($+$ $E2$) transition to the spin orbit partner and by a non-spin-flip $E2$ transition of the type $n \rightarrow (n - 1)$, $l \rightarrow (l + 2)$ to the ground state. The $M1$ transitions between spin-orbit partners are allowed, and thus one may assume with high confidence that the competing $E2$ admixture to the spin-flip transition is insignificant. The measured γ-ray intensities can then be used to derive the ratios of $B(M1; d_{3/2} \rightarrow d_{5/2})/B(E2; d_{3/2} \rightarrow g_{7/2}) = 1.65(15) \times 10^{-3}\ \mu_N^2/e^2\,\text{fm}^4$ for ^{133}Sb and $B(M1; f_{5/2} \rightarrow f_{7/2})/B(E2; f_{5/2} \rightarrow h_{9/2}) = 0.75(13) \times 10^{-3}\ \mu_N^2/e^2\,\text{fm}^4$ for ^{209}Bi, which are equal to 0.037(3) and 0.031(3), respectively, when the transition rates are expressed in Weisskopf units (W.u.). These numbers are indeed very similar, which is a direct consequence of the pure configurations and the large overlaps caused by the transition operators.

The $B(M1)/B(E2)$ ratios indicate that the absolute magnitude of the $M1$ strength is nearly the same in ^{133}Sb and ^{209}Bi. The allowed spin-flip $M1$ transitions are moderately hindered because the magnetic dipole field from an orbiting nucleon is partly screened by the other particles. This effect results in a known $B(M1; f_{5/2} \rightarrow f_{7/2}) = 0.024$ W.u. for the transition in ^{209}Bi. To estimate the $B(M1; d_{3/2} \rightarrow d_{5/2})$ in ^{133}Sb one may assume that the allowed $d_{3/2} \rightarrow g_{7/2}$ $E2$ transition should have a rate within a factor of 2 of $B(E2; f_{5/2} \rightarrow h_{9/2}) = 0.76$ W.u. found [16] for the corresponding $E2$ in ^{209}Bi. Very small values of $B(E2)$ cannot occur for such a single particle transition, since the $E2$ operator, due to its structure, is bound to produce large overlaps of similar magnitude in both ^{133}Sb and ^{209}Bi. Minor configuration admixtures cannot have a significant influence on the $B(E2)$. Furthermore, it is known [2] that the collective (core) quadrupole modes of ^{132}Sn and ^{208}Pb are of comparable strength and energy, resulting in admixtures which can be represented by effective $E2$ charges of similar magnitude in the two regions. Consequently, the very similar *ratios* of transition probabilities given above indicate that the absolute magnitude of the $M1$ quenching (and thus the $M1$ screening) is nearly the same for these transitions in ^{209}Bi and ^{133}Sb.

The screening effect will also reduce the allowed spin-flip $M2$ transition rates from the $h_{11/2}$ and $i_{13/2}$ states in these two single proton nuclei (see Fig. 2). In order to deduce the $M2$ rate of the 2791.3 keV transition in ^{133}Sb from our measured half-life, it is necessary to make an allowance for the expected $E3$ admixture. This $E3$ component is of the unfavored spin-flip type, and thereby considerably slower than the core $E3$ transition. A rate of a few W.u. may be expected. To be definite, we assume a 10% $E3$ admixture to the 2791.3 keV transition, which corresponds to a rate of 8 W.u. One then obtains $B(M2, h_{11/2} \rightarrow g_{7/2}) = 0.55(22)$ W.u. (where the uncertainty due to the estimate of the $E3$ admixture is of little significance) which should be compared to the corresponding $M2$ transition in ^{209}Bi with $B(M2, i_{13/2} \rightarrow h_{9/2}) = 0.27(18)$ W.u. Although the uncertainties are large, especially for the ^{209}Bi case, these $B(M2)$ values are of comparable magnitude and represent very high $M2$ transition rates. These values are practically identical to $B(M2) = 0.55(12)$ W.u. for the $j_{15/2} \rightarrow i_{11/2}$ transition between the single neutron states in ^{209}Pb, which is one of the fastest known $M2$ transitions. Thus for the $M2$ case as well, one can conclude for the first time that the transition rates, including screening effects, are highly similar in the two DCS regions.

The 1829.6 keV $E3$ transition in ^{133}Sb has no observed counterpart in ^{209}Bi. We obtain a $B(E3; h_{11/2} \rightarrow d_{5/2}) = 22(13)$ W.u. from the γ-ray branching and the level half-life. This is a nonretarded transition which should be compared to the core $B(E3)$ of about 15 W.u. recently deduced [2] for the ^{132}Sn region.

The similarity of corresponding observables in the DCS regions of ^{132}Sn and ^{208}Pb stems from nuclear symmetry properties which, in the shell model, can be expressed by the symmetry of the transformation $(n, l, j) \leftrightarrow (n, l + 1, j + 1)$. Originally, the correspondence was proposed [10] in order to explain similarities regarding single particle energies, without the need for a detailed understanding of their underlying reasons. The consequences of the corresponding shell structures are likely to be general, as exemplified by the transition rates discussed above and by a recent study of binding energies [15] where the proton-neutron effective interactions in the two heavy DCS regions were found to be strongly similar. Additional intercomparisons of various properties of these regions may in a longer term lead to better understanding of effective interactions, collective vibrations, and polarization effects.

In this context, the present identification of the $d_{3/2}$ state is of high significance. The numerical accuracy of modern large-scale shell model calculations for spherical nuclei is usually limited mainly by incomplete knowledge of single particle energies and effective two-nucleon interactions, not by intrinsic errors in the model or by truncations. With the accurate free nucleon-nucleon potentials now available, one is able to calculate matrix elements of the effective interaction to a precision of about 100 keV in heavy nuclei. In contrast, the errors of the single particle energies, calculated by similar methods, are usually about 1 MeV. The experimental single particle energies thus form a crucial ingredient in shell model calculations for nuclei with few valence nucleons.

The location of the $d_{3/2}$ state provides also for the rare determination of the spin-orbit splitting of the proton d orbit. This quantity, in a neutron-rich nucleus, is of key importance to test the mean field predictions towards the neutron drip line and for neutron matter. A detailed analysis is complex, however, and not without ambiguities. Recent theoretical works [17,18] do not agree on the impact of a relativistic treatment of the spin-orbit field. Apart from relativistic effects, there are other questions to be addressed such as the dependence of the spin-orbit splitting on spin, isospin, density, and nuclear size. Additional data are thus of substantial significance. Our identification of the $d_{3/2}$ state in ^{133}Sb now makes it possible for the first time to compare the spin-orbit splitting of the d orbitals, both as proton particles in ^{133}Sb and as neutron holes in ^{131}Sn. The new results give a splitting of 1477 keV for the former as compared to the 1655 keV [19] for the latter. The splitting is thus about 10% smaller for the proton orbitals. This is actually opposite to the situation regarding the corresponding f orbitals in ^{209}Bi and ^{207}Pb, also having just one node in the wave functions, where the proton particles show a 10% larger splitting than the neutron holes.

In summary, the present study led to the identification of one of the two missing single proton states at the ^{132}Sn DCS. It also provided the first data on absolute $M2$ and $E3$ single particle transition strengths in the region, as well as the absolute $M1$ strengths deduced from the relative rates of allowed $E2$ and $M1$ transitions. The $M1$ and $M2$ transition strengths in the DCS regions of ^{132}Sn and ^{208}Pb were found to be very similar, while a significant difference was seen for the spin-orbit splittings.

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