PHYSICAL REVIEW C VOLUME 16, NUMBER 6 DECEMBER 1977

Heavy odd-mass $^{127-133}$Sb isotopes

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(Received 7 July 1977)

The heavy odd-mass $^{129-133}$Sb isotopes have been studied. Partial level schemes are constructed and μs isomeric states are observed and located as follows: 3 μs (^{129}Sb), 50 μs (^{131}Sb), and 17 μs (^{133}Sb). By means of particle-core coupling as well as one-proton two-neutron-hole (1p-2h) shell-model calculations, many of the observed properties such as energy spectra, branching ratios, and isomeric states can be reproduced qualitatively and even quantitatively.

[NUCLEAR STRUCTURE ^{127,131}Sb levels and lifetimes. Unified model and shell-model calculations.]

The odd-mass Sb nuclei have been the subject of many experimental[1] as well as theoretical investigations,[2-6] since the interplay between the proton single-particle motion in the shell $50 < Z < 82$ and the quadrupole and octupole vibrations of the underlying core nuclei is manifest nicely in the mass chain $111 \leqslant A \leqslant 125$. For the heavier mass Sb isotopes, it is well known that in ^{127}Sb an 11 μs isomer has been observed.[7-8] Within the scope of the particle-core-coupling model, it is impossible to reproduce such levels where, as suggested, proton two-neutron-hole configurations are the origin of the isomerism.[8-9]

By means of the fission-fragment separator Lohengrin at the high flux reactor of the Institute Laue-Langevin (ILL) at Grenoble, a systematic study for microsecond isomeric levels was performed in the heavy odd-mass Sb region $129 \leqslant A \leqslant 133$. The β decay from the $1h_{11/2}^{-1}$ and $2d_{3/2}^{-1}$ neutron-hole states in the odd-mass ^{131}Sn isotope[10] has been studied. Additional evidence for the occurrence of levels with a half-life in the microsecond region in $^{129-133}$Sb results from fission-fragment-γ delayed coincidences. By combining the results of both types of experiments, partial level schemes as well as the excitation energy of the isomeric levels could be determined (Fig. 1). The results can now be discussed in terms of either particle-core-coupling calculations or exact one-proton n-neutron-hole shell-model calculations.

In the particle-core-coupling calculations, the necessary single-particle energies for the proton orbits considered, i.e., $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, and $1h_{11/2}$, are determined such as to reproduce the experimentally observed $J^{\pi} = \frac{5}{2}^{+}, \frac{3}{2}^{+}, \frac{1}{2}^{+}, (\frac{11}{2}^{-})$ levels, excited in the Te(d, τ)Sb reaction[11-12] for $A = 127$ and 129. In ^{133}Sb, the lowest proton single-particle levels are known,[13-14] i.e., $1g_{7/2}$, $2d_{5/2}$, and $1h_{11/2}$. For ^{131}Sb, interpolated values are used for the proton single-particle energies. In all cases (except ^{129,133}Sb), the $\hbar\omega_2$ and $\hbar\omega_3$ values are taken from the corresponding $I^{\pi} = 2^{+}$ and 3^{-} excitation energy in the doubly even Sn nuclei. The coupling strengths[3] ξ_2 and ξ_3 are taken, if known, from the experimental $B(E_2; 2_1^{+} \rightarrow 0_1^{+})$ and

TABLE I. The proton single-particle energies, relative to the $1g_{7/2}$ level, phonon energies ($\hbar\omega_2$, $\hbar\omega_3$) and coupling strengths (ξ_2, ξ_3) as used for the particle-core-coupling calculations in $^{127-131}$Sb. The experimental energies for ^{133}Sb (Ref. 14) are also given if known.

	^{127}Sb	^{129}Sb	^{131}Sb	^{133}Sb
$\epsilon d_{5/2}$	0.70	0.80	0.90	0.963
$\epsilon h_{11/2}$	2.55	2.30	2.05	(2.792)
$\epsilon d_{3/2}$	2.40	2.20	2.00	
$\epsilon s_{1/2}$	2.60	2.50	2.30	
$\hbar\omega_2$	1.164	1.2	1.217	
$\hbar\omega_3$	2.732	2.9	3.1	4.014
ξ_2	1.75	1.35	0.75	
ξ_3	1.0	0.75	0.50	

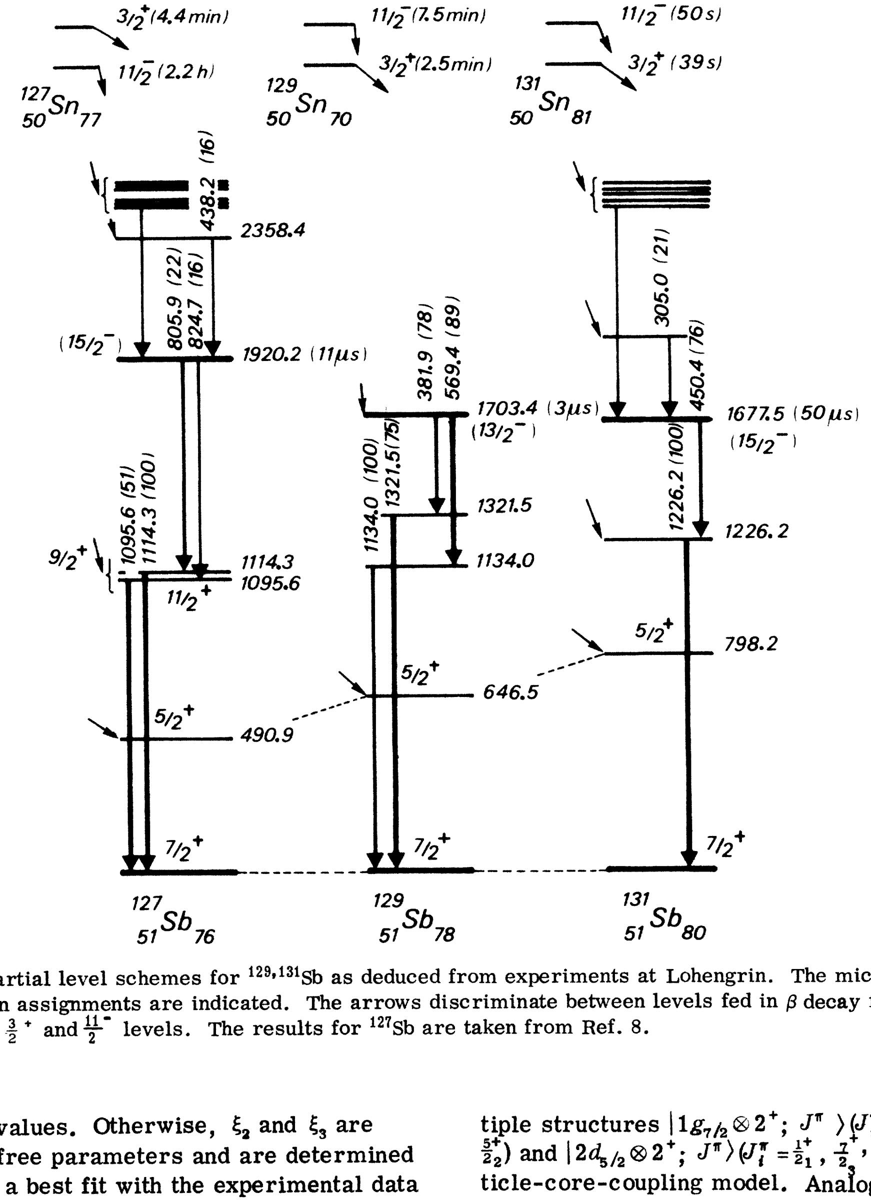

FIG. 1. The partial level schemes for ^{129,131}Sb as deduced from experiments at Lohengrin. The microsecond states and probable spin assignments are indicated. The arrows discriminate between levels fed in β decay from, respectively, the odd-mass Sn $\frac{3}{2}^+$ and $\frac{11}{2}^-$ levels. The results for ^{127}Sb are taken from Ref. 8.

$B(E3; 3_1^- \rightarrow 0_1^+)$ values. Otherwise, ξ_2 and ξ_3 are considered as free parameters and are determined so as to obtain a best fit with the experimental data (Table I). In order to calculate also the electromagnetic transition rates and moments, an effective proton charge $e_p = 1.5e$ has been used throughout and the nuclear stiffness coefficients C_2 and C_3 are determined from the corresponding ξ_2 and ξ_3 values.[3] For the gyromagnetic spin factor, the estimate $g_s = \frac{1}{2} g_s(\text{free})$ is used, whereas for g_R both the hydrodynamic estimate[3-8] $g_R = Z/A$ and $g_R = 0$[4] are used. For ^{127}Sb, branching ratios for levels with $E_x \lesssim 1.75$ MeV are known[7] and can be compared with the theoretical calculations. The detailed comparison for $g_R = 0$ giving the best agreement is made in Fig. 2. This same conclusion concerning the value of g_R was also obtained in Ref. 4. This comparison validates a description of levels with 1 MeV $\lesssim E_x \lesssim 1.75$ MeV by means of the multiple structures $|1g_{7/2} \otimes 2^+; J^\pi\rangle (J_i^\pi = \frac{3}{2}_1^+, \frac{9}{2}_1^+, \frac{11}{2}_1^+, \frac{7}{2}_2^+, \frac{5}{2}_2^+)$ and $|2d_{5/2} \otimes 2^+; J^\pi\rangle (J_i^\pi = \frac{1}{2}_1^+, \frac{7}{2}_3^+, \frac{9}{2}_2^+)$ in the particle-core-coupling model. Analogous calculations have been performed for ^{129,131}Sb.

Although the particle-core-coupling model is able to produce a level scheme for ^{131}Sb, we expect, however, limited validity for this approach due to the very strong deviation between the doubly even $^{130}_{50}\mathrm{Sn}_{80}$ nucleus and a harmonic quadrupole vibrator.[9,15,16] Therefore, we have performed in this particular case one-proton two-neutron-hole (1p-2h) shell-model calculations. The proton-particle neutron-hole as well as neutron-neutron interactions are determined by fitting the residual force chosen so as to reach a good description of the energy spectra in $^{132}_{51}\mathrm{Sb}_{81}$ and $^{130}_{50}\mathrm{Sn}_{80}$, respectively. For the neutron-neutron interaction a Gaussian force $V = V_0 e^{-\beta r^2}(P_S + tP_T)$ was used, in line with calculations performed for the $N = 82$ nuclei,[17-19] and with, as a result, $V_0 = -39$ MeV and $t = +0.2$. The operators P_S and P_T are the spin-singlet and -triplet projection operators, respectively. The residual proton-neutron short-range correlations are determined very well with a zero-range interaction

$$V = V_{\text{eff}}\,(1 - \alpha + \alpha\vec{\sigma}_p\cdot\vec{\sigma}_n)\,\delta(\vec{r}_p - \vec{r}_n),$$

which also proves very useful in a description of the doubly odd $50 \leq Z \leq 82$, $N = 81$ nuclei.[20] The best fit parameters in our case are $V_{\text{eff}} = -420$ MeV, $\alpha = 0.2$. The proton single-particle energies are the same as in the particle-core-coupling calculation, whereas the neutron single-hole energies ($2d_{3/2}^{-1}$, $3s_{1/2}^{-1}$, $1h_{11/2}^{-1}$, $1g_{7/2}^{-1}$) have been taken from the $^{131}_{50}\text{Sn}_{81}$ spectrum.[21] Only the $2d_{5/2}^{-1}$ orbit is not observed. In line with the systematics for odd-mass Sn isotopes[22] where the excitation energy for the $2d_{5/2}$ quasiparticle configuration is always higher than the $1g_{7/2}$ quasiparticle energy, we take the $2d_{5/2}{}^{-1}$ neutron single-hole energy at $\epsilon_{2d_{5/2}}{}^{-1} = 2.8$ MeV. The resulting spectrum for ^{131}Sb is compared with the experimental data in Fig. 3 with a clear reproduction of the negative parity $|(2d_{3/2}{}^{-1}1h_{11/2}{}^{-1})7_1^-$,

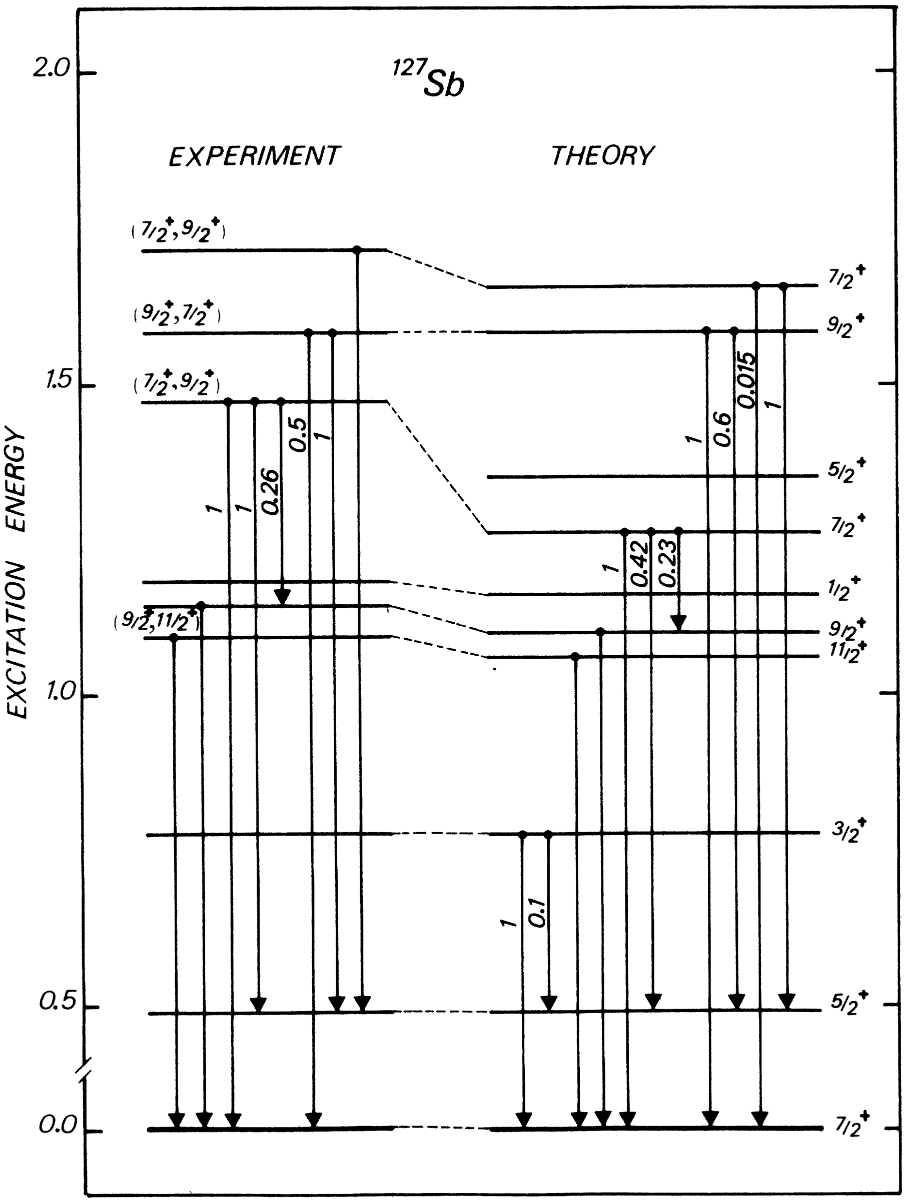

FIG. 2. The experimental level scheme and branching ratio's for ^{127}Sb up to 1.7 MeV as compared with the particle-core-coupling calculations. The branching ratio's are normalized to one.

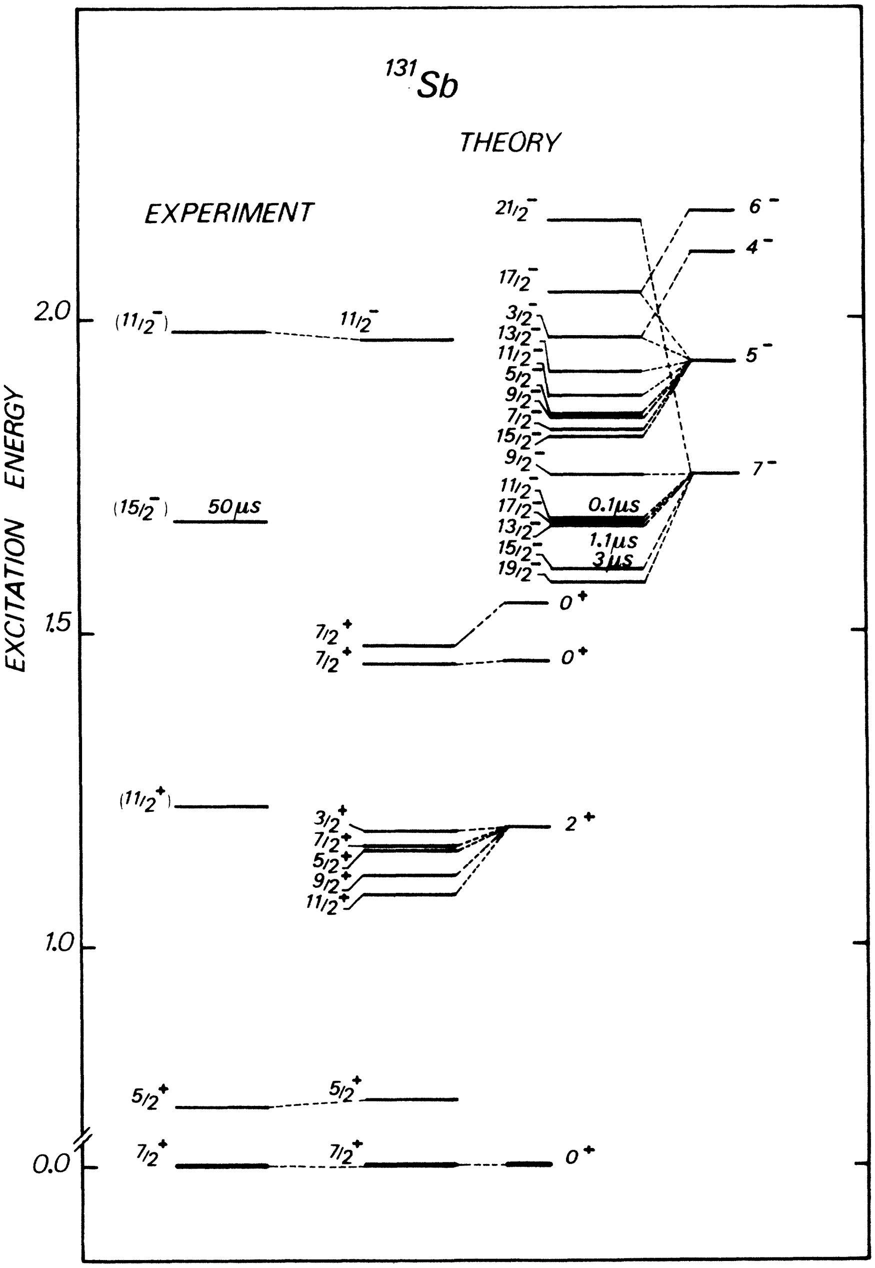

FIG. 3. Experimental and theoretical (1p–2h shell-model calculation) level schemes for ^{131}Sb are given. For the theoretical spectra, the parentage on levels in the doubly even core nucleus $^{130}_{50}$Sn$_{80}$ are also indicated.

$1g_{7/2}; J^\pi\rangle$ and $|(2d_{3/2}{}^{-1}1h_{11/2}{}^{-1})5_1^-, 1g_{7/2}; J^\pi\rangle$ multiplets. In the same figure, the parentage of the calculated spectrum in ^{131}Sb on levels in the doubly even ^{130}Sn is also indicated. Generally, the splitting for a particular multiplet $|I, j; J\rangle$ (I and j are the angular momenta of the core nucleus and the extra proton, respectively) is such as to give approximately an ordering with $J = I + j - 1, I + j - 3, \ldots, I + j - 2, I + j$, with growing excitation energy, at least for the highest angular momentum states.

In calculating the lifetime for these negative parity multiplets, the proton and neutron effective charges $e_p = 1.5e$, $e_n = 0.5e$, and g_s^p, $g_s^n = \frac{1}{2}g_s^p$(free), $\frac{1}{2}g_s^n$(free) gyromagnetic ratios have been used. As a result, the lifetimes are indicated in Fig. 3. The largest lifetime occurs for the $J^\pi = \frac{15}{2}^-$ level (3 μs), which is at least an order of magnitude smaller than the experimental value. Moreover, isomeric levels with even shorter half-lives (<1 μs) result from the calculation. We have to remark, however, that no short ($\lesssim 0.5$ μs) lifetimes can be observed with the experimental setup for determining isomeric levels as used at the ILL. Anyhow, these levels should be observed in the β decay of the $1h_{11/2}^{-1}$ and/or $2d_{3/2}^{-1}$ neutron-hole configurations.

Failure within new experiments with better statistics (which are in the progress of being analyzed) to indicate such levels means that either (i) the $J^\pi = \frac{13}{2}^-$ and $\frac{11}{2}^-$ levels occur above or close to the $\frac{11}{2}^-$ proton level at $E_x = 1.982$ MeV such that γ feeding becomes highly improbable or even forbidden, or (ii) the lifetimes calculated in the shell model are determined by the $1g_{7/2} \rightleftarrows 1h_{11/2}$ $M2$ transition. Thus small admixtures of the type

$$|(2d_{3/2}^{-2})I,\ 1h_{11/2};\ J_i\rangle\,,$$

$$|(3s_{1/2}^{-1}2d_{3/2}^{-1})I,\ 1h_{11/2};\ J_i\rangle\,,$$

$$|(3s_{1/2}^{-2})0,\ 1h_{11/2};\ \tfrac{11}{2}\rangle\,,$$

$$|(1h_{11/2}^{-2})I,\ 1h_{11/2};\ J_i\rangle\,,$$

in the initial state and the same configurations with the $1h_{11/2}$ proton orbit changed into the $1g_{7/2}$ proton orbit for the final state J_f contribute towards an incoherent sum of small terms. If, for instance, the configuration space is truncated to keep only the $1g_{7/2}$, $2d_{5/2}$, and $1h_{11/2}$ proton orbits and the $2d_{3/2}^{-1}$, $3s_{1/2}^{-1}$, and $1h_{11/2}^{-1}$ neutron states, the lifetime for the $J^\pi = \frac{15}{2}^-$, $\frac{13}{2}^-$, and $\frac{11}{2}^-$ levels becomes 22 μs, 1.6 μs, and 0.22 μs, respectively. The influence of changing the effective charges, gyromagnetic ratios, and neutron-neutron and proton-neutron forces within a reasonable range has been studied and only results in minor changes. In order to find more definite conclusions for ^{131}Sb and also for ^{129}Sb, 1p-4h calculations are in the process of being performed. These results, the new experimental analysis together with a more detailed account of the calculations, will be published separately.

One of the authors (K. H.) is much indebted to Professor A. J. Deruytter for his interest during the course of this work.

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