Doppler-shift attentuation method lifetime measurements in ^{115}Sb and ^{117}Sb

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The lifetimes of several low-lying excited levels in ^{115}Sb and ^{117}Sb have been measured by using the DSA method in the ^{115,117}Sn$(p,n\gamma)^{115,117}$Sb reactions, respectively. The structure of these nuclei is discussed in the frame of the interacting boson-fermion model.

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I. INTRODUCTION

The neutron-deficient Sb nuclei constitute an important link between the spherical, semimagic Sn nuclei and the transitional nuclei with Z above 52. At higher spins, considerable interest has been raised by the discovery of deformed bands due to proton excitation of the Sn core across the $Z = 50$ shell [1–3] or to the intruder band [4]. At lower excitation energies and spins, their structure should be dominated by the single-particle degrees of freedom (the lowest shell model orbitals in the 50-82 shell) coupled to vibrations of the Sn core. This picture, simple in principle, has never been tested in detail, however, since for most of these levels the electromagnetic transition probabilities are unknown.

In this work we present the first measurements of lifetimes of the low-lying levels in ^{115}Sb and ^{117}Sb. The existing information on the properties of these levels concerns mostly excitation energies and J^π values and comes mainly from studies of the $(p,n\gamma)$ reaction and light-particle induced transfer reactions [5,6]. We perform DSA measurements in the (p,n) reaction, which, although providing rather low recoil velocities, has the advantage that it can be performed almost at the threshold and thus populate directly only the levels of interest.

We interpret the properties of the low-lying level scheme of these two Sb isotopes on the basis of calculations performed with the interacting boson-fermion model (IBFM).

II. EXPERIMENTAL METHOD

The levels in ^{115}Sb and ^{117}Sb were excited via the (p,n) reaction. The proton beam was delivered by the FN Tandem Van de Graaf accelerator of the IAP, Bucharest. The incident beam energies have been chosen as close as possible to the threshold for the excited level(s) of interest, in order to minimize the sensitivity of the initial mean velocity of the residual nucleus to the angular distribution of the outgoing neutron and to eliminate the influence of the feeding from the higher states. Thus, the measurements have been performed at 5.5 and 5.9 MeV for the ^{115}Sn target ($Q_{(p,n)} = -3.809$ MeV) and 4.4, 4.8, and 5.4 MeV for the ^{117}Sn target ($Q_{(p,n)} = -2.523$ MeV). The beam intensities were kept between 10 and 20 nA, in order to reduce the collection dead times below 10%. The targets were metallic foils about 0.1 mm thick, with enrichments of 51.2% (^{115}Sn) and 84.8% (^{117}Sn), respectively.

The gamma rays were detected in a 20% efficiency HP Ge detector, placed at about 30 cm from the target. Spectra were accumulated at up to 10 different angles, taken in a random order in the range from 0° to 143° with respect to the beam axis.

A careful analysis of the spectra was undertaken in order to determine precisely the peak centroids, since the recoil velocities are less than $10^{-3}c$. A continuous monitoring of the energy calibration of the system was achieved by using ^{60}Co, ^{137}Cs, and ^{152}Eu radioactive sources. When possible, the first two were kept during the in-beam data acquisition, but in general, especially when this was not the case, calibration spectra were recorded both before and after each run. Spectra were rejected if the gain shift between two runs was larger than the imprecision in the photopeak location.

III. EXPERIMENTAL RESULTS

The energies of the γ rays measured at different detector angles θ have been fitted with the expression

$$E_\gamma(\theta) = E_0\left(1 + F_{\rm exp}\frac{v}{c}\cos\theta\right), \qquad (1)$$

where E_0 is the unshifted γ-ray energy, v is the mean initial recoil velocity, and $F_{\rm exp}$ is the experimental attenuation factor. Since the c.m. angular distribution of the outgoing neutron is isotropic (due to the compound nucleus reaction mechanism), the initial mean recoil velocity is just the velocity of the center of mass.

Figure 1 shows the experimental centroid energies as a function of cos θ; the $F_{\rm exp}$ values were determined from the slopes of the straight lines fitted to these data (shown in the figure), and are given in Table I. The error bars of the data points are determined by the statistical uncertainty of the centroid determination and an error originating either from the uncertainties of the coefficients of the energy calibration (second degree) polynomial determined from the adjacent calibration spectra, or from the determination of the position of a reference line (from sources kept during the run) which was closest to the peak of interest.

In extracting lifetimes from such low-energy recoil data, one of the main uncertainties comes from the imperfect knowledge of the stopping powers of Sb recoils in Sn. To get a feeling of this uncertainty, we have calculated the theoretical $F(\tau)$ values using different assumptions for the stopping powers. Thus, we have used first one of oldest "standard" choices in the description of the slowing down process: the Lindhard-Scharff-Schiott (LSS) [7] and the Blaugrund [8] treatment. In a second set of calculations we used the stopping powers calculated with the procedure of Winterbon [9]. Third, we have used the stopping powers calculated according to the procedure of Ziegler, Biersack, and Littmark (ZBL) [10]. The ZBL stopping power provides lifetimes which are about 15% larger than those of LSS, while the Winterbon one gives values smaller by up to $\sim$ 10% for lifetimes above $\sim$ 150 fs and practically identical with the LSS values below $\sim$ 100 fs. In Table I we report the lifetime values resulting by the comparison of the $F_{\rm exp}$ values with the LSS calculated $F(\tau)$ curve. From the discussion above, we may conclude that the lifetime uncertainties due to the stopping power evaluation are of the order of 15%.

The ^{115}Sb and ^{117}Sb levels listed in Table I, for which $F(\tau)$ has been measured in this work, are those listed in Refs. [5] and [6], respectively. For ^{117}Sb, the levels

TABLE I. Experimental $F(\tau)$ values and lifetimes for the indicated excited levels in ^{115}Sb and ^{117}Sb. The given lifetimes correspond to the LSS stopping powers (see the discussion in text) and the quoted errors are the statistical ones. The J^π values are those adopted in Refs. [5,6]. The value $J = (\frac{3}{2})$ for the 1504 keV level in ^{115}Sb is very unlikely (see discussion in text).

$E_{\rm level}$ (keV)	J^π	E_γ (keV)	$F(\tau)$ (%)	τ (fs)
		^{115}Sb nucleus		
770.4	$\frac{1}{2}^+$	770.4	8.0 ± 2.9	630^{+530}_{-210}
1071.7	$\frac{3}{2}^+$	1071.7	26.5 ± 3.6	134^{+30}_{-20}
1098.6	$\frac{7}{2}^+$	1098.6	9.8 ± 4.2	460^{+450}_{-150}
1504.2	$(\frac{3}{2})^+$	1504.2	24.4 ± 1.1	153^{+9}_{-9}
		^{117}Sb nucleus		
923.9	$\frac{3}{2}^+$	923.9	21.8 ± 6.4	170^{+100}_{-50}
1089.4	$(\frac{9}{2}^+)$	1089.4	18.0 ± 7.5	220^{+210}_{-80}
1310.5	$(\frac{9}{2}^+)$	1310.5	21.4 ± 16.9	≥ 80
1378.9	$\frac{7}{2}$	1378.9	18.3 ± 7.8	215^{+210}_{-80}
1453.8	$\frac{3}{2}$	1453.8	0.9 ± 0.9	
1471.7	$\frac{7}{2}$	1471.7	5.6 ± 3.3	≥ 530
1535.6	$\frac{7}{2}$	1535.6	8.2 ± 4.1	≥ 350
1623.3	$\frac{3}{2}$	905.7	11.9 ± 8.0	≥ 190
1716.3	$(\frac{1}{2}, \frac{3}{2}^+)$	1716.3	51.5 ± 4.9	46^{+10}_{-8}
1751.8		1751.8	12.8 ± 6.1	343^{+450}_{-135}
2085.2		1557.9	34.1 ± 7.9	95^{+43}_{-26}
2300.0	$\frac{1}{2}^+, \frac{3}{2}^+$	2300.0	72.5 ± 13.4	20^{+15}_{-11}

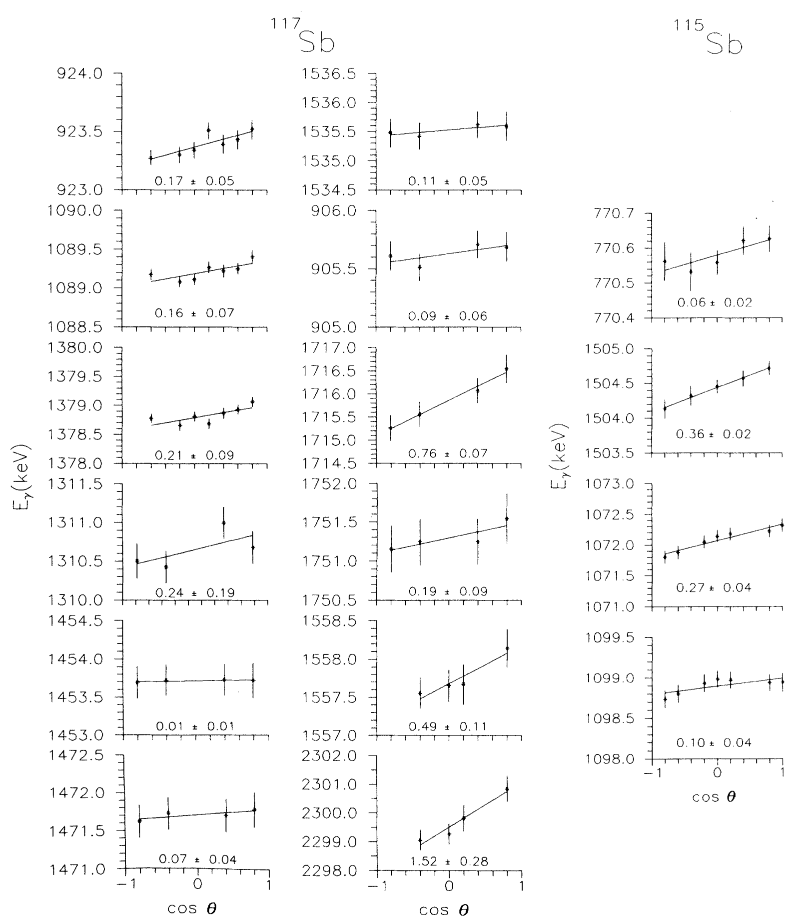

FIG. 1. Plots of the observed displacements of the γ-ray energies with the angle of observation. The continuous lines are fits to the data points with a straight line of slope as indicated in each case. The measurements have been performed at different incident energies, as follows. For ^{115}Sb: 5.5 MeV for the levels with E_x = 1098.6 and 1071.7 keV; 5.9 MeV for the levels at E_x = 770.4 and 1504.2 keV, respectively. For ^{117}Sb: 4.4 MeV for the levels at 923.9, 1089.4, and 1378.9 keV; 4.8 MeV for the levels at 1310.5, 1453.8, 1471.7, 1535.6, 1623.3 (E_γ = 905.7 keV), and 1716.3 keV; and 5.4 MeV for the levels at 1751.8, 2085.2 (E_γ = 1557.9 keV), and 2300.0 keV, respectively.

at 1378.9, 1471.7, 1535.6, and 1751.8 keV excitation are quoted [6] as seen only in the (p,n) reaction [11].

IV. IBFM CALCULATIONS AND DISCUSSION

The low-spin structure of the odd-A Sb isotopes is reasonably easy to understand, due to the shell closure at $Z = 50$. Thus, the isotopes $^{115-125}$Sb have been theoretically investigated by coupling an odd proton in the spherical shell model orbitals $2d_{5/2}$, $1g_{7/2}$, $3s_{1/2}$, $2d_{3/2}$, and $1h_{11/2}$ to the low excitations of the Sn cores. The lightest isotopes, 115 and 117, of interest in the present work, have been calculated in this way in the works of Sen and Sinha within a semimicroscopic model [12] and of Vanden Berghe and Heyde within the unified model [13] by coupling the above single particle degrees of freedom to the quadrupole and octupole excitations of the core. Due to the rather limited experimental information at the time, the calculated properties compared to the experimental ones concerned only some spectroscopic factors in the (^{3}He,d) reaction, and the electric quadrupole moment for the ground state. As concerns the electromagnetic transition probabilities, the unified-model calculations [13] predict lifetimes of 7 ps and 16 ps for the $7/2_1^+$ states in ^{115}Sb and ^{117}Sb, respectively, which agree with the present observations; other calculated properties of these isotopes are not published.

In the following, we shall present an interpretation of the low-spin, positive parity states of both ^{115}Sb and ^{117}Sb, in the framework of the interacting boson-fermion model (IBFM) [14], in which a fermion (the odd-proton) that can occupy any of the shell model orbitals mentioned above is coupled to a Sn core described by the interacting boson model (IBM) [15]. We use the IBFM-1 version of this model, which does not distinguish between protons and neutrons. The Sn nuclei, with a closed proton shell, are a special case for the IBM: they have only one kind of boson, namely, neutron bosons. Since active (valence) protons are missing, there is no neutron-proton interaction, so that the Sn nuclei cannot deform. On the other hand, they can be regarded as vibrators, their low-spin states (a 0^+, 2^+, 4^+ triplet at about twice the energy of the 2_1^+ state) resembling quite well the $U(5)$ (vibrational) limit of IBM; for ^{114,116}Sn, the $B(E2, 2_1^+ \to 0_1^+)$ values are in the range 12 to 16 W.u. [16], thus indicating collective (vibrational) effects. It has been shown previously that the low-energy part of the level schemes of $^{114-124}$Sn isotopes are well described by phenomenological IBM calculations [17]; in another paper [18], parameters of the IBM were derived microscopically from shell model calculations, and provided a similarly good description of the experimental data. Thus, an approach to the present light Sb nuclei within IBFM appears justified.

The Sn core nuclei were reasonably described by using an IBM Hamiltonian in the $U(5)$ limit. The calculations have been performed with the code PHINT [19]. For the isotopes 114–118 (7–9 bosons) we have used the same parameter set, namely (in the notation used by PHINT), EPS=0.65, PAIR=−0.05, ELL=0.03 (all in MeV). An average boson effective charge of 0.1 eb predicts reasonably well the $B(E2, 2_1^+ \to 0_1^+)$ values of around 0.5 $(e\text{b})^2$ for these isotopes [16].

The IBFM Hamiltonian has the form [14] $H = H_{IBA} + H_F + V_{BF}$, where the first and second terms represent the Hamiltonian of the core and of the single particle degrees of freedom, while the last term is the boson-fermion interaction. In principle, V_{BF} is rather complicated, but it has been shown that it is dominated by three terms, named the monopole-monopole, quadrupole-quadrupole, and exchange interaction, respectively [14]. The monopole interaction represents only a renormalization of the core Hamiltonian, while the relative importance of the other two is determined by the degree of emptiness of the shell model orbitals. Semimicroscopic parametrizations of these terms [20], which we use in our calculations, show that in our case (when these shells are practically empty) the exchange term is negligible. Thus, the low-lying structure of these nuclei should be determined by the quadrupole-quadrupole interaction alone (for simplicity, we give up also the monopole part), which reads [20]

$$V_{BF} = \sum_{jj'} \Gamma_{jj'} [(s^\dagger \tilde{d} + d^\dagger s)^{(2)} + \chi (d^\dagger \tilde{d})^{(2)}] (a_j^\dagger \tilde{a}_{j'})^{(2)} \quad (2)$$

with

$$\Gamma_{jj'} = \Gamma_0 (u_j u_{j'} - v_j v_{j'}) \langle j \| Y^{(2)} \| j' \rangle. \quad (3)$$

The calculations proceeded as follows. The single particle energies of the shell-model orbitals have been chosen according to the prescription of Reehal and Sorensen [21]. Then, the quasiparticle energies ϵ_j and the shell occupancies u_j, v_j have been calculated within a BCS approach. Thus, the only remaining parameter in the calculations is Γ_0, the strength of the quadrupole-quadrupole interaction. The calculations have been performed with the code ODDA [22].

Figure 2 shows the prediction of these calculations for the positive parity states, as a function of Γ_0, for both ^{115}Sb and ^{117}Sb, compared to the low-lying experimental states which have well determined spin and parity values. One can see that a value of Γ_0 =0.25 MeV gives a reasonably good description of the experimental spectrum for both the isotopes. A slight readjustment of the relative position of the $d_{5/2}$ and $g_{7/2}$ single particle levels would improve the description. The dominant structure of the wave functions for the states drawn in Fig. 2 is as indicated. Below about 1.7 MeV excitation, the $s_{1/2}$ and $d_{3/2}$ orbitals practically do not play any role. To calculate $B(E2)$ values of transition in these nuclei, with the operator used in PBEM [22], the boson and fermion effective charges were taken equal to those used for the core, of 0.1 eb.

Since no δ values (mixing ratios) are experimentally determined for the transitions in Table I, a straightforward comparison of the calculated $B(E2)$ values with experimental values can be done only for the pure $E2$ transitions. Thus, in ^{115}Sb, for the $1/2_1^+ \to 5/2_1^+$ transition, one gets $B(E2) = 476 \pm 230\ e^2\ \text{fm}^4$, which compares well with the calculated value of 382 e^2 fm^4. For the similar $1/2_1^+$ state in ^{117}Sb the lifetime could not be measured. In ^{117}Sb, other pure $E2$ transitions are those from the $(9/2^+)$ state at 1089.4 keV and $(9/2)^+$ state at 1310.5 keV, respectively, towards the $5/2^+$ ground state, but they are determined with rather large errors due to the large error in the observed shift.

$B(M1)$ values in these nuclei have not been calculated, due to well-known shortcomings of the $M1$-transition operator actually used in IBFM-1 calculations [23]. The present calculations indicate a "weak coupling" picture for the low-lying states: a relatively small splitting of the $2_1^+ \otimes d_{5/2}$ multiplet and $B(E2)$ values of the transitions from the states of this multiplet to the ground state (g.s.), comparable to that of the $2_1^+ \rightarrow 0_1^+$ transition of the core. If we consider these $B(E2)$ values equal to that of the core, then the lifetimes determined in the present measurements would correspond to reasonable δ values: $|\delta| \approx 0.25$ and $|\delta| \approx 0.43$ for the $3/2_1^+ \rightarrow 5/2_1^+$ transition in ^{115}Sb and ^{117}Sb, respectively, and $|\delta| \approx 0.48$ for the $7/2_1^+ \rightarrow 5/2_1^+$ (1098.6 keV) transition in ^{115}Sb.

For the higher excited states listed in Table I, a one-to-

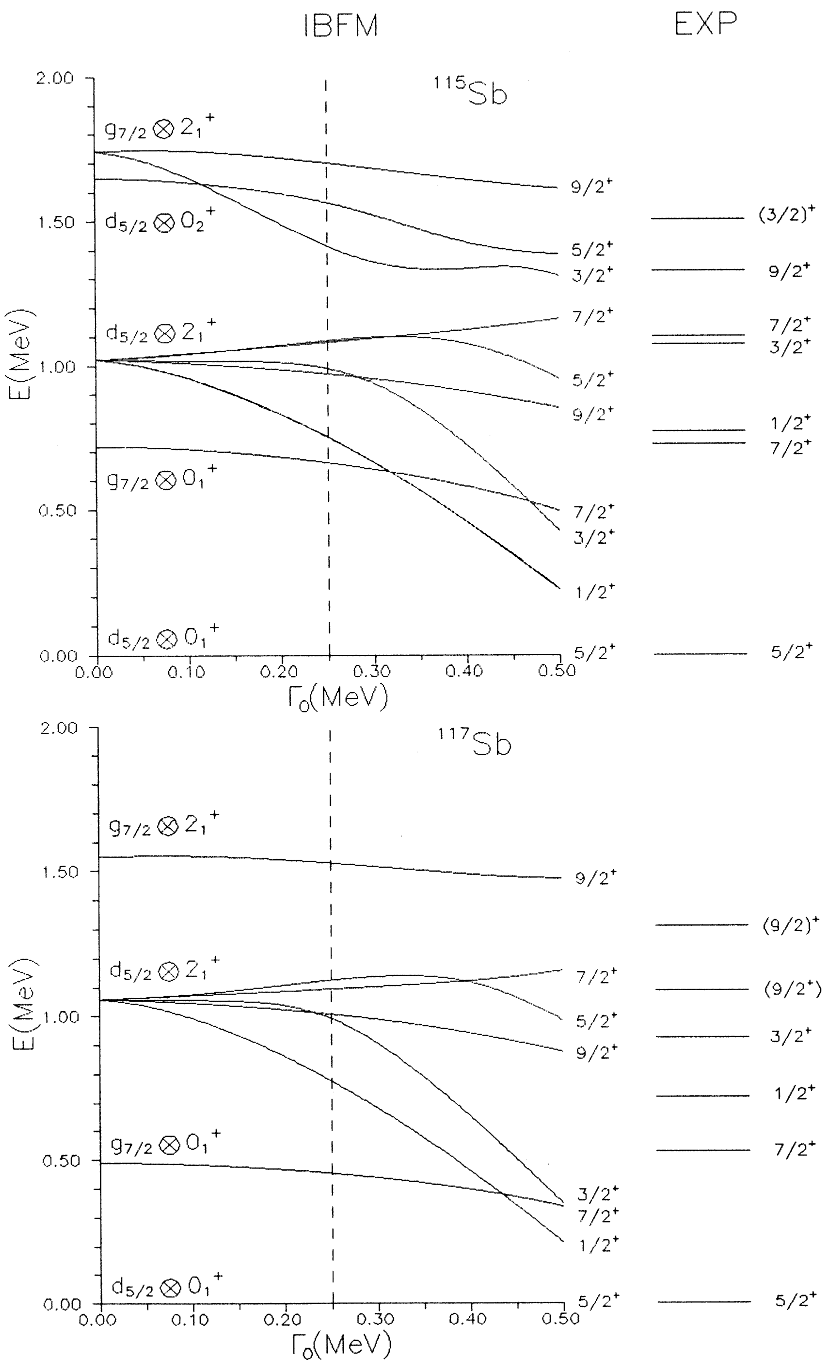

FIG. 2. Comparison between the experimental low-lying level scheme of ^{115,117}Sb and IBFM-1 calculations. The calculated levels are shown as a function of Γ_0, the strength of the quadrupole-quadrupole interaction, and their dominant configuration is indicated. Not all the states resulting from the coupling of $g_{7/2}$ to the 2_1^+ state of the core are shown. The dashed line indicates the value $\Gamma_0 = 0.25$ MeV, which provides a reasonable description of the level scheme for both isotopes.

one correspondence to the calculated states is not possible. For some of these states, the measured lifetimes can help to discuss their uncertain spin assignments. Thus, the state at $E_X = 1504.2$ keV in ^{115}Sb is quoted as having $J^\pi = (3/2)^+$ [5]. This state has important branches towards the $7/2^+$ states at 723.6 and 1098.6 keV excitation; if its spin is 3/2 then both these transitions would be pure $E2$. This is very unlikely since, with the present lifetime one would get extremely enhanced $B(E2)$ values, of 78 W.u. (for the 14.5% branch to the 723.6 keV state) and more than 2000 W.u. (for the 16.6% branch to the 1098.6 state).

In ^{117}Sb, we have measured the lifetimes of the states at 1716.2 and 2300.0 keV excitation, which are assigned as $1/2^+$, $3/2^+$. Both of them have the strongest branch towards the g.s., $5/2^+$ state. If we consider these branches as having an $E2$ multipolarity, we get slightly enhanced $B(E2)$ values, of 27.4 W.u. for the 1716.2 keV state and 18.2 W.u. for the 2300.0 keV state, respectively. Therefore, these values do not rule out a possible assignment of $1/2^+$ for both these states.

V. CONCLUSIONS

By measuring γ-ray DSA centroid shifts in the ^{115,117}Sn$(p,n\gamma)$ reactions we have determined lifetimes for 4 excited states (below 1.5 MeV) in ^{115}Sb, and for 7 states (below 2.3 MeV) in ^{117}Sb, as well as lower limits for other 4 states in ^{117}Sb, respectively. The low-lying positive parity states in these isotopes have been interpreted in the frame of multishell IBFM-1 calculations with only the quadrupole-quadrupole term for the boson-fermion interaction. The calculations had as free parameter the strength of this interaction, for which an optimum value $\Gamma_0 = 0.25$ MeV was determined from comparison with the data. The level and electromagnetic decay scheme of ^{115}Sb and ^{117}Sb below about 1.5 MeV excitation is consistent with a weak coupling of the odd proton in the $d_{5/2}$ and $g_{7/2}$ orbitals to the quadrupolar vibrations of the Sn cores.

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