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On the unusual properties of the 282 keV state in ^{135}Sb

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Abstract. Recently the first excited state in ^{135}Sb has been observed at the unexpectedly low excitation energy of only 282 keV and interpreted as mainly $d_{5/2}$ proton coupled to the ^{134}Sn core. Based on theoretical considerations it was suggested that its low excitation energy is related to a relative shift of the proton $d_{5/2}$ and $g_{7/2}$ orbits induced by the neutron excess. We have measured the lifetime of the 282 keV state by the advanced time-delayed $\beta\gamma\gamma(t)$ method. The measured half-life, $T_{1/2} = 6.1(4)$ ns, yields exceptionally low limits of $B(M1; 5/2_1^+ \to 7/2_1^+) \leq 3.0 \times 10^{-4}\ \mu_N^2$ and $B(E2; 5/2_1^+ \to 7/2_1^+) \leq 54\, e^2\text{fm}^4$. These strongly hindered $M1$ and slow $E2$ transition rates are similar to those for the transition de-populating the first excited state at 405 keV in ^{211}Bi. Results of shell model calculations with realistic interactions are presented. The $M1$ decay rate was found to be extremely sensitive both to the wave function and to the $M1$ effective operator.

PACS. 21.10.Tg Lifetimes – 23.40.-s β decay; double β decay; electron and muon capture – 21.60.Cs Shell model – 27.60.+j $90 \leq A \leq 149$

1 Introduction

The vigorous exploration of exotic nuclei is driven by theoretical studies (see, for example, ref. [1]), which predict a vastly different shell structure for very neutron-rich medium-heavy nuclei than the one established along the line of stability. These effects, attributed to the weakly bound neutrons forming a cloud surrounding the nuclear core, are expected to occur at very heavy neutron excess close to the neutron drip line, thus in regions that are not accessible to experiments yet. However, limited effects related to specific orbits, precursors of the major effects, perhaps could be observed at a smaller neutron excess. Of particular interest are relative shifts in specific neutron or proton orbits as a function of the neutron number.

Our study is focussed on ^{135}Sb, for which experimental results have been puzzling. ^{135}Sb is a perfect case for a critical evaluation of experimental data. It is very neutron rich, having 12 extra neutrons above stable ^{123}Sb, and at the same time it represents a very simple nuclear system located just above doubly magic ^{132}Sn and thus well suited to test the shell model predictions with high precision. The nucleus ^{135}Sb has a pair of neutrons and one proton above ^{132}Sn and represents the most exotic nucleus beyond ^{132}Sn for which substantial information exists on the excited states.

The first spectroscopic information on levels in ^{135}Sb came from the prompt fission study [2] where three excited states originating from the $\pi g_{7/2}\nu f_{7/2}^2$ configuration were identified at 707, 1118 and 1343 keV and given spin/parity assignments of $11/2^+$, $15/2^+$ and $19/2^+$. The energies of these states are close to those of the 2^+, 4^+ and 6^+ states of mainly $\nu f_{7/2}^2$ configuration [3] in ^{134}Sn, see fig. 1. In a recent study by Korgul *et al.* [4] performed at the OSIRIS separator, the first excited state in ^{135}Sb was located at an exceptionally low excitation energy of 282 keV. This result has been confirmed by Shergur *et al.* in their two subsequent studies [5,6] performed at the ISOLDE facil-

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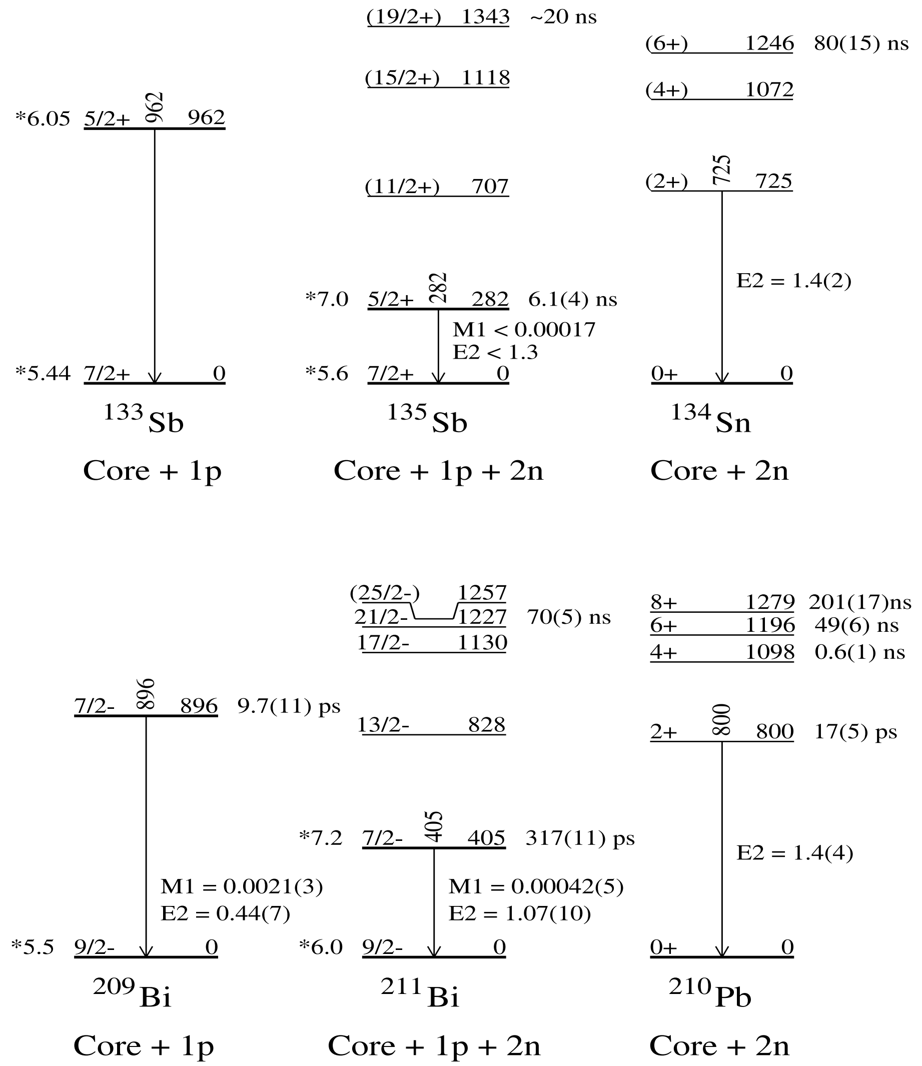

Fig. 1. Partial summary of the experimentally known [2–4, 6–10] properties of simple nuclear systems above ^{132}Sn (top) and ^{208}Pb (bottom): "Core+1 proton", "Core+2 neutrons" and "Core+1 proton+2 neutrons". Level half-lives are indicated to the right of the level, while $\log ft$ values from β decay of the parent are to the left marked by an asterisk (*). $M1$ and $E2$ represent experimental $B(M1)$ and $B(E2)$ values expressed in W.u. transition rates for ^{135}Sb are from this work.

ity that extended the information on ^{135}Sb. In [5] they reported exceptionally low $\log ft$ values to the ground and the 282 keV states with $\log ft = 5.63$ and 6.15, respectively. Both values are almost identical to those for the β decay of ^{133}Sn [7], where we expect pure single-particle configurations involved, namely the proton $g_{7/2}$ and $d_{5/2}$ states in ^{133}Sb populated in the β decay of $f_{7/2}$ neutron. This would imply that the dominant configuration for the 282 keV state in ^{135}Sb is the single-particle $d_{5/2}$ proton coupled to the ^{134}Sn core. However, determination of its $\log ft$ value critically depends on the intensities of transitions feeding the 282 keV state from above. We note a substantial difference for the relative intensity of the strongest transition feeding the state, the 732 keV line, for which 41(5) is given in [4] and 26(4) in [5]. The second work [6] corrects the β feeding to the 282 keV state now found almost eight times smaller than in [5] yielding $\log ft = 7.01$. The new intensity for the 732 keV line, 37(2), is now in agreement with our previous work [4]. The new $\log ft$ value is comparable to that for an equivalent transition in ^{211}Bi, see fig. 1, and implies a significant configuration mixing for the 282 keV state.

In order to understand the origin of the exceptionally low excitation energy of the $5/2^+$ state in ^{135}Sb, systematics of the lowest-lying $5/2^+$ states in the odd-proton nuclei near ^{132}Sn have been examined and shell model calculations were performed [5]. It was concluded [5] that the likely cause is a more diffuse nuclear surface that changes the relative binding energies of low-spin orbitals when compared to those of higher spin. By lowering of the single-particle proton $d_{5/2}$ state by 300 keV [5] a better fit for that level is obtained without disturbing the otherwise excellent agreement between theory and experiment. This conclusion was further supported in the second paper by the same authors [6], where additional excited states were identified in ^{135}Sb. The spin/parity assignments to

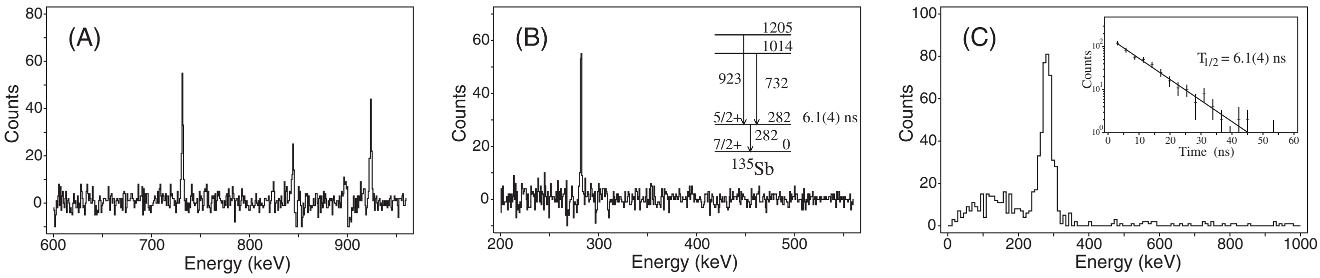

Fig. 2. (A) Part of γ-ray energy spectrum taken from $\beta\gamma\gamma$ coincidences involving two Ge detectors and gated by the 282 keV transition. The coincident γ-rays of energy 732 and 923 keV feed the 282 keV state from above. Compton-scattered peaks, with characteristic positive and negative contributions, are at energies of ~ 850 and ~ 900 keV. (B) Part of γ-ray energy spectrum gated by the 732 keV transition. The coincident γ-ray of energy 282 keV de-excites the 282 keV state. Insert: a partial level scheme of ^{135}Sb from the β decay of ^{135}Sn [4]. (C) BaF_2 sum spectrum in coincidence with the 732 and 923 keV transitions observed in Ge detectors. It shows full-energy γ-ray peak at 282 keV. Insert: time-delayed $\beta\gamma\gamma(t)$ spectrum due to the 282 keV level in ^{135}Sb selected outside of the prompt region. Fitting its slope yields the half-life of the 282 level, $T_{1/2} = 6.1(4)$ ns.

the new states are tentative [6] and largely based on the assumption that the observed γ-rays are fast $M1$ transitions, which face no competition from $E2$'s assumed to be slow. However, this is not assured as strongly hindered $M1$ transitions may also be present.

The interesting and controversial idea [5] that the location of the $5/2^+$ state in ^{135}Sb is related to a strong relative shift between the proton $d_{5/2}$ and $g_{7/2}$ orbits just above ^{132}Sn, due to the neutron diffuseness, can be examined via combined experimental and theoretical studies. Yet, little experimental data exist on nuclei with a few valence nucleons just above ^{132}Sn. The aim of our study was to measure the lifetime of this anomalously low-lying $5/2^+$ state in ^{135}Sb. Figure 1 illustrates the experimental situation near ^{135}Sb, which can be represented as one proton and two neutrons coupled to the core of ^{132}Sn, and of ^{211}Bi, which is an equivalent nucleus above the core of ^{208}Pb. In a naive expectation, since the $M1$ transition is forbidden between the $d_{5/2}$ and $g_{7/2}$ single-particle states and the $E2$ collectivity is small in a weakly deformed nucleus, one would expect for the 282 keV state in ^{135}Sb a very retarded $B(M1)$ rate, equivalent to the ^{211}Bi case, if there is a shift of the orbits, and a considerably faster one if the lowering of the state is due to collective effects. The experimental and theoretical results presented here supersede our preliminary reports [11,12].

2 Experimental procedures and results

Measurements were performed at the, now closed, OSIRIS fission-product mass separator at Studsvik in Sweden. The levels in ^{135}Sb were populated in the β^- decay of ^{135}Sn. The activity of Sn was produced from thermal neutron-induced fission of ^{235}U in the ANUBIS integrated target-ion source. The mass separated $A = 135$ beam was deposited onto an aluminized Mylar tape of a moving-tape system in the center of an experimental station. The source was dominated by the longer-lived activities from the decays of ^{135}Sb, ^{135}Te, ^{135}I and ^{135}Xe. In order to enhance detection of the short-lived activities due to ^{135}Sn, $T_{1/2} = 0.6(1)$ s, which represented about 1% of the total, the measurement was made in cycles. During the first 1.4 s the activities were collected on the tape. Then the beam was deflected and the source was let to decay out during the next 1.4 s. Finally, the old activity was moved away and a new cycle was started. Data collected during the first 2.1 s were analyzed off-line.

The lifetime of the 282 keV state in ^{135}Sb was measured using the advanced time-delayed $\beta\gamma\gamma(t)$ method [13]. Fast-response β and BaF_2 γ detectors, which provided lifetime information, as well as two Ge detectors, which allowed for the selection of γ cascades in the β decay of interest, were positioned in a close geometry at the beam deposition point. The $\beta\gamma\gamma(t)$ coincidences were collected involving β-Ge-Ge or β-BaF_2-Ge detectors. In the first step the $\beta\gamma\gamma$ coincidence energy spectra collected in the two Ge detectors were sorted out using a broad gate on the β energy spectrum. Figure 2 shows coincidence energy spectra. By selecting in Ge the 723 keV and 923 keV γ-rays (fig. 2B) feeding the 282 keV state from above and selecting a very strong and pure 282 keV peak in the coincident BaF_2 spectrum (fig. 2C), one obtains the time-delayed $\beta\gamma\gamma(t)$ spectrum due to the lifetime of the 282 keV state in ^{135}Sb (see insert to fig. 2C). It was verified independently that the feeding γ transitions do not carry any time-delayed components, which could affect fitting of the slope. They de-excite levels with $T_{1/2} \leq 66$ ps on the average.

The lifetime of the 282 keV level was measured as $T_{1/2} = 6.1(4)$ ns. Since the $M1/E2$ mixing ratio for the transition is unknown, we deduce upper limits for the $B(M1)$ and $B(E2)$ rates by assuming either a pure $M1$ or a pure $E2$ transition. One obtains strongly hindered $B(M1)$ and slow $B(E2)$ values, which are almost identical to the equivalent case in ^{211}Bi, see fig. 1, although the $B(M1)$ in ^{135}Sb is even lower than in ^{211}Bi.

3 Theoretical interpretation

Table 1 provides a comparison of the experimental $B(M1)$ and $B(E2)$ values to the shell model calculations by

Table 1. Comparison of the experimental $B(M1)$ and $B(E2)$ values and shell model calculations by Brown (B) and Covello and Gargano (CG) for the 282 keV $5/2^+ \to 7/2^+$ transition in ^{135}Sb, in units of 10^{-3} μ_N^2 and e^2fm^4, respectively

	exp	$\mathrm{B}^{\mathrm{th}}_{\mathrm{free}}$	$\mathrm{B}^{\mathrm{th}}_{\mathrm{eff}}$	$\mathrm{B}^{\mathrm{th}}_{\mathrm{eff\text{-}sh}}$	$\mathrm{CG}^{\mathrm{th}}_{\mathrm{free}}$	$\mathrm{CG}^{\mathrm{th}}_{\mathrm{eff}}$
$B(M1)$	≤ 0.30	13	0.34	2.2	25	4.0
$B(E2)$	≤ 54		23	23		32

Covello and Gargano (CG) and by Brown (B). Both calculations assume ^{132}Sn as a closed core with $(0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $0h_{11/2})^{Z-50}$ and $(0h_{9/2}$, $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $0i_{13/2})^{N-82}$ configurations for valence protons and neutrons, respectively.

In the Covello-Gargano calculation the two-body matrix elements of the effective interaction are derived from the CD-Bonn nucleon-nucleon (NN) potential [14]. The short-range repulsion of the latter is renormalized by constructing a low-momentum potential $V_{\text{low-}k}$ [15], which is then employed to derive the effective interaction within the framework of the $\hat{Q}$-box plus folded-diagram method [16]. Diagrams up to second order in $V_{\text{low-}k}$ are included in the $\hat{Q}$ box and their computation is performed within the harmonic-oscillator basis using intermediate states composed of all possible hole states and particle states restricted to five shells above the Fermi surface. The oscillator parameter is $\hbar\omega = 7.88$ MeV and the Coulomb force between protons is explicitly added to the $V_{\text{low-}k}$ potential. The proton and neutron single-particle energies are taken from the experimental spectra of ^{133}Sb and ^{133}Sn, respectively. The misssing experimental energies of the proton $s_{1/2}$ and neutron $i_{13/2}$ level are taken from refs. [17] and [18], respectively.

The results of this calculation are presented in detail in ref. [19]. Here, only the first excited $5/2^+$ state and its decay properties to the $7/2^+$ ground state are considered. A rather pure wave function is predicted for the latter state, the percentage of the dominant configuration $\pi g_{7/2}(\nu f_{7/2})^2$ being 75%. The $5/2^+$ state is predicted at 382 keV, only 100 keV above the experimental value. It is significantly admixed, with the first two leading terms 45% $\pi d_{5/2}(\nu f_{7/2})^2$ and 23% $\pi g_{7/2}(\nu f_{7/2})^2$.

The $B(M1; 5/2^+ \to 7/2^+)$ transition rate calculated with the free g factors is $25 \times 10^{-3}\, \mu_N^2$, which is about 100 times larger than the experimental limit. However, by using an effective $M1$ operator, which includes first-order diagrams in $V_{\text{low-}k}$, this $B(M1)$ becomes $4.0 \times 10^{-3}\, \mu_N^2$ and the discrepancy with experiment is reduced by about an order of magnitude. This is due to the fact that the effective operator has a non-zero off-diagonal matrix element between the $d_{5/2}$ and $g_{7/2}$ proton states which is opposite in sign to the diagonal $g_{7/2}$ matrix element. As a consequence, both components of the $5/2^+$ state may contribute to the $B(M1)$ value and these contributions partially compensate one another. The balance between these two contributions is very sensitive to small changes in the wave functions of the involved states and/or in the effective $M1$ operator. Based on these remarks, the CG result may be considered satisfactory, the more so as no meson exchange correction has been taken into account. For the $B(E2; 5/2^+ \to 7/2^+)$, using an effective proton charge of $1.55e$ [17] and a neutron charge of $0.70e$ [18], a value of $32\, e^2\mathrm{fm}^4$ is obtained in agreement with experiment.

In the CG calculation the peculiar features of the $5/2^+$ state arise from the admixed nature of this state. Why an admixed wave function is favored with respect to an essentially pure seniority-one state, as expected from the systematics of the odd Sb isotopes, is discussed in detail in ref. [19], where the role of the effective interaction as well as of the $5/2^+$ single-proton energy in determining this situation is examined. It is worth mentioning that the same Hamiltonian used in the CG calculation for ^{135}Sb has produced very good results also for ^{134}Sn [20] and ^{134}Sb [21], leading to a consistent description of ^{132}Sn neighbors beyond the $N = 82$ shell. In particular, the low-lying first-excited 2^+ state in ^{134}Sn and the observed members of the $\pi g_{7/2}\nu f_{7/2}$ and $\pi d_{5/2}\nu f_{7/2}$ multiplets in ^{134}Sb are very well reproduced. In regard to the neutron-proton effective interaction, in ref. [21] the key importance of the renormalizations which account for the configurations left out of the chosen model space has been evidenced. In this connection, it should be noted that in preliminary calculations, using an effective interaction derived with a reduced number of intermediate states in the $\hat{Q}$-box diagrams, the energies of the first-excited 1^- state in ^{134}Sb [21] and $5/2^+$ state in ^{135}Sb [11,12] were both overestimated.

In the Brown calculation derivation of the two-body matrix elements was obtained with the CD-Bonn-96 NN interaction [22] as described in [23]. The $M1$ operator is given by $\boldsymbol{\mu}_{\mathrm{eff}} = g_{l,\mathrm{eff}}\mathbf{l} + g_{s,\mathrm{eff}}\mathbf{s} + g_{p,\mathrm{eff}}[Y_2, \mathbf{s}]$. The values of g_{eff} given by table VI of [23] were obtained in perturbation theory and include first-order core polarization, higher-order core polarization and mesonic exchange current corrections as discussed in [23]. The $B(M1)$ values are given below in units of 10^{-3} μ_N^2 and expressed in the form $B(M1) = (A+B)^2$ where A is the contribution from the spin and orbital operators and B is the contribution from the tensor operator $g_{p,\mathrm{eff}}[Y_2, \mathbf{s}]$. This tensor operator gives the non-zero off-diagonal (ℓ-forbidden) matrix element between $d_{5/2}$ and $g_{7/2}$ discussed in connection with the CG results (where the mesonic-exchange currents were not included in the CG effective operator). The importance of the effective operator is observed in the magnetic moment of the $g_{7/2}$ single-particle ground state of ^{133}Sb with an experimental value of $3.00(1)\, \mu_N$ compared to the free-nucleon value of 1.717 and effective operator values of 2.824 (Brown) and 2.5 (CG). For a pure single-particle $d_{5/2}$ to $g_{7/2}$ transition that would apply to ^{133}Sb we obtain $B(M1)_{\mathrm{free}} = (0+0)^2 = 0$ and $B(M1)_{\mathrm{eff}} = (0+5.3)^2 = 28$.

The spectroscopic factors for adding a proton to ^{134}Sn ground state are 0.69 and 0.50 for the lowest $7/2^+$ and $5/2^+$, respectively, with the remaining strength split over many states up to about 2 MeV in excitation. For the $5/2^+$ to $7/2^+$ transition in ^{135}Sb we obtain $B(M1)_{\mathrm{free}} = (3.6 + 0)^2 = 13$ and $B(M1)_{\mathrm{eff}} = (5.4 - 4.8)^2 = 0.34$, with the effective-operator result being consistent with the experimental limit. The small value for the $B(M1)$ is due to cancellation between the spin plus orbital operators and the tensor operator. The $B(E2)$ obtained with SKX [23] Hartree-Fock radial wave functions and effective charges of $e_p = 1.5$ and $e_n = 0.6$ is $23\, e^2\,\mathrm{fm}^4$. The effective charges are chosen to reproduce the experimental $B(E2)$ values in ^{134}Te and ^{134}Sn. The calculated $B(E2)$ is consistent with the experimental limit for ^{135}Sb.

The excitation energy of 528 keV for the $5/2^+$ state is about 250 keV higher than the experimental value. In [5] calculations were also performed with the $d_{5/2}$ single-particle state shifted down by 300 keV. With this shift the $5/2^+$ state comes at 316 keV in better agreement with experiment. It was suggested in [5] that this shift which is observed in Hartree-Fock calculations (see fig. 16 in [5]) is not present in the CD-Bonn G-matrix, perhaps because the G-matrix is obtained with oscillator radial wave functions. Another reason may be three-body forces that are empirically contained in Hartree-Fock. The spectroscopic factors for adding a proton to the ^{134}Sn ground state are 0.69 and 0.58, respectively, for $7/2^+$ and $5/2^+$. With the $d_{5/2}$ shift the $5/2^+$ excited state becomes a little more single particle in character.

With the $d_{5/2}$ shift the electromagnetic results are $B(M1)_{\text{free-sh}} = (2.2 + 0)^2 = 4.8$, $B(M1)_{\text{eff-sh}} = (3.5 - 5.0)^2 = 2.2$ and $B(E2) = 23\, e^2\,\mathrm{fm}^4$. The effective-operator $M1$ result is ten times larger than experiment. However, due to the cancellation, the $B(M1)$ is very sensitive to details. Agreement with the experimental value could be obtained by changing $g_{p,\text{eff}}$ from its value of 3.21 in table VI of [23] to 2.6 or 1.7. The results for the single-particle $d_{5/2}$ to $g_{7/2}$ transition are $B(M1) = 23$ ($g_{p,\text{eff}} = 2.6$) are $B(M1) = 7.8$ ($g_{p,\text{eff}} = 1.7$). This is not yet measured in ^{133}Sb, but there is a similar l-forbidden $f_{7/2}$ to $h_{9/2}$ transition in ^{209}Bi for which we obtain $B(M1) = 22$ ($g_{p,\text{eff}} = 3.2$), $B(M1) = 16$ ($g_{p,\text{eff}} = 2.7$) and $B(M1) = 6.2$ ($g_{p,\text{eff}} = 1.7$), to be compared to the experimental value of 3.8(6). Thus, the overall agreement for l-forbidden $M1$ transitions in the ^{132}Sn and ^{208}Pb regions appears to require $g_{p,\text{eff}} \approx 1.7$.

4 Conclusions

We have measured the lifetime of the 282 keV level in ^{135}Sb, which yields restrictive limits on transition rates and imply very retarded $M1$ and noncollective $E2$ transition. These values were analysed within shell model calculations. We have shown that the $M1$ decay rate is extremely sensitive both to the wave function and to the $M1$ effective operator. More information, especially on the $M1$ matrix elements, on nuclei like ^{133}Sb, ^{135,137}I as well as ^{135}Sb is needed to clarify the situation.

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