EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-INTC-2006-003
INTC-P-201
17^{th} of January, 2006

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Ultra Fast Timing Measurements at ^{78}Ni and ^{132}Sn

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Abstract

We propose to measure level lifetimes in the exotic nuclei of ^{81}Ga and ^{80}Ga in the vicinity of ^{78}Ni and of ^{135}Sb and ^{134}Sb above ^{132}Sn by the time-delayed technique. These are relatively simple nuclear systems with a few particles and/or holes outside of the doubly-magic core thus can be treated rather precisely within the shell model. The anticipated new structure information on these nuclei, and in particular the lifetime results will put constrains on the model parameters and will serve to verify their predictions. The selected nuclei are some of the most exotic ones just above ^{78}Ni or ^{132}Sn, where the transition rates can be studied at present. Of the strongest interest is the nucleus of ^{81}Ga, which has only 3 valence protons outside of ^{78}Ni with the lowest proton orbits being $p_{3/2}$ and $f_{5/2}$. The M1 transition between these states, although allowed by the selection rules, should be l-forbidden thus very slow. This should give raise to a lifetime in the subnanosecond to nanosecond range. Similarly slow l-forbidden M1 transitions, between proton $d_{5/2}$ and $g_{7/2}$ orbits are studied by us in the odd-proton systems above ^{132}Sn, namely in ^{135}Sb and ^{137}I. The proposed studies on ^{80}Ga, ^{81}Ga, ^{134}Sb and ^{135}Sb are intended to complement our fast timing measurements in these regions, with several ongoing projects from data obtained at the OSIRIS facility at Studsvik. Moreover, they are complementary to other experimental studies in these regions performed at ISOLDE using advanced techniques.

For this project we ask for 20 shifts of radioactive beam to study the decay of ^{81}Zn to ^{81}Ga (5 shifts), ^{80}Zn to ^{80}Ga (3 shifts), ^{134}Sn to ^{134}Sb (3 shifts) and ^{135}Sn to ^{135}Sb (5 shifts), with additional 2 shifts for the time-response calibrations of the fast timing scintillators using the beams of ^{138}Cs and ^{88}Rb. In addition we ask for 2 shifts of radioactive beam for fine tuning of the HRS mass selection and the HRS slits prior to the Sn runs.

1. Introduction

The Ultra Fast Timing measurements on the neutron-rich nuclei have provided key information that did allow for a clear interpretation of the observed low-energy structure for a number of exotic nuclei. It is a well established technique at ISOLDE. These measurements are complementary to the direct in-beam lifetime measurements, Coulomb excitations, hyperfine interactions and beta-, gamma- or beta-delayed neutron spectroscopy. Most of these techniques are employed in the region of the doubly magic ^{78}Ni and ^{132}Sn at ISOLDE, with a number of current projects like: IS412, IS415, IS421, IS428, IS434, IS439. Due to the scarcity of information on the most exotic nuclei, any new information that can be provided by any of these techniques is of substantial importance. One should note that the research program at ISOLDE is very vigorous in these regions thanks to the unique beam capabilities of the ISOLDE sources and a steady improvement in the extraction techniques.

There is an extraordinary strong world-wide interest in the spectroscopy of the exotic nuclei near doubly magic ^{78}Ni and ^{132}Sn with many ongoing or planned activities. The aim of these projects is to understand the evolution of the shell orbits in exotic nuclei, to identify the impact of heavy neutron excess on nuclear structure, and to critically test the theoretical models, including the shell model. These issues are well described in various publications, thus one would concentrate here on a few selected aspects on which the proposed project is expected to make an impact.

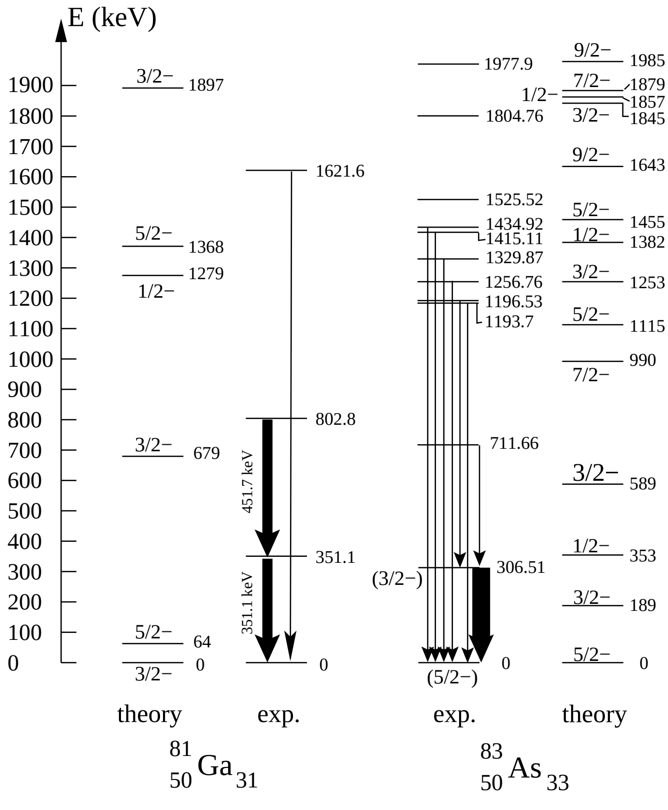

Figure 1: Tentative experimental level scheme for ^{81}Ga obtained recently at the PARRNe facility [1] compared with ^{83}As and the shell model calculations of Ji and Wildenthal [2]; this figure is taken from ref. [1].

2. ^{81}Ga

^{81}Ga is the closest odd-A nucleus to ^{78}Ni, for which the structure of the excited states can be studied. It has only three valence protons, expected to be in the $p_{3/2}$ and $f_{5/2}$ orbits, outside of the ^{78}Ni core. Until recently there was no information on the excited states in ^{81}Ga. Recently, however, in a study performed at the PARRNe facility in Orsay [1] the first evidence came for the two excited states at 351.1 and 802.8 keV respectively, see fig. 1.

Listed below is Table II copied from reference [2], which shows the results of the shell model calculations by Ji and Wildenthal [2] for ^{81}Ga. One notes a close-lying $3/2^-$ and $5/2^-$ ground state doublet, with the $5/2^-$ state located 64 keV above the $3/2^-$ ground state. The authors note that the occupation numbers show that the lowest $3/2^-$ state is basically a seniority-three $(f_{5/2})^3$ state, while the $p_{3/2}$ one-quasiparticle state is at 679 keV. Clearly there are significant differences between the shell model predictions and the observed structure. One possibility is that there could be other low-lying levels which population is weaker in the beta decay of ^{81}Zn. If such is the case, these are likely to be revealed in an experiment with much higher statistics.

TABLE II. States of ^{81}Ga: Calculated excitation energies (th) and occupation numbers. The index n refers to the first (1), second (2), state of a given value of J^π.

J^π	n	Energy (keV) th	Occupation of orbit j^π ($\times 100$) $j^\pi = \frac{5}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{9}{2}^+$
$\frac{3}{2}^-$	1	0	274	7	19	0
$\frac{5}{2}^-$	1	64	256	29	14	1
$\frac{3}{2}^-$	2	679	186	104	11	0
$\frac{1}{2}^-$	1	1279	172	118	11	0
$\frac{5}{2}^-$	2	1368	185	96	18	1
$\frac{3}{2}^-$	3	1897	181	102	16	0
$\frac{5}{2}^-$	3	2009	159	135	5	1
$\frac{2}{2}^-$	2	2134	183	18	99	0
$\frac{5}{2}^-$	4	3101	194	29	78	0
$\frac{3}{2}^-$	4	3105	119	155	25	1
$\frac{1}{2}^-$	3	3887	100	152	48	1
$\frac{9}{2}^+$	1	4243	185	9	5	101

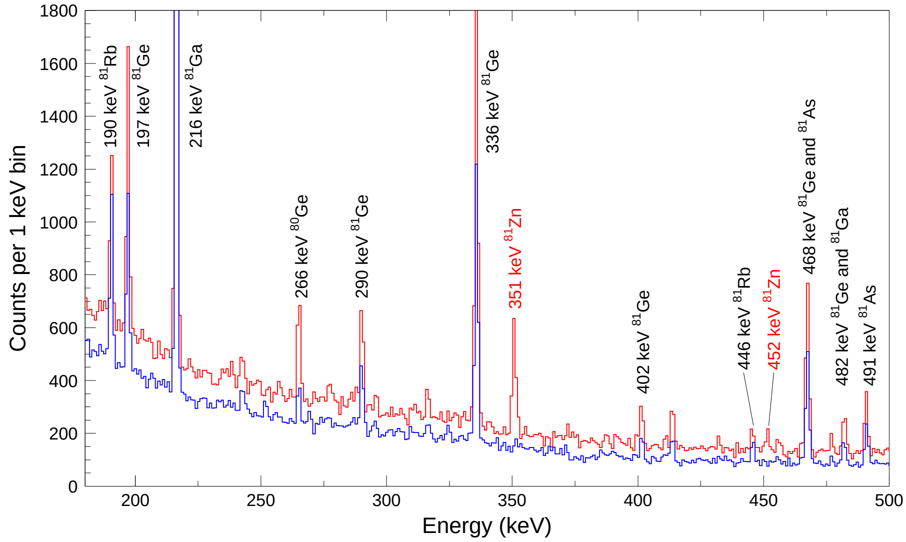

Figure 2: Part of gamma-ray spectrum measured [3] at ISOLDE on mass 81 in the 'laser on' (red) and 'laser off' (blue) mode, respectively, showing two peaks due to the 351 and 452 keV lines in ^{81}Ga. The measurement was performed using the fast timing station at ISOLDE in the summer of 2004. This very high statistics was obtained over only 5 min of data collection with no gating and no movement of the tape. This figure is taken from [3].

In the last few years, there were new advances in the extraction of exotic beams of the neutron-rich Zn isotopes at ISOLDE, including the beams of ^{80}Zn and ^{81}Zn. Some details of this development are discussed by Köster and collaborators in ref. [3]. Figure 2 shows part of the gamma ray spectrum collected at the fast timing station in the summer of 2004 over only 5 min of run. Note a strong peak-to-background ratio for the two lines in ^{81}Ga although there was no beta gating nor any periodic movement of the tape to suppress the longer-lived activities.

Spectra shown in fig. 2 clearly indicate the capability to perform high sensitivity measurements on ^{81}Ga at ISOLDE. Since the fast timing setup includes two Ge detectors, two scintillators (we plan to use $LaBr_3$(Ce)) and a beta-detector, therefore with the expected statistics, one would not only obtain in one measurement high quality multi-spectrum scaling gamma-ray spectra, gamma-gamma coincidences using Ge detectors but also level-lifetimes via the time-delayed $\beta\gamma\gamma$(t) method [4,5,6]. Of particular interest to us would be the transition rates between the low-lying levels, which would be measurable due to the energy factor alone. On the other hand, if the 351 keV state is the lowest one, it could have a long lifetime if the 351-keV transition is E2 or alternatively if it is l-forbidden M1 transition between the proton $p_{3/2}$ and $f_{5/2}$ configurations. Complementary fast timing measurements on exotic nuclei in this region have been performed at the OSIRIS fission-product mass separator at Studsvik before it was closed down in 2005. In particular, current analysis involves the data on ^{80}Ge, ^{83}As and ^{84}Se.

3. ^{80}Ga

^{80}Zn and the decay of ^{80}Zn to ^{80}Ga is of interest not only to nuclear structure physics but also to astrophysics as ^{80}Zn is the waiting point nucleus. This decay has been studied in very difficult experimental conditions at the TRISTAN facility at BNL [7]. A rather complex decay scheme was obtained, which is shown in fig. 3.

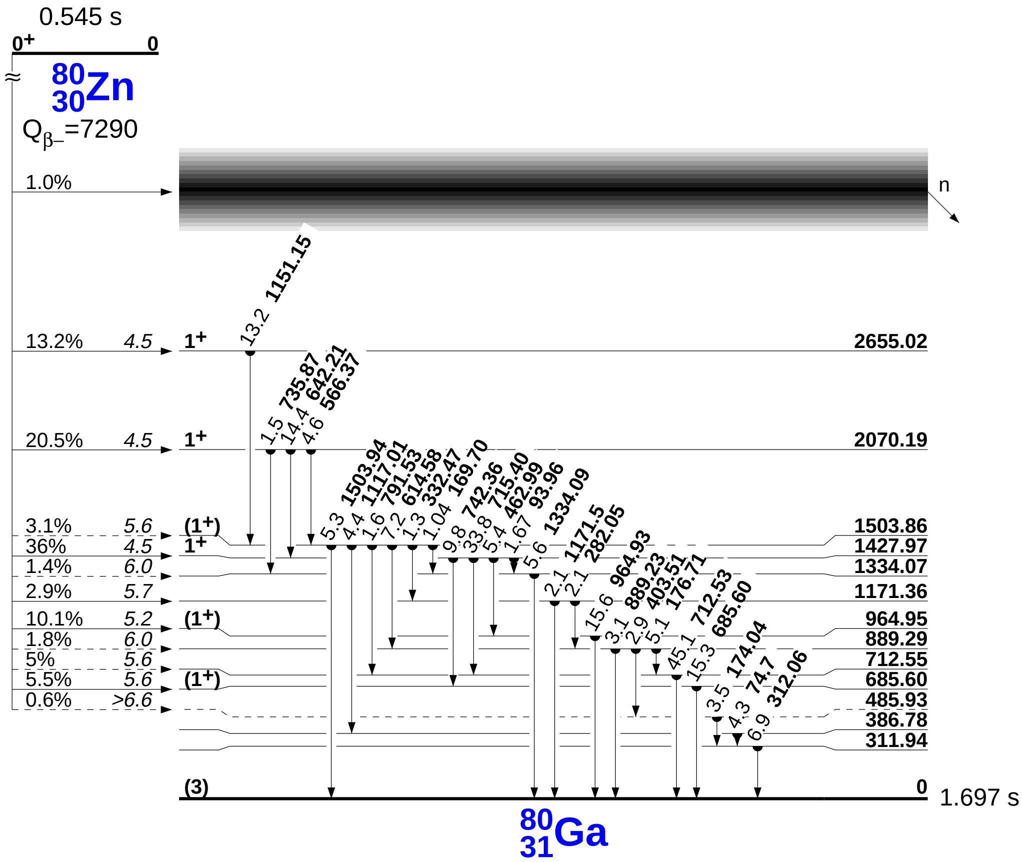

Figure 3: Level scheme in ^{80}Ga observed [7] in the beta decay of ^{80}Zn. Large number of low-energy transitions de-exciting levels, likely imply lifetimes in the nanosecond and subnanosecond range.

The re-measurement of this beta decay is of interest in order to improve the knowledge of the level scheme in ^{80}Ga, but also to learn more about the beta-delayed neutron emitters in A=81 that will be measured in the first part of this proposal (via gamma spectroscopy). Thus beta-decay studies of ^{81}Zn and ^{80}Zn are interlinked and should be done together.

Lifetime measurements are expected to play a major role in the structure interpretation of ^{80}Ga. This can be seen from the decay scheme illustrated in fig. 3, where many levels have low energy transitions as either the dominant or the only decay channel. One should also note that based on the data collected by us at OSIRIS, there is evidence that there are more than one beta-decaying isomers in ^{80}Ga. This issue perhaps could also be addressed in this study since the high- and low-spin isomers of ^{80}Ga will be differently populated in the laser-on and laser-off modes.

4. ^{135}Sb

The fast timing studies of ^{134}Sb and ^{135}Sb, populated in the beta decay of ^{134}Sn and ^{135}Sn, respectively, are also closely linked. Our main objective is to measure the lifetimes of the low-lying states in ^{135}Sb. In a recent study, see the paper by Korgul et al., attached as Addendum I to this proposal, we have measured the l-forbidden M1 transition in ^{135}Sb linking the proton $d_{5/2}$ and $g_{7/2}$ states. We follow the systematics of the low-lying 5/2+ and 7/2+ states in the neighbouring odd-proton nuclei of ^{133}Sb, ^{135}I and ^{137}I using the recently performed fast timing measurements at OSIRIS (these studies are in progress). As discussed in Appendix I, ^{135}Sb offers at present challenging results to the shell model interpretation and clearly more data, particularly on other transitions is ^{135}Sb, are strongly needed. The beam intensities available at ISOLDE would certainly make this task possible.

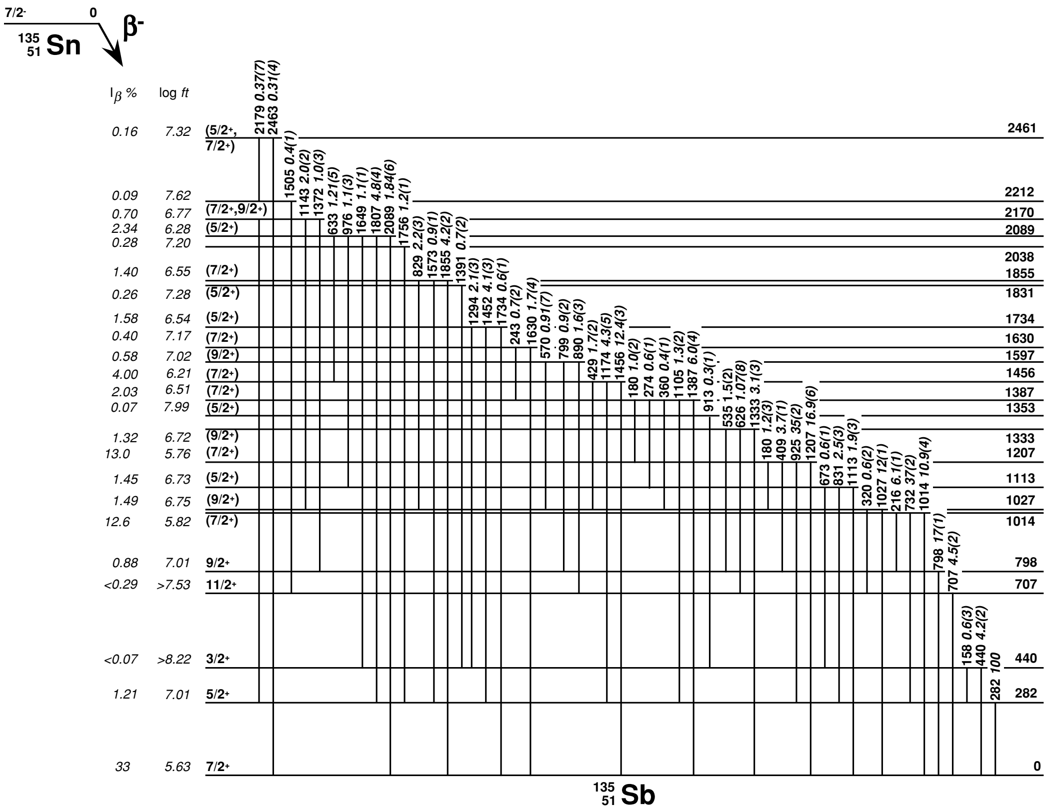

Figure 4: Level scheme in ^{135}Sb observed [8] in the beta decay of ^{135}Sn.

A detailed level scheme of ^{135}Sb populated in the beta decay of ^{135}Sn has been recently reported by Shergur et al.,[8] from a study performed ISOLDE, see fig. 4. Due to a number of low-lying states, and expected slow E2 transitions, the fast timing results would provide strong test of the proposed spin/parities assignments. One should keep in mind that this is the most exotic nucleus to the (north-)east of ^{132}Sn on which so much data exists.

5. ^{134}Sb

Very interesting information on the beta-delayed neutron decay of ^{135}Sn into ^{134}Sb was reported by Shergur et al., [9], see fig. 5. In particular, they have reported on candidates for the high spin members of the ($\pi g_{7/2} \nu f_{7/2}$) multiplet, which includes the 0^- ground state and a higher-lying 7^- isomer in ^{134}Sb. The latter one is of strong interest in order to define the excitation energy of the neutron single particle $i_{13/2}$ orbit in ^{133}Sn. Since some of these states should have lifetimes in the nanosecond range, there is a good chance that their lifetime would be measured despite their weak population in the decay. A separate measurement of the level lifetimes in ^{134}Sb populated in the beta decay of ^{134}Sn is necessary here. The level lifetimes of the low-spin members of the multiplet in this one-proton-one-neutron system above ^{132}Sn are also of strong interest.

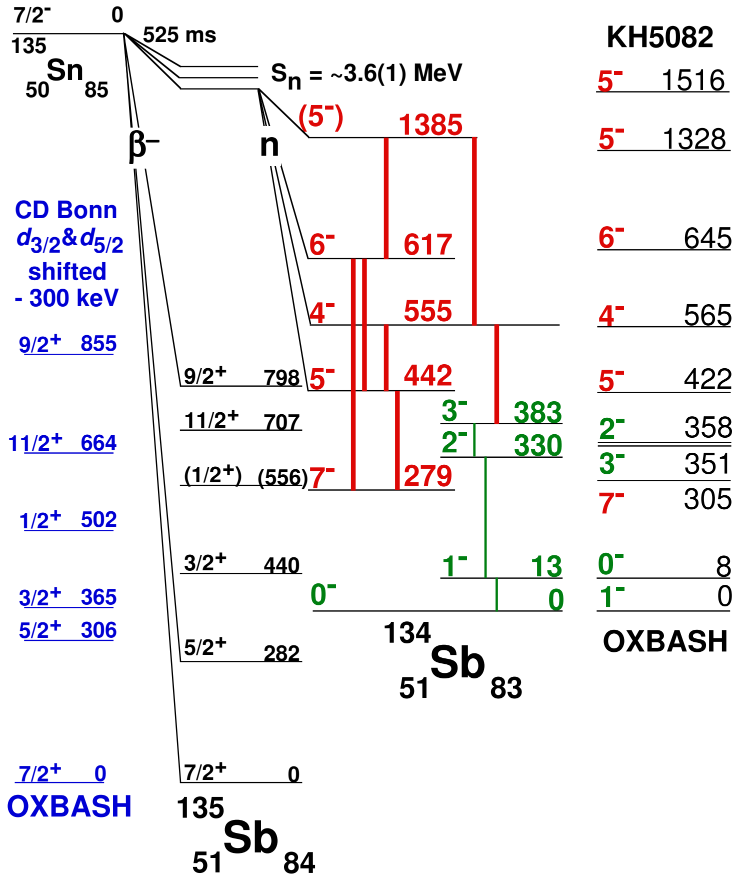

Figure 5: Population of the 'missing' levels in ^{134}Sb from the beta-delayed neutron emission of ^{135}Sn [9]; figure is taken from ref. [9].

6. Proposed Experiments: Technical Details

The Advanced Time-Delayed (ATD) $\beta\gamma\gamma$(t) spectroscopy [4,5,6] provides means to probe selected properties of the exited states populated in β-decay. Using an array of five detectors, of which three are fast response units, namely a β- and two fast $LaBr_3$(Ce)-detectors, and two large Ge detectors, one obtains basically two types of information. From the Ge-Ge $\gamma\gamma$ coincidences one constructs the decay scheme while from the time-delayed $\beta\gamma\gamma$(t) coincidences one can determine lifetimes of the excited states in the nanosecond and subnanosecond ranges with the precision of about 1-2 ps in favourable cases. Our typical experimental setup is shown in fig. 6, which was used for studies of the decay of ^{229}Fr. The possibility to study conversion electrons in this mass region would be useful for the case of possible E0 transitions or multipolarities of the low-energy transitions. However, measurements of the conversion coefficients considered here as an opportunity only.

For the production of ^{80,81}Zn we request a standard UCx/graphite target with a converter unit in combination with the selective RILIS. We request the addition of a medium temperature quartz transfer line for the retention of isobaric Rb and Ga contaminants. The latter has been used online during 2005 and has proven to deliver pure Zn beams, with no measurable radioactive background and enough yield of ^{81}Zn to perform mass measurements.

For the production of ^{134,135}Sn isotopes we request the use of a UCx/graphite target and the ISOLDE RILIS. In order to limit the isobaric contaminants, in particular Cs, we request the target unit to be equipped with a neutron converter. For the fast timing experiments on Sb we request the HRS separator.

The fast timing detectors and electronics will be prepared in Uppsala, and will be provided by the Fast Timing Collaboration Pool of Electronics. Our collaboration will provide the Ge detectors, tape system and the Mini Orange spectrometer as well as the acquisition systems. Some of the long-lived sources for time-response calibrations will have to be irradiated at a separate station for the off-line measurements. We foresee the use of two beam lines: LA1 and LA2.

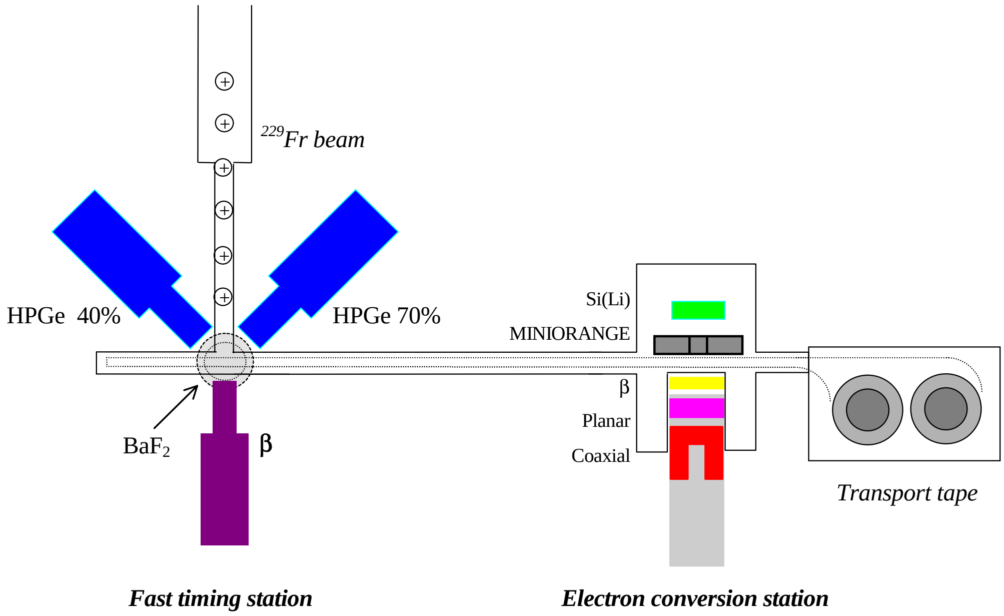

Figure 6: Typical setup of a Fast Timing experiment. The fast timing station at the beam deposition point includes five detectors: two Ge detectors and three fast response scintillators (one beta and two gamma detectors, like BaF_2 or $LaBr_3$(Ce)). The latter two are positioned below and above the horizontal plane facing the source. Connected by the tape transport system, is the conversion electron station, where a cooled Si(Li) detector for electrons and a Ge detector are set to measure conversion coeficients. Specific details refer to the IS386 setup used to study the decay of ^{229}Fr.

4. Summary of beam requests

In total, we request 20 shifts with radioactive beams.

Nucleus	# of shifts	Separator	Target	Ion source	Min.Intensity (cps)
^{80}Zn	3	GPS/HRS	UC	RILIS (+quartz)	400
^{81}Zn	5	GPS/HRS	UC	RILIS (+quartz)	200
^{134}Sn	3	HRS	UC	RILIS	1000
^{135}Sn	5	HRS	UC	RILIS	200
^{88}Rb	1	GPS/HRS	UC	SI	1x10^{4}
^{138}Cs	1	GPS/HRS	UC	SI	1x10^{5}
^{24}Na	0.1	GPS/HRS	UC	SI	1x10^{5}
HRS tuning (^{134,135}Sn)	2	HRS	UC	RILIS	
total radioactive	20				

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At the doorsteps to the *terra incognita* region of nuclear chart; the unusual properties of the 282 keV state in ^{135}Sb

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(Dated: November 22, 2005)

Recently the first excited state in ^{135}Sb has been observed at the 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. In order to provide more spectroscopic information on this anomalously low-lying $5/2^+$ state, we have measured its lifetime 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; $5/2^+_1 \rightarrow 7/2^+_1$) $\leq 3.0\times10^{-4}$ μ_N^2 and B(E2; $5/2^+_1 \rightarrow 7/2^+_1$) ≤ 54 e^2fm^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 are presented.

PACS numbers: 21.10-Tg, 23.40.-s, 21.60.Cs, 27.60.+j

The vigorous exploration of exotic nuclei is driven by theoretical studies [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 surronding the nuclear core are expected to occur at a very heavy neutron excess close to the neutron drip line. However, limited effects related to specific orbits, precursors of the major effects, perhaps could be observed at a smaller neutron excess. Our study is focussed on ^{135}Sb, for which new 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 $\pi g_{7/2}\nu f^2_{7/2}$ configuration were identified at 707, 1118 and 1343 keV and given spin/parity assignements 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 $\nu f^2_{7/2}$ 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 facility that extended the information on ^{135}Sb. In [5] they reported exceptionally low logft values to the ground and the 282 keV states with logft=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 logft 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 logft=7.01. The new intensity for the 732 keV line, 37(2), is now in agreement with our previous

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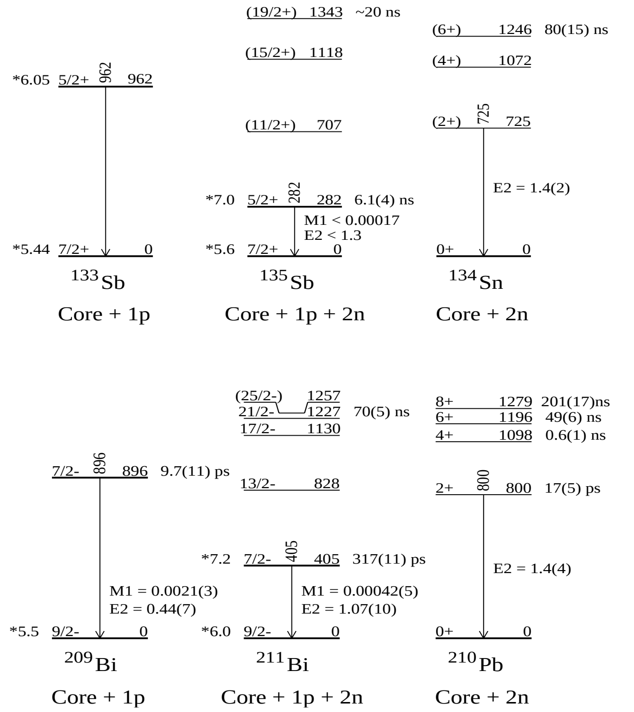

FIG. 1: Partial summary of the experimentally known [2–4, 6–10] properties of simple nuclear systems above ^{132}Sn (top) and ^{208}Pb (bottom): 'Core+1 proton', 'Core+2 neutrons' and 'Core+1 proton+2 neutrons'. Level half-lives are indicated to the right of the level, while logft values from β-decay 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.

work [4]. The new logft 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 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 principle, 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].

Measurements were performed at the OSIRIS fission-product mass separator located 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 spectra collected in the two Ge detectors were sorted out using a broad gate on the β energy spectrum. Figure 2 show 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 (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

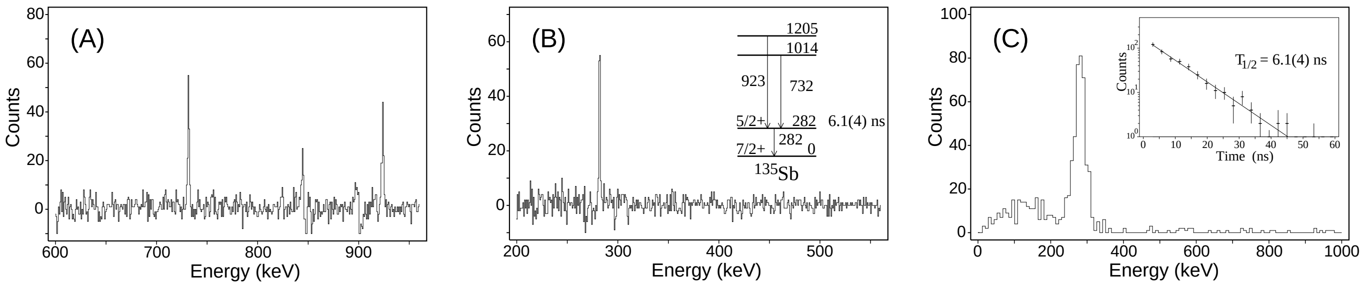

FIG. 2: **A:** part of γ-ray energy spectrum taken from $\beta\gamma\gamma$ coincidences involving two Ge detectors and gated by the 282 keV transition. The coincident γ rays of energy 732 and 923 keV feed the 282 keV state from above. Compton scattered peaks, with characteristic positive and negative contributions, are at the 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 as $T_{1/2}$=6.1(4) ns.

TABLE I: 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 $5/2^+ \rightarrow 7/2^+$ transition in ^{135}Sb, in the units of 10^{-3} μ_N^2 and $e^2 fm^4$, respectively

	exp	B^{th}_{free}	B^{th}_{eff}	B^{th}_{eff-sh}	CG^{th}_{free}	CG^{th}_{eff}
B(M1)	$\leq$ 0.30	13.3	0.34	2.1	25	4.0
B(E2)	$\leq$54		23	23		32

$T_{1/2}$=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 transitions. 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.

Table I provides a comparison of the experimental B(M1) and B(E2) values to the shell-model calculations by 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 $V_{\rm low-k}$ [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 $V_{\rm low-k}$ 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 three shells above the Fermi surface. The oscillator parameter is $\hbar\omega = 7.72$ MeV and the Coulomb force between protons is explicitly added to the $V_{\rm low-k}$ potential. The proton and neutron single-particle energies are taken from the experimental spectra of ^{133}Sb and ^{133}Sn, respectively. The missing 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], where attention is focused on the key role of the neutron-proton effective interaction in the description of the spectroscopic properties of ^{135}Sb. 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, predicted at 382 keV, 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 observed energy is overestimated by only 100 keV, while in preliminary calculations [11, 12] a 560 keV excitation energy was obtained. This is mainly because in [11, 12] a reduced number of intermediate states were used in the calculation of the $\hat{Q}$-box diagrams.

The B(M1; $5/2^+ \rightarrow 7/2^+$) 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 $V_{\rm low-k}$, 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. In the CG calculation no meson-exchange correction has been considered. For the

B(E2;$5/2^+ \rightarrow 7/2^+$), using an effective proton charge of 1.55e [17] and a neutron charge of 0.70e [18], a value of 32 e^2fm^4 is obtained in agreement with experiment.

In the Brown calculation derivation of the two-body matrix elements was obtained with the CD-Bonn-96 NN interaction [20] as described in [21]. The M1 operator is given by $\mu_{\rm eff} = g_{l,{\rm eff}}\mathbf{l} + g_{s,{\rm eff}}\mathbf{s} + g_{p,{\rm eff}}[Y_2, \mathbf{s}]$. The values of $g_{\rm eff}$ given by Table VI of [21] were obtained in perturbation theory and include first-order core-polarization, higher-order core-polarization and mesonic exchange current corrections as discussed in [21]. 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 contribition from the spin and orbital operators and B is the contribution from the tensor operator $g_{p,{\rm eff}}[Y_2, \mathbf{s}]$. 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) μ_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)$_{free}$=$(0 + 0)^2$ = 0 and B(M1)$_{eff}$=$(0 + 5.3)^2$ = 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)$_{free}$=$(3.6 + 0)^2$ = 13.3 and B(M1)$_{eff}$=$(5.4 - 4.8)^2$ = 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 [21] Hartree-Fock radial wavefunctions and effective charges of e_p=1.5 and e_n=0.6 is 23 e^2 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 300 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 wavefunctions. 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)$_{free-sh}$=$(2.2 + 0)^2$ = 4.8, B(M1)$_{eff-sh}$=$(3.5 - 5.0)^2$ = 2.1 and B(E2)=23 e^2 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 $g_{p,{\rm eff}}$ from its value of 3.21 in table VI of [21] to 2.6 or 1.7. The results for the single-particle $d_{5/2}$ to $g_{7/2}$ transition are B(M1) = 23 ($g_{p,{\rm eff}}$ = 2.6) are B(M1) = 7.8 ($g_{p,{\rm eff}}$ = 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 ($g_{p,{\rm eff}}$ = 3.2), B(M1) = 16 ($g_{p,{\rm eff}}$ = 2.7) and B(M1) = 6.2 ($g_{p,{\rm eff}}$ = 1.7), to be compared to the experimental value of 3.8(6). Thus overall agreement for l-forbidden M1 transitions in the ^{132}Sn and ^{208}Pb regions appears to require $g_{p,{\rm eff}} \approx 1.7$.

To conclude, 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 examining evidence for the shift of the proton $d_{5/2}$ orbit. We have shown that the M1 decay rate is extremely sensistive 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. The interpretation of the anomalously low-lying $5/2^+$ in ^{135}Sb remains a controversial issue. No doubt it will inspire strong experimental and theoretical efforts leading to a better understanding of this region of exotic nuclei and more refined theoretical models.

This research has been supported in part by the Swedish Research Council, US NSF grant PHY-0244453, Italian Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR) and the European Community-Access to Research Infrastructure contract No HPRI-CT 1999-00061. AK, WK and EW-M would like to thank OSIRIS group for their hospitality during the visit to Studsvik.

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