EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

21^{th} of April, 2008

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

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

Addendum: Measurements on heavy Ga nuclei at N=50

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Abstract

We propose to measure level lifetimes in the exotic nuclei of $^{77-82}$Ga in the vicinity of ^{78}Ni by the time-delayed technique. These are relatively simple nuclear systems with a few proton-particles and neutron-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, 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.

This study is a continuation and is also complementary to the one on the l-forbidden M1 transitions, between proton $d_{5/2}$ and $g_{7/2}$ orbits in the odd-proton systems above ^{132}Sn. The proposed studies on exotic Ga nuclei are also complementary to other experimental studies in these regions performed at ISOLDE using other advanced techniques.

The ISOLDE beam production of exotic Zn nuclei is unique. For this project we ask for 21 shifts of radioactive beam to study the decays of ^{81}Zn to ^{81}Ga (5 shifts), ^{80}Zn to ^{80}Ga (4 shifts), ^{79}Zn to ^{79}Ga (2 shifts), ^{78}Zn to ^{78}Ga (2 shifts), ^{77}Zn to ^{77}Ga (2 shifts) with additional 2 shifts for the time-response calibrations of the fast timing scintillators using the beams of ^{138}Cs and ^{88}Rb. We also ask for 3 shifts for an exploratory run to study the decay of ^{82}Zn to ^{82}Ga. In

addition we ask for 1 shift of radioactive beam for fine tuning of the HRS mass selection and electronics before the run.

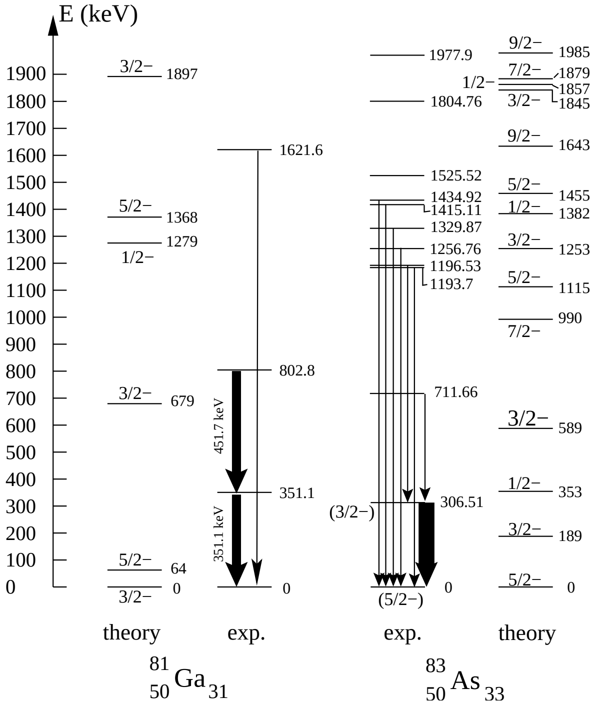

Figure 1: Tentative experimental level scheme for ^{81}Ga obtained recently at the PARRNe facility [1] compared with ^{83}As and the shell model calculations of Ji and Wildenthal [2]; this figure is taken from ref. [1].

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.

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

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 above 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.

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

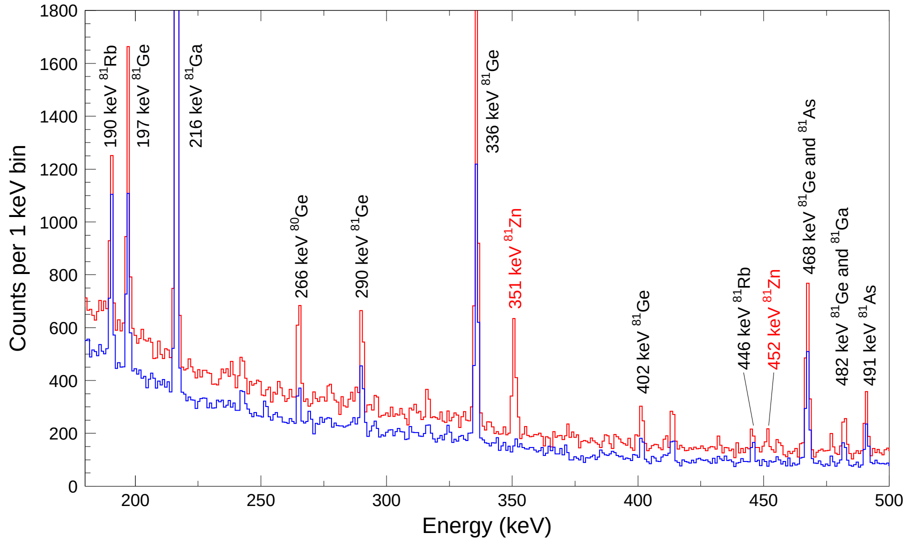

Figure 2: Part of gamma-ray spectrum measured [3] at ISOLDE on mass 81 in the 'laser on' (red) and 'laser off' (blue) mode, respectively, showing two peaks due to the 351 and 452 keV lines in ^{81}Ga. The measurement was performed using the fast timing station at ISOLDE in the summer of 2004. This very 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], although it was taken with our fast timing setup.

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.

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.

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

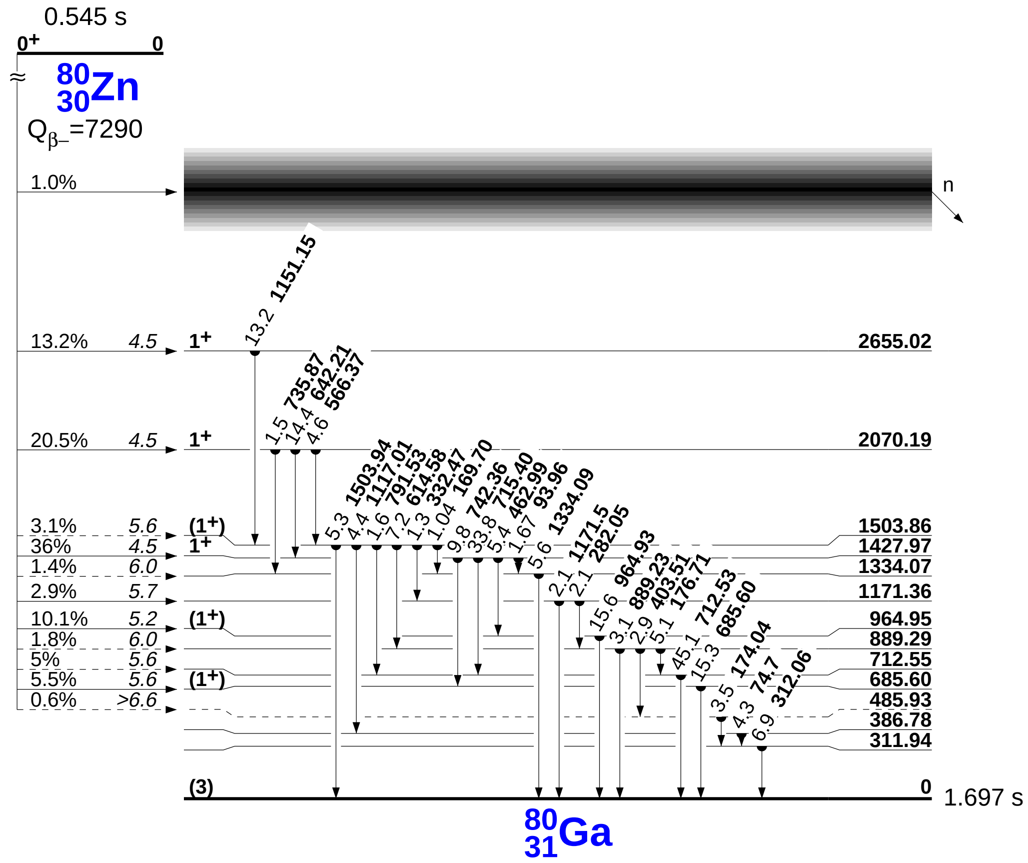

Figure 3: Level scheme in ^{80}Ga observed [7] in the beta decay of ^{80}Zn. Large number of low-energy transitions de-exciting levels, likely imply lifetimes in the nanosecond and subnanosecond range.

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. Report on the previous fast timing studies on ^{134}Sb, ^{135}Sb and ^{136}Te

Our IS441 collaboration has performed two series of fast timing measurements in 2006 and 2007 focused on the nuclei of ^{134}Sb, ^{135}Sb and ^{136}Te populated in the β decay of ^{134}Sn, βn decay of ^{136}Sn and via a chain of β decays from $^{136}\mathrm{Sn}\rightarrow^{136}\mathrm{Sb}\rightarrow^{136}\mathrm{Te}$, respectively. High purity Sn beams were extracted at the ISOLDE separator at CERN utilizing the molecular SnS^+ ions to isolate Sn from a strong isobaric contamination coming from less exotic fission products. In ^{134}Sb we have measured the lifetime of the 383 keV state as $T_{1/2}$=26(5) ps and branchings for weak γ-rays de-exciting the 383 and 330 keV states. The latter were found much smaller than previously reported. Our value of B(M1;$3^-\rightarrow2^-$) = 2.0(4) μ_N^2 is one of the fastest known M1 rates at low excitation energy in all nuclei. In ^{135}Sb we have identified the missing $1/2^+$ state at the energy of 523 keV. From its lifetime, $T_{1/2}$=1.24(6) ns, we have determined a very collective B(E2;$1/2^+\rightarrow5/2^+$) = 13.0(11) W.u. We have measured lifetime for the 2_1^+ state in ^{136}Te, $T_{1/2}$ = 42(8) ps, which implies a B(E2) value higher by $\sim$20% than the one previously reported. Results of shell model calculations were presented and compared with experimental data. The data are being analyzed by two research students. The early accounts were presented at the Zakopane School on Physics in 2006 [8], at the Vico Equence Conference in Italy and the INTC Conference in 2008. There are two publications currently in preparation and one already published [9] on top of the conference proceedings.

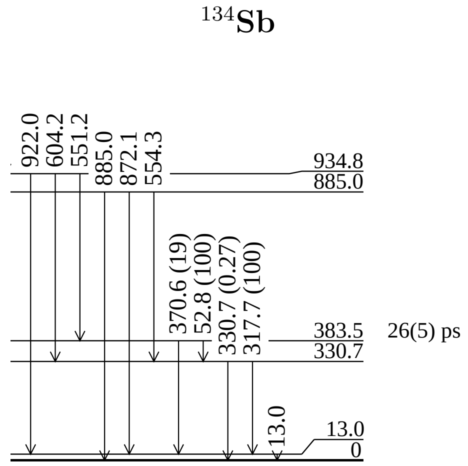

Figure 4: Partial level scheme for the decay of ^{134}Sn to ^{134}Sb determined in our study. The spin/parity for the lowest levels are (starting from the bottom): 0^-, 1^-, 2^- and 3^-, respectively.

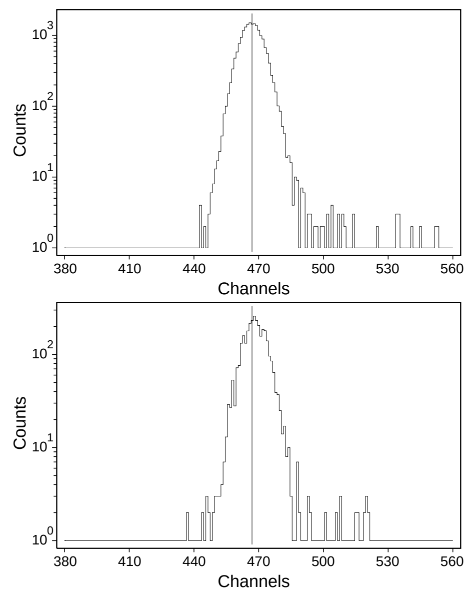

Figure 5: Time-delayed spectra started by β events and stopped by the 317-keV γ rays detected in the BaF_2 crystal. In the TOP spectrum (reference semi-prompt spectrum) the second coincidence γ ray detected in Ge was the 554-keV transition, while in the shifted BOTTOM spectrum the gate was set on the 551-keV transition. The vertical line identical in both spectra, shows the mean position of the TOP spectrum. The displacement of the centroid of the BOTTOM spectrum from the vertical line represents the meanlife of the 383-keV level in ^{135}Sb. It gives the level half-life of $T_{1/2} = 26(5)$ ps.

Our interest in the M1 transition rates in ^{134}Sb was inspired by the shell model calculations by Vadim Isakov. These calculations, which were recently published [10] predict the B(M1) values for the lowest multiplet to be exceptionally fast of the order of $\sim$1.5 μ_n^2.

Table 1: Comparison of the experimental $B(M1)$ and $B(E2)$ values and the shell model calculations by A. Brown (labelled AB), A. Covello and A. Gargano (CG) and V.I. Isakov (IS). The B(M1) and B(E2) values are in the units of μ_N^2 and e^2fm^4, respectively.

Nucleus	$J_i \rightarrow J_f$	$X\lambda$	$B(X\lambda)_{exp}{}^1$	$B(X\lambda)_{th}^{AB}$	$B(X\lambda)_{th}^{CG}$	$B(X\lambda)_{th}^{IS}$
^{134}Sb	$3_1^- \rightarrow 2_1^-$	M1	2.0(4)	1.60	1.39	1.81
	$3_1^- \rightarrow 1_1^-$	E2	118(26)	84	115	116
	$2_1^- \rightarrow 0_1^-$	E2	429(238)	90	123	104
^{135}Sb	$1/2_1^+ \rightarrow 5/2_1^+$	E2	527(26)	678	566	
	$5/2_1^+ \rightarrow 7/2_1^+$	E2	≤54	23	32	
	$5/2_1^+ \rightarrow 7/2_1^+$	M1	≤0.00030	0.0022	0.0040	
^{136}Te	$2_1^+ \rightarrow 0_1^+$	E2	206(30)^2			
	$2_1^+ \rightarrow 0_1^+$	E2	245(50)	452	360	

Additional motivation was provided by the need to establish B(M1) values in the vicinity of ^{135}Sb in order to understand better the properties of the latter nucleus. Note, however, that similar predictions for ultra-fast M1 transitions for an equivalent multiplet in ^{210}Bi were not confirmed experimentally. For the $2_1^- \rightarrow 1_1^-$ transition the predicted values for B(M1) ranged between 1.6−3.1 μ_N^2, and yet the measured [11] value is only 0.16 μ_N^2. The reason for the discrepancy is not clear. One suggestion [11] was that the measurement could have been distorted by time delayed components coming from side feeding.

Using the β-Ge-Ge data we have verified the previously proposed [12] level scheme for ^{134}Sb, and determined the intensities of weak γ rays de-exciting the the 383 and 330 keV states, see Fig. 1. Moreover, we have measured the lifetime of the 383 keV state as $T_{1/2}$ = 26(5) ps. Using these results, which are summarized in Fig. 4, we have obtained the experimental B(M1) and B(E2) values presented in Table 1. The measured B(M1;$3^- \rightarrow 2^-$) value of 2.0(4) μ_N^2 is one of the fastest M1 rates for any transition at low excitation energy in all known nuclei. Such a high value for B(M1) is very well reproduced by the shell model calculations by B.A. Brown [13] (labelled AB), A. Covello and A. Gargano [14] (labelled CG), and Isakov *et al.*, [10] (labelled IS). It should be mentioned that the lifetime of the 2^- 330-keV level has not been measured. In order to estimate the B(E2) for the 330 keV transition, we have assumed that the B(M1;$2^- \rightarrow 1^-$) is 1.8 μ_N^2.

Unlike in the case of ^{210}Bi, the ultra-fast M1 rate is confirmed in ^{134}Sb. This represents a unique transition rate. We have made a compilation of the known M1 rates for medium-heavy nuclei (A≥30) and for levels below 3 MeV in the excitation energy. There is a small number of cases where the B(M1) values of ~ 1 μ_N^2 are listed, however, many of them are not reliable due to the poorly determined level lifetime or the very weak γ-ray branching ratio. Thus the number of reliable cases, like ^{134}Sb, is indeed very small.

^{135}Sb

A number of low-lying states have been observed [15] in ^{135}Sb, but not the $1/2^+$ state predicted [15] at the excitation energy between 527 and 735 keV. Such a state was not expected to be significantly populated in the β decay of the $7/2^-$ ground state in ^{135}Sn. We have succeeded in the identification of this state via the β-delayed neutron decay of

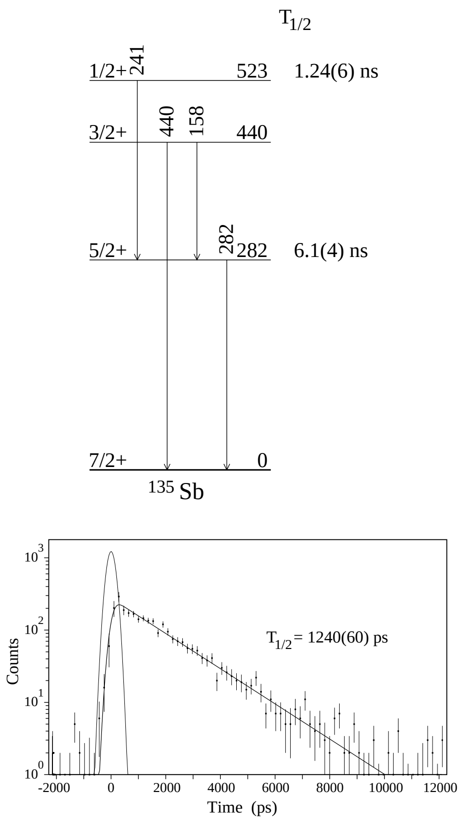

Figure 6: TOP: partial level scheme for the βn decay of ^{136}Sn to ^{135}Sb. BOTTOM: time delayed spectrum started by β events and stopped by the 241-keV γ rays detected in the BaF_2 crystal when the 282-keV transition is selected in the Ge detector. The slope is due to the lifetime of the 523-keV level in ^{135}Sb of $T_{1/2}$ = 1.24(6) ns.

the 0^+ ground state in ^{136}Sn. In this decay we have observed two γ-rays in coincidence with the 282 keV ground state transition in ^{135}Sb, see Fig. 6. The 158 keV line de-excites the known [15] $3/2^+$ state at 440 keV, while the 241 keV transition de-excites a new state at 523 keV. This state must have the spin and parity of $1/2^+$, since states of spin $3/2^+$ and higher were already observed [15] in the β decay of ^{135}Sn. There are only two low-spin states predicted [15] below 1.2 MeV in the excitation energy: the $1/2^+$ and $3/2^+$ states. Both of them are observed in the βn decay of ^{136}Sn, with the $1/2^+$ state being populated significantly stronger. Note that the predicted value of 527 keV by the AB calculations [15] (which included an explicit shift of 300 keV between the $d_{5/2}$ and $g_{7/2}$ orbits) comes very close to the experimental energy of 523 keV.

There is one more argument supporting the $1/2^+$ spin assignment for the 523-keV state, namely this state feeds the $5/2^+$ level at 282 keV via an E2 transition, necessitating the lifetime for the upper state of the order of a few ns. Indeed, the new state has a half-life of 1.24(6) ns, see Fig. 6, yielding a surprisingly collective B(E2) shown in Table 1. The shell model calculations reproduce this collective E2 rate quite well.

^{136}Te

The structure of ^{136}Te is also very simple with two valence neutrons and two valence protons beyond the doubly magic ^{132}Sn. Recently a very low B(E2;$0^+ \rightarrow 2^+$) value was reported [16] for ^{136}Te almost equal to the one for ^{134}Te (at N=82), which is at variance with the behavior of the Xe and Ba isotopes. This value is also lower than the predictions of shell-model calculations including those shown in Table 1. Using the Advanced Time-

Delayed method, and thus utilizing the fully calibrated response of the timing γ detectors to within $\sim$1-2 ps, we have measured via the centroid shift technique, the half-life of the 606-keV 2_1^+ state in ^{136}Te as $T_{1/2}$ = 42(8) ps (preliminary value) yielding B(E2; $2_1^+ \rightarrow 0_1^+$) = 245(50) e^2fm^2. The new result implies a B(E2) value $\sim$20% higher than that measured before in better agreement with the model predictions, see Table 1.

5. Proposed Experiments: Technical Details

We will use the Advanced Time-Delayed method described in more detail in Refs.[4-6]. The experimental setup include five detectors positioned in a close geometry around the Al stopper where the mass separated beam is continuously deposited creating a saturated source. Time-delayed information is provided by the β- (START) and fast γ-detectors (STOP). For the latter we use a large BaF_2 scintillator of Studsvik design, and separately, a smaller cylindrical 2.5 cm in diameter and 2.5 cm in length $LaBr_3$(Ce) (provided by Saint Gobain) with an effective Ce doping of 5%. The $LaBr_3$ crystal has a similar time resolution than BaF_2 but about 3 times better energy resolution. In addition there are two Ge detectors with a relative efficiency of 60-100% each. Triple coincidence $\beta\gamma\gamma$(t) events are collected using the β-Ge-Ge, β-Ge-BaF_2 and β-Ge-$LaBr_3$ detectors. The first data set allowed to verify or construct the decay scheme. The second and the third data sets are analysed separately and allow for level lifetime measurements in the low picosecond to nanosecond range.

For the production of $^{77-82}$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 fast timing experiments we request the HRS separator. Our estimates of the beam time requests per each nucleus are based on the tests of the Zn beams in 2005 where in fact our fast timing setup was used (see Fig. 2).

The fast timing detectors and electronics will be provided by the Fast Timing Collaboration Pool of Electronics. Our collaboration will provide the Ge detectors, 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 the LA1 beam line.

6. Summary of beam requests

In total, we request 21 shifts with radioactive beams.

Nucleus	# of shifts	Separator	Target	Ion source
^{82}Zn	3	GPS/HRS	UC	RILIS (+quartz)
^{81}Zn	5	GPS/HRS	UC	RILIS (+quartz)
^{80}Zn	4	GPS/HRS	UC	RILIS (+quartz)
^{79}Zn	2	GPS/HRS	UC	RILIS (+quartz)
^{78}Zn	2	GPS/HRS	UC	RILIS (+quartz)
^{77}Zn	2	GPS/HRS	UC	RILIS (+quartz)
^{88}Rb	1	GPS/HRS	UC	SI
^{138}Cs	1	GPS/HRS	UC	SI
^{24}Na	0.1	GPS/HRS	UC	SI
total radioactive	21 (including 1 shift for tuning and setup)			

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