EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time-of-Flight Committee

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Total Absorption Spectroscopy Studies with the LUCRECIA setup

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for the ISOLDE TAS collaboration

Abstract

To fully characterize a beta decay, it is important to know the beta transition probability to each individual level in the daughter nucleus. This information is relevant for the understanding of the nuclear structure involved in the process (both the structure of the parent state and the daughter states) and can also be important for practical applications. In this document we report on the progress of our active experiments, IS440, IS539 and IS570, devoted to the determination of the B(GT) distribution in the decay of isotopes of Pb, Hg, Se and Ge.

Experiments and remaining shifts: IS440 – 6 shifts, IS539 – 5.5 shifts, IS570 – 0 shifts

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Experimental setup/technique

Because of the nature of beta decay, the information on the decay probability to a particular level is commonly obtained in an indirect way from experiments using Ge detectors. The first step in the analysis of such experiments is the construction of the level scheme of the daughter nucleus from gamma coincidence relations. Then, once the level scheme is determined, from the gamma intensity balance populating and de-exciting the levels, the beta probability to the levels is deduced. Due to the low efficiency of standard Ge setups used in such experiments the beta decay probability to a particular level can be determined incorrectly. This systematic error is known in the literature as the Pandemonium effect [Hardy].

The total absorption spectroscopy technique is widely accepted as the only technique that can provide beta decay transition probabilities free of the Pandemonium effect. The technique is based on the detection of the gamma cascades that follow the beta decay using highly efficient detectors (see for example [Rubio, Tain]). This experimental method along with the complex data analysis that it involves has proved to be an invaluable tool in nuclear structure studies [Nacher, Poirier, Perez, Estevez] as well as practical applications [Algora, Fallot] and more recently in astrophysical applications [Tain2].

At ISOLDE a total absorption spectrometer (TAS) Lucrecia was installed in the framework of the Strasbourg – Madrid – Surrey – Valencia international collaboration. The Lucrecia TAS is one of the largest total absorption spectrometers available in the World. It is composed of one NaI mono-crystal of cylindrical shape of 38 cm diameter and 38 cm length, which is read by 8 photomultipliers. The detector has approximately 90 % efficiency for mono-energetic gamma rays in the range from 300 to 3000 keV, which implies an efficiency of almost 100 % for gamma cascades. The TAS setup can be combined with ancillary detectors: an X-ray detector to select the electron capture (EC) component of the decay or beta detectors for selecting coincidences with the betas. In many applications the EC component provides isotopically very clean decay data.

The Lucrecia detector has been used for nuclear structure studies in the A~80 and A~190 regions [Nacher, Poirier, Perez, Estevez], in particular in an application related to the determination of the shape of the nucleus based on the measurement of the beta strength to the levels in the daughter nucleus. In the following we will present the status of recent and current studies performed in the A~190 and A~70 regions.

Status report for IS440

Title: Shape effects along the Z=82 line: study of the beta decay of ^{188,190,192}Pb using total absorption (http://cds.cern.ch/record/887432/files/intc-2005-027.pdf)

Spokespersons: A. Algora, B. Rubio, W. Gelletly

Accepted isotopes: ^{188,190,192}Pb

Performed studies: The main goal of the proposal was to study the beta decay of ^{186,188,190,192}Pb isotopes using the total absorption technique. Theoretical calculations performed by Sarriguren et al. [Sarriguren, Moreno] showed that there are clear differences in the beta strength distribution in the daughter nuclei depending on the assumed deformation for the parent nucleus. This information can be used to infer the shape of the decaying state if combined with a proper measurement of the beta strength. Our idea was to study the feasibility of these studies in order to provide an additional method of study of nuclear shapes in this region of particular interest from the perspective of shape coexistence. This possibility was already studied in the A~80 region [Nacher, Poirier, Perez]. Concerning the experiment, TAS measurements were performed for the decay of the ^{188,190,192}Pb isotopes. Test data were also taken for half an hour on the decay of ^{186}Pb to determine the feasibility of a later study. The TAS data have been analyzed (^{188,190,192}Pb) and the results showed a spherical character of the studied nuclei (^{188,190,192}Pb) in their ground states in agreement with earlier results [DeWitte]. The analyses of the ^{188,190,192}Pb decays were part of the thesis work of E. Estevez (Ph.D Thesis, University of Valencia, 2012). The ^{190,192}Pb results have been published in [Estevez].

Future plans: Apart from the small amount of information available in the literature**,** the analysis of the ^{188}Pb TAS decay showed that the results of high-resolution studies of the decay of this nucleus to ^{188}Tl are very incomplete. We request to use the still available 6 shifts for high-resolution studies that will allow us to perform a better analysis of the TAS data of the ^{188}Pb isotope, to obtain information on possible beta-delayed particle emission of this decay and to prepare for a future TAS study of ^{186}Pb. For the beta decay of this last isotope nothing is presently known from high-resolution studies. The TAS study of ^{186}Pb requires improvements in the presently available tape station at the TAS setup. We are presently refurbishing a tape station at IFIC, to replace the one presently available at Lucrecia. This new tape station will work under vacuum and will allow us to perform measurements using shorter tape and counting cycles, which are not possible with the present system.

Future plans with <u>available</u> shifts:

(i) Envisaged measurements and requested isotopes

We propose to perform a high-resolution measurement of the decays of ^{186,188}Pb using the ISOLDE Decay Station (IDS) setup in combination with a particle detection setup for the measurement of conversion electrons. This idea has been already put forward in the IDS collaboration meetings in order to organize it within the IDS measurement campaigns. The IDS collaboration is at present developing an electron conversion setup for the IDS based on SPEDE [Papadakis] detectors.

The reasons for these measurements are the following: nothing is known from the decay of ^{186}Pb (populated levels) and very little is known from the decay of ^{188}Pb. The TAS analysis performed already for ^{188}Pb and presented in the thesis of E. Estevez, can be improved if a better high-resolution study of this decay is available. In the future we would like to perform a TAS study of the decay of ^{186}Pb, of particular interest because of the shape coexistence phenomena [Andreyev], which requires high-resolution data for the analysis. For the continuation of the TAS studies of the Pb isotopes (^{186}Pb) a future addendum is planned and as mentioned earlier we are upgrading a tape station to be able to measure such a case.

(ii) Have these studies been performed in the meantime by another group?

Not to our knowledge

(ii) Number of shifts (based on newest yields) required for each isotope

isotope	**yield (ions/μC)**	**target – ion source**	**shifts (8h)**
^{186}Pb	4.6E+04	UC_x - RILIS (Pb)	4
^{188}Pb	1.7E+06	UC_x - RILIS (Pb)	2

Total shifts: 6 shifts

Status report for IS539

Title: Shape effects in the vicinity of the Z=82 line: study of the beta decay of ^{182,184,186}Hg (http://cds.cern.ch/record/1411581/files/INTC-P-328.pdf)

Spokesperson: A. Algora, L.M. Fraile, E. Nácher

Accepted isotopes: ^{182,184,186}Hg

Performed studies: The experiment was aimed at the investigation of shape co-existence in the region of Hg/Pb nuclei by means of the study of the beta decay of the neutron-deficient ^{182,184,186}Hg nuclei via total absorption spectroscopy. The measurements of the Gamow-Teller strength distribution can be related to the shape of the ground state of the decaying Hg nuclei [Moreno] as in the case of the Pb isotopes already mentioned. The experiment was successful in collecting sufficient data on ^{182}Hg and ^{186}Hg, including isotope selective X-ray coincidence gates. One full shift was devoted to the measurement of ^{184}Hg, but given the fact that the analysis is based on complex coincidence conditions, it is difficult to evaluate the quality of the ^{184}Hg data at this moment (analysis is in progress).

The analysis of this experiment has been very challenging. The TAS spectrum of the studied Hg decays is marked by a large amount of beta feeding at very low excitation in the Au daughter (see Figure 1 for the ^{186}Hg case). We started the analysis with the ^{186}Hg decay because we thought that this should be the simplest case to analyse considering the relative completeness of the level scheme of the daughter at low excitation energies from high-resolution studies. Unfortunately in the earlier attempts the methods of analysis used in previously studied cases were not able to reproduce the measured TAS spectrum. We found later that the reason for that is related to the way we generate the response function for the analysis of the decays. In the electron capture (EC) analysis, the TAS spectrum was cleaned of isobaric contaminants using gates set on the Au X-rays (tag on the EC component). The decay of ^{186}Hg proceeds mainly to a 1^+ state (approximately with a 70 % branch) that de-excites by two gamma rays in a 112-251 keV cascade. These gamma rays are moderately converted, which also produces additional X-rays. The cause of the difficulties faced in this analysis was the penetration and summing of the X-rays associated with the 112-251 keV gamma cascade transitions. The summing of gamma transitions and X-rays was not an issue in earlier studies in the A~70 region, because the corresponding low energy X-rays generated were absorbed in the dead material layers of the TAS setup. In the Pb studies this effect was not clearly noticeable because of the lack of concentration of the feeding in a few states that decay with moderately converted lines contrary to what happens in the Hg decays. Internal conversion is taken into account in the calculation of the response function used in our conventional TAS analysis, but the explicit generation of X-rays after conversion was not introduced until now in the calculation of the full response because it was not considered necessary.

After realizing this problem new analysis codes have been developed. They take into account the generation of X-rays and accordingly the possible summing with X-rays. This is the main cause of the delay in reaching the results. Using the new codes we have been able to analyse the ^{186}Hg decay recently and a publication [Ganioglu] of these results is in preparation (see Figures 1, 2). Following this case the ^{182,184}Hg cases will be analysed (all calibrations and the necessary spectra are already generated).

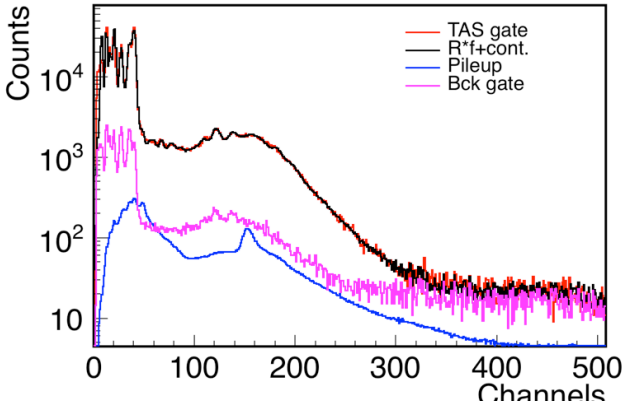

Figure 1. Comparison of the measured TAS spectrum (red) with the generated spectrum after the analysis (black) for the decay of ^{186}Hg. The contributions of the contaminants (pileup and background) in both spectra are also shown. The black spectrum (analysis) is obtained after multiplying the response function R with the feeding distribution determined in the analysis. To the contribution R*f, the contaminants are added (pileup and background) for the comparison with the experimental spectrum. The experimental spectrum is generated using a gate on the X-rays of ^{186}Au (EC component)

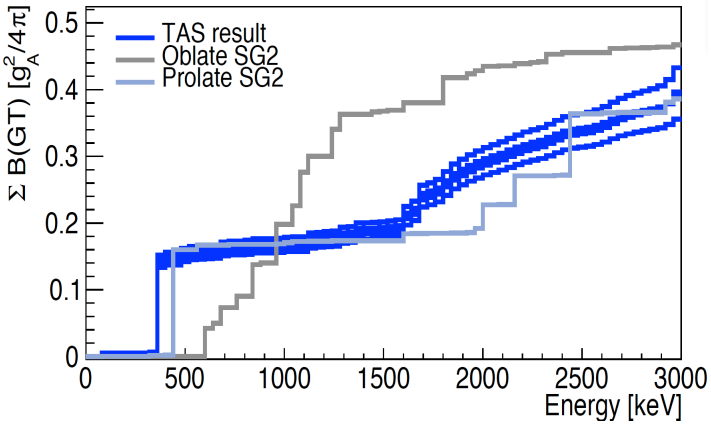

Figure 2. Comparison of the beta strength deduced from our analysis with theoretical calculations using the SG2 force (P. Sarriguren, private communication) for the decay of ^{186}Hg. The different blue curves show the effect of the uncertainty of the $T_{1/2}$ and the decay Q value on the strength calculation with our new experimental results. The preliminary results show a strong prolate contribution in the ground state of ^{186}Hg.

Future plans: We would like to use the remaining shifts for a high-resolution and beta delayed particle emission study of the decays of the relevant isotopes. For that we would like to use the ISOLDE Decay Station (IDS), which can provide highly efficient setups for gamma and charge particle detection.

In addition, once the analysis of the studied isotopes is in a more advanced status, an **addendum** is planned for the study of the odd cases. They are also of particular interest from the point of view of shape changes and shape coexistence. This addendum is not discussed here, since it will be presented at a later stage, once the analysis of all even isotopes is published. The theoretical calculations are already performed [J.M. Boillos & P. Sarriguren]. For the study of the odd-A Hg isotopes, such as ^{185}Hg, we will require isomerically pure beams provided by RILIS, in order to isolate the beta-decaying isomer. Isomer selectivity will make it possible to probe the shape of the co-existing decaying isomers in Hg. The new VADLIS, a combination of the ISOLDE RILIS and ISOLDE's FEBIAD type ion source (VADIS), coupled to a molten Pb metal target will be required for this purpose. The VADIS has already been successfully tested on-line for mercury beams [Day Goodacre].

Future plans with <u>available</u> shifts:

(i) Envisaged measurements and requested isotopes

The remaining shifts will be used to perform a high-resolution study of the $^{182\text{-}186}$Hg decays at the IDS in combination with a particle detection setup. These studies can give us the opportunity to have a more complete picture of the low excited states in the daughter nuclei, which can be of particular interest for ^{182,184}Hg. This information is relevant for the TAS analysis.

(ii) Have these studies been performed in the meantime by another group?

Not to our knowledge

(iii) Number of shifts (based on newest yields) required for each isotope

For these nuclides a molten Pb target coupled to a plasma ion source are better than UC_x + RILIS. The quoted numbers are obtained by scaling up by a factor of 5 those reported in the ISOLDE DB for the SC with Molten Pb metal and MK6 [Stora]. In addition no isobaric contaminations, such as Tl, have been observed.

Taking into account that the production of the different isotopes is more than enough for our measurement, our limitation in activity is imposed by the maximum counting rate accepted by the Germanium detectors. The distribution of shifts has then been estimated assuming a beta-delayed alpha branch of 10^{-5} – 10^{-4}. We plan to use a highly efficient setup for beta-delayed particles based on the use of six DSSD telescopes in close geometry, covering 70% of solid angle, and a vacuum chamber designed to maximize the gamma-ray transmission and detection efficiency, namely the one designed for experiment IS577.

isotope	**yield (ions/μC)**	**target – ion source**	**shifts (8h)**
^{182}Hg	4.0E+07	Pb - VADIS	1.5
^{184}Hg	6.5E+08	Pb - VADIS	2.5
^{186}Hg	2.8E+09	Pb - VADIS	1.5

Total shifts: 5.5 shifts

Title: Beta decay of the N=Z, rp-process waiting points: ^{64}Ge, ^{68}Se and the N=Z+2: ^{66}Ge, ^{70}Se for accurate stellar weak-decay rates (http://cds.cern.ch/record/1551738/files/INTC-P-374.pdf)

Spokesperson: E. Nácher, A. Algora, C. Domingo

Accepted isotopes: ^{68,70}Se

Performed studies: in May 2016 we performed a TAS experiment at ISOLDE that was aimed at measuring the beta decays of ^{68,70}Se for their importance in stellar weak-decay rates in the rp-process. Our plan was to extract the radioactive Se species in the molecular form SeCO to avoid the isobar contamination that would happen at mass 68 or 70. However, due to a high level of sulphur contamination of the target (mass marker), instead of ^{68}SeCO, at mass 96 (68+12+16), we could only see ^{64}GeS at the same mass (64+32). The decays of ^{64,68}Ge were also part of the proposal, and were only rejected by the INTC committee because it was not clear that ISOLDE could provide enough yields. Since we had enough production/extraction of ^{64}Ge, namely 200 ions/μC in the target position (measured at the tape station by J. Ballof), we decided to use our shifts to measure the beta decay of ^{64,68}Ge and the daughters, and leave ^{68,70}Se for the future (an addendum to get more shifts to measure ^{68,70}Se is foreseen). Over the 9 shifts that we used we could perform the total absorption spectroscopy of the beta decay of ^{64,65,66}Ge and their daughters ^{64,65}Ga (we could not measure the decay of ^{66}Ga because our tape-transport system broke during the last shift of the run). The analysis of the decay of ^{64}Ge and ^{64}Ga is now going on and part of it was presented in the last *Topical Workshop on Modern Aspects in Nuclear Structure, Bormio, March-2018*. The data have been cleaned and currently we are working on Monte Carlo simulations of the response function of the detector in order to proceed to the data unfolding. Already from the clean data and the Monte Carlo simulations based on the ENSDF decay data we observe that, the most important part of the decay as far as B(GT) determination is concerned, crucial for weak-decay rates, has remained unobserved in the previous experiments and has been measured now for the first time (see Figure 3).

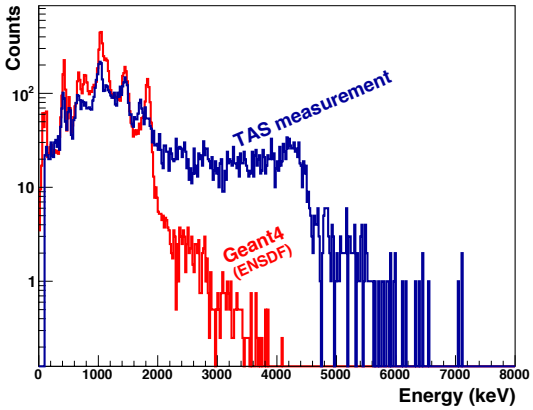

Figure 3. X-ray gated TAS spectrum measured during the IS590 run (blue) compared to the Geant4 simulation (red) of the same decay with the same TAS detector (data from ENSDF). Both histograms contain the same number of counts.

Future plans: we plan to continue with the analysis of the decay of ^{64}Ge and ^{64}Ga and present the status of the analysis in the ISOLDE Workshop. It will take time to finish since no student is devoted to do this analysis at present. Once we have some preliminary results on ^{64}Ge we plan to submit an addendum to the proposal to request some shifts for the measurement of the Se isotopes of interest. To perform such measurements there are two main requirements. First, we need to refurbish our tape-transport system because in its current status it cannot hold the required vacuum at the implantation point for short cycles. We are already building a new tape-transport system that operates fully in vacuum and plan to finish and install it during the long shut down period. Second, it needs to be proved that SeCO beams can be reliably produced at ISOLDE, since recent attempts have not been successful [Johnston].

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Appendix

IS440:

Publications

M. E. Estévez Aguado et al., Phys. Rev. C 92, 044321 (2015)

B Rubio, W Gelletly, A Algora, E Nacher and J L Tain, J. Phys. G: Nucl. Part. Phys. 44 (2017) 084004 (this publication is a summary of the work performed at Lucrecia)

Theses

M. E. Estevez, PhD thesis, TAS measurements for neutrino physics and nuclear structure: study of the beta decays of ^{150}Er, ^{152,156}Yb and ^{188,190,192}Pb, Univ. of Valencia, 2012, Summa Cum Laude, supervisor: A. Algora.

IS539:

A publication [E. Ganioglu et al.] is presently in preparation for the analysis of the B(GT) distribution for the ^{186}Hg decay

IS570:

Analysis is on-going