Precise half-life measurement of $^{110}$Sn and $^{109}$In isotopes

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The half-lives of $^{110}$Sn and $^{109}$In isotopes have been measured with high precision. The results are $T_{1/2} = 4.173 \pm 0.023 \text{ h}$ for $^{110}$Sn and $T_{1/2} = 4.167 \pm 0.018 \text{ h}$ for $^{109}$In. The precision of the half-lives has been increased by a factor of 5 with respect to the literature values which makes results of the recently measured $^{106}$Cd($\alpha, \gamma$)$_{110}$Sn and $^{106}$Cd($\alpha$,p)$_{109}$In cross sections more reliable.

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The stellar nucleosynthesis process originating heavy, proton rich isotopes - the so-called p-nuclei - is the astrophysical p-process [1]. The modeling of the p-process requires the knowledge of the nuclear reaction rates associated with the p-process reaction network. Due to lack of experimental data, these reaction rates are generally calculated with Hauser-Feshbach statistical model calculations [2, 3] which use nuclear physics inputs such as optical model potentials, nuclear level densities, ground state properties, $\gamma$-ray strength functions, etc. The ambiguities of these input parameters introduce considerable uncertainties into the reaction rate predictions and subsequently into the p-process model simulations. The reliability of the calculations can be checked by comparison with the experimental cross sections. This requires data in the relevant stellar energy range, known as Gamow window. Of particular relevance is the study of p-process reaction rates on neutron deficient nuclei in the Z=50, N=50 mass range. These reactions are associated with the production of the light p-nuclei, $^{92,94}$Mo, $^{96,98}$Ru up to $^{113}$In. In these cases p-process model predictions differ substantially from the observed p-process abundances [4]. While many alternative scenarios have been offered to explain these discrepancies it is clearly necessary to probe the reliability of the presently used nuclear physics input in calculating the p-process reaction rates in this mass range near the closed shell N=50 nuclei. Recently, a number of experiments has been devoted to the study of ($p, \gamma$) and ($\alpha, \gamma$) reaction cross sections at the astrophysically relevant energies and the results are compared with the model calculations (see e.g. [4]). Generally, the models are able to reproduce the experimental results reasonably well, however, deviations up to a factor of 2 have been observed. Comparing the experimental data with the model predictions could help find the best input parameter sets for the statistical model.

The activation technique has developed as the most important tool in ($p, \gamma$) and ($\alpha, \gamma$) p-process experiments [4, 5, 6, 7, 8, 9, 10]. In this technique the cross sections are determined by measuring the decay activity of the reaction product. The resulting cross sections are directly correlated with the half-life of the reaction product; deviations, ambiguities, and uncertainties in available half-life data translate directly into uncertainties of experimental cross section results.

Recently, the $^{106}$Cd($\alpha, \gamma$)$_{110}$Sn and $^{106}$Cd($\alpha$,p)$_{109}$In cross sections have been measured in the energy range relevant for the astrophysical p-process [11] and the results are compared with the model calculations. In order to reduce the systematic error of the measurement, the reaction has been measured independently in two laboratories. All major error sources such as target thickness, detector efficiency, charge collection, and counting statistics are determined independently in the two measurements thereby making the experimental results more reliable. The decay parameters such as the half-life of the reaction products, however, enter the analysis of both measurements. The error of the half-life is thus reflected directly in the error of the derived cross sections.

The half-lives of the reaction products found in the literature are $T_{1/2,adopted}^{(110)Sn} = 4.11 \pm 0.10 \text{ h}$ [12] and $T_{1/2,adopted}^{(109)In} = 4.2 \pm 0.10 \text{ h}$ [13]. These half-life values have relatively large errors and are based on measurements carried out many decades ago. The half-life of $^{110}$Sn is based on two experiments; one is only available as unpublished thesis result [14] while only very limited experimental detail is provided by the second work [17]. The situation is somewhat better in the case of $^{109}$In, where the compilation is based on four works [16, 17, 18, 19]. However, the quoted half-lives have large errors and there is no detailed discussion about the experimental setup and data analysis in those works. An independent confirmation of these results is in particular necessary to provide reliable reference data for the $^{106}$Cd($\alpha, \gamma$)$_{110}$Sn and $^{106}$Cd($\alpha$,p)$_{109}$In activation measurements. The aim of the present work is to check the reliability of the adopted half-life values and to reduce their errors.

In the present experiment the half-lives of $^{110}$Sn and $^{109}$In isotopes have been measured simultaneously. The sources were produced by bombarding a $^{106}$Cd target...
The size of the beam spot and hence the size of the source was about 500 nA and the irradiation lasted for 10 hours. The target was prepared by evaporating highly enriched metallic $^{106}$Cd (96.47% enrichment) onto a 3 µm thick Al foil. The thickness of the target was roughly 400 µg/cm². The α beam intensity was about 500 nA and the irradiation lasted for 10 hours. The size of the beam spot and hence the size of the source was roughly 8 mm in diameter. The $^{110}$Sn isotope was produced by the $^{109}$Cd($\alpha$,γ)$^{110}$Sn reaction. There are two ways to produce the $^{109}$In isotope: directly by the $^{106}$Cd($\alpha$,p)$^{109}$In reaction or since $^{109}$Sn decays to $^{109}$In, by the $^{106}$Cd($\alpha$,n)$^{109}$Sn reaction. In order not to have additional feeding to $^{109}$In during the half-life measurement (which might distort the result), the half-life of $^{109}$In can be determined precisely only after $^{109}$Sn has decayed completely ($T_{1/2} = 18.0 \pm 0.2$ min); therefore, the gamma-counting has been started 6 hours after the end of the irradiation.

The irradiated sample has been placed in front of a 40% relative efficiency HPGe detector in a holder fixed rigidly onto the end cap of the detector. Directly at the back of the sample a $^7$Be source has been put in the holder in order to be able to control any possible change in the detection geometry or the efficiency of the detector during the counting. The system was shielded by 5 cm thick lead. The decay of the $^{110}$Sn and $^{109}$In isotopes has been followed for 24 hours (roughly 6 half-lives) recording the γ-spectra in every 15 minutes. Altogether 96 spectra were collected. Fig. 1 shows a typical γ-spectrum.

The electron capture decay of $^{110}$Sn is followed by the emission of a single 280 keV γ-radiation with 100% relative intensity. The detection of this line was used to deduce the half-life of $^{110}$Sn. At the beginning of the counting the intensity of this line was roughly 6000 counts in 15 minutes which went down to about 100 counts in 15 minutes by the end of the measurement. The strongest γ-radiation following the β-decay of $^{109}$In is the 203 keV line which has a relative intensity of 74%. This line was used for the analysis. Its intensity reduced from about 67000 counts/15 min to 1200 counts/15 min in the course of the measurement.

The spectra were collected with 100 MHz Wilkinson type ADC with 8192 channel MCA having a built-in dead time correction. Owing to the very low counting rate, the dead time was always very low ranging from an initial value of $\approx 1%$ declining to a value of $\approx 0.1%$ by the end of the counting. Dead time corrections have been made for the final decay time analysis. To determine the effect of the dead time uncertainties, the decay time was determined assuming an initial dead-time between 2% and 0%. This changes the final half-life value by only $\approx 0.3%$; this uncertainty has been incorporated in the final error of the derived half-life (for the not normalized value, see Table. I).

The half-lives of the investigated isotopes were determined also by normalizing the intensities of the 203 and 280 keV peaks with the number of counts in the 478 keV peak coming from the decay of the $^7$Be reference source. In this case the slight change of the $^7$Be activity ($T_{1/2} = 53.22 \pm 0.06$ days, [20]) during the one day γ-counting has been taken into account. The counting rate of the 478 keV $^7$Be peak was about 900 counts in 15 minutes. The dead time correction affects equally the number of counts in the $^7$Be and $^{110}$Sn/$^{109}$In peaks; therefore, no dead time correction needs to be applied in the case of the normalized half-lives.

In all cases the half-lives have been determined from the parameters of the exponential fit to the measured data. As an example, Fig. 2 shows the decay curve of the $^{110}$Sn isotope without normalization.

Table I shows the results for both isotopes without and with normalization to $^7$Be. The two methods give the same result within the error bar for both isotopes indicating that there is no long-term instability in the detection system and the dead time correction is made properly. The weighted averages are listed in the last column of the Table. Since the two methods are statistically correlated, the error of the weighted average was chosen to be the error of the non-normalized value. Our final result for the half-life of $^{110}$Sn, $T_{1/2} = 4.173 \pm 0.023$ h, is slightly longer than the adopted value ($T_{1/2, adopted} = 4.11 \pm 0.10$ h) in the data compilations. The error is reduced from 2.4 to 0.5%. The obtained $^{109}$In half-life of $T_{1/2} = 4.167 \pm 0.018$ h is shorter than the adopted

| Isotope | Half-life [hours] | Without normalization | Normalized to $^7$Be | Weighted average |
|---------|-----------------|-----------------------|---------------------|-----------------|
| $^{110}$Sn | 4.179 ± 0.023 | 4.165 ± 0.035 | 4.173 ± 0.023 |
| $^{109}$In | 4.168 ± 0.018 | 4.166 ± 0.022 | 4.167 ± 0.018 |
FIG. 2: Decay of $^{110}$Sn measured for 24 hours. The points are the measured area of the 280 keV peak without the normalization with $^7$Be. The solid line is the exponential fit to the measurement.

Based on the new half-life values the uncertainty in the $^{106}$Cd($\alpha, \gamma$)$^{110}$Sn and $^{106}$Cd($\alpha,p$)$^{109}$In cross section measurements is significantly reduced and the comparison with statistical model calculations becomes more reliable.

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